Modeling Occurrence and Assessing Public Perceptions of De Facto Wastewater Reuse across the USA

by

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ABSTRACT

The National Research Council 2011 report lists quantifying the extent of de facto (or unplanned) potable reuse in the U.S. as the top research need associated with assessing the potential for expanding the nations water supply through reuse of municipal wastewater. Efforts to identify the significance and potential health impacts of de facto water reuse are impeded by out dated information regarding the contribution of municipal wastewater effluent to potable water supplies. This project aims to answer this research need. The overall goal of the this project is to quantify the extent of de facto reuse by developing a model that estimates the amount of wastewater effluent that is present within drinking water treatment plants; and to use the model in conjunction with a survey to help assess public perceptions. The four-step approach to accomplish this goal includes: (1) creating a GIS-based model coupled with Python programming; (2) validating the model with field studies by analyzing sucralose as a wastewater tracer; (3) estimating the percentage of wastewater in raw drinking water sources under varying streamflow conditions; (4) and assessing through a social survey the perceptions of the general public relating to acceptance and occurrence of de facto reuse. The resulting De Facto Reuse in our Nations Consumable Supply (DRINCS) Model, estimates that treated municipal wastewater is present at nearly 50% of drinking water treatment plant intake sites serving greater than 10,000 people (N=2,056). Contrary to the high frequency of occurrence, the magnitude of occurrence is relatively low with 50% of impacted intakes yielding less than 1% de facto reuse under average streamflow conditions. Model estimates increase under low flow conditions (modeled by Q95), in several cases treated wastewater makes up 100% of the water supply. De facto reuse occurs at levels that

surpass what is publically perceived in the three cities of Atlanta, GA, Philadelphia, PA, and Phoenix, AZ. Respondents with knowledge of de facto reuse occurrence are 10 times more likely to have a high acceptance (greater than 75%) of treated wastewater at their home tap.

To my beloved parents.
Thank you for your continuous love and support, and for instilling in me the traits and values that enabled me to get to this point.

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Chapter 1

INTRODUCTION

De facto reuse is defined as the unplanned or incidental presence of treated wastewater in a water supply source (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007). De facto reuse is depicted below as City 3 in Figure 1, where the source water to the drinking water treatment plant includes discharges from the wastewater treatment plants of City 1 and City 2. The goal of this dissertation is to develop a Graphical Information System (GIS) model of the continental United States (De-facto Reuse Incidence in our Nations Consumptive Supply (DRINCS) Model) coded to estimate the amount of treated wastewater effluent present within downstream potable water supplies (i.e., de facto reuse), and to perform social science surveys to assess public perceptions of de facto wastewater reuse. I hypothesize that de facto reuse occurs throughout the continental United States at rates much higher than lay public perceptions. This project takes an innovative approach to researching at the intersections of science, technology and policy. It is fitting that the research will be performed at Arizona State University (ASU), where integration of social science is our hallmark of interdisciplinary research.

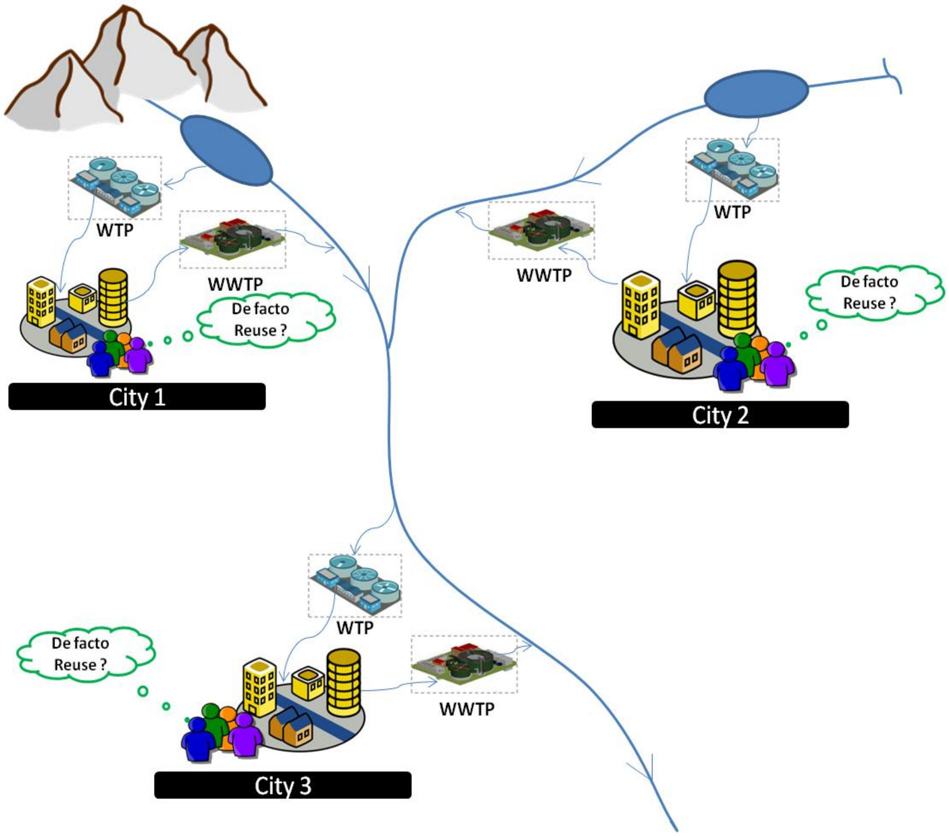

Figure 1.1. Conceptual map

A 2011 National Research Council report, lists quantifying the extent of de facto (or unplanned) potable reuse in the U.S. as the top research need associated with assessing the potential for expanding the nations water supply through reuse of municipal wastewater. Efforts to identify the significance and potential health impacts of de facto water reuse are impeded by outdated information regarding the contribution of municipal wastewater effluent to potable water supplies. "Because new water reuse projects could decrease the volume of wastewater discharged to water sources where de facto reuse is being practiced, the lack of understanding of the contribution of wastewater effluent to water supplies restricts our ability to assess the net impact of future water reuse on the nation's water resource portfolio (Council, 2012)." The report includes the comparison of estimated risks of a conventional drinking water source that contains a small amount of de facto potable reuse against the estimated risks of two different potable reuse scenarios. The analysis suggests that the risk of exposure to 24 selected chemical contaminants in the two planned potable reuse scenarios is lower than the risk encountered from many existing water supplies (Council, 2012). This highlights the significant connection that de facto reuse may have on public health, and the opportunity for the DRINCS Model to be a tool in future studies. This dissertation aims to directly address the NRC research need for the analysis of the extent of de facto reuse. Building the model within ArcGIS will result in a tool that supports decision-making through the improved communication of GIS-based maps and visualizations. Further understanding of de facto reuse can also spur the development and/or application of contaminant prediction tools at the continental scale, enhancing monitoring programs to increase public health protection.

The engineering need for the project is coupled by the call for attributions by this project to the social sciences. Globally, many countries have increasingly limited water resources in both quantity and quality (Baumann & Kasperso.Re, 1974; Dolnicar & Schafer, 2009). Traditionally, high stress regions have included California, Australia, the Middle East and the Mediterranean ((IWMI), 2006). A variety of wastewater treatment technologies are available to achieve recycled water of a quality that is often superior to existing potable water standards (Bixio et al., 2005; Weber, 2006). Despite this, the idea of drinking treated wastewater does not have wide public support. Introducing new alternative water schemes (i.e. recycled, desalinated, storm or grey water) is complicated by public acceptance. Hartley (2006) notes five critical dimensions of issues management in the context of water reuse decision making: (1) managing information; (2) maintaining motivation and demonstrating organizational commitment; (3) promoting communication and public dialog; (4) ensuring a fair and sound decision making process and outcome; and (5) building and maintaining trust (Hartley, 2006). In order to manage information we must understand the underlying informal institutions that are present in the general public (Bruvold & Ward, 1970). A portion of this dissertation is aimed towards conducting social surveys in order to find the current perceptions that exist in the public. The focus is set upon finding the extent to which the public is aware that wastewater effluent resides in their drinking water, and to determine what percent is "acceptable" within their home tap water.

Research Objectives

De facto wastewater reuse is not a new occurrence but there are large gaps in knowledge within the scientific community and general public. The work in this research is aimed at taking an interdisciplinary approach to evaluate de facto reuse across the continental United States. Figure 2 depicts the manner in which the engineering components of estimating occurrence are coupled with the public's perception of these occurrences. The research presented in this dissertation attempts to answer the question: To what extent does de facto wastewater reuse occur across the U.S. and how do these values compare to the public's lay perception? To answer this question a four-step approach was taken that includes: (1) creating a GIS database with information on WWTPs, WTPs and U.S. hydrography, and building a model in ArcGIS framework with Python programming; (2) validating the model with field studies analyzing sucralose; (3)

estimating the percentage of wastewater in raw drinking water sources under a range of flow conditions; (4) and assessing through a social survey the perceptions of the general public relating to acceptance and occurrence of de facto reuse. The objectives of this dissertation were to:

(1) Compare the wastewater percentages found in the Top 25 cities of the 1980 EPA Study with updated de facto reuse values.

(2) Quantify the percentage of wastewater effluent in drinking water treatment plant intakes at the continental scale. Forecast potential climate change impacts to these percentages through the analysis of historical temporal variation trends.

(3) Analyze the public's perceptions regarding the occurrence and acceptance of de facto wastewater reuse juxtaposed with predicted values.

(4) Assess WWTP discharge contributions to stream flow and emerging contaminant loading, within U.S. riverine ecosystems.

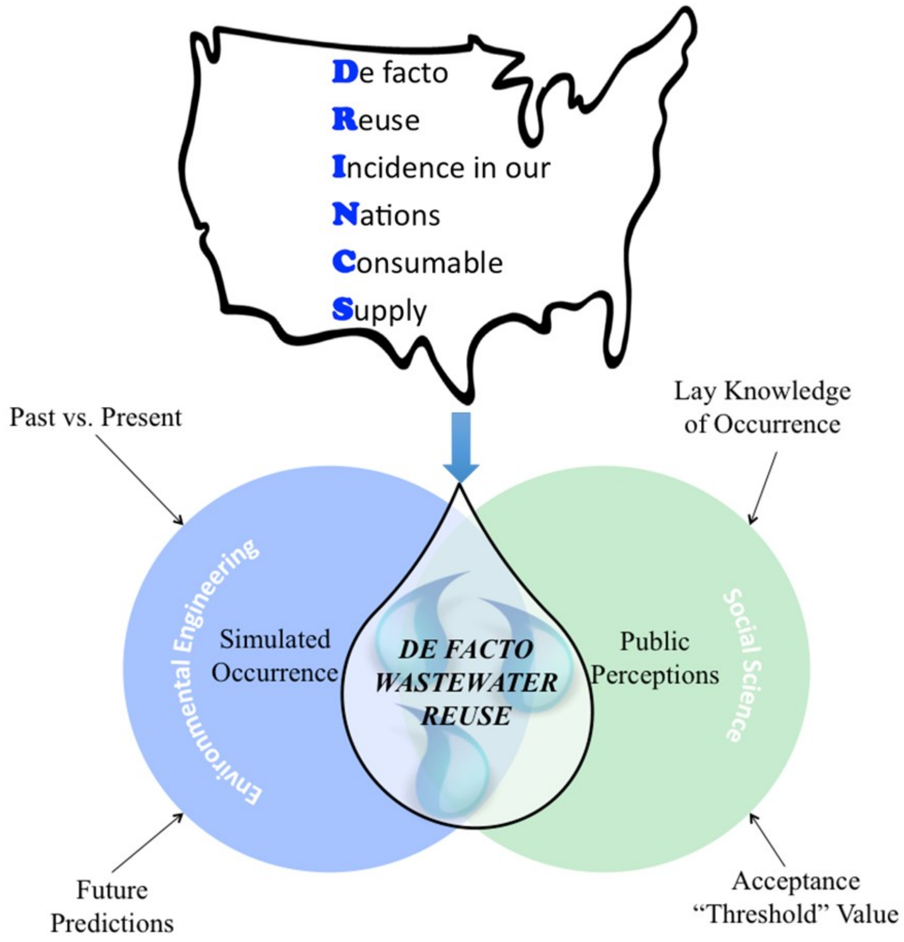

Figure 1.2. Visual overview of dissertation

Dissertation Organization

This dissertation includes 8 chapters. Chapter 1 is an introductory chapter that leads into Chapter 2, which is relevant literature review on de facto reuse. Table 1.1 details each objective, and publication status, of subsequent chapters. Chapter 3 has been published in a peer-reviewed journal; Chapters 4, 5, and 6 are in preparation for submission. Chapter 7 synthesizes the research chapters into a discussion on how the DRINCS model can be integrated into current decision-making efforts towards the protection of human health and the environment.

Table 1-1.

Dissertation Organization

Objective 1 *Compare the wastewater percentages found in the Top 25 cities of the 1980 EPA Study with updated de facto reuse values.* • Dissertation Chapter 3 • Published: Rice, J., Wutich, A., Westerhoff, P. Assessment of De Facto Wastewater Reuse across the USA: Trends between 1980 and 2008. Environ. Sci. Technol., 47(19), 11099-11105,2013.
Objective 2 *Quantify the percentage of wastewater effluent in drinking water treatment plant intakes at the continental scale. Forecast potential climate change impacts to these percentages through the analysis of historical temporal variation trends.* • Dissertation Chapter 4 • In preparation for peer-reviewed submission to *Environmental Science and Technology*: Rice, J., Westerhoff, P. Spatial and Temporal Variation of De Facto Wastewater Reuse in Drinking Water Systems across the U.S.
Objective 3 *Analyze the public's perceptions regarding the occurrence and acceptance of de facto wastewater reuse juxtaposed with the predicted values.* • Dissertation Chapter 5 • In preparation for peer-reviewed submission to Journal of Environmental Management: Rice, J., Wutich, A., White, D., Westerhoff, P. Assessing the 'Yuck' Factor Associated with De Facto Wastewater Reuse: A Three City Case Study.
Objective 4 *Assess WWTP discharge contributions to stream flow and emerging contaminant loading, in riverine ecosystems within the U.S.* • Dissertation Chapter 6 • In preparation for peer-reviewed submission to *Nature:* Rice, J., Westerhoff, P. Opposing Roles of Wastewater Discharges into the Aquatic Ecosystem.

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Chapter 2

BACKGROUND OF THE INTERDISCIPLINARY COMPONENTS OF DE FACTO WASTEWATER REUSE

De Facto Reuse

The term de facto reuse is an occurrence in any watershed for a drinking water treatment plant (DWTP) that contains discharges of wastewater. It’s not uncommon to have a substantial portion of the source water for these DWTPs originally derived from the upstream wastewater contribution (S. W. Krasner et al., 2009). In the past this occurrence has also been referred to as unplanned reuse, unintentional potable reuse, and indirect potable reuse. De facto potable reuse of wastewater has often occurred over the past century (Bunch, Barth, & Etting er, 1961). The occurrence will likely increase in the future as upstream wastewater treatment plants (WWTPs) discharge water into rivers or lakes that serve as downstream drinking water sources (S. W. Krasner et al., 2009). WWTP discharges are one of the main sources of numerous micropollutants and macronutrients in the environment (Chen, Nam, Westerhoff, Krasner, & Amy, 2009; EPA, 2009; Kolpin et al., 2002; Snyder, Westerhoff, Yoon, & Sedlak, 2003). Amongst these are pharmaceuticals and personal care products (PPCPs) and certain disinfection byproducts (DBPs) (S. W. Krasner et al., 2009). The occurrence of PPCPs in surface and drinking waters affected by treated wastewater discharges have been reported by the U.S. Geological Survey and other research groups (EPA, 2009; Glassmeyer et al., 2005; Kolpin et al., 2002; Snyder et al., 2004) . PPCPs have also been used as potential indicators of human fecal contamination. For example, the anticonvulsant primidone is stable in the environment and is considered a conservative indicator (Glassmeyer et al., 2005).

In 1980 the EPA published Wastewater in Receiving Waters at Water Supply Abstraction Points. The findings included the identification of, 1246 municipal water supply utilities using surface water from 194 basins serving 525 cities held to populations over 25,000. For each utility the number of upstream wastewater dischargers were calculated; as well as a cumulated estimate of wastewater discharge flow. The existence of this project highlights the relevance and need for an updated assessment. The top 25 municipalities with the highest effluent concentrations ranged from 2.3-16% under average flow conditions. Wastewater percentages increased under low flow conditions, and ranged from 7-100% (EPA, 1980). There is reason to believe that these percentages have significantly increased since the study. This is primarily due to the vast increase in population in the last 30-years. Population in the United States, as reported by the 1980 United States Census and predicted for 2010 by the US Census Bureau, has increased from 225,545,805 to 308,400,408, an increase of 36%. Secondly, the number of people on centralized sewer systems has also drastically increased.

Treated wastewater can represent a significant portion of the total flow in many receiving waters. Many cities have overdrawn the groundwater sources and have been obliged to turn to surface water containing amounts of treated wastewater for expanding the drinking supply. Subsequently, de facto potable reuse of wastewater in domestic and public water supply is widespread and increasing. Noteworthy examples include the Platte River downstream from the City of Denver; the Schuylkill River in Philadelphia, PA; the Quinnipiac River in Connecticut; the Santa Ana River in southern California; the

Ohio River near Cincinnati, Ohio; and the Occoquan Watershed southwest of Washington DC (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007; Chen et al., 2009; S.W. Krasner, Westerhoff, Chen, & Dotson, 2009; Mitch & Sedlak, 2004; Morehouse, Carter, & Sprouse, 2000; Spahr & Blakely, 1985).

The Occoquan Reservoir is a major water supply source for over 1.3 million people served by the Fairfax County Water Authority (FCWA). Analysis completed from 1969-1970 concluded that serious water quality problems in the Occoquan Reservoir were due to inadequately treated sewage discharged by eleven secondary treatment plants. To remediate the problems the Virginia State Water Control Board adopted the Occoquan Policy in 1971. The principal requirement of the policy was the construction of a regional water reclamation facility to replace the eleven existing treatment plants, resulting in the construction of the Upper Occoquan Service Authority (UOSA) ("UOSA History,"). UOSA discharges its reclaimed water into Bull Run, located nearly 6 miles above the headwaters of the Occoquan Reservoir and 20 miles above the water supply intake. From 1978 to 2008, reclaimed water from UOSA comprised about 4% of the total reservoir inflow. In the following period, from 1997 to 2002 the UOSA flow accounted for about 7.6% of the average annual streamflow (Van Den Bos, 2003). UOSA developed an expansion program in an effort to meet future needs resulting from increases in population and associated wastewater flows in its service area. This expanded the treatment plant capacity to 54 MGD as of 2005, and further increased the proportion of wastewater effluent to nearly 20% in the Occoquan Reservoir ("UOSA History,"). UOSA discharge can supply up to 90% of the water entering the reservoir, on a daily basis, under drought conditions (Van Den Bos, 2003).

As the above brief review illustrates, while it’s not uncommon for a substantial portion of the source water for a drinking water treatment plant (DWTP) to originate from upstream wastewater contribution (S. W. Krasner et al., 2009; Snyder et al., 2003). There hasn’t been a systematic evaluation of the treated wastewater to DWTPs completed in over 30 years (NRC, 2012; USEPA, 1998). This dissertation’s modeling efforts will serve as a viable way of locating occurrences of de facto reuse (such as the Occoquan Reservoir) on a national scale. Furthermore, initiating the following of more in-detail studies (at watershed scale) for sites with high levels of de facto reuse.

Wastewater Contaminants and Tracers

Risks associated with reclaimed wastewater are two-prong, biological and chemical risks (Salgot, Huertas, Weber, Dott, & Hollender, 2006). Microbiological criteria of wastewater reclamation and reuse include the use of multiple barriers for the control of pathogens. One of the major goals of wastewater treatment plants is to reduce pathogen loads in order to decrease public health risks associated with exposure. However, the effectiveness of pathogen control through the routine monitoring of the wastewater effluent by means of standard indicators such as fecal coliform is in question (Harwood et al., 2005). Several studies have demonstrated that coliform bacteria do not adequately reflect the occurrence of pathogens due to their relatively high susceptibility to chemical disinfection and failure to correlate with enteric viruses and protozoan parasites (Bonadonna, Briancesco, Ottaviani, & Veschetti, 2002; Harwood et al., 2005; Havelaar, Vanolphen, & Drost, 1993; Miescier & Cabelli, 1982).

Organic wastewater contaminants (OWCs) such as prescription and non-prescription drugs and their metabolites, fragrances, flame retardants, plasticizers, disinfectants, personal care products, fluorescent whiteners, detergent metabolites, products of oil use and combustion, and other extensively used chemicals are frequently detected in streams whose flow contains effluent from municipal wastewater treatment plants (Kolpin et al., 2002; Stackelberg et al., 2004). The term OWCs in the following studies refers to unregulated and regulated contaminants of wastewater origin. The prevalence of these contaminants was displayed in a USGS study that sampled 139 streams across 30 states. OWCs were found in 80% of the streams surveyed, and 82 of the 95 compounds were detected. Measured concentrations of the detected compounds were generally low, while benzo[a]pyrene and bis(2-ethylhexyl)phthalate exceeded their maximum contaminant levels. Stackelberg et. al sampled from streams containing 37-67% wastewater at low flow conditions, resulting in the detection of over forty OWCs cited as likely deriving from domestic and (or) industrial wastewater that are processed through municipal standard treatment plants. Standard wastewater treatment facilities are generally designed to remove dissolved inorganic constituents such, and are nor specifically designed to remove organic contaminants that are likely to be present at trace levels (Stackelberg et al., 2004). Therefore, OWCs are likely to be present in effluent from municipal WWTPs and their incomplete removal has been documented (Miege, Choubert, Ribeiro, Eusebe, & Coquery, 2009; Onesios, Yu, & Bouwer, 2009; Stumpf, Ternes, Wilken, Rodrigues, & Baumann, 1999). Krasner et. al sampled wastewater effluents and rivers impacted by wastewater discharges. Primidone analysis yielded a 10th percentile concentration of 2 ng/l, median of 7 ng/l, and max of 95 ng/l (Guo & Krasner, 2009).

PPCPs, perflourinated compounds and other chemical types are lumped together by the Environmental Protection Agency (EPA) as contaminants of emerging concern (CECs). Chemicals in this category often have a risk to human health and the environment associated with their presence, frequencies of occurrence, and/or source are not known (Snyder et al., 2004). The occurrences of CECs are expected to increase with the expansion of new contaminants; created by new chemicals or by changes in use and disposal of existing chemicals (Kolpin et al., 2002). It is impossible for the EPA to keep up with toxicological studies regarding the growing list of CECs. This project assist in the protection to drinking water intake from surface water in relation to CECs attributed to the surface water through wastewater effluent. Analytical chemists continually discover new CECs, while a group of seven surrogates for CEC occurrence and treatment have been identified (Dickenson, Drewes, Sedlak, Wert, & Snyder, 2009; Dickenson, Snyder, Sedlak, & Drewes, 2011). It may prove to be more beneficial for water utilities and stream ecologists to know the relative percentage of wastewater in a water body rather than the parts per trillion concentrations of over 50 chemicals. The percent wastewater can be used with site specific or average wastewater effluent concentrations to estimate, conservatively, relative concentrations of each CEC. This is critical, because it is unlikely CECs will be measured on any routine frequency or at all 17,000 WWTPs across the USA, due to analytical costs and uncertainty of their human health or ecological risk significance.

In recent years, the scientific community has begun to put more emphasis on the occurrence of drugs of abuse or illicit drugs (ID) in various environmental compartments. Although, fewer studies have been completed as compared to PCPPs. Key target chemicals for this group include cocaine, heroin, nicotine, amphetamine, methamphetamine, opiates or cannabis and their metabolites (Baker & Kasprzyk-Hordern, 2011; Huerta-Fontela, Galceran, & Ventura, 2007; Ratola, Cincinelli, Alves, & Katsoyiannis, 2012; van Nuijs et al., 2011). Similarly to PPCPs, IDs are only partially removed by WWTPs. Reported removal rates include, a range of 89.6 to 97.8% for cocaine, 69 to 93% for benzoylecgonine, and 48.6 to 80.1% for MDMA (commonly known as ecstasy) (Bones, Thomas, & Paull, 2007; Hummel, Loffler, Fink, & Ternes, 2006; Pedrouzo, Borrull, Pocurull, & Marce, 2011).

Several wastewater contaminants, including endocrine disrupting compounds (EDCs) and PCPPs, pose ecological threats. Endocrine disruptors are defined as “an exogenous substance or mixture that alters function(s) of the endocrine system and consequently causes adverse effects in an intact organism, or its progeny, or subpopulations (Vos et al., 2000).” EDCs impose their effects by mimicking endogenous hormones, antagonizing normal hormones, altering the natural pattern of hormone synthesis or metabolism, or modifying hormone receptor levels (Soto et al., 1995). The EDCs that are of higher concern for the aquatic wildlife are those originating from either treated or untreated municipal and industrial wastewaters. The most potent EDCs found in sewage are steroidal estrogens such as 17β-estradiol (E2), estrone (E1), and 17α-ethnyestradiol (EE2) (Pojana, Gomiero, Jonkers, & Marcomini, 2007). Several studies have shown that these EDCs have the potential to exert effects at extremely low concentrations (Jobling & Sumpter, 1993; Mills & Chichester, 2005; White, Jobling, Hoare, Sumpter, & Parker, 1994). Personal care products such as triclosan also pose ecological threats. Triclosan has shown to be acutely toxic to several different types of aquatic life (Dussault, Balakrishnan, Sverko, Solomon, & Sibley, 2008; Ishibashi et al., 2004; Orvos et al., 2002).

Several studies have suggested many anthropogenic organic compounds as chemical markers of municipal wastewater due to their loading and persistent behavior (Buerge, Buser, Kahle, Muller, & Poiger, 2009; Buerge, Keller, Buser, Muller, & Poiger, 2011; Glassmeyer et al., 2005; Guo & Krasner, 2009; Oppenheimer, Eaton, Badruzzaman, Haghani, & Jacangelo, 2011). Sucralose has been amongst these cited as an indicator compound of wastewater loading to surface water (Badruzzaman, Oppenheimer, & Jacangelo, 2013; Oppenheimer et al., 2011; Torres et al., 2011). Ideal wastewater indicators should hold the following characteristics: (a) source specificity (b) sustained effluent release because the indicator is not rapidly degraded by biological treatment processes, (c) demonstrated analytical methodology, (d) no attenuation during transport, and (e) virtually zero background (Oppenheimer et al., 2011). Sucralose is a chlorinated carbohydrate widely used as an artificial sweetener (Henkel, 1999). This artificial sweetener is not degraded in the human body and travels through the digestive system being excreted through urine and feces, making sewage its dominant source to the environment (Stuart W Krasner, 2008; Roberts, Renwick, Sims, & Snodin, 2000; Rodero, Rodero, & Azoubel, 2009). Its high loading to WWTPs is coupled by no significant degradation during wastewater treatment processes. Sucralose is a highly stable compound, which undergoes negligible metabolism in mammals, and displays a low biodegradation potential in the environment (Tollefsen, Nizzetto, & Huggett, 2012). This makes sucralose present in effluent waters and able to reach environmental water sources (Torres et al., 2011). For these reasons sucralose is used in the validation of DRINCS.

Impacts of Climate Change and Seasonal Variability

There is concern in climate change that the anthropogenic elevation of atmosphere CO2 and other greenhouse gases will induce global warming through the twenty-first century (Intergovernmental panel on climate change, 2001). Historic records and climate models are relatively consistent in predicting global warming, but precipitation patterns are more complex and regionally variable and are much more difficult to model (Rood, Samuelson, Weber, & Wywrot, 2005). A common view is that global warming will increase evaporative rates from oceans and thus promote the global hydrologic cycle and generally increase precipitation (Intergovernmental panel on climate change, 2001). This is on a macroscale view, regional variations are less certain due to the uncertainties in spatial pattern predictions. Many studies warrant for more extreme declines in stream flow on a regional level. From the 1940's to present, the general pattern of stream flow has been toward an increase in mean discharge in the autumn and winter months in most regions of the United States. Decreases have occurred in parts of the Pacific Northwest and the Southeast (Chiew & McMahon, 1996; Lettenmaier, Wood, & Wallis, 1994; H.F Lins & Michaels, 1994). Decrease in stream flow trends was also found in the Rood et. al study on the Rocky Mountain region. Analysis revealed flow declines exceeding 0.1% per year over the historic record for 21 reaches while 10 reaches had little change. The rivers displayed a reduction in mean flow equal to 0.22% per year, with four rivers having recent decline rates surpassing 0.5% per year. The authors predict it's likely that there will be continuing decline in future decades (Rood et al., 2005).

Nevertheless, while it is uncertain when or where impacts from climate change will take effect, present day interannual stream flow variations have proven to be very impactful. Interannual stream flow variability (not relating to climate change) in the United States has been defined by their seasonality and persistence. Month to month changes in dominant stream flow patterns reveal anomalies in stream flow variations across the U.S. Variations from the mean state, in the Upper Mississippi, South Atlantic/Gulf, Far West, Ohio Valley, Northeast and Eastern/Mid-Atlantic regions are observed in all seasons of the year. While irregularities in the Southern Plains and New England regions are observed in autumn, winter, and spring; occurrence in the Rocky Mountains and Middle Mississippi regions occur in the late spring and summer. The Upper Mississippi is the dominant region of stream flow variability across the U.S., responsible for 12-14% of the total variance in U.S. stream flow (H. F. Lins, 1997).

Spatial variations with gradients in water quality often related to tributary inflows that contain substantial amounts of wastewater effluent (Jones, Kelso, & Schaeffer, 2008). Effects can be enhanced if tributaries discharge into an embayment rather than directly into a larger water body. An embayment provides a recess in coastline that causes a lack of mixing. This occurs in the case of Green Bay, WI. Green Bay has substantially higher nutrient concentrations than Lake Michigan, the main body, due to tributary nutrient loading into a confined embayment that impedes mixing (Jones et al., 2008; Lathrop, Vandecastle, & Lillesand, 1990). This alludes to the importance that Strahler stream order can have.

Dilution factors play a large role in measuring the effects of wastewater effluent on downstream subjects. Guo et. al (2007) noted this occurrence in the Colorado watershed, where three pharmaceuticals and personal care products (PPCPs) were each approximately twice as high at the site between 2006 and 2007. This was explained by only half of the stream flow being measured in 2006 when compared to 2007 (Guo & Krasner, 2009). Similar effects were echoed in a study performed by Barber et. al (2006) on the Boulder Creek Watershed in Colorado. Natural and anthropogenic variation in flow led to percent effluent downstream of the Boulder WWTP ranging from 10-26% effluent during spring runoff and 39-74% effluent during base flow (Barber et al., 2006). An important aspect of this project is the analysis of de facto reuse calculated for the full spectrum of percentile stream flows based on historical USGS streamgage records. Benefits are two-fold, due to it allowing for the examination of possible impacts from future climate change impacts and current interannual variability.

Public Perception of Reclaimed Water for Potable Use

Public perception and acceptance is recognized as two primary hindrances for the successful implementation of water reuse projects. The early approach of water utilities was to persuade through marketing the public of the safety for the reuse of wastewater as a drinking water source. More recently it is accepted that social marketing or persuasion has proven to be ineffective in influencing people to use reclaimed water (Po, Kaercher, & Nancarrow, 2003). Studies show that increase in public acceptance regarding the logic of water reuse doesn’t correlate with the willingness to use the water for their personal usage. This leaves water utilities in the tough position of trying to battle strong opposition to wastewater reuse, without clear insight as to what makes this change.

Nevertheless, the public has expressed an interest in being meaningfully involved in water reuse decision-making and finding ways to ensure an independent and secure water supply for their communities (Bruvold, 1981, 1995; Lawrence, 2000). There are several different factors that are believed to influence the public's willingness to adapt a water reuse scheme. The factors include but are not limited to the following: disgust or "yuck" factor (Angyal, 1941; Ching, 2010; Po et al., 2003); risk perceptions associated with water reuse (Frewer, Howard, & Shepherd, 1998; Slovic, Finucane, Peters, & MacGregor, 2004); the specific use intended (Jeffrey, 2002); the source water being reused (Jeffrey, 2002); trust and knowledge (Kaercher, Po, & Nancarrow, 2003); and cost of reused water (Kaercher et al., 2003).

The "yuck" factor is a term that was adopted in the 1970's to describe the psychological disgust as a barrier to water reuse. The visceral nature of this reaction makes it hard for the water reuse community to overcome. The reaction of disgust is likely to be linked to the perception of water reuse as dirty. Common objects that have a similar disgust factor are urine, excrement, dirt and mud. Emotions of disgust are defined as the emotional discomfort generated from close contact with certain stimuli (Angyal, 1941). To counter disgust projects have strayed away from referring to water reuse as treated wastewater. The law of contagion is one possible reason as to why the levels of disgust attributed to excrement and urine are attached to water reuse no matter what level of treatment is completed to the end product. This law of contagion suggests that neutral objects can acquire disgusting properties from another object just by means of brief contact (Po et al., 2003). Further suggesting that public acceptance will not give way solely due to high levels of water treatment. It also touches on the possible irreversible nature of the “yuck” factor. Even though this human aversion is a well-recorded psychological fact, little has been written about it in connection to the use of water-reuse policies, and even less has been done to quantify this factor. In the field of water governance it can be seen that the “yuck” factor has been a fairly intractable problem in the implementation of water-reuse policies. On the contrary, some countries have overcome this feeling of disgust, so yuck must not be an immutable factor (Ching, 2010). The survey will quantify the public’s knowledge of de facto reuse within their water system, and their acceptance relating to a “threshold” value. I hypothesize that a correlation exists between the values, implying that people whom are aware of de facto reuse are more accepting of its occurrence. Further implying that the lay of contagion may also be applied to disassociate the “yuck” factor from potable reuse by attaching it to a natural occurrence.

The Singapore NEWater project is one of the few water reuse applications involving potable water reuse. Singapore was an area experiencing high uncertainty regarding future availability of water sources. Half of the country’s water supply is imported from Malaysia and disputes between the two countries threatened future water supplies (Po et al., 2003). The NEWater project was introduced as a strategic option that reuses the available water and was economically cheaper than desalination. Officials were aware of the unlikelihood of customer acceptance and to ease the public perception they decided to begin by mixing the recycled water with reservoir water. As of 2003, 1% of the treated wastewater is pumped to reservoirs before being piped to residential and office taps. The government’s goal is to meet 20% of the country’s needs from NEWater by 2015 (Collins, 2003). Officials of the NEWater project combined knowledge of factors affecting the public perception to mitigate through the task of gaining public acceptance. The term NEWater was adopted to counter the negative association of wastewater as the water source. Singapore government also took the step of introducing the water scheme as the best option for costs. This tied into the public's positive response to decrease in costs and to their need for transparency and dissemination of scientific knowledge. Mixing the wastewater with other natural water sources possibly had an association affect. The law of contagion could have caused the public to disassociate wastewater with the disgust of sewage terms, and associate the NEWater with personal emotions pertaining to natural rivers, streams and lakes. Environmental stressors and societal pressures relating to uncertainty in future water supplies are expected to have played a major role in the public's willingness to accept.

The law of contagion has been shown to work for and against public acceptance, by being cited as one of the main detriments of the "yuck" factor and as a tool for public acceptance of the NEWater. This study suggests that knowledge of de-facto reuse will influence the public's acceptance due to the law of contagion. Further suggesting that consumers whom are aware of de facto reuse occurring naturally within their environment will have stronger attitudes of acceptance towards their personal threshold.

GIS-based Hydrologic Modeling

It is commonly recognized that studies of water resources benefit from the use of Geographic Information System (GIS) (Panagopoulos, Bathrellos, Skilodimou, & Martsouka, 2012). Hydrologic modeling utilizing GIS has been in practice for over 20 years, for the pre- and post-processing of spatially distributed hydrologic modeling data (Ogden, Garbrecht, DeBarry, & Johnson, 2001). Benefits of incorporating GIS in hydrologic analysis include improved accuracy, less duplication, easier map storage, more flexibility, ease of data sharing, timeliness, greater efficiency and higher product complexity (Ogden et al., 2001). Qualitative and quantitative data can be integrated through spatial relationships rather than by attributes that may not be a an accurate representation (Frost, 1997). These spatial relationships lead to the visualization of data which is the most obvious and appealing feature of GIS. Interactive visualization of model results can provide support in decision making and in the assessment of sensibleness of the predictions (Miles & Ho, 1999).

Four distinct hydrologic applications of GIS include: hydrologic assessment, hydrologic parameter determination, hydrologic model set up using GIS, and hydrologic modeling inside GIS (steady-state processes) (Maidment, 1991). These four applications have resulted in an abundance of empirical studies. Early work focused on the influence of spatial aggregation on runoff through the raster imaging of soil conservation service curve numbers (Mancini & Rosso, 1989). Other studies areas include surface run-off estimation (Julien, Saghafian, & Ogden, 1995; Stuebe & Johnston, 1990), non-point pollution and water quality studies (Kao, 1992; Mitchell, Engel, Srinivasan, & Wang, 1993), storm water modeling (Kwadijk & Sprokkereef, 1998), flood risk assessments and hydrological drainage modeling (Ellis, Viavattene, Chlebek, & Hetherington, 2012; Shea, Grayman, Darden, Males, & Sushinsky, 1993), subsurface ground water modeling (Richards, Roaza, & Roaza, 1993), and economic and hydrologic interdependence (Ward & Lynch, 1996), amongst others. These have been completed along the continuum of geographical scales, ranging from the local watershed (Vivoni & Richards, 2005), to regional water resource planning (Arnold, Srinivasan, Muttiah, & Williams, 1998; Li, Chien, Hsieh, Dzombak, & Vidic, 2011; Schultz, 1994), and global water balances (Oki, Musiake, Matsuyama, & Masuda, 1995).

GIS has been used in surface water quality modeling applications of point-source pollution. The GIS-ROUT model is water quality model that provides determines the potential concentrations of consumer product ingredients in surface waters and their contributions to the water quality (Wang, Homer, Dyer, White-Hull, & Du, 2005; Wang, White-Hull, Dyer, & Yang, 2000). The model was recently built into web-based interface and is now known as ISTREEM. Strengths of ISTREEM lie in its web-based interface, ease of use and interpretation of results, ability to access previous runs, and the capability of exporting the results to Microsoft Excel. On the contrary, weaknesses lie in the time requirement for runs, the method of color coding results by a generic range of values (percentiles would be more significant), its inability to retrieve the count of upstream WWTPs, and the low resolution of the Reach File 1 in comparison to the higher resolution of the National Hydrography Dataset Plus. The RiverSpill, SWAT and BASINS models are more examples. RiverSpill calculates, locates and maps the population at risk from the introduction of contaminants to the public water supply by calculating the time of travel for the contaminant (Samuels, Bahadur, Amstutz, Pickus, & Grayman, 2002). The Soil and Water Assessment (SWAT) model is used to assess water supplies of point and non-point source pollution on small watersheds and large river basins. SWAT was designed to simulate major components and interactions of the hydrologic cycle (Arnold et al., 1998; Ogden et al., 2001). In more recent analysis SWAT can be used in conjunction with BASINS. Better Assessment Science Integrating point and Nonpoint Sources (BASINS) was developed by EPA's Office of Water to help states more efficiently target and evaluate waterbodies failing to meet water quality standards. BASINS integrates environmental data, analytical tools, and modeling programs allowing the user to assess water quality at selected stream sites throughout a watershed (Whittemore & Beebe, 2000).

Prior studies display the benefits and reinforce the promise of developing the model within GIS, but they also display the need for the DRINCS Model. While several surface water quality models have been presented none of the above models are capable of completing the type of analysis necessary to fulfill this projects objectives. Previously mentioned models fall short in their inability to model at the national scale, data limitations specific to de facto reuse and lower resolution stream routing. All of the aforementioned models perform stream routing analysis based on the Reach File 1 or Enhanced River Reach File. The DRINCS model differs in that it is being developed on a national scale and utilizes more current and higher resolution data of the National Hydrography Dataset Plus.

Summary of Research Needs

As demonstrated in the preceding review, de facto wastewater reuse is a multifaceted topic involving sustainability of water resources during climatic variations, national occurrence, and public perception. Previous studies have reported the presence of PPCPs and EDCs downstream of WWTP outfalls, but these have been performed at the watershed scale. Research is needed to gain a broader national-scale understanding of current CEC exposure to the public by means of de facto reuse. In the area of occurrence, de facto reuse has not been quantified within the continental U.S. for the past 30 years. Significant increases in the general population and in the ratio of U.S. residents on collective sewer systems deem an updated analysis imperative for future decision-making. The use of GIS-based hydrological models in previous work displays the benefits of developing this research within the GIS framework. Creation of the model in GIS also serves as a platform to expand. Future work could include additions of other point and non-point sources and/or land use practices that influence water quality. In the area of public perceptions, several studies have been conducted regarding varying reclaimed water schemes. On the contrary, no studies have reported the public's awareness of unplanned reuse. There lies the need to assess the extent to which the public is aware of this occurrence and statistically determine if higher awareness (knowledge) is correlated to higher acceptance. If indeed increased knowledge is correlated to increased acceptance; the information regarding occurrence of de facto reuse can be strategically used to combat the "yuck" factor.

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Chapter 3

ASSESSMENT OF DE FACTO WASTEWATER REUSE ACROSS THE U.S.: TRENDS BETWEEN 1980 AND 2008*

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Abstract

De facto wastewater reuse is the incidental presence of treated wastewater in a water supply source. In 1980 the EPA identified drinking water treatment plants (DWTPs) impacted by upstream wastewater treatment plant (WWTP) discharges and found the top 25 most impacted DWTPs contained between 2% and 16% wastewater discharges from upstream locations (i.e. de facto reuse) under average streamflow conditions. This study is the first to provide an update to the 1980 EPA analysis. An ArcGIS model of DWTPs and WWTPs across the USA was created to quantify de facto reuse for the top 25 cities in the 1980 EPA study. From 1980 to 2008, de facto reuse increased for 17 of the 25 DWTPs, as municipal flows upstream of the sites increased by 68%. Under low streamflow conditions, de facto reuse in DWTP supplies ranged from 7% to 100%, illustrating the importance of wastewater in sustainable water supplies. Case studies were performed on four cities to analyze the reasons for changes in de facto reuse over time. Three of the four sites have greater than 20% treated wastewater effluent within their drinking water source for streamflow less than the 25th percentile historic flow.

Introduction

The growing global economy and population couple to make water a limited resource in terms of both quantity and quality in many regions. High water stress regions have included California, Australia, the Middle East, and the Mediterranean (Insights from the Comprehensive Assessment of Water Management in Agriculture, 2006; "Water for people water for life: the United Nations world development report," 2003). Reclamation of water after treatment in modern wastewater treatment plants (WWTPs) will likely be an important and underutilized part of sustainable water resource management. The National Academy of Engineering (NAE) recently published a report on wastewater reuse, and the number one research need for human health, social, and environmental studies is quantification of the extent of de facto (unplanned) potable reuse in the United States (Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater, 2012). Efforts to identify the significance and potential health impacts of de facto water reuse are impeded by outdated information regarding the contribution of municipal wastewater effluent to potable water supplies. “Because new water reuse projects could decrease the volume of wastewater discharged to water sources where de facto reuse is being practiced, the lack of understanding of the contribution of wastewater effluent to water supplies restricts our ability to assess the net impact of future water reuse on the nation’s water resource portfolio (NRC, 2012).” This study begins to address this research need by creating a geospatial database of drinking water treatment plants (DWTPs) and WWTPs across the U.S. and utilizing it to quantify the degree to which de facto reuse occurs in selected cities.

De facto wastewater reuse is the unplanned or incidental presence of treated wastewater in a water supply source (Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater, 2012). It is not uncommon for a substantial portion of the source water for DWTPs to be originally derived from upstream treated wastewater contributions to the surface water resource. De facto reuse of wastewater in domestic public water supplies is not a new occurrence but rather is geographically widespread. Noteworthy examples include the South Platte River downstream from the City of Denver; the Schuylkill River in Philadelphia, PA; the Quinnipiac River in Connecticut; the Santa Ana River in southern California; the Ohio River near Cincinnati, Ohio; and the Occoquan Watershed southwest of Washington, DC (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007; Chen, Nam, Westerhoff, Krasner, & Amy, 2009; Krasner, Westerhoff, Chen, & Dotson, 2009; Mitch & Sedlak, 2004; Morehouse, Carter, & Sprouse, 2000; Spahr & Blakely, 1985). For example, the Occoquan Reservoir is a major water supply source for more than 1.3 million people served by the Fairfax County Water Authority (FCWA). Impacts resulting from de facto reuse in the Occoquan Reservoir warranted the need of a planned indirect reuse scheme by the Upper Occoquan Service Authority (UOSA). The UOSA was created to manage water quality issues in the Occoquan Reservoir caused by discharges of inadequately treated sewage. UOSA WWTP facilities were expanded to 54 MGD in 2005, which increased the proportion of wastewater effluent in the flow through the Occoquan Reservoir to nearly 20%, from an average of 7.6% between 1997 and 2002("Upper Occoquan Service Authority Website,"). Under drought conditions, UOSA discharge can supply up to 90% of the water entering the reservoir on a daily basis (Van Den Bos, 2003).

A systematic evaluation of treated wastewater contributions to DWTPs has not been completed in more than 30 years (NRC, 2012; USEPA, 1998; Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater, 2012). In 1980 the EPA published Wastewater in Receiving Waters at Water Supply Abstraction Points. This study identified 1246 municipal water supply utilities using surface water from 194 basins serving 525 cities with populations of more than 25 000. For each utility the total number of upstream wastewater discharges was tabulated, and upstream municipal flows were summed for each site. Among the 25 municipalities with the highest effluent concentrations, such concentrations ranged from 2.3 to 16% (Wastewater in Receiving Waters at Water Supply Abstraction Points, 1980). These percentages very likely have significantly increased since this study because of population growth. Population in the United States, as reported in the 1980 United States Census and predicted for 2010 by the US Census Bureau, has grown from 225 million to 308 million, an increase of 36%. Additionally, the number of people on centralized sewer systems also increased drastically (Burian, Nix, Pitt, & Durrans, 2000; USEPA, 1997); approximately 75% of the total population in the U.S. is connected to centralized sewer systems. U.S. WWTPs treat 32 billion gallons of wastewater per day, most of which is discharged into surface water (EPA, 2004). It is expected that as municipal sewers serve increased populations, de facto reuse increases. These treated municipal wastewater discharges provide a sustainable supply of streamflow.

WWTP discharges are a source of micropollutants (i.e., contaminants of emerging concern (CECs)) for aquatic systems (Kolpin et al., 2002; Snyder, Westerhoff, Yoon, & Sedlak, 2003). Among these are pharmaceuticals and personal care products (PPCPs), disinfection byproducts (DBPs), and microbes (S. W. Krasner et al., 2009). The presence of CECs in surface and drinking waters impacted by treated wastewater discharges has been reported (Glassmeyer et al., 2005; Kolpin et al., 2002; Snyder et al., 2004). The potential risks to human health and the environment associated with CEC presence, frequency of occurrence, and/or source are not known (Snyder et al., 2004). Thus, identification of waterways impacted by wastewater is important, but sampling alone cannot quantify CEC levels at all US DWTPs (n > 10 000) or under all streamflow conditions. A GIS-based model could facilitate the assessment of potential impacts from wastewater. This report includes analysis from an ongoing project to build such a model to complete a nationwide assessment. The need for this nationwide assessment is warranted by the lack in previous research. Several water quality models have been developed in Europe for this purpose (Kugathas, Williams, & Sumpter, 2012; Price, Williams, van Egmond, Wilkinson, & Whelan, 2010; Rowney, Johnson, & Williams, 2011; Williams, Churchley, Kanda, & Johnson, 2012; Williams et al., 2009). A recent paper describes a similar application for Europe (Johnson, Oldenkamp, Dumont, & Sumpter, 2013). One such paper includes a plot displaying percentage effluent in its analysis of decamethylcyclopentasiloxane in surface water (Price, Williams, Zhang, & van Egmond, 2010). A GIS-based water quality model has also been developed in the U.S. titled ISTREEM. ISTREEM is used to estimate concentrations of down the drain chemicals resulting from WWTP discharges ("American Cleaning Institute Website,").

The model developed in this analysis includes a larger data set of WWTPs and DWTPs, more expansive stream gauge data, and higher resolution hydrography than ISTREEM. Another key difference between the two models is the holistic approach taken in analyzing wastewater effluent rather than individual contaminants.

Streamflow variations due to potential climate change may amplify future occurrences of de facto reuse owing to decreases in streamflow that negate a river's natural dilution of wastewater during drought conditions. Areas of the U.S. that historically have been subject to drought are among the regions most likely to experience further streamflow declines. Since the 1940s, decreases in mean discharge during autumn and winter months have occurred in parts of the Pacific Northwest and Southeast (Chiew & McMahon, 1996; Lettenmaier, Wood, & Wallis, 1994; Lins & Michaels, 1994). Analysis of historic streamflow in the Rocky Mountain region revealed flow declines exceeding 0.1% per year. The rivers displayed a reduction in mean flow of 0.22% per year; four rivers had recent decline rates surpassing 0.5% per year. Continuing decline in future decades is likely (Rood, Samuelson, Weber, & Wywrot, 2005).

The aim of this paper was to assess the current extent of de facto wastewater reuse for the top 25 most impacted cities in the 1980 EPA study. This included (1) development of a model within the ArcGIS framework to determine spatial relationships between DWTP intakes and upstream WWTP discharges (based on more current data), (2) quantification of the amount of accumulated wastewater at each DWTP intake, (3) and examination of wastewater percentages under average and low-flow stream conditions. The 1980 results and updated values were compared to discern overall trends, and four cities were used as case studies to investigate drought by evaluating wastewater impacts based on a full range of historic streamflow percentiles, which in turn served as an analysis of streamflow conditions built around the uncertainties of climate change. This paper's assessment de facto reuse served a 2-fold purpose. Knowledge regarding the magnitude and occurrence of de facto reuse provided insight into the degree treated wastewater effluent contributes to the sustainable water supply and the magnitude of potential exposure of CEC's.

Materials and Methods

Modeling Approach

Data were mined from several different sources to achieve the three main objectives of this paper. The primary large data sets included the Clean Watershed Needs Survey (CWNS) of 2008, the National Hydrography Data set Plus (NHDPlus), and EPA's Permit Compliance System. Data from these sources were incorporated into a GIS model that was used to provide spatial context for updated water treatment plant locations in relation to upstream WWTP discharge points. Locations of a representative sample of WWTP discharge locations were visually ground-truthed via Google Maps. Sites were selected for the four case studies on the basis of outcomes of changes in municipal flow and streamflow. This allowed for a more detailed look into societal changes at the watershed scale that could have impacted the outcomes.

ArcGIS 10 was used as the framework for the model. Base layers for topography as well as city and state boundaries were obtained from the U.S. Geological Survey (USGS) through the National Atlas Web site. Hydrography layers were obtained from NHDPlus Version 1. NHDPlus incorporates features of the National Hydrography Data set (NHD), the National Elevation Dataset (NED), and the National Watershed Boundary Data set

(WBD). Stream networks were based on the medium-resolution NHD (1:100 000 scale). USGS stream gauges were also included within the NHDPlus suite; attribute data include average, min, max, and percentile streamflows. The statistical values were calculated on the basis of the entire record period until April 20, 2004 (the date NHD pulled the data for analysis) (USEPA, 2007). The 7 day 10 year (7Q10) low flow was calculated using EPA DFLOW 3.1 to assess low-flow streamflow conditions. Low-flow values for sites beside lakes were assumed to be the same as the 7Q10 values from 1980.

CWNS 2008 was the main data source for WWTP location and flow data because it was the most current and complete of the available sources. Therefore, the 2008 values were used as the baseline for WWTPs in the database. This study analyzed treated municipal wastewater discharges from WWTPs, which include combined sewer systems but do not take into consideration combined sewer overflows or wet weather by-passes (both of which yield significant micropollutant loads). There are approximately 15 837 US WWTPs according to CWNS 2008; we considered facilities (n = 14 651) that currently discharge to surface waters. Locations for WWTPs that were missing information were obtained through the Permit Compliance System and CWNS 2004. DWTP intake coordinate locations were obtained from the appendix to the 1980 EPA study (top 25) and other sources. Overall, 6 061 DWTPs are included in our GIS model. Following this study, further analysis will be completed on the remaining DWTPs. Coordinate data for the DWTPs and WWTPs were transcribed into Microsoft Excel and then added to ArcGIS as a vector layer of points representing the DWTP inlet or WWTP discharge point of each facility. Attribute data for the DWTPs included the municipality and population served; the WWTP data included facility name, CWNS number, level of treatment (primary, secondary, tertiary), and present design flow. The level of treatment was not included in the treated wastewater effluent calculations, but it is important to point out that potential threats of micropollutants significantly decrease with higher levels of treatment.

Updating the Top 25 of 1980

The GIS model was used to perform spatial analysis of DWTPs in relation to upstream WWTPs (as shown in Figure 3.1). Regional-level flowlines by hydrologic unit were transformed into a network via the network analysis tools within ArcGIS. ArcHydro Tools was used to trace water flow upstream of the water treatment plant locations. Once the upstream path was found, the contributing discharges of all WWTPs along it were summed. As in the 1980 EPA study, conservative assumptions were made, including (1) WWTP discharge was equal to that of the plant design flow, (2) WWTP effluent had no in-stream loss, and (3) all water bodies were completely mixed. A mass balance was performed for the wastewater effluent at each DWTP intake point under the assumption that the WWTPs were the only input of wastewater and the DWTP was the sole uptake. Therefore, the wastewater percentage was calculated by dividing the total upstream discharge by the average streamflow of the nearest USGS stream gauge. The previous study took the 1980 streamflow value as the annual average, whereas the updated values are based on historical averages. Historical averages were used in the update in place of the annual average for 2008 to avoid the possibility of streamflow values being skewed in the event that 2008 held extreme events. For comparison purposes, the 1980 streamflow values were kept as reported in the original study. This warranted the need to normalize for base streamflow conditions. Thus, the wastewater percentages were calculated under an additional condition, which assumed the same average streamflow as reported in 1980 (see Figure 3.3). This allowed a basic assessment of the sensitivity of wastewater percentage to changes in streamflow. Analysis of the two sites along the Del-Raritan Canal (Elizabeth and Princeton, NJ) was limited owing to the absence of coordinate data in the original EPA study. Current DWTP locations for these areas were used, but research suggests that, due to changes in water providers, the location studied is likely to be different from that in the 1980 study. Because of this limitation, direct comparisons of values cannot be made for these two sites.

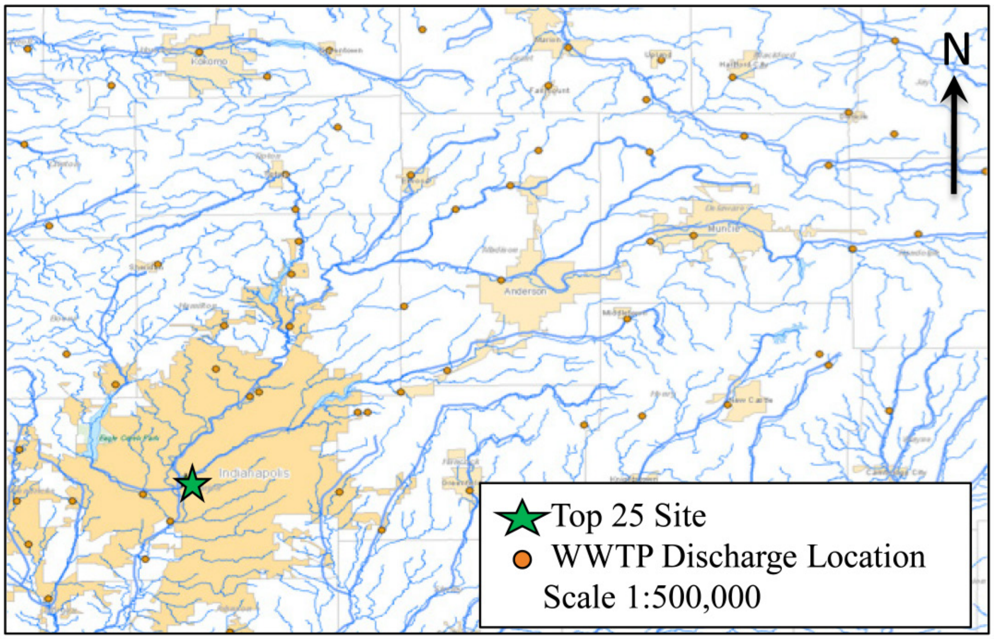

Figure 3.1. GIS screenshot of a river network with DWTP and WWTP sites.

Results and Discussion

Trends in Wastewater Effluent Contribution to Downstream DWTP Intakes

Quantifying the change in municipal flows upstream of the study sites was the first step in assessing the change in treated municipal wastewater impacts between 1980 and 2008. Between1980 and 2008, wastewater effluent contribution to the top 25 cities increased by 68% from 4 887 to 8 241 MGD (214 to 361 m3/s). Overall, 18 of the 25 cities received more wastewater contributions from upstream WWTPs in 2008, and the number of upstream WWTPs increased from 2 211 in 1980 to 2 613 in 2008. One of the largest changes was observed in Neshaminy Creek, PA, where municipal flows more than doubled, increasing by more than 23 MGD (1.0 m3/s) during this period. Figure 3.2 presents the increase in accumulated upstream WWTP discharges. Alton, IL, has the highest value for upstream municipal flows, which is largely attributed to its hydrologic location along the U.S.'s largest river, the Mississippi. Alton's number of upstream wastewater discharge sites increased from 1 567 to 1 892 from 1980 to 2008.

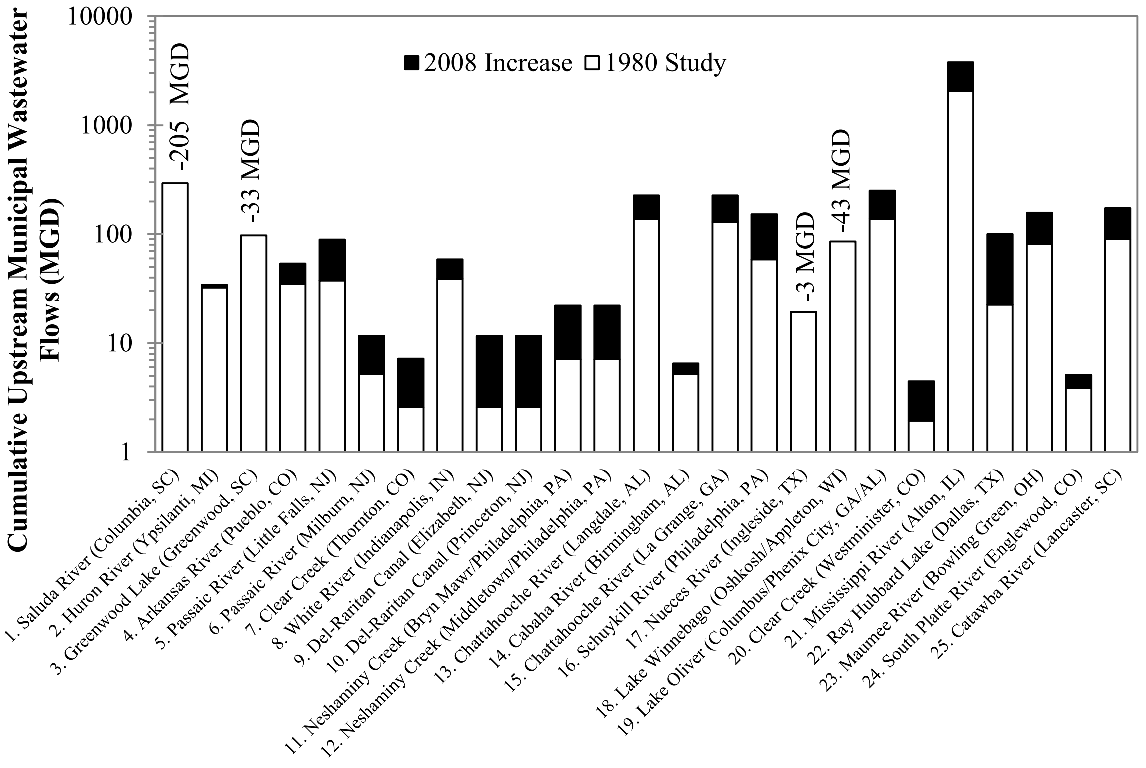

Figure 3.2. Cities with changes in upstream municipal flow between 1980 and 2008. Sites with decreases are annotated with the change in flow.

The next step in the analysis was to determine how increases in municipal flows translated into changes in the de facto reuse percentages at downstream DWTP intakes under average flow conditions. De facto reuse increased at 17 sites, with the average reuse (across the top 25) increasing from 4.9% in 1980 to 6.2% in 2008 (shown in Figure 3). Utilities along the Passaic River, Neshaminy Creek, Schuylkill River, and Ray Hubbard Lake had the highest wastewater percentages. Higher percentages result from an increase in municipal flow, a decrease in base streamflow, or a combination. For example, municipal flows for Westminister, CO, nearly doubled, but the percentage of wastewater during average flow conditions increased only slightly from 3.2% in 1980 to 3.7% in 2008. The higher percentage of wastewater was offset by higher average streamflow conditions. This observation highlights the need to determine the impact of increased municipal flows on wastewater percentages by normalizing wastewater percentages for base streamflow conditions reported in 1980 (see Figure 3.3). In many cases, lower streamflow values used in the 1980 study heightened the impact of increased municipal flows. For Westminister, CO, for example, assuming the same base flow yielded a dramatic increase in wastewater percentage. Although this value is based on 1980 streamflow and not the current estimate in the canal, it sheds light on the high sensitivity of wastewater percentages to changes in streamflow. Lower-order streams (based on the Strahler Stream Order Classification) are more susceptible to such changes because of their lower streamflow as compared to streams of higher order. Impacts of streamflow variation will be discussed further in the case studies below.

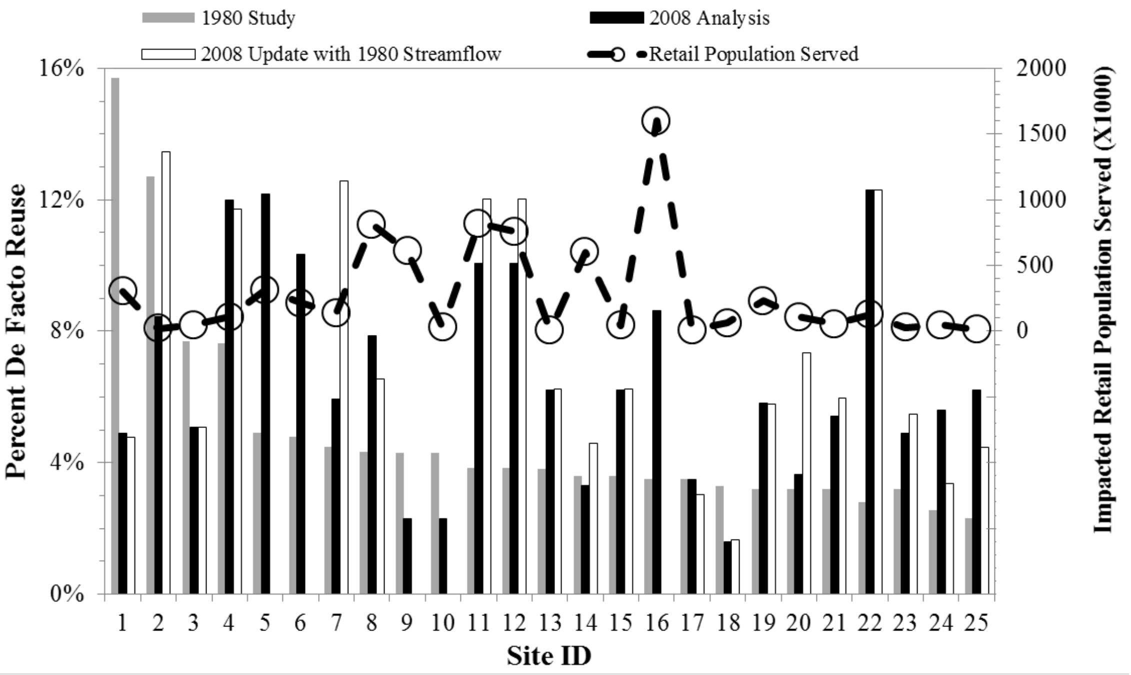

Figure 3.3. Trends in de facto reuse between 1980 and 2008 for EPA's top 25 of 1980. (The X-axis gives same site IDs as in Figure 3.2.)

The magnitude of de facto reuse during low-flow conditions was assessed through analysis of the lowest 7 day average flow that occurs on average once every 10 years (7Q10). As shown in Figure 3.4, de facto reuse increases during prolonged periods of dry weather. Ten of the 25 sites obtain water from sources that may be composed entirely of wastewater effluent (100%). Similar trends show that 14 of the 25 sites use source waters that are effluently dominated (contain greater than 50% wastewater effluent). On average, the wastewater percentage among the 25 sites was 68%. The proportion of wastewater effluent in the streams increased 10 fold between low-flow and average conditions. These values echo the important hydrologic role that WWTP discharges play during periods of low flow.

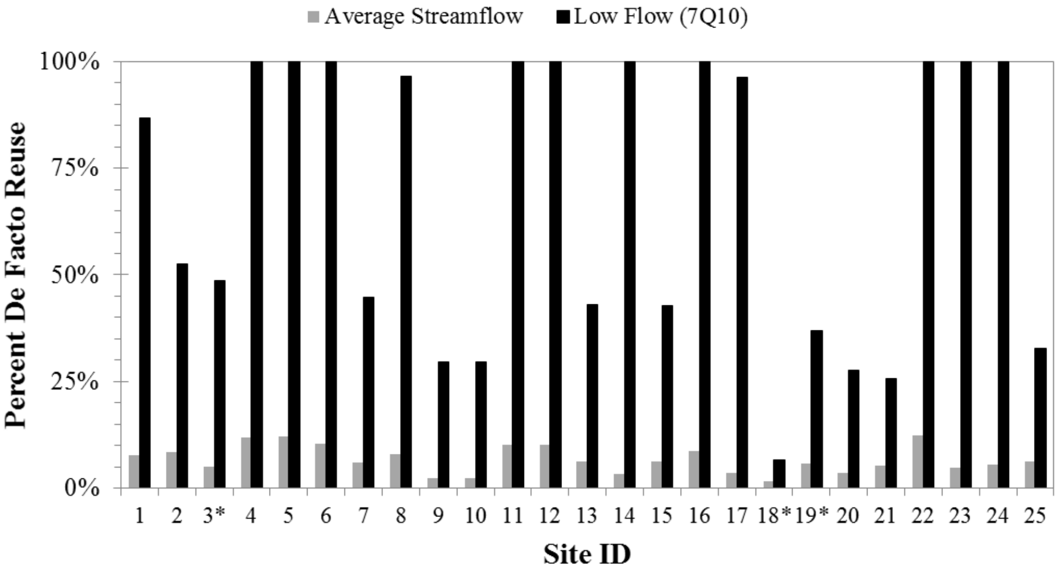

Figure 3.4. De facto reuse under low-flow conditions (modeled by 7Q10). Cities marked with an asterisk are calculated on the basis of 7Q10 streamflow values from the EPA 1980 study. (The X-axis gives same site IDs as in Figure 3.2.)

The population served by each DWTP site was included in the 1980 study and gave insight into possible human exposure to wastewater effluent through the distribution system. These population values were updated to the currently reported populations served in the Safe Drinking Water Information System (SDWIS) (see Figure 3.3). In this analysis, larger cities generally had higher percentages of wastewater effluent in their drinking water. The four largest cities in terms of population (populations greater than 750 000) all had wastewater percentages of 8% and higher. The largest DWTP population served was 1.6 million people, and its wastewater percentage was 8.6%. The focus on wastewater impacts in larger cities typically focuses on their deterioration of water quality for receiving cities downstream. In this study, larger cities are impacted by high wastewater percentages from upstream municipalities as well as contribute to wastewater loads downstream. Although the human health risk of CECs in wastewater is unknown, these results indicate that the population potentially impacted by CECs derived from wastewater is significant.

Four Case Studies

Case studies were performed to investigate the underlying anthropogenic changes that might explain the difference between the updated and original studies, including population changes, as well as the assessed potential future impacts of climate change. Temporal variations across a spectrum of base flows were used to depict the resulting treated wastewater percentages under a variety of hydrologic conditions. This served as a robust analysis of streamflow conditions built around the uncertainties of climate change. Historical USGS stream gauge data were used to plot the wastewater effluent percentages as a function of the full range of flow percentiles. All percentiles are based on historical values; therefore, all four cities have experienced variations in streamflow that have resulted in an effluent-dominated stream. Figure 3.5 illustrates how the level of de facto reuse varies with ranked percentiles of streamflow rates. These dependencies are described in more detail below.

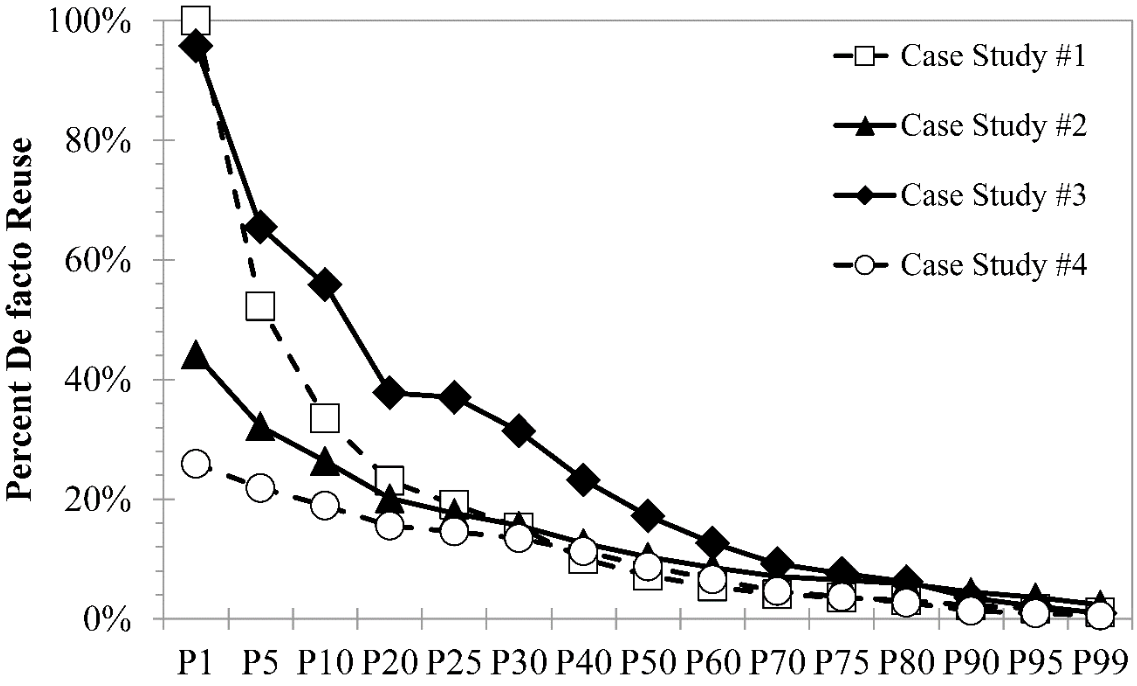

Figure 3.5. Case studies of de facto reuse based on USGS historic streamflow percentiles for each river system. (The X-axis gives the streamflow correlating to the Nth percentile, indicating the percent of historical streamflow that is equal to or less than it.)

Case Study #1. Site 1 is located along the Saluda River in EPA Region 4 and shows that societal changes play a large role in water quality. Site 1 had the highest wastewater percentage in the nation in 1980, 16%, which was attributed to 52 upstream WWTPs, but by 2008 de facto reuse had decreased to 7.6%. This unexpected change led to further analysis of the basin area. Changes between 1980 and 2008 in treated municipal sewage discharges were compared with the populations of the counties surrounding the river and multiplied by a common per capita discharge value. We found that the estimated wastewater flow based on the 2008 population was comparable to the value obtained from the model. The next step was to determine the reasons behind the drastic decline in wastewater discharge. Research indicated that prior to the early 1980s a textile boom occurred in Greenville, SC (the largest city upstream of Site 1) but has since subsided (Davidson, 2012). Greenville, SC (decreased in population by 15.4% between the U.S. Census of 1960 and 2000. The decrease in population is expected to be the cause for the decrease in treated wastewater percentage and in the reduction of upstream WWTPs from 52 in 1980 to 19 in 2008. The WWTP estimates do not include industrial discharges, therefore the reduction of WWTPs do not include the closed textile facilities. We inferred that the large number of closed WWTPs reflected the addition of WWTPs to accommodate the influx of people into undeveloped areas that closed after the textile boom subsided. This study site illustrates how not only temporal but also societal changes (as reflected in the census) can affect wastewater impacts. An influx of people to a particular area can pose burdens on downstream water quality, and effects can be exacerbated for streams of lower stream order and high streamflow variability.

At the DWTP intake in this example, the Saluda River has a Strahler Stream Order of 6, classifying it as a medium-sized stream. The river's average flow in 1980 was 82 m3/s, which diluted the 13 m3/s of municipal wastewater to 15% de facto reuse. The variability of the river's streamflow led to high interannual temporal variation, which further led to historical flow percentiles (1st to 99th flow percentile) ranging from 359 to 2.15 m3/s. This large variability in streamflow across the percentiles is depicted in Figure 5. At the 20th percentile, de facto reuse is nearly 40%.

Case Study #2. Site 2 is located in EPA Region 5 directly downstream of Ann Arbor, the sixth largest city in Michigan. Between 1980 and 2008, Ann Arbor's population increased by roughly 5%, which increased the wastewater flow downstream of the city. However, an increase in streamflow counteracted the increase in municipal flow. The historical average streamflow of the river in the 2008 update was nearly 60%

higher (18 m3/s) than the annual average used in 1980 (11 m3/s). This site serves as an example of how changes in streamflow can dilute increased wastewater flows from anthropogenic processes. Using long-term flow histories (Figure 3.5), streamflows < 20th percentile at this site result in > 20% de facto reuse.

Case Study #3. Site 8, which is located in EPA Region 5 along the White River, had the eigth highest wastewater percentage in the U.S. in 1980. The White River has two forks that flow through southern and central Indiana, is 362 miles long, serves as the main tributary to the Wabash River, and encompasses a 5 746 square mile basin area. In 1980 there were 16 WWTPs discharges upstream of Site 8 amounting to 1.7 m3/s. In 2008, the number of upstream WWTPs increased to 20 and flows to 2.6 m3/s. The long-term average streamflow of 33 m3/s through 2008 was 17% lower than the annual average used in the 1980 database. These factors combined for a near doubling of the de facto reuse from 4.3% in 1980 to 7.9% in 2008. This case illustrates how three factors can combine to generate a sizable increase in the proportion of wastewater present at the DWTP intake. De facto reuse for 7Q10 conditions for this site is 97%, showing that under drought conditions wastewater can be the main contribution to base flow. Historical periods of low flow influenced streamflow variations in the percentile rankings. This site may have > 20% de facto reuse for flows less than the historical 20th percentile streamflow.

Case Study #4. Site 20 (EPA Region 8) is located in north central Colorado along Clear Creek, a 66-mile-long tributary of the South Platte River. Prior to joining this river, the creek flows through Clear Creek Canyon in the Rocky Mountains just west of Denver. The flow of wastewater at this site has more than doubled, increasing from

0.08 m3/s in 1980 to 0.20 m3/s in 2008. However, the long-term average streamflow for 2008 was also higher than the annual average flow reported in 1980. Thus, these changes netted little difference in de facto reuse percentages (3.2% vs. 3.7%) between 1980 and 2008. The increase in streamflow offset the increase in wastewater effluent, but the increase in wastewater flow follows the population growth trend for this area. This site has > 10 % de facto reuse at the historic 20th percentile streamflow and does not reach 20% de facto reuse until the 10th percentile of streamflow.

Implications

Findings of this study demonstrate the increase in treated municipal wastewater discharges from 1980 to 2008. The unknown nature of potential risks to human health and environment associated with CECs affect the level of concern for the findings. However, guidance was developed in California to help the Drinking Water Program comment on wastewater discharge proposals. The California Department of Health has employed a guideline stating that wastewater contributions to a drinking water source should be less than 10% to avoid any chemical hazard. Using this guideline as a rubric, 6 of the 25 cities in this update exceed this limit under average long-term streamflow conditions. Taking into consideration temporal variations, three of the four case studies would exceed this percentage for streamflow conditions less than 40th percentile historic flow. The trends found in this study indicate the need for a similar analysis to be performed for the remaining DWTPs across the nation. Development of the GIS modeling tool in this study will be used to perform a national assessment of de facto reuse and thus provide information to support the NAE research need. Comparison of the new GIS model here to the 1980 EPA predictions was viewed as a critical first step toward a more national assessment of de facto reuse. We employed larger data sets of WWTP and DWTP locations than the 1980 study and more expansive USGS streamflow databases. Furthermore, compared to the computerized database used in the EPA 1980 study, our updated GIS model will allow for greater automation and visualization of a national analysis.

Supporting Information

Table SI-3.1.

Data sources used in the study.

GIS Layer	Source
WWTPs	Clean Watershed Needs Survey (CWNS) 2008, Permit Compliance System (PCS)
DWTPs	EPA Report EPA-60012-80-044
Hydrography (rivers, streams, and lakes)	National Hydrography Dataset Plus (NHDPlus) Version 1
Stream gauges	U.S. Geological Survey (USGS)
Topography (city and state boundaries)	U.S. Geological Survey (USGS), National Atlas Website

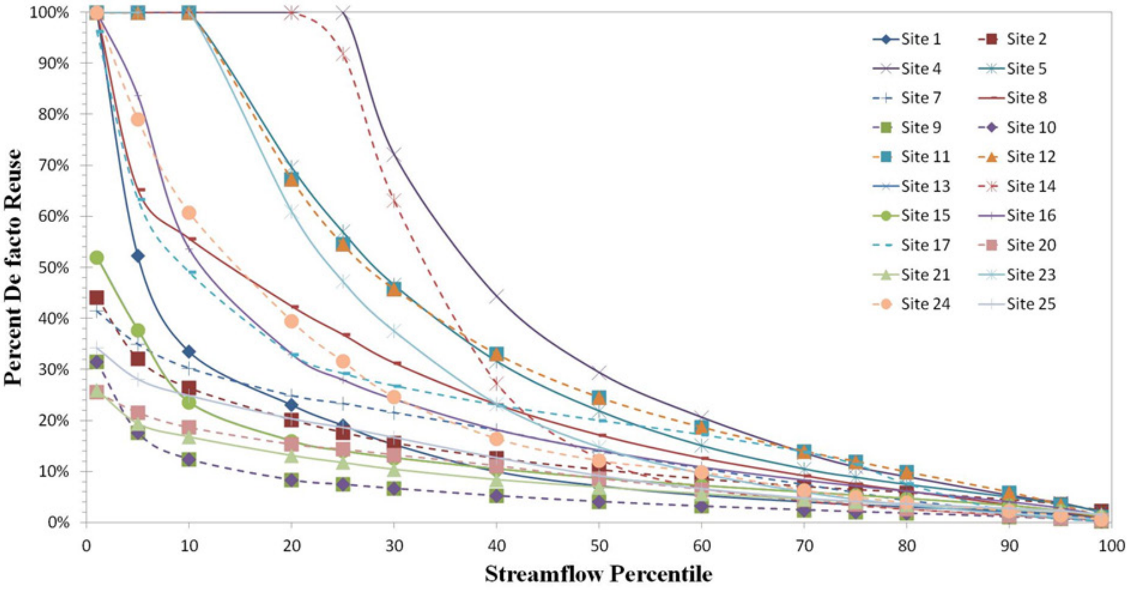

Figure SI-3.1. De facto reuse based on USGS historic streamflow percentiles for each river system. (The X-axis gives the streamflow correlating to the Nth percentile, indicating the percent of historical streamflow that is equal to or less than it.)

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Chapter 4

SPATIAL AND TEMPORAL VARIATION OF DE FACTO WASTWATER REUSE IN DRINKING WATER SYSTEMS ACROSS THE USA

*This chapter is in preparation for submission to *Environmental Science and Technology*, in collaboration with P. Westerhoff.

Abstract

De facto wastewater reuse occurs when treated wastewater is discharges in surface waters upstream of potable water treatment plants. Wastewater treatment plant (WWTP) discharges threaten water quality at the downstream drinking water treatment plant (DWTP), due to its role as one of the main anthropogenic inputs of micropollutants in the environment, but also provide a reliable water supply source. De facto reuse occurrence has been reported in regional studies, but a national assessment hadn't been completed in over 30 years. We analyze the upstream contribution of WWTP discharges to downstream DWTPs serving greater than 10,000 people (N=1,210 DWTPs). To do so, we develop an ArcGIS model to assess the spatial relationship between DWTPs and WWTPs, and couple the model with a python script designed to perform a network analysis on hydrologic regions across the U.S. Overall, 50% of the DWTP intakes were potentially impacted by upstream treated WWTP discharges. Contrary to the high frequency of occurrence, the magnitude of de facto reuse was relatively low with 50% of the impacted intakes containing less than 1% treated municipal wastewater under average flow conditions. The 25 highest ranked DWTP intakes ranged from 11 to 31%. Under average flow conditions 15 different municipalities spread across the U.S, serving roughly 4 million have an intake that has greater than 20% treated wastewater. The

magnitude of de facto reuse increases under low flow conditions, where 15 of the 37 sites potentially contained greater than 90% treated wastewater. This article provides knowledge regarding the contribution of municipal wastewater to potable water supply, and supports efforts for identifying the significance and potential health impacts of de facto reuse by identifying highly impacted areas.

Introduction

De facto reuse is defined as the unplanned or incidental presence of treated wastewater in a downstream water supply source(Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007). De facto potable water reuse is widespread and increasing, and it's not uncommon to have a substantial portion of the source water originally derived from an upstream wastewater contribution (Asano et al., 2007; Chen, Nam, Westerhoff, Krasner, & Amy, 2009; Krasner, Westerhoff, Chen, & Dotson, 2009; Mitch & Sedlak, 2004; Morehouse, Carter, & Sprouse, 2000; Rice, Wutich, & Westerhoff, 2013; Spahr & Blakely, 1985). Wastewater treatment plant (WWTP) discharges are one of the main sources of numerous micropolluatns in the environment, including pharmaceuticals and personal care products (PPCPs) and certain disinfection byproducts (DBPs) (Chen et al., 2009; EPA, 2009; Glassmeyer et al., 2005; Kolpin et al., 2002; S. W. Krasner et al., 2009; Snyder et al., 2004; Snyder, Westerhoff, Yoon, & Sedlak, 2003). Impacts of nutrients in wastewater discharges influence the stream ecology; the presence of pathogens and trace organics is a more recent concern. There are no regulations on co-location of DWTPs in relation to WWTP discharge sites located upstream on the same water source. Because wastewater flows from urban areas are less variable than natural rainfall runoff and resulting streamflow, the percentage of wastewater in streams tends to increase during droughts. Despite the potential impact of trace organics, bulk organics and pathogens present in wastewater effluents, limited data exists on the number or magnitude of de facto reuse across the USA and influence of variable streamflow conditions and historic variations on de facto reuse.

The U.S. population has increased by nearly 40% over the past 30 years and the number of people served by centralized municipal sewer systems has increased over the same period and now exceeds 80% of the U.S. population. Therefore, the amount of sewage collected daily, treated and discharged to surface waters has likewise increased dramatically over the past 30 years across the U.S. Streamflows over the last 30 years have largely remained within historic norms, but recent climate predictions suggest that future weather events may lead to more severe flooding or extended droughts. As treated wastewater is discharged into surface waters, it is diluted with water not impacted by upstream WWTP discharges; this may be changing and continue to change in light of variable streamflows under uncertain climate variations.

There is concern in climate change that the anthropogenic elevation of atmosphere CO2 and other greenhouse gases will induce global warming through the twenty-first century and alter streamflows (Intergovernmental panel on climate change, 2001). Historic records and climate models are relatively consistent in predicting global warming, but precipitation patterns are more complex and regionally variable and are much more difficult to model (Rood, Samuelson, Weber, & Wywrot, 2005). Hydroclimate observations and predictions at the regional scale report both increases and decreases in precipitation and runoff (Milly, Dunne, & Vecchia, 2005). A common macro scale view prediction is that global warming will increase evaporative rates from oceans and thus promote the global hydrologic cycle and generally increase precipitation (Intergovernmental panel on climate change, 2001). But at the regional scale, variations are less certain due to the uncertainties in spatial pattern predictions. Climate change has been predicted to have more low flows as opposed to high flows (Chunzhen & Schaake, 1989). Many studies warrant for more extreme declines in stream flow on a regional level. Milly et. al (2005) performed a study utilizing 12 climate models to achieve qualitative and statistically significant regional patterns of twentieth-century multidecadal changes in streamflow. These models projected 10-30% decreases in runoff for the western U.S. by the year 2050 (Milly et al., 2005). The western U.S. includes semi-arid and arid regions, characterized by ephemeral streams that are susceptible to being perennially dominated by wastewater effluent discharges (Brooks, Riley, & Taylor, 2006). The impact of streamflow variation on the dilution of wastewater effluent was observed in a study performed by Guo et. al (2007) in the Colorado watershed. PPCP concentrations doubled from 2006 to 2007 as stream flow dropped by half (Guo & Krasner, 2009). Similar effects were echoed in a study performed by Barber et. al (2006) on the Boulder Creek Watershed in Colorado. Natural and anthropogenic variation in flow led to effluent percentages ranging from 10-26% effluent during spring runoff and 39-74% effluent during base flow (Barber et al., 2006).

Drinking water treatment plants (DWTPs) are increasingly concerned with the deteriorations of receiving water quality from upstream WWTP discharges. Deteriorated water quality increases the burden of treating water to meet water quality standards, particularly in respect to the heightened concentrations of microbes and disinfection byproduct precursors. Concern also lies with unregulated pollutants present in wastewater effluents, and have been termed contaminants of emerging concern (CECs) (Sengupta et al., 2014). The presence of CECs such as endocrine disrupting compounds and PPCPs in surface and drinking waters impacted by treated wastewater discharges has been reported (Glassmeyer et al., 2005; Kolpin et al., 2002; Snyder et al., 2004). The potential risks to human health and the environment associated with CECs remains ill-defined; even the most robust national sampling campaigns only collect grab samples from a few WWTP of DWTPs, and fewer modeling strategies exist to assess at a national scale the potential of CECs in DWTPs (Kolpin et al., 2002; Snyder et al., 2004). Previously we developed a GIS based model and showed for 25 DWTPs that the extent of de facto reuse has increased from 1980 to 2008 for 17 sites in the USA, but little is known about regional or national level frequency or extent of de facto reuse(Rice et al., 2013). Higher de facto reuse estimates are believed to be a result of combine effects of the increase in U.S. population and the increase of the number people served by centralized sewer systems. In spite of these increases, the prediction of current de facto reuse in the U.S. is not straightforward, due to the slow decrease of wastewater flows as a result of recent water conservation efforts. The aim of this paper is to use a nation-scale GIS-based model that includes modules for WWTP, DWTP and river reaches to perform a national assessment regarding de facto reuse occurrence on the larger drinking water treatment plant (DWTP) systems serving greater than 10,000 people, and to assess potential impacts of stream flow variation. We took a 3-stage approach which consisted of (1) the estimation municipal de facto reuse occurrence at surface water DWTP intake sites under average stream flow conditions, (2) calculated de facto reuse under low-flow conditions, (3) and investigated the impact of Strahler Stream Order on sensitivity of de facto reuse when exposed to temporal variation.

Methods

Modeling Approach

Several of the DWTPs in the study have multiple surface water intakes, a total of 2,056 DWTP intakes were included in the study. Our current assessment expands upon the model developed by Rice et. al (2013), that included 25 DWTP sites to now include 1,210 DWTPs of the 1,292 of DWTPs in the U.S., which primarily use surface waters and serve greater than 10,000 people. This analysis is narrowed to large systems, which are defined as serving greater than 10,000 people (Rourke, 2009). Therefore, the percentages of de facto reuse presented in this article represent de facto reuse at any intake. Conservative assumptions in calculating de facto reuse were made similar to a 1980 EPA study and include: (1) WWTP discharge was equal to that of the present design capacity; (2) WWTP effluent had no in-stream loss; and (3) all water bodies were completely mixed. Our analysis of treated municipal wastewater discharges from WWTPs, which include combined sewer systems but do not take into consideration combined sewer overflows or wet weather by-passes (both of which yield significant micropollutant loads). Approximately 15,837 WWTPs are located in the U.S. according to Clean Watershed Needs Survey (CWNS) 2008; we considered the facilities (n = 14,651) that currently discharge to surface waters. Supporting data for the DWTPs included the municipality and population served; the WWTP data included facility name, CWNS number, level of treatment (primary, secondary, tertiary), and present design flow. The level of treatment was not included in the treated wastewater effluent calculations, but it’s important to point out that potential threats of micropollutants significantly decrease with higher levels of treatment.

A Python program was written to automate the process performed in the previous study (Rice et al., 2013). The program was developed to perform a network analysis on streamlines by hydrologic region. The algorithm utilized stream route identifiers from the value added attribute (VAA) data included in the National Hydrography Dataset (NHD) Plus. The process was designed to begin with headwater stream segments, then accumulate wastewater as it travels down the network and calculate the treated wastewater percentage at each link until the network was complete. In cases of diversions, wastewater was evenly distributed into each receiving node. The program results in wastewater percentage estimates for every streamline in the region. The resulting estimate represented a mass balance performed for the wastewater effluent at each DWTP intake point under the assumption that WWTPs were the only input into the network, and the DWTP intake was the sole uptake.

DWTP intakes were spatially joined to the nearest streamline within the ArcGIS framework. Special attention was taken to ensure that the intakes were attached to the correct stream. Results from the spatial join went through a two-stage quality assurance and control process. First, the attribute data of the two joined layers were compared to ensure they matched. This step composed of verifying that the source water of the DWTP intake matched the reach name of the joined stream. Secondly, for those that did not match due to wrong or incomplete information (N=1,428 out of 2,056), the joining stream was visually ground-truthed by using Google Maps and ArcGIS to select the stream segment most suitable for the intake location.

De Facto Reuse Analysis under Temporal Variation

The percentage of de facto reuse is first calculated under average flow for all intake sites, and subsequently a subset of the data was analyzed under varying flow conditions. Average streamflow estimates are obtained from NHDPlus for each streamline in the network. Streamflow estimates are derived by the enhanced runoff method that includes a gage adjustment step. Due to the gage adjustment being restricted by limitations in the number of stream gages, it was assumed that the average flows did not include municipal wastewater inputs. Therefore the wastewater percentage was equal to the accumulated wastewater flow divided by the sum of the average stream and accumulated wastewater flows. In an effort to assess the potential future impacts of climate change, temporal variations across a spectrum of streamflow conditions were used to depict the resulting treated wastewater percentages under a variety of hydrologic conditions. This served as a robust analysis of streamflow conditions built around the uncertainties of climate change, and bounded by historic flow values. For this portion of the analysis instead of using NHDPlus modeled streamflow estimates, we used measured data from USGS stream gauges. Wastewater effluent percentages were plotted as a function of the full range of historic flow percentiles.

Results and Discussion

De Facto Reuse Occurrence under Average Flow Conditions

De facto wastewater reuse occurs frequently (nearly 50%) in large DWTP systems across the U.S. Under average flow conditions, for DWTPs serving greater than 10,000 people 1006 of 2056 intakes (756 of 1210 DWTPs) were impacted by upstream treated municipal discharges from upstream WWTPs. The impacted sites are unevenly distributed across hydrologic regions, as displayed in Figure 4.1. USGS hydrologic regions were chosen to categorized reuse since these correspond to drainage basins, which naturally account the connectivity of DWTP intakes of the same network. The percentage of impacted to non-impacted DWTP intakes range from 5% in the Region 1 (New England), to 100% in Region 9 (Souris Red-Rain). The high percentage of Region 9 is partially due to only having 9 intakes. Region 12 (Texas Gulf) had the second highest frequency of de facto reuse at 90% of DWTP intakes.

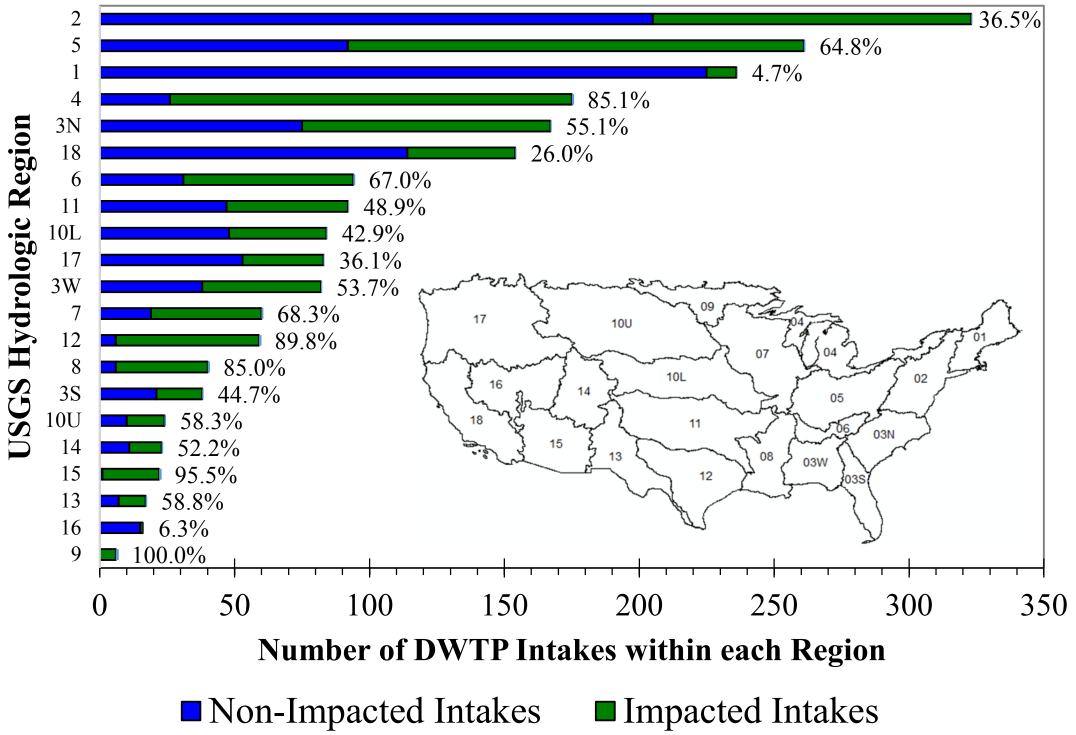


Figure 4.1. The frequency of de facto reuse occurrence at DWTP intakes across the U.S., grouped by USGS hydrologic region (shown in insert).

In contrast to de facto reuse occurrence frequency, the magnitude of de facto reuse under average flow was low. Fifty-percent of impacted intakes had less than 1% of accumulated upstream treated municipal wastewater impacts (see supplementary information). For all the DWTP intakes, 89% of the DWTPs had less than 5% in their source water, and 94% of the dataset was below 10%. Only 29 sites yielded an estimate of de facto reuse greater than 15%, of these 15 sites had greater than 20% of the average river flow consisting of aggregate wastewater flow at the downstream DWTP intake. Figure 4.2 depicts the 25 intake sites with the highest percentages of treated wastewater ranged from 11 to 31 percent, with sixteen of the sites serving greater than 100,000 people.

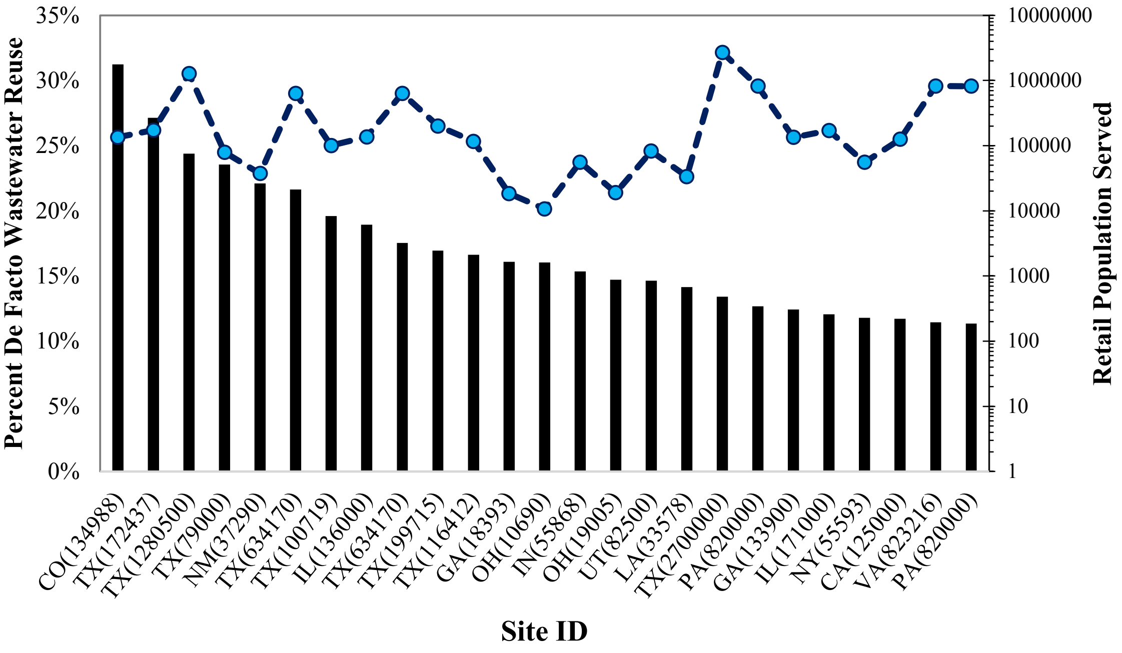


Figure 4.2. The 25 intakes with the highest estimates of de facto reuse under average flow conditions. Labeled for discretion and referred to by the state and retail population served in parentheses.

Only one site from this study, Ray Hubbard Lake (Texas), corresponds with those in the previous study reported by Rice et. al (2013). This is primarily due to higher values of de facto reuse for locations that were previously impacted by lower values in relation to other cities in the previous study. In EPA's 1980 study the DWTP impacted by the highest percentages of treated wastewater ranged 2.3 to 15.7 percent in 1980, in this article percentages ranged from 11 to 31 percent. Therefore, this study identifies new sites impacted by higher levels of treated wastewater effluent.

Figure 4.3 shows a bar and whisker plot for the percentage of de facto reuse across the hydrologic regions, only for the sites impacted by upstream treated wastewater. The distribution of the data displays slight variation across hydrologic regions, with the notable exceptions of regions 4, 14, and 17. Figure 4.4 geographically depicts de facto reuse, categorized by percentage values. Higher levels of de facto reuse impact DWTPs in the southwestern U.S. (regions 12 and 13); where the majority of intakes exceeding 10% reside. Regions 12 and 13 consist of the states of New Mexico and Texas, where semi-arid landscapes influence the wastewater contributions from highly populated upstream cities.

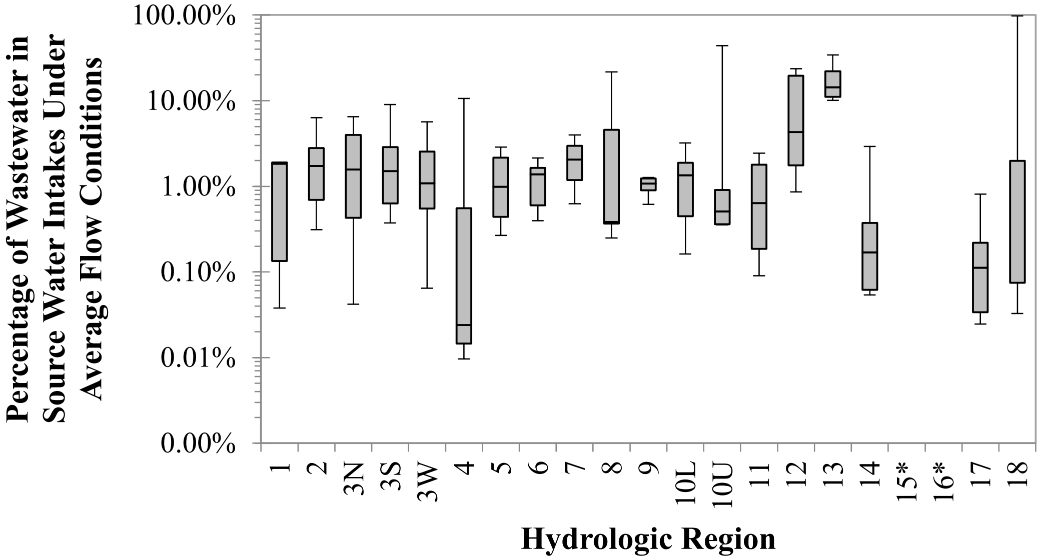


Figure 4.3. Statistical summary of the percentage of treated wastewater present at DWTP intakes across USGS hydrologic regions (key given in Figure 4.1). Regions with an asterisk did not have enough data points to be plotted. Top and bottom of box = 75th and 25th percentiles respectively; the top and bottom of whisker = 90th and 10th percentiles respectively; line across inside of box = median(50th percentile).

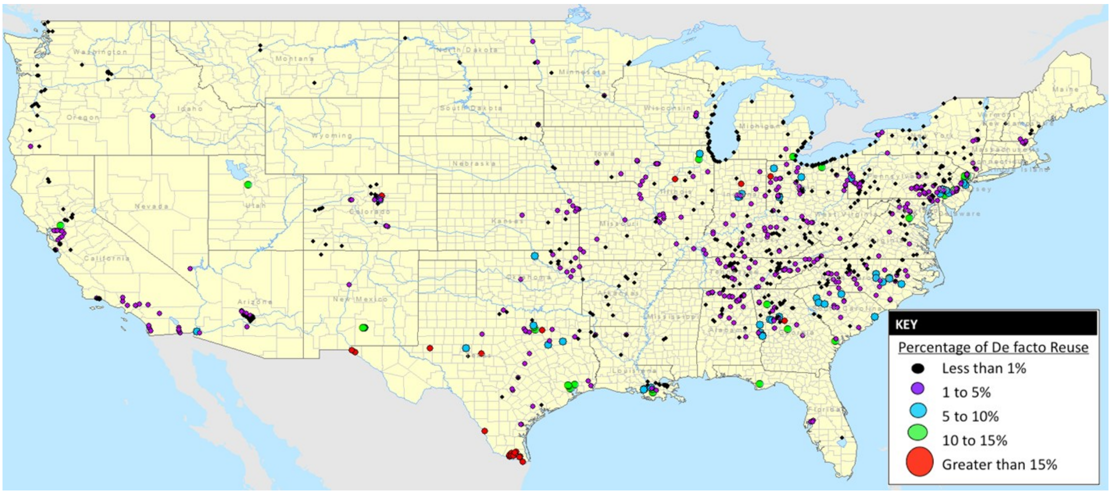


Figure 4.4. Magnitude of de facto wastewater reuse occurrence in large drinking water surface intakes across the U.S.

De Facto Reuse Estimates under Low Flow Conditions

Minimum stream flow during dry periods of the year has the potential to exaggerate the percentage of de facto wastewater reuse. Two approaches were considered for assessing the influence of streamflow variation on de facto reuse. First, the Q95 low flow index was used to assess the sensitivity of de facto reuse to low flow conditions. Q95 represents the flow that is exceeded 95% of the time, and has an estimated reoccurrence time of 15 years (Smakhtin, 2001).Previous studied have shown Q95 to have higher streamflow values as compared to the 7 day, 10 year low flow (7Q10) which is often used in NPDES permits, intended to protect aquatic ecosytems. A current limitation of NHDPlus is the inability to predict low flows, so low flow estimates were obtained from USGS stream gauges. This portion of the analysis was only completed in stages. In the first stage intake sites located on the same reach of stream as a USGS stream gage were identified. Next, additional sites were selected in areas underrepresented in the first stage, and estimates for Q95 were obtained using USGS Streamstats Web Application (SI-4.1). The extent of de facto reuse greatly increased under low flow periods, as displayed in Figure 4.5.

During low flow conditions, 23 of the 80 DWTPs had the potential to contain 100% treated wastewater in its intake. This infers that during drought conditions, the upstream municipal discharges are the sole input to the streams source waters. In addition, 32 of the 80 sites have greater than 50% treated wastewater. Overall the average percentage of de facto reuse across the sites increased from 3.6% under mean flow to 45.9% under low flow conditions. The sites in Figure 4.5 are in order of Strahler Stream Order from left to right, the sites towards the right of the graph have significantly lower values than the right. Strahler Stream Order defines stream size based on hierarchy of tributaries. Stream orders provide a rank and identification of relative sizes of channels. Smaller order streams are assigned to smaller, headwater streams typically found in upper reaches of a watershed. Streams from across the country were grouped by stream order, but streams of the same stream order may be very different when located in different ecosystems or climates. Strahler stream order increases when a tributary joins a stream with a stream order classification less than or equal to the tributary. Less de facto reuse in streams of higher stream order is a result of streamflow during low flow conditions remaining significantly higher in larger streams compared to streams of lower order, as well as the tendency for streams of higher order to have comparatively less seasonal fluctuations in streamflow.

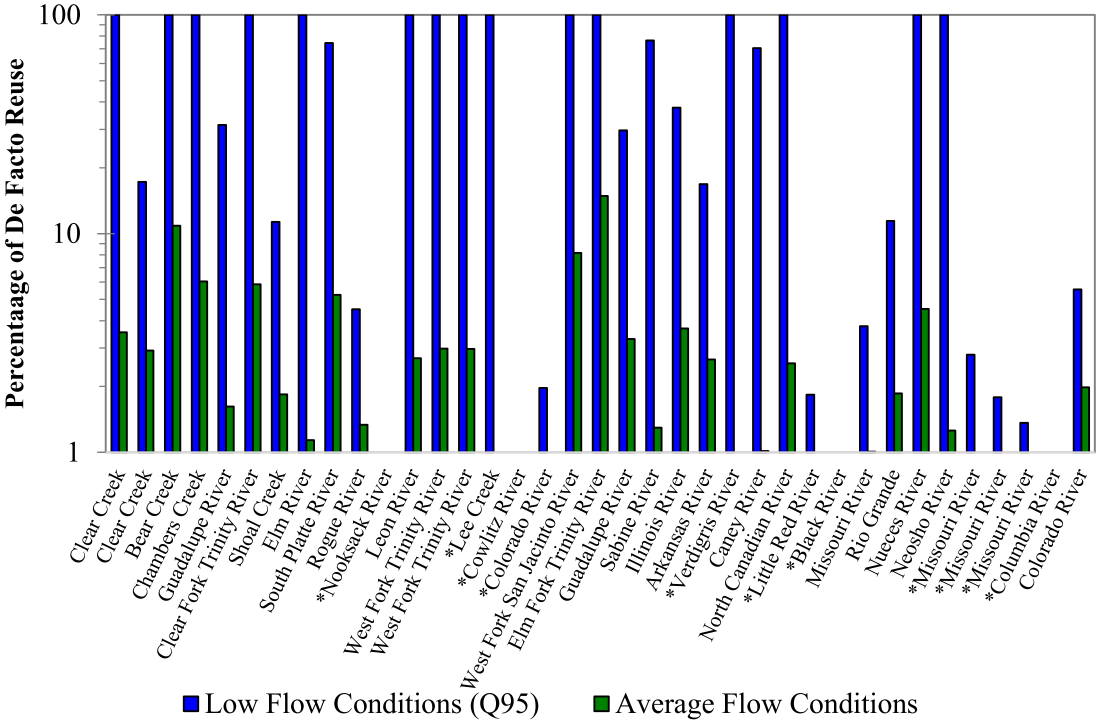


Figure 4.5. De facto reuse under average flow and low-flow conditions (modeled by Q95), citations represent sites with percentages of de facto reuse less than 1%.

Sites that weren't directly analyzed under Q95 low flow conditions are expected to follow the same trends as presented here in the subset of DWTP intake sites. The second approach takes into account additional sites in the western U.S. Wastewater contributions to DWTPs were analyzed under the climate change prediction by Milly et. al, which suggests that the western parts of the U.S. could have up to a 30% decrease in average streamflow conditions. For this investigation, 131 sites in the states of Arizona, California, Colorado, Nevada, New Mexico, Oregon, Utah, and Washington were considered. Overall the percentage of treated wastewater increased from 7.1 to 8.0% across the 131 sites. The majority of the sites (111 of the 131) increased by less than 1 percentage point. Notable exceptions include14 DWTP intake that increased from 1 to 5 percentage points, and 6 intakes that increased by greater than 10 percentage points. It's important to point out that this analysis is skewed by the amount of DWTP intakes that are supplied by streams of higher Strahler Stream Order. 76 of the 131 sites were from water sources with Strahler Stream Order classifications greater than 5. We believe this to be attributed by the notion that DWTPs of larger design capacity are more likely to utilize streams of higher stream order (as a result of higher average flows to meet demand requirements). The spatial distribution of DWTPs across the US mimics the population distribution. Generally, the spatial distribution of DWTPs in the western portion of the US is more clustered and less random than those of the eastern U.S. In turn, the western U.S. in comprised of fewer DWTPs that are larger in size, as compared to a higher number of DWTPs in the eastern U.S. with smaller design capacities.

Impact of Strahler Stream Order on Effects of Temporal Variation

Strahler Stream Order was also used to categorize de facto reuse impacts. This was performed with the expectation that intakes from stream of lower stream order would have higher de facto reuse than those from streams of higher order. The underlying assumption of the ordering system is that when two similar order streams join to create the next higher order stream, mean discharge capacity is doubled (Zaimes & Emanuel, 2006). Under average flow conditions intakes along streams classified as stream orders 3 through 9 have de facto reuse median values ranging from 1 to 3 percent (average values of 2 to 9%). In contrast, intakes from water sources classified as a stream order 2 were an order of magnitude higher, with a median value of 52% treated wastewater.

We also evaluated the impact that temporal variation plays on the magnitude of de facto reuse when categorized by stream order. In Figure 4.6, 37 of the sites previously analyzed under low flow conditions (Figure 4.5) were grouped by Strahler stream order and evaluated for treated wastewater percentages for a range of historic streamflow percentiles. The X-axis in Figure 4.6 represents streamflow that correspond to the percent of historical streamflow that is equal to or less than the value. There is a general trend of streams classified as lower stream orders having higher de facto reuse levels. The biggest difference in de facto reuse occurs between stream orders 4 and 9. Temporal variation of the streams is represented in Figure 4.6 by the slope of the curves, steeper curves represent higher variations of stream flow.

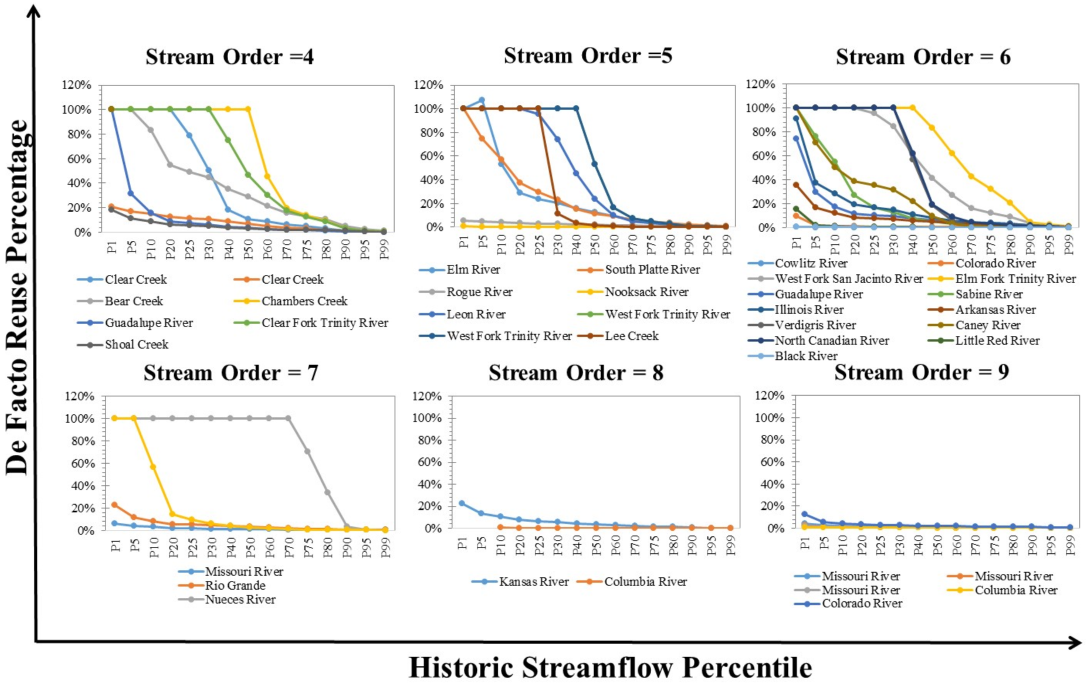


Figure 4.6. De facto reuse under temporal variation (modeled by historic streamflow percentiles) and grouped by Strahler Stream Order. (The X-axis gives the streamflow correlating to the Nth percentile, indicating the percent of historical streamflow that is equal to or less than it.)

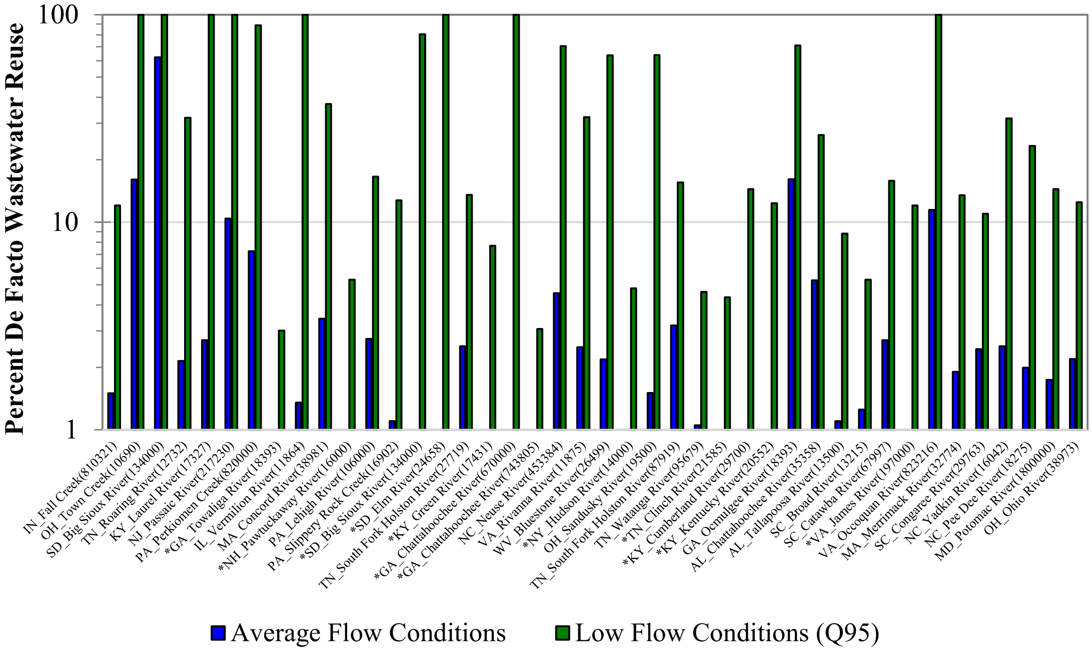
The Mississippi and Missouri rivers held some of the largest values of accumulated treated wastewater, with DWTP intake sites impacted by greater than 2.8 m3/s (100 cfs; 64.6 MGD) treated wastewater. In some cases the accumulated wastewater in the higher order streams were a level of magnitude higher than those in lower stream orders, but the capacity of the streams offered higher dilution potential. This was evident in the case of the Mississippi River, where sites in the downstream segments of the river yielded the highest accumulated flows by treated wastewater but remain less than 10% de facto reuse under drought conditions.

De facto reuse estimates under the median streamflow (P50 in Figure 4.6) were consistently higher than the values previously calculated based upon NHDPlus average flow estimates. We expect the difference between these two values to be a result of the limitations of the modeled NHDPlus average flow estimates, and the median statistic being a better fit for data with significant temporal variations in streamflow. In cases where data is clustered towards one end of the range and/or extreme values are present, the average can be skewed. Under these circumstances the median is a better representation of central tendency. Under median flow conditions, 9 of the 37 sites were greater than 20% de facto reuse and 5 sites were greater than 50 % treated wastewater; which are significantly higher than de facto reuse under average conditions in Figure 4.5 (see SI-4.2). Under the 25th percentile flow conditions, the number of sites greater than 20% increased to 12 and the number of sited greater than 50% treated wastewater increased to 15. Therefore, based upon USGS stream gage data, 15 of the 37 DWTP intake sites have experienced conditions where wastewater made up the majority of the source water. These trends are representative of all DWTP sites, and highlight the important role that treated wastewater discharges potentially play to the water supply of several sites during periods of drought and low flow conditions.

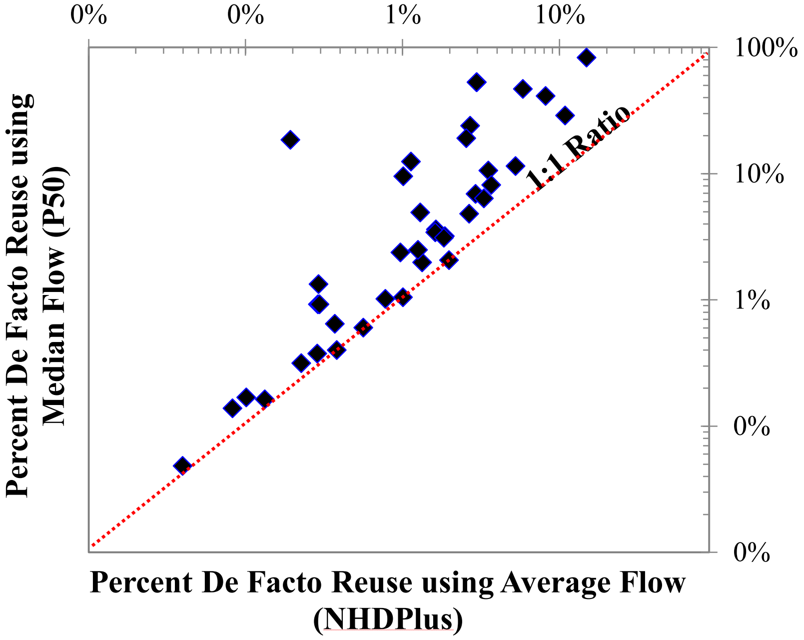
Implications

This study demonstrates that de facto reuse occurrence is frequent amongst drinking water treatment systems serving greater than 10,000 people, but the magnitude of occurrence is relatively low. This work answers many of the research needs regarding de facto reuse in the U.S., as stated by the National Academy of Engineering; specifically: (1) we provide knowledge regarding the contribution of municipal wastewater to potable water supply, and (2) support efforts for identifying the significance and potential health impacts of de facto reuse by identifying highly impacted areas. CECs are more likely issues for DWTPs with higher levels of de facto reuse. In addition, this paper contributes to the assessment of the magnitude of potential exposure. The NAE report identifies de facto reuse with 5% treated wastewater posed higher risks from wastewater contaminants than planned potable reuse schemes. Based upon this 5% de facto reuse level, under average streamflow over 15 million people are exposed to levels of wastewater contaminants greater than levels that would be expected under planned potable reuse schemes. This work also corroborates the notion for a holistic approach towards the protection of human health from emerging concern. The California Department of Health has issued a guideline stating that wastewater contributions to a drinking water source should be less than 10% to avoid any chemical hazard. Using this guideline as a rubric, 59 intakes serving 38 DWTPs (serving over 10 million people) exceed this value under average flow conditions. This modeling work can be used to guide CEC sampling and health studies for influence of indirect reuse. Geographic locations identified in this paper have the potential to be used in support of ongoing work regarding the evaluation of potential long-term effects posed by planned potable reuse schemes. The use of Strahler Stream Order emerges as a potentially useful indicator to the sensitivity of de facto reuse to varying hydrologic conditions. Our future work is aimed at quantifying de facto reuse for drinking water treatment plants serving less than 10,000 people.

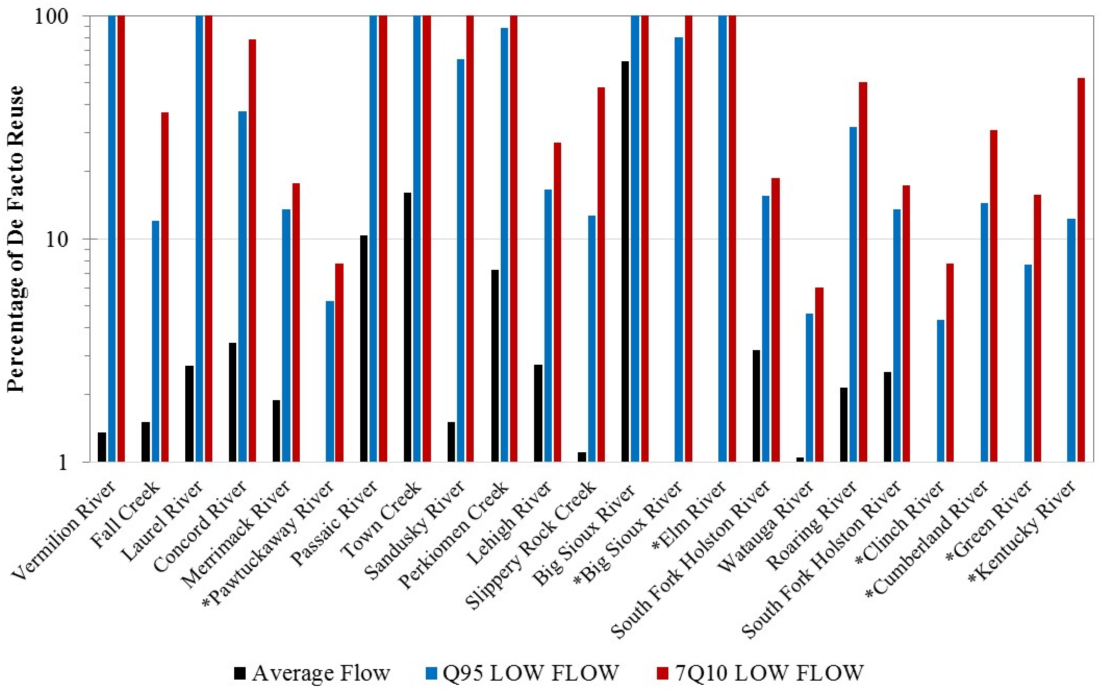
Supporting Information



SI-4.1. De facto reuse under average flow and low flow conditions (modeled by Q95) additional sites. (Follow-up to Figure 4.5)



SI-4.2. De facto reuse estimates based upon USGS Stream gage values for median and average flow. (Sites from Figure 4.5)



SI-4.3. De facto reuse estimates comparing the impacts of Q95 vs. 7Q10.

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Chapter 5

ASSESSING THE YUCK FACTOR ASSOCIATED WITH DE FACTO WASTEWATER REUSE: A THREE CITY CASE STUDY*

*This chapter is in preparation for submission to *Jounral of Environmental Management*, in collaboration with A. Wutich, D. White and P. Westerhoff.

Abstract

Increases in water treatment technology have made water recycling a viable engineering solution to water supply limitations. In spite of this, such water recycling schemes have often been halted by lack of public acceptance. Lack of public support is tied to the 'yuck' factor, a visceral response associated with wastewater reuse. Previous studies have captured the publics' attitudes regarding planned reuse schemes, but here we focus on unplanned reuse present in many cities across the U.S. De facto reuse is the unplanned occurrence of treated wastewater in a water supply source. We performed a survey in three metropolitan areas; which included Atlanta, GA (N=421), Philadelphia, PA (N=490) and Phoenix AZ (N=418) to assess basic perceptions of treated wastewater occurrence and acceptance in the public's water supply. These perceptions are then coupled by estimates of the actual extent of occurrence in the corresponding cities. The key results are that: (1) de facto reuse occurs at rates across the three cities higher than what is perceived; (2) roughly 25% of respondents perceive de facto reuse to occur in their home tap; and (3) respondents whom perceived de facto reuse to occur at their tap were ten times more likely to have a high level of acceptance for de facto reuse in their home tap.

Introduction

Globally, many countries have increasingly limited water resources in both quantity and quality (Dolnicar & Schafer, 2009). Water utilities that manage potable water treatment and wastewater treatment are increasingly practicing planned water reuse strategies as part of sustainable water resource management, in addition to reducing water usage (Anderson, 1996; Angelakis & Bontoux, 2001; Bixio et al., 2006; Miller, 2006). Water reuse (i.e. wastewater reuse) involves the treatment of municipal wastewater for the replenishment of available freshwater resources. A variety of wastewater treatment technologies are available to achieve recycled water of a quality that is often superior to existing potable water standards (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007; Bixio et al., 2005). Despite this technical evaluation, the idea of drinking treated wastewater does not have wide public support. Several factors hinder recycled water uptake and new problem solving approaches are needed (Weber, 2006). Debate is escalating about the acceptance and suitability of human-engineered water recycling within the global water cycle continuum. Public perception and acceptance are recognized as two of the main hindrances for the successful implementation of water reuse projects (Hurlimann & Dolnicar, 2010; Marks, 2006). For the past decade, water utilities attempted to persuade the public through marketing. More recently, it has become generally accepted that social marketing or persuasion has proven to be ineffective in influencing people to use reclaimed water (Po, Kaercher, & Nancarrow, 2003). Since the 1970's, survey and case study research has concluded that the public in many states support the general concept of water reuse and has been somewhat supportive of non-potable reuse initiatives.

There are several different factors that are believed to influence the public's willingness to adapt a water reuse scheme. Public acceptance of water reuse in the U.S. was noted by Hartley et al (2006) to be generally higher when the degree of human contact is minimal (e.g., water use for outdoor irrigation). Other factors that lead to increased acceptance include when the (1) protection of the environment and water conservation are promoted as clear benefits; (2) perception of wastewater as the source of reclaimed water is minimal; (3) role of reclaimed water in the overall water supply scheme is clear; (4) awareness of water supply problems in the community and perception of the quality of the reclaimed water is high;   (5) and the confidence in local management of public utilities and technologies is high (Hartley, 2006). Baumann and Kasperson (1974) suggest that a successful strategy should associate the water reuse program with pleasant activities the public enjoys and approves. For instance to "put the reclaimed water in an attractive setting and invite the public to look at it, sniff it, picnic around it, fish in it, and swim in it" (Baumann & Kasperson, 1974). This notion is corroborated in a study by Bruvold and Ward (1970), which found that opposition to recycled water dropped significantly after swimming in it, which implies that tying recycled water to a pleasant encounter can increase acceptance (Bruvold & Ward, 1970).

The "yuck" factor is a term coined by Arthur Caplan to describe the influence of instinctive responses against new technology (Schmidt, 2008). Publications dating back to the 1970's refer to psychological disgust as a barrier to water reuse (Baumann, 1983; Hanke & Athanasiou, 1970). The visceral nature of this reaction makes it hard for the water reuse community to overcome. The reaction of disgust is likely to be linked to the association of reclaimed water with wastewater (i.e. sewage). Common objects that have a similar disgust factor are urine, excrement, dirt and mud. Emotions of disgust are defined as the emotional discomfort generated from close contact with certain stimuli (Angyal, 1941). To counter the ‘yuck’ factor, water projects have strayed away from referring to water reuse as treated wastewater (Rock, Solop, & Gerrity, 2012). The law of contagion is one possible reason as to why the levels of disgust attributed to excrement and urine are attached to water reuse no matter what level of treatment is completed to the end product. This law suggests that neutral objects can acquire disgusting properties from another object just by means of brief contact (Po et al., 2003). In the field of water governance it can be seen that the “yuck” factor has been a fairly intractable problem in the implementation of water-reuse policies. On the contrary, some countries have overcome this feeling of disgust, so yuck must not be an immutable factor (Po et al., 2003).

In spite of the lack of public acceptance of wastewater reuse schemes, treated wastewater can represent a significant portion of the total flow in many receiving waters across the USA. De facto reuse is defined as the unplanned or incidental presence of treated wastewater in a water supply source (Trussell et al., 2012). Subsequently, de facto potable reuse of wastewater in domestic and public water supply is widespread and increasing. Previous research found that 25 sites across the U.S. water supply was comprised of 2 to 16% treated wastewater discharged upstream of water supplies (Rice, Wutich, & Westerhoff, 2013). This is seasonal and higher under low river flow and/or drought conditions, due to lower dilution potential. Noteworthy examples include the Platte River downstream from the City of Denver; the Schuylkill River in Philadelphia, PA; the Quinnipiac River in Connecticut; the Santa Ana River in southern California; the

Ohio River near Cincinnati, Ohio; and the Occoquan Watershed southwest of Washington, DC (Asano et al., 2007; S.W. Krasner, Westerhoff, Chen, & Dotson, 2009; Mitch & Sedlak, 2004; Morehouse, Carter, & Sprouse, 2000; Spahr & Blakely, 1985). Little is known regarding the public's awareness of de facto reuse occurrence, including how awareness impacts public perception of water reuse. Prior experience using water from alternative sources is positively correlated with the stated likelihood of use for water reuse in a previous study (Dolnicar, Hurlimann, & Grun, 2011). This study is the first to assess whether a similar trend holds true for respondents whom are aware of unplanned reuse. Here we aim to compare the public's perception of de facto reuse occurrence with the modeled amount of treated wastewater in their city's water supply, and investigate if a correlation is present between knowledge of occurrence and acceptance. We accomplish this by conducting a survey research study across three cities to determine: a) the extent to which the public is aware that wastewater effluent resides in their drinking water, and b) to elicit the amount of de facto reuse they find to be "acceptable." These values are compared to an estimation of the actual wastewater effluent in each city's surface waters. Using regression analysis we explore if correlation lies between knowledge of de facto reuse occurrence and acceptance. In doing so, we find that de facto reuse occurs at rates across the US higher than the public perceives, and that knowledge of occurrence is positively correlated with acceptance. This suggests that if managed successfully, the gap of knowledge of de facto reuse can serve as an opportunity to gain public support.

Materials and Methods

Overall Approach

An interdisciplinary approach was taken to answer the questions set forth in this article, integrating environmental engineering analysis and social science survey methods. In doing so, the methodology consisted of four steps (1) conduct a social survey to measure certain attitudes regarding de facto wastewater reuse; (2) estimate the actual extent of de facto wastewater reuse in the selected cities; (3) analyze the data to determine the traits of respondents associated with higher acceptance values; and (4) perform a spatial analysis to compare the actual and perceived values. Results from the social survey (generalized at zip code resolution) are added into an ArcGIS model, to represent the actual and perceived values of de facto wastewater reuse across the U.S.

Estimated Values of De Facto Reuse

De facto reuse was estimated by quantifying the contribution of upstream treated wastewater discharges to drinking water supplies in the metropolitan areas of Atlanta, GA, Philadelphia, PA and Phoenix, AZ. Estimates for Philadelphia source waters were previously reported in a study of de facto wastewater reuse (Stuart W Krasner, 2008; Rice et al., 2013). Calculations were completed for sites not included in the previous study based upon the same methodology (Rice et al., 2013). For anonymity we refer to the water supply source as opposed to the name of an actual drinking water treatment plant. We do not include all of the drinking water treatment plants that serve the three metropolitan areas, instead we have selected a representative sample of the drinking water treatment plants that are impacted by treated wastewater effluent and serve greater than 10,000 people.

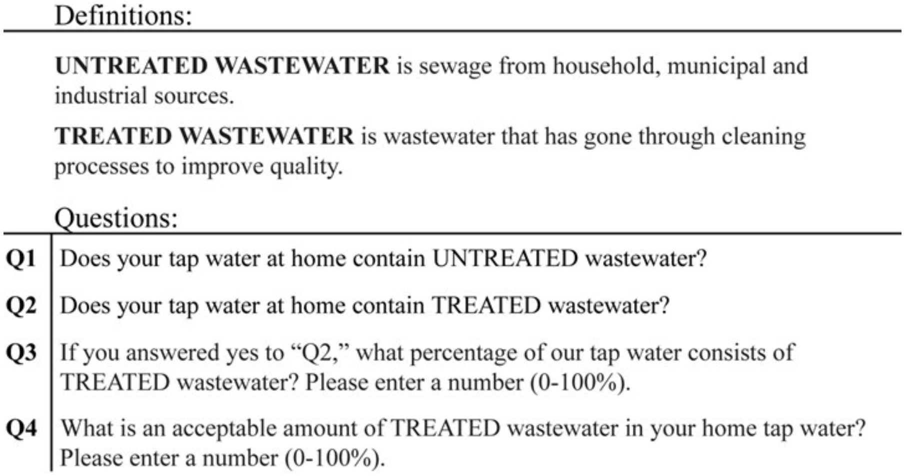
Social Study Design

A social survey was launched within a online survey platform across three cities. Survey Sampling International (SSI) provided survey sampling. SSI ensures data integrity through the use of timestamps to flag “speeder”, and quality control questions to identify inattention. Data is authenticated through several steps including digital fingerprinting, and matches against third party databases. Their approach to data integrity and authentication has earned them “outstanding” rating Grand Mean Auditors (external sample source auditors). 400 respondents were provided per city, this was done at the Metropolitan Statistical Area resolution. The cities studied include Atlanta, GA, Philadelphia, PA, and Phoenix, AZ; they were picked to represent different climate zones and water resource availabilities, as these are expected to impact the extent of de facto reuse present. Atlanta, GA is in the humid subtropical climate zone, which is attributed with rainfall evenly distributed throughout the year. From 2007 to 2008, the city underwent water shortages as Lake Lanier Reservoir shrank to historic lows. Rapid population increase from 1990 to 2007 (6.5 to 9.5 million people) was the main cause. Due to this, this area has one of the only indirect potable reuse systems installed in the US. Philadelphia has humid continental climate, which is characterized by precipitation that’s generally distributed throughout the year and hasn’t been affected by drought in recent years. Several source waters surrounding the Philadelphia Metropolitan Area have been previously reported to have significant levels of de facto reuse (Stuart W Krasner, 2008; Rice et al., 2013). Phoenix, AZ is another area that has been plagued by drought conditions in recent years. Phoenix has an arid climate, attributed by scarce rainfall through the year. Indirect wastewater reuse is present throughout the Phoenix valley by means of groundwater recharge and reclaimed water use in outdoor irrigation and industrial processes (Lauver & Baker, 2000).

The survey protocol was designed to elicit the emotional response of the respondents to the idea de facto reuse at their home-tap. In consideration of the fact that de facto reuse is not a common term, we chose to steer away from using it in the survey. Instead, we base our questions around the terms treated wastewater and untreated wastewater, both of which definitions are given. Untreated wastewater is defined as sewage from household, municipal and industrial sources. Treated wastewater is defined as wastewater that has gone through cleaning processes to improve its quality. Both of these definitions were displayed when the respondent was asked questions pertaining the topics. In taking this approach we avoided introducing into the survey the uncertainties attached to the different terms associated with wastewater reuse. This is important as the public has previously shown changes in acceptance of reuse schemes merely due to the wording used (i.e. wastewater reuse vs. water recycling) (Rock et al., 2012). The survey consists of eleven questions; four of these regarding de facto reuse and seven demographic questions. The dependent variable of the study was the acceptable value of treated wastewater present at the respondents' home tap water. This answer was solicited in the form of an open-ended question, asking the survey-taker to fill in the blank (0-100%). In doing so, we ensured that answers were not constrained by categorical values (being that there is no correct answer), and did not suggest the actual value. The independent variables include the perceptions of treated and untreated sewage presently in their home tap water, age, gender, born in the US, zip code, furthest level of education completed, race, employment status and occupation. Socio-demographic factors hypothesized in this study have previously been significantly correlated to water reuse acceptance in previous studies (Baumann & Kasperson, 1974; Dolnicar et al., 2011; Dolnicar & Schafer, 2009; Nancarrow, Leviston, Po, Porter, & Tucker, 2008; Tsagarakis, Mellon, Stamataki, & Kounalaki, 2007).

The survey went through a pre-test by a panel of methodological experts in the social science field. Table 5.1 displays survey questions relating to treated wastewater occurrence at the respondents home tap. The final step in the survey development was to complete cognitive interviews. Seventeen people underwent cognitive interviews to elicit the thought process behind their answers to the questions (DeMaio and Rothgeb 1996). This process proved to be a great benefit to the survey development because it validated that the respondents interpreted the questions the way they were designed to be interpreted. Beyond geographic location, the only restrictions that were placed on the sample population is that they be at least 18 years of age, have access to the internet, and be somewhat computer savvy (as the survey was launched online).

Table 5.1. *Survey protocol for questions regarding wastewater occurrence at the respondent's home tap*



Definitions:

UNTREATED WASTEWATER is sewage from household, municipal and industrial sources.

TREATED WASTEWATER is wastewater that has gone through cleaning processes to improve quality.

Questions:

Q1	Does your tap water at home contain UNTREATED wastewater?
Q2	Does your tap water at home contain TREATED wastewater?
Q3	If you answered yes to "Q2," what percentage of our tap water consists of TREATED wastewater? Please enter a number (0-100%).
Q4	What is an acceptable amount of TREATED wastewater in your home tap water? Please enter a number (0-100%).

Data Analysis

Results from the survey underwent a three types of analysis. All of the independent variables were assumed to be correlated with the acceptance of de facto reuse, and were initially included in the multivariate analysis with robust variance. Variables were selected for the model by stepwise forward selection. Selection was performed by adding the variable with the smallest p-value and utilizing the F-test to compare the model with this variable added against the model without the variable added. Variables that were tested in the model included all independent variables and all pairwise interactions, the selection process was stopped when all p-values were larger than 0.15, all but one variable fall within 95% confidence interval (p-value < 0.05). Therefore, only variables that significantly increase the explained variance are included in the final model. Lastly, the continuous data was placed into categories and the likelihoods were estimated by an ordinal logistic regression. Acceptance values of '1' to '100'were placed into categories representing the level of acceptance. Answers that were greater than or equal to 75 were labeled as high acceptance, those that were less than or equal to 25 were labeled as low acceptance. These breakpoints were set to capture the tri-modal distribution of the data. Two dummy variables were added to each category and observations that met the requirements were coded as "1", where "0" was the baseline. Therefore, the stated likelihoods and odds ratios represent the likelihood of the event to occur (i.e. belonging to that category) with the change in independent variables.

Results

Perceptions of wastewater presence in home tap water supply

The survey began by asking the respondent to pick from a list of choices where their water came from (i.e. municipality, private well, etc). Only those that identified as obtaining water from a public water supplier were including in the proceeding results. Over 97% of the responses came from customers of the public water system. Results presented in Figure 1 reveal that the knowledge whether or not untreated wastewater was present was invariable across the three cities studied. Roughly 4% of respondents replied *Yes* to the presence of untreated wastewater. The low frequency of *Yes* responses followed our expectations, but what was revealing was that nearly 40% of the respondents were unsure about the presence of untreated wastewater being in their home tap.

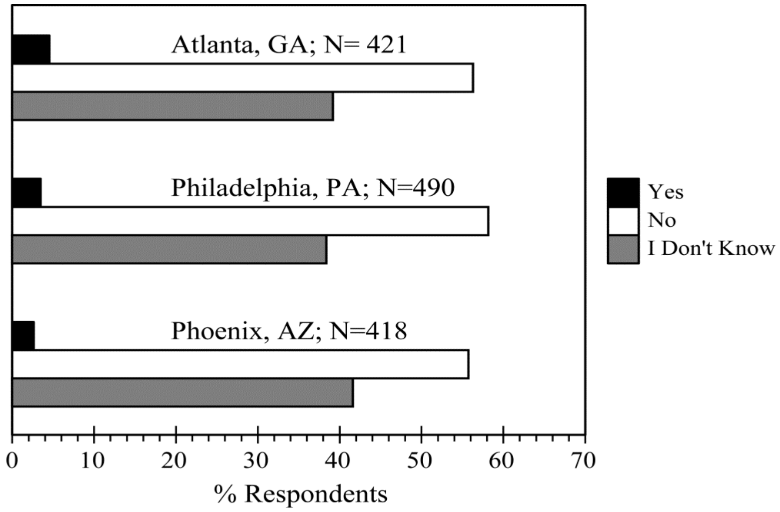


Figure 5.1. Response to the presence of UNTREATED wastewater (Q1) at home tap

In response to the presence of treated wastewater (Q2), the number of *Yes* responses increased to 25% from 4% for untreated wastewater, as displayed in Figure 5.2. There was also a large decrease in *No* responses, decreasing from 40% to 20%. However, 55% of respondents were unsure regarding the presence of treated wastewater. In general across the three cities consensus is that untreated wastewater isn't present in their tap water but that they are unsure if treated wastewater is present. While slight differences in response frequencies in both figures are displayed, apparent changes across the three cities were found to be statistically insignificant (p= 0.645). Revealing that the geographical and societal differences across the cities did not impact the responses significantly.

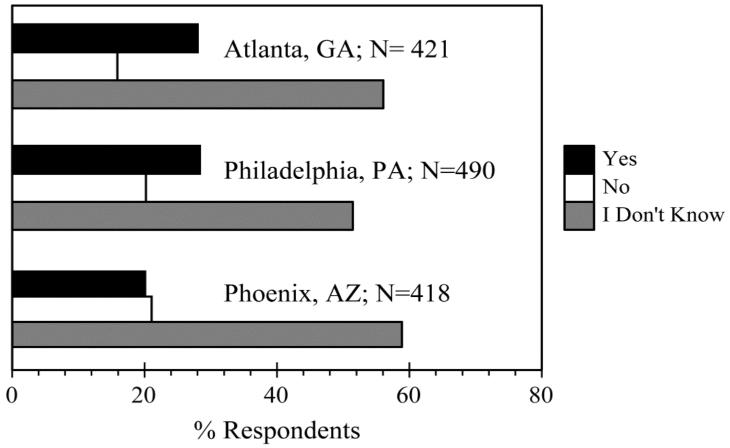
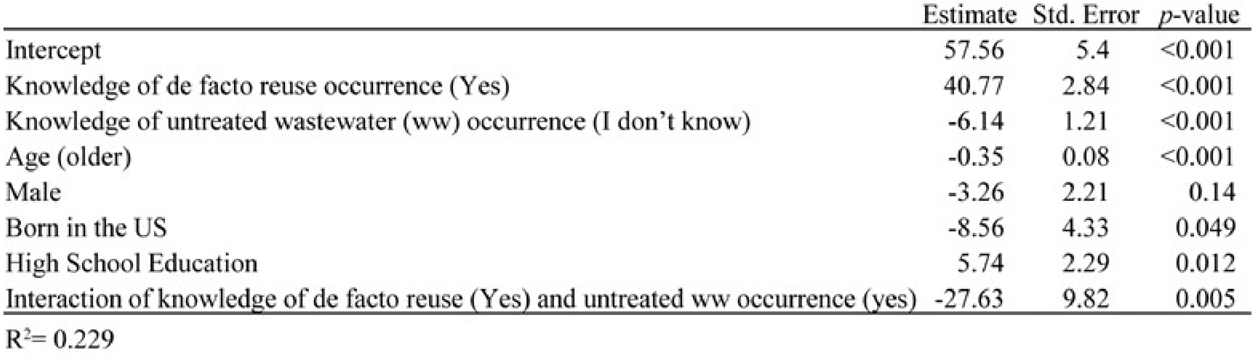


Figure 5.2. Response to the presence of TREATED wastewater (Q2) at home tap

De facto reuse acceptance

Q4 asked the acceptable percentage of treated wastewater within the respondents' home tap. The acceptance responses followed a trinomial distribution. Nearly 60% of the responses were in the extreme ends of the data set, either responding 0 (36% of responses) or greater than 90 (22% of responses). Results for the multivariate analysis are presented in Table 2 and Figure 5.3. In total 55 variables were tested when all the interaction terms are taken into account. Excluding the various interaction terms, 5 of the 11 variables tested were statistically significant at the 95% confidence level. Additionally, the interaction of perception of de facto reuse and untreated wastewater occurrence was added to the list of variables that included knowledge of de facto reuse occurrence (*Yes*), knowledge of untreated wastewater occurrence (I don't know), age, born in the US, and high school education. Nearly 23% of the variance is explained by these six variables. Figure 5.3 displays the relative sensitivity of acceptance level to each of the six standardized regression coefficients. Knowledge of de facto reuse occurring in the respondents' home tap had the highest impact on the acceptance level of de facto reuse.

Table 5.2. *Results to the multivariate analysis on acceptance of de facto reuse (Q4). All variables underwent a forward stepwise selection (p < 0.15).*



	Estimate	Std. Error	*p*-value
Intercept	57.56	5.4	<0.001
Knowledge of de facto reuse occurrence (Yes)	40.77	2.84	<0.001
Knowledge of untreated wastewater (ww) occurrence (I don't know)	-6.14	1.21	<0.001
Age (older)	-0.35	0.08	<0.001
Male	-3.26	2.21	0.14
Born in the US	-8.56	4.33	0.049
High School Education	5.74	2.29	0.012
Interaction of knowledge of de facto reuse (Yes) and untreated ww occurrence (yes)	-27.63	9.82	0.005

R^2= 0.229

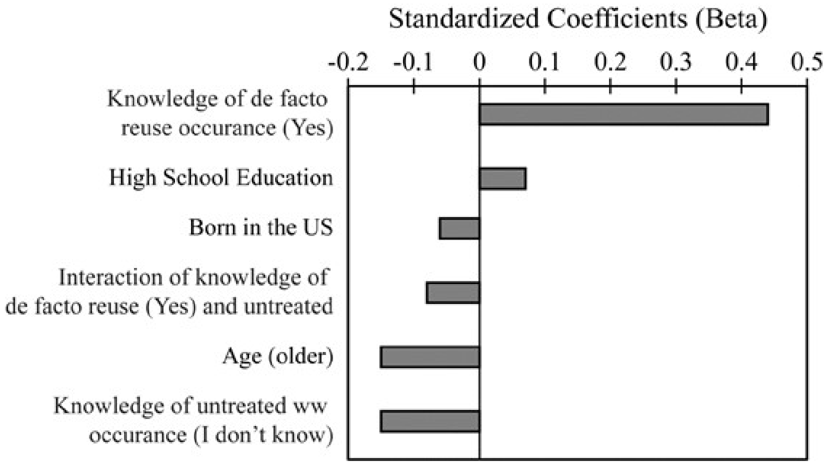


Figure 5.3. Standardized regression coefficients ($p < 0.05$), results to linear regression performed on Q4.

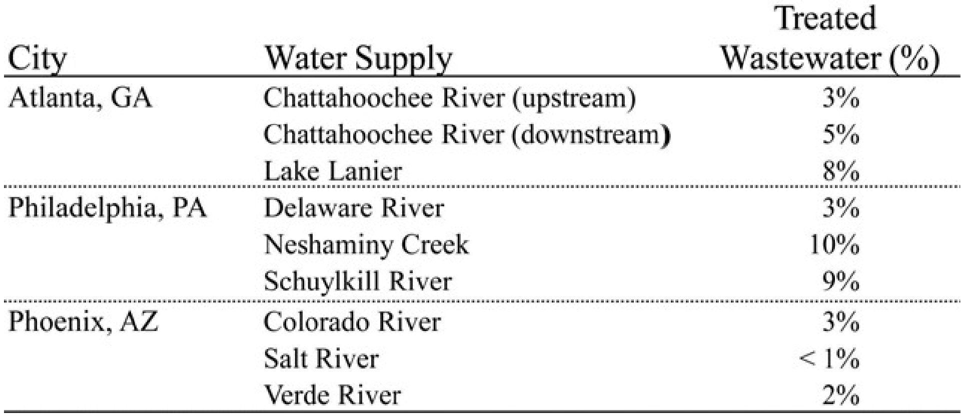
Due to the distribution of the datasets we grouped the responses into categories of acceptance (low acceptance and high acceptance). The logistic regression results are reported in odds ratio, to depict the odds that an outcome will occur given a particular factor. The first outcome tested was the odds that a person would belong to the low acceptance category. The odds ratio for knowledge of occurrence was 0.078, meaning those who have knowledge of occurrence are less likely to be part of the low acceptance group. After testing the second outcome of belonging to a high acceptance group, knowledge of de facto reuse occurrence held an odds ratio of 10.3, suggesting that responders with knowledge of de facto reuse at their home tap are 10 times more likely to have a high acceptance than those whom don't.

During this analysis, an additional variable was introduced that represented people whom believe high proportions of their tap water are made of previously treated wastewater. This dummy variable corresponded to the survey question that asked responders whom replied yes to having treated wastewater in their tap to list the percentage of tap water that is made up of treated wastewater (Q3). Responses that were higher than 75% were assigned to this group. Those in this group were 7.5 times more likely to also belong in the high acceptance group. This analysis reiterated the importance that the perception of de facto reuse occurrence had on the acceptance of de facto reuse in this study.

Estimated vs. perceived occurrence of de facto reuse

Overall, the amount of de facto reuse present in source waters across the three cities was greater than the perceived amount. Table 5.3 displays the estimated occurrence of the source water surrounding the Philadelphia Metropolitan Area under average streamflow conditions, under low flow conditions (modeled by 7Q10) treated wastewater discharges make up 100% of Neshaminy Creek and Schuylkill River. Philadelphia holds higher amounts of de facto reuse in comparison to the Atlanta and Phoenix metropolitan areas.

Table 5.3. *De facto reuse estimates for the metropolitan areas represented in this study.*



City	Water Supply	Treated Wastewater (%)
Atlanta, GA	Chattahoochee River (upstream)	3%
	Chattahoochee River (downstream)	5%
	Lake Lanier	8%
Philadelphia, PA	Delaware River	3%
	Neshaminy Creek	10%
	Schuylkill River	9%
Phoenix, AZ	Colorado River	3%
	Salt River	< 1%
	Verde River	2%

The multinomial linear regression and logistic regressions both displayed that the perception of de facto reuse occurrence was correlated to higher levels of acceptance. The next step in the analysis was to determine the spatial distribution of people's perceptions of occurrence. To do so, zip code polygons were color coded by the proportion of respondents whom perceive that treated wastewater is present in their home tap water (Figure 5.4). The number of survey responses were not equally distributed across each zip code area. Therefore, the values represent the ratio of people who respond yes to Q2, it was calculated to normalize for the amount of people surveyed per zip code. In Figure 5.4, only the zip codes with survey responses are shaded grey, darker shades represent a higher rate of perceived occurrence. The spatial distribution of the subset of the surveyed population that is unaware of de facto reuse occurrence is represented in the Figure 5.4 by the light grey shaded polygons. The majority of the zip code blocks fall into this category. The presence of these blocks in conjunction with the intersection of colored streamlines running through these areas highlight the opportunity to use the occurrence of de facto reuse as a tool to increase the likelihood of use of recycled and reused source water. The estimated occurrences were higher than the rate of perceived occurrence for all of the three cities surveyed. Across the three cities 55% of the responses to de facto reuse occurrence (Q2) were "I don't know". This subgroup of people would be the target audience of future efforts to increase acceptance of reuse schemes through knowledge of de facto reuse occurrence. Responses to Q4 for this group followed a trinomial distribution, with 65% of respondents belonging to the low acceptance category.

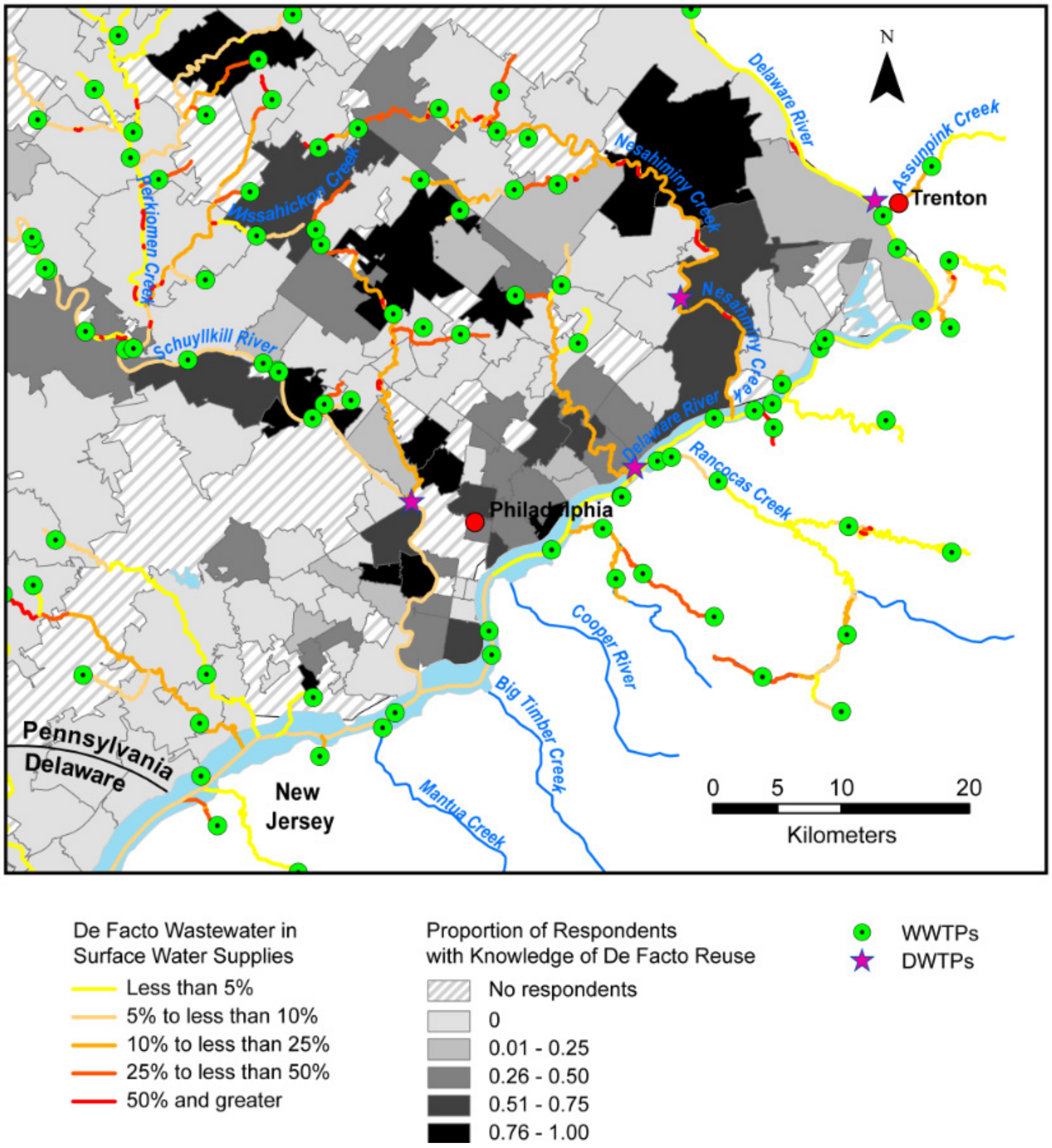


Figure 5.4. Estimated values of de facto wastewater reuse in Philadelphia, PA; overlaid with the ratio of respondents whom have knowledge of the occurrence.

Discussion

There are two possible underlying reasons for 4% of respondents replying *Yes* to the presence of untreated wastewater, which are that the results are indicative of respondents knowledge that untreated wastewater may be in the water or their emotional response to the water quality. If we assume the former, then this supports prior research regarding the ineffectiveness of municipal water quality reports (Johnson, 2003). Water quality reports are also referred to as consumer confidence reports, and generally aim to provide their customers with an overview of the water quality delivered by the system. The Safe Drinking Water Act requires municipalities to treat drinking water to strict standards. The notion that nearly 40% of the respondents are unsure regarding the presence of untreated wastewater (i.e. sewage) at the tap implies that there's a lack of knowledge regarding the origin of tap water. Further suggesting that such reports should include more basic information regarding the municipal water supply system and its place in the urban water cycle.

The interaction of perception of de facto reuse occurrence and untreated wastewater occurrence implies that between these two variables their combined effect is different from their separate effects. This interaction term was found to have a strong negative correlation to de facto reuse acceptance. This interaction represents the subset of people whom are aware of de facto reuse occurrence but are not informed about water quality basics, particularly the occurrence of untreated wastewater in their home tap water. One possible explanation is that respondents belonging to this subgroup aware of de facto reuse, respond more visceral to de facto reuse acceptance due to not having background knowledge of water quality issues, which supports the law of contagion's suggestion that feelings from a known subject are added to that of an unknown subject. In the study, high school level education was the only significant level of schooling correlated to acceptance. This was not in response to a lack in sample demographics, as 47.3% of the survey takers completed university or technical training, and 35.9% finished high school as their highest level of schooling completed. We initially expected that holding a college degree or some form of technical training would increase one's acceptance of de facto reuse, assuming that higher education was associated with increased knowledge of the subject matter. But, an alternative explanation is that more education may lead to people receiving more information regarding negative topics associated with wastewater and reuse such as the ecological threats posed by constituents found in wastewater. It's also important to point out that the underlying reasoning behind the occurrence can be derived from high school level knowledge of the water system as a closed system (i.e. no "new" water), therefore someone graduating high school is just as likely to have obtained this as someone who has graduated college. The negative correlation associated with being born in the US is possibly associated with the difference in societal norms of water between those born within and outside of the US, implying that those whom are born outside of the US hold higher acceptance of de facto reuse. The correlation to the country in which a person was born supports previous studies regarding ethnohydrology of water quality issues (Alhumoud & Madzikanda, 2010; Gartin, Crona, Wutich, & Westerhoff, 2010).

During cognitive interviews several people expressed their judgment formation consisted of answering yes to knowing that de facto reuse occurred naturally and the idea that there is no “new” water, in essence suggesting that all water has been reused in some way. This further solidifies the correlation between the knowledge of de facto reuse occurrence and acceptance. The magnitude of the influence of knowledge of occurrence is comparative to a study conducted in Australia, where it was found that a positive perception of recycled water had the highest impact on the likelihood of use of recycled water (Dolnicar et al., 2011). The phenomenon of respondents being aware of de facto reuse occurrence and therefore having higher acceptance is reminiscent of trends that have been shown in previous studies where positive perceptions and knowledge of reuse and environmental attitudes have been positively correlated with occurrence. It’s believed that attitudes and beliefs attached to de facto reuse (unplanned) occurrence are similar to those that are solicited from survey questions dealing with the perceptions and knowledge of planned water reuse.

Conclusion

This study was one of the few studies on de facto reuse within the United States, and one of the first to assess the ‘yuck’ factor as it relates to occurrence in a multicity analysis, with the notably exception of Rice et. al (2013) and U.S EPA Report (1980) (Rice et al., 2013; Wastewater in Receiving Waters at Water Supply Abstraction Points, 1980). One of the key findings was that many of the factors identified previously as being associated with higher levels of public acceptance of water reuse schemes are consistent with those reported in this study, in spite of the framing of the study around de facto reuse. Perhaps, the biggest finding that has emerged from this study is the support to Baumann and Kasperson (1974). We believe that more research is needed to gain a better understanding for the relationship between knowledge of occurrence and acceptance. Gaining more of an understanding for what reasoning and beliefs underlie our results will be the necessary first step in capitalizing on this information for the gain of public acceptance towards water reuse. Future work should be focused around developing a better understanding of the drivers behind increased acceptance in response to knowledge of de facto reuse occurrence. Due to monetary limitations and the approach of getting a multicity representative sample the survey questions were limited in number, preventing the structure of the survey from indirectly drawing out the survey takers' likelihood of use through a series of questions. It would prove to be beneficial to perform a study that is structured with the latter methodology based around de facto reuse, to validate the applicability of the results discussed in this research. We firmly believe that the results presented in this paper are a beneficial addition to the efforts of overcoming the "yuck" factor within the US.

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Chapter 6

NATIONAL EVALUATION OF PUBLICLY OWNED TREATMENT WORKS CONTRIBUTION TO ENVIRONMENTAL FLOWS IN FRESHWATER SYSTEMS*

*This chapter is in preparation for submission as a peer-reviewed letter to *Nature*, in collaboration with P. Westerhoff.

Abstract (fully referenced per Nature guidelines)

Wastewater treatment plant (WWTP) discharges are one of the highest anthropogenic inputs to natural waters (Schwarzenbach et al., 2006). Significantly contributing to the micropollutant load in the aquatic environment. Human effects of contaminants of emerging concern (CECs) are widely unknown, but several studies have shown that CECs in the form of endocrine disrupting compounds and PCPPs pose ecological threats. Conversely, wastewater is also a primary source of instream flow and critical in maintaining many aquatic and riparian wildlife habitats (Brooks, Riley, & Taylor, 2006; Davis, 1988; Lilly, 1980). Here we evaluate the degree to which publicly owned treatment works (POTW) wastewater discharges are both an ecological threat and beneficial contributor to sustained streamflow, by analyzing dilution factors as a proxy for the juxtaposed roles imposed to the ecosystem. The dilution factor represents the ratio of flow in the receiving stream to the flow of the treated wastewater. We found that wastewater discharges are vital to the sustainable water supply and an ecological threat within several sub-watersheds, making up greater than 50% of instream flows for over 900 receiving streams throughout the U.S. Dilution factors amongst the receiving streams 25th, 50th, and 75th percentile were 8, 43, and 287 respectively. The dilution potential for a receiving stream is greatly impacted by low flow conditions and lower

Strahler Stream Order values. This study demonstrated the balance of the posed ecological threat of wastewater discharges, with the benefit of sustained flow to riverine ecosystems.

Letter (Short Report)

Wastewater discharges hold the potential to play an important role in the U.S's water portfolio, as growing demands on the nations supply is compounded with the uncertainties of climate change impacts. Each day over 14,000 publicly owned treatment works (POTWs) release flows amounting to 32 billion gallons into surface water, 20 billion of those gallons are directly into rivers and streams that make up the nation's freshwater supply. Discharges from POTWs make beneficial water quantity contributions to sustained streamflow. Variability of natural streamflow affects the structure and function of stream ecosystems. With this, substantial alterations in flow regime pose the risk of significant changes in ecological organization of aquatic and riparian ecosystems. Reduction in streamflow has a direct impact on the biodiversity resources, limiting growth in all organisms.

Wastewater discharges make up greater than 50% of instream flow for over 900 receiving streams in the conterminous U.S. Making these streams effluently dominated (predominately composed of wastewater effluent). As displayed in Figure 6.1, dilution factors amongst the receiving streams under average flow conditions 25th, 50th, and 75th percentiles are 8, 43, and 287 respectively. Therefore, 25% of receiving streams have less than a ten-fold dilution. These results are greatly influenced by low flow conditions, where the 25th, 50th and 75th percentiles are 2, 14, and 134 respectively. It's important to point out that the low flow analysis was performed on a subset of the dataset

(N=1,049). Receiving streams with a USGS streamgage located on the same reach of stream as the POTW discharge are included in this subset, but the average flow estimates incorporate all 15, 837 POTW discharge sites. The low flow dilution factors are in turn over estimates due to the over representation of discharges into higher stream orders. This is a result of stream gages being more likely to be placed on larger river systems and on downstream segments rather than headwaters.

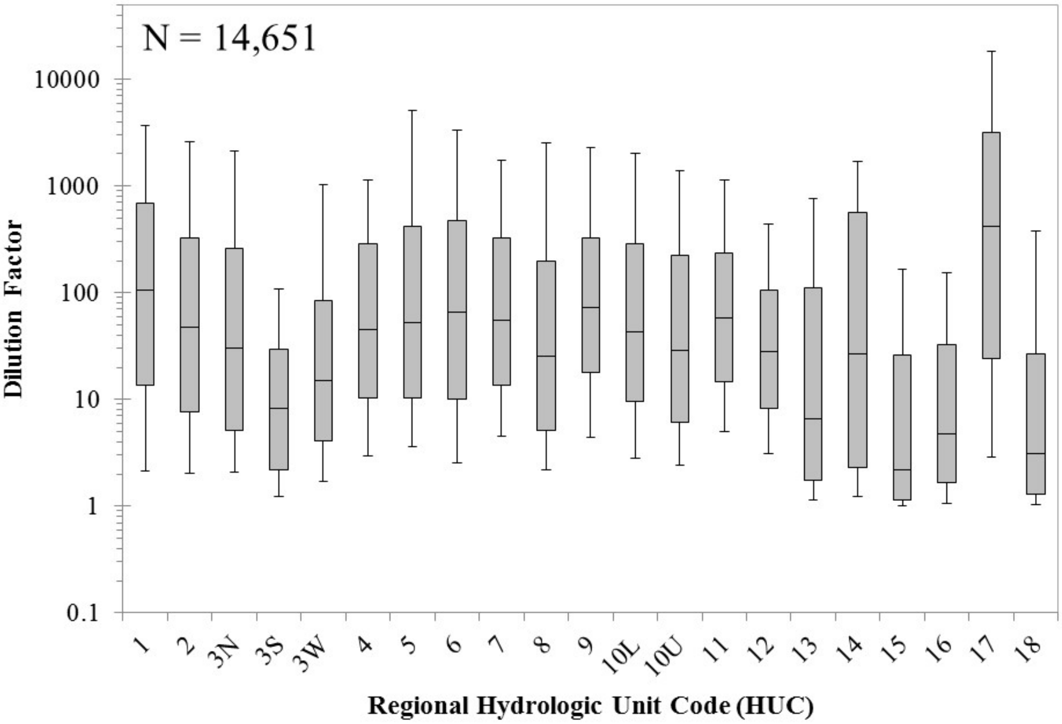


Figure 6.1. Dilution factors for municipal WWTP discharges by hydrologic region. Top and bottom of box= 75th and 25th percentiles respectively; top and bottom of whisker = 90th and 10th percentiles respectively; line across inside of box= median (50th percentile). Diamonds represent the average of values within the tenth and 90th percentiles.

Wastewater traditionally poses an ecological threat by way of nutrient loading, and more recently through the threat of contaminants of emerging concern. Habitat deterioration has been linked to depletion trends of freshwater fauna. Causes of deterioration include sediment loading and organic pollution, toxic contaminants from municipal and industrial sources, stream fragmentation, and channelization (Allan & Flecker, 1993; Benke, 1990; Dynesius & Nilsson, 1994; Ricciardi & Rasmussen, 1999; Richter, Braun, Mendelson, & Master, 1997). Treated wastewater discharges to surface water play several different roles towards the causes of deterioration. Wastewater treatment plant discharges are the primary entrance of anthropogenic compounds into waterways. In turn, municipal wastewater discharge makes significant contributions to the micropollutant load into the aquatic environment (Kolpin et al., 2002). Primary concerns to aquatic life stem from pharmaceutical and personal care products (PCPPS) and endocrine disrupting compounds (EDCs). There are nearly 3000 pharmaceuticals currently used in the U.S. and Europe posing ecotoxicological threats (Schwarzenbach, Egli, Hofstetter, von Gunten, & Wehrli, 2010; Ternes, 1998). EDCs impose their effects by mimicking endogenous hormones, antagonizing normal hormones, altering the natural pattern of hormone synthesis or metabolism, or modifying hormone receptors. The EDCs that are of higher concern for the aquatic wildlife are those that are found in treated and untreated municipal and industrial wastewaters. The most potent EDCs are found in sewage are steroidal estrogens such as 17β-estradiol (E2), estrone (E1), and 17α-ethnyestradiol (EE2)(Pojana, Gomiero, Jonkers, & Marcomini, 2007). Several studies have shown that EDCs have the potential to exert effects at extremely low concentrations (Jobling et al., 2003; Jobling & Sumpter, 1993; Mills & Chichester, 2005; White, Jobling, Hoare, Sumpter, & Parker, 1994).

To assess the threat of wastewater discharges we assess the receiving streams ability to meet or exceed the dilution factor representing the hazard quotient with a safety factor of 10. Hazard quotients are commonly used to estimate the potential ecosystem risk from individual contaminants. The quotient is equal to the maximum measures environmental concentration divided by either the 50% lethal effect concentration or the no observable effect concentration (Agency, 1998). We focus on EDCs as they have been reported to cause alterations to sexual differentiation, reproduction and growth impairments and subtle behavioral effects, and have been reported at levels exceeding the HQ within WWTP effluent (Barber et al., 2013). A subset of the data (N=1,049) was used to analyze hazard quotients under the Q95 low flow index, representing the flow that is exceeded 95% of the times. This flow has an estimated reoccurrence time of 15 years. As shown in Figure 6.2, the majority of receiving streams with a stream order from 1 to 3 fall below the lines for 17B-estradiol, estrone, and 17a-ethinylestradiol under low flow conditions. There are 699 streams that are impacted by a HQ value less than the 10 fold safety factor for at least one of the contaminants, and 334 below these markers for all three. 17a-ethinylestradiol is in such high concentrations in wastewater effluent that 421 receiving streams are at levels exceeding the HQ without the addition of a safety factor. This displays the susceptibility of the streams across the US under low flow conditions.

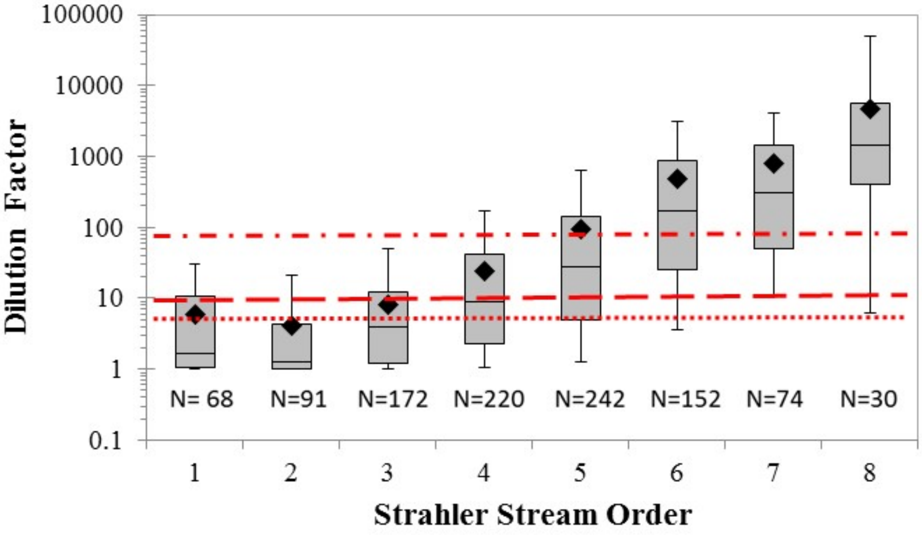


Figure 6.2. Dilution factors under low flow conditions (Q95). Red lines represent the dilution factors required for 17a-ethinylestradiol, estrone and 17B-estradiol (labeled from top to bottom) to fall below hazard quotients given a 10-fold safety factor. Dilution factors are set using measured concentrations from Babrber et. al, 2013. Top and bottom of box= 75th and 25th percentiles respectively; top and bottom of whisker = 90th and 10th percentiles respectively; line across inside of box= median (50th percentile). Diamonds represent the average of values within the tenth and 90th percentiles.

POTW discharges pose higher risks to receiving rivers that are of lower Strahler stream order due to lower average streamflow. Roughly 70% of WWTP discharges are into streams classified by a Strahler Stream Order of 3 or lower. As displayed in Figure 6.3, there is up to a four magnitude difference between dilution factors based upon stream orders in the same hydrologic region. The dilution factors decrease greatly when only taking into account lower stream order receiving streams; amounting to 5, 19, and 71 for the 25th, 50th, and 75th percentiles respectively.

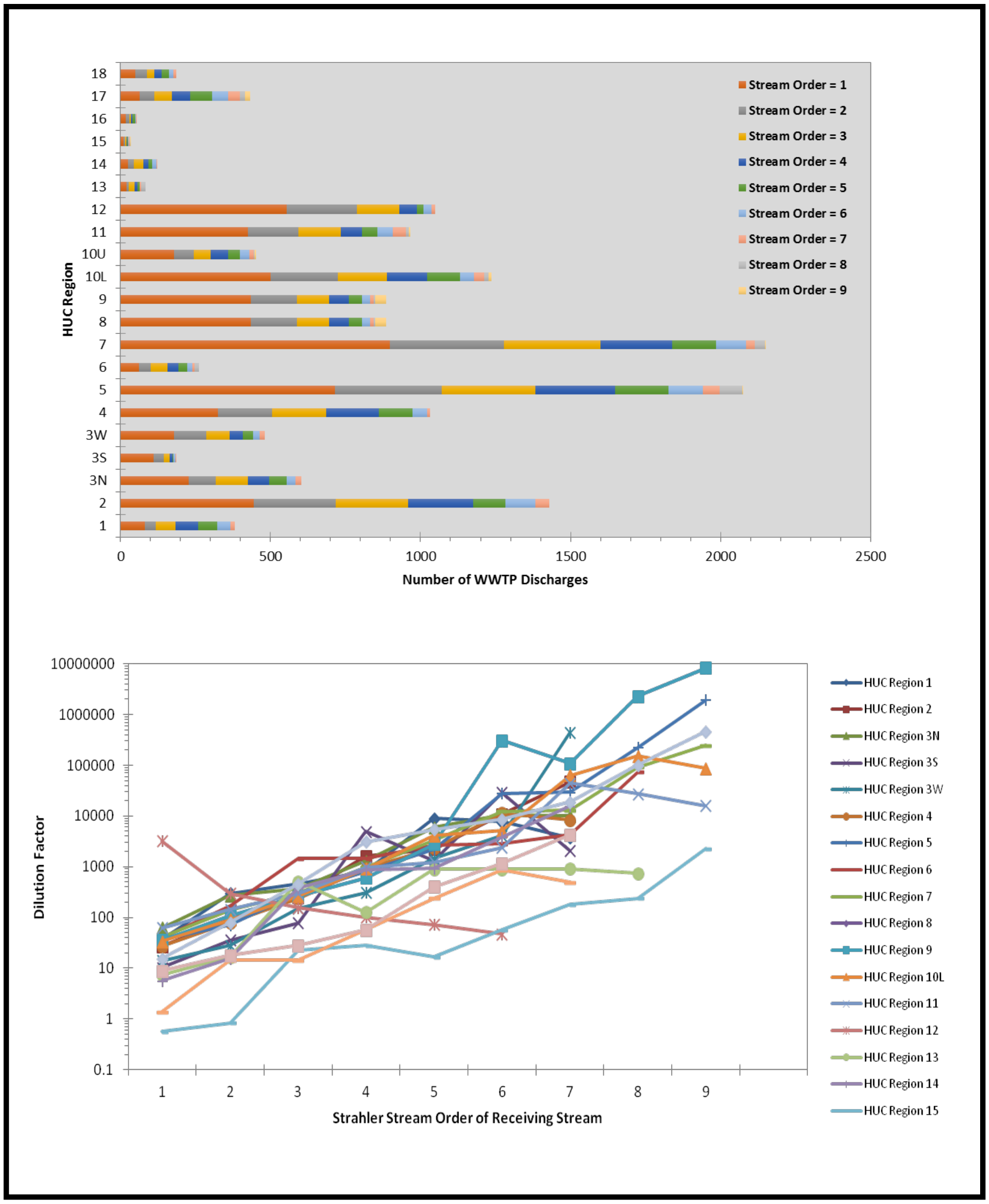


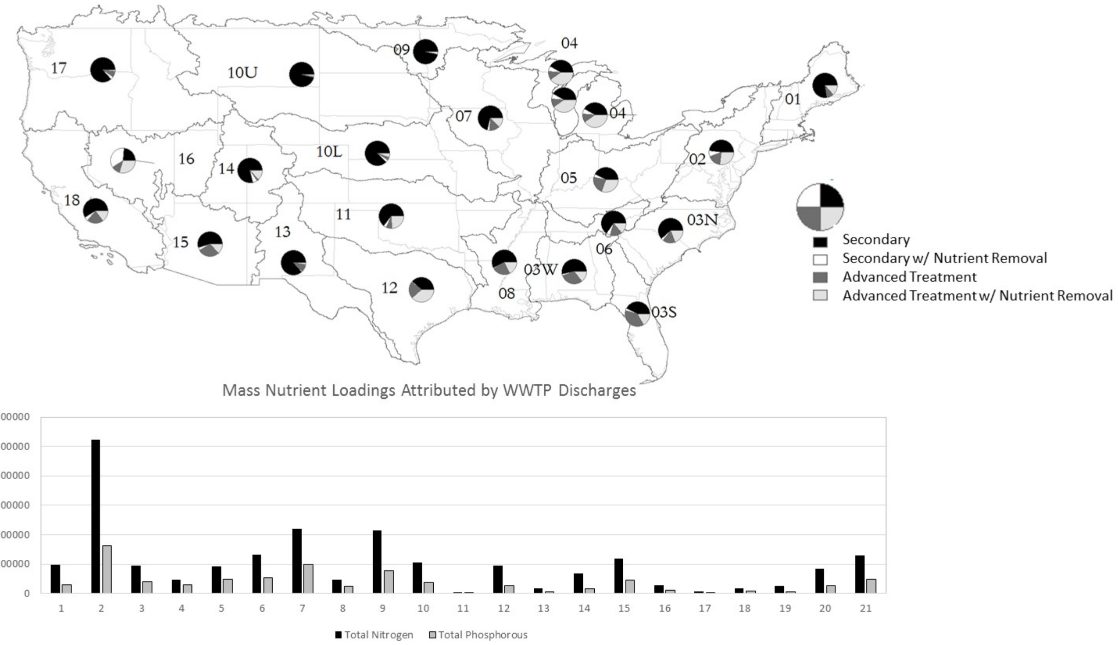
Figure 6.3. Susceptibility of streams characterized by a low Strahler stream order. The number of discharges categorized by Strahler stream order of the receiving streams are shown for each hydrologic region. Dilution factors are also plotted against Strahler stream order by hydrologic region.

Improvements in wastewater treatment have lessened ecological threat posed by nutrients, however nutrient loading still remains the cause for nearly 7,000 impaired water in the U.S (EPA, 2012). Overall, non-point sources such as agricultural runoff contribute the majority of the nutrient load; contrarily within a watershed point-sources (primarily wwtp discharges) can account for up to 77% of in-stream nitrogen loading (Puckett, 1994). Only about a third of treatment plants receive greater than secondary treatment. Secondary treatment of wastewater by conventional activated sludge removes pharmaceuticals at levels that vary greatly depending on the contaminant in question, in particularly EDC's have displayed poor removal (Gobel, McArdell, Joss, Siegrist, & Giger, 2007; Joss et al., 2005; Stasinakis et al., 2013). Advanced treatment options are available with higher contaminant removal efficiencies; such as ozone oxidation (Huber et al., 2005; Ternes et al., 2003). In spite of this, nationally secondary treatment is in place for the majority of WWTPs across the U.S. (SI-6.1).

Treated wastewater discharges are a primary anthropogenic input into the surface water supply. The results reported here, highlight the complex role that treated wastewater discharges play in our water supply. In our discussion of dilution factors, higher dilution factors are associated with less ecological threat of wastewater contaminants by means of lower contaminant concentrations. Making lower dilution factors equate to higher concentrations of wastewater contaminants i.e. higher posed ecological threats. However, the lower factors highlight the contribution of the wastewater effluent to sustained streamflow. Thus, future policy recommendations must balance the risk of higher CEC concentration attributed to wastewater discharges, with the benefit of sustained flow to riverine ecosystems. Receiving streams across the U.S. would reap higher benefit from an approach that emphasized the mitigation of ecological threats through increased levels of treatment, as opposed to instream dilution.

Supporting Information

Figure SI-6.1. Spatial distribution of wastewater treatment level and nutrient loading. Estimates based on nitrogen and phosphorus removal by treatment type.



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Chapter 7

DISSERTATION SYNTHESIS

Introduction

Decision makers have increasingly called upon science professionals to provide information and research for complex environmental issues (Browning-Aiken, Richter, Goodrich, Strain, & Varady, 2004; Liu, Gupta, Springer, & Wagener, 2008; Management, 1999; Matthies, Giupponi, & Ostendorf, 2007). This demand has made prevalent the need for more effective integration of science and decision-making (Liu et al., 2008). Nadeau and Raines (2007) suggests "we have good science but to make science useful requires an effective interface between science, policy and public participation (Nadeau & Rains, 2007)." In support of this, the purpose of this chapter is to synthesize de facto reuse occurrence and modeling presented in precious chapters into the current research and approaches aimed at protecting public health and the environment from anthropogenic processes and inputs.

A practice incorporating knowledge of de facto reuse occurrence has the potential benefit to aid these efforts for protection against emerging contaminants. Here we lay out a strategy that integrates the DRINCS Model as a tool to identify higher risk WTPs, and to manage and mitigate risks associated with WWTP discharges. This tactic suggests, (1) taking a preemptive approach to protect against contaminants with unknown effects; (2) capitalizing on knowledge of de facto reuse occurrence to aid in ongoing chemical risk assessments of emerging contaminants; and (3) shaping new policy recommendations that are resilient to future societal and climate changes in streamflow.

Prior to displaying how the DRINCS Model can be utilized for future policy efforts, it is important to discuss the model's limitations. DRINCS limitations are due in part to the datasets, calculations and validation performed on the model. Wastewater Treatment Plant discharge locations were obtained from EPA's Clean Watershed Needs Survey (CWNS 2008). Unfortunately the discharge location (latitude and longitude) often seemed to coincide with the office location rather than actual discharge site, and/or the site was not near a river reach. In these instances, alternative locations were looked up using the Permit Compliance System or CWNS 2004. Identities for Drinking Water Treatment Plant surface water intakes were obtained from the Safe Drinking Water Information System; while this may not be a complete dataset it is the most complete data available. Surface water intake locations were further limited to those serving greater than 10,000 people, analysis on the remaining intakes will be performed at a later time and were limited to a number that was manageable to complete at the present time. The model's hydrology was based upon the National Hydrography Dataset Plus (NHDPlus), this was the most complete dataset at the national scale. In spite of NHDPlus being the most complete dataset, low flow values are not included, therefore the majority of intake sites are limited to de facto reuse calculations based upon average flow conditions. Additional streamflow conditions, including low-flow modeled by Q95 and historic flow percentiles were obtained from USGS stream gages. This was complete in a two stage process, first surface water intakes were matched to stream gages by NHD reachcode, then a select group of ungaged sites were estimated using a drainage-area ratio estimate. De facto reuse was estimated from static model calculations based upon streamflow and WWTP discharges at different scales, which introduces error into the reported estimates.

This limitation is noted, but due to the aforementioned data limitations the most complete data was used. The model validation process was limited to 12 DWTP sites, this limits the generalizability of the validation results to all of the drinking water intakes modeled. In lieu of the validation data being limited in number, the sites were selected from various locations, with 10 different states represented in the validation.

Proactive Approach to Risk Management of Emerging Contaminants

Estimating CEC concentrations from de facto reuse

Contaminants of emerging concern (CECs) may have a risk to human health and the environment associated with their presence, frequencies of occurrence, and/or source are not known (Snyder et al., 2004). CEC occurrence is expected to increase as a result of the creation of new chemicals or by changes in use and disposal of existing chemicals (Kolpin et al., 2002). It is impossible for the EPA to keep up with occurrence and toxicological studies regarding the growing list of CECs. In an analysis of Mesa Wastewater Treatment Plant effluent we analyzed for a suite of contaminants, as displayed in Figure 1, where 15 of the 18 pharmaceuticals tested were identified. This is representative of treated water in WWTPs across the U.S., which are discharged into surface streams. However, without a national monitoring program for CECs there is limited data on their spatial occurrence and concentrations across wide ranges of streamflows. This dissertation provides a strategy that could be applied to estimate river reaches or WTPs over large geographic scales that may be of highest risk of impact by CECs of wastewater origin. In its current form, the DRINCS model could be used to estimate conservative levels of CECs at downstream WTPs by assuming they are refractory (i.e., no net decay in the river reach) and then multiplying a typical WWTP effluent concentration of a specific CEC ($C_{CEC,\ WWTP}$) by the % de facto reuse (%DFR); as displayed in Equation 7.1. In such scenarios, the DRINCS model can readily be run multiple times assuming different ranges of upstream WWTP treatment capacities and/or different stream flowrates, thereby coming up with a range for $C_{CEC,\ WWTP}$.

Equation 7.1.

$$C_{CEC,\ WWTP} = C_{CEC,\ WWTP}\ \mathrm{X}\ (\%DFR/100)$$

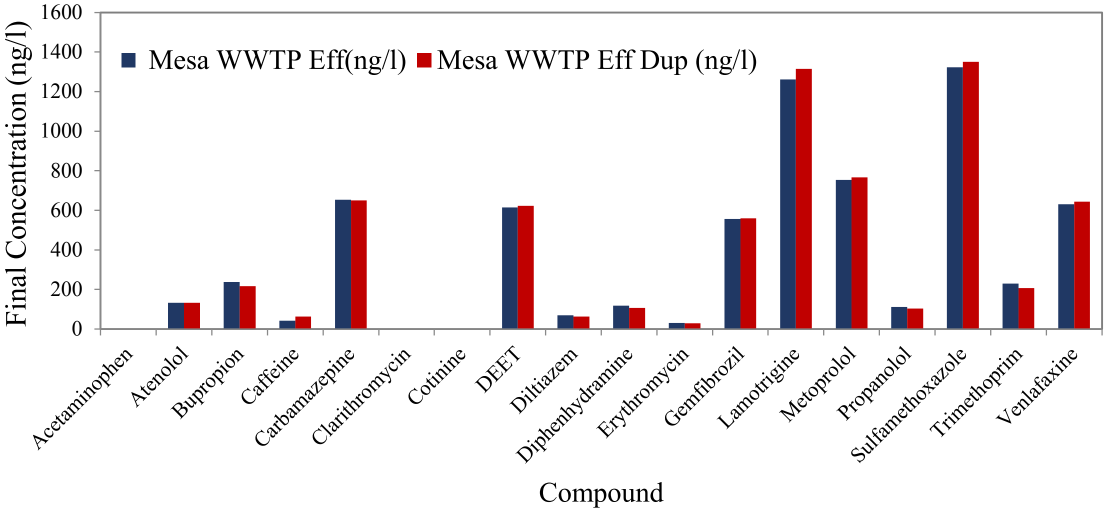

Figure 7.1. Suite of pharmaceuticals analyzed by LC/MS-MS for Mesa Wastewater Treatment Plant effluent.

In our national assessment we found that over 4 million customers (retail population served) of large drinking water systems in the U.S. are served by an intake that has greater than 20% treated wastewater. In the process of regulatory agencies determining if standards should be placed on emerging contaminants, millions of people are being exposed to potentially harmful chemicals. We suggest that a preemptive holistic approach be taken on monitoring wastewater's contribution to source waters, as it is the main input into the environment. Sites that are already being drawn from impacted wastewater can monitor the wastewater percentage and use that to estimate, conservatively, relative concentrations of each CEC. This is a more practical approach to quantifying parts per trillion concentrations of over 50 chemicals. The percent wastewater can be used with site specific or average wastewater effluent concentrations to estimate, conservatively, relative concentrations of each CEC.

Integrating DWTP treatment into de facto reuse estimates to assess CEC exposure

Previous research regarding the fate and occurrence of CEC's in the urban water cycle, have been focused more on wastewater treatments plants, as opposed to drinking water treatment plants. In spite of this, several studies have demonstrated the range of removal rates varying by contaminant and treatment methods (Benotti et al., 2009; Padhye, Yao, Kung'u, & Huang, 2014; P. E. Stackelberg et al., 2004; Paul E. Stackelberg et al., 2007; Wang et al., 2011). To illustrate how the DRINCS model can aid in the estimation of exposure of CECs to people, we use de facto reuse estimates for the top 5 most impacted DWTP intakes to assess potential contaminant concentrations at the tap (Figure 7.2). This is only an estimate and does not reflect the actual level of treatment or source waters present at the DWTP sites, as many DWTP's influent is mixed from multiple sources. Influent concentrations of carbamazepine, gemifibrozil and sulmethoxazole are estimated using concentrations found in Mesa WWTP effluent (Figure 7.1), and calculated using Equation 1. Removal efficiencies from prior research is used to estimate the final concentrations present under two different DWTP schemes. The first removal estimate resembles conventional drinking water treatment, consisting of coagulation/flocculation, filtration, free chlorine and residual chloramines, adopted from an investigation of five DWTPs in the U.S. by Snyder et. al (2010) (Snyder et al., 2010; Trussell et al., 2012). The second treatment scheme reflects removal by means of ozone oxidation, as research has found ozone to effectively remove many CECs (Benotti et al., 2009; Padhye et al., 2014). As displayed in Figure 7.2, DRINCS de facto reuse estimates can be used to assess potential contaminant levels; and when used in conjunction with contaminant removal rates, can forecast the potential levels resulting from varying treatment schemes.

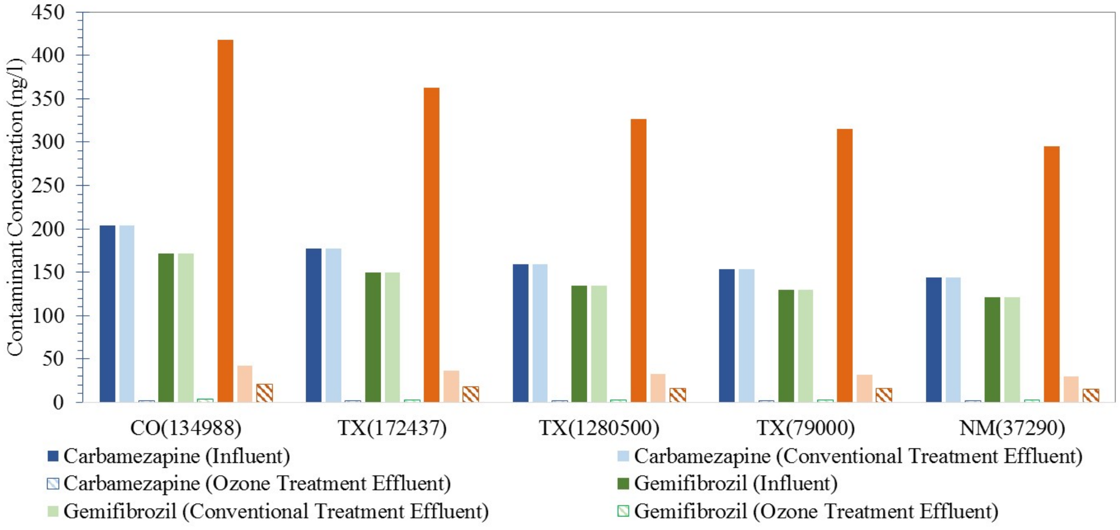

Figure 7.2. Estimates for carbamezapine, gemifibrozil, and sulmethoxazole DWTP effluent concentrations.

Balancing risks with benefits

Generally, human health and environmental health are aims that support each other (Titz & Doll, 2009). Special consideration in the implementation of policy regarding wastewater discharges must be taken in order for this to hold true. Future policy that impacts wastewater discharges must consider the beneficial additions to environmental flows. It's important to note that doing so doesn't disregard the potential threats posed by CECs, but instead aims to develop an approach that optimizes protection to contaminants and sustained environmental flows. Receiving streams characterized by lower dilution factors (less than 10:1) in Figure 7.3 depict the dependency of the stream to flow provided by upstream discharges, notably occurring in regions 3S, 15,16 and 18. Water withdrawals that may seem to have little impact at the regional scale can potentially have significant impact in the sustainability of freshwater ecosystems (Mubako, Ruddell, & Mayer, 2013). Therefore, negative ecosystems impacts are also possible for receiving streams with higher dilution factors. Environmental flow assessment models are necessary to fully understand the potential impact of reduced wastewater discharges. Several methods are available to be integrated with wastewater estimates from DRINCS for this assessment; including ecological limits of hydrologic alterations, species discharge relationships, and instream flow incremental methodologies (Bovee, 1982; Bovee, Lamb, Bartholow, Stalnaker, & Taylor, 1998; Poff et al., 2010; Sanderson et al., 2006; Spooner, Xenopoulos, Schneider, & Woolnough, 2011).

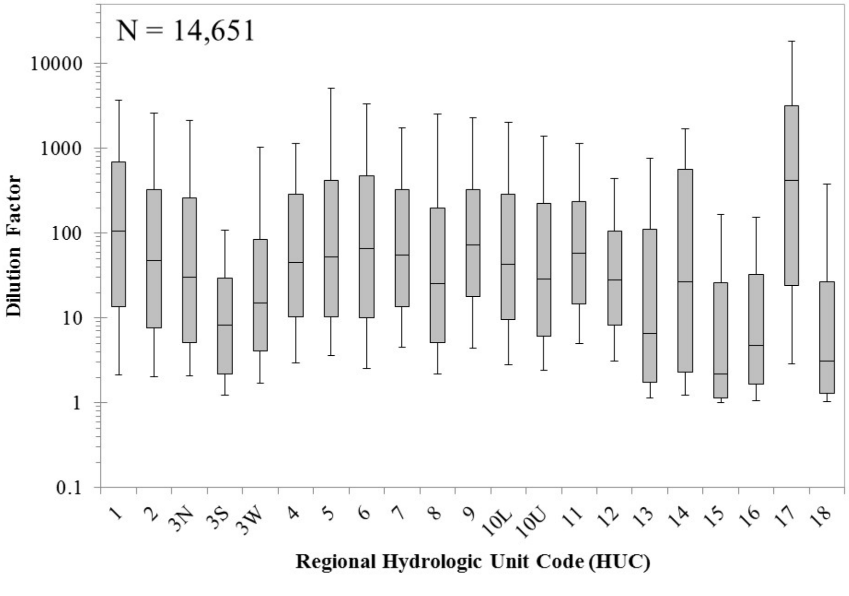

Figure 7.3. Dilution factors for municipal WWTP discharges by hydrologic region. Top and bottom of box= 75th and 25th percentiles respectively; top and bottom of whisker = 90th and 10th percentiles respectively; line across inside of box= median (50th

percentile). Diamonds represent the average of values within the tenth and 90th percentiles.

Setting the stage for a preemptive approach with the precautionary principle

Understanding the potential impacts from CECs on human health is hindered by the need for risk assessments. Efforts to complete the necessary risk assessments are impeded by the large number of pharmaceutical agents (and their metabolites) and difficulty in determining chronic effects. Assuming that further research will focus on this need, it is still unlikely to reduce the uncertainty involved in risk assessments in the short term (Titz & Doll, 2009). It has been argued that in situations such as this, where risks remain unquantifiable due to limited scientific knowledge, invoking the precautionary principle is a reasonable option (Titz & Doll, 2009; von Schomberg, 2006). The precautionary principle as put forth by the United Nations in the Rio Declaration of Environment and Development (1992) is defined as follows: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation (Declaration, 1992)." This principle has yet to be used in the U.S. for emerging drinking water contaminants, but was adopted in the EU and set the precedence for their pesticide standards (Dolan, Howsam, Parsons, & Whelan, 2013). Daughton (2004) notes that a new paradigm would be welcomed, as a proactive approach where future concerns are anticipated long before preventive or remediation measures have major economic ramifications (Daughton, 2004).

Social benefits of having a proactive risk management approach

Public discussion and dispute about the existence and extent of risk takes place in public and semi-public discourses. Socially, this dialogue influences how we think about possible risks, how we perceive possible risks, what we state as true and false, and how we act and behave in times of risk-based uncertainty and crisis (Jekel et al., 2013). This holds true for discussions surrounding drinking and surface water contaminants, where the public is exposed to reports concerning pharmaceuticals in their own tap water in conjunction with discourse regarding reported ecological effects from such pharmaceuticals (i.e. fish feminization). Under these circumstances, water professionals must acknowledge the role that trust plays in communication and make efforts to gain and keep the trust of the public; as trust is the strongest indicator of positive reporting and comments in media (Ragain, 2009). We as water professionals and policy-makers have generally fallen short of communicating to the public that we are taking a proactive approach towards protecting water consumers from the potential risks of emerging contaminants. Public perceptions of involuntary risks are magnified when environmental problems are stated with vague health concern and no suggested actions or corrections (Ragain, 2009).

Our study presented in Chapter 5 displayed how the correlation between knowledge of reuse and acceptance changed from positive to negative, when the survey taker was misinformed about the presence of untreated wastewater (i.e. sewage) in their tap water. This serves as an example of how a lack of information and/or lay knowledge in the public can impact the perception of risk identified with that object, as displayed by the willingness (or lack thereof) to consume. Ragain (2009) notes that "the more water utilities know about public perceptions regarding drinking water,… the better able they will be to respond – even if the concern isn't completely understood." I add that understanding public perceptions of drinking water is important, but it's equally as important to instill in the public the trust in knowing that those overseeing their water quality are proactively protecting public health. Researchers are aware of the many research efforts that keep this aim in mind, but very few of these get disseminated to the public in a meaningful manner. Communicating to the public the research and policy measures being taken at both the national and local level must be a priority within risk communication. The preemptive approach presented in this chapter could also benefit public perceptions of water quality by establishing trust between the water provider and customer, by acting instead of reacting to potential threat of emerging contaminants. The primary difference in risk communication in relation to typical communication is its emphasis on using science and data for decisions and addressing perceptions in addition to facts (Ragain, 2009). Surveys such as the one completed in chapter 5 play an important role in understanding public perceptions, and should be expanded upon to understand the public's concern and risks of emerging contaminants.

Capitalizing on De Facto Reuse to Assess Emerging Contaminant Risks

Knowledge and information regarding incidental reuse throughout the U.S. can be used in the assessment of risk associated with its occurrence. An integral step in a chemical risk assessment is determining how, and in what quantity a chemical enters our human body. For several CECs, the primary pathway from the environment to human contact is expected to be through impacted water supplies. Exposure from this pathway include the digestion of the impacted water, and direct skin contact from showers. A study of 139 streams across 30 states in the U.S. found CECs and other organic waste contaminants in 80% of the streams studied. This study also shed light onto the necessity of identifying the potential interactive effects, as a median of 7 and as many as 38 contaminants were found in a sample (Kolpin et al., 2002). Our analysis of Mesa WWTP effluent further emphasizes the need for cumulative risk assessments, as displayed in Figure 1. The EPA acknowledges that, "the traditional approach of assessing the risk from a single chemical and a single route of exposure may not provide a realistic description of real-life human exposures and cumulative risks that result from those exposures," Dr. Valerie Zartarian (EPA scientist) (EPA). Therefore, there is now a push towards an approach that incorporates cumulative assessments.

The National Research Council has recommended longitudinal studies in human populations exposed to endocrine disruptors, in lieu of evidence from animal studies supporting reproductive and developmental abnormalities and inadequacy of human data (Falconer, Chapman, Moore, & Ranmuthugala, 2006; Knobil et al., 1999). Yet longitudinal and cross sectional studies have been slow to emerge. Risk assessments are often halted by complexities and uncertainties surrounding exposure frequency and timing, exposure duration, exposure complexity, prior exposure history, and/or other factors including delayed-onset toxicity. These current limitations warrant the need for progress toward holistic assessment that account for the wide range of potential environmental pollutants and the pinpointing of pollutant scenarios with highest health-effects potential (Daughton, 2004). Prior research has incorporated epidemiology into the assessment of the association between exposure to trihalomethanes and birth issues within the U.S. and Europe (Grazuleviciene et al., 2011; Jeong et al., 2012; Porter, Putnam, Hunting, & Riddle, 2005; Swan et al., 1998; Villanueva et al., 2011).

Recent work has integrated previously used methods into new approaches, in an effort to overcome some of these complexities; such as a study of the occurrence and toxicity of disinfection byproducts in European drinking waters that integrated quantitative in vitro toxicological data with analytical chemistry and human epidemiologic outcomes (Jeong et al., 2012). Future work concerning emerging contaminants should also aim to integrate methods and models. Occurrence estimates from the DRINCS model can aid in the assessment by providing information regarding a conservative estimate of dose, duration, and frequency, as well as spatially identify areas where people have been exposed to higher level of treated wastewater. These estimates can then be input into an exposure predictions model, such as the model developed by Kim et. al (2004) which predicts exposure and absorbed dose for chemical contaminants in household drinking water through inhalation, direct and indirect ingestion and dermal penetration (Kim, Little, & Chiu, 2004). Cities selected for epidemiology studies should include sites that held high levels of de facto reuse in the current study, as well as the 1980 study. This would set the stage for longitudinal analysis, since there are possible cohorts of people that have been exposed to wastewater contaminants over the past 30 years. The Philadelphia metropolitan area (depicted in Figure 7.4) is a good candidate for these assessments, due to the presence of three source waters impacted by higher levels of de facto reuse in both studies.

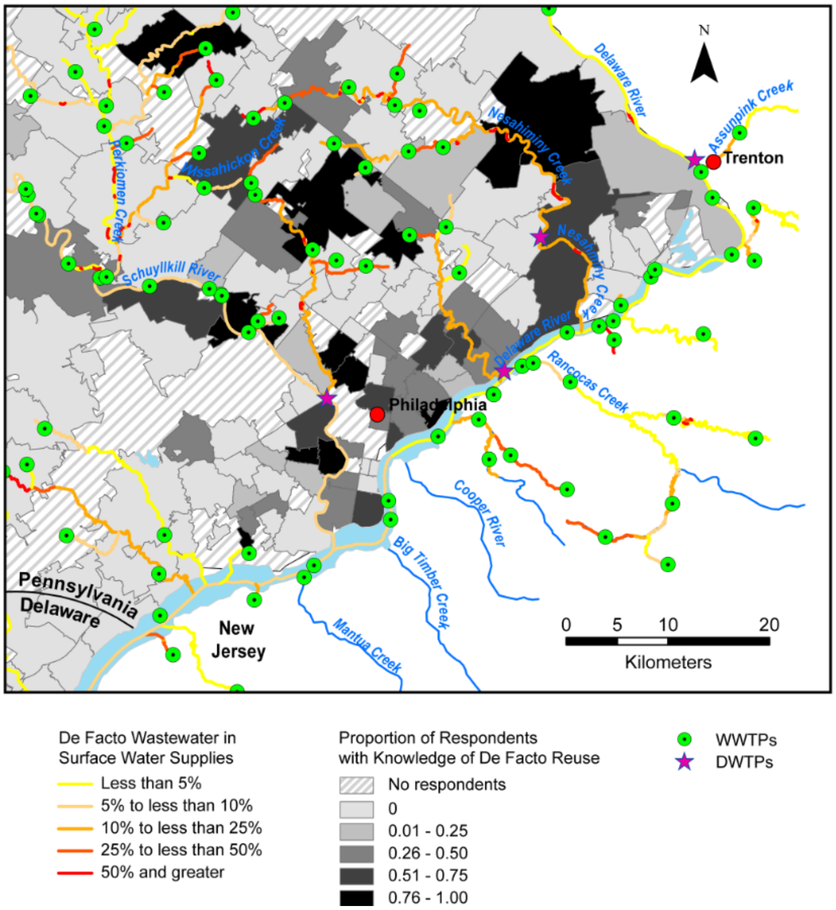

Figure 7.4. Estimated values of de facto wastewater reuse in Philadelphia, PA; overlaid with the ratio of respondents whom have knowledge of the occurrence.

Resiliency of Future Policy Recommendations

It's important that future policy recommendations are resilient to potential impacts associated with climate change, population growth, and societal changes in use and consumption. Dilution factors play a large role in measuring the effects of wastewater effluent on downstream subjects. Guo et. al (2007) noted this occurrence in the Colorado watershed, where three CEC's were each approximately twice as high at the site between 2006 and 2007. This was explained by only half of the stream flow being measured in 2006 when compared to 2007 (Guo & Krasner, 2009). Similar effects were echoed in a study performed by Barber et. al (2006) on the Boulder Creek Watershed in Colorado. Natural and anthropogenic variation in flow led to percent effluent downstream of the Boulder WWTP ranging from 10-26% effluent during spring runoff and 39-74% effluent during base flow (Barber et. al, 2006). Our analysis of de facto reuse under low flow conditions and historic variations corroborate these findings, and highlights the role of decreased streamflow exaggerating impacts of treated wastewater.

A number of factors may increase the number and concentration of CECs in treated wastewater. Population growth holds the potential to increase in the loading of anthropogenic inputs, particularly pharmaceuticals and personal care products. Effects of population growth can be further exaggerated by an increase in the consumption rates of prescriptions, food and personal care products that contain emerging contaminants. Water conservation efforts aimed at decreasing the amount of water used in residential homes, will decrease the volume of wastewater but perhaps increase the concentration of chemicals. This would result from a decrease in the dilution potential of wastewater at the point of the wastewater treatment plant influent, as the amount of water entering the sewer system would decrease but the chemical loadings would likely increase (due to the previous factors). DRINCS can be used to predict the future impacts that population increase and changes in societal use patterns have on wastewater contaminant loading. This can be done by integrating population changes into land use data within GIS, or can be calculated based upon the future plant design capacity data that is already part of the dataset.

In lieu of the potential impacts posed by changes in climate scenarios, population and use patterns; future approaches to policy recommendations should take into special consideration the mass loadings of chemicals when setting guidelines for concentrations limits. End users of the water (i.e., DWTPs) will have increased difficulty in meeting such guidelines under any of the aforementioned future scenarios. A possible way to address these concerns would be to direct the focus of guidelines addressing CECs to WWTP discharges. Currently, when an emerging contaminant is found to be a risk to human health guidelines are placed on the DWTP to treat water to increased standards. In addition to this, an emphasis should be placed on the quality of wastewater discharged into streams; as they are the main pathway into the environment. Such an approach, would incorporate removal guidelines of chemical contaminants into current policy. An added benefit to this approach is the protection it yields to the aquatic environment in turn for decreasing the load of contaminants into streams.

Visual Summary of Synthesis

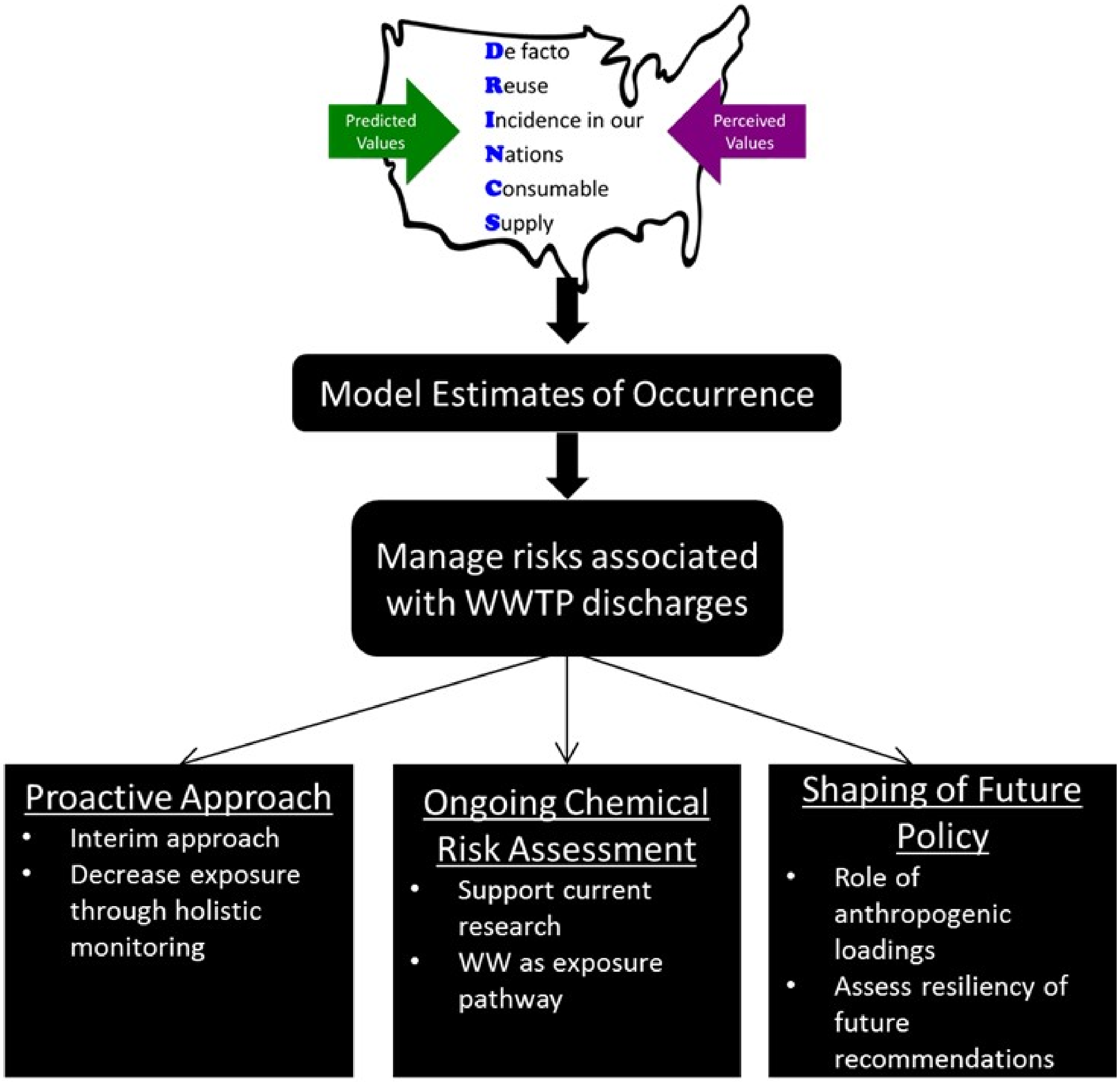

Figure 7.5. Visual depiction of a three-phase approach aimed at integrating DRINCS into current policy efforts, as put forth in this chapter.

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Chapter 8

SUMMARY, CONCLUSIONS and FUTURE RESEARCH DIRECTIONS

The main goal of this research was to develop a Geographical Information System (GIS) model of the continental United States (De facto Reuse Incidence in our Nations Consumptive Supply (DRINCS) Model) coded to estimate the amount of treated wastewater effluent present within downstream potable water supplies (i.e. de facto reuse), and to perform social science surveys to assess public perceptions of de facto wastewater reuse. The objectives of this dissertation were to:

1. Compare the wastewater percentages found in the Top 25 cities of the 1980 EPA Study with updated de facto reuse values.
2. Quantify the percentage of wastewater effluent in drinking water treatment plant intakes at the continental scale. Forecast potential climate change impacts to these percentages through the analysis of historical temporal variation trends.
3. Analyze the public's perceptions regarding the occurrence and acceptance of de facto wastewater reuse juxtaposed with predicted values.
4. Assess WWTP discharge contributions to stream flow and emerging contaminant loading, within U.S. riverine ecosystems.

Each of the main chapters in this dissertation (Chapters 3 through 6) was presented to fulfill each of these objectives. A summary of the primary findings from each chapter is provided in this chapter.

Summary of Findings

Chapter 3: Assessment of De Facto Wastewater Reuse across the U.S.: Trends between 1980 and 2008. Published: Rice, J., Wutich, A., Westerhoff, P. Assessment of De Facto Wastewater Reuse across the USA: Trends between 1980 and 2008. Environ. Sci. Technol., 47(19), 11099-11105,2013.

- De facto reuse ranged from 2 to 16% during average flow conditions, and during low flow conditions (7Q10) ranged from 7% to 100%, in the top 25 most impacted DWTPs from a 1980 EPA study;
- In a four-city case study, three sites have greater than 20% treated wastewater effluent within their drinking water source for streamflow less than the 25th percentile historic flow;
- Between 1980 and 2008, wastewater effluent contribution to the top 25 cities increased by 68% from 4.9 to 8.2 billion gallons per day;
- 17 of the 25 sites increased in de facto reuse from 1980 to 2008, with the overall average increasing from 4.9% in 1980 to 6.2% in 2008;
- Several WTP intake sites (6 of 25) contained treated wastewater percentages that exceed the California Department of Health guideline of 10%.

Chapter 4: Spatial and Temporal Variation of De Facto Wastewater Reuse in Large Drinking Water Systems across the USA. Prepared for peer-reviewed submission to Environmental Science and Technology

- In a national assessment of 2,056 intakes serving 1,021 DWTPs, each with populations > 10,000 people, treated wastewater discharge impacted 50% of DWTP intakes;
- Contrary to the high frequency of occurrence, the magnitude of de facto reuse was relatively low with 50% of the impacted intakes yielding less than 1% treated municipal wastewater under average streamflow conditions;
- The 25 highest ranked sites ranged from 11% to 31% DFR;
- Intakes impacted by greater than 20% treated wastewater under average flow serve 4 million people at 15 different municipalities across the US;
- Low flow conditions (modeled by Q95) increased the percentage de facto reuse, out of the 80 sites analyzed, 23 sites had 100% de facto wastewater reuse.

Chapter 5: Assessing the Yuck Factor Associated with De Facto Wastewater Reuse: A Three City Case Study. Prepared for peer-reviewed submission to Journal of Environmental Management.

- De facto reuse occurs at levels that surpass what is publicly perceived in the three cities of Atlanta, GA, Philadelphia, PA, and Phoenix, AZ;
- Roughly 25% of survey respondents (N= 1,329) perceive de facto reuse to occur in their home tap, and over 50% are unsure of its occurrence;

- The acceptable percentage of treated wastewater at home taps is positively correlated to, knowledge of de facto reuse occurrence, high school as the highest level of education completed; and negatively correlated to being born in the U.S., age (older), being unaware if untreated ww occurs at home tap, and the interaction of knowledge of de facto reuse and misunderstanding that untreated wastewater occurs at their home tap;
- Survey respondents with knowledge of de facto reuse occurrence at their home tap were 10 times more likely to have high acceptance (greater than 75%) of treated wastewater at home tap.

Chapter 6: National Evaluation of Publicly Owned Treatment Works Contribution to Environmental Flows in Freshwater Ecosystems. Prepared for peer-reviewed submission to Nature.

- Wastewater discharges make up a significant proportion of the streamflow for many receiving streams, making up greater than 50% of instream flow for over 900 receiving streams throughout the U.S.;
- Dilution factors amongst receiving streams 25th, 50th, and 75th percentile are 8, 43, and 287 respectively;
- In a subset (N=1,049) analysis of the exposure of 17B-estradiol, estrone, and 17a-ethinylestradiol under low flow conditions (Q95); 421 streams are impacted by a Hazard Quotient value less than the 10 fold safety factor for all three contaminants;

- Impacts are exaggerated in streams of lower Strahler Stream Order, with up to a four-magnitude difference between dilution factors based upon stream orders in the same USGS hydrologic region.

Conclusions

I developed the DRINCS (De facto Reuse in our Nations Consumable Supply) model to predict the percentage of treated wastewater in river reaches and WTP intakes across the USA. The spatially explicit GIS model includes raster and vector layers for WTP and WWTP locations, hydrography, and base map topography for the continental United States. Effluent discharges from over 17,000 WWTP sites are included, each site contains attribute data for the present design flow capacity, location coordinates, level of treatment, receiving stream name, and population served. Over 2,000 DWTP intake sites belonging to “large” systems (plants serving greater than 10,000 people) are incorporated into the model. I wrote a Python script to perform a network analysis for river networks, ran by hydrologic region. The algorithm was designed to utilize the NHDPlus Dataset’s hydrologic sequencing routing attributes. The resulting model was validated through the analysis of sucralose as a wastewater tracer for twelve drinking water treatment plants (with surface water intakes) located across the U.S. The model proved to be a good estimate of de facto reuse under average flow conditions, standard error increased during low flow conditions and in sites impacted by higher levels of de facto reuse (greater than 10%).

Creating the DRINCS model allowed for the first reassessment of the contribution of wastewater to drinking water supplies in the US in the past 30 years. An update to the top cities of 1980 displayed that de facto reuse estimates increased according to 2008 data. The percentage of treated wastewater under average flow conditions increased at intake sites due to an increase in upstream wastewater discharges and/or decreased in streamflow. De facto reuse during low flow conditions, modeled by 7Q10, further increased wastewater contributions to the water supply, with 14 of the 25 sites being effluently dominated (greater than 50% treated wastewater).

Analysis of DWTP intakes was extended to include 2,056 intakes belonging to roughly 1,200 DWTPs, each serving greater than 10,000 people. Model estimates displayed that incidence of de facto reuse occurrence was frequent across the U.S., with nearly 50% of intake sites impacted. Contrary to the high frequency of occurrence, the magnitude was relatively low with the overwhelming majority (89%) of intakes yielding less than 5% treated wastewater. In spite of the low estimates at the majority of intake sites, a subgroup of the U.S. population (15 million people) is potentially subjected to levels of CEC's higher than what would be expected in planned reuse schemes, as a result of exposure through de facto reuse.

Model predictions exceeded public perceptions of de facto reuse occurrence. Public attitudes regarding de facto reuse in the cities of Atlanta, GA, Philadelphia, PA, and Phoenix, AZ, give way to the potential benefit of the DRINCS model to reach beyond the environmental engineering discipline. Knowledge of de facto reuse proved to be strongly correlated to the acceptable amount of treated wastewater in home tap water. This was displayed by the subgroup of respondents (25% of total) being ten times more likely to have stated a high level of acceptance (75% or greater treated wastewater). The majority of survey respondents were unsure regarding the occurrence, it is this subgroup that could potentially be targeted in future efforts aimed at increasing public acceptance of planned reuse schemes. More research is needed to understand the reasoning behind the correlation between knowledge and acceptance in order to determine if this could be used as a social instrument to increase public acceptance. Nevertheless, these results support recent water reuse research efforts aimed at educating the public on the urban water cycle, as done in a WateReuse Research Foundation study entitled *Effect of Prior Knowledge of Unplanned Potable Reuse on the Acceptance of Planned Potable Reuse*.

The DRINCS model was also used to assess the contribution of wastewater discharge contributions to stream flow and emerging contaminant loading. Specifically, the percentage of wastewater present in receiving streams can be multiplied by typical CEC concentrations to estimate the upper-bound CEC concentrations. Using this methodology to assess exposure of 17B-estradiol, estrone, and 17a-ethinylestradiol for a subset of 1,049 streams; I found that over a third of the receiving streams are impacted by a hazard quotient that is below the recommended 10 fold safety of factor for all three contaminants under low flow conditions. Furthermore, running the DRINCS model for receiving river reaches found that lower stream orders depend significantly upon WWTP discharge as a source of “wet” water during times of drought. Under the lower percentile flow conditions, not only do many rivers contain greater than 50% treated wastewater but several could approach 100% treated wastewater. Thus, the risk of higher CEC concentration attributed to percentage of de facto reuse increases has to be balanced against moderated extremes in low streams simply by the presence of wastewater.

Recommendations for Future Work

Future research should build upon expanding the DRINCS model current capabilities and applications. The model could be augmented to support more applied studies regarding environmental and public health exposures to contaminants, put forth by de facto reuse occurrence. Two potential projects are in regard to posed threats to ecology, and one project based on a more in depth approach to assessing CEC exposure. The first project is based on the expansion of the DRINCS model to incorporate non-point source pollution. Basin level runoff models based on land use will be scaled up, enabling the quantification of pollutant loading to surface water to be completed at the national scale. This will further allow for the comparison of mass loadings of nitrogen and phosphorous to our waters from point and non-point sources.

The second project would focus on developing a model for the evaluation of ecological impacts stemming from municipal wastewater discharges. The aim will be to assess the current impacts, utilizing an ecological indicator such as ecological diversity, and to develop a predictive tool that estimates changes in ecological impacts from improvements in wastewater effluent (higher levels of treatment). Major additions to the modeling effort will include, fate and transport equations, contaminant removal (endocrine disrupting compounds) based on differing levels of wastewater treatment, toxicity estimates, and a graphical user interface (GUI). The final product would include a web-based interface to allow it to be used as a tool for outside researchers and decision makers. Several stakeholders (i.e. water managers, government officials, etc) should be consulted during the development stage to ensure that the important components, terms, and units are being used in the model, making it a more effective decision-making tool.

The third project recommendation is an inquiry to the public health impacts of de facto reuse. The focus of this project will be to perform an exposure assessment of CEC's by way de facto wastewater reuse, and to compare the epidemiology of cities in the U.S. highly impacted by de facto reuse to cities in other countries with a direct or indirect water-recycling scheme. A suite of CEC's should be selected that have proven to be persistent and stable within the environment. Modeling efforts would include estimations for the removal of CEC's based on WWTP treatment level, fate and transport of CEC's within surface water, and removal of CEC's based on the level of drinking water treatment. Countries such as Australia have begun to perform quantitative chemical exposure assessments of water recycling. Forming collaborations with universities that have ongoing research in this area should prove to be an integral part of the data mining process regarding CEC removal rates and providing a comparison for the environmental epidemiological study. This project should also comprise of a social survey to attain the public's risk perceptions of tap water, my hypothesis is that as chemicals get "closer to the mouth" people seem more cautious. A committee of social scientist, engineers, and policy makers should be formed to discuss the key results of the survey, using them to develop recommendations (education, propaganda, etc.) built around cleaning up the misconceptions of tap water.

Future efforts aimed at increasing public acceptance of planned water reuse schemes could further research the correlation between knowledge of occurrence and acceptance found in this study. More research is necessary to determine why the correlation exists; whether the correlation is a result of a rational decision made by the individual or an emotional response. Additional knowledge regarding the correlation will help to determine if knowledge of occurrence could be used as a social instrument to increase public acceptance. Assuming that it proves to be a viable option, ongoing research would also be warranted to determine how knowledge of occurrence should be disseminated to the public. My survey results display that knowledge of occurrence combined with misinformation of raw sewage present at a person’s home tap, negatively effects public acceptance; which highlights the necessity to approach this option with caution. Research aimed to use de facto reuse occurrence as a tool to gain support of planned reuse schemes must be cognizant of the threat of this outcome to ensure that outreach efforts are performed in a way that ensures they aren’t causing more negative than positive impacts to public opinion and acceptance.

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APPENDIX A

SUPPORTING INFORMATION FOR DRINCS MODEL

Table A.1. *DRINCS data sources*

GIS Layer	**Source**
WWTPs	Clean Watershed Needs Survey (CWNS) 2008, Permit Compliance System (PCS)
DWTPs	EPA Report EPA-60012-80-044
Hydrography (rivers, streams, and lakes)	National Hydrography Dataset Plus (NHDPlus) Version 1
Stream gauges	U.S. Geological Survey (USGS)
Topography (city and state boundaries)	U.S. Geological Survey (USGS), National Atlas Website

Model Framework

The framework for this analysis was composed of ArcGIS 10 and Python. NHDPlus flowlines, WWTP and DWTP locations were placed into ArcGIS to determine the spatial relationships between the three layers. Each WWTP and DWTP was spatially joined to a flowline. The NHDPlus flowline attribute DBF was edited to amend the WWTP discharges to each link that had been spatially joined in the previous step. Extra columns were added to the file in an effort to preprocess the file for the Python Script, columns were added for the wastewater accumulated and the ratio of wastewater to streamflow in the river segment. Figure 3 displays a flowchart for the complete process. Once the DBF file was preprocessed and saved as a Excel 2007 file it was imported into Python. PyScripter was utilized as an interface for the Python program. The program calculates the percentage of wastewater present in the stream by completing a mass balance where zero accumulation and degradation is assumed. Therefore the percentage of wastewater is simply equal to the volume of wastewater divided by the volume of water within the river.

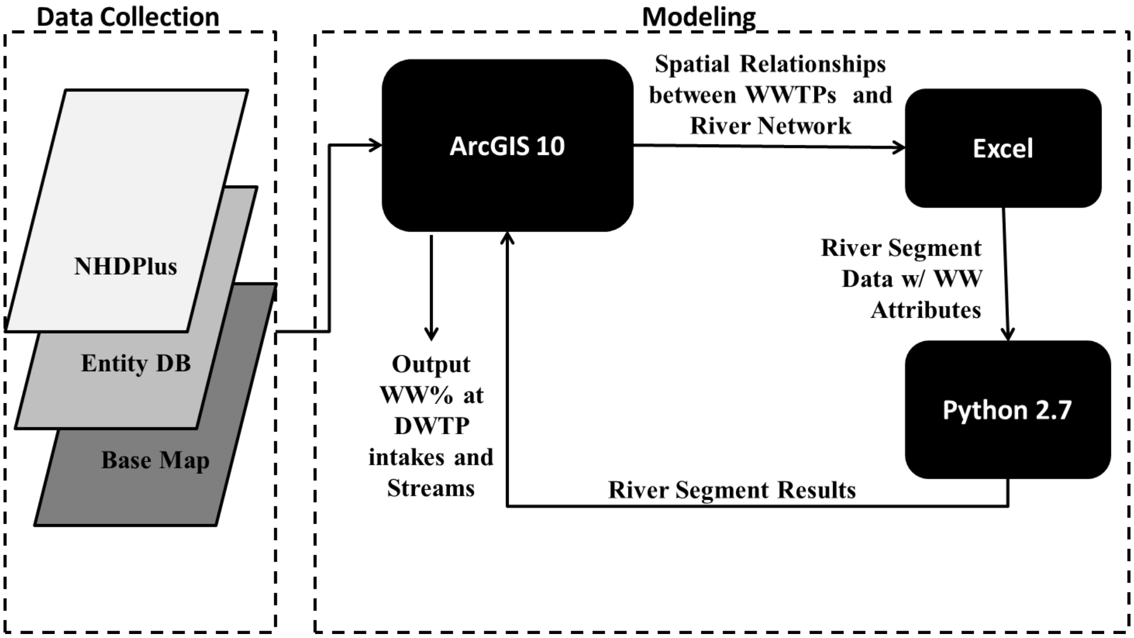


Figure A-1: Model Framework

Python Code

A Python script was designed to perform network analysis on USGS hydrologic regions. The algorithm is built upon the river network included in the NHDPlus dataset. Data was preprocessed by hydrologic region, the resulting spreadsheets included rows representing each stream segment within a region.The Python Script is designed to iterate through the network stepwise. The preprocessed Excel file is ranked by Hydrolological Sequence (HydroSeq) in descending order. HydroSeq is a numbering system for the links, where each segment is numbered in order with the highest values being the most upstream. In addition to the HydroSeq attribute, each river segment is also attributed with Start Flag, From Node, and To Node values. The Start Flag is given a value of one if it is the most upstream point, and a zero if there are other line segments upstream of it.

The From and To Node values identify the numerical identifier of the node upstream and downstream of the river segment. Each river segment only has one From and To Node, but multiple river segments can reference the same From or To Node. The Python Script iterates from each line segment (starting at the most upstream point and searches for any line segment previous of that line cursor that has a To Node value that matches the From Node of the current line). The full code is provided in Appendix B.

Mississippi River Basin HUC Region Order and Connections

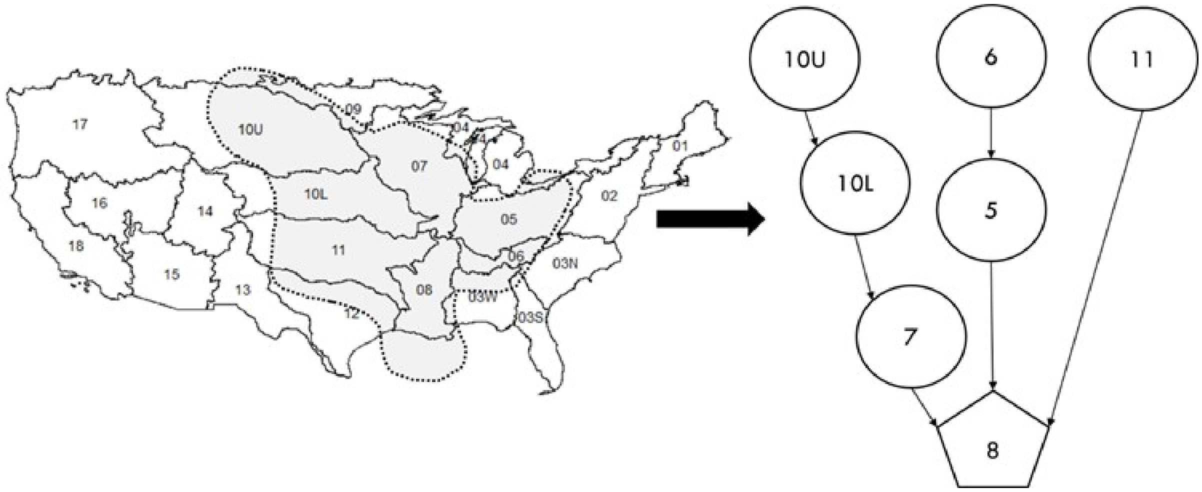


Figure A.2. Mississippi River Basin Schematic

Model Verification

Model verification was completed in two stages. The first stage was aimed at verifying that the python script was working correctly; and that the algorithm was a good representation of the conceptual model. The script was executed for a test scenario. The test case was a selected subsection located in the northeast corner of the region. The study area consisted of 743 line segments. Five fictitious WWTPs were added to the network. The program executed in 0.74 seconds. After comparing the model results to the actual estimates, it was found that the python script performed successfully. The next stage of the verification was to assess the amount error caused by the spatial joining of the WWTPs to the stream segments. Model output was compared to hand calculations previously completed as part of the 2008 update of de facto reuse for the Top 25 of EPA's 1980 study. Verification for this section was done in two steps. The first step was a comparison of the accumulated wastewater estimates at each intake site. Next, the wastewater percentages were compared for each site. The model estimates were adjusted to control for the differences in streamflow between the two estimates. Comparing these estimates also allowed the script to be further tested under varying scenarios. Overall, there were no issues found with the model algorithm. Differences between the two estimates were attributed by differences in methodology and datasets. Divergences are handled differently in the model algorithm to account for stream braiding, the amount of wastewater is equally divided into the number of nodes at the end of the link. The spatial join process was the source of error for only one of the sites, and this was due to the bad location data from the CWNS database. Disparity in accumulated wastewater discharges did not carry over into large changes in de facto reuse estimates. Nineteen of the 25 sites varied by less than 0.5 percentage point, as displayed below.

Table A.2. *Model Verification Results*

	% De Facto Reuse		
Site	**2008**	**Model**	**DELTA**
1. Saluda River (Columbia, SC)	7.6%	6.7%	0.9%
2. Huron River (Ypsilanti, MI)	8.5%	8.9%	-0.4%
3. Greenwood Lake (Greenwood, SC)	5.1%	4.5%	0.6%
4. Arkansas River (Pueblo, CO)	12.0%	11.8%	0.2%
5. Passaic River (Little Falls, NJ)	12.2%	12.1%	0.1%
6. Passaic River (Milburn, NJ)	10.4%	10.3%	0.1%
7. Clear Creek (Thornton, CO)	5.9%	5.2%	0.7%
8. White River (Indianapolis, IN)	7.9%	7.9%	0.0%
9. Del-Raritan Canal (Elizabeth, NJ)	2.3%	2.3%	0.0%
10. Del-Raritan Canal (Princeton, NJ)	2.3%	2.3%	0.0%
11. Neshaminy Creek (Bryn Mawr/Philadelphia, PA)	10.1%	12.9%	-2.8%
12. Neshaminy Creek (Middletown/Philadelphia, PA)	10.1%	12.9%	-2.8%
13. Chattahooche River (Langdale, AL)	6.3%	6.3%	0.0%
14. Cabaha River (Birmingham, AL)	3.3%	3.3%	0.0%
15. Chattahooche River (La Grange, GA)	6.2%	6.3%	0.0%
16. Schuykill River (Philadelphia, PA)	8.6%	8.7%	-0.1%
17. Nueces River (Ingleside, TX)	3.5%	1.8%	---
18. Lake Winnebago (Oshkosh/Appleton, WI)	1.6%	1.6%	0.0%
19. Lake Oliver (Columbus/Phenix City, GA/AL)	5.8%	5.8%	0.0%
20. Clear Creek (Westminister, CO)	3.7%	2.9%	0.7%
21. Mississippi River (Alton, IL)	5.4%	5.5%	-0.1%
22. Ray Hubbard Lake (Dallas, TX)	15.2%	15.4%	-0.2%
23. Maumee River (Bowling Green, OH)	4.9%	4.9%	0.0%
24. South Platte River (Englewood, CO)	5.6%	5.3%	0.3%
25. Catawba River (Lancaster, SC)	6.1%	6.2%	-0.1%

Model Validation

Model predictions were validated through the analysis of sucralose as a wastewater tracer. De facto reuse estimates from the model were compared to wastewater estimates based upon measured sucralose concentrations. Sucralose measurements from 12 DWTP intake sites were used in this analysis, and provided by an outside lab. Sucralose estimates for the percentage of wastewater at each DWTP intake were found using equation A-1, and matched with the corresponding sites in the model. The concentration of sucralose within wastewater effluent variable was set to 51 ug/l, the average value found in our round-robin analysis on a Phoenix-Area WWTP effluent. The full round-robin sucralose analysis can be found in Appendix E. The model was evaluated for average (normal) flow conditions and low flow conditions. To assess the model's predictive power under low-flow events, model estimates were calculated for a range of streamflow conditions that were present during the sampling days for Site 9 (obtained from a nearby streamgage). The source water for Site 9 has high streamflow variation and was sampled several times throughout the year, streamflow ranged from 17,100 to 364,800 CFS. As displayed in Figure A-4, the model over-predicts de facto reuse under low flow events. Statistics based upon the model's predictive power are displayed in Table A.3.

Eqn A.1

$$\mathrm{WW\%} = \frac{C_{\mathrm{Sucralose}}\ \mathrm{@WTP\ Intake}}{C_{\mathrm{Sucralose}}\ \mathrm{in\ WW}}$$

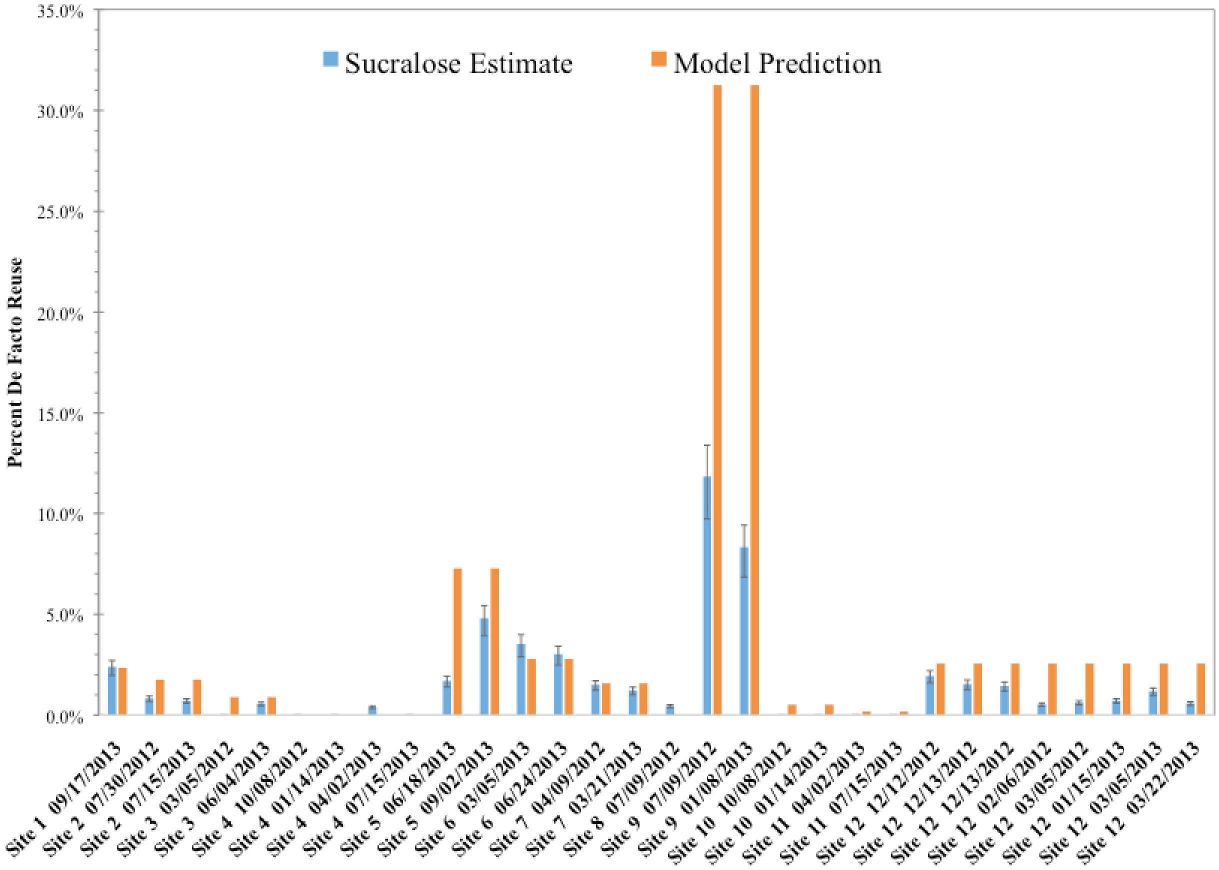


Figure A.3. Model Predictions for the 12 sites compared to tracer estimates. The error bars represent sucralose estimates based on ± 1 ST DEV from the mean.

Table A-3: Model Performance Statistics and Indices

	Average Streamflow Conditions	Average Streamflow Conditions (Omit Site 9)	Low-Flow Conditions
Standard Error	0.009	0.002	0.020
Standard Deviation	0.054	0.016	0.046
Nash-Sutcliffe Efficiency	-2.06	0.41	-8.58
PBIAS	-99.91	47.76	-192.26

APPENDIX B

PYTHON CODE FOR DRINCS MODEL NETWORK ANALYSIS

```
import xlrd
import numpy as N
import time

start_time = time.time()
#Open Excel File
book = xlrd.open_workbook("C:\\Documents and Settings\\jjrice\\My
Documents\\Research\\Program\\Final\\Region3NCOUNT.xlsx")

#Display sheet name
print book.sheet_names()

#Assign Excel columns to numpy array
sh = book.sheet_by_index(0)

#Access each column from excel
a = sh.col_values(0) #ComID
b = sh.col_values(1) #FromNode
c = sh.col_values(2) #ToNode
d = sh.col_values(3) #Hydroseq
e = sh.col_values(4) #StartFlag
```

```
f = sh.col_values(5) #Streamflow(CFS)

g = sh.col_values(6) #IncWW

h = sh.col_values(7) #AccWW

i = sh.col_values(8) #WWRatio

j = sh.col_values(9) #NumWWTP

k = sh.col_values(10) #CumWWTP


#Convert each column into an (N X 1) Numpy Array

a = N.array(a,dtype=N.int)

b = N.array(b,dtype=N.int)

c = N.array(c,dtype=N.int)

d = N.array(d,dtype=N.int)

e = N.array(e,dtype=N.int)

f = N.array(f,dtype=N.float64)

g = N.array(g,dtype=N.float64)

h = N.array(h,dtype=N.float64)

i = N.array(i,dtype=N.float64)

j = N.array(j,dtype=N.float64)

k = N.array(k,dtype=N.float64)


#Compile into one numpy array (N X 11)
```

```
streams = N.column_stack((a,b,c,d,e,f,g,h,i,j,k))

print streams.shape
print streams[0] #print the first row of the array

#Preprocessing to handle the issue of divergences: Create a dictionary to store all of the
branches = {} #create the branches dictionary
for row in streams: #iterate through the entire array by row and add the from node to the
dictionary, if its there more than once add +1, dictionary will return the number of entries
   if row[1] in  branches: #if the from node is already in dictionary add +1 to it
      branches[row[1]] += 1
   else: #if the from node isn't already in the dict then add it to the dict
      branches[row[1]] = 1

#Set the index to the first row and iterate down in the array in order completing each
operation stepwise
for index in range(len(streams)): #for loop setting the current row as [index], for the
entire length of the streams array
   if streams[index][4] == 1: #if the start flag is equal to 1 then there are no upstream
rivers so the accumulated flow is equal to the incremental flow
      streams[index][7] = streams[index][6]
```

```
        streams[index][10] = streams[index][9]


    else : #if the start flag does not equal 1 then must go through the process of connecting
from and to nodes in the network
        upstreams = [] #create an empty list to store the upstream line segments
        numberww = [] #create an empty list to store the number upstream wwtps
        for row in range(0,index): #iterate through each row in the array above the current
row index therefore go from zero to the index row
            if streams[row][2] == streams[index][1]: #if the To Node in the current row (inner
for loop) equals the From Node of the index row the append the accumulated ww
/branches dict value for # divergences
                upstreams.append(streams[row][7]/branches[streams[row][2]])
                numberww.append(streams[row][10]/branches[streams[row][2]])
        streams[index][7] = sum(upstreams) + streams[index][6] #set the accumulated ww
value for the index row equal to the sum of all the appended values in the upstreams list
        streams[index][10] = sum(numberww) + streams[index][9]
    if streams[index][5] > 0: #To overcome the issue of dividing by zero, if the streamflow
is greater than zero then set the ratio equal to the AccWW/Streamflow
        streams[index][8] = streams[index][7]/ streams[index][5]
```

```
fp = open("C:\\Documents and Settings\\jjrice\\My
Documents\\Research\\Program\\Final\\Results\\Region3NWW.txt","w")
for index in range(len(streams)):


    fp.write("%d\t%d\t%d\t%d\t%5.8f\t%5.8f\t%5.8f\t%5.8f\t%5.8f\t%5.8f\t%5.8f\n"
%(streams[index][0], streams[index][1] ,streams[index][2] ,streams[index][3]
,streams[index][4] ,streams[index][5] ,streams[index][6] ,streams[index][7]
,streams[index][8] ,streams[index][9] ,streams[index][10]))


fp.close()


print "done"


print time.time() - start_time, "seconds"
```

APPENDIX C

SURVEY MATERIALS

INFORMATION LETTER

An Assessment of Unintentional Indirect Reuse

Dear Potential Participant:

Arizona State University is conducting a study of public perceptions of water quality across the United States. The research objective is to understand peoples' threshold for reclaimed water in drinking water sources, find how these values vary regionally and to compare them to actual predictions.

You are being asked to participate in this study to help us understand public perceptions tied to indirect reuse. You must be 18 years or older to participate. Your participation would involve answering questions about water, and some background information. We will not ask your name, address, or any other personal identity information. No one will be able to identify the responses you give to you. 1,500 people are being invited to participate in the study. Your involvement should take 15 minutes.

Your participation in this study is voluntary. If you choose not to participate or to withdraw from the study at any time, there is no penalty. The results of the research study may be published, but your name and other uniquely identifying information will never be published or associated with your answers.

Although there may be no direct benefit to you, the possible benefit of your participation is an improved understanding of how the public understands and accepts the extent of wastewater effluent in drinking water sources.

If you have any questions concerning the research study, please call us at 011(480) 965-9010 or email me on amber.wutich@asu.edu.

Sincerely,

Amber Wutich, Ph.D.	Jacelyn Rice, M.S.
Assistant Professor	Research Assistant
School of Human Evolution and Social	School of Sustainable
Engineering and Change	the Built Environment
Arizona State University	Arizona State University

If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at 011-(480) 965-6788 or email research.compliance@asu.edu

Questionnaire Protocol:

SECTION A: WATER

1. Where does your tap WATER come from?
   - ☐ The water company
   - ☐ Private Well
   - ☐ Other
   - ☐ I don’t know

SECTION B: WASTEWATER

Now, I have some questions about WASTEWATER.

First, here are some definitions you might find useful.

UNTREATED WASTEWATER is sewage from household, municipal and industrial sources.

TREATED WASTEWATER is wastewater that has gone through cleaning processes to improve its quality.

2a. Does your tap water at home contain untreated wastewater?
- ☐ YES
- ☐ NO
- ☐ DON’T KNOW

2b. Does your tap water at home contain treated wastewater?
- ☐ YES
- ☐ NO
- ☐ DON’T KNOW

2c. If you answered yes to question 3, what percentage of your tap water consists of treated wastewater?
PLEASE ENTER A NUMBER (0-100) ____ %

3. What is an acceptable amount of treated wastewater in your tap water?
PLEASE ENTER A NUMBER (0-100) ____ %

SECTION C: ABOUT YOU

4. Were you born in the United States?
- ☐ YES
- ☐ NO
- ☐ REFUSED/ DON’T KNOW

5. In what year were you born? [ENTER YEAR] ☐☐☐☐

6. What is your zip/postal code? ☐☐☐☐☐ - ☐☐☐☐

7. How long have you lived in YOUR CURRENT town/suburb/city? Please enter the number of years, if less than a year; please enter the number of months.

Is this ☐☐ number for: __ Years __Months

8. Please list your current occupation or how you earn money. If you are an administrative assistant, student, lab technician, or similar position, please indicate what industry you work for. For example, if you are a student, specify your field of study. If you are an office assistant, specify what type of office (e.g. dentist, marketing company).

____

9. What is the highest level of school you have had a chance to complete?
- ☐ Primary school
- ☐ Secondary school
- ☐ High school
- ☐ University or technical training (e.g. nurse)
- ☐ Graduate/professional school (master's degree, Ph.D., M.D., J.D., etc.)

10. Please write the ethnic group with which you primarily identify:

____

11. Are you male or female?
- ☐ Male
- ☐ Female

APPENDIX D

SUPPORTING INFORMATION: NATIONAL DE FACTO REUSE RESULTS

DWTP Intake Sites Impacted by Greater than 0.5%

REGION	STATE	PWSID	INTAKE SOURCE	DE FACTO REUSE (%)
1	MA	MA3031000	Concord River	3.4%
1	MA	MA3295000	Merrimack River	1.9%
1	MA	MA3009000	Merrimack River	1.9%
1	MA	MA3149000	Merrimack River	1.9%
1	MA	MA3181000	Merrimack River	1.9%
1	MA	MA3160000	Merrimack River	1.8%
1	NH	NH1621010	Merrimack River	1.3%
2	MD	MD0070011	Big Elk Creek	4.8%
2	MD	MD0100015	Monocacy River	2.1%
2	MD	MD0120016	Susquehanna River	1.9%
2	MD	MD0120012	Susquehanna River	1.8%
2	MD	MD0120016	Susquehanna River	1.8%
2	MD	MD0150003	Potomac River	1.7%
2	MD	MD0150005	Potomac River	1.7%
2	MD	MD0100030	Potomac River	1.4%
2	MD	MD0210010	Potomac River	0.7%
2	MD	MD0120016	Gunpowder Falls	0.5%
2	NJ	NJ1605002	Passaic River	10.7%
2	NJ	NJ0712001	Passaic River	10.4%
2	NJ	NJ0712001	Passaic River	10.4%
2	NJ	NJ0906001	Rockaway River	10.3%
2	NJ	NJ1219001	South River	7.5%
2	NJ	NJ1214001	Raritan River	5.3%
2	NJ	NJ1225001	Raritan River	5.3%
2	NJ	NJ1605002	Pompton River	4.4%
2	NJ	NJ1613001	Pompton River	4.4%
2	NJ	NJ1613001	Ramapo River	3.8%
2	NJ	NJ2004002	Raritan River	3.5%
2	NJ	NJ1605002	Pompton River	2.8%
2	NJ	NJ2004002	Raritan River	2.0%
2	NJ	NJ2004002	Raritan River	2.0%
2	NJ	NJ2004002	Raritan River	2.0%
2	NJ	NJ1111001	Delaware River	1.5%

2	NJ	NJ1215001	Delaware River	1.5%
2	NY	NY0100192	Mohawk River	2.7%
2	NY	NY7003493	Hudson River	2.1%
2	NY	NY7003493	Croton River	1.4%
2	NY	NY0100198	Mohawk River	1.3%
2	NY	NY0100205	Normans Kill	1.1%
2	NY	NY4519111	Hudson River	1.0%
2	NY	NY7003493	East Branch Delaware River	0.9%
2	NY	NY0701008	Chemung River	0.9%
2	NY	NY0900217	Saranac River	0.8%
2	NY	NY7003493	West Branch Delaware River	0.5%
2	PA	PA1460073	Chester Creek	12.7%
2	PA	PA1460073	Neshaminy Creek	11.4%
2	PA	PA1510001	Schuylkill River	7.3%
2	PA	PA1510001	Schuylkill River	7.3%
2	PA	PA1460073	Perkiomen Creek	7.3%
2	PA	PA1460046	Schuylkill River	6.0%
2	PA	PA1460046	Schuylkill River	6.0%
2	PA	PA1150098	East Branch Brandywine Creek	5.2%
2	PA	PA1150166	Schuylkill River	5.1%
2	PA	PA1150077	Schuylkill River	5.0%
2	PA	PA1150077	Schuylkill River	5.0%
2	PA	PA1460037	Schuylkill River	4.4%
2	PA	PA7210029	Conodoguinet Creek	3.7%
2	PA	PA7670100	South Branch Codorus Creek	3.4%
2	PA	PA7220015	Swatara Creek	2.9%
2	PA	PA1510001	Delaware River	2.8%
2	PA	PA7360058	Conestoga River	2.8%
2	PA	PA3390024	Lehigh River	2.7%
2	PA	PA1460073	Schuylkill River	2.5%
2	PA	PA1090001	Delaware River	2.3%
2	PA	PA7220017	Swatara Creek	2.3%
2	PA	PA1090026	Delaware River	2.2%

2	PA	PA1150106	West Branch Brandywine Creek	2.0%
2	PA	PA7210029	Yellow Breeches Creek	1.9%
2	PA	PA1230004	Susquehanna River	1.9%
2	PA	PA7670086	Susquehanna River	1.8%
2	PA	PA3060066	Tulpehocken Creek	1.7%
2	PA	PA7360058	Susquehanna River	1.7%
2	PA	PA7670100	Susquehanna River	1.7%
2	PA	PA7360123	Susquehanna River	1.7%
2	PA	PA7210028	Yellow Breeches Creek	1.7%
2	PA	PA1090037	Delaware River	1.5%
2	PA	PA1090074	Delaware River	1.5%
2	PA	PA7220015	Susquehanna River	1.3%
2	PA	PA7220049	Susquehanna River	1.3%
2	PA	PA4490007	Susquehanna River	1.3%
2	PA	PA7210002	Conodoguinet Creek	1.2%
2	PA	PA7360124	Conewago Creek	0.9%
2	PA	PA2359008	Roaring Brook	0.9%
2	PA	PA3060059	Maiden Creek	0.8%
2	PA	PA3060059	Maiden Creek	0.8%
2	PA	PA2359008	Roaring Brook	0.7%
2	PA	PA3480050	Delaware River	0.7%
2	PA	PA3480057	Lehigh River	0.6%
2	VA	VA6059501	Occoquan River	11.5%
2	VA	VA2065480	Rivanna River	2.5%
2	VA	VA2187406	South Fork Shenandoah River	2.0%
2	VA	VA3670800		1.7%
2	VA	VA6107300	Potomac River	1.6%
2	VA	VA6059501	Potomac River	1.5%
2	VA	VA4760100	James River	0.9%
2	VA	VA4087125	James River	0.9%
2	VA	VA2840500	North Fork Shenandoah River	0.8%
2	VA	VA6685100	Broad Run	0.5%
2	WV	WV3301905	Shenandoah River	1.5%
2	WV	WV3300218	Potomac River	1.0%
3N	GA	GA0510004	Abercorn Creek	11.1%

3N	GA	GA0730000	Savannah River	0.7%
3N	GA	GA0730000	Savannah River	0.7%
3N	GA	GA2450000	Savannah River	0.7%
3N	NC	NC0351070	Neuse River	10.2%
3N	NC	NC0351010	Neuse River	9.5%
3N	NC	NC0319126	New Hope River	6.7%
3N	NC	NC0392020	New Hope River	6.7%
3N	NC	NC6054001	Neuse River	6.5%
3N	NC	NC0353010	Cape Fear River	6.2%
3N	NC	NC0343010	Cape Fear River	5.3%
3N	NC	NC0343045	Cape Fear River	4.9%
3N	NC	NC0392010		4.5%
3N	NC	NC0326010	Cape Fear River	4.3%
3N	NC	NC0241010	Haw River	4.1%
3N	NC	NC0410045	Cape Fear River	3.9%
3N	NC	NC0465010	Cape Fear River	3.9%
3N	NC	NC0465010	Cape Fear River	3.9%
3N	NC	NC0496010		3.2%
3N	NC	NC0136010	South Fork Catawba River	3.0%
3N	NC	NC0184010	Yadkin River	2.5%
3N	NC	NC0184010	Yadkin River	2.5%
3N	NC	NC0378010	Lumber River	2.4%
3N	NC	NC0229025	Yadkin River	2.3%
3N	NC	NC0180010	Yadkin River	2.2%
3N	NC	NC0362010	Pee Dee River	2.1%
3N	NC	NC0377109	Pee Dee River	2.0%
3N	NC	NC0149010	Catawba River	1.9%
3N	NC	NC0136010	Catawba River	1.9%
3N	NC	NC0136020	Catawba River	1.9%
3N	NC	NC0155010	South Fork Catawba River	1.9%
3N	NC	NC0114010	Catawba River	1.8%
3N	NC	NC0118010	Catawba River	1.8%
3N	NC	NC0433010	Tar River	1.7%
3N	NC	NC0112010	Catawba River	1.6%
3N	NC	NC0474010	Tar River	1.6%
3N	NC	NC0498010	Contentnea Creek	1.1%

3N	NC	NC0230015	Yadkin River	0.9%
3N	NC	NC0498010	Tar River	0.8%
3N	NC	NC0234010	Yadkin River	0.8%
3N	NC	NC0464010	Tar River	0.8%
3N	NC	NC0285010	Yadkin River	0.8%
3N	NC	NC0464010	Tar River	0.8%
3N	NC	NC0234010	Yadkin River	0.7%
3N	SC	SC3010001	Rabon Creek	9.6%
3N	SC	SC2220010	Waccamaw River	7.7%
3N	SC	SC1220002	Catawba River	6.2%
3N	SC	SC2410001	Saluda River	5.8%
3N	SC	SC3610001	Saluda River	5.7%
3N	SC	SC2810001	Wateree River	4.4%
3N	SC	SC2820001	Wateree River	4.4%
3N	SC	SC4010001	Saluda River	4.4%
3N	SC	SC3210004	Saluda River	4.3%
3N	SC	SC1010001	Back River	3.6%
3N	SC	SC4610002	Catawba River	2.7%
3N	SC	SC4610002	Catawba River	2.7%
3N	SC	SC3210004	Congaree River	2.4%
3N	SC	SC3810001	North Fork Edisto River	1.6%
3N	SC	SC4410001	Broad River	1.3%
3N	SC	SC0720003	Savannah River	1.2%
3N	SC	SC4210001	Pacolet River	0.8%
3N	SC	SC1920001	Savannah River	0.7%
3N	SC	SC1010001	Edisto River	0.6%
3N	SC	SC1110001	Broad River	0.6%
3N	VA	VA5780600	Dan River	1.0%
3N	VA	VA5031150	Big Otter River	0.7%
3N	VA	VA5590100	Dan River	0.6%
3S	FL	FL6290327	Hillsborough River	3.0%
3S	FL	FL6290327	Hillsborough River	2.9%
3S	FL	FL6290327	Hillsborough River	2.9%
3S	FL	FL6290327	Hillsborough River	2.4%
3S	FL	FL4470257		0.6%
3S	FL	FL4470257		0.6%
3S	GA	GA0350051	Ocmulgee River	16.1%

3S	GA	GA0210001	Ocmulgee River	12.4%
3S	GA	GA0630000	Big Cotton Indian Creek	6.7%
3S	GA	GA1510003	Walnut Creek	2.4%
3S	GA	GA0090001	Oconee River	1.5%
3S	GA	GA0090001	Oconee River	1.3%
3S	GA	GA1750002	Oconee River	1.1%
3S	GA	GA0630000	Little Cotton Indian Creek	0.8%
3S	GA	GA0350051	Towaliga River	0.5%
3W	AL	AL0000820	Chattahoochee River	5.4%
3W	AL	AL0001142	Chattahoochee River	5.2%
3W	AL	AL0000763	Black Warrior River	2.7%
3W	AL	AL0000738	Cahaba River	2.5%
3W	AL	AL0001671	Coosa River	1.7%
3W	AL	AL0000577	Coosa River	1.4%
3W	AL	AL0001783	Blue Springs Creek	1.3%
3W	AL	AL0000816	Halawakee Creek	1.2%
3W	AL	AL0000870	Tallapoosa River	1.1%
3W	AL	AL0001070	Tallapoosa River	1.0%
3W	AL	AL0001265	Tallapoosa River	0.6%
3W	AL	AL0000738	Mulberry Fork	0.6%
3W	FL	FL1230545	Chipola River	11.6%
3W	GA	GA0150002	Chipola River	11.6%
3W	GA	GA1130001	Line Creek	8.4%
3W	GA	GA2850001	Chattahoochee River	6.7%
3W	GA	GA1450011	Chattahoochee River	5.8%
3W	GA	GA1130001	Whitewater Creek	5.3%
3W	GA	GA2150000	Chattahoochee River	5.3%
3W	GA	GA1210001	Chattahoochee River	3.0%
3W	GA	GA1130001	Flint River	2.4%
3W	GA	GA2550000	Flint River	2.2%
3W	GA	GA1210009	Big Creek	2.0%
3W	GA	GA1150002	Etowah River	1.8%
3W	GA	GA2930000	Potato Creek	1.4%
3W	GA	GA1150002	Oostanaula River	1.1%
3W	GA	GA0890001	Chattahoochee River	0.8%
3W	GA	GA0450002	Little Tallapoosa River	0.8%

3W	GA	GA1170000	Chattahoochee River	0.8%
3W	GA	GA1170050	Chattahoochee River	0.8%
3W	GA	GA1390001	Chattahoochee River	0.7%
3W	GA	GA1350004	Chattahoochee River	0.7%
3W	GA	GA1350004	Chattahoochee River	0.7%
4	IN	IN5202020	Saint Joseph River	1.2%
4	MI	MI0004450	River Raisin	10.5%
4	MI	MI0000220	Huron River	2.3%
4	MI	MI0001800	Detroit River	0.8%
4	MI	MI0001800	Detroit River	0.8%
4	MI	MI0001800	Detroit River	0.5%
4	MI	MI0007210	Detroit River	0.5%
4	NY	NY3100564	Niagara River	1.1%
4	NY	NY3100572	Niagara River	1.1%
4	NY	NY3100572	Niagara River	1.1%
4	NY	NY3100564		1.1%
4	NY	NY1800544	Tonawanda Creek	1.0%
4	NY	NY3401156		0.8%
4	OH	OH8100611	Town Creek	16.1%
4	OH	OH8100611	Town Creek	16.1%
4	OH	OH1800111	East Branch Rocky River	14.7%
4	OH	OH1700011	Sandusky River	5.6%
4	OH	OH2000111	Maumee River	5.2%
4	OH	OH8700311	Maumee River	4.2%
4	OH	OH0200811	Auglaize River	2.8%
4	OH	OH7400614	Sandusky River	1.8%
4	OH	OH2201511	Vermilion River	1.8%
4	OH	OH7200311	Sandusky River	1.5%
4	OH	OH0200811	Ottawa River	1.5%
4	OH	OH0200811	Ottawa River	1.1%
4	OH	OH7700011	Cuyahoga River	0.6%
4	OH	OH7700011	Cuyahoga River	0.6%
4	OH	OH7700011	Cuyahoga River	0.6%
4	WI	WI4710334	Fox River	1.6%
4	WI	WI4710348	Fox River	1.6%
4	WI	WI4710348	Fox River	1.6%
4	WI	WI4710457	Fox River	1.1%

4	WI	WI4710457	Fox River	1.1%
5	IL	IL1835120	North Fork Vermilion River	0.6%
5	IL	IL1995200		0.5%
5	IN	IN5234007	Wildcat Creek	15.4%
5	IN	IN5249004	White River	6.0%
5	IN	IN5249004	White River	5.8%
5	IN	IN5249008	Eagle Creek	5.8%
5	IN	IN5282002	Ohio River	2.9%
5	IN	IN5247001	East Fork White River	2.5%
5	IN	IN5249004	Eagle Creek	2.2%
5	IN	IN5249004	Fall Creek	1.5%
5	IN	IN5289012	East Fork Whitewater River	1.4%
5	IN	IN5219009	Patoka River	1.3%
5	IN	IN5218012	White River	1.1%
5	IN	IN5216002	Flatrock River	1.1%
5	IN	IN5209006	Eel River	0.8%
5	KY	KY1050157	North Elkhorn Creek	4.1%
5	KY	KY0510188	Ohio River	2.9%
5	KY	KY1180085	Laurel River	2.7%
5	KY	KY0610016	Laurel River	2.7%
5	KY	KY0560258	Ohio River	2.6%
5	KY	KY0560258	Ohio River	2.5%
5	KY	KY0810275	Ohio River	2.3%
5	KY	KY0590220	Ohio River	2.2%
5	KY	KY1070144	West Fork Drakes Creek	2.2%
5	KY	KY0170360		2.2%
5	KY	KY0090343	Stoner Creek	2.1%
5	KY	KY0730533	Ohio River	2.0%
5	KY	KY0100011	Ohio River	1.8%
5	KY	KY0470175	Nolin River	1.8%
5	KY	KY1110019	Cumberland River	1.4%
5	KY	KY0110097	Dix River	1.3%
5	KY	KY0840180	Kentucky River	1.3%
5	KY	KY1200439	Kentucky River	1.3%
5	KY	KY0030239	Kentucky River	1.3%
5	KY	KY0370143	Kentucky River	1.3%

5	KY	KY0310114	Nolin River	1.1%
5	KY	KY0050929		0.9%
5	KY	KY0160052	Green River	0.7%
5	KY	KY0470990	Otter Creek	0.7%
5	KY	KY1140038	Barren River	0.6%
5	KY	KY0540936	Green River	0.6%
5	KY	KY0430616	Green River	0.6%
5	NC	NC0195010		0.9%
5	NY	NY0400345	Olean Creek	1.0%
5	OH	OH2503411	Alum Creek	9.7%
5	OH	OH5703512	Mad River	7.4%
5	OH	OH5703512	Mad River	7.4%
5	OH	OH5703512	Great Miami River	4.5%
5	OH	OH2101412	Olentangy River	3.5%
5	OH	OH5501211	Great Miami River	3.1%
5	OH	OH7501214	Great Miami River	2.6%
5	OH	OH7501214	Great Miami River	2.6%
5	OH	OH1500811	Ohio River	2.6%
5	OH	OH4102411	Ohio River	2.6%
5	OH	OH2504412	Scioto River	2.5%
5	OH	OH7600011	Mahoning River	2.4%
5	OH	OH7300111	Ohio River	2.2%
5	OH	OH3102612	Ohio River	2.2%
5	OH	OH3102612	Ohio River	2.2%
5	OH	OH2100311	Olentangy River	1.9%
5	OH	OH2100311	Olentangy River	1.9%
5	OH	OH4400711	Ohio River	1.8%
5	OH	OH5400011		1.7%
5	OH	OH5703512		1.6%
5	OH	OH5100414	Scioto River	1.3%
5	OH	OH2504412	Big Walnut Creek	0.8%
5	OH	OH7600011		0.7%
5	OH	OH2504412	Big Walnut Creek	0.7%
5	OH	OH5100414	Little Scioto River	0.6%
5	OH	OH1900714	Greenville Creek	0.5%
5	PA	PA5040012	Beaver River	5.5%
5	PA	PA5040012	Beaver River	5.3%

5	PA	PA6370034	Shenango River	3.1%
5	PA	PA5020043	Ohio River	2.3%
5	PA	PA5020011	Ohio River	2.1%
5	PA	PA5020045	Ohio River	2.1%
5	PA	PA5020025	Youghiogheny River	1.7%
5	PA	PA5020039	Monongahela River	1.6%
5	PA	PA5650070	Allegheny River	1.2%
5	PA	PA5020036	Allegheny River	1.1%
5	PA	PA5020056	Allegheny River	1.1%
5	PA	PA5020038	Allegheny River	1.1%
5	PA	PA6370011	Slippery Rock Creek	1.1%
5	PA	PA5020039	Monongahela River	1.0%
5	PA	PA5020108	Allegheny River	1.0%
5	PA	PA5630039	Monongahela River	0.9%
5	PA	PA5100012	Allegheny River	0.9%
5	PA	PA5300017	Monongahela River	0.9%
5	PA	PA6430054	Shenango River	0.9%
5	PA	PA5630045	Monongahela River	0.8%
5	PA	PA5260005	Monongahela River	0.8%
5	PA	PA6160001	Clarion River	0.7%
5	PA	PA4110014	Quemahoning Creek	0.7%
5	TN	TN0000639		2.2%
5	TN	TN0000639		2.2%
5	TN	TN0000405	Roaring River	2.1%
5	TN	TN0000386	Stones River	1.9%
5	TN	TN0000286	Cumberland River	1.8%
5	TN	TN0000191	Cumberland River	1.7%
5	TN	TN0000116	Cumberland River	1.7%
5	TN	TN0000133		1.6%
5	TN	TN0000373	Barren River	1.1%
5	TN	TN0000494	Cumberland River	1.0%
5	TN	TN0000666	Red River	0.8%
5	TN	TN0000424	Cumberland River	0.7%
5	TN	TN0000494	Cumberland River	0.6%
5	TN	TN0000253	Cumberland River	0.5%
5	TN	TN0000743	Cumberland River	0.5%
5	TN	TN0000294	Cumberland River	0.5%

5	TN	TN0000745	Cumberland River	0.5%
5	VA	VA1750100	New River	0.6%
5	WV	WV3303516	Ohio River	2.6%
5	WV	WV3300516	Ohio River	2.6%
5	WV	WV3304513		2.2%
5	WV	WV3300608	Ohio River	2.0%
5	WV	WV3300608	Ohio River	1.9%
5	WV	WV3303111	Monongahela River	1.0%
5	WV	WV3301046	New River	0.9%
5	WV	WV3302502	Tygart Valley River	0.6%
5	WV	WV3301705	West Fork River	0.5%
6	AL	AL0000933		4.7%
6	AL	AL0001092	Tennessee River	1.8%
6	AL	AL0000327	Tennessee River	1.7%
6	AL	AL0000314	Tennessee River	1.7%
6	AL	AL0000899	Tennessee River	1.6%
6	AL	AL0000899	Tennessee River	1.6%
6	AL	AL0000882	Tennessee River	1.6%
6	AL	AL0001084	Tennessee River	1.6%
6	AL	AL0000321	Tennessee River	1.6%
6	AL	AL0000783	Tennessee River	1.6%
6	AL	AL0000934	Tennessee River	1.6%
6	AL	AL0000943	Tennessee River	1.6%
6	AL	AL0000728	Tennessee River	1.6%
6	AL	AL0001422	Tennessee River	1.6%
6	AL	AL0001422	Tennessee River	1.6%
6	AL	AL0000509	Tennessee River	1.6%
6	AL	AL0000729	Tennessee River	1.6%
6	AL	AL0000882	Tennessee River	1.6%
6	AL	AL0000833	Elk River	0.7%
6	AL	AL0000824	Elk River	0.6%
6	TN	TN0000349	South Fork Holston River	3.2%
6	TN	TN0000073	South Fork Holston River	2.5%
6	TN	TN0000396	Tennessee River	2.4%
6	TN	TN0000474	Holston River	2.4%
6	TN	TN0000109	Holston River	2.4%
6	TN	TN0000515	Holston River	2.2%

6	TN	TN0000500	French Broad River	1.9%
6	TN	TN0000409	Tennessee River	1.7%
6	TN	TN0000366	Tennessee River	1.7%
6	TN	TN0000107	Tennessee River	1.7%
6	TN	TN0000628	Duck River	1.6%
6	TN	TN0000174	Tennessee River	1.5%
6	TN	TN0000367	French Broad River	1.4%
6	TN	TN0000548	French Broad River	1.4%
6	TN	TN0000617	French Broad River	1.3%
6	TN	TN0000219	Tennessee River	1.3%
6	TN	TN0000517	Duck River	1.2%
6	TN	TN0000331	Watauga River	1.0%
6	TN	TN0000667	Duck River	1.0%
6	TN	TN0000400	Duck River	0.9%
6	TN	TN0000754	Elk River	0.9%
6	TN	TN0000242	Elk River	0.8%
6	TN	TN0000338	Nolichucky River	0.8%
6	TN	TN0000128	Duck River	0.8%
6	TN	TN0000371	Clinch River	0.8%
6	TN	TN0000273	Nolichucky River	0.7%
6	TN	TN0000514	Clinch River	0.6%
6	TN	TN0000768	Clinch River	0.6%
6	TN	TN0000322		0.5%
6	TN	TN0000371	Clinch River	0.5%
6	TN	TN0000522	Clinch River	0.5%
6	VA	VA1191883	Middle Fork Holston River	1.4%
6	VA	VA1520070	South Fork Holston River	0.5%
7	IA	IA9083012	Des Moines River	3.0%
7	IA	IA8222001	Mississippi River	2.6%
7	IA	IA2909053	Mississippi River	2.2%
7	IA	IA5625062	Mississippi River	2.1%
7	IA	IA5640019	Mississippi River	1.8%
7	IA	IA5225101	Iowa River	1.3%
7	IA	IA5225079	Iowa River	1.3%
7	IA	IA5225079	Iowa River	1.3%
7	IA	IA7727031	North Raccoon River	1.2%

7	IA	IA7727031	Des Moines River	1.0%
7	IL	IL1435030	Illinois River	18.9%
7	IL	IL0894070	Fox River	12.1%
7	IL	IL0894380	Fox River	9.2%
7	IL	IL1195150	Mississippi River	4.5%
7	IL	IL1635040	Mississippi River	3.6%
7	IL	IL0010650	Mississippi River	3.1%
7	IL	IL0010650	Mississippi River	3.1%
7	IL	IL1195030	Mississippi River	3.0%
7	IL	IL1635040	Mississippi River	3.0%
7	IL	IL1610250	Mississippi River	2.6%
7	IL	IL1610650	Mississippi River	2.6%
7	IL	IL1610450	Mississippi River	2.6%
7	IL	IL0915030	Kankakee River	2.6%
7	IL	IL0915030	Kankakee River	2.6%
7	IL	IL1214220	Kaskaskia River	1.7%
7	IL	IL1055030	Vermilion River	1.4%
7	IL	IL1671200	South Fork Sangamon River	1.1%
7	IL	IL0995030	Vermilion River	0.8%
7	IL	IL1671200	Sugar Creek	0.6%
7	MN	MN1620026	Mississippi River	1.3%
7	MN	MN1270024	Mississippi River	1.0%
7	MN	MN1730027	Mississippi River	0.6%
7	MO	MO4010136	Mississippi River	4.0%
7	MO	MO6010715	Mississippi River	2.7%
7	MO	MO2010344	Mississippi River	2.7%
7	MO	MO6010716	Meramec River	1.3%
7	MO	MO6010716	Meramec River	1.3%
7	MO	MO6024293	Big River	0.8%
8	LA	LA1109001		14.1%
8	LA	LA1109001		14.1%
8	LA	LA1109002		11.1%
8	LA	LA1057003		6.5%
8	LA	LA1101005	Lower Atchafalaya River	5.2%
8	LA	LA1101005	Lower Atchafalaya River	5.1%
8	LA	LA1057001		3.2%

8	LA	LA1057001		3.2%
8	LA	LA1057001		3.2%
8	LA	LA1073031	Bayou de Siard	2.8%
8	LA	LA1007001		0.7%
8	LA	LA1007001		0.7%
9	MN	MN1140008	Red River of the North	1.3%
9	ND	ND0900336	Red River of the North	1.3%
9	ND	ND1800410	Red Lake River	1.1%
9	ND	ND1800410	Red River of the North	1.0%
9	ND	ND0900336	Sheyenne River	0.9%
10L	CO	CO0101150	South Platte River	31.3%
10L	CO	CO0103045	Bear Creek	7.4%
10L	CO	CO0130040	Clear Creek	2.7%
10L	CO	CO0130001	Clear Creek	2.7%
10L	CO	CO0130030	Bear Creek	1.6%
10L	CO	CO0103045	South Platte River	1.1%
10L	CO	CO0135485		1.0%
10L	CO	CO0107152	Middle Boulder Creek	0.8%
10L	CO	CO0135257		0.7%
10L	IA	IA7820080	Missouri River	0.8%
10L	KS	KS2016914	Smoky Hill River	3.7%
10L	KS	KS2009110	Kansas River	2.0%
10L	KS	KS2004503	Kansas River	2.0%
10L	KS	KS2020906	Missouri River	1.8%
10L	KS	KS2009110	Missouri River	1.8%
10L	KS	KS2010317	Missouri River	1.7%
10L	KS	KS2000506	Missouri River	1.6%
10L	KS	KS2017701	Kansas River	1.4%
10L	KS	KS2017701	Kansas River	1.4%
10L	MO	MO3010409	Missouri River	2.0%
10L	MO	MO1010415	Missouri River	1.8%
10L	MO	MO6010716	Missouri River	1.8%
10L	MO	MO5010754		1.7%
10L	NE	NE3105507	Missouri River	0.6%
10U	ND	ND5301012	Missouri River	0.8%
10U	ND	ND0800080	Missouri River	0.5%
10U	ND	ND3000596	Missouri River	0.5%

10U	SD	SD4600294		1.5%
10U	SD	SD4600294		1.5%
10U	SD	SD4600294	Big Sioux River	1.0%
10U	SD	SD4600020	Elm River	0.9%
10U	SD	SD4601089	Missouri River	0.6%
11	AR	AR0000056	Illinois River	4.3%
11	AR	AR0000250	White River	0.7%
11	CO	CO0151500	Arkansas River	2.4%
11	CO	CO0151650	Arkansas River	2.4%
11	CO	CO0151750	Arkansas River	1.8%
11	CO	CO0151500	Arkansas River	1.7%
11	CO	CO0151500	Arkansas River	1.7%
11	LA	LA1015004	Red River	1.2%
11	LA	LA1015004	Red River	0.6%
11	LA	LA1017006	Big Cypress Bayou	0.5%
11	MO	MO5010413	Shoal Creek	1.5%
11	MO	MO5010560	Shoal Creek	1.0%
11	OK	OK1021220	Arkansas River	6.4%
11	OK	OK1021701	Illinois River	3.2%
11	OK	OK1020210	Illinois River	2.4%
11	OK	OK1020902	North Canadian River	1.9%
11	OK	OK1021508	Verdigris River	1.8%
11	OK	OK1021529	Verdigris River	1.8%
11	OK	OK1021401	Caney River	1.4%
11	OK	OK1021614	Neosho River	1.4%
11	OK	OK1021607	Neosho River	1.0%
11	OK	OK1021507	Verdigris River	0.6%
11	OK	OK1020418	Verdigris River	0.5%
11	OK	OK1021418	Verdigris River	0.5%
11	TX	TX2430001	Holliday Creek	2.1%
11	TX	TX0920004	Big Cypress Creek	0.7%
12	TX	TX0570004	East Fork Trinity River	24.4%
12	TX	TX0310002	Rio Grande	23.6%
12	TX	TX0310002	Rio Grande	23.6%
12	TX	TX1080004	Rio Grande	23.6%
12	TX	TX1080006	Rio Grande	23.6%
12	TX	TX1080006	Rio Grande	23.6%

12	TX	TX1080029	Rio Grande	23.6%
12	TX	TX1080029	Rio Grande	23.6%
12	TX	TX1080029	Rio Grande	23.6%
12	TX	TX1080029	Rio Grande	23.6%
12	TX	TX1080029	Rio Grande	23.6%
12	TX	TX1080029	Rio Grande	23.6%
12	TX	TX0680002	Colorado River	19.6%
12	TX	TX2210001		16.6%
12	TX	TX1010013	Trinity River	13.4%
12	TX	TX0570004	Elm Fork Trinity River	11.3%
12	TX	TX1010013	San Jacinto River	11.3%
12	TX	TX1010013	West Fork San Jacinto River	11.1%
12	TX	TX1010013	West Fork San Jacinto River	11.1%
12	TX	TX0570004	Elm Fork Trinity River	10.7%
12	TX	TX2260001	Colorado River	7.5%
12	TX	TX0610004	Elm Fork Trinity River	7.5%
12	TX	TX0610004	Elm Fork Trinity River	7.5%
12	TX	TX2200012	Chambers Creek	6.6%
12	TX	TX2200018	Chambers Creek	6.6%
12	TX	TX2120004	Neches River	5.3%
12	TX	TX2200012	Clear Fork Trinity River	4.3%
12	TX	TX1780003	Nueces River	4.0%
12	TX	TX1780003	Nueces River	4.0%
12	TX	TX2270001	Colorado River	3.6%
12	TX	TX0140005	Leon River	2.9%
12	TX	TX2350002	Guadalupe River	2.8%
12	TX	TX1550008	South Bosque River	2.8%
12	TX	TX2200012	Cedar Creek	2.5%
12	TX	TX2200018	Cedar Creek	2.5%
12	TX	TX2200012	West Fork Trinity River	2.4%
12	TX	TX2200012	West Fork Trinity River	2.2%
12	TX	TX2200012	West Fork Trinity River	2.2%
12	TX	TX1050001	Guadalupe River	2.1%
12	TX	TX2200001	Village Creek	1.8%
12	TX	TX0570004		1.5%
12	TX	TX1230009	Neches River	1.4%

12	TX	TX0920004	Sabine River	1.4%
12	TX	TX0460001	Guadalupe River	1.3%
12	TX	TX2210001	Clear Fork	1.2%
12	TX	TX1230001	Neches River	1.0%
12	TX	TX0920004		0.9%
12	TX	TX0920004		0.9%
12	TX	TX0610002		0.8%
13	NM	NM3513319	Fresnal Creek	22.1%
13	NM	NM3513319	Fresnal Creek	11.2%
13	NM	NM3513319	Fresnal Creek	11.1%
13	NM	NM3513319	Fresnal Creek	11.0%
13	NM	NM3513319	Fresnal Creek	11.0%
13	NM	NM3510701	Rio Grande	1.4%
13	TX	TX0310001		27.1%
13	TX	TX0710002	Rio Grande	21.6%
13	TX	TX0710002	Rio Grande	17.5%
13	TX	TX2400001	Rio Grande	16.9%
14	CO	CO0119786	Eagle River	3.8%
14	CO	CO0119786	Eagle River	3.2%
15	AZ	AZ0414024	Colorado River	8.8%
15	AZ	AZ0407025	Agua Fria River	3.3%
15	AZ	AZ0414004	Colorado River	2.0%
15	AZ	AZ0407017	Colorado River	2.0%
15	AZ	AZ0407025	Colorado River	2.0%
15	AZ	AZ0407025	Colorado River	2.0%
15	AZ	AZ0407093	Colorado River	2.0%
15	AZ	AZ0407098	Colorado River	2.0%
15	AZ	AZ0407504	Colorado River	2.0%
15	NV	NV0000076	Colorado River	1.4%
16	UT	UTAH18027	Jordan River	14.6%
17	OR	OR4100587	Snake River	1.3%
17	OR	OR4100342	Rogue River	1.3%
17	OR	OR4100954	Willamette River	0.8%
17	OR	OR4100225	Willamette River	0.7%
17	WA	WA5372250	Yakima River	1.7%
18	CA	CA4810007	Cache Slough	11.7%
18	CA	CA0110001		4.5%

18	CA	CA0110010		4.5%
18	CA	CA0110010		4.5%
18	CA	CA1910067		4.5%
18	CA	CA1910142		4.5%
18	CA	CA1910227		4.5%
18	CA	CA3610018		4.5%
18	CA	CA3610064		4.5%
18	CA	CA4210004		4.5%
18	CA	CA4210010		4.5%
18	CA	CA4310011		4.5%
18	CA	CA4310020		4.5%
18	CA	CA0710001	San Joaquin River	2.4%
18	CA	CA1310001	Colorado River	2.0%
18	CA	CA1310002	Colorado River	2.0%
18	CA	CA1310004	Colorado River	2.0%
18	CA	CA1310004	Colorado River	2.0%
18	CA	CA1310006	Colorado River	2.0%
18	CA	CA1910067	Colorado River	2.0%
18	CA	CA1910142	Colorado River	2.0%
18	CA	CA1910225	Colorado River	2.0%
18	CA	CA3310005	Colorado River	2.0%
18	CA	CA3710020	Colorado River	2.0%
18	CA	CA3710020	Colorado River	2.0%
18	CA	CA3710029	Colorado River	2.0%
18	CA	CA0710002		1.9%
18	CA	CA0710003		1.9%
18	CA	CA0710003		1.9%
18	CA	CA0710003		1.9%
18	CA	CA0710003	Old River	1.9%
18	CA	CA0710007		1.9%
18	CA	CA0710003	New York Slough	1.6%
18	CA	CA3410020	Sacramento River	0.5%

APPENDIX E

SUCRALOSE ROUND ROBIN SUMMARY

Introduction

The goal of the analysis was to assess the variability of sucralose measurements within wastewater effluent. Previously reported sucralose values within the U.S. range from 2,800 to 40,000 ng/l. The study site was the City of Mesa's Northwest Reclamation Plant, an advanced 18 MGD treatment facility. The effluent is discharged to two recharge sites and the Salt River. Final effluent samples were collected and shipped on March 5th. Due to the range of analytical methods of the participants, the samples were not pre-treated. In response to sucralose previously being measured at Mesa WWTP an order of magnitude lower than other published WW effluents, a spiked sample was added. Each of the five participants analyzed two samples; (1) Mesa WWTP Eff and (2) Mesa WWTP Eff + Spike. The following summary details the results of the round-robin analysis.

Participants

- Arizona State University (Tempe, AZ)
- Metropolitan Water District of Southern California (La Verne, CA)
- Southern Nevada Water Authority (Henderson, NV)
- University of Colorado at Boulder (Boulder, CO)
- University of Arizona (Tucson, AZ)

Methods

Analytical Methods across Participants

To maintain confidentiality, the above participants are assigned number-ID's randomly. The table below displays the analysis performed by each lab. Lab #2 reported results for two different methods. Several labs provided details regarding sample preparation and analysis, this information can be found in the appendix.

Table E.3. *Analytical Methods*

Lab-ID	Type of Analysis
Lab 1	LC/MS-MS by Direct Injection (ESI Negative)
Lab 2_1	LC/MS-MS by SPE (ESI Positive)
Lab 2_2	LC/MS-MS by Direct Injection (ESI Positive)
Lab 3	LC/MS-MS by SPE
Lab 4	LC/MS-MS by SPE (ESI Positive)
Lab 5	LC/MS-MS by Direct Injection (ESI Positive)

Evaluation

Results were evaluated according to ISO 5725-2 "Accuracy (trueness and precision) of measurement method and results." Due to the low number of samples no samples were excluded from the results, therefore tests were not conducted to test for consistent bias or high variances. Repeatability standard deviation (S_r), standard deviation between laboratories (S_L) and reproducibility standard deviation (S_R) were calculated from the mean squares within group (MSW) and mean squares between groups (MSB). MSW and MSB were calculated using one-way analysis of variance (ANOVA). Reported results should be taken with caution due to the low number of samples involved in the analysis between groups (N=2 for each lab).

Results

Average Sucralose Concentration by Lab

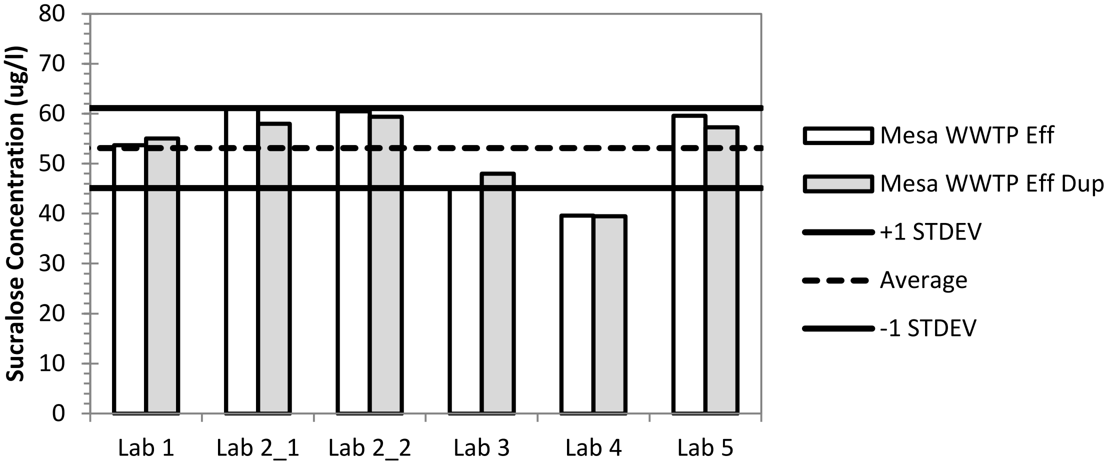


Figure E.1. Mesa WWTP Effluent

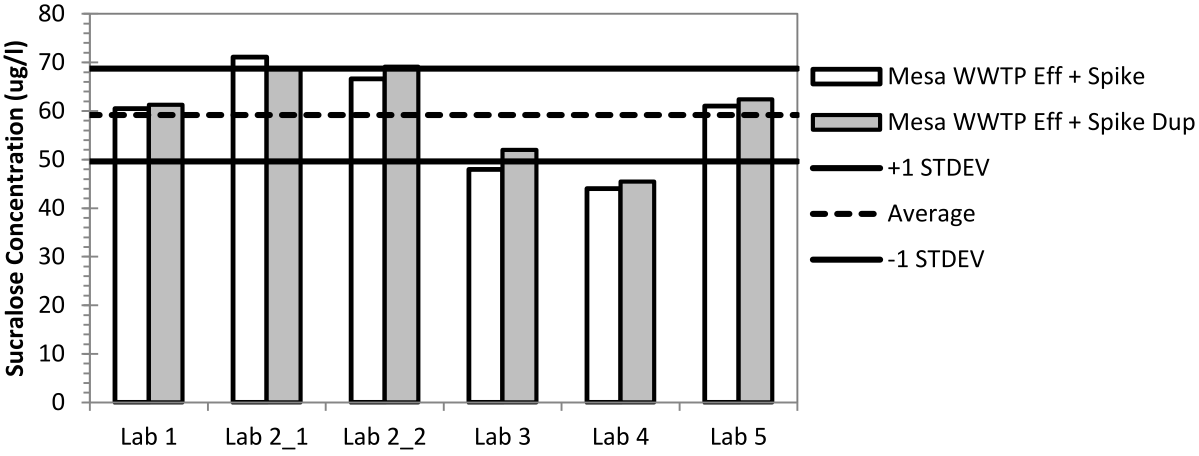


Figure E.2. Mesa WWTP Effluent + Spike

Overall Sucralose Trends

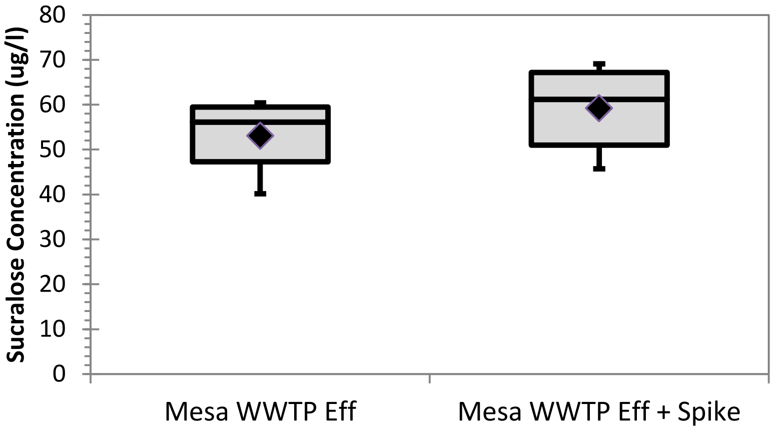


Figure E.3. Top and bottom of box= 75th and 25th percentiles respectively; top and bottom of whisker = 90th and 10th percentiles respectively; line across inside of box= median(50th percentile).

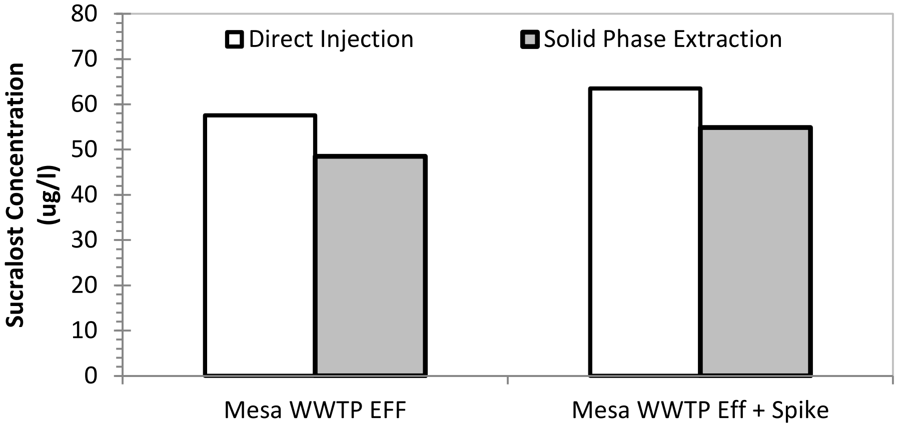


Figure E.4. Direct Injection and Solid Phase Extraction.

Repeatability, Between Laboratory Standard Deviation and Reproducibility

Table E.2. Repeatability and Reproducibility (all participants)

	S_r (ug/l)	S_L (ug/l)	S_R(ug/l)
Mesa WWTP Eff	1.5	6.7	6.9
Mesa WWTP Eff + Spike	1.6	8.1	8.2

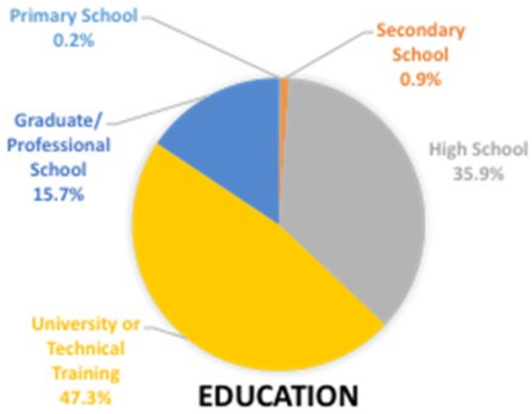
Table E.3. Repeatability and Reproducibility (omitting datasets outside of ± 1 St Dev)

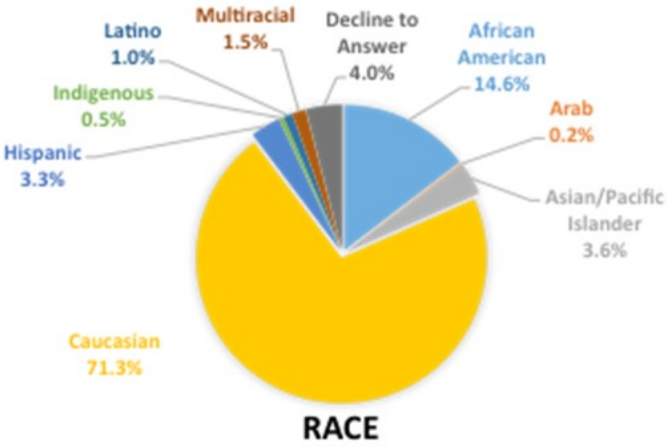
	S_r (ug/l)	S_L (ug/l)	S_R(ug/l)
Mesa WWTP Eff	1.7	4.5	4.8
Mesa WWTP Eff + Spike	1.7	6.3	6.5

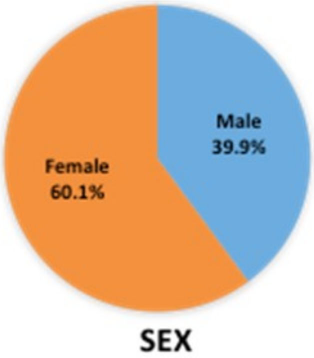
APPENDIX F

SUPPORTING INFORMATION: SURVEY ANALYSIS

Survey Demographics







Codebook

Dummy Variable (1=yes, 0=no, baseline no)	
educn1	Primary school
educn2	Secondary school
educn3	High school
educn4	University or technical training (e.g. nurse)
educn5	Graduate/professional school (master's degree, Ph.D., M.D., J.D., etc.)
msa1	Atlanta, GA
msa2	Phildelphia, PA
msa3	Phoenix, AZ
publicsys	Water Company
treat1	Perceives treated ww in home tap
untreat1	Perceives untreated ww in home tap
usborn	Born in the US
male	
race1	African American
race2	Arab
race3	Asian/Pacific Islander
race4	Caucasian/White
race5	Hispanic
race6	Indigenous or Aboriginal
race7	Latino
race8	Multiracial
sciemploy	
Continuous Variable	
accept	
residence	
age	

Coding for open-ended questions		
Profession		
	1	Employed for wages
	2	self-employed
	3	unemployed
	4	homemaker
	5	student
	6	military
	7	retired
		split employed for wages into industry type:
	11	Healthcare Support
	12	Personal Care and Service
	13	Healthcare Practitioners and Technical
	14	Community and Social Service
	15	Construction and Extraction
	16	Computer and Mathematical
	17	Business and Financial Operations
	18	Life, Physical, and Social Science
	19	Education, Training, and Library
	20	Transportation and Material Moving
	21	Installation, Maintenance, and Repair
	22	Arts, Design, Entertainment, Sports, and Media
	23	Sales and Related
	24	Building and Grounds Cleaning and Maintenance
	25	Protective Service
	26	Legal
	27	Architecture and Engineering
	28	Office and Administrative Support
	29	Food Preparation and Serving
	30	Management
	31	Production
	32	Farming, Fishing, and Forestry
Race		
	1	African American or Black
	2	Arab
	3	Asian/Pacific Islander
	4	Caucasian/White
	5	Hispanic
	6	Indigenous or Aboriginal
	7	Latino
	8	Multiracial
	9	Would rather not say

Stata program for logistic regression analysis

```
version 11
clear
clear matrix
capture log close
set mem 30m
global path ~/Documents/Research/Defacto/Survey1
cd $path //set path
log using PS3, replace text
set more off

insheet using defacto.csv


*Formulate dummy variables
tabulate msa, generate(msan)

gen treat1=treated

recode treat1 (2/3=0)

gen untreat1=untreated

recode untreat1 (2/3=0)

gen untreat2=untreated

recode untreat2 (2=0)
recode untreat2 (3=1)

gen untreat3=untreated
recode untreat3 (3=1)
recode untreat3 (1=0)
recode untreat3 (3=0)

gen HiTreat = occur >= 50 if age<.

gen male=sex

recode male (2=0)
```

```
gen usborn=us

recode usborn (2/3=0)

gen publicsys=supply

recode publicsys (2/4=0)

tabulate educ, generate(educn)

gen SciEmploy = 0
replace SciEmploy = 1 if employ==18
replace SciEmploy=1 if employ==27

gen treatuntreat = treat1*untreat1

*generate variable for treated and untreated answers to respondents only on public supply
gen pubtreat1 = treat1 if publicsys==1

gen pubuntreat1 = untreat1 if publicsys==1

gen puboccur = occur if publicsys==1

gen pubaccept = accept if publicsys==1

*perform logisitic regression by grouped categories of acceptance
**very low (0), low (1-25), moderate (26-50), high (51-75), very high(90-100)
*generate dummy variable "acceptcat"
gen acceptcat = 1 if publicsys == 1
replace acceptcat = 2 if accept >=1
replace acceptcat = 3 if accept >=26
replace acceptcat = 4 if accept >=50
replace acceptcat = 5 if accept >=90

ologit acceptcat treat1 untreat1 age male i.educ usborn HiTreat occur treatuntreat, or

*perform logit on likelihood of very high acceptance ODDS RATIO RESULTS
gen acceptcat_hi = 1 if publicsys == 1
replace acceptcat_hi = 2 if pubaccept >=50

ologit acceptcat_hi treat1 untreat1 untreat2 male age residence educn3 HiTreat i.msa
```

```
SciEmploy, or

*perform logit on likelihood of very low acceptance ODDS RATIO RESULTS
gen acceptcat_lo = 1 if publicsys == 1
replace acceptcat_lo = 2 if pubaccept == 0

ologit acceptcat_lo treat1 untreat1  untreat2 male age residence educn3 HiTreat i.msa
SciEmploy, or

*perform logit on likelihood of very high acceptance COEEFS

ologit acceptcat_hi treat1 untreat1 untreat2 male age residence educn3 HiTreat i.msa
SciEmploy

*perform logit on likelihood of very low acceptance COEFFS

ologit acceptcat_lo treat1 untreat1  untreat2 male age residence educn3 HiTreat i.msa
SciEmploy

*odds ratio only including variables found to be statistically significant in stepwise
ologit acceptcat_hi treat1 untreat3 male age educn3 usborn residence HiTreat, or
ologit acceptcat_lo treat1 untreat3 male age educn3 usborn residence HiTreat, or

*stats by zip code
tabstat puboccur, stats(n mean) by(zip)
tabstat pubaccept, stats(n mean) by(zip)

*kernel density histograms
hist accept, bin (10) kdensity
hist accept, bin (20) kdensity
```

APPENDIX G

DE FACTO REUSE ACCEPTANCE GENERALIZED BY ZIP CODE

```
Summary for variables: pubaccept
 by categories of: zip

 zip |        N      mean
---------+--------------------
 1810 |        1        50
 1940 |        1       100
 1985 |        1         0
 5044 |        1         0
 8003 |        3  28.33333
 8004 |        0         .
 8009 |        2       5.5
 8012 |        3         0
 8015 |        0         .
 8016 |        2         0
 8021 |        3  36.66667
 8022 |        2         5
 8028 |        3  48.33333
 8029 |        1        50
 8030 |        1         1
 8031 |        1         0
 8033 |        0         .
 8035 |        1         0
 8043 |        1         0
 8045 |        0         .
 8046 |        2         0
 8048 |        2        75
 8051 |        2         0
 8052 |        2        75
 8053 |        9  51.66667
 8054 |        7  50.14286
 8057 |        2         1
 8061 |        1       100
 8062 |        1       100
 8066 |        2      97.5
 8071 |        1         0
 8075 |        3        60
 8077 |        4        25
 8078 |        1       100
 8080 |        3  16.66667
 8081 |        5      13.2
 8083 |        1         0
```

```
 8084 |         2     97.5
 8086 |         1        0
 8088 |         0        .
 8093 |         2     52.5
 8094 |         3 66.66667
 8096 |         4     32.5
 8104 |         1      100
 8106 |         1        0
 8107 |         1      100
 8108 |         5     10.4
 8109 |         2        0
 8110 |         2       25
 8318 |         0        .
 8343 |         0        .
 8344 |         0        .
 8505 |         3       50
 8512 |         1       90
 8861 |         1       80
10012 |         1        5
14904 |         1        8
18036 |         0        .
18054 |         0        .
18073 |         1       10
18074 |         1      100
18076 |         1       50
18655 |         0        .
18901 |         1        0
18911 |         0        .
18914 |         2       75
18925 |         0        .
18938 |         1       50
18940 |         1       20
18946 |         1        0
18951 |         4     57.5
18954 |         1      100
18955 |         2       40
18960 |         2       25
18964 |         2        0
18966 |         1        0
18969 |         1       75
18974 |         5       23
18976 |         1        0
```

```
18977 |         0          .
19001 |         1         10
19002 |         1         20
19004 |         2          5
19006 |         2          0
19007 |         1         25
19008 |         2         65
19013 |         2         25
19014 |         4         35
19015 |         1         50
19018 |         6   13.33333
19020 |         7   50.85714
19023 |         3   33.33333
19026 |         1         10
19027 |         3   83.33333
19030 |         2       26.5
19031 |         1          0
19033 |         1          0
19034 |         2          5
19036 |         3   61.66667
19038 |         1          0
19040 |         2       87.5
19044 |         4         20
19046 |         1          0
19047 |         3         75
19050 |         2          0
19053 |         1         25
19055 |         1         90
19056 |         2          6
19057 |         1         20
19060 |         1          0
19061 |         2         95
19063 |         1         10
19064 |         3   16.66667
19066 |         1          0
19067 |         3         50
19074 |         1        100
19075 |         1        100
19079 |         1          5
19082 |         5         27
19083 |         1          0
19086 |         2        2.5
```

```
19087 |        1          0
19090 |        2       12.5
19101 |        1          5
19104 |        2         75
19105 |        1         70
19106 |        3   36.66667
19107 |        2          5
19111 |        4       62.5
19114 |        2         50
19115 |        1         95
19119 |        4      52.75
19120 |        3   56.66667
19124 |        5         38
19125 |        3   21.66667
19126 |        1         20
19127 |        1         50
19128 |        4      63.75
19130 |        1        100
19131 |        7   48.57143
19133 |        2         70
19134 |        3         35
19135 |        8     23.375
19136 |        3   36.66667
19137 |        1          0
19139 |        2         35
19140 |        4      81.25
19141 |        0          .
19143 |        5       10.4
19144 |        5         85
19145 |        3         35
19146 |        2         55
19147 |        2         25
19148 |        4         70
19149 |        5        100
19150 |        2       54.5
19151 |        1          2
19152 |        4         30
19153 |        1         95
19154 |        1         40
19301 |        1        100
19311 |        2         .5
19320 |        1          3
```

```
19335 |          4     15.25
19341 |          1         0
19348 |          1       100
19350 |          0         .
19355 |          2       2.5
19362 |          0         .
19363 |          2         5
19365 |          1         0
19380 |          1         0
19382 |          3        25
19390 |          0         .
19401 |          4        45
19403 |          1        30
19406 |          3  33.33333
19422 |          1        35
19425 |          1         0
19426 |          2       2.5
19428 |          2      82.5
19440 |          2        .5
19444 |          2        50
19446 |          4     48.75
19454 |          3        33
19460 |          1        50
19462 |          0         .
19464 |          3  33.33333
19465 |          1        70
19468 |          1         0
19473 |          2        15
19520 |          1         0
19701 |          2      99.5
19703 |          1         0
19706 |          1       100
19709 |          7        29
19711 |          3  36.66667
19713 |          2        50
19717 |          1        70
19720 |          6  16.66667
19801 |          1         0
19802 |          1         0
19803 |          2         5
19805 |          3  16.66667
19806 |          1         0
```

```
19808 |          4      6.25
19809 |          3  21.33333
19810 |          1         1
20003 |          1        20
21050 |          1        50
21903 |          1         0
21921 |          1         0
30004 |          3        25
30005 |          2        25
30008 |          6      51.5
30011 |          3  6.666667
30012 |          3  26.66667
30013 |          3        45
30016 |          1         0
30017 |          4     56.25
30019 |          4     49.25
30021 |          3        20
30022 |          8      36.5
30024 |          2      97.5
30030 |          2      12.5
30032 |          3  25.33333
30034 |          2      22.5
30035 |          1       100
30038 |          3  66.33333
30039 |          4         5
30040 |          6      25.5
30041 |          5        32
30043 |          5        42
30044 |         18  29.05556
30045 |          2        95
30046 |          3  16.66667
30047 |          6  23.33333
30052 |          3  1.666667
30054 |          1         0
30058 |          3        50
30060 |          3  73.33333
30062 |          3  33.33333
30064 |          2      12.5
30066 |          5        24
30067 |          7        20
30068 |          3  33.33333
30075 |          7  15.71429
```

```
30078 |        2          0
30080 |        2         48
30082 |        3          0
30083 |        3         60
30084 |        3   42.66667
30087 |        3   66.66667
30092 |        2         25
30093 |        6       42.5
30094 |        3   8.333333
30096 |        7   30.71429
30097 |        3   66.66667
30101 |        8     71.875
30102 |        2         50
30106 |        1        100
30107 |        2         50
30110 |        1          5
30113 |        1          2
30114 |        6         25
30115 |        2         50
30116 |        0          .
30117 |        2          0
30120 |        1         25
30121 |        2         50
30126 |        2         50
30127 |        5         35
30132 |        1         20
30134 |        1          0
30135 |        2       42.5
30141 |        3   18.33333
30143 |        1        100
30144 |        6         35
30157 |        2       52.5
30168 |        2        100
30170 |        1         25
30176 |        1         10
30179 |        1        100
30180 |        1         30
30185 |        0          .
30188 |        7   20.57143
30189 |        3   36.66667
30204 |        1         99
30205 |        1        100
```

```
30213 |        3  91.66667
30214 |        2        50
30215 |        2        15
30222 |        0         .
30223 |        2      37.5
30224 |        3        30
30228 |        3        25
30233 |        3        45
30236 |        2         0
30238 |        0         .
30240 |        1        20
30248 |        1       100
30251 |        1         0
30252 |        3        55
30253 |        5        21
30257 |        1         1
30260 |        2        90
30263 |        5        38
30265 |        4     47.25
30269 |        1         0
30274 |        1       100
30277 |        1         1
30281 |        4     53.75
30288 |        1       100
30291 |        1         1
30292 |        1        90
30293 |        0         .
30294 |        3       100
30296 |        1        50
30297 |        1         0
30303 |        1       100
30305 |        1         0
30306 |        3  43.33333
30307 |        1         0
30308 |        2        50
30309 |        3  13.33333
30310 |        3  36.66667
30311 |        2         5
30313 |        1        20
30314 |        1         0
30315 |        1        90
30316 |        1        90
```

```
30319 |      3  56.66667
30327 |      1       100
30328 |      4       1.5
30329 |      1         0
30331 |      2       100
30338 |      2        15
30340 |      2        35
30341 |      2        50
30342 |      1         1
30344 |      3  96.66667
30345 |      0         .
30346 |      3  48.33333
30349 |      0         .
30350 |      3  16.66667
30363 |      1        10
30518 |      6  34.16667
30519 |      2      52.5
30534 |      1        20
30620 |      2        25
30655 |      1       100
30656 |      0         .
30666 |      1         0
30680 |      2         0
31064 |      0         .
31313 |      1         0
31406 |      0         .
32608 |      0         .
33626 |      1         0
37146 |      0         .
38655 |      1        40
39238 |      1         0
39921 |      1        98
60651 |      1       100
62711 |      1       100
78746 |      1        30
79918 |      0         .
80425 |      1        45
85004 |      1        80
85006 |      3  46.66667
85007 |      2      27.5
85008 |      1        50
85009 |      3        60
```

```
85011 |       1        80
85012 |       1        25
85013 |       2        75
85014 |       3  .3333333
85015 |       4     37.75
85016 |       1         0
85017 |       4      27.5
85018 |       5      20.6
85019 |       2        50
85020 |       5        64
85021 |       5        31
85022 |       7        40
85023 |       2        25
85024 |       1        10
85027 |       3  13.33333
85029 |       6  14.33333
85030 |       1       100
85031 |       2        25
85032 |       7        55
85033 |       2        50
85035 |       2        55
85037 |       3  86.66667
85040 |       1        80
85041 |       1         0
85042 |       0         .
85044 |       6  31.66667
85045 |       1         0
85048 |       3  13.66667
85050 |       2         5
85051 |       3  33.33333
85053 |       5        28
85054 |       1         0
85083 |       4      1.25
85085 |       0         .
85086 |       1         0
85087 |       1         0
85119 |       5       1.2
85120 |       4     26.25
85121 |       0         .
85122 |       5      64.4
85123 |       2        25
85132 |       0         .
```

```
85137 |         2         0
85138 |         2       100
85139 |         3        45
85140 |         1        80
85142 |         4        35
85154 |         1       100
85173 |         1         0
85201 |         4      12.5
85202 |         3  31.66667
85203 |         3  16.66667
85204 |         7  15.85714
85205 |         1        50
85206 |         2      12.5
85207 |         5        50
85208 |         5      10.2
85209 |         6        26
85210 |         3  1.666667
85212 |         1         0
85213 |         2         0
85215 |         1         5
85224 |         1       100
85225 |         6  6.666667
85233 |         1       100
85234 |         5      60.8
85248 |         6  16.66667
85249 |         2        50
85251 |         4     33.25
85253 |         1         0
85254 |         2        50
85255 |         7  27.14286
85256 |         0         .
85257 |         2      62.5
85258 |         2      12.5
85260 |         2      57.5
85262 |         1       100
85266 |         1        10
85268 |         5        17
85281 |         4     33.75
85282 |         3  36.66667
85283 |         3  28.33333
85284 |         4      37.5
85286 |         1       100
```

```
85295 |         2      12.5
85296 |         6  20.66667
85297 |         2         0
85298 |         2         0
85301 |         5        26
85302 |         9  57.77778
85303 |         4     43.75
85304 |         3  1.666667
85305 |         1        10
85306 |         5        36
85307 |         1         1
85308 |         9  27.22222
85310 |         2         0
85323 |         2       2.5
85326 |         3         0
85331 |         4       7.5
85335 |         4        20
85338 |         1        75
85339 |         2        50
85340 |         1         0
85345 |         6  19.16667
85351 |         6      43.5
85353 |         4        55
85354 |         1         0
85364 |         1         0
85373 |         4     31.25
85374 |         6  31.66667
85375 |         4      12.5
85379 |         5        13
85381 |         3        50
85382 |         2        10
85383 |         3  28.33333
85387 |         1         0
85388 |         4     26.25
85392 |         2        10
85395 |         1       100
85396 |         1         0
85420 |         1       100
850209 |         1         0
---------+-------------------
```