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A Framework for Modeling the Fate and Transport of *Giardia* and *Cryptosporidium* in Surface Waters[1]

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ABSTRACT

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The feasibility of modeling the environmental fate and transport of cysts and oocysts of the protozoan pathogens *Giardia lamblia* and *Cryptosporidium* spp. in surface waters is examined. A kinetic and modeling framework successfully applied for fecal bacteria is considered for this application. The model utilizes a mass balance approach and accommodates inputs from tributary loads and sediment resuspension, losses to sedimentation and inactivation and mass transport. Recommendations are provided for the design of a program of field monitoring and experimental studies which would support model development. Requirements for model application are considered within the context of Cannonsville Reservoir, a component of the New York City drinking water supply system.

Key Words: *Cryptosporidium*, *Giardia*, oocysts, cysts, reservoir, surface water, fate and transport model.

Protection of drinking water supplies from waterborne pathogens has long been a primary concern of municipal engineers and public health officials. Although a variety of organisms transmit waterborne disease, water quality managers have traditionally focused on bacteria and viruses. The protozoan pathogens *Giardia lamblia* and *Cryptosporidium* spp. have become of increasing interest to the water supply industry following outbreaks of giardiasis (Craun 1988; Hibler and Hancock 1990) and cryptosporidiosis (Fox and Lytle 1993; Pett et al. 1993; Bridgman et al. 1995) resulting in illness and loss of life. The U.S. Environmental Protection Agency (EPA) has established risk guidelines for protozoan pathogens which would mandate treatment of raw water supplies subject to contamination by *Giardia* and *Cryptosporidium* (U.S.

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EPA 1989). As an alternative to treatment by filtration and/or chemical disinfection (and their associated cost), water quality managers may seek to reduce levels of protozoan pathogens closer to the source, i.e., in the raw water supply.

The remediation process for surface water supplies is often supported by mathematical models, guiding managers in establishing cost-effective pollution abatement strategies. Model frameworks for simulating the environmental fate of organisms indicative of fecal bacteria pollution (e.g., fecal coliforms, fecal streptococci, and *E. coli*) are described in water quality modeling manuals (Bowie et al. 1985) and texts (Chapra 1997; Thomann and Mueller 1987) and have been the subject of articles in the primary engineering and science literature (Freedman et al. 1980; Palmer and Dewey 1984; Canale et al. 1993) Protozoan pathogens present a challenge to modelers because qualitative and quantitative information on sources of these microorganisms and on the importance of environmental factors in mediating their fate are lacking, especially for lakes and reservoirs. Auer and Niehaus (1993) describe and quantify phenomena governing the environmental behavior of fecal coliform (FC) bacteria in lakes and Canale et al. (1993) integrate those findings in a fc model. The utility of that kinetic framework has not, however, been evaluated for application to protozoan pathogens. Chapra (1997) demonstrates the development of a simple model for *Giardia* and *Cryptosporidium* in a stratified lake, but does not address environmentally-mediated loss kinetics (e.g., effects of light and temperature on death/inactivation).

Here we propose a theoretical framework for modeling protozoan pathogens intended to guide the program of field measurement and laboratory experimentation required for development of a full management model, i.e., loading data, kinetic coefficients relating to source/sink terms, and a model calibration and verification data base. The proposed framework is considered here for application to the reservoirs comprising the 580 billion gallon New York City water supply, one of the largest in the nation. The City of New York operates and maintains 19 drinking water reservoirs in upstate New York under the aegis of the New York City Department of Environmental Protection (NYC DEP). Seeking to improve levels of watershed protection and source water quality, NYC DEP is cooperating in the development of water quality models for these systems, beginning with Cannonsville Reservoir, the third largest, most distant, and most eutrophic of the NYC reservoirs. Water quality (Doerr et al. 1998) and hydrothermal (Gelda et al. 1998; Owens 1998a) models have been developed for Cannonsville Reservoir and are described elsewhere in this issue. The proposed protozoan model framework focuses on this system as well.

Approach

In the documentation for the general purpose water quality model CE-QUAL-W2, Cole and Buchak (1995, p.19) urged that models, "be used as a starting point for limnological investigations of a waterbody, with the data and formulations continuously refined to reflect the increased understanding of the system and processes gained over time," and lamented that "this approach is rarely taken in practice due in large part to the inability of aquatic biologists/limnologists and engineers to collaborate." Here we seek to promote that collaboration, placing into consideration the framework developed by Canale et al. (1993) for FC bacteria in Onondaga Lake, New York for application to protozoan pathogens. Data requirements for model development and application are considered within the context of a protozoan pathogen monitoring program being carried out on the reservoirs which comprise the NYC water supply (Stern 1996a,b,c) and an AWWARF-sponsored research program investigating environmental mediation of *Giardia* and *Cryptosporidium* survival in watersheds (Sattar et al. 1994). This consideration of an existing framework for application to the complex and critical problem of protozoan pathogens and to guide future field and laboratory studies is proposed as a most timely and appropriate use of the modeling art.

Model Development

Canale et al. (1993) utilized a mass balance approach which accommodated tributary and point source loadings, mass transport through advection and dispersion, and kinetic terms, i.e., losses to death and settling. A two-dimensional geometry was applied to capture both horizontal gradients over the lake surface and vertical gradients associated with seasonal thermal stratification. Mathematically, the mass balance for a pair of adjoining model cells (i and j) may be represented as in Eq. 1:

$$V_i \cdot \frac{dC_i}{dt} = W_i + \sum_j [Q_{ij}\,(C_j - C_i)] + \sum_j [E_{ij}(C_j - C_i)] - V_i \,.\, k \cdot C_i \quad (1)$$

in which C = FC bacteria concentration in model cell i or j (cells · m^{-3}), E'_{ij} = dispersive exchange between model cells i and j ($m^3 \cdot d^{-1}$), k = first order loss coefficient (d^{-1}), Q_{ij} = advective exchange between model cells i and j ($m^3 \cdot d^{-1}$), t = time (d), V_i = volume of model cell i (m^3), and W_i = FC bacteria loading to cell i ($cells \cdot d^{-1}$).

The state variable for modeling the target protozoan pathogens is the infective stage, termed cysts (produced due to asexual reproduction) for *Giardia* and oocysts (produced due to sexual reproduction) for *Cryptosporidium* and commonly referred to here as (oo)cysts. The framework proposed here for modeling (oo)cyst dynamics would require characterization of advective and dispersive exchange. In Cannonsville Reservoir, this is accomplished through a mass transport submodel (Owens 1998a; Doerr et al. 1998). For clarity of presentation, the proposed model framework is described here for a single water column model cell, recognizing that the full model would include complete spatial segmentation, as presented in the spirit of the segmentation used by Canale et al. (1993), and consistent with the geometry of the study site. The mass balance on (oo)cysts for a single water column cell is given by Eq. 2:

$$V_{wc} \cdot \frac{dC_{wc}}{dt} = W - Q \cdot C_{wc} - V_{wc} \cdot k \cdot C_{wc} \qquad (2)$$

in which C_{wc} = water column cyst concentration [(oo)cysts · m^{-3}], k = first order loss coefficient (d^{-1}), Q = inflow ($m^3 \cdot d^{-1}$), t = time (d), V_{wc} = water column volume (m^3), and W = (oo)cyst loading [(oo)cysts · d^{-1}]. The first order loss term (k in Eq. 2) includes the effects of death or inactivation [if reliable methods for (oo)cyst viability become available] and settling. Rewritten to identify these sink terms explicitly yields Eq. (3):

$$V_{wc} \cdot \frac{dC_{wc}}{dt} = W - Q \cdot C_{wc} - V_{wc} \cdot k_d \cdot C_{wc} - V_{wc} \cdot k_s \cdot C_{wc} \qquad (3)$$

in which k_d = first order death/inactivation coefficient (d^{-1}) and k_s = first order settling loss coefficient (d^{-1}).

The FC bacteria model framework developed by Canale et al. (1993) did not include a term for resuspension of bacterial cells from the sediment. This was an appropriate omission because that model focused on the recreational season, a period during which the target lake is thermally stratified and resuspension is negligible. It is known, however, that sediment resuspension of bacterial cells may be an important source term, especially in riverine environments (Sherer et al. 1992; Stephenson and Rychert 1982). Application of the framework of Canale et al. (1993) to the NYC reservoir system requires that the period of interest be expanded to the entire year and that a sediment component be added to accommodate resuspension during the unstratified seasons. The sediment mass balance is given in Eq. 4:

$$V_{sed} \cdot \frac{dC_{sed}}{dt} = V_{wc} \cdot k_s \cdot C_{wc} - V_{sed} \cdot C_{sed} \cdot (k_r + k_d + k_b) \qquad (4)$$

in which C_{sed} = sediment (oo)cyst concentration [(oo)cysts · m^{-3}], V_{sed} = volume of the active sediment layer (m^3), and where the various rate coefficients accommodate (oo)cyst inputs from the water column due to settling (k_s), losses in the sediment due to death/inactivation (k_d) and burial (k_b) and resuspension from the sediment to the water column (k_r).

In summary, the model framework proposed for protozoan pathogens would retain the attention to vertical and horizontal segmentation and the mathematical treatment of advective and diffusive mass transport characteristic of the FC bacteria model (Canale et al. 1993), applying a kinetic approach comparable to that developed by Auer and Niehaus (1993). It is recognized that death/inactivation kinetics and especially the role of environmental factors in mediating those kinetics may differ for cysts and oocysts and especially for the kinetics for (oo)cysts as compared with FC bacteria. The proposed model framework further differs from that of Canale et al. (1993) by inclusion of a sediment component (as recommended by Chapra 1997). The protozoan framework is compared to that for FC bacteria (Canale et al. 1993) in Fig. 1. Model components common to both are indicated with solid lines, while those specific to the protozoan framework are identified by dashed lines.

Modeling Test System

Application of the proposed protozoan fate and transport model requires selection of a test system. Here we consider Cannonsville Reservoir, a water body well-suited for that purpose due to its location, patterns of watershed development, and well-defined hydrology (Owens et al. 1998). Land use within the watershed is diverse, but the reservoir itself is fairly isolated from urban populations. The system's hydrology is well understood (Owens et al. 1998) and readily trackable, in contrast with other reservoirs within the NYC system (Stepczuk and Lounsbury 1995). Seasonal drawdowns of up to 15 m occur in Cannonsville Reservoir making this an excellent candidate for exploration of resuspension effects (Stepczuk and Lounsbury 1995). Such extreme drawdowns have not been reported in reservoirs further downstream in the NYC drinking water system. Mechanistic hydrodynamic (Owens 1998a; Gelda et al. 1998) and water quality models (Doerr et al. 1998) recently developed for Cannonsville Reservoir and the availability of some (oo)cyst loading data would provide invaluable support for development of

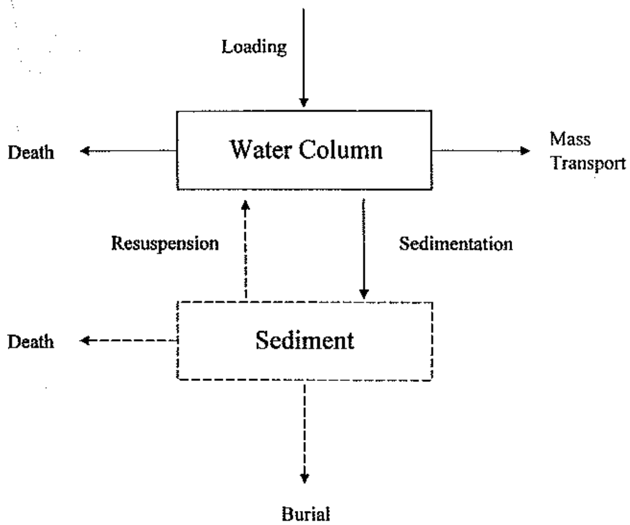

Figure 1.–Comparison of fecal coliform model (Canale et al. 1993; solid lines) and proposed (oo)cyst model (solid plus dashed lines).

a protozoan cyst model. Integration of these models and submodels with the protozoan cyst model is discussed below.

Monitoring efforts are required to support loading calculations, to provide data for model calibration and verification and to facilitate control of (oo) cyst sources in the watershed. NYC DEP has been conducting routine sampling for (oo)cysts in Cannonsville Reservoir for over three years (Stern 1996a, b, c). The EPA-approved method used for this monitoring program provides detection of cyst and/or oocyst presence, but does not determine species, viability, or infectivity (Fout et al. 1996). Pathogen sampling sites have been established at various locations on the West Branch of the Delaware River (including at its discharge to Cannonsville Reservoir designated as WBDN) and at the beginning and end of the aqueduct carrying water from Cannonsville to Rondout Reservoir. These stations have been monitored for the presence of *Giarida* cysts and *Cryptosporidium* oocysts on an approximately monthly basis (biweekly at WBDN). The presence of cysts and oocysts has been confirmed at all of these sites, albeit infrequently and at low levels. Although the effluent from Cannonsville to Rondout Reservoir is monitored, no sampling stations are presently located within the main body of Cannonsville Reservoir.

Model Inputs and Model Application

Beyond identification of a suitable test system, application of the proposed model framework requires specification of a suite of model inputs. Here we address issues related to model application, specifically the availability and development of requisite model input information. Information flow among the components of the proposed (oo) cyst model, as applied to Cannonsville Reservoir, is illustrated in Fig. 2.

Kinetic Resolution

It is implicit in the development of this model framework that the state variables will be the concentration of *Giardia* cysts and *Cryptosporidum* oocysts. As noted by Bagley et al. (1998), however, it is possible to distinguish three states for (oo)cysts detected in a water or sediment sample: (1) non-viable, (2) viable, but not infective, and (3) viable and infective. The only reliable method for determination of viability is host infection; a costly and time-intensive approach which may not be consistent with data requirements for modeling. The selection of a particular physiological state for modeling purposes will significantly influence the cost and difficulty of developing a supporting data base and the interpretation of model output for management use. This issue certainly merits the attention of scientists, modelers, and managers.

Loading Sub-Model

External loads are the primary forcing condition for the proposed (oo)cyst model. Such information specific to (oo)cysts is typically unavailable for lakes and reservoirs. As noted above, some cyst and oocyst loading data are being developed for the test system as part of the NYC DEP pathogen monitoring program. However, even this database is limited in comparison with that typically utilized in support of water quality (e.g. fecal bacteria) models. Rough loading estimates (Chapra 1997) for use in a preliminary screening model for (oo)cyst dynamics could be developed through published estimates of (oo) cyst levels in various water samples (cf. LeChevallier and Norton 1995; Stern 1996a,c) and of (oo) cyst export coefficients (cf. Hansen and Ongerth, 1991). However, the large degree of variability in the data base, the lack of in-reservoir measurements for model validation, and uncertainties in the determination of (oo) cyst viability and infectivity may make such an effort impractical for specific systems (e.g., Cannonsville Reservoir). Rigorous testing of a (oo)cyst model will require the development of a more detailed loading data base. Such a program could be aided by evaluation of data from preliminary studies (e.g., NYC DEP's watershed monitoring program) to define the requisite monitoring frequency and the need to address special issues, i.e., storm/resuspension

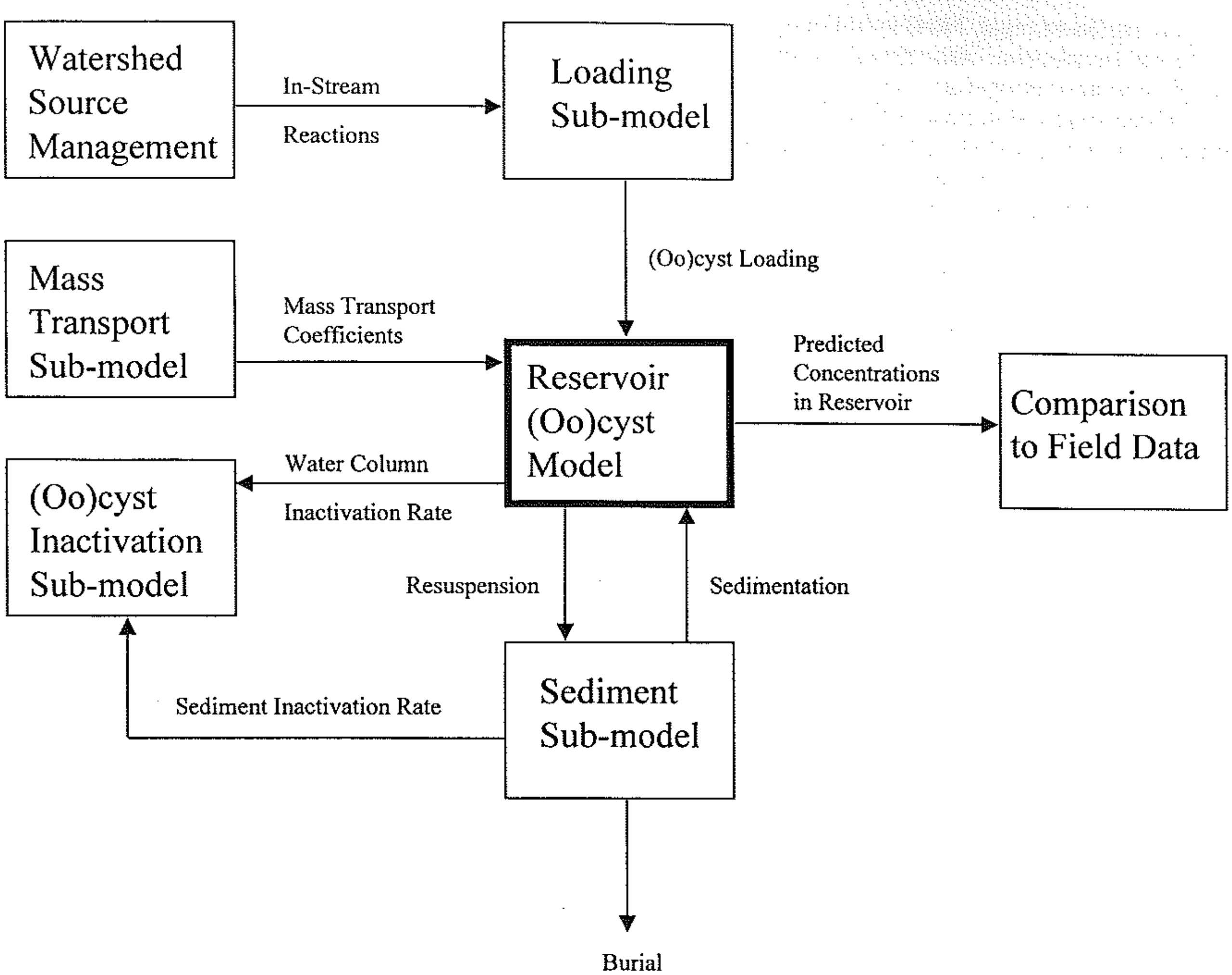

Figure 2.–Information flow for proposed (oo)cyst model.

events in the watershed and in upstream reaches of the tributaries.

Mass Transport Sub-Model

The fate of (oo) cysts within a lake or reservoir and thus their potential for passage to a point of delivery in a water supply system is determined, in part, by the system's hydrodynamics. The advective and dispersive flow regime of a lake or reservoir must be accurately modeled. A two-dimensional (longitudinal and vertical) hydrodynamics model has been calibrated and verified for Cannonsville Reservoir (Gelda et al. 1998). Testing was supported by detailed measurements of currents (Owens 1998b) and temperatures (Owens 1998c) in these dimensions. The model can be used to quantify the rate of advective mass transport and dispersive exchange of (oo) cysts among model cells (segments). The hydrodynamics model may be linked to the water quality (protozoan pathogen) model directly or may serve as a submodel component of the main conceptual framework.

Sediment Sub-Model

Losses from the water column through settling and subsequent re-introduction through resuspension are additional processes mediating (oo)cyst fate. Quantification of FC bacteria settling velocities was a key contribution of the kinetic studies conducted by Auer and Niehaus (1993). In that effort, sediment traps were used to determine the rate of loss of FC bacteria from the water column due to settling. It is not known whether (oo)cysts settle primarily on an individual basis or in association with other (oo)cysts or larger, heavier particle flocs. The topic of (oo)cyst resuspension is poorly defined as well. However, results from a detailed study of (oo)cyst inactivation in the sediments (Sattar et al. 1994) could help to clarify the potential importance of the resuspension mechanism for protozoan pathogens.

These source/sink terms may be quantified through a sediment transport sub-model which accommodates particle transport, sedimentation, resuspension, and burial. Submodel development should be supplemented by field studies characterizing settling velocities specific to cysts and oocysts. The submodel should be mechanistic in nature and incorporate the effects of storm events and seasonal drawdown. Given the extended viability of (oo)cysts at low temperatures (as reviewed by Bagley et al. (1998) and the documented effect of drawdown on sediment re-suspension, it seems especially important to address these phenomena in studies of pathogen fate in drinking water reservoirs.

Cyst Inactivation Sub-model

The last process considered as influencing (oo)cyst fate is inactivation (equivalent to death for FC bacteria). Several studies have investigated the role of environmental conditions in mediating the abundance and viability of *Giardia* cysts and/or *Cryptosporidium* oocysts (see Bagley et al. 1998). However, the majority of these studies focused on the relationship between treatment/disinfection and environmental conditions rather than on fate and viability in surface waters. In natural systems, temperature, pH, solar radiation, and redox conditions, either singly or in combination, may influence fate and viability. Inactivation rates in the sediment may differ from those in the water column due to the absence of solar radiation and marked differences in pH, temperature, and redox conditions. Further, it is not clear, nor is it even likely, that cysts and oocysts will respond similarly to changes in environmental conditions. Bagley et al. (1998) were unable to identify any quantitative information regarding either rates of inactivation in natural (*vis-a-vis* engineered) systems or functional relationships between inactivation rates and environmental conditions. While it may be possible to derive kinetic coefficients from a composite of literature data for *Cryptosporidium* oocysts (Carrington and Ransome 1994) and *Giardia* cysts (Meyer 1979), such an effort is complicated by differences in the various experimental protocols utilized in these studies.

Support for the development of an (oo)cyst inactivation submodel should be forthcoming from an AWWARF-funded study cited previously (Sattar et al. 1994). The effects of light (UV and sunlight), temperature, pH, redox levels, freeze-thaw and temperature cycles, pressure, and shearing and abrasion on *Giardia* cyst and *Cryptosporidium* oocyst viability/inactivation are being studied singly and in combination. Values for kinetic coefficients are being developed and functional relationships between inactivation rates and environmental factors will be proposed. (Oo)cyst survival in natural waters (primarily rivers) and sediments will also be compared. Some of these data are available (e.g., Battigelli et al. 1996; Chauret et al. 1995a,b), although kinetic coefficients have not yet been published. The data and kinetic coefficients from the AWWARF-funded study may ultimately be able to be incorporated into the cyst inactivation sub-model with little or no modification.

Comparison to Field Data

Testing of a (oo) cyst model necessitates the development of a field data base for comparison to model output. A data base of the appropriate spatial and temporal resolution is rarely available unless the sampling program is designed specifically to complement the modeling process. In Cannonsville Reservoir, for example, only the inflows and outflows are being monitored for the presence of protozoan pathogens; no sites within the reservoir are monitored. It may be inappropriate to proceed with more detailed monitoring until the questions of kinetic resolution outlined above can be addressed. Advances in methods for assessing (oo) cyst detection and viability may result from the AWWARF-funded study. Model application would further require measurement or specification of those environmental conditions mediating (oo)cyst fate.

Watershed Source Management

Model output would ultimately be applied in managing watershed sources of cysts and oocysts, seeking to minimize risk exposure to users of the water supply. The (oo)cyst issue differs markedly from parameters typically addressed in water quality studies, e.g., coliform bacteria, where loads and loading sources are well defined. The data base on watershed sources for protozoan pathogens will certainly expand as the intensity of watershed monitoring increases. For example, NYC DEP is collecting information on (oo) cyst levels at various sites on the West Branch of the Delaware River, including urbanized, undisturbed, and agricultural portions of the watershed (Stern 1996a). At present, samples are collected on a monthly basis. NYC DEP is currently exploring the possibility of increasing storm sampling as preliminary results from other watersheds in the NYC reservoir system indicate that there is a noticeable increase in detection and concentrations of (oo)cysts during wet-weather events. NYC DEP has also considered modifying terrestrial models which simulate loads from the Cannonsville Reservoir watershed to include protozoan cysts and oocysts. These modifications would include information pertaining to pathogen sources and in-stream reactions influencing (oo)cyst viability. NYC DEP has concluded, however, that the available information on factors influencing cyst and oocyst fate and transport in the watershed is insufficient for predictive modeling purposes (Schniederman et al. 1995) and that the use of an (oo)cyst loading model to support management actions in the basin must await identification and quantification of (oo)cyst sources. Until that time, NYC DEP plans to limit the application of model simulations to the consideration of drinking water treatment strategies.

Summary

Kinetic (Auer and Niehaus 1993) and modeling (Canale et al. 1993) frameworks developed for FC bacteria were examined for application in the simulation of protozoan pathogen dynamics, i.e., the infective (oo)cyst stage of *Giardia* and *Cryptosporidium*. Those frameworks, modified to accommodate sediment interactions, are considered appropriate for this purpose. At present, however, model application is limited by the ability to define model inputs, e.g., loads, kinetic coefficients, monitoring data. Some of that information may be forthcoming from an AWWARF-funded study of *Giardia* and *Cryptosporidium*, while other information must be developed on a site-specific basis. Implementation of the recommendations presented below, intended to support the development of a (oo)cyst model for Cannonsville Reservoir and similar systems, should be conducted in concert with a careful review of progress in this new and evolving field of study.

Recommendations

Specific recommendations for field monitoring and experimental studies on Cannonsville Reservoir and comparable systems are made here for the purpose of: 1) developing a detailed (oo)cyst loading database, 2) identifying site-specific values for kinetic coefficients, and 3) compiling a database for model calibration and verification. Additional, general recommendations are made which are critical in defining the model framework. The recommendations are as follows:

1. An appropriate level of kinetic resolution must be identified, considering advances in (oo)cyst detection/viability/infectivity and the specific application of modeling results for water supply management.

2. Sources of (oo)cysts and opportunities for source management must be identified and quantified. This effort could proceed within the framework of an extant monitoring study, but may require changes in sampling sites/frequency as well as selected site-specific monitoring.

3. A pathogen monitoring program must be established to develop a detailed loading database. Selection of a master loading site and sampling regime must include consideration of in-stream gains and losses and the importance of storm events in governing loads.

4. An in-reservoir pathogen monitoring program must be established to provide data for model calibration and verification.

5. System-specific (oo)cyst sedimentation rates must be developed using sediment traps positioned at the in-reservoir monitoring sites.

6. The potential for resuspension must be evaluated, especially to define the active sediment zone, rate of resuspension, and burial velocity. (Oo)cyst abundance in the active sediment zone must be assessed.

7. Kinetic coefficients made available through the AWWARF-sponsored research should be evaluated and recommendations made regarding their application to the reservoir (oo)cyst model. Where required, site-specific determination of selected model coefficients would be recommended.

8. A screening-level (oo)cyst model should be developed based on extant mass transport and sediment models and the kinetic framework of Auer and Niehaus (1993). This screening model would be used to insure that the field programs outlined above are designed to have maximum value at minimum cost.

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References

Auer, M. T. and S. L. Niehaus. 1993. Modeling fecal coliform bacteria - I. Field and laboratory determination of loss kinetics. Wat. Res. 27:693-701.

Bagley, S. T., M. T. Auer, D. A. Stern and M. J. Babiera. 1998. Sources and fate of *Giardia* cysts and *Cryptosporidium* oocysts in lakes and reservoirs. Lake and Reserv. Manage. 14(2-3):379-392.

Battigelli, D. A., M. W. LeChevallier and M. Abbaszadegan. 1996. Environmental resistance of *Cryptosporidium parvum* and *Giardia muris*. Abstract No. Q-91, Am. Soc. Microbiol. Annu. Meeting, P. 73.

Bowie, G. L., W. B. Mills, D. B. Porcella, C. L. Campbell, J. R. Pagenkopf, G. L. Rupp, K. M. Johnson, P. W. H. Chang, S. A. Gherini and C. Chamberlin. 1985. Rates, constants, and kinetics formulations in surface water quality modeling, 2nd edition, EPA/600/3-85/040. U.S. Environmental Protection Agency, Athens, GA.

Bridgman, S. A., R. M. P. Robertson, Q. Syed, N. Speed, N. Andrews and P. R. Hunter. 1995. Outbreak of cryptosporidiosis associated with a disinfected groundwater supply. Epidemiol. Infect. 115:555-566.

Canale, R. P., M. T. Auer, E. T. Owens, T. M. Heidtke and S. W. Effler. 1993. Modeling fecal coliform bacteria - II. Model development and application. Wat. Res. 27:703-714.

Carrington, E. G. and M. E. Ransome. 1994. Factors Influencing the Survival of *Cryptosporidium* Oocysts in the Environment. FR0456. Crown and Foundation for Water Research, Bucks, UK.

Chapra, S.C. 1997. Surface water quality modeling. McGraw-Hill, Inc., New York, NY. 844 p.

Chauret, C., N. Armstrong, J. Fisher, R. Sharma, S. Springthorpe and S. Sattar. 1995a. Correlating *Cryptosporidium* and *Giardia* with microbial indicators. J. Am. Water Works Assoc. 87:76-84

Chauret, C., P. Chen, S. Springthorpe and S. Sattar. 1995b. Effect of environmental stressors on the survival of *Cryptosporidium* oocysts. Proc. AWWA Water Quality Technol. Conf. 95. P. 1567-1585.

Cole, T. M. and E. M. Buchak. 1995. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 2.0. User Manual. Instruction Report EL-95, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, 57 p.

Craun, G. F. 1988. Surface water supplies and health. J. Am. Water Works Assoc. 80:40-52.

Doerr, S. M., E. M. Owens, R. K. Gelda, M. T. Auer and S. W. Effler. 1998. Development and testing of a eutrophication model for Cannonsville Reservoir, New York. Lake and Reserv. Manage. 14(2-3):301-321.

Fout, G. S., F. W. I. Schaefer, J. W. Messer, D. R. Dahling and R. E. Stetler. 1996. ICR microbial laboratory manual. Cincinnati, Ohio, Environmental Protection Agency National Exposure Research Laboratory.

Fox, K. R. and D. A. Lytle. 1993. The Milwaukee cryptosporidiosis outbreak: Investigation and recommendations. Proc. Water Qual. Technol. Conf. 2:1767-1783.

Freedman, P. L., R. P. Canale and J. F. Pendergast. 1980. Modeling storm runoff impacts on a eutrophic lake. J. Envir. Engng Div., Am. Soc. Civ. Engrs 106 (EE2):335-349.

Gelda, R. K., E. M. Owens and S.W. Effler. 1998. Calibration, verification, and an application of a two-dimensional hydothermal model [CE-QUAL-W2(T)] for Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):186-196.

Hansen, J. S. and J. E. Ongerth. 1991. Effects of time and watershed characteristics on the concentration of *Cryptosporidium* oocysts in river water. Appl. Environ. Microbiol. 57:2790-2795.

Hibler, C. P. and C. M. Hancock. 1990. Waterborne giardiasis. In: McFeters, G. A. (ed.). Drinking water microbiology, Springer-Verlag, New York, 1990. P. 271-293.

LeChevallier, M. W. and W. D. Norton. 1995. *Giardia* and *Cryptosporidium* in raw and finished water. J. AWWA 87:54-68.

Meyer, E. A. 1979. Determination of *Giardia* cysts viability. Project Report No. EPA-600/2-79-063. US Environmental Protection Agency: Cincinnati, OH.

Owens, E. M. 1998a. Development and testing of one-dimensional hydrothermal models of Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):172-185.

Owens, E. M. 1998b. Identification and analysis of hydrodynamic and transport characteristics of Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):162-171.

Owens, E. M. 1998c. Thermal and heat transfer characteristics of Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):152-161.

Owens, E. M., R. K. Gelda, J. M. Hassett and S. W. Effler. 1998. Hydrologic analysis and model development for Cannonsville Reservoir. Lake and Reserv. Manage. 14(2-3):140-151.

Palmer, M. D. and R. J. Dewey. 1984. Beach fecal coliforms. Can. J. Envir. Engng 11:217-224.

Pett, B., F. Smith, D. Stendahl and R. Welker. 1993. Cryptosporidiosis outbreak from an operations point of view: Kitchner-Waterloo, Ontario Spring 1993. Proc. Water Qual. Technol. Conf. 2:1739-1766.

Sattar, S. A., C. Chauret, V. S. Springthorpe, M. Abbaszadegan and M. W. LeChevallier. 1994. *Giardia* cyst and *Cryptosporidium* oocyst survival in watersheds and factors affecting inactivation. Proposal to the AWWA Research Foundation. (Project funded and in progress.)

Schneiderman, E., Stern, D.A. and W. Tone. 1995. Report on investigation of feasibility of incorporating pathogen loading into terrestrial models being developed for Cannonsville Reservoir. Communication to US EPA, June 30, 1995.

Sherer, B. M., J. R. Miner, J. A. Moore and J. C. Buckhouse. 1992. Indicator bacterial survival in stream sediments. J. Environ. Qual. 21:591-595.

Stepczuk, C. and D. Lounsbury. 1995. Model Inputs (Hydrological) - Cannonsville Reservoir. Report for the New York City Department of Environmental Protection (March, 1995). 21 p.

Stephenson, G. R. and R. C. Rychert. 1982. Bottom sediment: a reservoir of *Escherichia coli* in rangeland streams. J. Range Man. 35:119-123.

Stern, D. A. 1996a. DEP Pathogen studies of *Giardia* spp., *Cryptosporidium* spp., and enteric viruses: Progress brief. New York City Department of Environmental Protection, Valhalla, NY.

Stern, D. A. 1996b. Initial investigation of the sources and sinks of *Cryptosporidium* spp. and *Giardia* spp. within the watersheds of the New York City water supply system. Watershed restoration management, physical, chemical and biological considerations, Syracuse, NY, American Water Resources Association.

Stern, D. A. 1996c. Monitoring for *Cryptosporidium* spp. and *Giardia* spp. and human enteric viruses in the watersheds of the New York City water supply system. Watershed '96, Baltimore, MD.

Thomann, R. V. and J. A. Mueller. 1987. Principles of surface water quality modeling and control. Harper & Row Publishers, New York, NY. 644 p.

U.S. Environmental Protection Agency. 1989. Drinking water; National primary drinking water regulations; Disinfection, turbidity, *Giardia lamblia*, viruses, *Legionella*, and heterotrophic bacteria; Final rule. Federal Regulation 54:27486-27541.