Cryptosporidium and *Giardia* in Water: Reassessment of Occurrence and Significance

Jerry E. Ongerth, Ph.D., P.E., F.ASCE[1]

Abstract: The current approach in the U.S. water industry for monitoring *Cryptosporidium* and *Giardia* has weaknesses that have contributed to the difficulty of interpreting resulting data. This often leads to potentially significant and dangerous misinterpretation. The purpose of this paper is to summarize information on which the conflicting conclusions on the occurrence and distribution of *Cryptosporidium* and *Giardia* have been based. Effort is made to determine the most plausible and supportable interpretation. The objective is to provide a basis for rethinking the current approach to monitoring and management of *Cryptosporidium* and *Giardia* in water. The importance of measuring recovery efficiency and reporting measurements of these organisms in terms of concentration to any quantitative application is emphasized. Data presentation to illustrate critical features of organism concentration levels and variation is reviewed. Analysis of major data sets resulting from the U.S. Environmental Protection Agency Information Collection Rule Supplemental Survey (USEPA ICR SS) and the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2) monitoring and other previously published relevant data sets is presented to illustrate key features of *Cryptosporidium* and *Giardia* occurrence in surface water and their universal geographic distribution. Current thinking emphatically requires revision. **DOI: 10.1061/(ASCE)EE.1943-7870.0001161.**

Introduction

When considering issues related to *Cryptosporidium* and *Giardia* today, public water systems (PWS) find themselves in an unusual position. *Cryptosporidium* and *Giardia* are acknowledged as waterborne pathogens with prominent outbreaks caused by transmission through the public water supply attributed to both organisms (USEPA 2005a). Both organisms are regulated contaminants under the National Primary Drinking Water Regulation (USEPA 1996). The regulation specifies control by treatment technique and sets maximum contaminant level goals (MCLGs) of zero for both organisms. The companion regulation, the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) or simply LT2, requires monitoring for *Cryptosporidium* by all PWS using surface water serving a population >10,000 (USEPA 2006). The principal objective of the LT2 monitoring is to identify surface water locations having higher *Cryptosporidium* levels, and consequently a greater risk of waterborne illness. The regulation imposes risk management in the form of four ascending incremental requirements for *Cryptosporidium* control proportional to the level of *Cryptosporidium* found in the LT2 monitoring (USEPA 2005b). The result of LT2 monitoring, based on a total of nearly 45,000 samples from 1,670 locations on surface waters throughout the United States, was that no *Cryptosporidium* was found in 93 percent of all field samples analyzed. No *Cryptosporidium* was found in any of the 24 or more consecutive monthly samples analyzed at over half (51 percent) of all sampling locations. Furthermore, according to the LT2 bin criteria, only about 75, or 4 percent, of the nearly 1,700 sample locations appeared to exceed the bin 1 limit of <0.075 *Cryptosporidium*/L (raw numbers only, not taking recovery efficiency into account). And no sample locations had apparent levels greater than the bin 2 limit (0.075 to <1.0 oocysts/L).

Considering the LT2 data, a logical conclusion based on these results alone could be that in the United States surface waters used by PWSs, *Cryptosporidium* only rarely occurs at levels of concern. However, a detailed examination of the LT2 data site-by-site has shown that for more than 100 locations throughout the United States, *Cryptosporidium* is present at levels of potential concern (Ongerth 2013a). Reexamination of the previous (1999–2000) Information Collection Rule Supplemental Survey (ICR SS) data has provided further evidence of characteristic *Cryptosporidium* (and *Giardia*) occurrence levels and variability at surface water locations throughout the country (Ongerth 2013c). Additional previous descriptions of *Cryptosporidium* and *Giardia* findings (Hansen and Ongerth 1991; LeChevallier et al. 1991; Ongerth 1989) further support the conclusion, contrary to that suggested previously by the USEPA LT2 analysis, that these organisms are present at detectable levels continuously and in virtually all surface water regardless of location. Furthermore, the site-by-site analysis demonstrates that risk at any individual site is proportional not only to the level of organism presence (concentration), but also to the degree of variability over a typical annual cycle.

In light of these observations, a surface water-using PWS is faced with apparently conflicting interests. Clearly, *Cryptosporidium* and *Giardia* have caused, and undoubtedly will at some time in the future, cause additional waterborne outbreaks. Also, both organisms have ample sources in every watershed in the United States (and worldwide), but, with suitable planning and implementation, monitoring can provide information describing their concentrations over typical annual cycles useful to the individual PWS for water quality and treatment management. However, a PWS must comply with a level of zero for these organisms for both the MCLGs and Consumer Confidence Reporting Requirements. If monitoring shows relatively high *Cryptosporidium* (and *Giardia*) occurrence, the capital and operating cost increments associated with higher bin levels would be imposed. An unambiguous understanding of the role of *Cryptosporidium* and *Giardia*, present universally in surface water, in waterborne illness, and specifically in waterborne

[1]Principal Honorary Fellow, Civil, Mining, and Environmental Engineering, Univ. of Wollongong, CME Bldg. 4 EEC, Wollongong, NSW 2522, Australia. E-mail: jongerth@uow.edu.au

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outbreaks, is needed but is currently not defined or well understood. The apparent tolerance, or even official requirement for use of monitoring conditions demonstrated to produce incomplete and misleading data open to dangerous misinterpretation, reinforces a lack of motivation for a PWS to define relevant *Cryptosporidium* and *Giardia* conditions.

The purpose of this paper is to summarize the information on which the conflicting conclusions presented here are based and to determine which is more plausible and supportable. The objective is to reach logical conclusions and to assist in providing a basis for rethinking the current approach to monitoring and management of *Cryptosporidium* and *Giardia* in water. The objective is specifically not to equate organism presence to risk, but to emphasize that well-conceived and implemented monitoring can and will provide water suppliers using surface water with the information needed to understand potential risk in relation to the spectrum of concentrations elsewhere and their variations over typical annual cycles at relevant sampling locations. Such information is essential to providing for catchment and treatment management planning.

Methods and Procedures

The data and information used in this paper are all either previously published in the open literature or available on the Internet without restriction. Data sources are identified at the point of presentation herein. Where available, data on *Cryptosporidium* and *Giardia* have been generated using USEPA Method 1622/1623 and are presented in the terms reported, i.e., as raw numbers/L. Data in this form are referred to as *occurrence*. In a few cases where data were generated before development of Method 1622/1623, the analytical method that was used is referenced. In cases where data are presented as *concentration*, they resulted from raw numbers/L divided by the recovery efficiency measured for individual samples.

Measurement of concentration

Comparison of *Cryptosporidium* and *Giardia* data from the same sampling site between sampling times, or in comparing data between sampling sites, requires measuring concentration. Data expressed as raw numbers/L are not fully quantified without taking recovery efficiency into account. Measuring concentration requires measuring recovery efficiency relevant to each individual sample. It has been shown that the variations in organism occurrence at any specific site are independent of the variations in recovery efficiency. Using USEPA Method 1622/1623, recovery efficiency is provided by the Matrix Spike (MS) tool. Importantly, an MS value measured for another sampling location, or even the same location at a different sampling time, is not a relevant value as has been shown previously (Ongerth 2013b). Recovery efficiency measured at the same site has been demonstrated to vary significantly over relatively short time periods as shown in Figs. 1(a–c).

The degree of variation in recovery efficiency is demonstrated by the New South Wales (NSW) data over seven annual cycles with clear and substantial differences between sites on the same water course. The northwest United States data over three annual cycles provide compelling evidence that recovery efficiency must be measured routinely for each sample having unique source and sampling time characteristics. Data have also been published demonstrating that variations as shown in Figs. 1(a–c) are not random but systematic and reproducible Ongerth (2013b).

The magnitude and significance of the difference between the expression of *Cryptosporidium* and *Giardia* data as raw numbers, and as concentration taking recovery efficiency into account, has also been illustrated. In the LT2 data, 319 individual *Cryptosporidium* measurements resulting in a positive (nonzero) finding were accompanied by a corresponding MS recovery efficiency measurement permitting calculation of concentration. Cumulative frequency plots of the raw numbers and of the concentration values Ongerth (2013b) showed that concentrations averaged nearly three

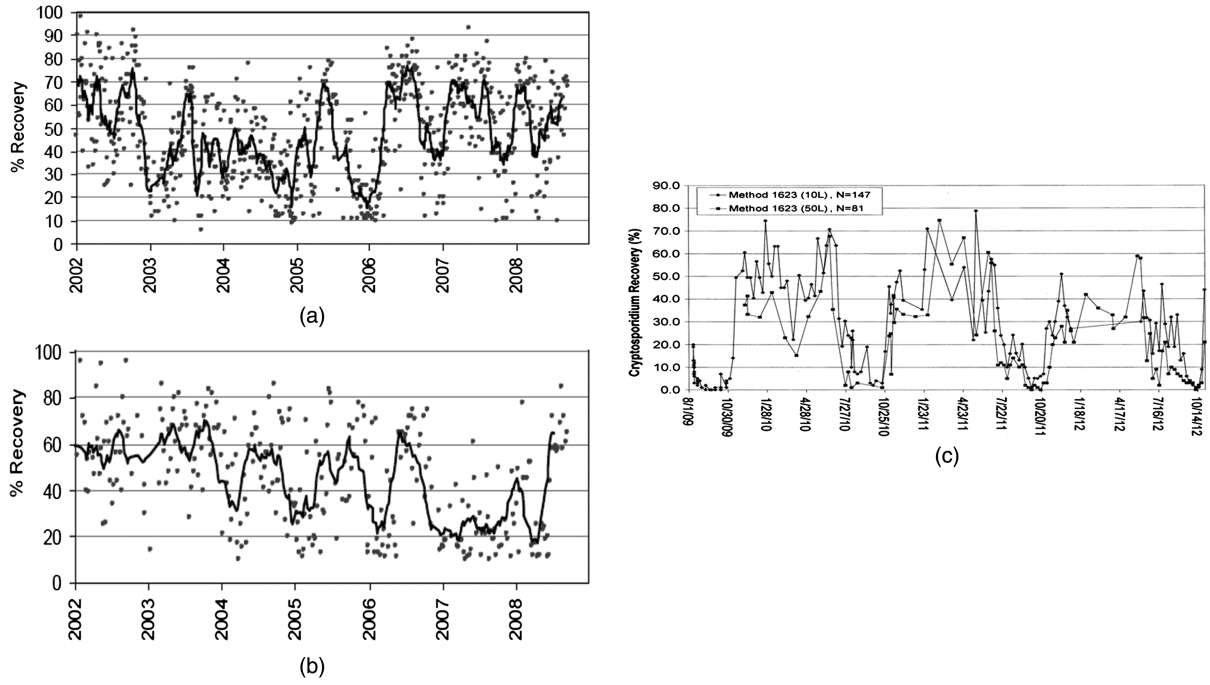

Fig. 1. (a and b) Matrix spike (MS) recovery efficiencies of *Cryptosporidium* with moving average, measured weekly over seven annual cycles using USEPA Method 1622 at two sampling stations about 30 km apart on same water system in New South Wales, Australia; (c) MS recovery efficiency measured weekly over three annual cycles using USEPA Method 1623 in water from a northwest U.S. reservoir

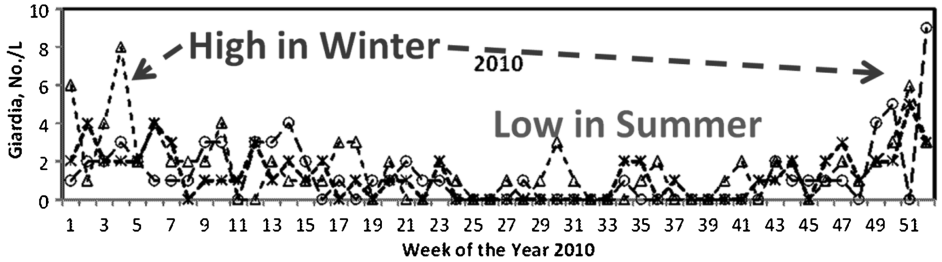

Fig. 2. Chronological presentation of *Giardia* raw numbers/L data from three related sampling sites in calendar year 2010

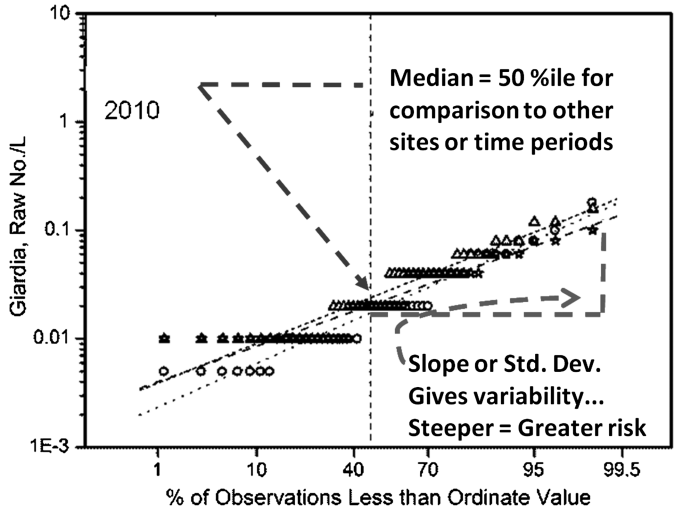

Fig. 3. Cumulative frequency distributions of *Giardia* raw numbers/L data from three related sampling sites in calendar year 2010

times the magnitude of raw numbers, reflecting the average recovery efficiency of 39 percent. In addition, the degree of variability in concentrations was more than double that of the raw numbers, reflecting the independent variation of recovery efficiency and numbers of organisms found. Clearly, data lacking adjustment for recovery efficiency do not accurately reflect the magnitude of organism presence and if used for comparison can only lead to misinterpretation.

Expression of data for interpretation and comparison

Data from individual sampling sites have little meaning until sufficient observations are available for comparison to data from the same site in other time periods or to data produced on a comparable basis from other sites. Two common methods of presentation for annual data sets are chronological (Fig. 2) and cumulative frequency (Fig. 3), as illustrated. The same data were used to produce Figs. 2 and 3. Chronological presentation allows identification of the period of the year in which relatively high and low occurrence may be expected. The cumulative frequency presentation provides a simple statistical summary in which the median values indicate the magnitude relative to other locations or time periods. Characteristically, many types of natural occurrences including water quality data are approximately log-normally distributed (Chow 1954). This feature allows graphical comparison where the slope indicates the degree of variability at individual sites. A steeper slope shows a more highly variable occurrence and greater frequency of high occurrences relative to the typical or average condition. Such relatively high occurrences are important for surface water users as they represent *critical conditions* for treatment management or to target watershed management activities. A commercially available tool for log-probability plot preparation is *OriginPro*. Manipulation of data for development of log-probability plots using this software has been previously described (Ongerth 2013a).

Data on *Cryptosporidium* and *Giardia* in Surface Water

The subsequent information presented has been assembled to illustrate features that are specifically relevant to questions that surface water–using PWS should ask to provide for effective watershed and/or treatment management for control of *Cryptosporidium* and *Giardia*. Questions include:

- What data are needed to describe *Cryptosporidium* and *Giardia* at a specific surface water location?
- How can data on *Cryptosporidium* and *Giardia* concentrations be analyzed to describe the degree of concern (relative risk) for a specific source?
- What background information is available for comparison of *Cryptosporidium* and *Giardia levels* (occurrence or concentration)?
- What are the likely sources of these organisms?

Data on Cryptosporidium and Giardia Concentrations

As previously reported (Ongerth 2013b), very little of the information in the literature on *Cryptosporidium* and *Giardia* in water has been presented in terms of concentration. As shown in subsequent data, virtually all literature on both *Cryptosporidium* and *Giardia* monitoring report *occurrence* or *density* without adjusting the numbers found according to the recovery efficiency. Such data are referred to as occurrence in raw numbers/L (raw no's/L) to be specifically distinguished from concentration in terms of oocysts or cysts/L. The only data reported as concentration were developed in research conducted at the University of Washington from 1985 to 1995, sponsored by the PWS in the northwest, and summarized in Fig. 4. These data were uniformly adjusted for recovery efficiency that was consistently measured relevant to every water sample processed.

Three sampling points for which *Cryptosporidium* concentrations are described in Fig. 4 span median concentrations ranging from about 0.05 oocysts/L at the upstream station above human activity except for widely dispersed mountain recreation, to more than 10 oocysts/L at the station having drainage from a dairy farming area. The *Giardia* concentrations were only measured in water from protected sources. Later unpublished data showed *Cryptosporidium* concentrations similar in both levels and variabilities to that of *Giardia* at that source (Ongerth 1989).

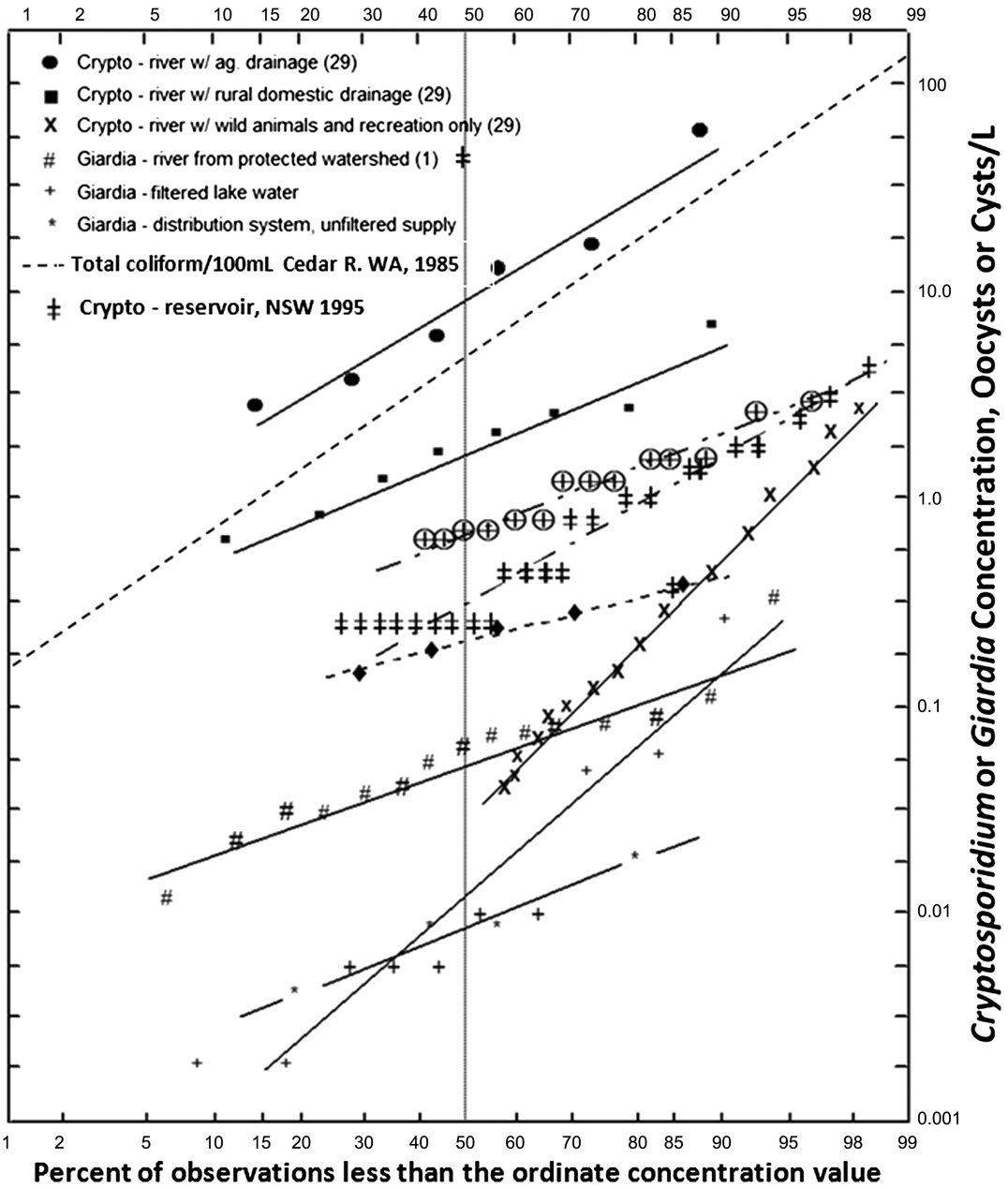

Fig. 4. Data on concentrations of *Cryptosporidium* and *Giardia* in or from surface waters of the Pacific Northwest, summarized from (data from Hansen and Ongerth 1991; Ongerth 1989; Ongerth, unpublished data, 1994)

Data on Cryptosporidium and Giardia Occurrence (Raw Numbers/L)

Two immense and unique data sets containing data on *Cryptosporidium* and *Giardia* occurrence (raw no's/L) have been produced resulting from USEPA requirements. The first was the Supplemental Survey of the Information Collection Rule (ICR SS). Only the Supplemental Survey data were used, but not the previous ICR data. Only the ICR SS used the newly developed Method 1622/1623, thus producing data that could be compared directly to later data. In the ICR SS both *Cryptosporidium* and *Giardia* were measured by Method 1622/1623 in twice-monthly 10 L samples from 87 PWS selected from representative large ($L > 100{,}000$) and medium ($>10{,}000 > M > 100{,}000$) systems throughout the United States. In the ICR SS data median occurrence ranges for both *Cryptosporidium* and *Giardia* spanned about 2-logs from about 0.002 to 0.2 raw no's/L, as shown in Fig. 5. If adjusted for the typical average MS recovery reported in the ICR SS, the levels are well below that of previously reported concentration data, as shown in Fig. 4.

The second major data set was from monitoring required by the LT2 regulation affecting all PWS >10,000 using surface water. These data are for *Cryptosporidium* alone and were also produced using analysis by Method 1622/1623. Samples were predominantly, but not limited to, 10-L volumes, collected monthly over at least a period of 24 months. The LT2 data from 50 representative individual sampling sites having sufficient nonzero sample results for cumulative probability analysis are shown with the comparable ICR SS *Cryptosporidium* data from Fig. 5 and then in the shaded area of Fig. 6. The LT2 *Cryptosporidium* occurrence data cover a somewhat broader range of median concentrations than did the ICR SS data.

A much larger pool of PWS was included in LT2 monitoring; 1,670 sampling locations compared to 87 in the ICR SS. Also,

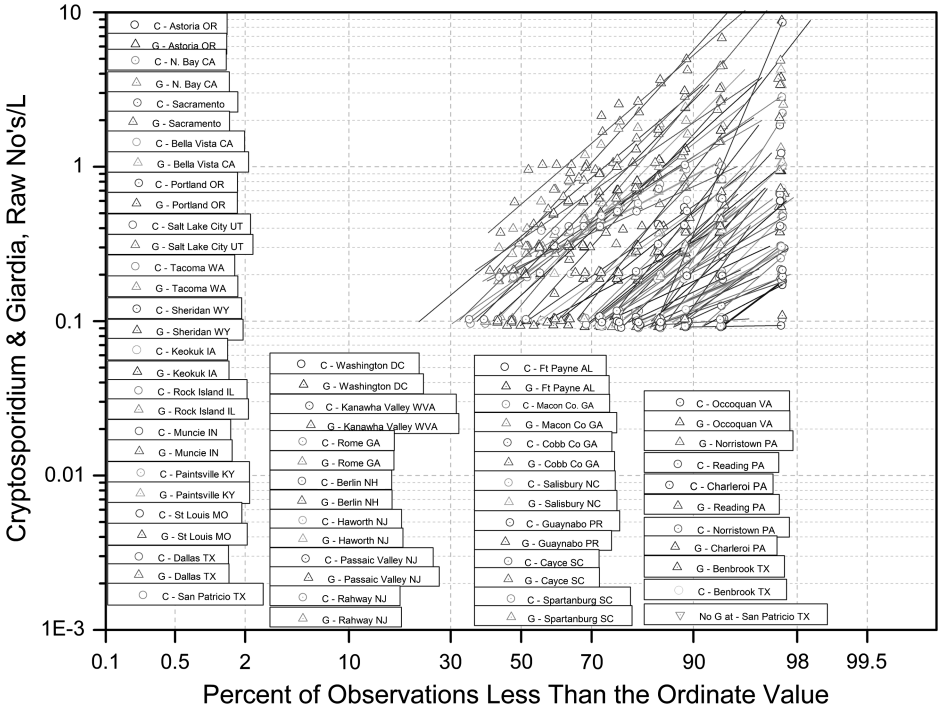

Fig. 5. Cumulative probability plots of *Cryptosporidium* and *Giardia* occurrence data from 34 sampling sites of ICR SS (data from Ongerth 2013c)

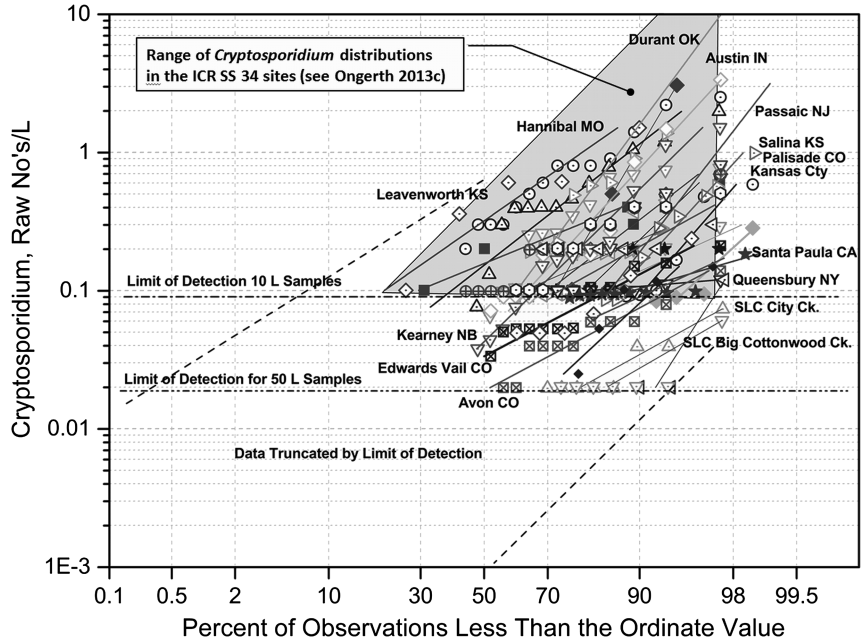

Fig. 6. Cumulative probability plots of LT2 50 representative sites (data from Ongerth 2013a) with area encompassed by *Cryptosporidium* distributions of ICR SS 34 sites overlayed (Fig. 5) (data from Ongerth 2013c)

whereas the ICR SS data are all truncated by sample volumes limited to 10 L, several of the PWS in the LT2 survey analyzed samples of 20 L, 30 L, and 50 L. The data from those larger sample volumes demonstrate that occurrence is continuous at lower levels (Ongerth 2013a). Accordingly, this emphasizes that interpretation of a zero finding as *absence* is incorrect. A zero finding simply means that the organism level was below the limit of detection imposed by the sample volume.

Some additional published and unpublished data provide useful perspectives to the range of *Cryptosporidium* and *Giardia* occurrence in surface water provided by the ICR SS and LT2 data. Important data illustrating the distribution of both *Cryptosporidium* and *Giardia* in U.S. surface water were published in 1991 (LeChevallier et al. 1991). Between December 1988, and June 1990, raw water samples of about 100 L were analyzed from 66 water treatment plants in the United States, mostly in central and northeastern regions. *Giardia* was found in 69 of the 85 raw water samples at levels ranging from 0.04 to 66 raw no's/L. *Cryptosporidium* was found in 74 of the 85 raw water samples at levels ranging from 0.07 to 484 raw numbers/L. The distribution of both the

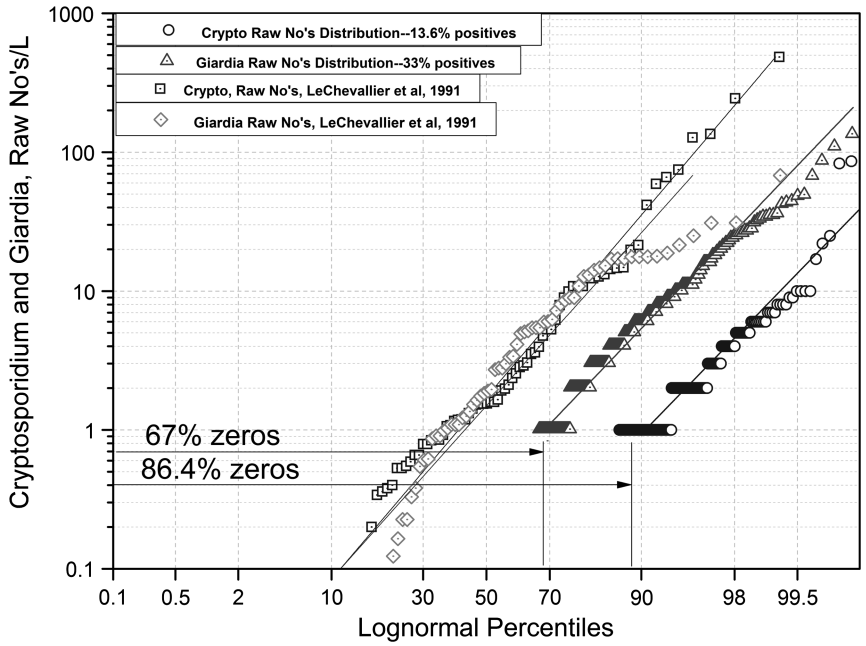

Fig. 7. Comparison of *Cryptosporidium* (squares) and *Giardia* (diamonds) occurrence distributions between 66-site data (data from LeChevallier et al. 1991) and ICR SS data sets for *Giardia* (triangles) and *Cryptosporidium* (circles)

Cryptosporidium and the *Giardia* occurrence from this study is compared to the distribution of all nonzero *Cryptosporidium* and *Giardia* findings of the ICR SS, as shown in Fig. 7. It should be noted that this figure extends 2-logs above all of the other log-probability plots. As illustrated by the LT2 data from PWS having analyzed sample volumes greater than 10 L, the distribution of the data from the 66 sites further demonstrates the continuity of organism occurrence below the limit of detection restricted by analysis of samples limited to 10 L. The apparent difference in median occurrence between the two data sets is anomalous. The sample locations, although mostly different, were representative of surface waters having similar characteristics. Also, the data from the 66 sites were produced using the earlier generation ASTM or essentially the ICR analytical method (USEPA 1995), which has been widely described as having a typically lower recovery efficiency than the USEPA Method 1622/1623 (USEPA 2005a) used in the ICR SS. Nevertheless, the data from the 66 sites clearly describe higher occurrence than was observed in the ICR SS.

An additional data set was published at about the same time describing the distribution of *Cryptosporidium* in surface water (Haas and Rose 1996). The data resulted from analysis of weekly water samples from the water supply reservoir of a utility in the northwest United States and was analyzed by essentially using the ICR method. Sample volumes ranged from about 20 L to 230 L and the number of oocysts identified in the 52 samples included 3 samples at three oocysts each, 4 samples at two oocysts each, 12 samples at one oocyst each, and 33 in which no oocysts were found. After calculating the number of oocysts/L of a sample, the cumulative frequency of occurrence was plotted and the data overlaid along with the 66-site data and the LT2 50-site data, as shown in Fig. 8.

Overall, the data summarized in Fig. 8 illustrate several apparently fundamental features of *Cryptosporidium* and *Giardia* occurrence levels and variability in surface water sources in the United States. The overall range of median occurrence (raw numbers/L) appears to span about three orders of magnitude, 0.005 to 5/L. Where data are expressed as concentration taking recovery efficiency into account, the span would also be about three orders of

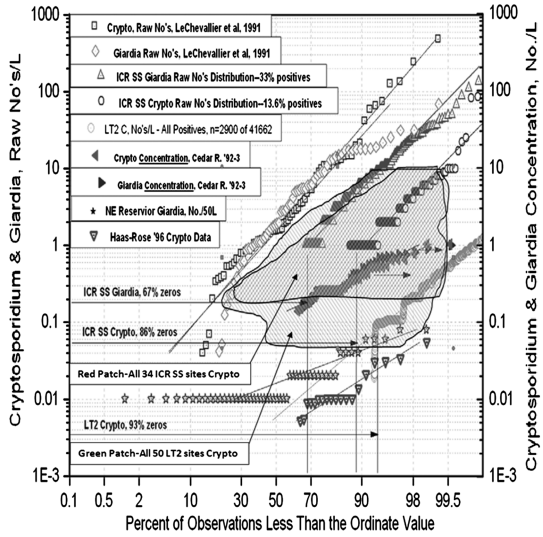

Fig. 8. Combined plot showing relation of major data sets cited in text; areas encompassed by distributions of *Cryptosporidium* raw numbers from 50 individual representative LT2 sites (back-hatched) and 34 ICR SS sites (smaller cross-hatched area) are overlayed on distributions of 66-site raw number data (data from LeChevallier et al. 1991), 1989–90 N.W. reservoir data (data from Haas and Rose 1996), and the 50-L sample *Giardia* data (N.E. reservoir, undisclosed site); included are *Cryptosporidium* and *Giardia* concentration data (data from Ongerth, unpublished data, 1994; Ongerth 1989) for comparison

magnitude, but the range would be from two to 10 times higher, i.e., about 0.05 to 50/L. When data are presented as cumulative frequency distributions (log-probability plots) all data sets are truncated by the limit of detection determined by the sample volume and recovery efficiency (Ongerth 2013b). Variability of data at individual sampling sites represented by the slope (standard deviation) and resulting risk appears to span about three orders of magnitude from 0.05 to 50/L. The lowest occurrence and concentrations

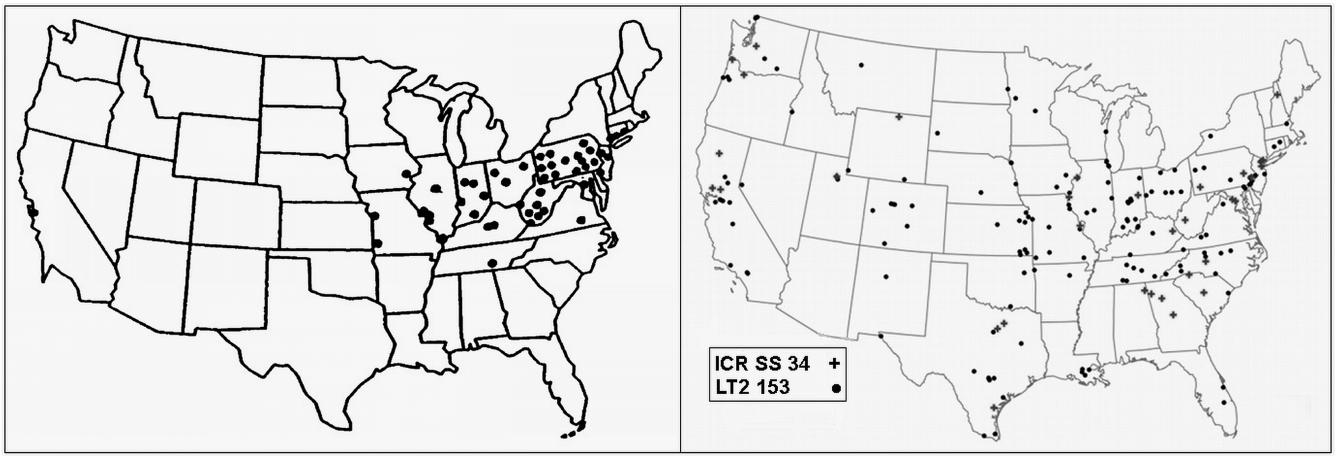

Fig. 9. Sampling locations of (a) 66-site survey (data from LeChevallier et al. 1991) and (b) nonzero sites of both LT2 (data from Ongerth 2013a) and ICR SS (data from Ongerth 2013c)

have been observed in water from relatively remote and well-managed watersheds, e.g., Fig. 8 N.E. reservoir *Giardia*, Fig. 8 N.W. reservoir *Cryptosporidium*; Seattle *Cryptosporidium* and *Giardia*; and Fig. 6 Colorado and Utah, mountain watersheds *Cryptosporidium*. The 66-site data and the distributions of ICR SS data show the cumulative frequency of individual measurements made at the 66 and 87 sites, respectively. Nevertheless, it is clear that the observations made in the 66-site survey were significantly higher than subsequent findings. Also, the ICR SS observations taken together had a *Giardia* median level nearly 1-log lower than the 66-site survey with a *Cryptosporidium* median level more than 1.5-logs lower. The LT2 data have previously been compared to the ICR SS data by the USEPA (Messner 2011). That comparison indicated that overall, the LT2 *Cryptosporidium* level was only about one-fifth of that observed in the ICR SS. However, comparison of the LT2 and ICR SS data, analyzed on a site-by-site basis (as shown in Fig. 6), indicate that the *Cryptosporidium* occurrences were within the same ranges of both median levels and variability.

Examining all of the data together as shown in Fig. 8, it appears that virtually the entire range of *Cryptosporidium* and *Giardia* occurrence in U.S. surface waters has been described. The range on a true concentration basis for both organisms appears to be from around 0.01/L to as much as 50/L. *Giardia* concentrations appear to be somewhat higher than *Cryptosporidium* concentrations in most locations, which is best illustrated by the ICR SS data (Ongerth 2013c). However, the greater environmental stability of *Cryptosporidium* may contribute to maximum concentrations higher than those of *Giardia* under conditions of maximum time and higher temperatures in the environment (USEPA 2005a). The geographical distribution of the sampling sites included in the 66-site survey and the nonzero sampling sites of the ICR SS and LT2 surveys shown in Fig. 9, illustrates the extent of *Cryptosporidium* and *Giardia* occurrence in all regions of the United States. The extent of anomalies in the findings of the different surveys is also apparent. For example, all of the ICR SS representative sampling sites were also included in the more comprehensive LT2 sampling. The observation of multiple nonzero findings among the 34 ICR SS sites [Fig. 9(b) plus signs] that in the later, but similar LT2 sampling, had no positive *Cryptosporidium* findings is difficult to understand. Perhaps most important is the description of occurrence throughout the country regardless of geographic location. The watersheds represented include virtually all possible areas and types, from mountain forests in the west to the Eastern seaboard, large and small, hot and cold, dry and wet. This reinforces the assertion that no watershed of extent relevant to public water supply could be found anywhere that would be free from sufficient sources of either *Cryptosporidium* or *Giardia* to support levels detectable by suitable application of Method 1622/1623.

As has been described previously (Ongerth 1989, 2013a; Hansen and Ongerth 1991), the appearance of *Cryptosporidium* and *Giardia* in surface water must bear a logical relation to their sources in the tributary watershed. Animal and human sources of these organisms have been thoroughly described in the literature as ubiquitous. That is, as stated earlier, no watershed of a size relevant to a public water supply anywhere in the United States can conceivably exist without sources of both organisms amply capable of supporting concentrations in the range identified previously (e.g., Fig. 8). Previous work has shown examples for both organisms suggesting the utility of estimating organism (oocyst and/or cyst) production rates per unit area (mi^2) per unit of time (month or year) that may provide a useful means of checking on the likely accuracy of surface water monitoring data (Ongerth 1989, 2013a; Hansen and Ongerth 1991). Additional comparisons to similar sites upstream or downstream in the same watershed, or to other watersheds known to have similar characteristics, should be similarly useful.

Summary and Conclusions

The stated purpose of this paper is to present information on which conflicting conclusions have been based and to determine which is more plausible and supportable. Critical elements include the interpretation of negative (zero) analytical results; sampling and analysis conditions leading to negative analytical results; the value of positive versus negative analytical results; interpretation of real (nonzero) data; an approach to minimizing negative analytical findings; and a logical approach to future monitoring and examining resulting implications. Key elements of the information presented in the text are summarized next, and some logical conclusions/recommendations are suggested.

Among critical elements for effective monitoring of *Cryptosporidium* and *Giardia* is the distinction between the raw numbers observed at the end of the analytical process and concentration. Concentration cannot be calculated without measuring the recovery efficiency accompanying essentially every sample. As shown in Ongerth (2013b), recovery efficiency varies with a degree and

frequency that requires measurement with every sample, as shown in Fig. 1, and contributes to differences between raw numbers and concentration that cannot be ignored without preventing accurate interpretation of the data.

Data dominated by negative (zero) results, e.g., the LT2 data having 93 percent zeros, have become the rule rather than the exception. Regulatory elements contribute incentive to continue sampling practices that reinforce such results (Ongerth 2013a, c). Clearly, a monitoring program that produces only zeros provides no useful information for the water quality manager. Sampling programs can easily be adjusted to provide useful data with added cost justified by the improved value of the data. Comparison between data sets resulting from analysis of 10-L samples and 50-L samples demonstrates that zeros do not mean absence, rather that the limit of detection dependent on sample volume was above the ambient concentration (Ongerth 2013b, 1989).

For a PWS wishing to understand and, if possible, manage water quality with respect to *Cryptosporidium* and *Giardia*, or at least to manage its water treatment for optimum control of these organisms, instituting and maintaining a monitoring program over succeeding annual cycles is needed. Analyzing such data to identify critical conditions and for comparison between sampling locations and succeeding annual cycles can be facilitated by two types of presentation: chronological plotting allows identifying the period(s) in the annual cycle when highest concentrations are most likely, for example, in Fig. 2; and preparation of log-normal cumulative frequency plots provides estimates of the median concentration and the degree of variability, as shown in Fig. 3. The relative risk depends on both features (magnitude and variability) of an annual distribution.

Examination of available data including the limited data describing concentrations of *Cryptosporidium* and *Giardia*, and the more common data on occurrence (raw numbers/L) demonstrates that these organisms are distributed in surface waters throughout the United States, as shown in Figs. 8 and 9. The concentration range appears to span about 2 logs from approximately 0.01 to 20–50 L. Available information indicates that organism concentrations and their variability at any surface water location should have a logical relation to the nature and extent of organism sources in the tributary watershed.

Development of an effective and efficient monitoring program for a PWS using surface water should include the following elements:

- Provide enough volume to avoid zeros in the majority of samples
- Measure recovery efficiency relevant to every sample
- Analyze all samples for both *Cryptosporidium* and *Giardia*
- Sample monthly for a year initially
- Adjust the monitoring program based on initial data

Adjustment of a *Cryptosporidium* and *Giardia* monitoring program that has historically produced consistent negative results must be expected to attract attention to an apparent finding of pathogens previously viewed (although incorrectly) as absent. The details of planned changes in monitoring and the anticipated results must be clearly and fully described to customers and media beforehand. The fact that absolutely no change in water quality could possibly result from the change in monitoring must be made clear. Whatever historic concentrations have been, and will continue to be, will not be altered in any way by the change in monitoring. Careful and accurate presentation of the data can be used to show that levels to be identified by a more effective monitoring program are simply below what could be defined by previous monitoring conditions. Data from elsewhere (for example, as presented here in Figs. 4–6, and 8), can be used effectively to show how new data will compare to conditions elsewhere. Last but not least, the value of the new information expected to result from a more effective monitoring program to the PWS's ability to manage sources and/or treatment should be described.

Finally, it is important to recognize that no clear evidence is available describing a relation between levels of *Cryptosporidium* and *Giardia* in water and the likelihood of a waterborne outbreak. On the other hand, the literature on both organisms suggests that it is prudent to consider that a single *Cryptosporidium* oocyst or a single *Giardia* cyst is *capable* of causing an infection under suitable (unfavorable) conditions. Ample uncertainty will always exist regarding what species, subtypes, and degree of viability and virulence of these pathogens may be produced in any given watershed at any time. According to Murphy's law, under the most unfavorable circumstances for the PWS prudent monitoring should be conducted to account for all *Cryptosporidium* and *Giardia* produced in the watershed, not just types shown previously to cause human infection, and not just the viable fraction measured at any point in time. Whether renewed effort to refine existing risk assessments or refined applications of quantitative microbial risk assessment can contribute better direction to PWS for monitoring and management for control of these organisms remains to be seen.

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