

Actiflo® Carb Process in the Removal of a Series of Trace Organic
Compounds, as well as Phosphorus, in Addition to a
Conventional Wastewater Treatment Line



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Executive Summary

The concentration of Trace Organic Compounds (TOrcs) has increased in the wastewater stream as more people rely on these products for everyday uses. A better understanding of the removal of TOrcs in the wastewater treatment process is sought in many areas worldwide to reduce discharge into the environment and protect human health. Many TOrcs have poor removal in traditional primary and secondary treatment processes and information is still lacking on the fate of these compounds in the environment. Numerous systems have been used to remove TOrcs from drinking water or wastewater treatment facilities, but the results vary greatly.

Milwaukee Metropolitan Sewerage District (MMSD) and Veolia Water Milwaukee (VWM) were also interested in such questions and partnered with University of Wisconsin-Milwaukee (UW-M) and Dr. Rebecca Klaper in 2009-2010 to assess the occurrence of a large variety of TOrcs at successive stages of wastewater treatment and in the environment (Lake Michigan for instance), with samples collected at different times of the year. From this assessment study, it appeared that the average final removal of all compounds across all treatment dates was 56%, with a wide variation in the removal rates across various compounds. The literature demonstrates that the majority of TOrcs removal is completed through the secondary treatment process (activated sludge), and this study agreed with such a fact for the majority of compounds with high removal efficiencies.

A series of compounds however were still present in significant enough concentrations in the final effluent to warrant further evaluation on the potential for impacts on the environment and wildlife. These results prompted MMSD and VWM to engage in discussions about testing a process that would allow the removal of various TOrcs and Actiflo® Carb was proposed. This technology relies on the use of powdered activated carbon (PAC) which is recirculated in the process. Indeed, PAC is known for its ability to remove pesticides, taste-and-odor causing compounds, natural organic matter and many types of trace organic compounds (designation that includes Pharmaceuticals and Personal Care Products).

In addition, the removal of phosphorus to very low levels in wastewater treatment is a growing concern, in Wisconsin where the State regulatory agency has been considering lowering current discharge limits, and in many other States across the US as well. With the use of coagulant (metallic salts) in Actiflo® Carb (or Actiflo®), this process has the ability to perform high removal of Phosphorus.

The Actiflo® Carb pilot trailer was set up at the South Shore Water Reclamation Facility (Oak Creek, WI), and more specifically by the final disinfection basins in order to have access to secondary effluent (after activated sludge treatment).

After some initial batch tests that validated the type of activated carbon to be used into the system, two pilot testing phases were conducted, the first in April and the second from mid-July to mid-August. The same schedules were followed for each of these periods, while having two

separate phases allowed to account for the impact of seasonality. TORCs samples were taken and sent to Dr. Rebecca Klaper's lab while the phosphorus samples were sent to the MMSD lab. Following the previous research study led by Dr. Rebecca Klaper on the occurrence of TORCs within the wastewater treatment line, the following series of compounds was selected: Carbamazepine (Anti-epileptic), Fluoxetine (Anti-depressant), Trimethoprim (Antibiotic), Sulfamethoxazole (Antibiotic), Ofloxacin (Antibiotic), Diltiazem (Anti-hypertension), Diphenhydramine (Anti-histaminic), Triclosan (Biocide), Naproxen (Anti-inflammatory), Caffeine (Tracer).

The initial results from batch tests with two different PACs (coconut and wood based) pointed out that the wood-based one was the most efficient in removing the series of selected compounds, likely due to its diversity in porous distribution. This powdered activated carbon was hence chosen for the pilot testing.

Several parameters considered for their influence on the process performance during the pilot trials and TORCs removal were evaluated all along. The average TORCs removal rate across all compounds and treatment conditions reached 75%:

- Two PAC dosages, 10 and 20 mg/L, were tested and showed that higher removals were obviously obtained by using a higher dose. However, a dosage of 10 mg/L still obtained 68% of average removal across all TORCs (83% in the case of 20 mg/L dosage). With the 20 mg/L PAC dosage, 8 compounds out of 10 were removed above 75%;
- Spiking was used on the influent coming to the pilot unit to ensure that significant levels of concentrations were tested. The process showed very good capability in maintaining performance in removing TORCs from influent concentrations much higher than the observed annual averages;
- Overall, regarding average removal, the order of performance for all 10 compounds is the following: Diltiazem, Trimethoprim, Triclosan, Diphenhydramine, Carbamazepine, Ofloxacin, Sulfamethoxazole, Fluoxetine, Caffeine, Naproxen.

On the other hand, regarding phosphorus removal, effluent concentrations between 0.02 and 0.05 mgP/L have been consistently achieved while using coagulant (ferric chloride) dosages from 7 to 12 mg/L (expressed in metal) – while the influent (the treated wastewater plant effluent) presented P concentrations ranging from 0.28 to 0.77 mgP/L. Molar ratio (Fe concentration over P removal) between 7 and 17 have been observed for the process performance, which is expected for such low P removal achievements.

This is an interesting aspect with Actiflo® Carb, being able to target P removal at the same time as TORCs removal. Indeed, a regular approach would rely on Actiflo® (no carbon) to perform P removal, and such performance was confirmed by some tests at the end of each pilot phase. But the Actiflo® Carb proved to be as efficient in removing phosphorus.

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Acronyms

| | |
|-------|---|
| dP | Dissolved Phosphorus |
| d | Day |
| EBPR | Enhanced Biological Phosphorus Removal |
| h | Hour |
| HRT | Hydraulic Retention Time |
| Kow | Octanol-water Partition Coefficient |
| L | Liter |
| mg | Milligram |
| min | Minute |
| mL | Milliliter |
| MGD | Millions Gallons per Day |
| MMSD | Milwaukee Metropolitan Sewerage District |
| ng | Nanogram |
| OrP | Orthophosphate |
| P | Phosphorus |
| PAC | Powdered Activated Carbon |
| PAOs | Phosphate Accumulating Organisms |
| PPCPs | Pharmaceutical and Personal Care Products |
| SRT | Sludge Retention Time |
| SSWRF | South Shore Water Reclamation Facility |
| sqft | Square foot |
| TOrC | Trace Organic Compound |
| TP | Total Phosphorus |
| TSS | Total Suspended Solids |
| USEPA | United States Environmental Protection Agency |
| VWM | Veolia Water Milwaukee |
| WERF | Water Environment Research Foundation |
| WWTP | Wastewater Treatment Plant |

I. BACKGROUND AND OBJECTIVES

I.1. General Context

Because of concerns related to public and aquatic health, there is increasing interest in evaluating occurrence and removal of TOrcs during wastewater treatment and water reclamation. Milwaukee Metropolitan Sewerage District (MMSD) and Veolia Water Milwaukee (VWM) were also interested in such questions and partnered with University of Wisconsin-Milwaukee (UW-M) and Dr. Rebecca Klaper in 2009-2010 to assess the occurrence of a large variety of TOrcs at successive stages of the wastewater treatment and in the environment (Lake Michigan for instance), with samples collected at different times of the year. From this assessment study, it appeared that the average final removal of all compounds across all treatment dates was 56%, with a wide variation in the removal rates across various compounds. The literature demonstrates that the majority of TOrcs removal is completed through the secondary treatment process (activated sludge), and this study agreed with these findings for the majority of compounds with high removal efficiencies.

At the same time, the removal of phosphorus to very low levels in wastewater treatment is a growing concern, in Wisconsin where the State regulatory agency has been considering lowering current discharge limits, and in many other States across the US as well. Indeed, phosphorus is an important parameter to be looked at since this is an essential nutrient for the plants and animals that make up the aquatic food web. Since this is the nutrient in short supply in most fresh waters, even a modest increase in phosphorus can set off a whole chain of undesirable events in a stream including accelerated plant growth, algae blooms, and low dissolved oxygen levels resulting in the death of certain fish, invertebrates, and other aquatic animals.

MMSD and VWM then engaged in discussions about testing a process that would allow the removal of various TOrcs and Actiflo® Carb was proposed. This technology relies on the use of powdered activated carbon (PAC) which is recirculated in the process. PAC is known for its ability to remove, with proven efficiency (Vieno et al., 2007; Stackelberg et al., 2007; Soliman et al., 2007), pesticides, taste-and-odor causing compounds, natural organic matter and many types of trace organic compounds. With the use of coagulant (metallic salts) in Actiflo® Carb (or Actiflo®), this process has the ability to perform high removal of phosphorus.

I.1.1. Trace Organic Compounds Removal in Wastewater Treatment

The concentration of Trace Organic Compounds (TOrcs) has increased in the wastewater stream as more people rely on these products for everyday uses. A better understanding of the removal of TOrcs in the wastewater treatment process is sought in many areas worldwide to reduce discharge into the environment and protect human health. Many TOrcs may have poor removal

in traditional primary and secondary wastewater treatment processes and information is still lacking on the fate of these compounds in the environment. Numerous systems have been used to remove TORCs from drinking water or wastewater treatment facilities, but the results vary greatly.

In Milwaukee, a series of compounds appears to be still present in significant enough concentrations in the final effluent of the wastewater treatment facility to warrant further evaluation to determine the potential for some impacts on the environment and wildlife. Since discharge of treated wastewater effluent must protect beneficial uses of receiving streams, including fishing, swimming, recreation, and municipal drinking water supply, minimizing the discharge of TORCs is desirable.

Regarding TORCs removal in wastewater treatment, findings from previous studies have demonstrated that sorption onto suspended solids, aerobic and anaerobic biotransformation, chemical attenuation via processes such as hydrolysis, and volatilization are the primary removal mechanisms for TORC during conventional wastewater treatment (Clara et al., 2005; Stevens-Garmon et al., 2011). Aqueous solubility and hydrophobicity determine whether and to which extent compounds are physically removed. Physicochemical properties will influence whether a TORC will remain in the aqueous phase (like many of the acidic, neutral, and basic hydrophilic pharmaceuticals) or interact with solid particles (such as estrogens or certain antibiotics, which have a higher potential to be sorbed to sewage sludge). Sorption and volatilization are physical processes and their relevance for specific contaminants can be predicted using physicochemical property information, like the octanol-water partition coefficient (K_{ow}) (Rogers, 1996). Structural properties of TORC will also determine the likelihood for biotransformation of the parent compound. For degradable compounds, several operational factors such as sludge retention time (SRT) (Oppenheimer et al., 2007) seem to be correlated with removal, resulting in lower effluent TORC concentrations for longer SRTs.

1.1.2. Phosphorus Removal in Wastewater Treatment

Different approaches may be chosen when dealing with phosphorus removal in wastewater treatment and are for the most driven by the regulatory limits for phosphorus discharge. Among these approaches, the following can be listed:

- Physical processes, filtration for particulate phosphorus or membrane technologies;
- Chemical processes, like precipitation or physical-chemical adsorption;
- Biological processes, like assimilation or enhanced biological phosphorus removal (EBPR)

The greatest interest and most recent progress has been made in EBPR, which has the potential to remove P down to very low levels at relatively lower costs. Membrane technologies are also receiving increased attention, although their use for P removal has been more limited to date.

About the physical treatment options, by considering that 2-3% of organic solids is phosphorus, an effluent total suspended solids (TSS) of 20 mg/L may then be equivalent to 0.4-0.6 mg/L of effluent phosphorus (Strom, 2006b). In plants with EBPR the P content in residuals is even higher. Thus sand filtration or other method of TSS removal (e.g., membrane, chemical precipitation) is likely necessary for plants with low effluent TP permits (Reardon, 2006).

Membrane technologies have been of growing interest for wastewater treatment in general, and most recently, for P removal in particular. In addition to particulate P, membranes also can remove dissolved P. Membrane bioreactors (MBRs, which incorporate membrane technology in a suspended growth secondary treatment process), tertiary membrane filtration (after secondary treatment), and reverse osmosis (RO) systems have all been used in full-scale plants with good results.

In regards to chemical treatment, chemical precipitation has long been used for P removal. The chemicals most often employed are compounds of calcium, aluminum, and iron (Tchobanoglous et al., 2003). Chemical addition points include prior to primary settling, during secondary treatment, or as part of a tertiary treatment process (Neethling and Gu, 2006). It is generally agreed (e.g., Hermanowicz, 2006), however, that the process is more complex than predicted by laboratory pure chemical experiments, and that formation of and sorption to carbonates or hydroxides are important factors. In fact, full-scale systems may perform better than the 0.05 mg/L limit predicted. Takács (2006) suggests the limit is probably 0.005-0.04 mg/L.

Chemical phosphorus removal is achieved by adding chemicals to the wastewater at a well-mixed location, followed by flocculation and solids removal. The commonly used chemicals are aluminum and iron based salts. Aluminum is dosed in the form of alum, polyaluminum chloride. Iron is added as ferric or ferrous iron salt (chloride), but in some cases "pickle liquor" (from industrial iron works) that contains primarily ferric chloride, can be used.

Finally, when it comes to biological phosphorus removal, this treatment aspect from wastewater has long been achieved through biological assimilation – incorporation of the P as an essential element in biomass, particularly through growth of photosynthetic organisms (plants, algae, and some bacteria, such as cyanobacteria). Traditionally, this was achieved through treatment ponds containing planktonic or attached algae, rooted plants, or even floating plants (e.g., water hyacinths, duckweed).

Strong interest has been seen in enhanced biological phosphorus removal (EBPR). This is because of its potential to achieve low effluent P levels at modest cost and with minimal additional sludge production. Neethling et al. (2005) recently showed the performance of EBPR in full-scale plants for significant time periods, but Greenburg et al. (1955) and then Levin and Shapiro (1965) were initially the ones who demonstrated the benefits of this process at a large scale. To summarize (Strom, 2006a and 2006b), phosphate accumulating organisms (PAOs), that

are able to develop under anaerobic or aerobic conditions, do store polyphosphate as an energy reserve in intracellular granules under the former conditions and release orthophosphate under anaerobic conditions, in the presence of fermentation products.

Chemical phosphorus removal very well achieve high level of performance and with the choice of Actiflo® technology in the case of this project, this is a particular arrangement of high rate ballasted flocculation that is considered here. Actiflo® relies on the addition of a metal salt to achieve its performance and has already demonstrated its performance in producing very low phosphorus effluent (O'Hare and Perry, 2010).

I.2. Objectives

Based on these considerations, this project was assigned a dual objective, while using an Actiflo® Carb pilot unit trailer:

- Evaluate the removal of a series of Trace Organic Compounds (TOCs) from the wastewater effluent produced by the South Shore Water Reclamation Facility, part of the MMSD's sewage system – More details are given in the Part II about the selection of compounds;
- Evaluate the removal of phosphorus by the Actiflo® Carb while removing TOCs, and perform additional testing using the regular version of Actiflo® (coagulant use only). The phosphorus concentration considered as a target to achieve has been 0.05 mg/L.

II. MATERIALS AND METHODS

II.1. Information on South Shore Water Reclamation Facility and location of the pilot unit trailer

The South Shore Water Reclamation Facility (SSWRF) is a 300 MGD (in capacity) wastewater treatment plant which is located approximately 13 miles south of downtown Milwaukee. It is sitting on the shore of Lake Michigan (see Figure 1 for geographical location). The SSWRF is part of the MMSD facilities, which also include another wastewater treatment facility, the Jones Island Water Reclamation Facility, located close to downtown Milwaukee. These two facilities together have the ability to treat wastewaters coming from the entire 400 sq.mi. Milwaukee Metropolitan Sewerage District service area, which represents a population of 1.2 million inhabitants. The Actiflo® Carb pilot unit trailer was set up at the SSWRF (Oak Creek – Wisc.), and more specifically by the final disinfection basins (Figure 2) in order to have access to secondary effluent (after activated sludge treatment).

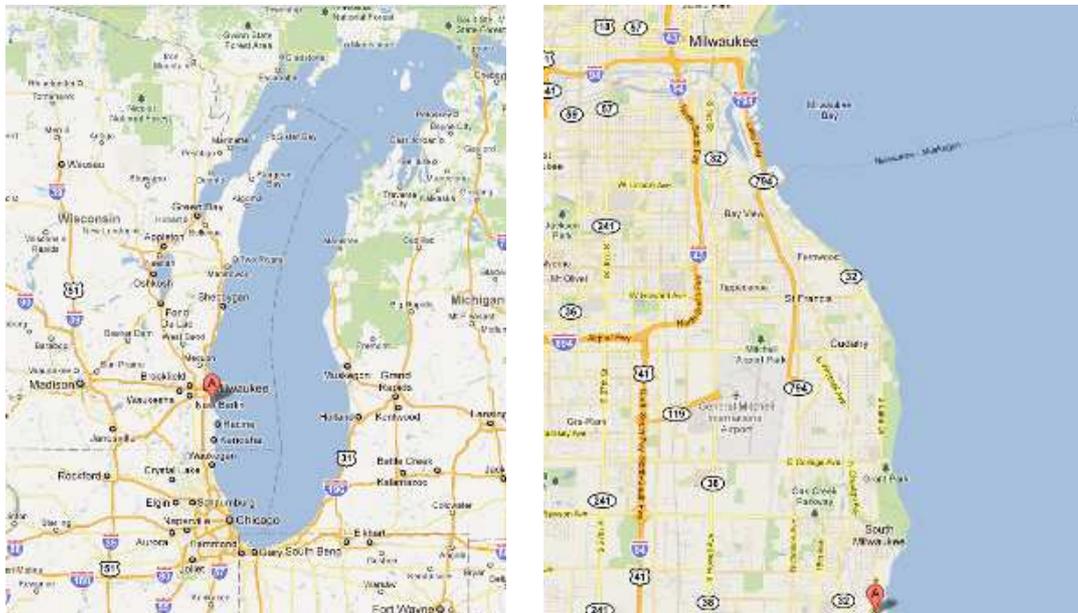


Figure 1: Location of the South Shore Water Reclamation Facility



Figure 2: Aerial view of the pilot unit location within SSWRF's grounds



Figure 3: View of the pilot unit trailer located by the secondary effluent channel

II.2. Description of the process: Actiflo® and Actiflo® Carb

Actiflo® is a compact (small area footprint) process that operates with microsand (Actisand™) that acts as a seed for floc formation. Actisand™ provides surface area that enhances flocculation and also works as a ballast or weight to facilitate rapid settlement. Actiflo® is applicable to surface water clarification, industrial process water production, wastewater treatment, or storm flow water settlement.

The process itself successively consists in (see Figure 4):

- One coagulation tank where the coagulant (mostly a metallic salt) is added to generate suspended particles destabilization;
- One flocculation tank where, via a polymer addition, the destabilized particles agglomerate to form flocs that additionally are ballasted with microsand;
- And one sedimentation tank (with lamella plate settlers), at the bottom of which the sludge is pumped, and at the top of which the clarified water overflows;
- The sludge (flocs and microsand) is then recirculated through a hydrocyclone system, where the microsand particles are separated from the actual sludge and returned to the flocculation stage.

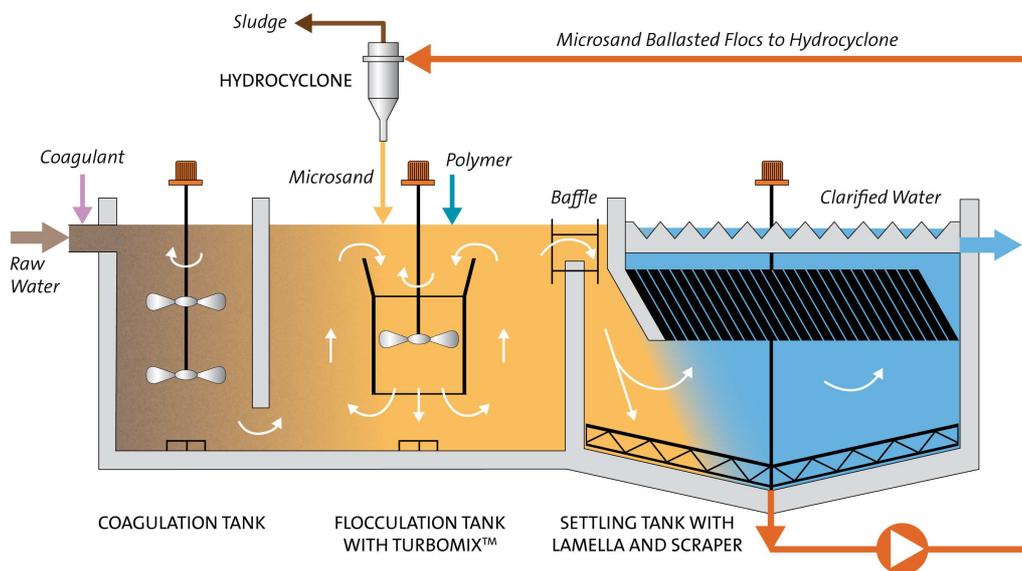


Figure 4: General view of the Actiflo® process

The Actiflo® Carb process is simply a derivative from the Actiflo® process that includes an additional powdered activated carbon contact tank prior to the regular stages of the process. The Figure 5 presents an overview of the Actiflo® Carb process.

The powdered activated carbon (PAC) is composed of carbon particles that have been activated by a specific process, giving it a dramatically high surface area available per gram of material, allowing the removal of an important concentration of undesirable compounds by utilizing a minimal dose of PAC. Usually, the PAC is simply injected in the raw water to remove pesticides or taste and odor causing compounds for instance, but this is performed with a short contact time and the adsorption capacity of the carbon is therefore not fully used in this case. By combining the use of PAC and the Actiflo®, it becomes possible to separate and recirculate the particles of activated carbon, which maximizes the full use of the adsorption capacity.

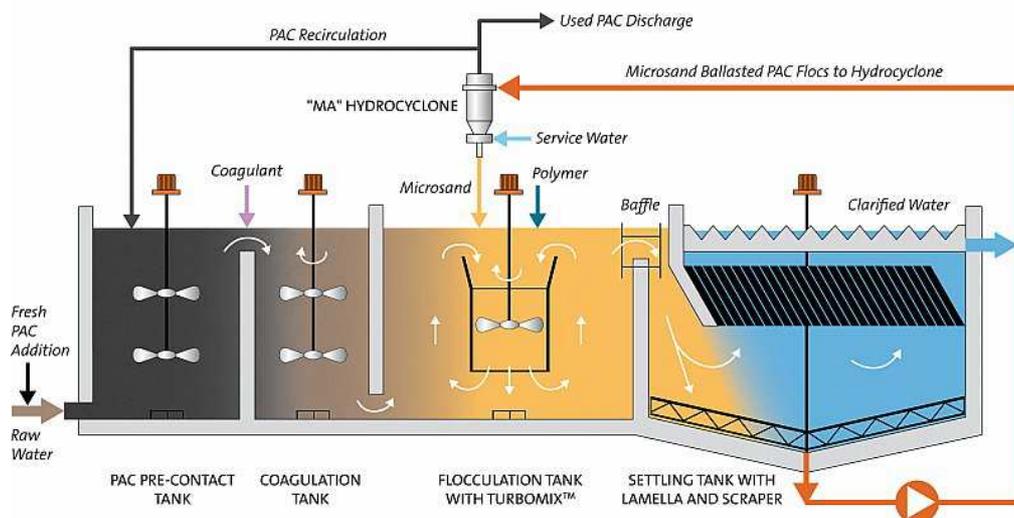


Figure 5: General view of the Actiflo® Carb process

The Figure 6 presents a panoramic view of the inside of the pilot trailer, and specifically of the process section. The way the trailer is set up allows for sampling at any step of the treatment and visually control the correct operation of the process.



Figure 6: Inside view of the pilot unit trailer
(from the carbon contact tank on the left to the weir section on the far right end)

II.3. Testing plan

II.3.1. Preliminary tests regarding activated carbon

Initial batch tests have been conducted in order to determine the best powdered activated carbon for the purpose of removing the series of selected TOCs:

- From the literature, the coconut-based activated carbons appear to be quite efficient on particular specific pollutants, provided that there are no competitive effects from the

matrix as the presence of organic matter for instance. In this case, the choice of coconut should have then probably been discarded because of potential matrix interferences but this would remain an aspect to further investigate;

- Wood-based powdered activated carbons have demonstrated their efficiency, thanks to a large porosity distribution (and this type of carbon remains the reference while used with this treatment process);
- Coal-based activated carbons are known to show slightly higher efficiencies in a lot of cases, but their price is also a major factor to take into account, and they are not considered environmental-friendly because of the nature of the base.

To ensure having preliminary references regarding the performance of the activated carbon, coconut- and wood-based materials were tested through jar-testing, based on the following approach:

- The real wastewater treatment plant (South Shore Water Reclamation Facility) effluent was used, spiked with the predefined shortlist of TOCs to be used during the pilot-scale tests;
- Two different dosages (10 and 20 mg/L) of powdered activated carbon were evaluated as well, along with two different contact times (30 and 60 minutes).

Following this step, the PAC evaluated would be used during the pilot-scale tests at the same two different PAC renewal dosages: 10 and 20 mg/L. Going above this level of dosage is allowed but would induce operating expenditures difficult to support on an industrial-scale basis.

II.3.2. Pilot testing

Once the type of activated carbon to be used was validated, two pilot testing phases were conducted, the first in April 2011 and the second from mid-July to mid-August 2011. The same schedules were followed for each of these periods, while having two separate phases allowed to account for the impact of seasonality.

Each testing period lasted four weeks:

- As a matter of preparation and optimization, the first week has been dedicated to connecting the pilot unit hydraulically and electrically;
- Two weeks were dedicated to the operation of Actiflo® Carb;
- One week was dedicated to the operation of Actiflo®.

Regarding sampling on the pilot unit, the Figure 7 presents the locations where phosphorus and TOCs samples were taken.

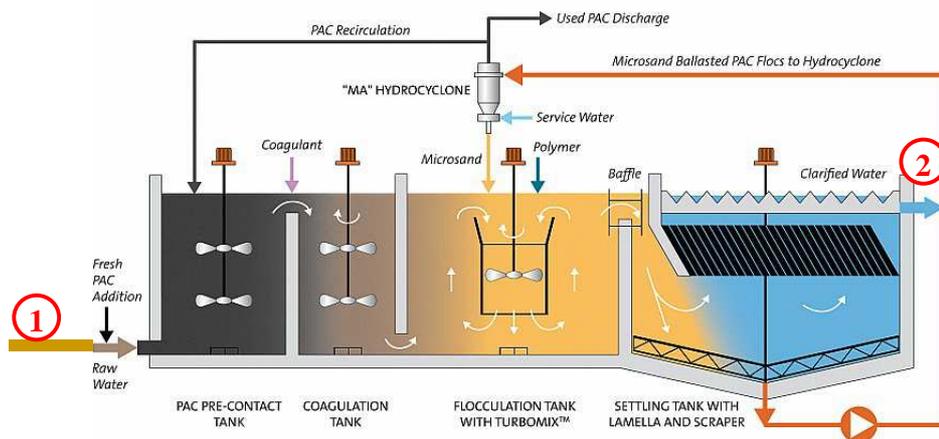


Figure 7: General view of the Actiflo® Carb process, with sampling locations (1- Sample location for influent TOCs and phosphorus, 2- Sample location for effluent TOCs and phosphorus)

II.4. Selection of Trace Organic Compounds

II.4.1. List of TOCs

Following the previous research study led by Dr. Rebecca Klaper (University of Wisconsin-Milwaukee; Great Lakes WATER Institute) on the occurrence of TOCs within the wastewater treatment line, the Table 1 presents the compounds that have been selected for monitoring regarding removal by Actiflo® Carb.

Table 1: Listing of the selected trace organic compounds and their target concentrations

| Compound | Type | Typical concentration in SSWRF effluent (ng/L) | Target concentration in Actiflo® Carb influent (ng/L) |
|------------------|-------------------|--|---|
| Carbamazepine | Anti-epileptic | 200 | 300 |
| Fluoxetine | Anti-depressant | 100 | 300 |
| Trimethoprim | Antibiotic | 100 | 300 |
| Sulfamethoxazole | Antibiotic | 150 | 300 |
| Ofloxacin | Antibiotic | 150 | 300 |
| Diltiazem | Anti-hypertension | 100 | 300 |
| Diphenhydramine | Anti-histaminic | 100 | 300 |
| Triclosan | Biocide | 100 | 300 |
| Naproxen | Anti-inflammatory | 300 | 500 |
| Caffeine | Tracer | 1,500 | 2,000 |

Additional details on these molecules are given in the Appendix A.

II.4.2. Management of TOrCs influent concentrations

The real effluent coming from the SSWRF outlet prior to disinfection would be used (two days per week of Actiflo® Carb testing), and to simulate peak concentrations in the effluent, spiking additions of the selected compounds would be performed using standard solutions (two days per week of Actiflo® Carb testing). Naturally occurring concentrations of trace organic compounds in wastewater effluents may vary significantly, but it was considered important to spike the wastewater secondary effluent with significant doses of compounds to challenge the capacity of the process for the removal of these species.

In terms of sampling protocol, it was chosen to take composite samples, e.g. one sample of influent and one sample of effluent per day of TOrCs removal testing: each sample was composed of fractions taken at 1-hour intervals, which was representative considering the quick process cycle of Actiflo® Carb.

II.5. Analytical methods

II.5.1. Trace Organic Compounds

The methods to quantify the series of TOrCs are based upon US EPA Method (USEPA, 1992) 1694 protocols (modified) and consist in the following successive steps:

- 1-liter liquid samples were filtered through Whatman GF-A glass fiber filter media to retain particulate material;
- The filtrate was pH adjusted to 2 with concentrated sulfuric acid and 0.5 g of EDTA was added to chelate minerals for acid analytes (or pH adjusted to 10 with concentrated ammonium hydroxide for basic extraction analytes);
- Liquid samples were then spiked with a suite of mass labeled internal standard compounds and extracted with 20 mL, 1 g Waters Oasis HLB cartridges and eluted sequentially with 12 mL methanol, 6 mL methanol:acetone (50:50), and 6 mL MTBE:methanol (90:10) for acid analytes (or 6 mL of methanol followed by 9 mL methanol with 2% formic acid for basic analytes);
- The elution solvents were concentrated under nitrogen to approximately 0.2 mL and quantitatively transferred to 1.0 mL of final volume with methanol pending analysis;
- Solids - Particulates on glass fiber filters or 1 g aliquots of other solids, such as soils and biosolids, were placed in 50mL polypropylene centrifuge tubes with pH 2 phosphate buffer:acetonitrile, spiked with a suite of mass labeled internal standard compounds, and extracted three times by sonication;

- The pooled acetonitrile was removed from the extract using a rotary evaporator and the aqueous extract was brought to 200 mL volume with 18 MΩ/cm water before further processing by the liquids method described above;
- 15 µL of extract was injected onto a Phenomenex Synergi MAX-RP 250x4.6 mm, 4 mm column and separated by a binary gradient employing an Agilent 1100 HPLC system. Detection was achieved with an Applied Biosystems/MDS SCIEX API 4000 MS/MS system operating with Turbo Ion Spray ionization and multiple-reaction monitoring (MRM) detection.

II.5.2. Phosphorus

Monitoring phosphorus is challenging because it involves measuring very low concentrations down to 0.01 mg/L or even lower. While there are many tests for phosphorus, three of them were utilized for the purpose of the study:

- The *total orthophosphate* (Or-P) test is largely a measure of orthophosphate. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate. The EPA-approved method for measuring total orthophosphate is known as the ascorbic acid method;
- The *total phosphorus* (TP) test measures all the forms of phosphorus in the sample (orthophosphate, condensed phosphate, and organic phosphate). This is accomplished by first "digesting" (heating and acidifying) the sample to convert all the other forms to orthophosphate;
- The *dissolved phosphorus* (dP) test measures that fraction of the total phosphorus which is in solution in the water (as opposed to being attached to suspended particles). It is determined by first filtering the sample, then analyzing the filtered sample for total phosphorus.

TP and dP analysis were performed at the MMSD laboratory facility (the dP samples were filtered on-site by using 0.45 µm syringe filters): the samples were analyzed using EPA Method 365.1, "Phosphorus by semi-automated Colorimetry". The samples were digested with sulfuric acid which converts the polyphosphates and some of the organic phosphorus compounds to ortho-phosphate. Ammonium molybdate and antimony potassium tartrate are then reacting with these compounds to form an antimony phospho-molybdate complex. This complex is reduced with ascorbic acid to a blue complex. The intensity of the latter is measured at 880 nm. On the other hand, Or-P samples have been performed directly on-site using equipment provided with the pilot unit trailer. These analyses were performed by using a Hach Pocket Colorimeter II, which relied on the methodology (Hach, 1992) of the reaction with ascorbic acid

(a prepackaged powder reagent, consisting of sulfuric acid, potassium antimonyl tartrate, ammonium molybdate, and ascorbic acid (or comparable compounds), is added to the water sample. This colors the sample in blue in direct proportion to the amount of orthophosphate in the sample and absorbance is then measured at 880 nanometers.

II.3.3. Other physical-chemical parameters

The performance monitoring and potential process adjustments of Actiflo® Carb process were made possible through monitoring classical water quality parameters:

- pH and turbidity have been monitored thanks to Hach® equipment on-line devices set up on Actiflo® Carb piping;
- Total suspended solids (TSS) and alkalinity have been analyzed on a more point basis, in order to have information about the wastewater stream.

III. RESULTS

III.1. Trace organic compounds removal

III.1.1. Initial determination of the activated carbon

The initial results from batch tests with two different PACs (coconut and wood based) pointed out that the wood-based one was the most efficient in removing the series of selected compounds, likely due to its diversity in porous distribution. This powdered activated carbon was hence chosen for the pilot testing.

The jar-tests performed with the 10 selected compounds to compare the two activated carbons showed that removal efficiency was variable depending on the molecules: some of them (flouxetine, ofloxacin...) were better removed by wood-based PAC while others (sulfamethoxazole) were better eliminated by coconut-based PAC; but in general, the average efficiency was almost equivalent for both the activated carbons, as it appears on the Figure 8. The best removed trace organic compound was triclosan.

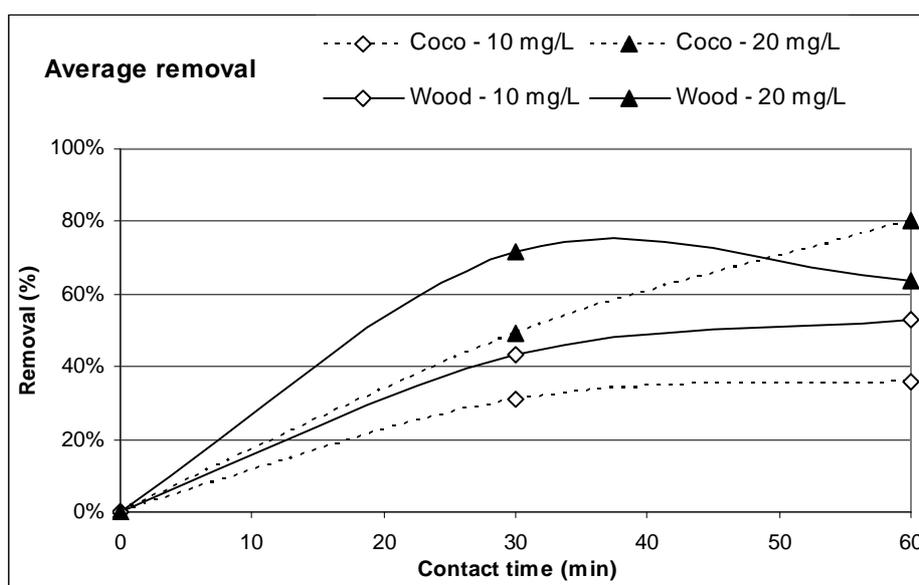


Figure 8: Average removal of trace organic compounds obtained during preliminary jar-testing

It was decided to proceed with the wood-based activated carbon because other projects in Europe also use this type of activated carbon and could therefore be used as references. Information on the individual removal rates per molecule is given in the Appendix B.

III.1.2. Removal by Actiflo® Carb

For each testing period, the influence of several process parameters has been considered. The range of operational conditions that were tested is presented in the Table 2.

Table 2: Operational conditions of Actiflo® Carb

| Operational parameters | Values |
|--------------------------|---------------------|
| Influent flow rate | 75 – 95 gpm |
| System HRT | 27 – 34 min |
| Rise rate | 13 – 16 gpm/sf |
| Waste rate (Residuals) | 750 to 3,300 ml/min |
| Residuals concentration | 8 to 11 g/L |
| PAC dosage | 10 – 20 mg/L |
| Coagulant type | Ferric chloride |
| Coagulant dosage (as Fe) | 7 – 12 mg/L |
| Polymer dosage | 1.5 to 3.2 mg/L |
| Microsand effective size | 82 µm |
| Microsand concentration | 14 – 16 g/L |

From a general perspective, it appeared that:

- Higher removals were obviously obtained by using a higher PAC dose. However, a carbon dosage of 10 mg/L still enabled to obtain 68% of average removal across all TORCs (83% in the case of 20 mg/L dosage). With the 20 mg/L PAC dosage, 8 compounds out of 10 were removed above 75%;
- The rise rate did not have any significant influence on the performance of the process;
- Spiking was used on the influent coming to the pilot unit, to ensure that significant levels of concentrations were tested. The process showed very good capability in maintaining removal performance in removing TORCs from influent concentrations much higher than the observed annual averages;
- Overall, regarding average removal, the order of performance for all 10 compounds is the following: Diltiazem > Trimethoprim > Triclosan > Diphenhydramine > Carbamazepine > Ofloxacin > Sulfamethoxazole > Fluoxetine > Caffeine > Naproxen.

The average TORCs removal rate across all compounds, while taking into accounts all treatment conditions, reached 75%. In more details, the Table 3 presents the listing of removal percentages for the performance of Actiflo® Carb versus each one of the selected molecules, while the Figure 9 presents the same results via a bar-type graphic.

Table 3: Removal rates per molecule depending on the PAC dosage

| Molecule | PAC dosage (mg/L) | Average removal (%) |
|------------------|--------------------------|----------------------------|
| Caffeine | 10 | 44 % |
| | 20 | 74 % |
| Carbamazepine | 10 | 68 % |
| | 20 | 88 % |
| Diltiazem | 10 | 89 % |
| | 20 | 95 % |
| Diphenhydramine | 10 | 81 % |
| | 20 | 92 % |
| Fluoxetine | 10 | 52 % |
| | 20 | 78 % |
| Naproxen | 10 | 42 % |
| | 20 | 67 % |
| Ofloxacin | 10 | 69 % |
| | 20 | 75 % |
| Sulfamethoxazole | 10 | 54 % |
| | 20 | 75 % |
| Triclosan | 10 | 90 % |
| | 20 | 88 % |
| Trimethoprim | 10 | 87 % |
| | 20 | 97 % |

With the Actiflo® Carb process, it is more than dramatic to ensure the minimal carryover of activated carbon to the treated water effluent. Once the targeted pollutants, the trace organic compounds in this case, have been in contact with the powdered activated carbon during the required contact time of the process, the PAC needs to be properly separated to avoid seeing it go into the treated effluent: indeed, the captured molecules may still be able to desorb from the PAC particles once in contact with a more dilute aqueous environment.

That's why polymer is a key component in operating the Actiflo® Carb since it properly retains the particles of activated carbon.

Overall, the removal rates presented here have been calculated for each PAC dosage across all other treatment conditions, especially by merging results from regular secondary effluent and spiked secondary effluent. Given this clarification, it means that a removal rate of 50% is already very interesting and it shows that using a dosage of carbon of 10 mg/L or so may still fulfill the objectives in terms of significantly removing trace organic compounds from the wastewater effluent. But since this quality parameter is still unregulated, it is not possible to discuss performance achievement in regards to reaching a given particular concentration.

It is nevertheless reasonable to point out that the removal performance would still be the same if the influent to be treated was containing a trace organic compounds average concentration of either 1,000 ng/L or 100 ng/L as the extent of performance in adsorbing such compounds is mainly defined by physical chemical characteristics and not levels of concentrations seen in the wastewater.

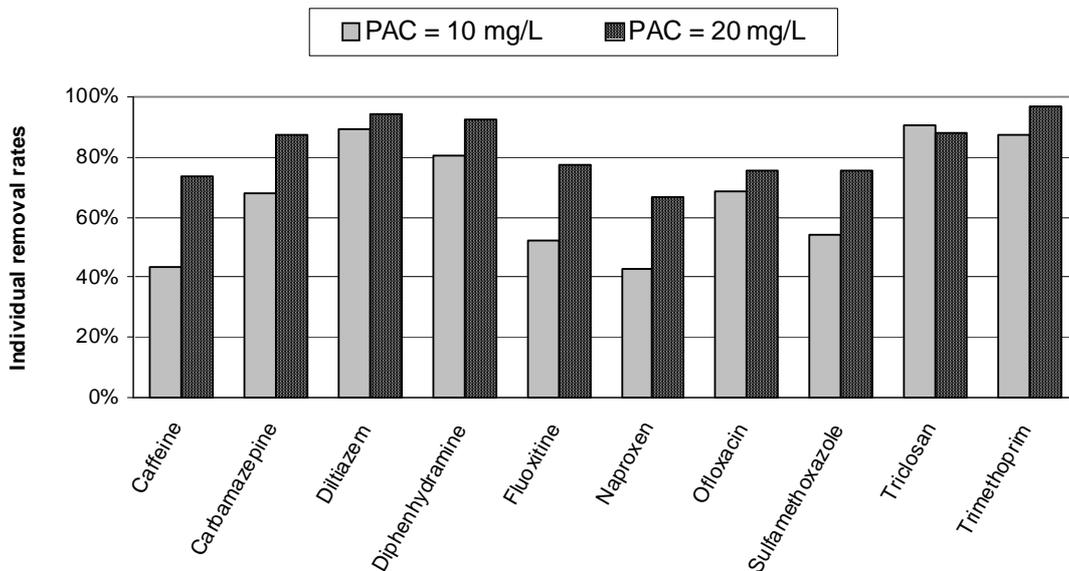


Figure 9: Removal rates per molecule depending on the PAC dosage

Each molecule's removal is strongly impacted by its own physical-chemical characteristics and the octanol-water partition coefficient (K_{ow}) may help understanding the extent of removal that is observed. For this study it appears that the removal performance of many of the selected molecules is not correlated with the K_{ow} . However, it still can explain what is seen for some molecules, like the triclosan, which is very well removed and presents a $\log(K_{ow})$ of 4.76, the highest of the 10 molecules considered in this study.

III.2. Phosphorus removal

III.2.1. Information regarding removal by the plant

Regarding the conventional process at the plant, phosphorus is removed via addition of ferric chloride or pickle liquor. The current regulatory limit for the SSWRF is 1.0 mgP/L (reported on a monthly rolling average). During the time Actiflo® Carb was being tested, the SSWRF received phosphorus concentrations ranging from 0.76 to 7.50 mgP/L (average was 3.75 mgP/L), achieving final effluent P levels from 0.18 to 0.94 mgP/L (average was 0.47 mgP/L). Considering the Fe dosages used (in terms of metal), the associated average molar ratio (Fe / P) was 1.57.

III.2.2. Removal by Actiflo® Carb / Actiflo

Overall, regarding phosphorus removal by Actiflo® Carb, concentrations between 0.02 and 0.05 mgP/L have been consistently achieved in the pilot unit effluent while using coagulant (ferric chloride) dosages from 7 to 12 mg/L (expressed in metal). This meant the achievement of molar ratio (Fe concentration over P removal) between 7 and 17 have been observed for the process performance, which is expected for such low P removal achievements (in comparison to the average ratio of 1.57 for the conventional treatment).

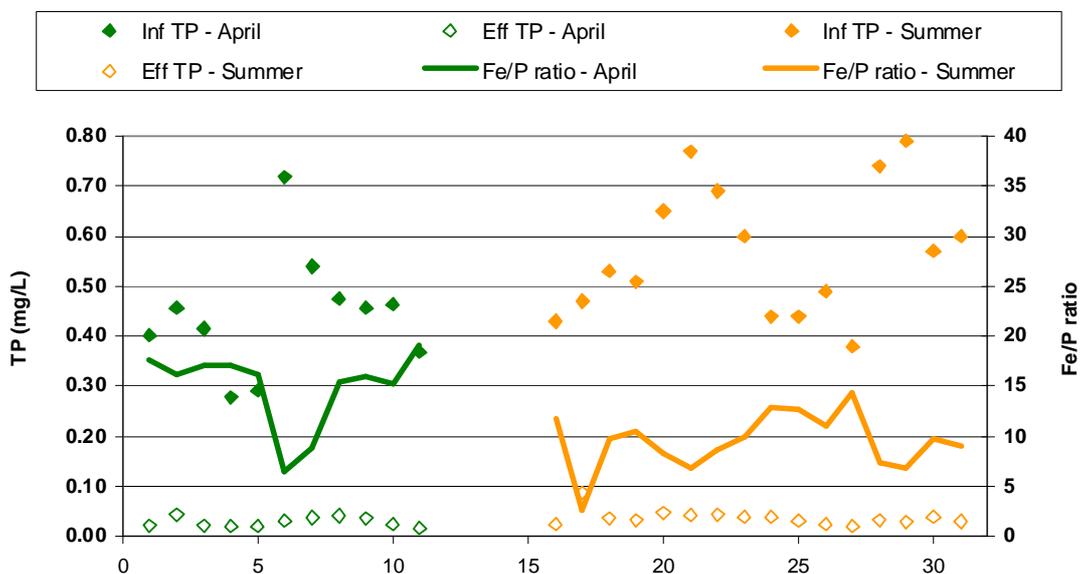


Figure 10: Total phosphorus concentrations in pilot influent and effluent, vs. Fe / TP molar ratio, for both testing periods with Actiflo® Carb

The Figure 10 presents the results obtained with Actiflo® Carb for Total Phosphorus removal for both testing periods. Some optimization was needed for the process, especially polymer dosage: indeed, a polymer dose close to 3 mg/L was required to avoid carryover and therefore having flocs or particles, including phosphorus, going to the pilot effluent. Once this process aspect was resolved, a very low and consistent total phosphorus concentration was achieved in the effluent. Concentrations in the influent were significantly variable, which explains the large range seen in the values of Fe / TP molar ratio.

The regular Actiflo® process was tested for phosphorus removal as well. Similarly to the figure 10, the Figure 11 presents the results obtained with Actiflo® for total phosphorus (TP) removal for both testing periods. Again, a very consistent removal of TP was achieved; Actiflo® Carb appears to be very versatile in being able to target phosphorus removal while at the same time removing TORCs. Indeed, the usual approach would rely on Actiflo® (no carbon) to perform P removal, but with the growing concern about the presence and effect of TORCs on humans and the environment, the Actiflo® Carb may be an effective solution in meeting both removal targets (TP and TORCs).

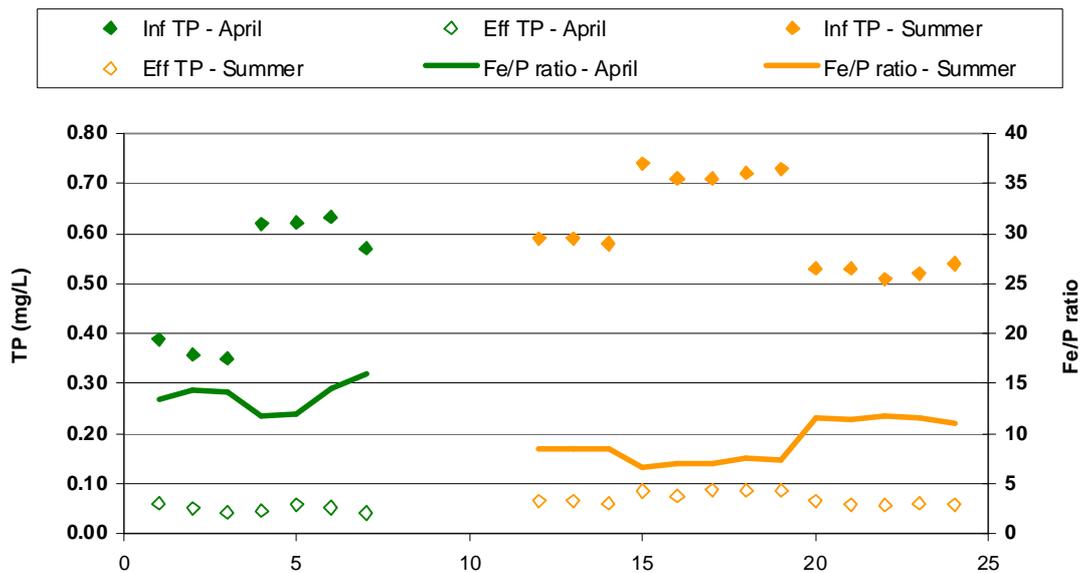


Figure 11: Total phosphorus concentrations in pilot influent and effluent, vs. Fe / TP molar ratio, for both testing periods with Actiflo®

III.3. Information on the operating cost

To discuss the potential operating cost of an Actiflo Carb process, we may consider:

- 10 MGD process unit, operating 24 hours a day;
- A polymer dosage of 3.0 mg/L (polymer is \$4,000/ton);
- A sand consumption (loss) of 2 g per treated cubic meter (sand is \$200/ton);
- A coagulant dosage of 10 mg/L (as FeCl₃) (coagulant is \$340/ton);
- A fresh dosage of 15 mg/L (PAC is \$2200/ton);
- Equipments installed with 100 horsepower (and power cost of \$ 0.08/KW hr).

Based on these assumptions, the total estimated daily operating cost would be \$ 2,164.46, which is equivalent to an operating cost of \$216 per million of gallons treated.

What is really driving the operating costs are both the powdered activated carbon and the polymer, knowing that PAC dosage is easily adjusted depending on the need for treatment – it was presented in the section regarding TOCs removal that a dosage of 10 mg/L was already showing good performance.

Additional information is given about this aspect in the Appendix D.

IV. CONCLUSIONS

This project had two different objectives: evaluating the performance of Actiflo® Carb in removing a series of selected trace organic compounds (TOrcs), while simultaneously removing phosphorus from wastewater effluent. The pilot unit was set up two times (spring and summer time, 2011) for a duration of four weeks in a row to perform extended testing of the process.

First, regarding TOrcs removal, the approach was to rely on the previous project led by Dr. Rebecca Klaper and to use the molecules that occurred in most significant levels at the end of the SSWRF wastewater treatment line. Ten TOrcs molecules were selected representing eight distinct classes of compounds in terms of therapeutic use. The average removal across all molecules and testing conditions reached 75%. Good removal was observed at the 10 mg/L PAC dosage with slightly better removal for most molecules at the 20 mg/L PAC dosage as would be expected. Overall, regarding average removal, the order of performance for all 10 compounds is the following: Diltiazem > Trimethoprim > Triclosan > Diphenhydramine > Carbamazepine > Ofloxacin > Sulfamethoxazole > Fluoxetine > Caffeine > Naproxen.

Secondly, once the process was optimized (sufficient polymer dosage), Actiflo® Carb was able to achieve very consistent and low phosphorus concentrations below 0.05 mgP/L in the effluent, with Fe / P molar ratios from 7 to 17, which are expected in such treatment conditions. The main beneficial results comes out from the capacity of Actiflo® Carb to be performing as well as Actiflo® in removing phosphorus from wastewater while also removing TOrcs at a high level of efficiency.

Finally, when considering a treatment unit presenting a capacity of 16 MGD and treating a flow of 10 MGD, the operating cost would \$216 per million gallons treated, with the majority of the cost allocated to the activated carbon and the polymer.

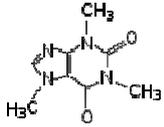
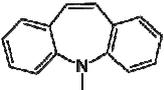
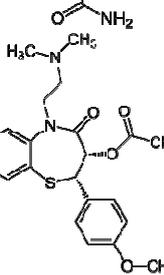
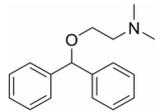
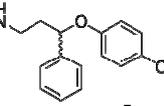
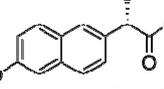
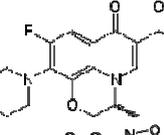
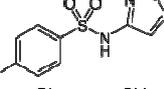
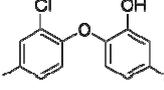
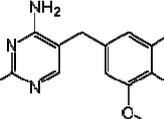
Bibliographic references

- APHA (1992) Standard methods for the examination of water and wastewater. *Eighteenth Edition*, American Public Health Association, Washington, DC, 1268.
- Beausse J. (2004) Selected drugs in solid matrices: A review of environmental occurrence, determination and properties of principal substances. *Horizontal European Union research project, DS-26 Pharmaceuticals*.
- ChemSpider database (2011) Available at: www.chemspider.com.
- Clara M., Strenn B., Gans O., Martinez E., Kreuzinger N. (2005) Removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds in a membrane bioreactor and conventional wastewater treatment plants. *Water Research*, **39**(19), 4797-4807.
- Greenberg A.E., Levin G.V., Kauffman W.J. (1955) The effect of phosphorus removal on the activated sludge process. *Sewage and Industrial Wastes*, **27**, 227.
- Hach Company (1992) Hach water analysis handbook. *2nd Edition*, Loveland, CO.
- Hermanowicz S. (2006) Chemical fundamentals of phosphorus precipitation. *Session P2 in WERF Workshop*, 2006.
- Levin G.V. and Shapiro J. (1965) Metabolic uptake of phosphorus by wastewater organisms. *Journal of the Water Pollution Control Federation*, **37**, 800-821.
- Neethling J.B., Bakke B., Benisch M., Gu A., Stephens H., Stensel H.D., Moore R. (2005) Factors Influencing the Reliability of Enhanced Biological Phosphorus Removal. *Final Report*, Water Environment Research Foundation, Alexandria, VA.
- Neethling J.B. and Gu A. (2006) Chemical phosphorus removal constraints – Introduction. *Session P2 in WERF Workshop*.
- O'Hare J.P., Perry T. (2010) Investigating treatment options to meet a 70 ug/L phosphorus discharge limit for the Boise River in Idaho. *WEFTEC Proceedings, New Orleans, LA*, pp. 908-913.
- Oppenheimer J., Stephenson R., Burbano A., Liu L. (2007) Characterizing the passage of personal care products through wastewater treatment processes. *Water Environment Research*, **79**(13), 2564-2577.
- Reardon R. (2006) Technical introduction of membrane separation processes for low TP limits. *Session P3 in WERF Workshop*.
- Rogers H.R. (1996) Sources, behaviour and fate of organic contaminants during sewage treatment and in sewage sludges. *Science of the Total Environment*, **185**(1-3), 3-26.
- Snyder S.A., Adham S., Redding A.M., Cannon F.S., DeCarolis J., Oppenheimer J. (2007) Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals. *Desalination*, **202**(1-3), 156-181.
- Soliman M.A., Pedersen J.A., Park H., Castaneda-Jimenez A., Stenstrom M.K., Suffet I.H. (2007) Human pharmaceuticals, antioxidants, and plasticizers in wastewater treatment plant and water reclamation plant effluents. *Water Environment Research*, **79**(2), 156-167.

- Stackelberg P.E., Gibs J., Furlong E.T., Meyer M.T., Zaugg S.D., Lippincott R.L. (2007) Efficiency of conventional drinking-water-treatment processes in removal of pharmaceuticals and other organic compounds. *Science of the Total Environment*, **377**(2-3), 255-272.
- Stevens-Garmon J., Drewes J.E., Khan S.J., McDonald J.A., Dickenson E.R. (2011) Sorption of emerging trace organic compounds onto wastewater sludge solids. *Water Research*, **45**(11), 3417-3426.
- Strom P.F. (2006a) Introduction to phosphorus removal. *Invited Presentation for Wastewater Treatment Operator's Workshop, 91st Annual Meeting, NJWEA, Atlantic City, NJ.*
- Strom P.F. (2006b) Phosphorus removal techniques. *Invited Presentation for Water Quality Trading, 91st Annual Meeting, NJWEA, Atlantic City, NJ.*
- Takács I. (2006) Modeling chemical phosphorus removal processes. *Session P2 in WERF Workshop.*
- Tchobanoglous G., Burton F.L. and Stensel H.D. (2003) Metcalf & Eddy, Inc.'s Wastewater Engineering: Treatment, Disposal, and Reuse, *4th Edition. McGraw-Hill, Inc., New York.* 1819 pp.
- USEPA (1983) Methods for chemical analysis of water and wastes. *2nd ed. Method 365.2. U.S. Environmental Protection Agency, Washington, DC.*
- Vieno, N.M., Harkki H., Tuhkanen T., Kronberg L.. (2007) Occurrence of pharmaceuticals in river water and their elimination in a pilot-scale drinking water treatment plant. *Environmental Science & Technology*, **41**(14), 5077-5084.

Appendix A: Detailed characteristics of the selected molecules

Table 4: Listing of the selected TOCs and their characteristics

| Name | Formula | Therapeutic use | Log(Kow) |
|------------------|---|---|---------------|
| Caffeine |  | Stimulant, world's most widely consumed psychoactive drug, | 0.07* |
| Carbamazepine |  | Anticonvulsant, Mood-stabilizing | 2.45* |
| Diltiazem |  | Antihypertensive | 2.82* |
| Diphenhydramine |  | Antihistamine (treatment of allergies) | 3.11 - 3.27** |
| Fluoxetine |  | SSRI Antidepressant (also known by the trade names Prozac, Sarafem, Fontex) | 4.05* |
| Naproxen |  | Non-steroidal anti-inflammatory drug | 3.18* |
| Ofloxacin |  | Antibiotic | 0.35*** |
| Sulfamethoxazole |  | Bacteriostatic antibiotic | 0.89* |
| Triclosan |  | Antimicrobial, disinfectant | 4.76* |
| Trimethoprim |  | Bacteriostatic antibiotic | 0.91* |

* Snyder et al. (2007), ** Chemspider database (2011), *** Beausse (2004)

Appendix B: Detailed results of the TOrcs removal tests for PAC selection

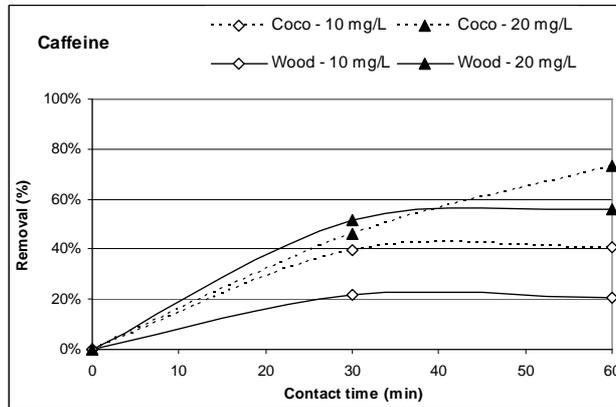


Figure 12: Removal of caffeine by wood or coconut carbons obtained during batch jar-testing

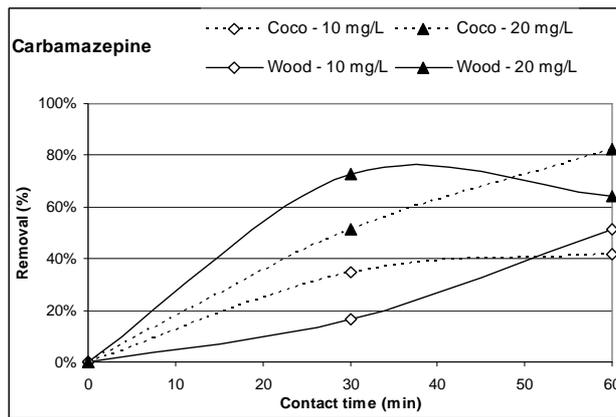


Figure 13: Removal of carbamazepine by wood or coconut carbons obtained during batch jar-testing

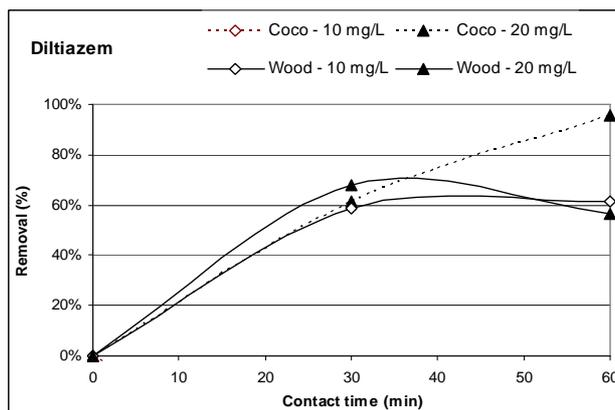


Figure 14: Removal of diltiazem by wood or coconut carbons obtained during batch jar-testing

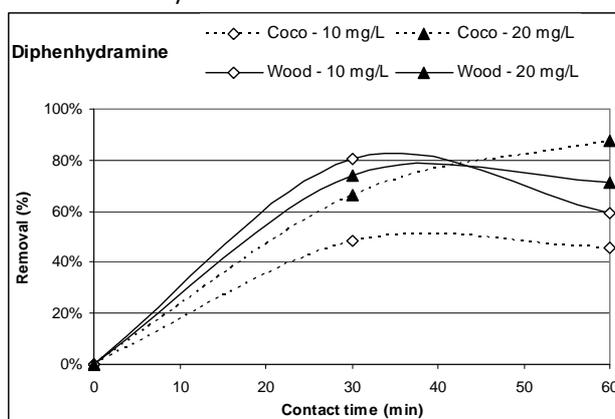


Figure 15: Removal of diphenhydramine by wood or coconut carbons obtained during batch jar-testing

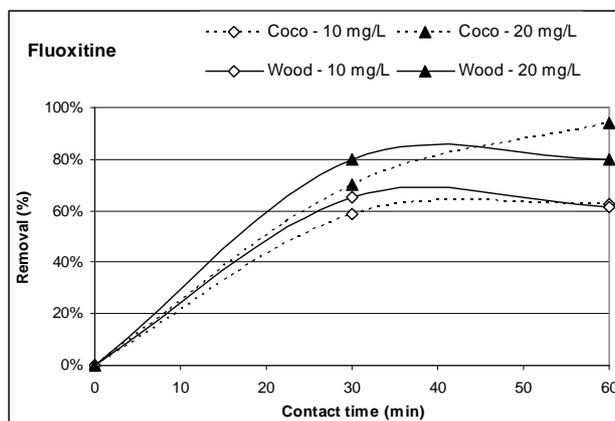


Figure 16: Removal of fluoxetine by wood or coconut carbons obtained during batch jar-testing

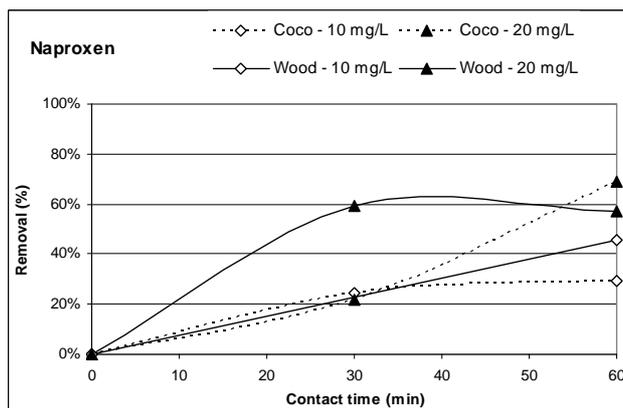


Figure 17: Removal of naproxen by wood or coconut carbons obtained during batch jar-testing

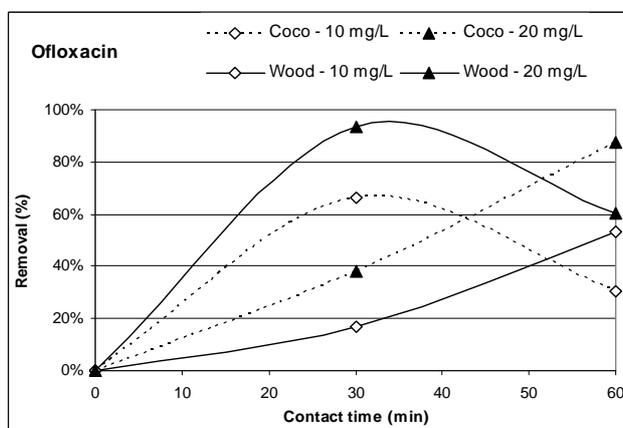


Figure 18: Removal of ofloxacin by wood or coconut carbons obtained during batch jar-testing

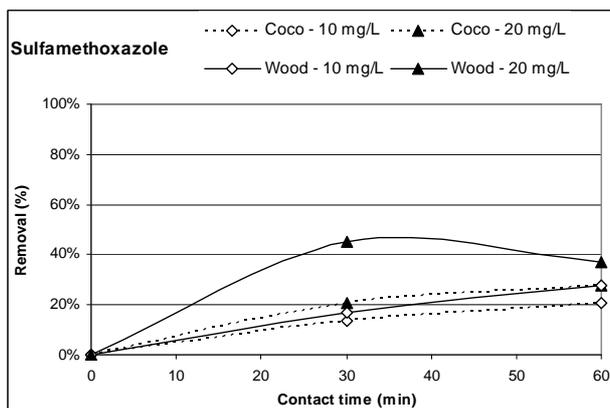


Figure 19: Removal of sulfamethoxazole by wood or coconut carbons obtained during batch jar-testing

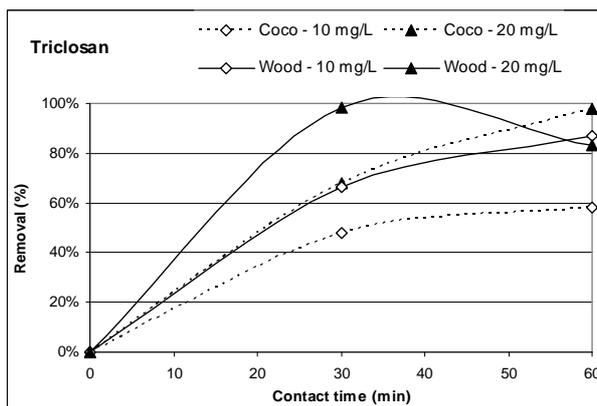


Figure 20: Removal of triclosan by wood or coconut carbons obtained during batch jar-testing

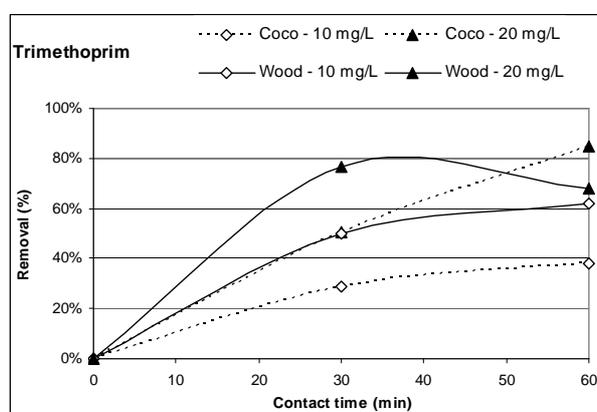


Figure 21: Removal of trimethoprim by wood or coconut carbons obtained during batch jar-testing

Appendix C: Detailed results of the TOrCs removal by Actiflo® Carb

Table 5: Individual removal rates depending on the treatment conditions

| Operating parameter | Values | | | | |
|---|------------------|------------|------------|-----------|------|
| Carbon dosage (mg/L) | 10 | 10 | 20 | 20 | |
| Flow rate (gpm) | 95 | 75 | 95 | 75 | |
| Contact time (min) | 27 | 34 | 27 | 34 | |
| Waste rates (residuals) (mL/min) | 1,650 | 1,300 | 2,020 | 1,600 | |
| Coagulant dosage as Fe (mg/L) | 1.5 - 5.4 | 2.1 - 6.0 | 2.1 - 5.6 | 2.1 - 5.6 | |
| Polymer dosage (mg/L) | 1.5 - 3.2 | 1.5 - 3.3 | 3.0 - 3.2 | 3.1 - 3.2 | |
| Residuals concentration (g/L) | 9.9 - 11.3 | 7.7 - 11.4 | 9.7 - 12.0 | 8.8 - 9.9 | |
| Trace organic compounds removal rates (%) | Caffeine | 56 % | 34 % | 70 % | 86 % |
| | Carbamazepine | 65 % | 71 % | 86 % | 91 % |
| | Diltiazem | 92 % | 87 % | 96 % | 95 % |
| | Diphenhydramine | 77 % | 84 % | 93 % | 95 % |
| | Fluoxetine | 52 % | 53 % | 82 % | 84 % |
| | Naproxen | 44 % | 41 % | 56 % | 63 % |
| | Ofloxacin | 68 % | 69 % | 82 % | 77 % |
| | Sulfamethoxazole | 53 % | 56 % | 72 % | 78 % |
| | Triclosan | 89 % | 91 % | 90 % | 89 % |
| Trimethoprim | 87 % | 88 % | 97 % | 97 % | |

Appendix D: Information on Actiflo® Carb costs

Table 6: Construction cost estimate for Actiflo® Carb (16 MGD capacity unit)

| Description | Percentage | Project cost |
|---|------------|--------------------|
| Equipment Cost | | \$2,000,000 |
| Electrical & Instrumentation | | \$300,000 |
| Mechanical | | \$300,000 |
| TOTAL DIRECT CONSTRUCTION COSTS | | \$2,600,000 |
| Contingency | 25% | \$650,000 |
| Subtotal | | \$3,250,000 |
| General Conditions, General Contractor Overhead, Profit & Risk | 10% | \$325,000 |
| Subtotal | | \$3,575,000 |
| TOTAL ESTIMATED CONSTRUCTION COST | | \$3,575,000 |
| Engineering, Legal & Administration Fees | 25% | \$893,750 |
| Owner's Reserve For Change Orders | 10% | \$357,500 |
| TOTAL ESTIMATED PROJECT COST | | \$4,826,250 |

Table 7: Annual operation and maintenance cost estimate for Actiflo® Carb (16 MGD capacity unit)

| Description | Cost |
|--|------------------|
| Polymer (\$4,000/ton) | \$146,000 |
| Sand Consumption (\$200/ton) | \$5,000 |
| Coagulant (As FeCl ₃) (\$340/ton) | \$41,000 |
| Fresh PAC (\$2,200/ton) | \$402,000 |
| Energy Cost (\$0.08/kW-hr) | \$38,000 |
| Labor (\$50.00/hr) | \$20,000 |
| Annual Repair and Replacement Cost (based upon the 1% of the equipment cost) | \$20,000 |
| Total Annual O&M Cost | \$672,000 |