Resource recovery from wastewater and sludge: Modelling and control challenges

Peter A. Vanrolleghem* and Céline Vaneeckhaute*

*model*EAU*, Département de génie civil et de génie des eaux, Université Laval
1065, avenue de la Médecine, Québec G1V 0A6, QC, Canada
E-mail : peter.vanrolleghem@gci.ulaval.ca, celine.vaneeckhaute.1@ulaval.ca

Abstract

Wastewater treatment plants (WWTPs) have been renamed water resource recovery facilities (WRRFs). Our industry is quickly moving from an end-of-pipe environmental protection service to an economic producer of valued products for society. Based on a critical review of resource recovery technologies that are currently applied or in advanced development, it became obvious that most of these technologies are based on physicochemical unit processes (precipitation, volatilization, sorption, …). Current industrial practice for the design and operation of WRRFs is based on mathematical models describing the traditional biological processes. The modeling challenge therefore is to provide practice with proper models for the physicochemical resource recovery processes. The fact that the WRRFs aim at delivering valued products that can partially replace those produced by other means (typically in the chemical industry) leads to a paradigm shift in specifications of the outputs of the facility: no longer treated wastewater and biosolids, but products that have to compete with what is already on the market. The tighter specifications will thus impose a challenge on the process control systems that will be required to guarantee the quality of the products of the WRRFs.

Keywords: mathematical modelling, nutrient recovery, physicochemical modelling, process control, water resource recovery facility

Introduction

In the handling of wastewaters or, better named, used waters, a paradigm shift is occurring. Wastewater treatment plants are increasingly regarded as a place where resources can be recovered from the used water, hence their new name water resource recovery facilities (WRRFs). Next to the long recognized and successfully recovered resources, water itself and energy, attention is growing to extract more valued products from used waters, in particular nutrients. Although today many processes for the recovery of nutrients from used water have already been proposed and applied to varying degrees (Vaneeckhaute et al., 2014), challenges remain with regard to the recovery of these nutrients as marketable products with added value for the agricultural sector, such as slow-release granular fertilizer products. This will form the underlying cause of the process control challenge developed below.

From a technological perspective, nutrient recovery from waste (water) can be represented by a three step framework: 1) nutrient concentration, e.g. precipitation and enhanced biological P removal, 2) nutrient release/stabilization, e.g. anaerobic digestion (AD), and 3) nutrient extraction. From literature, the techniques for nutrient extraction available or under development today are: 1) chemical crystallization, 2) gas stripping and absorption, 3) acidic air scrubbing, 4) membrane separation, and 5) biomass production and harvest (Vaneeckhaute et al., 2014). These processes include weak acid–base reactions (ionization), spontaneous or chemical dose-induced precipitate formation and chemical redox conversions, which influence pH, gas transfer, and directly or indirectly the biokinetic processes themselves.

Treatment trains are being conceived to maximize the recovery of interesting products at minimal cost and environmental impact. A state-of-the-art example is given in Figure 1 and further examples can be found in Verstraete and Vlaeminck (2011).

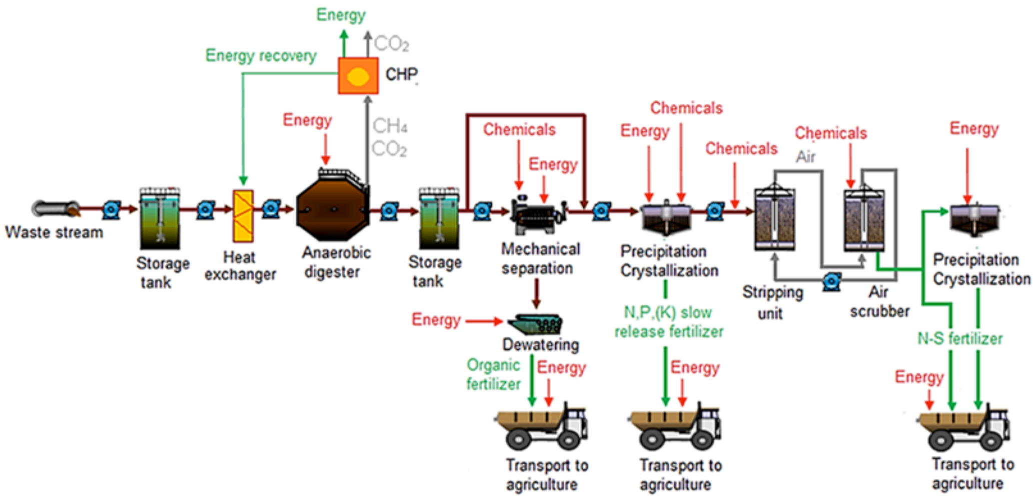

Figure 1. Water Resource Recovery Facility recovering energy, organic fertilizer, ammonium-sulfate fertilizer and N-P-K slow release fertilizer from a waste stream.

What is striking in the set of technologies among which engineers choose to set up these treatment trains, is that they consist almost uniquely of physicochemical processes. Looking beyond nutrient recovery systems, this observation is confirmed: an overview was made of technologies that have been successfully proposed to recover a wide range of products (in brackets) from used water:

- Stripping (NH_3, fatty acids)
- Precipitation (struvite, calciumphosphate)
- Filtration (paper fibers)
- Extraction (polyhydroxyalkanoates)
- Ion exchange (NH_4^+)
- Reverse osmosis (water, nutrient-rich concentrates)
- Phase separation (butanol)
- Pyrolysis, gasification, incineration (energy)
- Chemically enhanced primary treatment (organic matter)

Again, these are all physicochemical processes and this observation forms the basis of this paper's claim of the existence of a most important challenge to the modelling community.

Modelling challenges

Mathematical models have become very important tools for technology design, optimizing performance and process troubleshooting of wastewater treatment plants as they are both time and cost efficient (Rieger et al., 2012). Although a number of models of treatment facilities have been developed and applied extensively (Henze et al., 2000), these state-of-the-art models usually implicitly assume that the chemical and physical processes can be described by relatively simple models compared to the biological processes (e.g. the precipitation model in ASM2d). Consequently, the wastewater modelling community has given relatively little attention to these physicochemical processes. The current models used to describe these important physicochemical processes have therefore indeed remained relatively simple:

- Aeration: Kla (C_{sat}-C)
- pH: f(pKa, TAN, Alk, …)
- Precipitation: MeOH/MeP
- Membrane: $J = TMP/\mu.(R_m+R_f+R_c)$

However, these simplifications make that the application of these models has to be restricted to situations where the simplifying assumptions remain valid. It is stated here that this may be the case for a wide range of traditional WWTPs where biological processes are central, but not for WRRFs where the physicochemical processes dominate.

Modelling physicochemical reactions in WRRF's will thus be critical for their design and optimal operation, e.g. considering ion activities and solution supersaturation, to operate precipitation, extraction, stripping, phase separation, crystallization, sorption and filtration processes for recovery. A recent study (Batstone et al., 2012) has shown that a lot of consensus-building and development of critical model elements will be needed for a physicochemical modelling framework to be fully operational. Critical elements to be dealt with include accurate descriptions of acid-base reactions, slow precipitation kinetics, liquid-gas exchange and sorption/desorption in the complex mixture of chemicals that the resource recovery systems in place deal with. Moreover, model outputs should provide information on the physicochemical characteristics of the recovered products (e.g. macronutrient content, particle size, density, …) in order to determine and control their properties (see also the control challenge below).

First important steps are made towards a modelling framework for physicochemical models compatible with the current more biological process-oriented modelling frameworks (Takács et al., 2006; Grau et al., 2007; Yu et al., 2011; Batstone et al., 2012; Fernandez et al., 2014; Hauduc et al., 2014; Lizzaralde et al., 2014). However, considerable research is still required before integrated models will be available that will allow designing and optimizing water resource recovery facilities in the same way as is now possible for traditional biological wastewater treatment plants.

Control challenges

When recovered resources have to be put on the marketplace, an important paradigm shift will have to occur when transforming wastewater treatment plants into water resource recovery facilities. Rather than aiming for an effluent whose specifications are expressed in one-sided quality aspects (maximum concentrations of certain pollutants), putting a recovered product on the market will impose two-sided specifications. The recovered product will have to contain at least and at most such and such concentrations of a chemical of interest. Depending on the product, the specifications may be really narrow because the process industry with its purely chemical processes and its choice of raw products can guarantee narrow margins. This leads to the specification challenges that WRRFs will have to cope with to be successful. Recovery facilities do not have that luxury to choose the raw products: they have to work with the wastewaters that are sent to them as raw materials.

In summary, products with narrow specification margins must be recovered from a raw material to which no specifications can be imposed. This is quite a challenge on its own!

Because of this specification challenge, the process control systems in use today in wastewater treatment plants will have to be upgraded considerably in water resource recovery facilities. Let us first reconsider what current control systems have allowed achieving at treatment plants. Figure 2 shows on the left that having control systems allows reducing the safety margins that are imposed on process operations (and associated costs like over-aeration) because the treatment plant becomes more consistent: Process disturbances like load variations and wet weather have less impact because the control system activates counteracting actions (addition of chemicals, changing aeration intensity and pump flow rates, etc.).

However, in water resource recovery facilities this desirable property of control systems is getting challenged, for two reasons. First, there is less margin of error and the control authority must be increased. Second, while in classic wastewater treatment one-sided specifications are set, giving a way out on the other side, no such liberty exists any longer as two-sided limits are imposed. From a control engineering perspective this makes quite a difference. Finally, the product specifications may be described in unmeasurable quantities and indirect control strategies may have to be devised, further complicating the process control task.

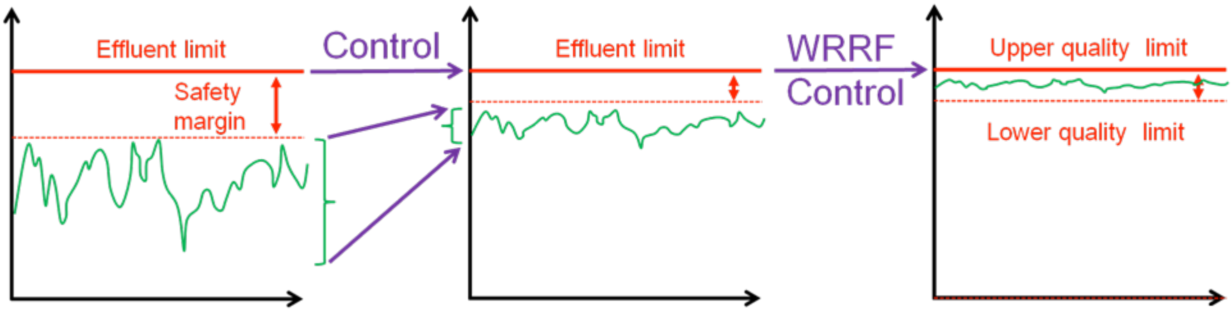

Figure 2. Paradigm shifts involving process control. Left-to-middle paradigm shift from non-controlled WWTP with large safety margins to controlled WWTP with reduced safety margin; Middle-to-right paradigm shift from one-sided specifications for WWTPs to two-sided, narrower, specifications for WRRFs

Conclusions

Successfully dealing with the modelling and control challenges presented in this contribution will improve the competitiveness of recovered products with respect to conventional mineral fertilizers and help to better classify these products in environmental legislation, thereby stimulating their use. Ultimately, the wasting of finite resources and environmental pollution will be greatly reduced and residues will acquire economic value. This will open up new opportunities for sustainable and more bio-based economic growth and thus create a win-win situation for both the environment, the society and the economy world-wide.

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References

Batstone D.J., Amerlinck Y., Ekama G., Goel R., Grau P., Johnson B., Kaya I., Steyer J.-P., Tait S., Takács I., Vanrolleghem P.A., Brouckaert C.J. and Volcke E. (2012) Towards a generalized physicochemical framework. Wat. Sci. Tech., 66, 1147-1161

Fernández-Arévalo T., Lizarralde I., Grau P. and Ayesa E. (2014) New systematic methodology for incorporating dynamic heat transfer modelling in multi-phase biochemical reactors. Water Res., 60, 141-155.

Grau P., de Gracia M., Vanrolleghem P.A. and Ayesa E. (2007) A new plant-wide modelling methodology for WWTPs. Water Res., 41, 4357-4372.

Hauduc H., Takács I., Smith S., Szabo A., Murthy S., Daigger G.T. and Sperandio M. (2014) A dynamic model for physicochemical phosphorus removal: Validation and integration in ASM2d. In: Proceedings 4th IWA/WEF Wastewater Treatment Modelling Seminar (WWTmod2014). Spa, Belgium, March 30 - April 2 2014.

Henze M., Gujer W., Mino T. and van Loosdrecht M.C.M. (2000) Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. IWA Scientific and Technical Report No 9, IWA Publishing, London, UK.

Lizarralde I., Brouckaert C.J., Vanrolleghem P.A., Ikumi D.S., Ekama G.A., Ayesa E. and Grau P. (2014) Incorporating water chemistry into wastewater treatment process models: Critical review of different approaches for numerical resolution. In: Proceedings 4th IWA/WEF Wastewater Treatment Modelling Seminar (WWTmod2014). Spa, Belgium, March 30 - April 2 2014.

Rieger L., Gillot S., Langergraber G., Ohtsuki T., Shaw A., Takács I. and Winkler S. (2012) Guidelines for using activated sludge models. IWA Scientific and Technical Report No.22, IWA Publishing, London, UK

Takács I., Murthy S., Smith S. and McGrath M. (2006) Chemical phosphorus removal to extremely low levels: experience of two plants in the Washington, DC area. Wat. Sci. Tech., 53(12), 21-28.

Vaneeckhaute C., Lebuf V., Belia E., Meers E., Tack F.M.G. and Vanrolleghem P.A. (2014) Nutrient recovery from (digested) bio-waste: Systematic technology review and product classification. Submitted.

Verstraete W. and Vlaeminck S.E. (2011) ZeroWasteWater: Short-cycling of wastewater resources for sustainable cities of the future. Int. J. Sust. Dev. World Ecol., 18, 253-264.

Yu L., Zhao Q., Jiang A. and Chen S. (2011) Analysis and optimization of ammonia stripping using multi-fluid model. Wat. Sci. Tech., 63(6), 1143-1152.