Emerging Implications of Balancing Disinfection and Primary Treatment as an Element in CSO Control: Model Requirements

A.C. Rowney[1], R. Field[2] and Thomas P. O'Connor[3]

[1]ACR, LLC, 184 Tollgate Branch, Longwood, Florida, USA
[2]US EPA Urban Watershed Management Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Edison, NJ, USA
[3]US EPA Urban Watershed Management Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Edison, NJ, USA

Abstract

This paper describes early results and directions arising from ongoing research into factors that affect the preferred balance between primary treatment and disinfection in a conventional wastewater treatment plant during periods of wet weather overflow. Despite the fact that national policy and regional regulations have required or implied use of these elements of treatment for decades, there remain some basic issues that are unresolved. In the context of a wet weather overflow event, the selection of an optimum point and manner for disinfection as it relates to the degree solids removal is one such issue. The factors that affect the choice of this point, particularly as reflected by the current state of microbiological understanding of quantification methods and of the influences of water chemistry on disinfectant behavior and indicator bacteria partitioning between solid and liquid phase components of the flow stream, are examined. Potential avenues for improved treatment practices are noted, and research directions are discussed.

Introduction

EPA's national CSO policy requires primary treatment plus disinfection, depending on state and policy context. These technologies and the design considerations involved in their implementation are among the best known of available treatment options, a fact that can be gleaned from a quick review of any basic textbook on wastewater treatment. Nevertheless, the linkages between them have not been fully addressed in US practice in that they are clearly interdependent physically but are not positioned in current policy and regulation to account for that fact.

This interdependence is potentially significant, because the interactions between the two are a net determinant of treatment efficiency and ultimately cost. For example, conventional disinfection best deals with free suspended and possibly surface attached microorganisms and is generally not as effective for microorganisms contained in larger protective solids. This in turn raises the question of the total amount of bacterial biomass exported from the treatment system. Changing the degree to which microorganisms are in fluid vs. solid phase constituents of the fluid being disinfected can change the net efficiency of the process. Increasing pressures to deliver improved receiving water quality at a time when implementation and operational funds are not inexhaustible and must increasingly compete with other national interests makes a deeper understanding of performance and cost containment related to these factors advisable. Given the tonnages of disinfectants used annually nationwide, and the focus on aging infrastructure that currently prevails, beneficial results of improved practice in these root areas of wastewater treatment could be considerable in terms of economic impact and receiving water protection.

To avoid redundancy and duplication of prior work, an achievable subset of the possible avenues of research was sought as this project was developed. It was considered that the governing physical and chemical equations for sedimentation and disinfection are well documented in a plethora of engineering manuals and wastewater textbooks (see for example Stencel et al, 2004), some of which EPA has been instrumental in developing and promulgating at a national level. Therefore, the present focus was on gathering information that exists, and building on the understanding of unit processes and exploring their dynamic interactions with modeling or interpretation.

The interactions of unit process elements in combination inherently involve analytical complexity greater than the functions of the process elements themselves, because the total system encompasses not only those discrete processes, but the net system consequences and interactions as well. The benefits of improved computational capability made this mathematical complexity a reasonable target for investigation. This is proceeding. An interim objective, which is the focus of this paper, is the development of a conceptual basis for this modeling. The simulation of process reactors and fluid transport mechanisms are generally well understood and will not be addressed further here. In contrast, the microbiological aspects of the problem are highly complex and even now only partially resolved, and choices must be made as to how they might be represented so that meaningful model results can be obtained.

Process Drivers

To evaluate the impact of primary treatment and disinfection, a variety of factors need to be considered. At an elementary level, the more sediments that are removed the more efficient the disinfection, because less disinfectant is consumed reacting with sediments. This is a function that will be accommodated in the model as one of the primary decision factors, and needs little further discussion here. Secondary effects, however, may also be important as bacteria are known to move between solid and fluid phases of a solution and the question arises as to how this movement relates to disinfection efforts. The following discussion provides a brief review of some factors relevant to these secondary effects.

An interesting element of this problem relates to residual bacterial biomass which remains in the sediments removed during treatment. Recent publications (WERF, 2006; Higgins et al, 2006; EPA, 2006; Qi et al, 2004) have noted that sludge, which had a low concentration of indicator bacteria such as fecal coliforms (FCs) prior to dewatering, were found to have a high concentration after dewatering. An interpretation of this finding was a presumption that the bacteria were in place in the sludge, but in a state that could not be cultured but that was nevertheless viable. That notion is not new, as it has been suggested in earlier publications (Roszak et al, 1987). Other hypotheses (found in the above references) for the reemergence of bacteria as a residual include a suggestion that there may be a growth inhibiting component in the sludge that is removed by dewatering, and that there may be some repair of bacteria which had been injured by the treatment process but not totally eradicated. Growth per se seems unlikely because of the time scales involved; it appears that enumeration methods or media were not the cause of this increase in numbers. Mechanical shearing of the media was not able to reproduce this effect directly. However, shearing may have an indirect impact, and one suggestion is that the shearing of the media released constituents that enabled their reappearance by stimulating reactivation. Whatever the cause of this phenomenon, a major point is that the transport of indicator organisms and pathogens in the wastewater treatment process is not a simple process and it is not fully understood. This underlines the need to review treatment processes and disinfection alternatives at a level that includes the biological responses of the bacteria in question.

Fully defining the behavior of bacteria in the highly heterogeneous conditions characteristic of a wastewater treatment facility, and the linkage of that behavior to engineering design, is challenging. An element of bacterial trait relevant to this problem is the bacterial production of a glycocalyx which a polysaccharide matrix that plays a role in protection and adhesion of communities or bacteria. Glycocalyx formation is important in several ways. As well as protecting bacteria directly it allows them to adhere to other bacteria or to solid surfaces. At a gross level, this phenomenon is associated with the slime upon which some treatment processes depend. It also has an impact on indicator bacteria survival. In even apparently pristine or near pristine waters it has been observed to have a pronounced impact on indicator bacteria presence and growth (Hunter et al, 2006). In rotating biological contactors (RBCs) it has been observed that the adhesion of bacteria by means of this mechanism is the major mechanism for removal, greater than actual dieoff (Tafwik et al, 2004).

Association with sediments in the natural environment is also a characteristic of indicator bacteria. Literature results have shown that the majority of indicator bacteria are associated with sediments, by means of physical incorporation within those materials or by attachment to them, and recent research has indicated that it is possible to model the association of E. Coli with sediments as an irreversible process in which bacteria move from the fluid phase to the solid phase (Jamieson et al, 2005a). Analysis in this case was approached by simulating sediments as an independent process, and associating removal of indicator organisms with sediment losses. The association of bacteria with sediments was based on experimentally determined partition coefficients; the irreversible nature of the reactions may be particular to the site and circumstances of that research. Other work (Jamieson et al, 2005b) indicates that resuspension during flow changes can re-introduce indicator bacteria that have been deposited in river sediments.

The association of bacteria and sediments, and the interactions between them, suggest the utility of considering a multi-phase model for use in representing bacteria in a treatment plant. The nature of the glycocalyx or the chemical dependence of isotherm associations suggests that a reversible or variable association may be a common result. Recent research indicates that the adhesion of bacteria to sediments can be influenced by concurrent exposure to other waterborne contaminants. Guber et al (2005) found that manure in the water stream changed both the degree of attachment to a soil, with a linear isotherm characterizing *E Coli* attachment without this additive, and a non-linear result otherwise, and with the degree of attachment much greater without than with. An interesting added complication attests to the influence of water quality on attachment in research that indicated bacteria were much more strongly associated with sediments than fluid when the solution was favorable for growth, while association with the solid phase was greater when the solution was unfavorable for growth (Yolcubal et al, 2002). Degree of saturation has similarly been shown to have an impact on indicator bacteria transport through a soil medium (Powellson et all, 2001), which may prove to be relevant to the problem at hand if whole cycle evaluations are contemplated and sludge at various degrees of saturation becomes an evaluation factor.

The heterogeneity of the underlying bacterial population further adds to this picture. Indicator bacteria are defined by a reaction to a stated test, and there can be considerable variation between species that exhibit this reaction. A recent study (Yang et al, 2004) measured about 280 *E Coli* isolates from an animal feedlot. That same study determined that motility varied very broadly within the population, and that this was correlated with biofilm forming ability as a function of the selected medium. Another researcher (Molina, 2005) explored the association of *Enteroccus* with manure, and found significant temporal and spatial variations in behavior. This work clearly demonstrated that *Enteroccoci* were non-ideal indicators of cattle in that context, and results are suggestive that this is generally true, since the work cites that some apparently likely correlations were absent or limited. Other research has shown that charge differences and other cell properties can render the transport properties of indicators and pathogens quite differently (Bolster et al, 2006). Given the various factors affecting fate and mobility, it is perhaps hardly surprising that the utility of indicators is conditional, but the fact is that for pragmatic and good reasons, indicators remain an important element in the arsenal of water quality managers.

Model Development

The picture which emerges is that there is a clear case to be made that effective simulation of bacteria in the context of a plant operation must explicitly consider more than the movement associated with the fluid and as influenced by dieoff. The heterogeneity of the population, the variations in water chemistry, the variations in substrate candidates, and environmental variables such as temperature, some varying temporally, are all potential factors represented in a truly comprehensive model, and the various component systems would be coupled and potentially non-linear. Such a model would be enormously complex. Viewing 'indicator bacteria' as a composite phenomenon or surrogate parameter, the notion that identification of perhaps many dozens of parameters would be required for the successful application of such a tool, and that resolving such a model if it contained significantly non-linear terms could be a substantial numerical challenge in practical contexts. This is by no means a new observation, and there are examples of models which cope with complexity in a variety of ways (see for example Burns, 2000). A collection of some publicly available technologies relevant to the problem at hand can be found at http://cfpub.epa.gov/crem.

In the face of the complexity of the reality, choices have to be made for viable models to be proposed and developed. Fortunately, simpler tools do have utility and have been known to work effectively in a variety of circumstances. A model which coupled sediment and bacteria by means of an irreversible absorption model was effective in its chosen physical context (Jamieson et al, 2005a). Even simpler models have also been shown to be effective; for example in the application of a dynamic version of QUAL-II which treated FC as a solute subject to first order decay and was found to produce good results in simulating dynamic FC behavior in an urban stream (Rowney et al, 1982). The question therefore is to consider what degree of complexity is required for present purposes, namely, to resolve the behavior of bacteria as a function of primary settling.

For the present work, the next logical step and the framework selected for development and analysis in this project is to include two sets of relationships. A solids phase will be represented as a two component system (discrete and hindered settling). Bacteria will be represented as a single component, and will be partitioned between the solid and liquid phases by means of an isotherm model. The variability in response of different components of a real bacterial population will be approximated by incorporating a random component in the representation of bacterial partitioning and die-off. Disinfectant behavior will be represented using standard disinfectant dose/response relationships. The literature cited here, together with other available sources, provide sufficient information for a reality based representation of parameters. This assembly will provide a useful next step in this research, and a sufficient basis to guide further analysis and experimentation. Ultimately, a tool useful in the optimal design of primary treatment and disinfection systems will result.

The immediate applications of the developed model will be to determine on the basis of available data:

i) those elements of the system that are most critical in terms of information gaps, so that further research can be considered to enhance model reliability, and

ii) the apparent potential for changes in process train management in the primary and disinfection system components to achieve economies in operation and potentially develop an optimum response strategy.

Further details of the model, including the above components and selected representative site and wet weather conditions will be provided in future publications.

Conclusion

The microbiological response to primary settling followed by disinfection is simple in concept but highly complicated in detail. The basic notions of indicator bacteria responses to environmental stressors are well understood, but quantifying them to the point where meaningful predictive models can be applied is in practice presently only applied to a limited degree. Disinfection is a function of the dose and duration with which a medium is exposed to a particular disinfectant, but the factors that govern the rate and completion of that disinfection are numerous. Adhesion to surfaces, embedding in a matrix, stress responses of the indicator organisms, and recovery of those organisms from their stressed state all work to reduce the degree of disinfection. The survival, re-growth, re-emergence or recovery of those organisms counters the intent and efficiency of disinfectant addition. Accounting for these realities explicitly offers a potential that disinfection practices can be adjusted to remove target organisms to better effect. Research opportunities to better determine and quantify the factors at work in this area, and to ultimately enable better predictive capability, are under way. As a start, a five compartment model (bacteria, disinfectant, fluid and two solid phases) which is justifiable given the nature of available data has been proposed, and will be used to explore options for treatment enhancement as well as to guide future research.

References

Bolster, Carl H., Sharon L. Walker, and Kimberly L. Cook. 2006. Comparison of Escherichia coli and Campylobacter jejuni Transport in Saturated Porous Media. *Journal of Environmental Quality* 35:1018-1025.

Burns, Lawrence A. 2000. *Exposure Analysis Modeling System (EXAMS): User Manual and System Documentation*. US EPA National Exposure Research Laboratory, Athens, Ga.

Guber, A.K., D.R. Shelton, and Ya. A. Pachepsky. 2005. Effect of Manure on Escherichia coli Attachment to Soil. *Journal of Cave and Karst Studies* 34:2086-2090.

Higgins, Matthew J. et al. ScienceDirect - Water Research : Reactivation and growth of non-culturable indicator bacteria in anaerobically digested biosolids after centrifuge dewatering. *Water Research* 41, no. 3.

Hunter, Andrea J., Diana E. Northup, Clifford N. Dahm, and Penelope J. Boston. Persistant Coliform Contamination in Lechuguilla Cave Pools. *Journal of Cave and Karst Studies* 66, no. 3:102-110.

Jamieson, Rob, Doug M. Joy, Hung Lee, Ray Kostaschuk, and Robert Gordon. (a) 2005. Transport and deposition of sediment-associated Escherichia coli in natural streams. *Water Research* 39:2665-2675.

Jamieson, Rob C., Doug M. Joy, H. Lee, R. Kostaschuk, and Robert J. Gordon. (b) 2005. Resuspension of Sediment-Associated Escherichia coli in a Natural Stream. *Journal of Environmental Quality* 34:581-589.

Molina, Mariosa. *Temporal and Spatial Variability of Fecal Indicator Bacteria: Implications for the Application of MST Methodologies to Differentiate Sources of Fecal Contamination*. US EPA National Exposure Research Laboratory, Athens, Ga.

Powelson, David K., and Aaron L. Mills. 2001. Transport of Escherichia coli in Sand Columns with Constant and Changing Water Contents. *Journal of Environmental Quality* 30:238-245.

Qi, Y, S. Gillow, D.S. Herson, and S.K. Dentel. Reactivation and/or growth of Fecal Coliform Bacteria During Centrifugal Dewatering of Anaerobically Digested Biosolids. *Water Science and Technology* 50, no. 9:115-120.

Roszak, D.B., and R.R. Colwell. 1987. Survival Strategies of Bacteria in the Natural Environment. *Microbiological Reviews* 51, no. 3:365-379.

Rowney, A. Charles, and Larry A. Roesner. 1982. Continuous Simulation of Instream Fecal Coliform Bacteria. In *Proceedings of the Water Quality Manager's Conference*, Alexandria, Va: EPA.

Stensel, H.David, George Tchobonoglous, and Franklin L. Burton. 2003. *Wastewater Engineering: Treatment and Reuse (4 Ed)*. McGraw-Hill.

Tafwik, A., A. Klapwijk, J.C.L. van Buuren, F. El-Gohary, and G. Lettinga. 2004. Physico-chemical factors affecting the E.coli removal in a rotating biological contactor (RBC) treating UASB effluent. *Water Research* 38, no. 5:1081-1088.

US EPA. 2006. *A WERF Study Finds Fecal Coliforms Appear to Reactivate In Centrifuge Dewatered Solids at Four of Seven Facilities Tested*. US EPA Office of Water .

Water Environment Federation. 2006. *Reactivation and Regrowth of Fecal Coliforms in Anaerobically Digested Biosolids*.

Yang, Hsiao-Hui, Robert T. Vinopal, Domenico Grasso, and Barth F. Smets. 2004. High Diversity among Environmental Escherichia coli Isolates from a Bovine Feedlot. *Applied and Environmental Microbiology* 70, no. 3:1528-1536.

Yolcubal, Irfan, Shelley Pierce, Raina M. Maier, and Mark L. Brusseau. 2002. Biodegradation during Contaminant Transport in Porous Media: V. The Influence of Growth and Cell Elution on Microbial Distribution. *Journal of Environmental Quality* 31:1824-1830.