Groundwater & livestock production and husbandry, part 1, biosecurity

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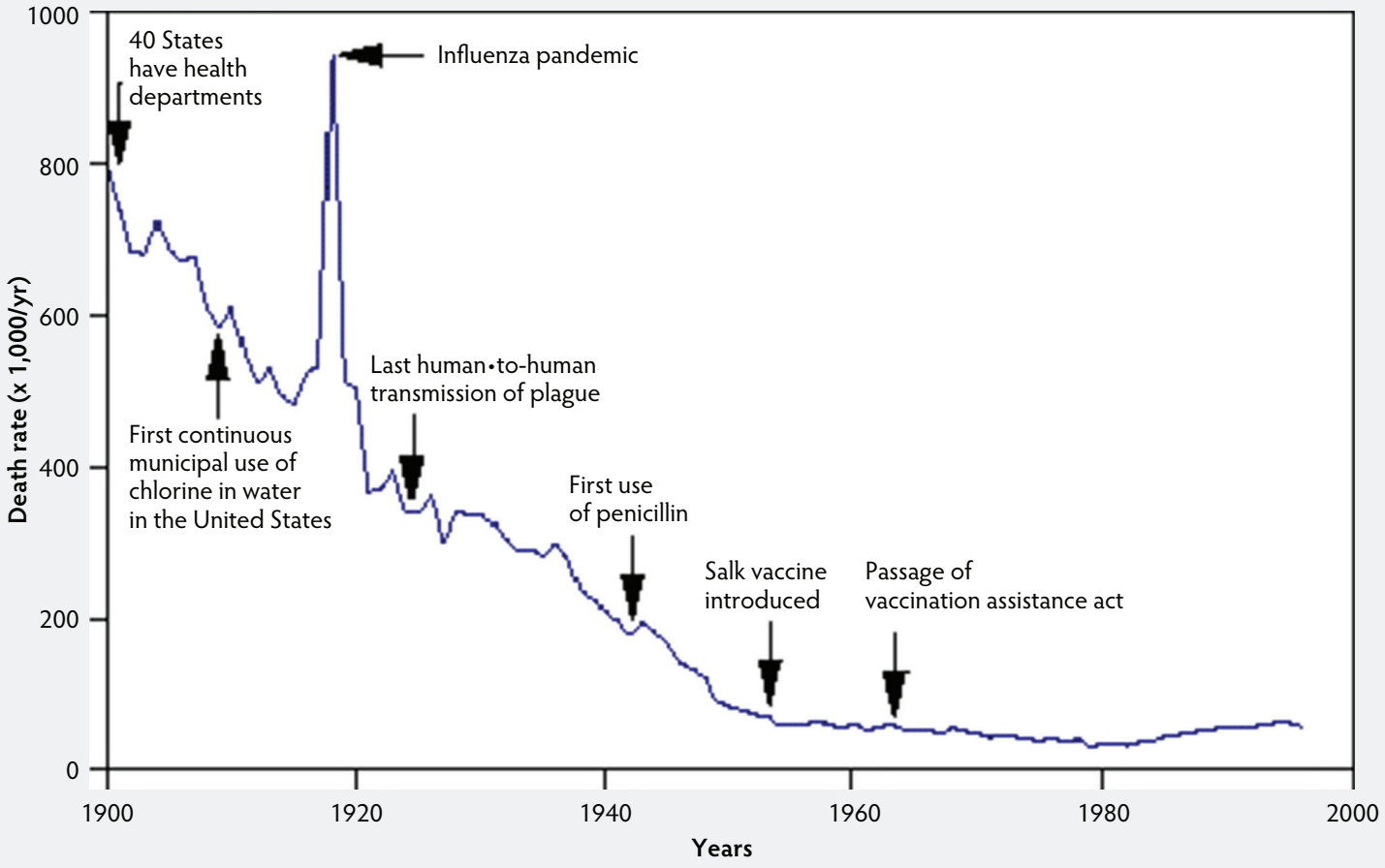
Forward

Misconceptions about what causes a disease and how it spreads have been very numerous. At times, so engrained in the scientific community, that to suggest anything quant air was branded as ludicrous. For instance, throughout history a prevailing idea behind disease transmission had been the miasma theory and "bad air" was thought to cause disease in areas that contained a bad stench or aura of sickness. John Snow was skeptical of this and when a cholera outbreak occurred in London in 1854, he had a chance to investigate. In his study, he was able to link the outbreak to contaminated well water. Yet, public health protection agencies continued to reject the possibility of groundwater containing pathogens until the introduction of the Ground Water Rule (GWR)[1] 152 years later in 2006. Today the agricultural industry may possess a similar level of hubris regarding groundwater and biosecurity.

A note of interest is in 1908 public water systems (PWS) began disinfection and treatment of drinking water. Over the next decade, thousands of cities across the United States followed suit. As they did, the number of deaths from infectious diseases declined markedly as shown in Figure 1.[2] This decline contributed to a sharp drop in infant and child mortality and a 29.2-year increase in life expectancy. Disinfection and treatment of public water supplies represents one of the greatest achievements in public health of the 20th century.[2]

Figure 1: Death rate (x 1,000/yr) for infectious disease - United States 1900 - 1996.



Center for Disease Control and Prevention (CDC): History of Drinking Water Treatment, A Century of US. Water Chlorination and Treatment: One of the Ten Greatest Public Health Achievements of the 20th Century. https://www.cdc.gov/healthywater/drinking/history.html/

Primary and secondary disinfection

During this period technologies, engineering design standards, and performance validation/verification protocols became well established to ensure water entering a drinking water distribution system is microbiologically safe, this practice is referred to as Primary Disinfection and addressed within this paper (Part 1). Secondary disinfection ensures water remains absent of pathogens as it travels through a water distribution system and will be addressed within a subsequent paper (Part 2).

Enteric viruses

Over 100 types of pathogenic viruses are excreted in human and animal wastes. These viruses can be transported in the environment through groundwater aquifers. Collectively known as enteric viruses, are transmitted via the fecal-oral route and primarily infect and replicate in the gastrointestinal tract of the host. Such are shed in extremely high numbers in the feces of infected individuals, typically between 10^5 and 10^{11} virus particles per gram of stool.[4]

Enteric viruses can be transmitted by food, water, fomites, and human contact. In addition to causing acute diseases, they are of public health concern due to their low infectious dose. For example, the probability of infection from exposure to one rotavirus is 31%, and no more than 1 plaque-forming unit (PFU) is required to cause infection in 1% of healthy adults. The risk of infection when consuming viruses in drinking water is 10- to 10,000-fold greater than that for pathogenic bacteria at similar exposures. Because of the potential for contamination from a variety of sources, enteric viruses in water are of particular concern. Since the 1980s, with significant advancements in the area of environmental virology, enteric viruses have been recognized as the causative agent in many nonbacterial gastroenteritis cases and outbreaks.[4]

Two of the most studied groups of enteric viruses as potential water quality indicators are the enteroviruses and adenoviruses. While the occurrence of human enteric viruses in the environment and their role in waterborne transmission have been studied extensively, little information is available on environmental transmission of enteric viruses in animals. Although, while 70% (62 serotypes) of nonpoliovirus enteroviruses have been associated with human infections, 30% have been associated with animal infections. Animal-specific enterovirus infections in hosts such as cattle and pigs are often asymptomatic but may cause diseases ranging from diarrhea to reproductive failure and neurological disorders. Two bovine enteroviruses (BEV), three porcine enteroviruses (PEV), 11 porcine teschoviruses (PTV) (10 were formerly classified as porcine enteroviruses), and 1 ovine enterovirus have been identified.[4]

While most studies are specific to pathogens infectious to human vs. swine populations. The question of address in this paper is related to the survivability and transport of virus in general. Though, PEV have a prevalence of 65% in pigs and wild hogs. PEV and PTV have been identified as the etiologic agents of the neurological disorder known as Teschen-Talfan disease, polioencephalomyelitis, vesicular diseases, myocarditis, pneumonia, diarrhea, fertility disorders, and dermal lesions in swine. Five porcine adenoviruses (PAdV), five bovine adenoviruses (BAdV), and six ovine adenoviruses have been classified under the genus *Mastadenovirus*. PAdV also has been isolated from pigs with encephalitis and pneumoenteritis.[4]

Presence of enteric viruses in groundwater

A plethora of peer-reviewed research conducted in advance of 2006 served to validate groundwater as a significant vehicle for disease transmission and subsequently served as the foundation from which the GWR was formulated and included within the US Safe Drinking Water Act (SDWA).[5] The GWR now represents an enforceable standard to protect the health of individuals connected to PWS's.

Although, the presence of pathogens in groundwater still accounts for more than 50% of disease outbreaks related to public drinking water supplies within the United States[6] and the CDC estimates up to 33 million cases of acute gastroenteritis illnesses occur each year due to the presence of pathogens within US PWS's. The following studies (by reference) provide further validation for the presence of infectious virus within groundwater aquifers.[7-22]

Virus entry, travel and spatial dispersion in aquifers

Due to their size (Table 1) relative to the interstitial (void) space(s) within soils and unconsolidated sedimentary layers they pass through (Table 2 & Figure 2) virus are easily transported through soils and throughout aquifers. Several researchers have reported viruses primarily travel through preferential pathways. To help emphasize how efficiently pathogens within surface water sources may be transported into aquifers, it is estimated that up to 96% of water is transported through only 0.32% of the soil volume via preferential pathways.[52] Pathways of preferential flow can develop due to structures present in surface and subsurface soils and geologic structure(s)[23] and serve serve to carry water and contaminants to depths very rapidly, resulting in greater impact on water quality than previously expected.[23]

Such hydraulic pathways serve to reduce potential interactions from occurring between particulates (virus) and soils related to

Table 1: Size of virus

	Size of virus
Virus	Average diameter (microns)
ASF	0.18
PRRS	0.06
PED	0.13

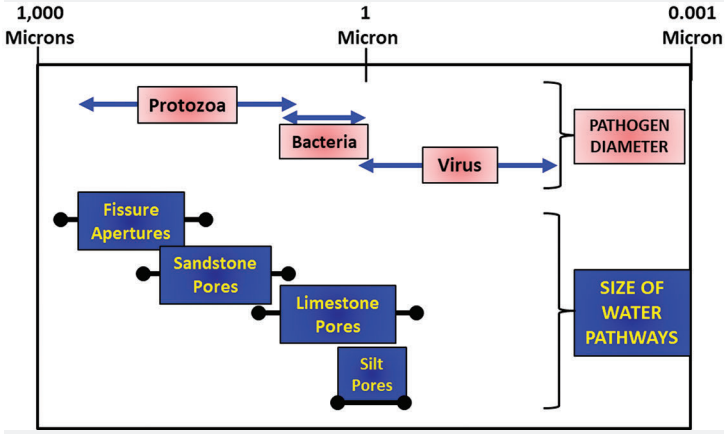
Britannica

Table 2: Size of hydraulic pathways within soils and aquafers

Size of hydraulic pathways within soils and aquafers				
Soil type	**Diameter size range (microns)**		**Average (microns)**	**Interstitial space = diameter x 15.47% (microns)**
Gravel	2,048,000	1,000	1,024,500	158,490.2
Sand	20	2,000	1,010	156.2
Silt	4	6	5	0.8
Clay	5	1	3	0.5

US Bureau of Soils

Figure 2: Comparative size of pathogens and hydraulic pathways.



the following mechanisms: A.) Adsorption, B.) Brownian motion, C.) Ion exchange, D.) Sedimentation, E.) Size exclusion, F.) Surface charge (+/-), and E.) Van Der Waals (forces).

Due to the mechanics of fluid dynamics, preferential pathways also prevent particles (virus) from exiting channels of liquid flowage while other forces cause the extraction of water. These forces include: A.) Osmotic pressure (Low → High concentrate solutions); Effect –The amount of water extracted is dictated upon the difference in ionic concentration of groundwater verses the water being transported (typically surface water). As water is extracted, particulates and virus are not, causing their concentration within the remaining volume of water within such pathways to increase. Because ground water conductivity (ionic strength) is typically associated with higher concentrations of calcium, magnesium, sulfates and chlorides, susceptibility to this phenomenon is typically associated with higher concentrations of these ions. B.) Capillary Force; Effect – the smaller the interstitial spaces between (and within) granules of subsurface soils, the greater the force becomes to attract and retain fluids within them. This will affect water to migrate into areas where particulates and virus cannot. In turn, this also serves to dewater preferential pathways and concentrate virus. In addition, particulates such as microorganisms (virus) are transported as colloids.[52] Accordingly, they will not settle and cannot be removed from water by the mechanisms described above and facilitates their transport to (and throughout) drinking water aquafers.

These phenomena are further described within the following references. [10,24-29] Studies report virus may be transported from a contaminant source to municipal wells that were 220 to 300 meters deep within a matter of weeks[21] and on the order of hours in fractured bedrock.[30]

Penetration of pathogenic viruses through soils and geological strata into aquifers seems much more likely than for pathogenic bacteria and protozoa[31] and survive for extended periods of time[9,32] and transported over long distances.[33] In addition to what is described above, Table 3 provides a selection of factors that influence virus entry and travel within groundwater aquifers.

An additional note of interest is due to their unique genetic signatures, coupled with our current ability of detecting them in trace quantities, epidemiologists are now considering the use of clinical data as a means of tracing plumes of viral pathogens in aquifers over time (≤ 3 years). Such data sets produce virus "snaphots" of infected populations. Wherein, when correlated with the presence of viral pathogens, as measured within localized groundwater sources, serve as a marker for tracking virus and groundwater movement.[34]

The presence of viral genomes in groundwater demonstrate travel times in aquifers of two to three years.[35] A conservative estimate for virus survival in groundwater is three years, whereas[32] a reasonable estimate is one to two years.[9] Figure 3 provides an overview of factors influencing virus survival.

Hydraulics and sensitive geographies

One factor of note for livestock facilities is related to the volume of water they use in comparison to neighboring homes and farms. As larger volumes of water are extracted from the aquifer at such a facility (vs. other wells) the static water level is reduced at the farm's location. Accordingly, groundwater supplying their well system is pulled from greater distances and transported through and/or around numerous soils and geologic structure(s). Flow pathways are not uniform on either horizontal or vertical planes.

Table 3: Factors that influence virus entry and travel throughout an aquifer

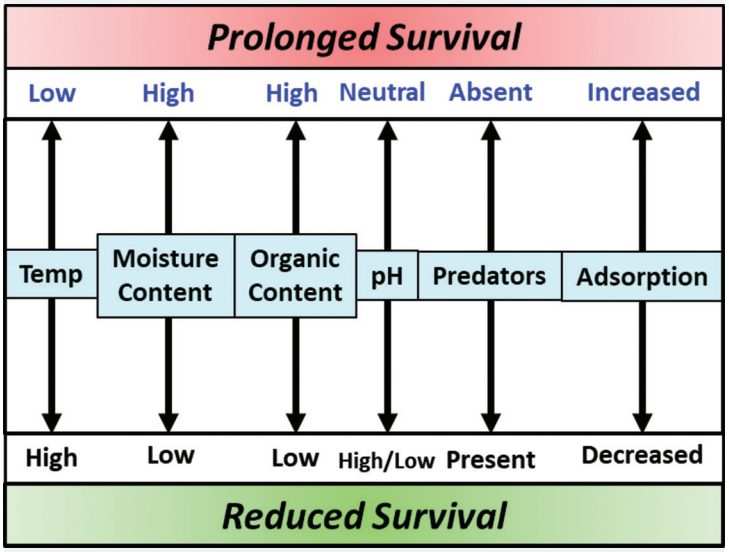
Factor (in no order)	Comment
Location of fecal source	For a well to become contaminated with enteric viruses, there must be a fecal source. Sources of fecal contamination include, but are not limited to: leaking sanitary sewers, septic system effluent, landfills, field-applied sludge or septage, effluent holding ponds, wastewater irrigation sites, injection wells, reclaimed water recharge sites, surface water infiltration. The closer the source, the higher the risk potential.
Water table depth	Viruses released by a fecal contamination source directly into the saturated zone or at a depth where the water table seasonally raises will be the least attenuated. Subsurface fecal contamination sources, such as leaking sanitary sewers or septic systems, often discharge very close to the water table.
Groundwater pH	Viruses are generally less attenuated in water of neutral or alkaline pH compared to acidic water.
Aquifer material	Viruses are generally less attenuated in coarser material (coarseness continuum = gravel > sand > silt > clay) although positively charged mineral phases, such as iron, aluminum and manganese oxides or clays, can electrostatically adsorb viruses. For confined aquifers, it is important that the integrity of the aquitard be evaluated (i.e., maximum depth of open fractures and thickness) and preferential pathways through the aquitard be identified and characterized (i.e., local, extensive with window, extensive with fractures or unfractured).Water supply wells in karst and fractured bedrock aquifers are considered highly vulnerable to contamination; management of groundwater resources in karst and fractured bedrock should not be conducted in the same way as sand and gravel aquifers.
Ionic strength and rainfall	Rainfall may enhance virus transport because of its low ionic strength.
Dissolved organic matter	Fecal contamination sources with high concentrations of dissolved organic matter (i.e., septic system effluent, leaking sanitary sewers) present a greater potential for virus transport than fecal contamination sources with lower dissolved organic matter concentrations.
Virus survival	Temperature and time are important determinants of virus survival. Viruses survive much longer at cool groundwater temperatures. If the groundwater travel time is greater than the virus survival time, viruses are unlikely to be infectious when they reach the well. It is reasonable to assume that water with a travel time of two to three years or less is likely to transport infectious viruses. However, it is difficult to accurately determine travel times, particularly in fractured bedrock or karst formations.
Pumping rate	High capacity wells can create large hydraulic gradients and local groundwater velocities that draw in contamination and/or prevent virus attachment to the aquifer material.
Thickness of overburden	Viruses are less likely to be attenuated where a thin or shallow overburden exists. An increase in the vertical distance from a fecal contamination source to a well (i.e., overburden thickness) reduces the risk potential.
Well design and construction	Some considerations include well depth, well age, ingress prevention (e.g., adequate clearance from ground elevation, proper cap/cover, no cracks in casing, grouted annular space, ground condition within 10 m radius of the wellhead), multi-aquifer well.

Health Canada (2017). Enteric Viruses in Drinking Water: Document for Public Consultation—Prepared by the Federal-Provincial-Territorial Committee on Drinking Water, Health Canada, Ottawa, Ontario. Available at `https://www.canada.ca/en/health-canada/programs/consultation-enteric-virus-drinking-water/document.html`. Accessed 15 October 2019

Greater volumes will be pulled through more porous areas and gravitational force will cause greater amounts of water to flow from higher elevations of an aquifer that are closer in proximity to areas susceptible to surface water (pathogen) intrusion. These factors serve to increase the potential of microbial contamination of well systems proving drinking water for such facilities.

Understanding the mechanisms influencing entry, survival, transport and concentration of virus in groundwater it is accepted their distribution can be very rapid, broad, irregular and multidirectional (vertical/diagonal/horizontal) with higher viral inputs in areas of watersheds and/or events, that can be described as one, or a combination of the following: A.) Changes in hydraulic pressure in response to calendar season (i.e.: Winter, Spring runoff), B.) Climatic events (i.e.: rainfall/drought), C.) Areas of crop irrigation, D.) Change in elevation of (inflows) of localized geography(s), E.) Capacity, number and geographic locations of aquifer

Figure 3: An overview of factors influencing virus survival.



recharge/discharge in relation to changing (localized) hydraulic pressures, F.) Proximity to pathogen source(s) (i.e.: septic systems, wastewater treatment plants, feed lots, manure, landfills, lakes/streams, etc., G.) Locations of unconsolidated, porous, fractured or cavernous geologies, H.) Uniformity, continuity, multiplicity and porosity (natural & manmade) of confining horizons, I.) Prevalent direction, speed and depths of groundwater flowage.

Survival, accumulation and release of virus within aquifers

As it is known temperature, protection from sunlight, presence of organic compounds, association with particulates and less microbial activity[37-39] influence survivability of virus in groundwater, speciation (virus) and soil composition do so as well. Clay particles are particularly effective at protecting virus from natural decay.[40,41] Some types of organic matter (i.e., proteins) are also reported to better protect viruses from inactivation.[42]

Of particular interest is the manner which virus accumulate within geologic strata by adsorption. Over time, virus in such areas become highly concentrated. Then subsequently desorbed unilaterally into the flowage of an aquifer, inherently creating highly concentrated plumbs of virus.[39,42] Since virus-soil interactions are very sensitive to surface charge, any water quality change that is enough to cause a charge reversal will result in the desorption of virus.[43,44] Water quality changes that can result in desorption include an increase in pH, a decrease in ionic strength, and the presence of organic matter.[40,45-47] For example, when alkaline septic effluent mixes with groundwater, the increased pH allows rapid desorption and transport of virus, especially under saturated flow conditions.[48] Rainfall recharge after a storm may decrease ionic strength and cause virus to desorb and transported. As such, viruses may continue to contaminate an aquifer at high concentrations on a periodic basis long after their initial entry.[40,49]

Due to the seasonality of porcine epidemic diarrhea (PEDV) and porcine reproductive and respiratory syndrome (PRRSV) outbreaks, it is apparent water temperature may serve as a critical factor regarding their survivability.

In a year-long survey of the occurrence of adenoviruses in drinking water in South Africa, adenovirus detection peaked in July (winter in South Africa), when up to 30% and 60% of treated and raw water samples were positive for adenoviruses, respectively. Enteroviruses were detected from an estuary in southwest Florida only when the water temperature was below 23° C. In an in vitro study, enhanced poliovirus survival and detection were observed at 22° Celsius (C) compared to 30° C in seawater. In artificial seawater, viruses were detected by reverse transcription polymerase chain reaction (RT-PCR) for at least 60 days at 22° C but for only 30 days at 30° C. Similarly, in seawater, it took 671 days to inactivate 90% of poliovirus and hepatitis A virus at 4° C and only 25 days at 25° C. In a study evaluating both human and bovine enteric viruses by polymerase chain reaction (PCR) in a mixed-use estuary, it was found that all virus types were correlated with cool water temperatures as shown in Figure 4.[23]

Concentration of virus in groundwater

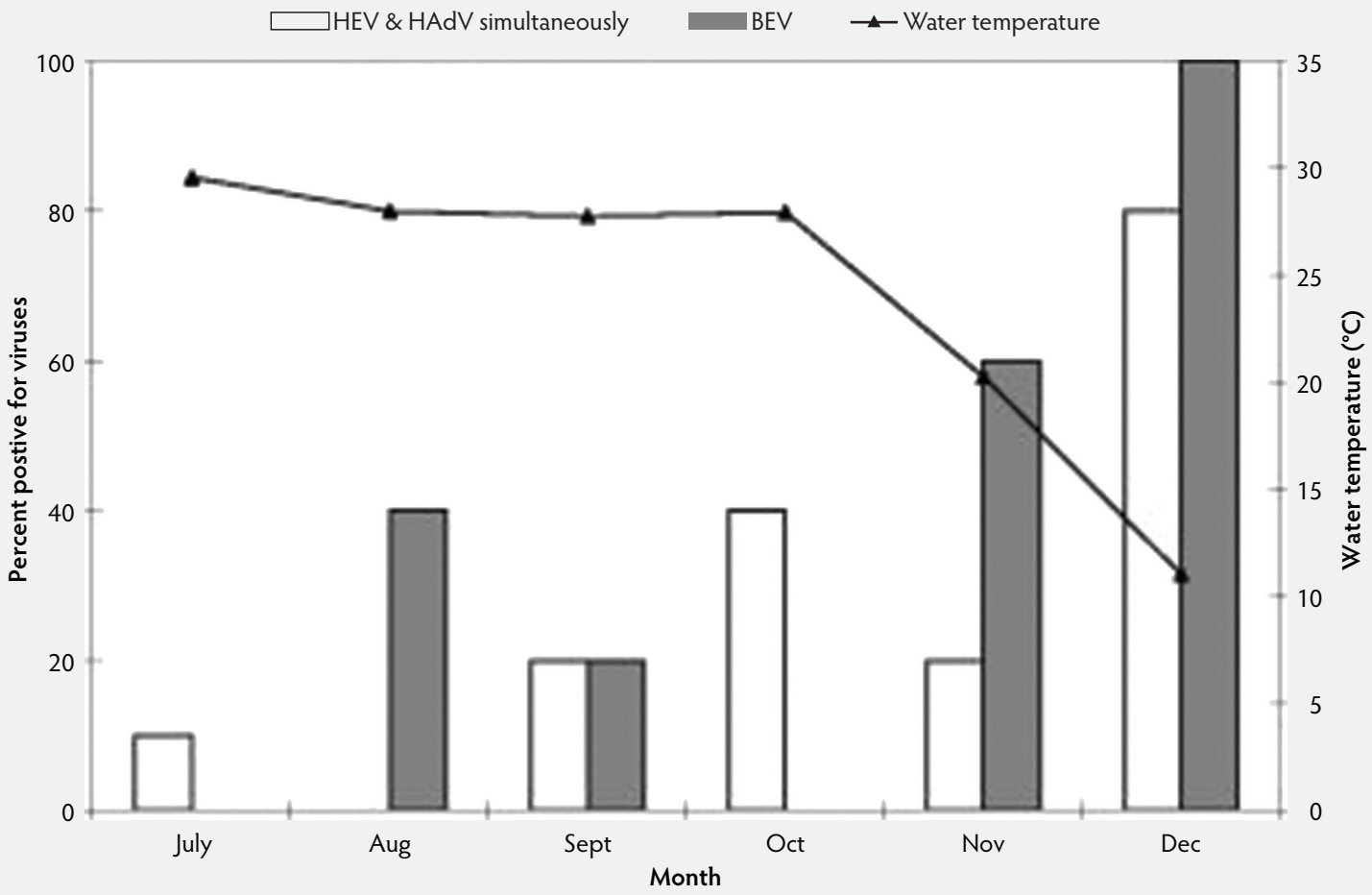
Short-term peaks in pathogen concentration may increase risk of disease transmission considerably. Furthermore, results of water quality testing for microbes are normally unavailable in time for management to take action and prevent the supply of unsafe water from entering a livestock facility.[50] In general, virus occurrence and concentration in groundwater can be characterized as transient, intermittent or ephemeral, because wells are often not virus-positive for two sequential samples and the detection frequency is low on a per sample basis.[14,51] This may be attributable to A.) preferential flow patterns; B.) concentration of virus populations within diminishing volumes of water flowing through them; C.) adsorption-desorption processes. Accordingly, it is necessary to consider the extremely high numbers by which they are shed into the environment and how rapidly they may reach an aquifer. In fact, viral concentrations in deep municipal wells are generally as high as, or higher than virus concentrations in lake (surface) water.[21] The number of virus from infected individuals (and animals) range from 100,000 up to *100,000,000,000 per gram of stool[53] and can be representative of the potential concentration of virus within groundwater aquifers.

*Interpretation of aquifer input concentration potential: If a virus represented 1 inch, the lineal distance of the number of virus contained within 1 gram of stool would be equivalent to the distance of 63.4 times the circumference the Earth.

Current synopsis: disinfection of drinking water within the livestock industry

Viral illnesses such the Avian Influenza (Poultry), foot-and-mouth (Cattle) and PRRSV, PEDV & African swine fever (ASF) (Swine) continue to be a significant concern within the livestock

Figure 4: Human and bovine enteric viruses by PCR in a mixed-use estuary, correlated with cool water.



* Percentage of samples positive for human enteroviruses and human adenoviruses (detected simultaneously), as well as bovine enteroviruses, by month versus the mean monthly water temperature (°C) along the lower Altamaha River, Georgia, between July and December 2002 (n = 5).[4]
Enteric Viruses of Humans and Animals in Aquatic Environments: Health Risks, Detection, and Potential Water Quality Assessment Tools. Theng-Theng Fong, Erin K. Lipp Microbiol Mol Biol Rev. 2005 Jun; 69(2): 357–371.

industry and have proven to be very resilient to an exhaustive list of mitigation strategies, including disinfection of drinking water. Although, a performance standard (level of disinfection required) for swine facilities remains elusive. Thusly, performance specifications required for the purchase of water disinfection systems remain absent, along with performance monitoring systems required to validate if an installation is, in fact working. A disinfection program, absent of a means to specify equipment and validate its performance on an ongoing basis lends itself to defeating its purpose. In this case, the worst-case scenario would include marketing such a program under the guise of providing a viable measure of biosecurity.

This has left one of the most recognized means for disease transmission; continue throughout the agricultural industry as being unaddressed, underestimated, and out-of-mind. Possibly, this is representative of, at least one of the underlying factors as to how it is possible for the avian influenza (poultry) and PRRSV & PEDV (swine), to persist over such a long period of time.

Is there a viable model employed for drinking water biosecurity elsewhere?

Within the public drinking water industry, disinfection of drinking water serving a municipal water distribution system must include a means to: a.) Inactivate or otherwise remove bacteria, viruses, and other potentially harmful organisms from entering; and is referred to as Primary Disinfection; b.) Maintain water quality by killing potentially harmful organisms and prevent the formation of biofilms as it flows through a drinking water distribution system and is referred to as Secondary Disinfection.

It is believed most water disinfection installations within the livestock production industry today simply use a chemical metering pump to inject a disinfectant directly into a water main serving a plumbing distribution system. Understanding the purpose of Primary and Secondary disinfection, this practice would lend itself to the latter and serves no relevance as a measure of biosecurity and preventing pathogens from entering a farms' drinking water supply. Presumably, the level of biosecurity, otherwise required to achieve

this objective remains unknown and what has been predominately installed to date would be considered grossly insufficient as a measure to ensure drinking within a livestock facility will not serve as a causal agent for transmission of infectious disease.

Furthermore, it must be understood the term "disinfection" itself does not translate to a water supply as being free of pathogens. Rather, disinfection as it relates to drinking water, refers to the probability a water supply is absent of pathogens based upon efficacy of the technologies employed, the manner they are applied, installed, and a continuing performance verification to ensure that is. Whereas, in the event various drinking water disinfection systems are being considered for purchase, vendors whom suggest their technology disinfects water, and omits qualification (e.g. ? Log_{10} inactivation/removal virus at ? flow rate ? temperature and ? pH) and the means to verify this performance (via ASTM standards) on-site on a daily basis should be avoided.

This situation will continue until the agricultural industry, accepts groundwater as a vehicle for disease transmission. Thereafter, how critically important performance claims for equipment have been validated and ongoing performance verified will be understood and implemented.

Disinfection system design and performance validation

Today it is accepted virus are present within groundwater aquifers in varying concentrations, may remain infectious from days to years, travel at various speeds and direction in advance of being detected and then subsequently disappear (from a groundwater well system). In other words, to prevent waterborne pathogens from entering a livestock operation, water tests would need to be performed on a continuous basis. Plus, analytical methods capable of providing results in real-time become a necessity. In addition, due to the implications of a False-Positive result, analytical methods employed must be reliable and procedures (QA/QC) vigorously implemented.

Alternatively, the installation of a robust pathogen barrier may represent a more economical and practical approach. Public Water Systems (PWS) have been charged with the production and distribution of microbiologically safe drinking water for many years. Technology selection, engineering design and ongoing operation of such disinfection systems are well known and have proven to be effective and reliable. Utilizing such a tried and proven model may serve as a practical approach the livestock industry would consider.

Operative model for PWS's

In advance of the installation of a disinfection system a PWS is required submit an engineering plan for State (regulatory) review and acceptance. This plan must include equipment specifications and validation that it has been, or otherwise can be *validated to achieve and sustain a minimum of 4 Log_{10} (99.99%) inactivation/removal of virus over a defined range of water conditions, composition and flow rates. Understanding, higher removal and/or inactivation rates translate to a higher probability of maintaining a safe water supply. Within the PWS industry, 4 Log_{10} (99.99%) removal/inactivation represents the greatest balance in regard to performance (Biosecurity), cost and complexity with an acceptable level of protection against pathogens from entering and/or proliferating in public drinking water distribution systems.

*Via third-party testing under protocols, methodologies, and standards accepted specifically for this specific purpose.

This model is referred to as the CT Concept and is used for validation of disinfection efficacy in response to applied Disinfectant Concentration (mg/L) and Contact Time (minutes) and constituents of water composition, such as Temperature & pH and the means to confirm and record these parameters on a daily basis, via the use of accepted *Standard Methods* American Standard Test Method (ASTM).

Disinfectants

Currently this list includes chlorine, chloramine, chlorine dioxide and ozone. CT values for chloramine illustrate it is a much weaker disinfectant and recommended for secondary vs. primary disinfection or otherwise, if the formation of disinfection by-products present an issue. Alternative disinfectants can be used based upon proof of validity, safety, and ability to verify applied dose(s) for inactivation of select pathogens.

Ultraviolet Irradiation is accepted. Although performance (Ultraviolet (UV) dose) is dependent upon factors, including hydraulic profile within the reactor, flow rate, UV transmittance of the water, UV intensity, lamp output, lamp placement, lamp aging, fouling and microbe inactivation kinetics.[56,57] Extensive pretreatment technologies are typically required to ensure consistent performance and considered impractical for livestock applications.

Ozone must be generated on-site and adds to complexity, extensive site-specific engineering and sophisticated O&M practice. In addition, in atmospheric conditions ozone is gaseous, hazardous and only partially soluble in water. Its use is not recommended in the absence of a trained, licensed water treatment plant operator.

Hydrogen peroxide (H_2O_2) is currently employed within the livestock industry as a disinfectant. Unfortunately, the EPA, the governing body assigned enforce public drinking water quality standards, does not consider H_2O_2 a viable disinfectant and finds no reason to assign CT values for its use. Nor is the author aware if CT values have been developed by an independent 3rd party on behalf of a H_2O_2 manufacturer and/or distributor.

Chlorine dioxide (ClO_2) can be explosive. This presents significant issues in regard to shipping and storage. Similarly, the solid residue left from evaporated liquid ClO_2 presents a concern. ClO_2 must be generated on-site via mixing undiluted concentrations of Sodium Chlorite with an Oxidant (e.g. Chlorine) and/

or a Strong Acid (e.g. Hydrochloric Acid) in a controlled and safe manner. While there may have been an advancement in ClO_2 chemistry and it is now being shipped, stored, injected into a water line safely and measured thereafter at sufficient concentrations, this advancement remains unknown to this author. Accordingly, in the event you have, or currently use such a transportable ClO_2 product, the use of an ASTM standard or EPA approved method (www.hach.com) is recommended to verify measurable concentrations of ClO_2 are achieved and maintained throughout your plumbing distribution system.

Chlorination is an effective primary disinfectant for the inactivation of pathogens and commonly preferred for secondary disinfection as well. Further, A.) It is the easiest and least expensive disinfection method, regardless of distribution system size; B.) In a liquid state, such as sodium hypochlorite can easily be injected into water in advance of retention systems, measured and controlled; C.) The technology for chlorination is well developed as it is the most widely used and understood disinfection method throughout the world; D.) Although aqueous Cl solutions have a limited shelf life.

CT concept

The efficacy of chemical disinfectants can be predicted based on knowledge of the residual concentration of a disinfectant and factors that influence its performance, mainly temperature, pH, contact time and the level of disinfection required.[54] This relationship is commonly referred to as the CT concept, where CT is the product of "C" (the residual concentration of disinfectant, measured in mg/L) and "T" (the disinfectant contact time, measured in minutes) for a specific microorganism under defined conditions (e.g., temperature and pH). To account for disinfectant decay, the residual concentration is measured at the exit of the hydraulic contacting system.

Contact time T is calculated using a T_{10} value, defined as the detention time at which 90% of the water meets or exceeds the required contact time. The T_{10} value can be estimated by multiplying the theoretical hydraulic detention time by a baffling factor, dictated by the design of the retention system. Otherwise, a hydraulic tracer test may be performed to determine the actual contact time under expected maximum flow (rate) conditions. The T value is dependent on retention volume and the hydraulics related to the design of the retention system. Improving flow hydraulics to achieve CT requirements serves greater utility than increasing the disinfectant concentration and managed with physical modifications (such as to achieve laminar flow and/ or increasing the distance of flow paths) within the contacting system. CT tables for 2 log, 3 log and 4 log inactivation of viruses can be found in an Environmental Protection Agency (EPA) Guidance Manual.[55] Selected CT values are presented for a range of 4 Log_{10} values using disinfectants that have been proven and acceptable for drinking water.

Determination of disinfection dose:

Log_{10} inactivation is based on the Delivered Dose, "CT"

"C" is the disinfectant residual (mg/L)

"T" is the exposure or contact time (minutes)

Multiply them:

C • T = mg/L • min = (delivered dose)

CT Values can be found in US EPA tables to determine log inactivation based on specific monitored parameters (pH, disinfectant residual and/or temperature):

Example

Design a 20 gallon per minute (gpm) water disinfection system capable of inactivating up to 99.99% of all viruses on a continuous basis within the water supply for a Livestock operation. Chlorine is the preferred disinfectant water pH and Temperature is 7° and 10° C respectively.

From Table 4 a CT Value of 6 is identified to achieve 4 Log_{10} inactivation of virus with Free Chlorine within a source water with a pH between 6 and 9 and a temperature of 10° C.

A disinfection system of the design as described in Figure 5 can be validated as described below.

Hydraulic Factor (by Tracer Study @ 20 gpm) = 0.5

Net Hydraulic Retention Time (T) = (114 gallons/20 gpm) × .5 = 2.85 minutes

Calculation of Free Chlorine Concentration to achieve 4 Log_{10} Inactivation:

(CT Value/T) = mg/L

6/2.85 = 2.11 mg/L

With the performance parameters described above, when a chlorine solution enters the inlet of the first tank at a rate that will provide a concentration of Free Chlorine of ≥ 2.11 mg/L in the water exiting the last tank, performance is validated with an inactivation rate of 99.99% against viral pathogens.

Refer to Table 5 for concentrations (mg/L) providing less security (99% & 99.9%).

The same model applied for Chlorine Dioxide is shown in Table 6.

CT Value (mg/L*min) to achieve 4 Log_{10} inactivation of virus with Free Chlorine. With a water temperature of 10° C and a pH between 6.0 and 9.0 = 25.1 Net Hydraulic Retention Time (T) = (114 gallons/20 gpm) × .5 = 2.85minutes.

Calculation of Chlorine Dioxide Concentration to achieve 4 Log_{10} Inactivation:

(CT Value/T) = mg/L

25.1/2.85 = 8.81 mg/L

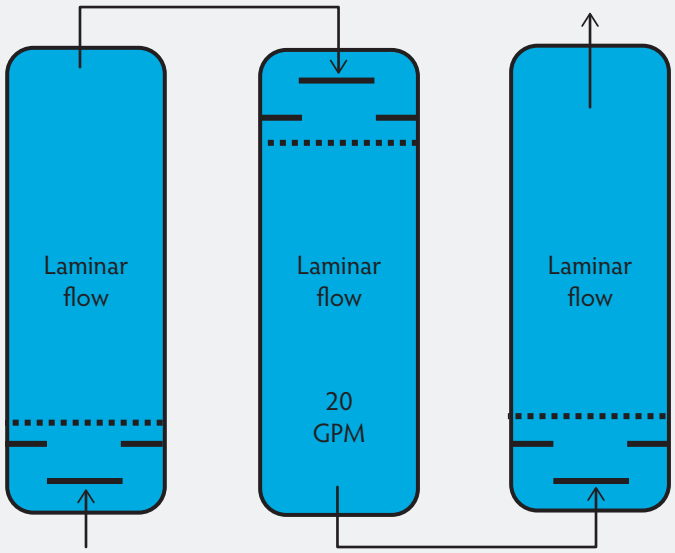
With the performance parameters described above, when a Chlorine Dioxide solution enters the inlet of the first tank at a rate that will provide a concentration of 8.81 mg/L in the

Table 4: Inactivation of viruses by free chlorine, pH 6.0-9.0

Concentration mg/L × Time (minutes) CT values for inactivation						
Disinfectant:	Chlorine (free)			pH: 6 - 9	VIRUS	
Safety level	Temperature (Celsius)					
	≤ 1	5	10	15	20	25
2-Log_{10} 99%	6	4	3	2	1	1
3-Log_{10} 99.90%	9	6	4	3	2	1
*4-Log_{10} 99.99%	12	8	6	4	3	2

* Required safety level (barrier) for potable drinking water systems

Figure 5: Example of retention system design.



Multiple 38 gallon water columns
Total volume = 114 gallons

water exiting the last tank, the level of protection is validated with an inactivation rate of 99.99% against viral pathogens. Concentrations providing less security (99% & 99.9%) are shown in Table 7.

Water composition and pretreatment

The type of treatment prior to primary disinfection, and the manner it is prescribed, designed, and operated, will have a significant influence on the performance of each water disinfection system. Due to the vast array of groundwater chemistries and density of micro-particulates/microorganisms, to ensure expected performance outcomes are achieved and to avoid the promulgation biofilms within piping and fixtures, prefiltration is typically necessary (or required with the presence of constituents such as iron, arsenic, manganese and suspended solids). Reducing pH to < 7.5 becomes an important consideration with the use of sodium hypochlorite as a disinfectant.

The following parameters must be known and presented to the livestock facility manager(s) within the engineering design for each water treatment system:

1. Allowable concentration of disinfectant within the drinking water.
2. Lethality of the disinfectant in relation to targeted pathogens.
3. The amount of retention (contact) time (T_{10}) required to achieve 90%, 99%, 99.9%, 99.99% .... etc. inactivation/removal per measured concentration of disinfectant.
4. The means to validate T_{10}.
5. The means to validate an installations' expected performance in advance (of purchase), vs. what is claimed by the manufacturer, distributor, or vendor.
6. The means to accurately verify disinfection performance (ASTM test standards) in real-time and/or daily.
7. The means to accurately forecast an installations performance for the specific application(s) and site-specific conditions, including:
   a. A water analysis including all parameters that would serve to influence performance of the technologies to be installed.
   b. An understanding the degree the source water's composition may change beyond the first year of the well systems installation and thereafter.
8. The maximum flow rate available from the well system accounting for:
   a. Static water level.
   b. Flow capacity of the well (gpm)
   c. Flow capacity of the well's pump.

Table 5: Inactivation of viruses by free chlorine, providing less security

Concentration mg/L values for inactivation

For 20 GPM with 3 - 38 gallon columns @ laminar flow

Disinfectant:	Chlorine (free) (mg/L)**			pH: 6 - 9	VIRUS	
Safety level	Temperature (Celsius)					
	<1	5	10	15	20	25
2-Log_{10} 99%	2.11	1.40	1.05	0.70	0.35	0.35
3-Log_{10} 99.90%	3.16	2.11	1.40	1.05	0.70	0.35
*4-Log_{10} 99.99%	4.42**	2.81	2.11	1.40	1.05	0.70

* Required safety level (barrier) for potable drinking water systems

** Concentration limit for potable drinking water = 4.0 mg/L

Table 6: CT– Inactivation of viruses by chlorine dioxide, pH 6.0-9.0

Concentration mg/L × Time (minutes) cT values for inactivation

Disinfectant:	Chlorine Dioxide (mg/L)			pH: 6 - 9	VIRUS	
Safety level	Temperature (Celsius)					
	≤1	5	10	15	20	25
2-Log_{10} 99%	8.4	5.6	4.2	2.8	2.1	1.4
3-Log_{10} 99.90%	25.6	17.1	12.8	8.6	6.4	4.3
*4-Log_{10} 99.99%	50.1	33.4	25.1	16.7	12.5	8.4

* Required safety level (barrier) for potable drinking water systems

d. Total (actual) flow capacity available at the installation site based upon the following parameters:
   i. Calculated friction loss based upon static water level and piping (to installation site).
   ii. Specified performance curve (gpm vs. total friction loss + required operating pressure (water treatment plant and livestock operation).

9. With this information, a water treatment plant may be designed to ensure initial and ongoing performance of the disinfection system (primary) will be achieved with continued disinfection throughout the water distribution system (secondary).
10. Equally important is the availability of on-site personal that can be assigned responsibility to perform water analysis, record visual operational parameters of the water treatment plant, and monitor feed supply of chemical metering pump(s).

Economic considerations

The benefit of nearly all biosecurity systems are realized in response to events that occur on a periodic and unpredictable basis. Accordingly, the economic value they provide is based upon factors such as: a.) How well they perform during these events; b) The probability such an event will occur; c.) Potential of financial loss if it does; d.) Virulence and lethality of the pathogen it removes.

Therefore, the value of any biosecurity system is based on assessment of risk and cost. For water disinfection systems both capital and operating costs are directly dependent upon:

Table 7: CT– Inactivation of viruses by chlorine dioxide, providing less security

Concentration mg/L values for inactivation

For 20 GPM with 3 - 38 gallon columns @ laminar flow

Disinfectant:	Chlorine dioxide**			pH: 6 - 9	VIRUS	
Safety level	Temperature (Celsius)					
	≤1	5	10	15	20	25
2-Log_{10} 99%	2.94	1.96	1.47	0.98	0.74	0.49
3-Log_{10} 99.90%	8.98	6.00	4.49	3.02	2.25	1.51
*4-Log_{10} 99.99%	17.58	11.72	8.81	5.86	4.39	2.94

* Required safety level (barrier) for potable drinking water systems

** Concentration limit for potable drinking water = 4.0 mg/L

1. Process flow rate (gpm)
2. Water composition, temperature and pH
3. Reliability of equipment components
4. Selection of disinfectant
5. Desired level of
   a. Level of assurance (probability) water will be free of pathogens
      i. i.e.: 90% - > 99.99% inactivation
      ii. System efficacy and reliability.
   b. Automation and instrumentation
   c. Fail-safe options
6. Pretreatment requirements
7. If and to what degree, the installation may (+/-) affect:
   a. Livestock performance metrics
   b. Operating cost(s)

As described above, while most, if not all current installations within the livestock industry may not provide much in the order of primary disinfection, it is evident many have served to provide other favorable outcomes in regards to livestock performance metrics and operating costs (i.e. cleaning or replacement of plugged water fixtures, evaporative cool cells, etc.). Meaning, drinking water "disinfection" even with a minimal degree of efficacy has proven to be a component of a viable economic model beyond serving as a measure of biosecurity.

Cautionary notes

1. The Safe Drinking Water Act (SDWA) is enforceable for establishments either serving as a place of employment and/or accessible to the public.[7] Companies engaged within the livestock industry may remain unaware of this consideration, nor associated litigious issues they present. This becomes especially poignant if substances, intentionally added to a water supply may deleteriously affect its potability.
2. Administering solutions, (such as disinfectants, acids, sequestering agents, and/or medications) into a potable water distribution system (i.e. connected to a washroom, office area, bathrooms) at concentrations that may cause (directly or indirectly) water to become non-potable, is a concern. Similarly, is the practice of storing and handling concentrated (hazardous) substances within an area absent of appropriate ventilation, eye wash, physical separation of concentrates (such as acids and oxidants), and the manner they are transferred into a pressurized water line, (leaking metering pumps), etc. in the absence of appropriate safety protocols and supplies.
3. Note: If the purpose of a plumbing distribution system is solely dedicated for the conveyance of water to livestock and other non-potable uses, it is considered a non-potable water distribution system and must be well identified and remain isolated from any fixture that potentially could be used (i.e. inadvertently) as a potable drinking water source.
4. The use of pressurized gaseous disinfectants are generally not recommended within the livestock production industry.
5. Metering pumps
   a. Vapor or gas bubbles can form due to gasification (i.e. the degradation of sodium hypochlorite) produces a gas which is mostly oxygen, particularly if the solution is below atmospheric pressure. This can lead to gas locking of the suction line in a diaphragm pump. Therefore, pumps should be provided with a flooded suction (i.e. the pump inlet should always be located below the liquid level in a storage tank). Today this limitation has been addressed in the design of a number of newer diaphragm pumps.
   b. The use of peristaltic metering pumps have become prevalent within the livestock industry. Most have been

associated with a higher degree of maintenance and operator attention, resulting in chemical leakage and a continued state of disrepair. This is not representative of good practice in regard to biosecurity nor laws governing the use of hazardous chemicals. All metering pumps must be observed daily and maintained frequently. Further, the purchase of a quality pump is representative of a good investment and the acceptance of a pump used as a marketing ploy may not be.

6. Because Chlorine Dioxide serves to cause nervous system effects for infants and young children and anemia, the US EPA has a maximum contaminant level (MCL) of 1 mg/L for chlorite (from which ClO_2 is generated) and a maximum residual disinfection level (MRDL) of 0.8 mg/L for ClO_2.
7. Because Chlorine serves to cause eye/nose irritation and stomach discomfort the US EPA has assigned an MCL and MRDL of 4 mg/L for Cl.
8. The pH of sodium hypochlorite (a common chlorine solution) is high because sodium hydroxide is used in its manufacture to reduce decomposition and increase the stability of the product. Care is needed when dosing water with a high concentration of hardness ions or waters with carbon dioxide present as the highly alkaline product can lead to scale formation within plumbing systems leading to lower flow rates and plugged dosing quills.
9. While the following note may be painfully obvious, it is worth mentioning. Water containing either a high concentration of an oxidant and/or acid will serve toward the demise of any metallic component or elastomer within a plumbing distribution system and associated fixtures.
10. In the event Test Strips are used for water analyses, verify their accuracy with the use of an ASTM or EPA standard method frequently.
11. Installations as represented in Figures 6A, 6B, 6C, 6D, 6E provide examples of appropriate water treatment plant designs for biosecurity, process control, instrumentation and QA/QC for swine production facilities including; A.) Boar-Stud, B.) Sow/Gilt, C.) Nursery or Gilt, D.) Wean and/or Finish.
12. A water analysis providing verification of the absence of *E coli* or Coliforms cannot be used to suggest the absence of viral pathogens.

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Figure 6 A: Boar stud facility – Water treatment plant design includes primary disinfection – filtration – secondary disinfection. Water used within laboratory and dilution semen also includes: residual disinfectant removal, 1 micron absolute pharmaceutical grade filtration, reverse osmosis and mixed bed DI with virgin, non-regenerated IX media, with continuous recycle through ultrapure water distribution system comprised of polyvinylidene fluoride (PVDF) materials and ultraviolet irradiation (254 nm @ 40+mJ/cm^2) disinfection (per each recycle) and online/continuous instrumentation for monitoring of step-processes, performance verification and QA/QC.

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Figure 6 B: Sow site A - water treatment plant design, primary disinfection – filtration – secondary disinfection. With a plumbing distribution manifold to accommodate each of multiple barns with multiple variations of water composition, medication(s) & pH, and provide independent water distribution lines for living quarters, utility, sprayer & compost applications.

Figure 6 C: Swine nursery or gilt site. (Comparative difference (before/after) in water treatment plant design).

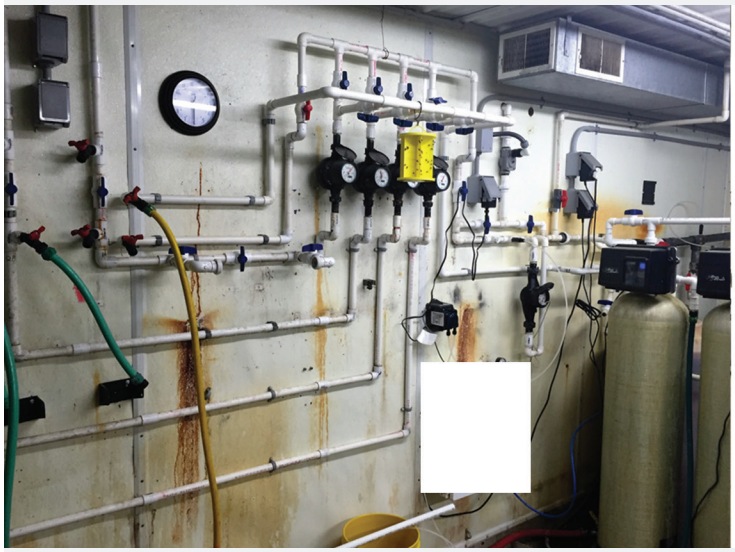

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Figure 6 D: Wean-to-finish and Finish. (Comparative difference (before/after) in water treatment plant design).

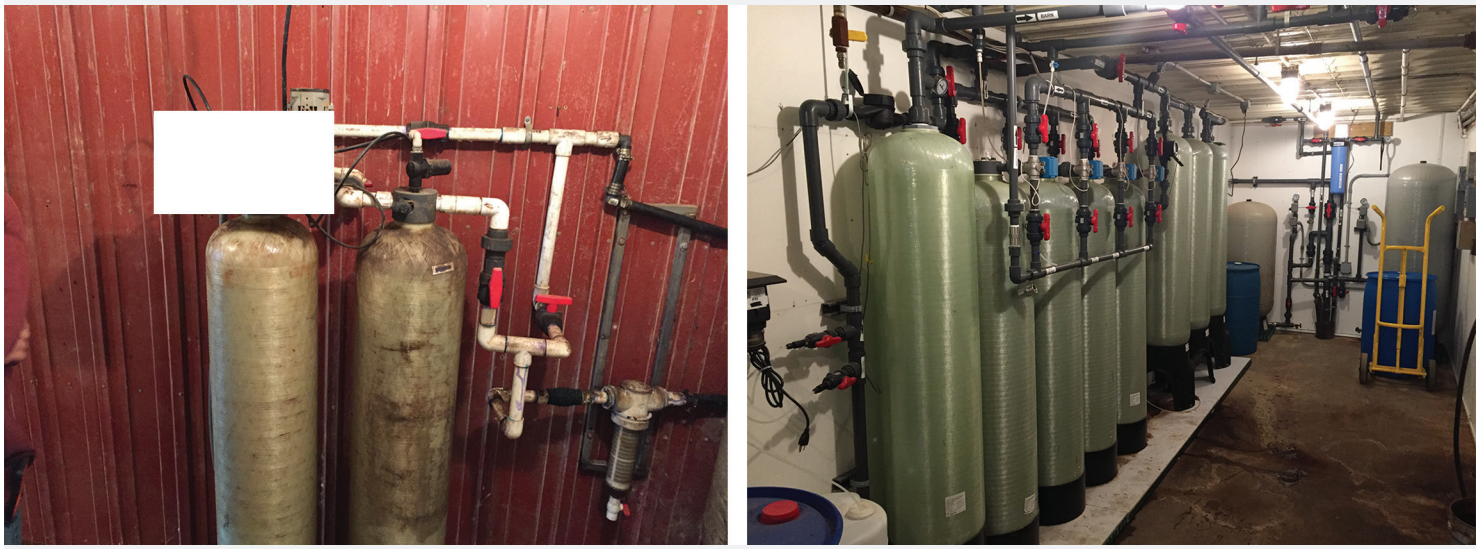

Figure 6 E: Chemical metering station - example.

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