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A review of emerging pollutants of concern in drinking water and wastewater

Rebekah Corinne Guill

A REVIEW OF EMERGING POLLUTANTS OF CONCERN IN DRINKING WATER AND WASTEWATER

A Project

Presented to the

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ABSTRACT

The purpose of this project is to identify emerging pollutants of concern in wastewater and drinking water and the challenges associated with their discovery. This review covers the definition of emerging pollutants, lists of contaminants, the source and possible sinks of contamination, methods used to identify the pollutants, treatment capabilities, regulatory involvement, and public interest. The information herein is based on a compilation of recent works from the past eight years and recent interviews with some influential and well respected members of the scientific community. The most frequently detected contaminants taking the spotlight included pharmaceuticals, personal care products, and endocrine disrupting chemicals at ultra trace levels (sub-µg/L or lower). These commonly used, engineered compounds and their by-products are free to interact biologically and chemically in the environment, which has resulted in an increased interest in their impacts on human and environmental health.

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CHAPTER ONE

INTRODUCTION

Overview

Our ability to protect the safety and quality of drinking water from being contaminated and our ability to minimize the impacts from wastewater discharge has become an illusive quest. This project will be used to identify emerging pollutants of concern in wastewater and drinking water and the challenges associated with their discovery. It is based on a compilation of recent works from the past eight years and recent interviews with some influential and well respected members of the scientific community.

The purpose of this review is to determine which emerging pollutants are the most problematic, how they are being discovered, the significance of their concentration, and how their impacts on human and environmental health are being evaluated and prevented. This review will also endeavor to provide an understanding of the scientific, political, and public perceptions of these emerging pollutants of concern.

These goals will be accomplished by (1) defining the nature of emerging pollutants; (2) developing a list of

those compounds commonly detected from recent works; (3) indentifying the known or likely sources and possible sinks of contamination; (4) reviewing the methods used to quantify and identify the pollutants; (5) reviewing treatment capabilities; (6) reviewing regulatory involvement; and (7) evaluating public interest and concern.

Background

In 2002 a National Reconnaissance conducted by the U.S. Geological Survey was the first of many efforts leading to a frenzy of projects focusing on emerging water contaminants. Although it was preceded by a number of individual studies on pharmaceuticals, pesticides, fire retardants, various classes of polar organic compounds (POCs), etc., it is widely accepted in the scientific community as the onset in emerging organic wastewater contaminant (OWC) discovery (Kolpin et al., 2002).

The data collected in the study, during 1999 and 2000, was obtained from newly developed analytical methods measuring concentrations of 95 pollutants in samples from a network of 139 streams across 30 U.S. states. Prior to this study by the U.S. Geological Survey there were no

analytical methods that could detect such low concentrations (10-100 ng/L or parts per trillion (ppt)) representative of common environmental conditions. None of the samples exceeded drinking water maximum concentration levels (MCLs); however, a majority of the compounds did not have established MCLs (Kolpin et al., 2002).

Furthermore, Kolpin et al. (2002) opened concerns related to the synergistic (antagonistic) effects of these trace pollutants in our major wastewater streams. There was no literature available that covered potential interactions of the chemicals. Beyond synergistic interactions, another concern was the formation and interactions of the degradation products. Metabolites of these pollutants were not yet being studied. Questions arose regarding how these counterparts will be transported in the hydrologic cycle, whether the mode of action would present a greater toxicological risk in comparison to the parent material, and whether or not they would exhibit greater persistence in the environment.

The unknown ecological and toxicological effects of these constituents are a persistent concern in the subsequent years of research on emerging contaminants. Observations of acute effects are limited based on the

environmental concentrations. Long-term or chronic effects studies become the key in assessing risk to human and environmental health.

A New Concern; Defining the Term

The first step towards understanding the human risk of exposure to drinking water and wastewater contaminants is to characterize the pollution. During the past five years the heightened effort to evaluate "new" or "emerging" pollutants has taken the spotlight. In order to identify emerging pollutants, we must look at the definition that qualifies a pollutant as "emerging".

In 2004 Daughton, chief of the U.S. EPA Environmental Chemistry Branch, took great care and precision in clearly and separately defining the qualifications of "emerging" contaminants. He delineated three groupings of emerging pollutants: (1) pollutants that have been newly introduced in the environment, (2) newly detected pollutants, and (3) pollutants associated with presenting new environmental health concerns. Daughton explained that the focus of the emerging pollutant concern has been confused by not properly defining the extent of the term. The following

groupings address the definition of the term as depicted by Daughton (Daughton, 2004).

Newly Introduced Pollutants

The term "emerging pollutants" has been used to describe those that have been introduced by commerce and then detected in wastewater streams and in drinking water resources. Without the human influence, these pollutants may otherwise not have been introduced into the environment, as many of them are proprietary manufactured substances.

Newly Detected Pollutants

Newly detected pollutants arise from our ever changing detection and isolation technologies. This group is already present in wastewater and drinking water. It has not been newly introduced to the environment; rather it has been newly identified based on lower concentration detection capabilities.

New Health Concern Pollutants

Historically, humans have discovered that pollutants that persist in the environment are more likely to accumulate and reach concentrations that may present harmful health effects. We have been limited by our technology to determine what substances are present, which

of these substances exhibit the most persistence, and which are directly linked to causing ecological damage and/or human health effects. In this regard, "emerging pollutants" is used to define the concern rather than the substance.

A chemical substance known to be present in wastewater and drinking water, which otherwise was not drawing attention or not documented as having environmental repercussions, can become suspect once it has come to light as suggested by toxicological, ecological, biological, or epidemiological evidence demonstrating a potential risk to human or environmental health. Daughton describes this as "… a newly hypothesized concern regarding an old pollutant… pollutants that have long occupied our attention can gain new notoriety with the revelation of new aspects of their occurrence, fate, or effects…" (Daughton, 2004, p. 716).

Soaring through Chemical Space

In 2005 Daughton provided one of the most current perspectives on emerging contaminants in an EPA publication. He described that they exist in chemical space. He defines 'chemical space' as the limitless combinations of a small group of atomic elements that can yield an infinite number of chemicals. This chemical space

is under-represented by the pollutants on regulatory lists, since they are a mere fraction of those in the environment.

Daughton (2005) reported that, according to the American Chemical Society's Chemical Abstract Service (CAS) Registry, more than 26 million organic and inorganic substances had been indexed, a third of which were commercially available, and less than a quarter million were inventoried or regulated by government entities worldwide. In 2008 Daughton and Ruhoy remind us that we have only identified a minuscule fraction of the chemical inventory that exists in the environment; therefore, the true extent and magnitude of contamination has been only partly delineated (Daughton & Ruhoy, 2008).

This review will attempt to evaluate our current standing on the subject. To what extent are we identifying emerging drinking water and wastewater contaminants? What can we practically do to minimize impacts to human and environmental health? Daughton (2005) points out that the legal standing of a chemical will impact the degree to which it will be studied. He stated that "the environment does not discriminate between pollution from legal or illegal chemicals". This may lead us to find that

government interest may overrule scientific findings by narrowing our perspective in chemical space.

As time goes on the spatial dispersion of chemicals may actually prove to be infinite since we continue to engineer new compounds which find their way into the environment. Once exposed to the elements these parent materials can give rise to a long list of transformation offspring. These chemical offspring are free to interact biologically and chemically in the environment. This is notably true of engineered compounds which are designed to be reactive in order to serve a specific function.

CHAPTER TWO

CHEMICALS IN THE SPOTLIGHT

Emerging Pollutants Established by National Efforts

Of the 95 chemicals identified by the 2002 National Reconnaissance conducted by the U.S. Geological Survey, the most frequently detected contaminants took the spotlight. These are summarized in the following table.

Table 1

2002 Frequently Detected Contaminants in United States Streams

Chemical	Use
coprostanol	fecal steroid
cholesterol	plant and animal steroid
N,N-diethyltoluamide	insect repellant
caffeine	stimulant
triclosan	antimicrobial disinfectant
tri(2-chloroethyl)phosphate	fire retardant
4-nonylphenol	nonionic detergent metabolite

Kolpin et al. (2002) documented that out of all the compounds that have received heightened attention; including antibiotics, nonprescription drugs, prescription drugs, and reproductive hormones; the nonprescription drugs were the most frequently detected. This was attributed to

the suspected higher domestic annual use, as these compounds are readily available.

Once again in 2008, the U.S. Geological Survey conducted a National Reconnaissance to evaluate more recent data from the study of pharmaceuticals and other organic wastewater contaminants (OWCs) in U.S. drinking water sources. Samples were analyzed for 100 analytes, 36 being pharmaceuticals (including antibiotics and prescription drugs), with sub-part per billion detection limits (i.e. < 1.0 µg/L. The targeted compounds were selected based on chemical properties (e.g. water solubility), known or suspected ecological toxicity, and/or the large quantities that are manufactured or used in commerce. The most frequently detected contaminants are listed as follows in Tables 2 and 3; from Focazio et al., 2008, p. 212.

Targeted drinking water sources selected for sampling consisted of untreated groundwater and surface water sources that were suspected of being exposed to human or animal waste streams. The untreated drinking water sources included twenty-five groundwater and forty-nine drinking water sites. The assessment yielded that 63% of the selected analytes were detected in one or more samples, 60% of the pharmaceuticals were not detected at all. Even with

reporting levels in parts per billion or lower, 38% of the targeted analytes were not detected in any samples (Focazio et al., 2008).

Table 2

2008 Frequently Detected Groundwater Contaminants in United States Drinking Water Sources

Groundwater Contaminants		
Chemical	**Classification**	**Detection**
tetrachloroethylene	solvent	24%
carbamazepine	pharmaceutical	20%
bisphenol-A	plasticizer	20%
1,7-dimethylxanthine	caffeine metabolite	16%
tri (2-chloroethyl) phosphate	fire retardant	12%

Table 3

2008 Frequently Detected Surface Water Contaminants in United States Drinking Water Sources

Surface Water Contaminants		
Chemical	**Classification**	**Detection**
cholesterol	natural sterol	59%
metolachlor	herbicide	53%
cotinine	nicotine metabolite	51%
β-sitosterol	natural plant sterol	37%
1,7-dimethylxanthine	caffeine metabolite	27%

The study showed that pharmaceuticals were detected less frequently than other analytes of interests; including some pesticides, fragrance/flavor compounds, steroids, non-

prescription drugs, plasticizers, flame retardants, and detergents. The data also demonstrated a median of 4 compounds detected at each site, suggesting that the target contaminants are prone to be present as mixtures in the environment (Focazio et al., 2008).

Target compounds will have the opportunity to transform and metabolize through environmental processes once discharged into waterways. It is likely that due to the lack of analytical methods available at the time of the study, that said metabolites could not be detected, thus the data do not provide a full representation of the potential contaminants lurking in drinking water supplies (Focazio et al., 2008).

Commonly Detected Emerging Pollutants

Bolong et al. (2009) acknowledge that the emerging contaminants that have continued to gather concern and attention circulate around a mixed and ever expanding group of endocrine disrupting chemicals (EDCs). As defined in their works, EDCs are "exogenous substances which interfere with the normal hormones at very low concentrations in the human body". These EDCs are comprised primarily of pharmaceuticals and personal care products (PPCPs), as well

as a variety of industrial compounds. Since EDCs have great influence at disrupting normal hormone behavior at low concentrations, it is assumed that even ultra trace (sub-µg/L or lower) concentrations present in water and wastewater may have considerable impact.

These compounds have not been addressed by the treatment methods designed into our current wastewater treatment systems (WWTS). This has resulted from a lack of regulatory involvement, mostly due to the historical and existing void of risk exposure data. The documented effects of EDCs on humans are still under study, while the effects on animals are well documented, especially for aquatic systems. This is because it has been easier to identify the complex endocrine responses in simpler, more vulnerable organisms. Bolong et al. (2009) stress that these emerging contaminants have been released "knowingly and unknowingly" into the environment and that swift action is needed to resolve this oversight.

The 2009 review prepared by Mompelat, Le Bot, and Thomas covered the quality and safety issues surrounding the presence of pharmaceutical products and by-products in drinking water. It showed that recent works have uncovered approximately 160 pharmaceutical products and 30 by-

products from human and veterinary sources. The four classes of contaminants that dominated studies included non-steroidal anti-inflammatory drugs (NSAIDs), anticonvulsants, antibiotics, and lipid regulators. The compounds that predominately took the spotlight from these studies included ibuprofen and diclofenac (NSAIDs), gemfibrozil (the most studied lipid regulator), carbamazepine (anticonvulsant), and a variety of antibiotics including sulfamethoxazole and trimethoprim (Mompelat, Le Bot, & Thomas, 2009, p. 803).

In another study, Razavi et al. (2009) focused on the degradation of three pharmaceuticals: clofibric acid, bezafibrate, and gemfibrozil, selected specifically due to their widespread use. For example, they reported an annual use of gemfibrozil at 280,000 kg, with ultra trace concentrations detected in surface waters in North America and Europe (Razavi et al., 2009).

Some other typical pollutants that have gathered attention according to Söderström, Lindberg, and Fick (2008) include antibiotics, such as trimetoprim and ciprofloxacin; antidepressants, such as fluoxetine and doxepine; NSAIDs, such as ibuprofen and naproxen; and select pesticides, including fluconazole, miconazole,

chlorpyrifos, and dichlorvos (Söderström Lindberg, and Fick 2009, p. 624).

In yet another study, Bennotti et al. (2009) provided the results of a 2006-2007 drinking water monitoring study that conducted analyses for 51 compounds from source water, finished drinking water, and distribution system (tap) water. The water served more than 28 million people and was monitored from 19 U.S. water utilities. The target compounds included a mixed group of pharmaceuticals, potential endocrine disrupting compounds (EDCs), and other unregulated organic contaminants.

Out of the 51 targeted compounds, 34 were found in at least one sample, while the remaining compounds were not detected at all. Table 4 lists the 11 most frequently detected compounds of the study. Five of the most frequently detected pharmaceuticals were not listed in the top 200 prescribed pharmaceuticals for 2006 and 2007. Therefore, Bennotti et al. (2009) warn us not to rely solely on prescription information without taking into account the dosage, pharmacokinetics, treatment efficiency, or environmental fate.

Table 4

2009 Most Frequently Detected Compounds in United States Drinking Water (sub-µg/L and lower)

Chemical	Use	Group	Detected in
atenolol	beta-blocker	pharmaceutical	source water
atrazine	herbicide	endocrine disruptor	source water, finished water, tap water
carbamazepine	anticonvulsant	pharmaceutical	source water
estrone	steroid hormone	endocrine disruptor	source water
gemfibrozil	antilipidemic	pharmaceutical	source water
meprobamate	antianxiety	pharmaceutical	source water, finished water, tap water
naproxen	non-steroidal anti-inflammatory	pharmaceutical	source water
phenytoin	anticonvulsant	pharmaceutical	source water, finished water, tap water
sulfamethoxazole	antibiotic	pharmaceutical	source water
TCEP	Flame retardant	other	source water
trimethoprim	antibiotic	pharmaceutical	source water

CHAPTER THREE

THE CONTAMINATION OF WASTEWATER AND DRINKING WATER

Pollution by Our Own Design

As evidenced by the works reviewed herein, researchers from this past decade have focused on the long list of trace pollutants that have tainted our drinking water sources and/or are linked to wastewater discharges. Predominately the attention is drawn to emerging pharmaceuticals and personal care products (PPCPs), endocrine disrupting compounds (EDCs), and their byproducts. There is an increased interest in the environmental and human ecological consequences of the ever growing and widespread use of pharmaceuticals and personal care products.

The United States is the largest market for pharmaceuticals worldwide, with sales exceeding $200 billion dollars in 2007 (Glassmeyer et. al, 2009). By 2008, over 3,000 pharmaceuticals were approved for prescription in the U.S., while hundreds of others were available for over-the-counter use or as ingredients to personal care products (Bennotti et al., 2009). It has been observed that in North America the consumption of pharmaceuticals

increases nearly 10% each year, while Europe has also been shown to consume hundreds of tons annually (Mompelat et al., 2009).

Sales data have been shown to provide potential correlation to environmental concentrations. A 2010 study demonstrated that annual loads, calculated from concentrations in surface water, could be correlated to pharmaceutical annual sales conducted upstream (ter Laak et al., 2010).

Sources of Contamination

Human and animal wastewater effluents are currently the most prominent and direct sources of environmental contamination to water resources. As a result, emerging pollutants of concern have been found at trace levels in surface and wastewaters throughout the world. Their occurrence is due to effluents from wastewater treatment plants, hospitals, agriculture, livestock management, septic storage facilities, municipal sources, urban runoff, landfill leachates, and industrial activities (Focazio et al., 2008; Bennotti et al., 2009).

Human pharmaceuticals are released into aquatic resources from sewer emissions. The final destination of

household pharmaceuticals is dependent on three possible modes of discharge. These paths are best visualized in Appendix A from Glassmeyer et al. (2009). The first route is through the excretion after ingestion, injection, or infusion. The second is the removal through bathing by washing off topical medications or washing off quantities excreted through perspiration (Glassmeyer et. al, 2009; Daughton & Ruhoy, 2008). The third is the disposal of unwanted or leftover pharmaceuticals. The common avenues of disposal of unwanted pharmaceuticals is either by flushing down the toilet, washing down the sink, or discarding as household trash (Glassmeyer et. al, 2009; Song et al., 2008).

Veterinary pharmaceuticals are more directly introduced through agricultural applications. It is not uncommon for manure from treated animals to be applied to fields. Likewise, veterinary pharmaceuticals are released into aquatic systems from fish farming (Zukowska, B., Breivik, K., & Wania, F., 2006; Razavi et al., 2009).

In agriculture, sewage sludge has been routinely applied as fertilizer. The nutrient content of this waste stream has provided benefits through reuse. The reuse of sewer sludge has been a favorable disposal alternative to

conventional landfill and incineration options. However, growing concern has mounted regarding the contaminants carried in this fertilizer source and its re-entry into the environment, specifically discharge and leaching into water resources under such concentrated conditions (Spongberg & Witter, 2008).

Without an accurate assessment of quantitative data, there is no successful way to evaluate the full scale of the environmental impacts. There can be an infinite number of inputs and outputs. For example, as reflected by the figure in Appendix B, the origins of pharmaceutical products are spatially and temporally shared (Mompelat et al., 2009).

Possible Sinks of Contamination

The fate of pharmaceutical products and by-products in the environment can be unpredictable as it is dependent on product-specific physical and chemical parameters, the origin of the products, disposal path, level of treatment, if any, and other variables. Contamination is also influenced by whether or not the product was used (all or partially metabolized) or unused (disposal of expired and potentially degraded merchandise).

A 2004 study indicated that approximately 80% of the pharmaceuticals that enter treatment plants will likely be discharged to surface waters (Cahill, J.D., et al., 2004, p. 172). More recent studies confirm that pharmaceuticals, personal care products, and byproducts are not fully removed from treated sewage effluents prior to being discharged to surface waters (Daughton & Ruhoy, 2008).

Once introduced into the environment via one of the variable routes of contamination, the options are endless for the fate of the contaminant. The effluent will be diluted in the surface water and the pharmaceutical products and by-products are therefore diluted to trace levels (µg/L to ng/L). The contaminant can be absorbed on suspended solids, or other phases such as colloids or dissolved organic matter. Another possibility is biotic degradation or chemical transformation (Mompelat et al., 2009)

Mompelat, Le Bot, and Thomas (2009) believe that the current literature gives less credit than is due to the roles that photodegradation and biodegradation play in the fate of pharmaceutical products and by products. They believe these mechanisms can potentially create more harmful contaminants. For example…

> The indirect photodegradation enhancement of carbamezepine through interaction with Fe (III) colloids and Cl^- ions has been highlighted in artificial conditions, and one of its direct photodegradation BP (by-product), acridine, has shown toxicity, mutagenicity and carcinogenicity. (Mompelat et al., 2009, p. 809)

Pharmaceutical by-products include metabolites and transformation by-products. Pharmaceutical transformation by-products can form in the environment, with other metabolites, and during the treatment processes. It is still not operationally clear how transformation products differ from the metabolites because the reactions which each undergoes may be remarkably similar through the body, environment, or treatment process. Metabolites are broken down by biochemical reactions, including oxidation, reduction, and hydrolytic cleavages resulting in more polar compounds. The metabolized pharmaceutical products are excreted and discharged into the sewer which is then directed to the wastewater treatment plant (WWTP), or it is discharged directly into a residence's septic system. Both of which are not designed to treat and eliminate these polar organic compounds. The products may then be released

back into the environment via treated wastewater effluent, from overflows at the WWTP during heavy rains, or into the ground water from residential septic systems (Mompelat et al., 2009; Song et al., 2008).

Daughton (2005) explains that little significance lies with whether a chemical is synthetic or naturally occurring in the environment because some microorganisms are capable of synthesizing a vast array of chemicals that would otherwise seem to be foreign. Therefore, we cannot ignore that many chemicals appear from natural and anthropogenic sources.

> Multitudes of chemicals originate both from natural processes and from anthropogenic sources, including synthesis-by-design of new molecular entities and inadvertent formation of byproducts from these syntheses or from the molecule's destruction (incineration is an example). (Daughton, 2005, p.8)

Redefining Persistence

Due to the variability and multitude of processes that emerging pollutants may undergo, most of the scientific community has agreed that they are generally not persistent in the environment. Many of the pharmaceuticals and

personal care products have been found to have a residence time of less than one year; however, this is contradictory to the contamination that persists in the environment.

Traditionally our focus has been on persistent organic pollutants (e.g. chlorinated pesticides, etc.), but many of these are no longer as relevant because developed countries have either banned many of them or established regulatory exposure limits. Today the newer focus is on the pollutants present at low concentrations (<μg/L). This group of compounds does not need to be persistent in the environment because they are continuously introduced. Researchers have observed that their high transformation and removal rates are offset by their continuous replenishment; typically from wastewater sources (Jones, Lester, & Voulvoulis, 2005; Shon, Vigneswaren, & Snyder, 2006).

With the emergence of seemingly new chemicals we are forced to reevaluate the concept of persistence. We can no longer acknowledge a chemical as being persistent due to its ability to avoid degradation and removal mechanisms. Instead we must recognize emerging contaminants as exhibiting "pseudopersistence".

Daughton (2005) explains that environmentally persistent chemicals are those that resist structural

alteration by making and breaking covalent bonds via transformation processes. The continual release of pollutants to open waters by sewage treatment plants and septic systems creates an on-going environmental presence. Even for chemicals with relatively short half-lives (e.g. one year) the degradation processes are offset by constant replenishment (i.e. pseudopersistence) (Daughton, 2005; Daughton & Ruhoy, 2008). This results in a low, but steady-state concentration of these compounds, which represents the balance between inputs and removal processes.

CHAPTER FOUR

FINDING THE "USUAL SUSPECTS"

Looking through the "Universe of Contaminants"

As Daughton (2004) discusses, we have only scratched the surface of the "universe of contaminants" that exist in the environmental pool known as chemical space. Richardson (2007) discusses this point in his literature review on non-regulated water contaminants. He stated that in the group of pharmaceuticals alone, studies to date that have addressed only approximately 150 of them, whereas we know of approximately 3,000 compounds that are in production. This list will have increased in the last two years.

Monitoring

Monitoring in past years has shown that polar organic compounds (POCs), such as many PPCPs have been detected in wastewater, drinking water, and in surface water in trace concentrations (at ng/L-µg/L levels). Söderström, Lindberg, and Fick (2009) evaluated monitoring strategies for emerging water contaminants. Primarily they emphasized the usefulness of polar organic passive samplers, as an alternative to active samplers.

Traditionally, active sampling and biological sampling have been utilized in environmental monitoring. Active sampling is conducted with pumps or by grab methods. The drawbacks to these methods are seen through the detection limits of the analytical method applied and the need to deactivate or preserve samples containing biologically active components (i.e. sewage effluent). In biological sampling, water concentration is estimated based on the known or predicted distribution relationship between biological samples and water samples. Limitations are linked to the mortality of the specimen, complexity of biological matrices, metabolism of the chemicals, variability in species characteristics, and inconsistency in sampling rate (Söderström, Lindberg, & Fick, 2009).

Söderström, Lindberg, and Fick explain that passive samplers were developed with the intent to handle complex biological matrixes with the advantage of collecting *in situ*, complex organic pollutant samples via diffusion, absorption, and/or adsorption. Their standard configuration, which includes a mass transfer rate limiting membrane, presents low variability. "The sampling rate depends on the properties of the target compounds, the sampler design, and the environmental conditions". The

problem with this form of sampling is that the passive samplers require calibration for the uptake of the subject analyte (Söderström, Lindberg, & Fick, 2009).

Their work focused on the "state-of-the-art" integrative passive samplers because they were interested in POCs and PPCPs in water where the environmental conditions are variable. In one sample collection, the integrative passive sampler allows for an estimated time weighted average concentration and, typically, the determination of the bioconcentrated fraction of the target analyte over an extended time. The advantages seen by the use of integrative passive samplers includes costs benefits, more stable samples, improved detection limits, and *in situ* collection for toxicological assessment (Söderström, Lindberg, & Fick, 2009).

Due to the pre-calibration requirements for the integrative passive sampler, environmental conditions effecting sampling rate must be measured and adjusted. These environmental conditions include temperature, bio-fouling, pH, and salinity. Since the sampler measures the dissolved fraction of the analyte and the compounds bound to small particles, increased temperatures leading to increased water solubility will lower partitioning to

particles. Bio-fouling, or algal and microbial growth can interfere with the mass transfer processes on the surface of the membrane. Certain functional groups of the analyte(s) can be ionized or neutralized at different pH levels, thus resulting in variable uptake rates. Lastly, high salinity can decrease water solubility and decrease the uptake of the dissolved fraction (Söderström, Lindberg, & Fick, 2009).

Research has shown the limited usefulness of biological sampling in comparison to the integrative passive sampler. Likewise, the integrative passive sampler is an advantageous alternative to the traditional active sampler. This is based on its simplistic design for the collection of time-integrative samples from one collection, its comparative cost benefits, absence of power supply, and no maintenance requirements. The polar time-integrative sampler also offers source specific detection, which is not practically accomplished from grab sampling. With further development, integrative passive samplers have the potential to overcome calibration issues and therefore gain approval from the scientific community as the standard for water quality monitoring (Söderström, Lindberg, & Fick, 2009).

Current monitoring attempts can easily overlook, omit, or ignore the number of chemicals that are truly representative of an environmental sample, as Daughton (2005) points out. Water monitoring data, based on dissolved concentrations to predict total pollutant loads in water resources, can potentially yield misleadingly low values, since many pollutants have alternative forms or can exist in different phases, such as bound to suspended particulates or sediments (Daughton, 2005).

Development of Analytical and Detection Methods

As introduced in Chapter 1, the data collected in the 2002 National Reconnaissance of Pharmaceuticals study was obtained from using five newly developed analytical methods to measure concentrations of OWCs in water samples. The analytical methods used were developed in independent laboratories; therefore, procedures were adapted for different study objectives. Table 5 provides a summary of the extraction methods and instrumental analyses used in the analytical methods applied in the study. This study was the commencement for detection in the ultra trace concentrations range (0.010-0.100 µg/L) in the environment (Kolpin et al., 2002).

Table 5:

2002 National Effort Analytical Methods

Extraction/Analysis Methods	Acronym
Solid Phase Extraction	SPE
Whole Water Continuous Liquid to Liquid Extraction	CLLE
Liquid Chromatography/ Mass Spectrometry Positive Ion-Electrospray	LC/MS-ESI(+)
Gas Chromatography/Mass Spectrometry	GC/MS
Selected Ion Monitoring	SIM

As it was developed and used in the National Reconnaissance of Pharmaceuticals in the USA, the procedure for the combined solid-phase extraction (SPE) isolation and high-performance liquid chromatograph-electrospray ionization mass spectrometry (LC/MS ESI (+)) analysis was further characterized in a 2004 report. The list of targeted compounds determined by this method included the commonly found gemfibrozil, sulfamethoxazole, and trimethoprim pharmaceuticals. The study concluded that a large data set is necessary for characterizing precision at ambient concentrations and that highly polar compounds and compounds that act as an acid or a base (amphoteric behavior) presented the greatest detection and isolation challenges (Cahill et al., 2004).

The race to find advanced analytical methods, extraction materials, lower detection limits, and qualification criteria has surrounded the investigation of emerging contaminants in drinking water and wastewater. Modern preferred methods typically include MS coupled with GC or high pressure liquid chromatography (HPLC), which are restricted by the nature of the target compounds as well as accessibility to instrumentation (Spongberg & Witter, 2008; Song et al., 2008).

As of 2003, Petrović et al. documented that only a limited amount of research was available that covered the development of analytical procedures for evaluating polar drugs in wastewater. At this time the preferred separation methods included GC and LC, while detection included MS. This GC-MS approach proved time consuming, with extensive laboratory preparation requirements, which presented opportunity for sample contamination and analytical error. As for the pesticides, by 2003, there was an abundance of laboratory documentation on the degradation of these pollutants, but limited documentation is available on studies covering the dynamics of these compounds in wastewater (Petrović et al., 2003).

In 2008 Dr. Snyder of the Southern Nevada Water Authority gave a statement before the Senate Subcommittee on Transportation Safety, Infrastructure Security, and Water Quality regarding the potential risks of pharmaceuticals. During his talk he addressed recent growing concerns related to these "emerging contaminants" in US drinking waters. He pointed out that if their work had been limited to part-per-billion (µg/L) detection capabilities, then none of the pharmaceuticals targeted by the study would have been found; since they existed at part-per-trillion (ng/L) concentrations. He emphasized that…

> The fact that more pharmaceuticals are detected today is not due to greater contamination of our nation's water, but a reflection of the increasingly sensitive analytical technology that allows us to identify and quantify diminishingly minute concentrations of these chemicals in water. (Snyder, 2008, p.1)

Tracking Analytical Development

In a review conducted in 2007, Richardson documented trends in water analysis for POCs. The results are summarized in Table 6.

Table 6

2005-2006 Analytical Trends in Water Analysis for Polar Organic Compounds

Extraction Methods	Modern Chromatography
Increased use of stir bar sorptive extraction	Two-dimensional (2-D) GC
Hollow-fiber membrane microextraction	Hydrophilic interaction liquid chromatography (HILIC)
Passive samplers	Ultra-performance liquid chromatography (UPLC)

In extraction, Richardson (2007) describes that the sorbent coated stir bar allows for the extraction of the desired constituent which is readily desorbed and available for GC/MS analysis. The two-dimensional GC picks up trace contaminants that otherwise would not be found due to its enhanced separation capabilities for sifting through complex mixtures (Richardson, 2007).

Furthermore, Richardson states that Hydrophilic Interaction Liquid Chromatography (HILIC) is a preferred new technique because it provides improved separation for highly polar compounds. Likewise, Ultra-performance Liquid Chromatography (UPLC) is a preferred technique that provides shortened analysis times, narrow LC peaks, and improved chromatographic separation. Additionally, he points out that LC/electrospray ionization (ESI),

atmospheric pressure chemical ionization (APCI)-MS, and multiple reaction monitoring (MRM) with MS/MS have began to dominate methods used for analysis of aqueous samples due to the increased selectivity and sensitivity (Richardson, 2007).

The newer and highly developed analytical methods used in the 2008 National Reconnaissance conducted by the U.S. Geological Survey were given concentrated attention in the past several years. They were revised and adapted to reach research objectives. Each method relies on mass spectrometry and chromatographic retention to provide clear, undisputable identification of a compound. These methods used for the 100 targeted analytes, including 36 pharmaceuticals, were as follows:

- 22 antibiotic compounds were extracted from filtered water samples by SPE and analysis by LC/MS with electro-spray ionization set in positive mode and selected-ion monitoring,
- 3 antibiotics and 16 human prescriptions and non-prescription drugs were extracted from filtered water samples by SPE and analysis by LC/MC using a polar reverse-phase octylsilane (C8) HPLC column,

- 59 compounds were extracted from whole-water samples using CLLE and analyzed by capillary-column GC/MS (Focazio et al., 2008).

Never-ending Detection Limits

With the almost exponential increase in detection capabilities that have been brought about in the past few years, it seems that it is easily forgotten we have come from reading concentrations in the µg/L range to the ng/L range. The advancement seen in instrument technology, especially in the mass spectrometry field, will continue to increase detection capabilities. The more sensitive and versatile the equipment; the lower and lower the limits, and the more precise identification is possible. We now see contaminants in a new light, specifically when it comes to studying transformation processes and determining the effective removal by treatment methods (Richardson, 2007; Gros, Petrović, & Barceló, 2009).

Daughton (2005) warns us that "Lowering the limits of detection challenges our concepts of 'purity,' 'zero,' and 'safe,' which must then be revised".

Recent Trends and Necessary Advancements

In the past decade, many researchers have employed the methods used in the 2002 National Reconnaissance of Pharmaceuticals for identifying emerging contaminants of concern. Many took these methods and applied them with some variations. Bolong et al. (2009) described the problems seen this past decade with detection and analysis of emerging contaminants that are classified as EDCs. Refer to Appendix C for a summary of these points of conflict from Bolong et al. (2009).

Investigations have thoroughly covered experimental methods for analysis of emerging pharmaceuticals, personal care products, and by-products; however there was not a clear consensus on the preferred method. This has only changed recently. Under EPA Method 1694, published in 2007, the guidelines for screening pharmaceuticals call for analysis by SPE followed by LC/MS-MS using triple quadrupole technology (Ferrer, Zweigenbaum, & Thurman, 2010).

Much of the emphasis has been placed on reporting an abundance of data for emerging pollutants, but during the past three years more focus was placed on standardizing these methods of choice to provide the most efficient

presentation of data. Recent analytical trends have moved toward the use of "generic" analytical methods that are capable of analyzing many different classes of compounds (Gros, Petrović, & Barceló, 2009; Quintana et al., 2010; Spongberg & Witter, 2008).

Gros, Petrović, & Barceló (2009) worked at refining analytical methods in order to simultaneously detect and measure a target group of 73 pharmaceuticals of concern. They determined the technique of choice to be liquid chromatography-tandem mass spectrometry (LC-MS/MS) using electrospray ionization (ESI) as the interface between LC and MS. This technique is desired due to its "versatility, specificity, and selectivity". With that in consideration their objective was to develop a multi-residue analytical method based on SPE followed by LC-ESI-MS/MS, while combining different functions of classical triple quadruple scans for the simultaneous analysis of an extended list of trace compounds.

Their method was successfully applied to the analysis of pharmaceutical residues in surface waters and treatment waters. Analytes included atenolol, carbamazepine gemfibrozil, naproxen, sulfamethoxazole, and trimethoprim, among others. This single analytical extraction step

considerably simplified sample preparation, which they recommend for future routine analysis of multi-class pharmaceuticals (Gros, Petrović, & Barceló, 2009).

In 2010, an investigation by Ferrer, Zweigenbaum, and Thurman further evidenced that SPE and LC/MS-MS is the ideal method for quantitative multi-residue analysis of pharmaceuticals in drinking water and wastewater. Seventy pharmaceuticals were analyzed, including the compounds most frequently detected in past investigations (carbamazepine, gemfibrozil, naproxen, sulfamethoxazole, trimethoprim, and others). Under the guidelines of EPA 1694 they refined a methodology by including additions to the MS technique, and by using distinct chromatographic gradients and LC conditions for separate polarity groups within their list of pharmaceuticals (Ferrer, Zweigenbaum, & Thurman, 2010).

CHAPTER FIVE

TREATMENT

Conventional Treatment

Conventional WWTPs provide treatment in four steps: preliminary, primary, secondary, and tertiary advanced treatment. Preliminary or pretreatment typically consists of removal of solids that can be easily collected from raw wastewater. Inorganic solids are collected by screening, removal of settled grit, and sometimes fat and grease skimmers. Primary treatment employs clarifiers or sedimentation tanks for the removal of suspended solids via scraping sludge. Secondary treatment removes organic oxygen-demanding pollutants using aerobic and/or anaerobic biological processes: activated sludge, trickling filter beds, aerated lagoons, membrane ultra filtration, or soil bio-technology. Lastly, tertiary treatment removes remaining organic pollutants through filtration, nutrients by nitrification and denitrification, and final disinfection by chlorination, UV, or ozone. Ion exchange or neutralization may also be used to adjust the pH (Shon, Vigneswaren, & Snyder, 2006; van Loon & Duffy, 2005).

There are numerous studies conducted that continue to validate that conventional treatment methods such as ozone, chlorination, nanofiltration, activated sludge, trickling filter, photodegradation, and granular activated carbon filtration for reducing concentrations of emerging pollutants in wastewater and drinking water sources. However, even with the reduction from these costly technologies, there are still trace amounts of parent material and potentially toxic by-products (Gros, Petrović, & Barceló, 2009; Mompelat et al., 2009; Quintana et al., 2010; Razavi et al., 2009; Song et al., 2008; Stackelberg et al., 2007).

Studies (Bennotti et al., 2009; Quintana et al., 2010) have shown that the treatment processes most responsible for removal of pharmaceuticals and EDCs are oxidation by chlorine or ozone. Chlorine is a strong oxidant, while ozone is an even stronger oxidant; therefore, emerging contaminants detected in finished drinking water may be an indication of whether or not chlorine or ozone was employed.

The more soluble the compound, the more problematic it will be. The traditional treatment regimes are more effective at removal of the solids because the lipophilic

compounds will adsorb onto the solids. Therefore, the more lipophilic compounds present less of a concern to the treatment operators (personal interview, Dr. Armstrong, OCSD, August 19, 2009).

Several drug compounds, such as the anti-epileptic drugs carbamazepine and primidone, and the lipid regulators clofibric acid and gemfibrozil, can attribute their resistance to treatment methods to their physiochemical properties, high solubility, and poor degradation (Jones, Lester, & Voulvoulis, 2005, p. 163). In fact, it is more likely that concentrations of emerging pollutants and by-products will be reduced through phototransformation and partitioning to sediments vs. biodegradation and abiotic processes (Song et al., 2008).

The majority of our WWTPs were not originally designed to address pharmaceuticals and personal care products in trace concentrations. In many cases, the transformation and metabolized by-products are also bypassing treatment. There is a real need to retrofit our existing WWTPs with more stringent technologies, but this may not yet be practical.

The Influence of Effluent Organic Matter

Organic matter originating from WWTP effluents is commonly referred to as effluent organic matter (EfOM). Its removal is often the greatest challenge for wastewater reclamation/reuse. Shon, Vigneswaren, & Snyder (2006) reviewed EfOM removal by a variety of treatment processes and evaluated removal efficiency from several perspectives including the successful removal of endocrine-disrupting chemicals (EDCs), pharmaceuticals and personal care products (PPCPs). Past research has indicated that removal of EDCs and PPCPs from EfOM is quite variable ranging from 35% to 90% (Shon, Vigneswaren, & Snyder, 2006).

The treatment processes investigated included flocculation, adsorption, biofiltration, ion exchange, and advanced oxidative processes (ozone/UV and membrane technology). Shon, Vigneswaren, & Snyder found that reverse osmosis and nanofiltration membrane technologies provided the most abundant removal of the emerging pollutants. Specifically, nanofiltration did not discriminate, removing almost all molecular weight ranges. Results from flocculation, adsorption, and oxidation showed variable trends depending on the individual compound. Table 7 provides the universal performance assessment resulting

from their investigation. They concluded that selection of a treatment method is dependent on the individual compounds and should be based on pollutant-specific sensitive toxicological analysis (Shon, Vigneswaren, & Snyder, 2006).

Table 7

Performance Summary of Water Treatment Methods to Remove Pharmaceuticals and Personal Care Products (PPCPs), and Endocrine Disrupting Chemicals (EDCs)

Modified from: Shon, Vigneswaren, & Snyder (2006)

Group	Chemical Class	Treatment Method Removal Efficiency (%)					
		AC	O_3/AOP	Cl_2/ClO_2	F	NF	RO
PPCPs	Antibiotics	40-90	40-90	<20-90	<20-40	>90	>90
	Anti-depressants	70-100	20-100	<20-70	<20-40	70-100	>90
	Anti-inflammatory	>90	>90	<20-70	<20	70-100	>90
	Sunscreens	70-100	20-100	<20-70	<20-40	70-100	>90
	Antimicrobials	70-100	20-100	<20-70	<20-40	70-100	>90
	Surfactants/ detergents	>90	40-90	<20	<20-40	>90	>90
EDCs	Pesticides	>90	20-100	<20-100	<20	70-90	>90
	Industrial chemicals	>90	40-90	<20	<20-40	>90	>90
	Steroids	>90	>90	>90	<20	70-90	>90
	Metals	70-90	<20	<20	40-90	70-90	>90
	Inorganics	<20-40	<20	<20	<20	70-90	>90
	Organo-metallics	70-100	20-100	<20-40	<20-40	70-100	>90

Note. AC, Activated Carbon; AOP, Advanced Oxidative Processes; O_3, Ozone, Cl_2/ClO_2, Chlorination; F, Flocculation; NF, Nanofiltration; RO, Reverse Osmosis

A Treatment Effluent Study

The data for emerging contaminants detected in wastewater have been highly variable, as influenced by the level of treatment provided and the population receiving service by the treatment plant. In a 2008 study, Spongberg and Witter analyzed the influent and effluent of biosolids from research conducted for three treatment plants as well as from a local stream that received treatment discharges. The results were used to quantify the level of pharmaceuticals and personal care products present after treatment. The treatment plant types and capacity, as described in the study, are summarized as follows:

1. Rural Plant: 100,000 gal/day capacity batch Class B plant serving an agricultural residential population,
2. Suburban Plant: 3-4 million gal/day capacity serving residential and limited industrial sources, and
3. Urban Plant: 5 million gal/day capacity serving a wide variety of industrial sources.

For the collection of influent and effluent samples, traditional grab sampling methods were used. The analytical methods employed included solid phase extraction methods (SPE) and LC-ESI-MS/MS chromatographic analysis. Data from samples taken upstream and downstream of the urban plant's

effluent discharge point facilitated Spongberg and Witter's assessment of the potential for environmental impacts caused by effluent discharges. The study showed that about 80% of the contaminants were detected upstream of the effluent discharge point, with 50% of the contaminants yielding higher concentrations 5 meters downstream. The majority of the contaminants had significant drops in concentration by 50 meters downstream, with the exception of a handful that showed elevated concentrations (Spongberg & Witter, 2008).

Effluent from the urban plant showed that caffeine (stimulant), gemfibrozil (lipid regulator), and salicylic acid (skin care product) concentrations decreased by an order of magnitude or more. While antibiotics, including carbamazepine (antiepileptic), clindamycin (antibiotic), diclofenac (analgesic), and sulfamethoxazole (antibiotic), showed elevated effluent levels compared to influent levels, suggesting enrichment during the treatment process. Carbamazepine and clindamycin were detected in every influent, effluent, and biosolid sample collected from the urban plant for the three sampling dates. This suggests that the compounds were not affected by the treatment. On the other hand, cotinine (nicotine metabolite) was detected

in the influent, but not present in the biosolids or effluent, suggesting successful removal.

Effluent from the rural plant yielded approximately double the concentration of cotinine and caffeine in comparison to the urban plant. While the comparison showed that carbamazepine, ciprofloxin (antibiotic), salicylic acid, and sulfamethoxazole (antibiotic) were unique to the urban effluent. Diclofenac yielded similar effluent concentrations to that of the urban effluent.

The suburban plant generated much higher biosolid content than that of the urban plant. Biosolid concentrations from the suburban plant for salicylic acid and ciprofloxin were half or less of that of the urban plant, while carbamazepine and gemfibrozil were higher in the suburban biosolid content. The comparison yielded that tetracycline (antibiotic) was unique to the suburban plant, and clarithromycin (antiobiotic) was unique to the urban plant.

With such varying results, it is complicated to draw conclusions. Overall, the study provides an indication that the wastewater treatment plants are not effective at reducing the selected contaminants based on the detection of the effluents and biosolids, and their overall

persistence in surface water. Rather, Spongberg and Witter suggest that these plants can introduce and amplify the concentration of the contaminants. In addition, differences in seasonal effluent and influent concentrations from WWTPs should be monitored. Spongberg and Witter concluded that the short term temporal variability within a single treatment plant, the variability of concentration and occurrence between plants, and the variability in populations served by the plants suggests that additional study is needed to understand the potential environmental release of contaminants after treatment (Spongberg & Witter, 2008).

Advanced Treatment Processes

To progressively assist in evaluating the removal of emerging contaminants by modern treatment methods, a 2009 study by Bolong et al. assessed the effectiveness of the available WWTP technologies to remove unregulated EDCs. They found that physiochemical treatment (coagulation-flocculation) was unsuccessful in the removal of EDCs and PPCPs. Biological removal (activated sludge) was limited to removing the polar contaminants. Oxidation methods like chlorination or ozone, although promising in terms of the

degradation of EDCs and PPCPs, presented the risk of introducing reactive and uncharacterized by-products. In advanced treatments, ultra-violet (UV) photolysis and ion-exchange showed successful removal of 50-80% of the contaminants. However, this level of efficiency was dependent on the technique being applied at a hundred times that of typical disinfection (Bolong et al., 2009).

Membrane Filtration

Membrane filtration, another advanced treatment method, presents a constructive alternative to traditional chemical applications and methods that require concentrating refuse for reuse/recycling purposes. Typical membrane filtration technology includes reverse osmosis (RO) and nanofiltration (NF) methods. However, Bolong et al. (2009) explained that although RO provides almost 100% removal, it is less desirable than NF in the treatment industry, due to its high energy costs. Therefore, their work evaluates the removal mechanisms of NF, and encourages its use.

According to Bolong et al. (2009), the effectiveness of NF technology is variable depending on the target EDC compound and that means it is important to understand the dominant removal mechanisms (i.e. absorption, size

exclusion, and charge repulsion) and the target compound's parameters in order to optimize removal efficiency. Their research showed that the initial hydrophobic interactions on the membranes present the highest effective absorption, which decreases as saturation takes over. After saturation, molecular size and steric exclusion play the largest role in rejection through the "sieving" process, and molecular size can increase from the creation of hydrogen bonds when hydrophilic molecules have the opportunity to hydrate. The membranes also have electrostatic interaction which allow for the removal of ionic compounds and compounds with lower molecular weight. Thus, all parameters must be considered when determining the appropriate retention for EDCs removal (Bolong et al., 2009).

Advanced Oxidation/Reduction Processes (AO/RPs)

In 2008 Song et al., highlight that an alternative to conventional treatment may be advanced oxidation/reduction processes (AO/RPs). AO/RPs use free radical reactions to directly degrade chemicals. Hydroxyl radicals in photosensitized oxidation play a key role during environmental degradation. The study's objective was to determine the absolute rate constants for the reaction of the hydroxyl radical and hydrated electron for a set of β-

blocker pharmaceutical compounds; cardiovascular drugs used to treat disorders such as hypertension, angina, and arrhythmias. The study provided an initial evaluation of AO/RPs efficiency, showing that both oxidative and reductive processes could be used to remove the targeted compounds. However, they emphasized that future kinetic modeling would be necessary to fully evaluate the intermediates formed during the reactions (Song et al., 2008).

In their research, Razavi et al. (2009) found that biological treatment processes (ie. activated sludge or trickling filter) are not efficiently removing pharmaceuticals and by-products, while nanofiltration and reverse osmosis processes appear to be effective alternatives for this group of contaminants. However, similarly to the previous investigations they found that in both nanofiltration and reverse osmosis, bio-fouling of membrane elements and energy consumption of the processes are treatment setbacks. To continue the work by Song et al. (2008) they investigated AO/RPs degradation mechanisms as the alternative.

In order to evaluate the removal of the pharmaceutical contaminants in natural waters, they established kinetic

measurements by finding the bimolecular reaction rate constants for the hydroxyl radical and hydrated electron with the pharmaceuticals. They found that the reaction with the hydroxyl radical provided transient absorption spectra and that the major reaction pathway appeared to be the reactions of hydroxyl radicals with the compound's aromatic rings. They found that…

> The bimolecular reaction rate constants for reaction of the fibrate pharmaceuticals (clofibric acid, bezafibrate, and gemfibrozil) with the hydroxyl radical were determined using the change in the rate of the appearance of the transient maximum wavelength at various concentrations of the starting material. (Razavi et al., 2009, p. 1290)

Razavi et al. found that due to the chemical stability of these compounds in the environment that it is possible for them to be present in drinking water sources. They concluded that AO/RP technologies would be an effective alternative for the treatment and removal of these compounds. Specifically, the electron beam process produced both hydroxyl radical and hydrated electrons, presenting an advantage over those methods that produce only the hydroxyl radical. In the electron beam process the application of an

intense stream of electrons facilitated the complete reaction of the solvated electron (free in solution) with oxygen (at saturation) yielding an efficient reduction reaction. The combined hydroxyl radical and hydrated electron reactions with the target compounds yielded 62-98% removal efficiency (Razavi et al., 2009).

Rosario-Ortiz, Wert, and Synder (2010) further confirm that beyond the overall concentration of EfOM in wastewater, that the reactivity of the EfOM has a major influence on the removal rates of pharmaceuticals. Using advanced oxidation treatment via low pressure UV light, coupled with hydrogen peroxide (UV/H2O2), they found highly variable removal (0% to >90%). They explain that alkalinity, nitrite, and specifically effluent organic matter affect the reactivity towards the hydroxyl radical (HO·), thus affecting the removal rates.

During a discussion of his research on advanced oxidation/reduction processes, Dr. William Cooper of the Urban Water Research Center at the University of California in Irvine (UCI) addressed the following questions:

- Do you think that the advanced oxidation/reduction processes could be a method that is easily retrofitted into our conventional treatment regime?
- Are we a long way from this because a full kinetic model is still needed, and dissolved natural organic matter (NOM) and hydroxyl radical "scavengers" may also present other issues?

He replied that "In water reuse, these processes (UV and hydrogen peroxide) are already used in Orange County". In terms of the scavengers he stated that…

> We don't know what would be the biological activity of the by-products. In general when we degrade these compounds they become more degradable thereafter. We don't know what toxicological data should be used. We do not know what this (toxicological data) would be for breakdown products. (personal interview, August 18, 2009)

CHAPTER SIX

TOXICOLOGICAL AND ECOLOGICAL IMPACTS

Toxicological Evidence

Fate and Exposure

Water is essential for life. The purity and abundance of our drinking water supply will never cease to be a priority. Consumers will have heightened awareness of water quality concerns for this resource. It is a direct route for potential pollutant exposure. But beyond ingestion, we are also faced with indirect pathways, including bathing (absorption and inhalation), crop irrigation (ingestion), and agricultural uses for amended sewer-sludge (ingestion and up-take by crops).

In a 2006 study, Zukowska, Breivik, & Wania presented a modeling approach for predicting the fate and distribution of pharmaceuticals in the environment to be used for future monitoring. The modeling approach is based on the use of poly-parameter linear free energy relationships (PP-LFERs) to express environmental phase partitioning of POCs, namely pharmaceuticals.

PP-LFER was developed by Breivik and Wania (2003) in response to the use of the traditional single-parameter

linear free energy relationships (SP-LFERs) method for organics, which was not designed to address the partitioning characteristics of pharmaceuticals. Traditional LFER are…

> an empirical correlation between the standard free energies of reaction (ΔFo) or activation (ΔF≠) for two series of reactions, both subjected to the same variations in reactant structures or reaction conditions. (Lyman, W. J., 1990, p.6.6)

It focuses on a single type of media at a time. For their investigation the media were wastewater and drinking water. Therefore, LFER would be used to estimate the rate of hydrolysis of the POCs. However, since the behavior of trace pharmaceuticals is unknown territory a multidimensional approach was applied (Zukowska, Breivik, & Wania, 2006).

Zukowska, Breivik, & Wania suggest that PP-LFER provides a better approach for environmental distribution modeling since it employs five linear free energy relationships for concentrations and media fluxes across air, water, soil, and sediment. Data on air to water partitioning was hard to obtain since pharmaceuticals are basically non-volatile. To address this dilemma Zukowska,

Breivik, & Wania employed the octanol-water partition coefficient, as per the approach by Breivik and Wania (2003), with the assumption that organic matter of atmospheric particles would exhibit the same behavior. As previously mentioned in the discussion of contamination, the final results of the modeling suggested that pharmaceuticals have a high affinity to remain in water (80%) with the rest presiding in soils. They concluded that PP-LFER based modeling supports the concept that "the smaller the molecule and the higher its hydrogen basicity (hydrogen bond basicity), the higher its environmental mobility is likely to be" (Zukowska, B., Breivik, K., & Wania, F., 2006). Zukowska, Breivik, & Wania demonstrated that accurate quantitative data for the environmental half-lives of pharmaceuticals in water is key to predicting environmental fate, and that the PP-LFER based modeling can be useful in fate determination as part of future environmental risk assessment.

Following his lead involvement in the investigation of pharmaceuticals in U.S. drinking waters, Snyder (2008) prepared a statement to help put exposure concerns into perspective. He instructed that the therapeutic doses have been found to be a magnitude of 5,000,000 times greater

than the highest concentration of a given pharmaceutical detected in the U.S. drinking waters.

He illustrated this point in an example explaining that, "This concentration is roughly equivalent to ½ of an inch in the distance between the earth and the moon, or in terms of time, this concentration would be equivalent to approximately one second in approximately 750 years". Furthermore he stated that…

> Based upon our four-year study of the health relevance of trace pharmaceuticals, using the highest concentrations found and the most conservative safety factors to protect susceptible populations such as infants and pregnant women, our report will demonstrate that one could safely consume more than 50,000 eight-ounce glasses of this water per day without any health effects. (Snyder, 2008, p. 2)

But having said this, he encouraged that further investigation would be beneficial and researchers should not be discouraged from future study.

Risk Assessment

With the great need for risk assessment data covering emerging contaminants, comes the need to standardize exposure and effects research. In regard to the improved

detection capabilities developing through modern analytical chemistry, Daughton (2005) explains that, "It becomes increasingly difficult to assess risk and to design regulatory programs for new and moving targets". He points out that we need to discover a more "holistic view" of risk, since target-based monitoring limits us to a narrowed view of occurrence. Thus we are left with data that purposefully neglects what may be a significant portion of unidentified contaminants.

Hansen (2007) breaks down the approach to risk management for evaluating emerging contaminants in aquatic systems. He stresses that new methods are needed, and the optimization of existing methods is necessary for assessment of emerging water contaminants. The purpose of his investigation was to improve the understanding of environmental threats as it relates to human health through characterization of effects and exposure (Hansen, 2007).

Hansen summarized the strategies and applications of environmental risk assessment for the sustainable development of surface water, soil, and human health protection. The following figures, as modified from Hansen (2007), provide this information. Figure 1 summarizes the strategies of exposure assessment and Figure 2 summarizes

the strategies of effects assessment. For Figure 1, Hansen states that parameters of interest include compound properties, route of exposure, formulation, biotransformation, metabolites, degradation kinetics, and bioavailability (Hansen, 2007).

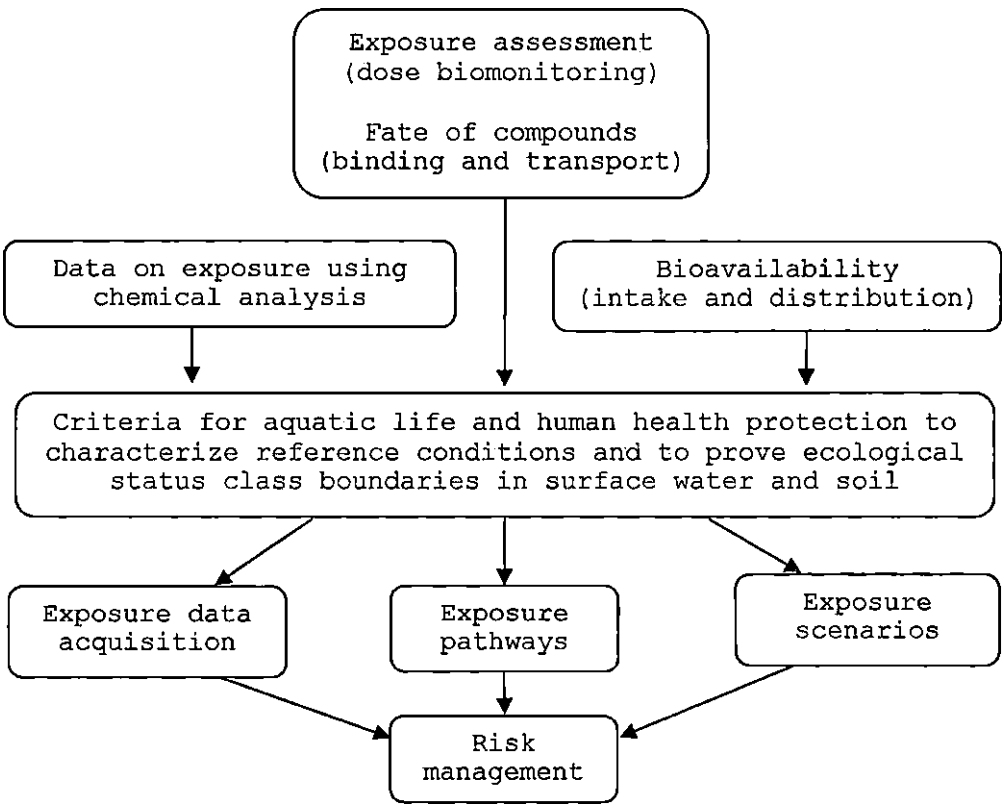


Figure 1

Exposure Assessment – Strategy on Environmental Risk Assessment for Water, Soil, and Human Health Protection

Reprinted from Risk Assessment of Emerging Contaminants in Aquatic Systems, Vol 26, Hansen, P., Trends in Analytical Chemistry, pp. 1096-1097, Copyright 2007, with permission from Elsevier.

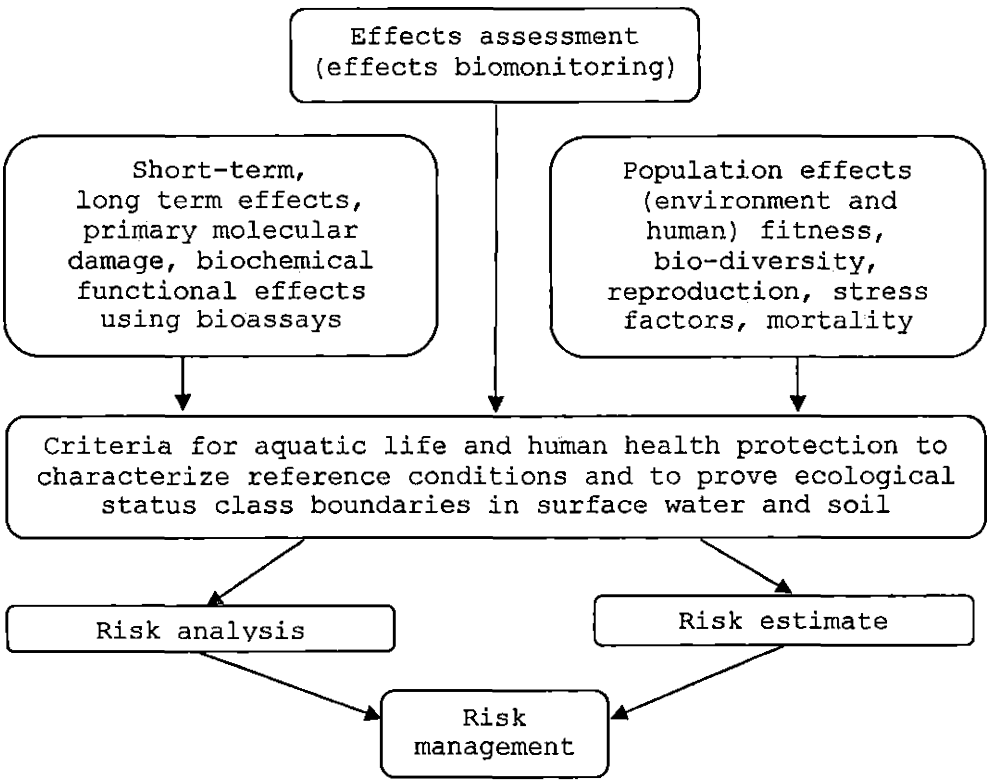


Figure 2

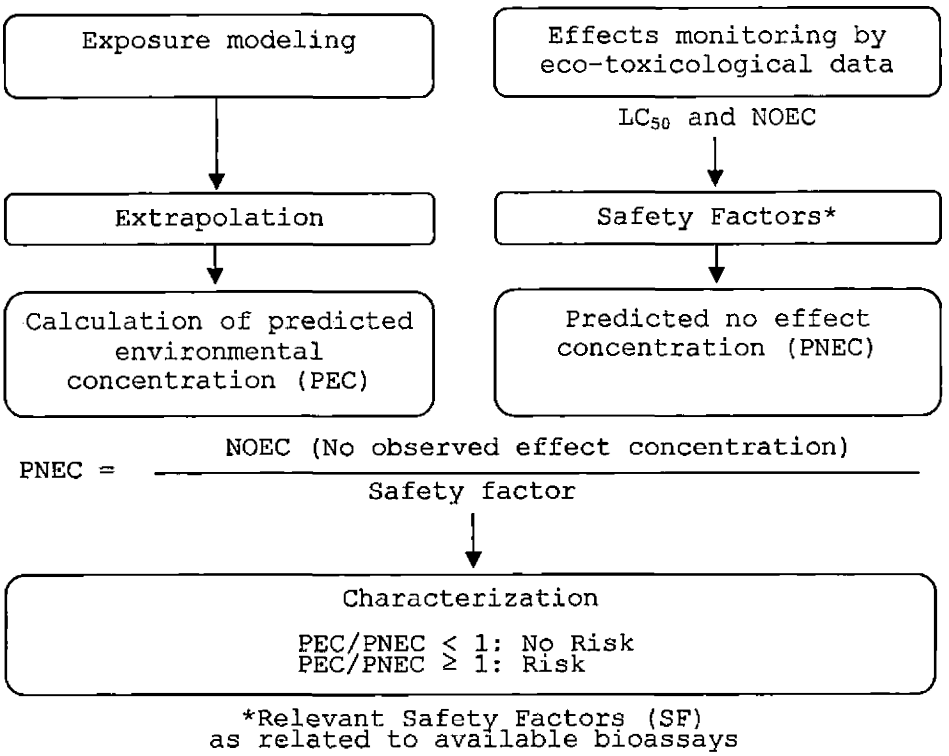
Effects Assessment - Strategy on Environmental Risk Assessment for Water, Soil, and Human Health Protection

Reprinted from Risk Assessment of Emerging Contaminants in Aquatic Systems, Vol 26, Hansen, P., Trends in Analytical Chemistry, pp. 1096-1097, Copyright 2007, with permission from Elsevier.

For Figure 2, Hansen states that the baseline data can be generated from "biomarkers", including traditional bioassays, bioaccumulation assays, and/or reproduction toxicology, with the end points of the biomarkers expressed in terms of acute or chronic toxicity (Hansen, 2007).

For risk characterization involving exposure and effects, Hansen points us to a schematic for monitoring and evaluation of a single substance. The schematic is summarized in Figure 3, as modified from Hansen (2007), p. 1096 Figure 1 and p. 1097 Table 3. Hansen explains that in order to verify the relevance of the characterization, as related to aquatic systems, safety factors must be used to reflect the trophic levels available through acute and chronic bioassays. These safety factors are shown below.

Through his investigation, Hansen concludes that bioassays and bio-analytical systems serve as an early warning for identifying unknown substances and that exposure and effects assessment are the key to evaluating ecological impact. However, he further explains that in order to sustainably protect the aquatic systems and human health, a comprehensive strategy is needed to characterize conditions through effective monitoring methods. It will be important to develop environmental quality standards to adequately serve as management tools in this endeavor (Hansen, 2007).



Assay	Trophic	SF
1 acute assay	1	1000
1 long term, chronic assay	1	100
2 long term, chronic assay	2	50
3 long term, chronic assay	3	10

Note. LC_{50}, Lethal Concentration of 50% of the population; NOEC, No Observed Effect Concentration

Figure 3

Risk Characterization - Involving Exposure and Effects, and Predicted by Environmental Concentrations from No Effect Concentrations and Safety Factors from Available Bioassays

Modified from: Hansen (2007)

As we are presented with an ever expanding list of contaminants, facilitated by the developing detection technologies, we are faced with the dilemma of determining what the detected concentration means to human and environmental health. Specifically, the on-looking public wants to know how they are potentially affected. Schriks et al. (2010) attempted to derive provisional drinking water guideline values for a selection of 50 "emerging" pollutants. Though the intention was good, their list of pollutants only included 5 pharmaceuticals and only 2 of these have been noted in past investigations as commonly reoccurring. They did not consider degradation by-products, nor did they consider finished drinking water from different treatment technologies by region (Schriks et al., 2010; Schirmer, Martienssen, & Schirmer, 2010).

As of 2010, the science community has only begun to scratch the surface on the toxicological exploration of "emerging" pollutants. One of the first reports of interspecies ecotoxicity correlation to determine the sensitivity of wildlife to 77 pharmaceuticals was conducted for *Daphnia magna* (zooplankton) and fish. They successfully identified key structural groups and fragments that were responsible for the toxicity. Prediction models were

developed to aid future risk assessment efforts (Kar & Roy, 2010).

Similarly another environmental risk assessment was conducted in Spain. For three bioassays commonly used in risk assessment (fish, *Daphnia*, and algae), Ginebreda et al. (2010) estimated hazard quotient indexes for the most frequently detected river pollutants from a list of 29 pharmaceuticals by using the ratio between sample concentration and EC_{50} (effect concentration for 50% of the population) reported values. They found that quotients increased when going downstream; however, they recommend that the results be "tentatively", not conclusively interpreted as cause-effect. Their work yielded some outlier correlations which they attributed to previously reported river pollutants from nearby industry. With so many influential variables, we need to continue toxicity exploration so that we may use the new data to extrapolate human toxicity prediction models for pollutants of interest, and determine if additional regulatory involvement will be necessary.

Ecological/Biological Evidence

Under real-life conditions, organisms are not exposed to an individual chemical at any given time in the environment. They are never strictly isolated to allow for such a scenario. Therefore, in order to develop a "holistic view" of risk, assessment models must take into account that in aquatic systems the organisms have constant interaction with a myriad of chemicals and associated by-products. The composition of which can break apart, reform, and/or transform, contributing to their "pseudo-persistence". Additionally, Daughton explains that…

> Completely different types of biological effects can occur at different exposure concentrations. Such a multitude of variables and possible interactions pose complex challenges for predicting the trajectory of exposure outcomes for an organism. (Daughton, 2005, p. 15)

The Orange County Sanitation District (OCSD) works in collaboration with the University of California in Riverside, California, and California State University in Long Beach, California, to look for the presence and absence of environmental effects on aquatic species populations. Until recently they have not been looking at

specific compounds, rather endocrine disruption in wild flat fish populations (i.e. English sole and Hornyhead Turbot) in general. As of late, they are now starting to evaluate target classes of compounds. In the aquatic biosphere they see that the two most critical points, more so than the concentration, are the duration of exposure and the life stage of exposure (personal interview, Dr. Armstrong, OCSD, August 19, 2009).

Other Consequences

Synergistic Effects

"Drugs are designed to be biologically active, and it is possible that unintended effects on non-target organisms and/or receptors occur at lower concentrations than the intended therapeutic effects" (Jones, Lester, & Voulvoulis, 2005, p. 165). The human health effects of the mixture of emerging contaminants in our drinking water supply are unknown. Specifically the collective pool of trace concentrations of endocrine disruptors may present synergistic effects. Health risk assessments should focus on chronic exposure to mixtures of sub-therapeutic concentrations of pharmaceuticals and personal care products. Exposure at these concentrations (ppb and ppt)

may have little to no effect on healthy adults, but drinking water is a necessity for all. The young, elderly, and pregnant may reap the consequences of continuous exposure to trace amounts of chemicals. That is why toxicological data is needed from population assessment. The effects on those in vulnerable developmental stages or those with weakened or suppressed immune systems are unknown, and they have a more limited ability to eliminate toxic substances.

During personal correspondence Dr. Jeff Armstrong, Senior Scientist for the Orange County Sanitation District (OCSD), Social Monitoring Program, stated…

> Just because you can measure something in drinking water, does not necessarily mean it is of concern. However, there are other factors to consider such as the synergistic (antagonistic) effects. Or do they cancel out? You have to look at these contaminants as a complex mixture... that is really how the water gets muddied. Individually they may do nothing, but together they may be devastating. Even the traditional chronic exposure toxicity tests are not enough. We need life cycle assessments; the mechanisms behind the driving forces, not just the concentrations. There are

> people that do not want this found. We do not know what the proper end points are. How do you regulate something that you really do not know how to measure? (personal interview, August 19, 2009)

Bacteria Resistance

The development of antibiotic resistant pathogens is another area of concern. If these compounds, which have been manufactured to kill bacteria, are easily integrated into our water supply, then there is a fear that bacteria will build a resistance (Le-Minh, Drewes, & Stuetz, 2010). In Germany a study showed antibiotic resistance genes in drinking water bacteria from inoculated biofilms (Schwartz, et al., 2002).

Daughton and Ruhoy (2008) present the perspective that the minute concentrations of antibacterial residues introduced to the water system are probably not significant enough to promote bacterial resistance. However, the transient concentrations from unwanted/unused pharmaceuticals could promote resistance within the sludge of the sewer lines. Transient concentrations are the intermediate chemical forms resulting from transformation processes in the environment. Daughton and Ruhoy expect that transient concentrations from unwanted/unused

pharmaceutical disposal will be present in higher concentrations in the sewers than those from metabolized products that are excreted or washed off during human or domestic animal use.

Limits of Evidence

Dr. Daniel Schlenk, Professor of Aquatic Ecotoxicology at the University of California in Riverside (UCR), acknowledges that there have been great advances in analytical chemistry. But he advises that we need to focus on using an exposure based risk assessment to determine which compounds will be present longer, which can be taken up by animals, which will be eliminated through biological processes, and which will accumulate. Risk assessment is needed to look at the individual compounds, narrowing the focus to those that present toxic effects at low concentration and those present in high or consistent abundance (personal interview, September 10, 2009).

Dr. Schlenk also warns that if these emerging contaminants are a direct concern, then we should be seeing fish kills everywhere and populations crashing. According to Dr. Schlenk…

> Population comes into play in observation of sub-lethal effects. The EPA will be looking for growth, survival, and reproduction. Survival is an acute effect, and growth is just a measurement. Are we influencing these parameters? (personal interview, September 10, 2009)

Other researchers have warned us that in order to understand the effects we must fully understand the occurrence of the emerging contaminants.

> The degree to which this issue has drawn interest across disciplines is illustrated by the voices of concern stemming from medical professionals, environmental scientists, drinking water municipalities, government agencies, and the general media. However, if risk assessors and epidemiologists are to link any potential health outcomes with pharmaceutical and EDC exposure, a better understanding of their occurrence in drinking water is critical. (Bennotti et al., 2009, p. 597)

Richard (2007) presents the latest trends in research involving the review of the effectiveness of chlorination and ozone treatments of PPCPs, which have shown that they are not entirely broken down, but rather they are

transformed. This raises concern regarding the toxicity, "pseudo-persistence", and fate of the altered compounds. As in most cases it is unknown if they will be more detrimental than the parent material.

Likewise, Dr. Cooper of UCI provided insight of our current shortcomings on evaluating the growing list of emerging contaminants in chemical space.

> We know that pharmaceuticals have a metabolic effect, but we don't know what the biological effect is of this potpourri of compounds. We don't know what the effect is on developing fetuses and small children. (personal interview, August 18, 2009)

Dr. Robert Phalen, a Certified Industrial Hygienist and an Assistant Professor of Health Science and Human Ecology at the California State University in San Bernardino (CSUSB), stated…

> The U.S. EPA and the scientific community should continue to investigate, evaluate, and conduct risk assessments on new and emerging contaminants. If a new contaminant was found to pose a significant threat to human health then control measures and alternatives should be evaluated. (personal email correspondence, August 3, 2010)

It is not realistic to develop a risk assessment for every individual medication, personal care product, pesticide, and other emerging contaminants. A prioritization scheme needs to be developed for these groups of substances that require further study (Jones, Lester, & Voulvoulis, 2005).

CHAPTER SEVEN

REGULATORY INTEREST

Evaluating the Need for Regulatory Involvement

PPCPs and EDCs of interest, such as those included in Table 4, have been detected in finished drinking waters at levels far below the U.S. EPA's typical MCL concentrations (Bennotti et al., 2009). Also they have not been routinely monitored in on-going monitoring programs, even though they have been commonly identified as today's emerging pollutants (Shon, Vigneswaren, & Snyder, 2006; Söderström, Lindberg, & Fick, 2008). Daughton (2004) describes that no one really knows how many compounds we are talking about at these concentrations. The regulatory community can not avoid the obvious fact that "the industrial and technological breakthroughs have outpaced the regulatory practices" (Bolong et al., 2009). So the question becomes: how are the government agencies and water authorities involved in investigating and potentially regulating these emerging pollutants that are being detected at ultra trace levels?

Current Drinking Water Standards

Snyder (2008) suggests that under the Safe Drinking Water Act there are established processes for identifying and regulating drinking water contaminants to protect human health. The Safe Drinking Water Act and associated Amendments require that the U.S. EPA identify a list of no more than twenty-five (25) unregulated contaminants to be monitored, using five different analytical methods. This list is updated at least once every five years. This list is available for review under the EPA's home page for the Unregulated Contaminant Monitoring Rule (UCMR) found at http://water.epa.gov/scitech/datait/databases/drink/ucmr/basicinformation.cfm.

According to the EPA's UCMR, public water supply agencies are required to monitor select unregulated contaminants in our finished (treated) drinking water. Historically these lists have not included organic wastewater contaminants (OWCs), including pharmaceuticals, due to the lack of occurrence data on a national scale, which would be necessary to support the decisions of policy makers and regulators (Focazio et al., 2008).

As part of this program the Second Unregulated Contaminants Monitoring Rule or UCMR-2 was proposed on

August 22, 2005, superseding the original rule issued in 1999. It requires that drinking water utilities monitor for 26 chemicals over a 12-month period in 2007-2011. The evolution in detection methods is anticipated to present insightful data from this monitoring effort (Richardson, 2007).

The EPA's Contaminant Candidate List (CCL) is used to inform us of the new candidates identified as needing drinking water standards. In compliance with the requirements of the Safe Drinking Water Act, periodically the EPA must decide to regulate at minimum five of the contaminants included on the list. Historically three CCLs have been published, and contaminants selected for regulatory determinations have predominately included metals, pesticides, some microbial contaminants, and other agricultural and industrial related contaminants. The current CCL list, CCL3, (2009) can be viewed online at the EPA's homepage for CCL and Regulatory Determination. This list does not include the frequently detected emerging pollutants shown in Table 4.

While there are no maximum exposure levels (MELs) established in the U.S. for emerging contaminants that are specifically classified as EDCs, the European Commission

has been more aggressive in developing strategies to address these environmental pollutants. Unfortunately the regulatory practices that originate close to home (U.S.) are lackluster and show little progressive coordination. The extent of current regulatory progress has been limited to reliance on the ecological testing of the Food and Drug Administration (FDA), and the U.S. EPA's screening of the potential EDCs resulting from manufacturing and processing that may contaminate water or food supply. There has been no criterion established for water and wastewater sources (Bolong et al., 2009).

There has been a lot of buzz regarding how the U.S. regulators should or should not be involved in tackling emerging pollutants of concern that exist in trace concentrations. Researchers have expressed concern that…

> …'emerging' or 'new' unregulated contaminants have become an environmental problem, and there is widespread consensus that this kind of contamination may eventually require legislative intervention. (Petrović, Gonzalez, & Barceló, 2003, p. 685)

Disconnection

Some argue that there is no disconnect between the regulatory community and the science community in terms of

developing standard disinfection procedures. Rather, the regulatory community is a political box that unfortunately is subject to a lot of pressure from lobbying groups (personal interview, Dr. Armstrong, OCSD, August 19, 2009).

In personal correspondence Dr. Jeff Armstrong, OCSD, shared his experience of being on a national committee reviewing the newly emerging contaminants.

> There were 25 of us on the committee and most of them were from the pharmaceutical companies. We spent most of the time trying to determine what to call these constituents. My group said to call them what they are; 'contaminants of concern', but the pharmaceutical companies are concerned about turning people off of their products and would not accept the term. (personal interview, Dr. Armstrong, OCSD, August 19, 2009)

This does not demonstrate disconnect between the science community and regulators. This is an example of the regulators trying to seek balance between the business community and the science community; however, the business community has great influence and is applying pressure in order to avoid losing business.

When asked about the relationship between the science community and the regulatory agencies, Dr. Cooper responded that…

> It's really important that there is no fundamental disconnect between the Universities, EPA, NIA (National Institute on Aging; Biology of Aging Gordon Research Conferences). The agencies look to the universities for these determinations. This will become stronger in the next couple of years. It comes as a result of us doing a good job. For example, people's life expectancies have improved because we have made past determinations. (personal interview, August 18, 2009)

Updating the Environmental Protection Agency's List of Drinking Water Contaminants

When asked if the EPA's list should include these emerging contaminants, Dr. Cooper stated…

> Their hands are tied, they cannot regulate unless we know that there is an associated health effect. What is the occurrence? How do we look at health effects data? Then we can start regulating. It will be 15 years before we have them in the list because there is so little information available… not only regarding

the parents, but also the byproducts… (personal interview, August 18, 2009)

When asked the same question Dr. Schlenk of UCR, replied that…

> The real issue is that most of the data is acute testing; low duration types of exposure. We need the long term low dose exposures. We also have to consider differences in waterways; some are more readily exposed to waste streams. (personal interview, September 10, 2009)

He described pseudopersistence, which is not persistence in nature, but rather persistence in the environment as a result of being continuously released, and therefore continuously present throughout an animal's life stage.

Dr. Phalen of CSUSB responded to the issue by explaining that,

> … The decision to establish or revise a drinking water standard should be based on sound scientific evidence of toxicity near the human exposure concentrations, available water treatment options, and the potential consequences of treatment. The mere existence of a potential hazard or the concentration should never be

the focus for setting a standard… (personal email correspondence, August 3, 2010)

He explained that the EPA's focus should be on determining if a contaminant poses a significant hazard at the current or future environmental concentrations. They must consider if the benefits of the compound outweigh the potential consequences by determining reasonably safe exposure concentrations. They must also weigh our ability to control it through cost effective applications while at the same time reduce human health risk. When we find a potentially harmful compound we need to research safer alternatives that have comparable benefits.

Pharmecovigilance

Daughton and Ruhoy (2008) elaborate on the role of "pharmecovigilance"; a term used to link the prevention of both human and ecological consequences of pharmaceutical pollutants. They proposed that the responsibility lies with the prescribers, patients, and health care industry. They recommend embracing pharmecovigilance programs not only to reduce the environmental footprint of healthcare, but also to take advantage of the opportunity to optimize the delivery, effectiveness, and cost of healthcare, while at

the same time protect human and ecological health. They want intricate pharmecovigilance programs to promote the assignment of effective prescriptive dosages, by dispensing quantities in a conservative manner over a duration with which patients will comply, thus minimizing leftover medications.

Disposal Management

In 2007 the White House Office of National Drug Control Policy introduced standard guidance for consumer disposal of unused drugs (Daughton & Ruhoy, 2008).

In a 2009 study Glassmeyer et. al explore the current practices for the disposal of residential medications in the U.S. They found that in order to acquire an effective approach to environmental stewardship that it is absolutely necessary to establish cooperation between the healthcare community and patients. Medications would need to be consumed at optimal amounts to avoid leftovers and lower disposed quantities of unwanted products.

Patients are faced with the decision of how to dispose of unwanted pharmaceuticals. While there are national efforts through state and local collection programs, the seriousness of improper disposal is not fully realized by

the public. One of the primary challenges is that there are guidelines for the public, but no federal requirements. One could argue that the challenge is that there are too many hands in the pot. The USEPA is responsible for protecting human health and the environment from chemical exposure. This led to the Resource Conservation and Recovery Act (RCRA), the Clean Water Act, and the Safe Drinking Water Act. The FDA (Food and Drug Administration) is responsible for ensuring the safety and security of human and veterinary drugs through the federal Food, Drug and Cosmetic Act and the Prescription Drug Marketing Act. The DEA (Drug Enforcement Administration) enforces the controlled substances laws and regulations to prevent improper use of substances (Glassmeyer et. al, 2009).

This long list of governmental agencies has jurisdiction over pharmaceuticals in one regard or another. Some of these agencies delegate authority to the states. The states then have the ability to enforce more stringent policy. But, overall we see that household pharmaceutical disposal falls into exemptions at the federal level through the RCRA, which does not require proper hazardous waste management for residences. This presents a grey area to the public. Unless state or local policy requires some form of

environmental stewardship, the rest of the country is free to throw and flush the excess away at their discretion. This pseudo commitment to implement/encourage proper disposal methods can be frustrating to the public, both to those who do not fully understand the environmental repercussions and to those who do understand the importance of environmental stewardship.

Recycled Water

The California State Water Resources Control Board (SWRCB) has currently developed a draft report serving to guide the State in pursuing a comprehensive way of addressing emerging contaminants in recycled water, titled "Monitoring Strategies of Chemicals of Emerging Concern (CECs) in Recycled Water". Their strategies are based on the USEPA's Candidate Contaminant list 3 (CCL3) selection process for identifying compounds in the environment that pose a potential treat to recycled water quality and are not currently regulated. Their focus is primarily on what the SWRCB panel considers "unknown, unknowns", "known, knowns", and "unknown, knowns". The "unknown, unknowns" are the compounds in recycled water that have not yet been identified and are currently without analytical methods

available for their detection. The "known, knowns" are compounds that have previously been identified in recycled water, which have established analytical methods for their detection, and data for their measured environmental concentrations (MECs). The "unknown, knowns" include transformation products that have been identified in recycled water, but that do not have established analytical methods for their detection (Anderson et al., 2010).

There is a good amount of baseline monitoring data available for CECs in recycled water. The CA SWRCB wants to push the effort forward by providing comprehensive recommendations for ways to improve future monitoring and the gathering of toxicological information for determining which CECs pose the most significant threat to human and environmental health. These recommendations include further development of analytical methods, development of bio-analytical screening techniques, and development of prediction processes to determine environmental concentrations based on use and fate. The SWRCB urges the State to also develop a method to compile, summarize and evaluate data, prioritize on a triennial basis; and establish an independent review panel to oversee CEC selection, water reuse practices, and monitored

environmental concentrations, based on the high volume of data that have recently been produced (Anderson et al., 2010).

"Use Caution"

Dr. Armstrong encourages the science and regulatory communities to use the "Precautionary Principle":

> When you don't know about something, err on the side of caution until you know. We have a whole class of chemicals that show that they are likely to be of concern… we need to further research them. There is enough evidence that these things (chemicals) have an environmental effect in certain areas. We don't see population level effect, but there are exposure effects. Is that enough to warrant source control or treatment changes? We have to call them what they are, in order to properly research (personal interview, Dr. Armstrong, OCSD, August 19, 2009).

Dr. Shane Snyder stated that…

> I think it's a shame that so much money is going into monitoring to figure out if these things are out there, and so little is being spent on human health… They need to just accept that these things are

> everywhere, every chemical and pharmaceutical could be there. It's time for the EPA to step up to the plate and make a statement about the need to study effects, both human and environmental. (AP investigation, The MetroWest Daily News, 2008)

Also, Snyder (2008) cautioned the science and regulatory communities against reporting preliminary occurrence data without also providing corresponding information of human health effects. He warned that it is irresponsible to report what can be measured without providing a frame of reference for what it means to us. Therefore, we should not make policy based on our ability to find contaminants; rather we have to find a correlation between these measurements and protecting public health.

CHAPTER EIGHT

PUBLIC INTEREST

Understanding Threats to Water Quality

The lack of awareness and understanding by the general public can sometimes prove shocking as evidenced by the work of a junior high school student in Idaho Falls. In 1997, a 14-year-old conducted a social experiment for his science fair project by circulating an article about "The dangers of Dihydrogen Monoxide". Unbeknownst to his peers the article was a hoax, advertising that the substance contributes to the greenhouse effect, is found in nuclear power plants, distributed in pesticides, found in tumors of terminal patients, a major component of acid rain, and the list goes on. An overwhelming 86% majority of the students who received the article responded that it should be banned. The remaining students were undecided, and only one student understood that it was merely a reference to water (Mikkelson & Mikkelson, 2007).

This hoax was revived in 2004, when a paralegal convinced the City of Also Viejo, California that 'dihydrogen monoxide' was a threat to public health. It went as far as instigating a vote by the City Council to

propose a ban on foam products made with this substance. The truth was unveiled before the Council was further made to look foolish. This demonstrates that with little effort, even the most harmless of substances can be made dangerous in the eyes of the unknowing public (Mikkelson & Mikkelson, 2007).

According to Dr. Cooper of UCI…

> It's not trivial to educate the public; it takes a lot of time and money. Often the public cannot read what we are writing. The federal, state and local level agencies should be proactive in teaching the public. There is a general distrust in the government, so the universities should be proactive to help out in this way. (personal interview, August 19, 2009)

Daughton (2004) described that effective risk communication will be vitally important in the future since the inventory of newly discovered and introduced water pollutants is ever expanding, and drinking water supplies will continue to decline while the demand for recycling increases. This cannot be addressed without meeting the challenge of giving the public the proper tools to make good long-term decisions. Daughton (2005) states that…

> The lay public's bewilderment with the jargon required for expressing these concentrations has fostered the perception that essentially all concentrations are the same—whether they are minuscule or large. (Daughton, 2005, p. 11)

Daughton (2004) explained that…

> A better understanding is needed of the origins of the chasm existing between hazard/risk communication and how the public perceives risk… The ultimate, unmet challenge is to convey the significance of chemical exposure to the public in a way that allows sound decision making… (Daughton, 2004, pp. 728-730)

Media Frenzy

The tables are turned when contamination is publicized through the media. Instead we see what resembles panic because the public is not given all the information to properly gauge the severity of the issue. Dr. Armstrong has personally been confronted with this dilemma. He gave a press release pertaining to research that he conducted a while back and a reporter built an article around one word in the middle of a sentence that he gave in the meeting. When he confronted the reporter about it, the reporter

stated, "I am not paid to write or disseminate accurate information... that is why it is called news story and not news fact." Because of this approach people don't know what to think. Unfortunately, they tend to believe the media because it is right in their faces. Dr. Armstrong believes that the science community is partially responsible for these elaborate communication tactics:

> People tend not to trust scientists and view us as reactionary. The blame lies with scientists; we have not done a good job of communicating science to the public. They only know the media hype. (personal interview, Dr. Armstrong, OCSD, August 19, 2009)

In contrast, the Contra Costa County Water District (2008), in California, seems to be up to par on communicating issues to the public. They provided a fact sheet on pharmaceutical and personal care products (PPCPs). They specifically called out a list of pharmaceuticals that included sulfamethoxazole, atenoloo, trimethoprim, dilantin, carbamazepine, gemfibrozil, naproxen, estrone, apigenin, chrysin, diclofenac, meprobamate, and tricolsan. Many of these were detected in parts per trillion, which was defined to the public using descriptive analogies to which they could relate.

The District documented that they are currently addressing PCPPs using the existing ozone, granulated activated carbon, and chlorine treatment regimes, with a 75%-80% removal efficiency. The fact sheet concluded that standard analytical methods and exposure limits have not been established for PPCPs by regulators. In the meantime, the District has teamed up with the California Department of Health and the American Water Works Association Research Foundation for further study.

A 2008 news article included comments from zoologist John Sumpter of Brunel University in London. "These are chemicals that are designed to have very specific effects at very low concentrations. That's what pharmaceuticals do. So when they get out to the environment, it should not be a shock to people that they have effects" (AP investigation, The MetroWest Daily News, 2008).

In a 2008 Massachusetts' newsletter, The MetroWest Daily News by Associated Press (AP), the public's attention was brought to the "… vast array of pharmaceuticals… found in the drinking water supplies of at least 41 million Americans". It explains that the concentrations are at trace levels (ppt) and that the public utilities vow that it's safe to drink. However the article stresses that the

scientific community is concerned about the long term exposure to the long list of contaminants, and that water providers rarely disclose the levels of pharmaceuticals and are not prepared to interpret the results.

The article informed the public that more recent works uncovering the effects of these trace contaminants on humans and wildlife has been very alarming, having significant ecological effects on sensitive species. The AP investigation yielded that, "the situation is undoubtedly worse than suggested by the positive test results in the major population centers". The article goes on to explain to the public that contamination is not confined to the U.S., as over 100 different pharmaceuticals have been detected in surface waters of the world to date; specifically in Asia, Australia, Canada, and Europe.

It is explained that the investigation shows a discrepancy between the results of municipal or regional water providers, the pharmaceutical industry, and that of independent researchers. In addition, some of the water providers stated the waters have not been analyzed for the trace contaminants, while independent scientific publications, by local universities, showed that they had. Experts in the pharmaceutical industry state there is a

minuscule risk to human health from pharmaceuticals in the environment.

Concentrating on Concentration

Even USA Today (2008) reported that the Executive Director of the California Urban Water Agencies thinks that the public is not able to accurately interpret the severity of water contamination issues. The public is merely alarmed because a contaminant is reported as present, but without understanding concentration measurements they have no understanding of the representativeness of a detected substance. The majority of the public believe they have a good handle on the subject because, by law, they are provided consumer confidence reports. These reports are based on reporting contaminants as listed by the EPA. It does not include many of the emerging species that are of current interest, as these are not regulated… yet.

This news article, like many similar news articles, did not disclose the concentrations of the pharmaceutical contaminants. Rather it reads as if the regulators, federally funded researchers, and private experts of sorts are pulling the wool over the eyes of the public, simply by avoiding the issue in conference. This is not necessarily

the case, as there are many federal, state, private, and public researchers that continue to study the concentrations of emerging contaminants in wastewater and drinking water. Several of these groups provide data to the EPA to assist in monitoring.

Furthermore, since the article did not disclose the concentrations of the pollutants, the public has no perception of the level of contamination. This clouds the public's perception of risk; however, many people do not understand measurements of concentration anyway. In these instances the public is panicked by the mere mention of a pollutant. It is not clearly explained that they would need to be chronically exposed to the pollutant at a consistent concentration in order to present an adverse effect.

In April 2008, the George Washington University Medical Center's School of Public Health and Health Services (GW SPHHS) issued a paper on the topic of pharmaceuticals in drinking water as part of their Rapid Public Health Policy Project. The paper was developed as a spin off of the original National Reconnaissance effort published in 2002, as well as many publications that followed thereafter. The intent was to provide insight directly to the public to help defog the underlying panic

associated with this topic. The message stressed that there are no known immediate adverse health effects linked to the "tiny" concentrations of the drugs detected in waterways. Instead the scientists are namely worried about "the consequences of long-term, low-level exposure". Pharmaceuticals are manufactured specifically to provide a biological interaction at low doses in order to present a targeted impact. This is what separates them from other pollutants and raises concerns amongst scientists. The GW SPHHS paper provided real perspective on the significance of exposure to the emerging contaminants.

> The levels being detected today are measured in the parts per billion (equivalent to one drop of water in an Olympic-sized swimming pool, or a single blade of grass in a football field) or parts per trillion (that drop of water in one thousand pools, that blade of grass in one thousand football fields). (The George Washington University, 2007)

Incentive

According to Dr. Jeff Armstrong, Senior Scientist for the Orange County Sanitation District (OCSD), Social Monitoring Program, the public has little interest in the

topic of water contamination. The OCSD has done public service announcements and sent out information on the proper disposal of pharmaceuticals and personal care products, yet most of the public is reluctant to take part. Dr. Armstrong believes that the average person will not participate in pollution prevention practices. In his experience he does not expect the public to be interested in the proper handling and disposal of potential drinking water contaminants, such as pharmaceuticals, pesticides, antibiotics, and hormones (personal interview, August 19, 2009).

People may need an incentive to participate in pharmecovigilance, but they tend to listen clearly when water contamination is mentioned. A 2008 fact sheet regarding "Pharmaceuticals in water" prepared by the Water Quality Association, a non-profit organization, was made available to the public to address concern for the best protection of drinking water in the domestic setting. In summary it covered home filter systems, calling them the "final contaminant barrier" in excess of the EPA's drinking standards. However, these systems do not have performance standards for the removal of pharmaceuticals. The fact sheet provides general encouragement that successful

treatment can be led by nano-filtration, reverse osmosis, activated carbon, distillation, ozonation, and advanced oxidation methods. Although many of the methods are cost prohibitive, they have presented success in the removal of target pharmaceutical contaminants. However, success rates vary depending on the target contaminant and available resources. This very simplified fact sheet was one of the most realistic in terms of communicating treatment control options to the public.

Responsibility to the Public

When asked if the public is being properly educated about drinking water contaminants, Dr. Phalen of CSUSB stated…

> I strongly feel that it is the responsibility of the U.S. EPA and scientific community to investigate, evaluate, and report environmental health hazards. With this said, I also feel that it is irresponsible to report potential hazards that have not been properly evaluated by a risk assessment… We must consider the benefits and consequences of our actions when evaluating a potential hazard. I also feel that it is equally important to evaluate multiple

alternatives to every action… Unfortunately, the U.S. EPA typically does not evaluate the risks, costs, and benefits of potential regulatory actions. In fact, they are often legally bound to not evaluate the cost to society in any risk assessment. Thus, I feel that it is the responsibility of the scientific community to look after the best interest of our society and make a concerted effort to investigate, evaluate, and report the risks, benefits, and consequences associated with identified environmental hazards. The scientific community needs to be that voice of reason and wisdom within the community. Whereas the regulatory agencies are restricted in their actions, the scientific community does not need to be 'politically correct' when it comes to the health and wellbeing of our community and our children. (personal email correspondence, August 3, 2010)

CHAPTER NINE

CONCLUSION AND RECOMMENDATIONS

General Conclusions

This review is a compilation of works by others. The conclusions drawn herein are greatly influenced by their conclusions and thus the nature of them may not be original. It's quite easy to make some generalizations after reviewing the information about emerging pollutants in drinking water and wastewater, namely PPCPs and EDCs. Some of these generalized conclusions include the following:

- The list of frequently detected pollutants in wastewater and drinking water will continue to increase and change based on the variety of substances introduced through commerce;
- The more we consume these biologically active substances, the more we can expect them to be introduced into the environment;
- The ever-increasing detection capabilities will continue to yield evidence of newly introduced

pollutants, existing pollutants, and by-products that linger on in trace amounts;

- The lack of epidemiological evidence continues to expand the void between data retrieved and interpreting risk;
- Future water treatment research is necessary to identify contaminants that require more robust removal methods;
- We will never fully grasp the inventory that exists in "chemical space". Our actions continue to change what is introduced, and we have no control over the inventory that already exists due to natural processes in the environment.

Summary and Conclusions

This review has not been prepared by someone with a PhD in biochemistry or toxicology, but it has been developed by someone who works professionally in environmental regulatory compliance consulting in water quality.

In most cases conclusions are built on facts, but the fact is that, based on this review, there remains a

significant void in complementary studies for the comparison of production, consumption, disposal, degradation, fate, and toxicity of PPCPs and EDCs in water. However, some recent works have raised the correct questions. These questions will lead to regulatory actions, in the interest of public and environmental health, that hopefully are guided more by the recommendations of the researchers and less by the industry responsible for the production of these compounds.

Contaminants

Several classes of chemicals occurring at residual environmental concentrations have received heightened attention as a result of new technology capabilities and monitoring efforts. Namely these have included veterinary and human antibiotics, prescription drugs, non-prescription drugs, deodorizers, antioxidants, fragrances, polycyclic aromatic hydrocarbons (PAHs), plasticizers, pesticides, detergents, solvents, fire retardants, steroids, and hormones. Collectively the most attention has been given to PPCPs and EDCs, specifically in the last 5 years.

For the purpose of this review, the works described herein commonly refer to the most frequently detected pharmaceuticals as shown in Table 4, as the emerging

pollutants in drinking water and wastewater. The degree to which a chemical is studied obviously affects its public interest. In turn, the public's reaction then brings more attention by the regulators, as they typically want to avoid panic. So there exists some level of bias regarding which contaminants take the spotlight, vs. what is really representative of the "chemical space".

Contamination

We know that with the earth's ability to vastly distribute and transport contaminants through the hydrologic cycle that we will continue to uncover an extensive list of contaminants in water resources. So the question no longer pertains to determining if a contaminant is out there, but rather what should we do to reduce its negative effects.

Monitoring

2009 research demonstrates that the integrative passive sampler is an advantageous alternative to the traditional active sampler. It also can provide *in situ* collection for toxicological assessment, which will be necessary for interpreting sample collection data. It's only foreseen shortcomings include its sensitive

calibration requirements, which may be overcome by future innovations.

Detection

Our technological advancements have surpassed our ability to understand contamination, in other words, "zero" contamination escapes us. In the words of Albert Einstein, "Not everything that can be measured is worth measuring, and not everything worth measuring is measurable". The environment will not willingly tell us where to place the decimal, in concentration measurement, when deciding how to implement exposure guidelines. The researchers and regulators will have to jointly quantify the concentration that is representative of "zero" to humans. That will likely be different than the concentration that is "zero" (NOEL) to the environment. These differences must be plainly communicated to the public.

Analysis

As of 2007, the EPA has established guidelines for analytical methods to identify pharmaceuticals in water samples, and studies conducted prior to and since then have shown that SPE and LC/MS-MS is a favorable and effective method. This technique of choice may change in the near future, as other refinements are made. However, it is

apparent that current shortcomings in the pursuit of emerging contaminants do not include our ability to find them; rather it is our ability to interpret their presence.

Treatment

As for treatment, traditional ozone and chlorination applications have been shown to be moderately effective at removal of the emerging pollutants, but not without creating some undesirable by-products. A variety of advanced treatment processes have been explored in the past decade. Ultra-violet (UV) photolysis and ion-exchange have demonstrated effective removal, but only when applied at levels higher than standard disinfection applications. As an alternative to chemical applications, nanofiltration has been shown to be energy effective, but there have been issues with bio-fouling of the membrane. Advanced oxidation/reduction processes have proven effective, but further study is needed to consider the influence of effluent organic matter.

It is not plausible to simultaneously retrofit all of the conventional treatment facilities with some of the more robust methods determined to effectively remove emerging pollutants or, at minimum, destroy their biological activity. This is especially true, given the economic

turmoil of the U.S. and, specifically, since the pollutants are found predominately at ultra trace levels. The cost to our resources would outweigh the benefit to human health. Instead a gradual progression is the only reasonable application.

Toxicology

There has been much postulation concerning the long-term risks of exposure to sub-parts-per-billion or lower levels. Several researchers say the risk is negligible while others argue that we should remain wary of the unknown. The toxicological implications are not clear. As previously stated, with so many influential variables, we need to continue toxicity exploration so that we may use the new data to extrapolate human toxicity prediction models for pollutants of interest, and determine if additional regulatory involvement will be necessary. It will not be plausible to conduct assessments for individual compounds, so we will have to focus on classes of compounds. In agreement with works described herein, we must look beyond groupings by common uses and consider polarity, biological reactivity, hydrophilic functional groups, etc.

When we conduct future epidemiological studies of this "potpourri" of pollutants that exists in trace amounts in our water resources, we will likely not be able to differentiate effect levels from other pollutants that people are exposed to in significant concentration. Whether during routine living, employment in heavy industry, or circumstantial exposure (a favorite vacation spot); there are too many outside influences to pinpoint a single product or by-product at concentrations in parts-per-billion or lower, and then slap on an effects observation. Someone has to say "enough, is enough, we are wasting valuable resources".

It has also been said that a prioritization scheme for classes of pollutants needs to be developed soon in order to avoid the waste of time and resources that may otherwise be available to focus on pollutants that exist in significant concentration. The EPA already has a decent grasp on approaching risk reduction. The CCL is a valuable tool for determining prospective compounds that may need regulatory involvement.

Recommendations

Communicating Pharmecovigilance

The lack of "pharmecovigilance" will feed the pseudopersistence of pharmaceutical residues in drinking water. In agreement with Daughton and Ruhoy (2008), this may lead to the consumer's loss of confidence in municipal water supplies and rejection of water recycling programs. The EPA strongly encourages the public to take part in the proper disposal of household hazardous wastes, including pharmaceuticals, as evidenced by the education information on their website. The number of pharmaceutical collection programs across the U.S. is continuously increasing, even though they consume a considerable amount of organization, time, resources, and money. Programs are advertised to the public, primarily by local community organizations, by targeting the effort to eliminate unwanted medications from entering the environment, from being stolen, or from contributing to accidental poisoning.

Since the government only plays a partial role, pharmacies nationwide should also play a proactive central role in communicating and encouraging proper waste management practices to patients in order to strive for human safety and environmental integrity. The patient

receiving the medication will most likely lend an ear to the real individual behind the counter in lieu of some agency postings or collection program advertisement that could be easily forgotten.

Future Research

Treatment performance analysis has been, and continues to be, evaluated. In agreement with the recommendations of Shon, Vigneswaren, & Snyder (2006), treatment and removal is dependent on the individual compound. Even though it is not plausible to do a toxicological assessment of every pollutant in existence, as it would be a never ending list, it may be plausible to inventory treatment removal data for the pollutants we know, whether in significant or trace quantity.

For evaluating treatment efficiency, I recommend development of a database that can be used to compile historical and future monitoring results for the removal of specific constituents of interest found in source water, drinking water, and finished water. It should be designed such that the water authorities, publically owned treatment works, and the private researchers can populate information for a specific compound, prioritized by the region of collection. Other information could include the cost of the

treatment methods employed in terms of monetary strain and a description of resource and time consumption during treatment processing.

Although we may not yet know the human and environmental implications of this information, it would advance the effort for the collection of occurrence data, establish a history of contamination by region, and put cost benefits into perspective. Having said that, it is likely that such efforts are already underway, but that was not apparent during this review.

To those of you who argue that something needs to be done about the synergistic effects of chemicals or our continuous exposure to a mixture of residual contaminants, consider that our knowledge of synergistic chemical behaviors has only been unveiled within the past decade or so. That did not prevent chemicals from having synergistic interactions 20, 100, or 250 years ago at the start of the Industrial Revolution. Some how, humans have survived the last 250 years, even while exposed to environmentally foreign compounds.

Instead of focusing solely on how the sub-parts-per-billion or lower (ultra trace) concentrations affect us, we should continue to investigate the damage caused to the

aquatic ecosystems. The public, at large, may not care about the algae or the salmon etc., but they are fragile and have a significant influence on the biological network that surrounds us. It will be up to the government and educators to communicate this to the public and repair the perception of "harmful concentration". After all, we have a much greater tolerance to toxins than our companions on this planet.

APPENDIX A

SOURCE PATHWAYS OF HOUSEHOLD PHARMACEUTICALS

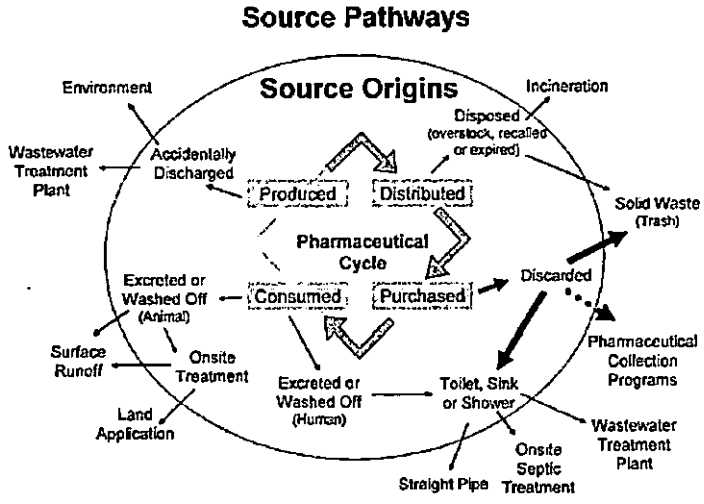


Figure A

Source Pathways of Household Pharmaceuticals

Source: Glassmeyer et al. (2009)

Reprinted from Environment International, Vol. 35, Glassmeyer, S. T., Hinchey, E. K., Boehme, S. E., Daughton, C. G., Ruhoy, I. S. , Conerly, O., Daniels, R. L., Lauer, L., McCarthy, M., Nettesheim, T. G., Sykes, K., & Thompson, V. G., Disposal Practices for Unwanted Residential Medications in the United States, Page No. 567, Copyright 2008, with permission from Elsevier.

APPENDIX B

ORIGIN AND ROUTES OF PHARMACEUTICALS

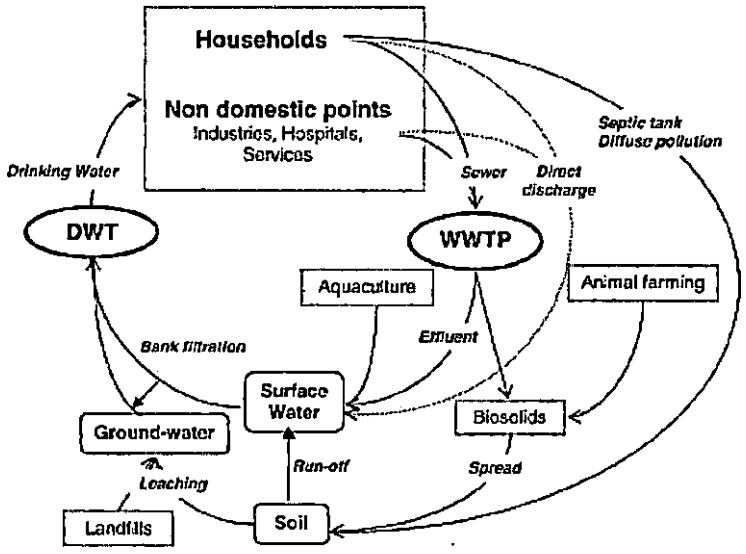


Figure B

Origin and Routes of Pharmaceuticals

Source: Mompelat et al. (2009)

Reprinted from Occurrence and fate of pharmaceutical products and by-products, from resource to drinking water, Vol 35, Mompelat, S., Le Bot, B., & Thomas, O., Environment International, p. 806, Copyright 2008, with permission from Elsevier. Also Trends in Analytical Chemistry special credit -Reprinted from Trends in Analytical Chemistry, Vol. 22, No. 10, Petrović, M., Gonzalez, S., Barceló, D., Analysis and Removal of Emerging Contaminants in Wastewater and Drinking Water, Pages 686, Copyright 2003, with permission from Elsevier.

APPENDIX C

SUMMARY OF PROBLEMS IN DETECTION AND ANALYSIS OF EMERGING CONTAMINANTS

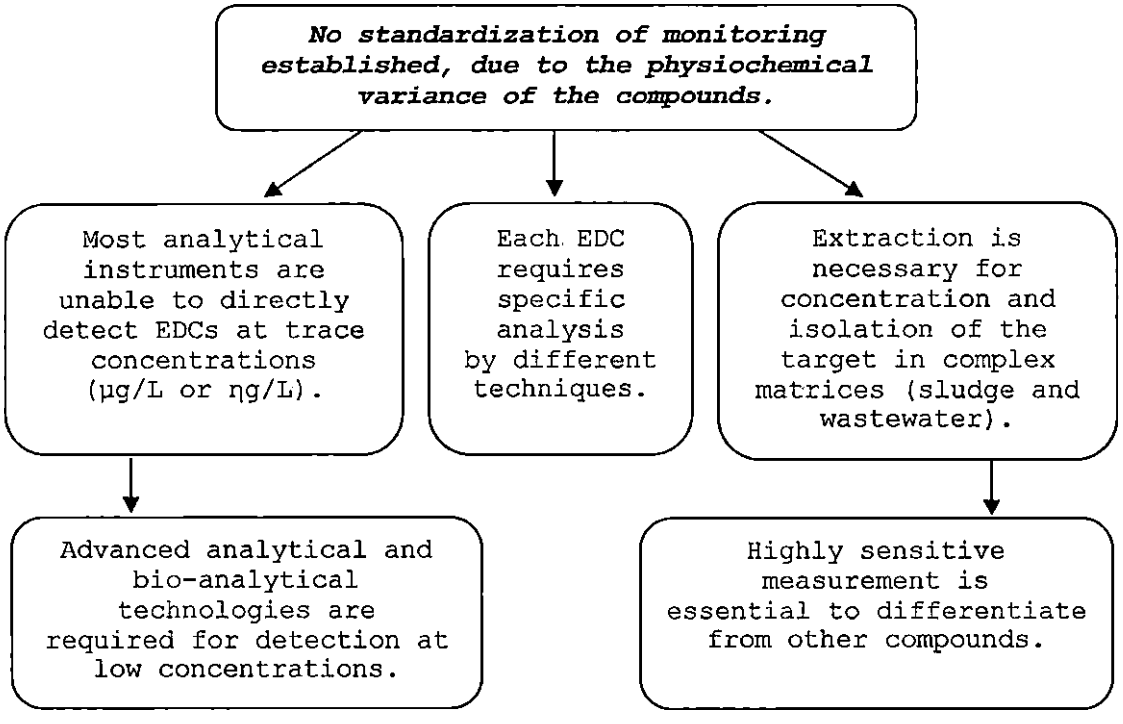


Figure C

Summary of Problems in Detection and Analysis of Emerging Contaminants

Modified from: Bolong et al., 2009, p. 231.

APPENDIX D

ACRONYMS AND ABBREVIATIONS

The following is a list of acronyms or abbreviations used in this review, which are commonly used in the scientific community:

Advanced oxidation/reduction processes (AO/RPs)

California State University, San Bernardino (CSUSB)

Chemicals of Emerging Concern (CECs)

Contaminant Candidate List (CCL)

Continuous Liquid to Liquid Extraction (CLLE)

Effect Concentration of 50% of the population (EC_{50})

Electrospray ionization (ESI)

Gas Chromatography (GC)

High performance liquid chromatography (HPLC)

Effluent organic matter (EfOM)

Endocrine disrupting compounds (EDCs)

Lethal Concentration of 50% of the population (LC_{50})

Liquid chromatograph-electrospray ionization mass spectrometry (LC/MS ESI)

Mass Spectrometry (MS)

Maximum concentration levels (MCLs)

Maximum exposure levels (MELs)

Measured environmental concentrations (MECs)

Nanofiltration (NF)

National Institute on Aging (NIA)

Natural Organic Matter (NOM)

Non-steroidal anti-inflammatory drugs (NSAIDs)

No Observed Effect Concentration (NOEC)

Orange County Sanitation District (OCSD)

Organic wastewater contaminant (OWC)

Pharmaceuticals and personal care products (PPCPs)

Polar organic compounds (POCs)

Polycyclic aromatic hydrocarbons (PAHs)

Reverse osmosis (RO)

Selected Ion Monitoring (SIM)

Solid-phase extraction (SPE)

Spectrometry (LC/MS ESI)

State Water Resources Control Board (SWRCB)

Wastewater treatment systems (WWTS)

Ultra-performance liquid chromatography (UPLC)

Ultra violet (UV)

University of California, Irvine (UCI)

University of California, Riverside (UCR)

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