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Spatial and Temporal Variation in De Facto Wastewater Reuse in Drinking Water Systems across the U.S.A.

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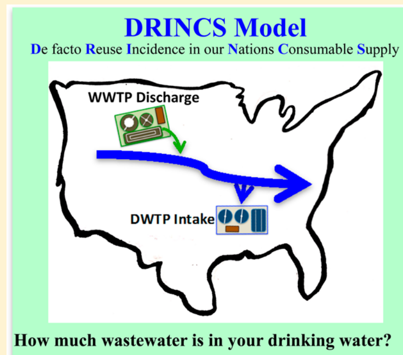
Supporting Information

ABSTRACT: De facto potable reuse occurs when treated wastewater is discharged into surface waters upstream of potable drinking water treatment plant (DWTP) intakes. Wastewater treatment plant (WWTP) discharges may pose water quality risks at the downstream DWTP, but additional flow aids in providing a reliable water supply source. In this work de facto reuse is analyzed for 2056 surface water intakes serving 1210 DWTPs across the U.S.A. that serve greater than 10 000 people, covering approximately 82% of the nation's population. An ArcGIS model is developed to assess spatial relationships between DWTPs and WWTPs, with a python script designed to perform a network analysis by hydrologic region. A high frequency of de facto reuse occurrence was observed; 50% of the DWTP intakes are potentially impacted by upstream WWTP discharges. However, the magnitude of de facto reuse was seen to be relatively low, where 50% of the impacted intakes contained less than 1% treated municipal wastewater under average streamflow conditions. De facto reuse increased greatly under low streamflow conditions (modeled by Q95), with 32 of the 80 sites yielding at least 50% treated wastewater, this portion of the analysis is limited to sites where stream gauge data was readily available.



INTRODUCTION

De facto potable reuse has been defined by a National Academy of Engineering (NAE) study as the unplanned or incidental presence of treated wastewater in a downstream water supply source.[1] De facto potable water reuse is widespread and increasing, and it is not uncommon to have a substantial portion of the source water originally derived from an upstream wastewater contribution.[1−7] Wastewater treatment plant (WWTP) discharges are one of the main sources of micropollutants in the environment, including endocrine disruptors (EDCs), pharmaceuticals, and personal care products (PPCPs) and certain precursors for disinfection byproducts (DBPs), as well as nutrients that influence stream ecology, and pathogens, thereby posing ecological and human health risks.[2,8−14]

While contaminants of emerging concerns (CECs) such as EDCs and PPCPs in surface and drinking waters impacted by treated wastewater discharges have been reported in the literature,[10−14] their potential risk to human health and the environment in drinking water sources still remain inadequately defined. Even the most robust national sampling campaigns have involved collecting grab samples from a limited number of WWTPs and DWTPs, and currently there exist only a few modeling strategies for assessing on a national scale the potential of CECs in DWTPs.[11,12] Moreover, there are no federal regulations on colocation of drinking water treatment plants (DWTPs) in relation to WWTP discharge sites located upstream of the same water source. In fact, Connecticut and Rhode Island are the only two states with regulations prohibiting discharges from WWTPs within public water supply watersheds.[15] Despite the potential presence and impact of trace organics, bulk organics, and pathogens in wastewater effluents, limited data exist in the U.S. on de facto reuse occurrence and the influence of variable streamflow conditions.

Despite significant advances in computational capabilities dealing with large data sets, national occurrence of de facto reuse has not been updated in over 30 years. Since this last assessment, the U.S. population has increased by nearly 40%, and the number of people served by centralized municipal sewer systems has increased over the same period, now exceeding 70% of the U.S. population.[16,17] Therefore, the amount of daily sewage that is collected, treated, and discharged to surface waters has likewise increased dramatically over the past three decades.

While streamflows during the past 30 years have largely remained within historic norms, recent climate predictions suggest that future weather events can lead to increased flooding or extended droughts. Such events hold the potential to impact the extent of de facto reuse. For example, when treated wastewater is discharged into surface waters, it is diluted. Since wastewater flows form urban areas are less variable than natural rainfall runoff that result in streamflows, the percentage of wastewater in streams tends to increase

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during droughts. If climate change or other factors increase frequency, duration, and/or intensity of droughts, then the amount of discharged treated wastewater in DWTP source waters (i.e., magnitude of de facto reuse) may also increase.

Milly et al. (2005)[18] performed a study using 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.[18] The western U.S. includes semiarid and arid regions characterized by ephemeral streams that are susceptible to being perennially dominated by wastewater effluent discharges.[19] The impact of streamflow variation on the dilution of wastewater effluent was observed at multiple sites within the Colorado watershed, where concentrations of wastewater contaminants doubled during periods of decreased streamflow.[20,21] Future climate predictions differ at the macro and regional scale, but climate change is expected to result in more low flows as opposed to high flows.[22,23] There are many studies that warrant for more extreme declines in streamflow on a regional level.[18,24−26] Future declines in streamflow can potentially worsen current spatial variation in wastewater contributions at the regional scale. Brooks et al. (2006), for example, take into account ecological impacts from wastewater discharges; nationally, 23% of regulated releases enter streams that receive less than 10-fold in-stream dilution. Regionally, however, particularly within the south central states, nearly half of the streams may contain greater than 90% treated effluent under low streamflow conditions.[19]

Regional scale de facto reuse occurrence has been reported in several river and watershed studies across the U.S. They include the following: Santa Ana River, CA; Trinity River, TX; Santa Cruz River, AZ; South Platte River downstream into the city of Denver, CO; Schuylkill River, Philadelphia, PA; Quinnipiac River, CT; and Occoquan Watershed, southwest of Washington, DC.[2,6,27−31] The threat posed by low streamflow conditions was raised in the Trinity River study, in which, under low flow conditions de facto reuse was estimated to be 83%.[27] Increased levels of de facto reuse were also estimated under average flow conditions in some of the other studies, for example the South Platte River at 41% de facto reuse.[8] Documented occurrences of de facto reuse at the regional scale, therefore, further warrant a national study.

The aim of this paper is to build and use a national-scale GIS-based model that includes modules for WWTP, DWTP, and river reaches to perform a national assessment of de facto reuse occurrence on larger drinking water treatment plants (DWTPs) and assess the potential impacts of streamflow variation. In earlier research, we developed a GIS-based modeling approach, which showed that from 1980 to 2008 the extent of de facto reuse had increased for 17 of 25 sites in the U.S.A.[7] However, our knowledge of regional or national level frequency or magnitude of de facto reuse is currently limited, primarily because prediction of de facto reuse in the U.S. is a complex task involving large numbers of WWTP and DWTP facilities, compounded by the frequent lack of United States Geological Survey (USGS) data for measuring streamflows.

The current analysis in this paper is limited to large systems defined by the EPA as serving greater than 10 000 people.[32] As of 2010, large (and very large) systems serve 82% of the population on community water systems.[33] In this research, we adopt a three-stage approach, which consists of (1) estimating de facto reuse occurrence at surface water DWTP intake sites under average streamflow conditions, (2) calculating de facto reuse under low-flow conditions for a subset of sites selected based on available streamflow data, and (3) investigating impact of the Strahler Stream Order on the sensitivity of de facto reuse when exposed to temporal variation in streamflow.

■ MATERIAL AND METHODS

Modeling Approach. A GIS model of WWTP discharges and DWTP intake locations entitled DRINCS (De facto Reuse Incidence in our Nations Consumable Supply) was developed and spatially linked with USGS hydrologic data. Our current assessment expands on the model developed by Rice et al. (2013),[7] which included only 25 DWTP sites. In this work, we include 1210 DWTPs of the 1292 of DWTPs in the U.S., which primarily use surface waters and serve greater than 10 000 people.[34] The missing 82 DWTP sites were omitted from the study due to a lack of or incorrect location data. The 1210 DWTPs obtain water from 2056 surface water intakes, with some DWTPs having multiple water location sources. The percentages of de facto reuse presented in this article represent de facto reuse at a DWTP intake. Conservative assumptions in calculating de facto reuse were made similar to a 1980 EPA study and include: (1) WWTP discharge equal to that of the present design capacity, based upon 2008 data; (2) WWTP effluent with no in-stream loss; and (3) complete mixing of all water bodies. Our analysis includes 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) in 2008; we considered those facilities (n = 14 651) that currently discharge to surface waters. The GIS model includes supporting data for the DWTPs including the municipality and population served. The WWTP data also record the facility name, CWNS number, level of treatment (primary, secondary, tertiary), and present design capacity.

A Python program was written to automate the process performed in the previous study.[7] This program was developed to perform a network analysis of streamlines by hydrologic region. The algorithm utilized stream route identifiers from the value added attribute (VAA) data included in the National Hydrography Data set (NHD) Plus. The process was designed to begin with headwater stream segments, accumulate wastewater as it travels down the network, and calculate treated wastewater percentages at each link until the network was complete. In cases of diversions, wastewater was evenly distributed into each receiving node. The resulting estimates represent a mass balance performed for the wastewater effluent at each DWTP intake site under the assumption that WWTPs were the only input to the network, and each DWTP intake was the sole uptake (i.e., uptake from upstream DWTP intakes are not considered).

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. The spatial joining process underwent a two-stage quality assurance and control process. First, the attribute data of the two joined layers were compared to ensure matching. This step verified that the source water of the DWTP intake corroborated with the reach name of the joined stream. Second, for those intakes that did not match (primarily due to incomplete attribute data), the joining stream was visually ground-truthed using Google

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Table 1. Scenario Development

scenario	description	number DWTP intakes	number DWTPs	results shown	data source
1	average flow	2056	1210	Figures 1–4, andSI-5	NHDPlus estimate
2	median flow-gauged sites	37	33	Figure SI2	USGS streamgauge
3	low flow (Q95)-gauged sites	37	33	Figure SI-3a	USGS streamgauge
4	low flow (Q95)-ungauged sites	43	43	Figure SI-3b	USGS streamstats
5	30% decrease in avg streamflow conditions for western states	131	91	text	Milley et. al, 2013
6	historic flow percentiles	37	33	Figure 5	USGS streamgauge

Maps and ArcGIS so that we could select the stream segment most suitable for the intake location.

Model estimates of de facto reuse were validated through the use of sucralose as a wastewater tracer. The percentage of treated wastewater present at 12 DWTP intake sites across the U.S. were calculated by comparing measured sucralose concentrations at the intake site to the concentration of sucralose within a WWTP effluent from the Phoenix area (secondary treated effluent), assuming no in-stream loss. Measured sucralose concentrations at DWTP intakes are from prior studies that were taken at confidential locations, and were made available through AWWA research foundation reports.[8,29] For a limited number of sites (N = 12) where sucralose data were available, our GIS modeling results of de facto reuse was calculated. In lieu of the limitations on sucralose data, a presence and absence comparison was performed in place of a complete model validation. De facto reuse model estimates remained less than 1% for sites with false positives, sucralose estimates were below 1% for sites with false negatives, and sites with elevated levels (>10% de facto reuse) were indicated in both estimates (Supporting Information Figure SI-1).

Scenario Development. De facto reuse is examined via six scenarios (Table 1) representing a range of current and historic (or potential future) streamflow conditions. Estimates of de facto reuse are first calculated under average flow for all intake sites (Scenario 1). Average flow conditions are then compared to USGS gauge measurements for median (50th percentile) flow (Scenario 2), and subsequently a subset of the data is analyzed under varying streamflow conditions (Scenarios 3–6). Average streamflows were obtained from National Hydrography Data set Plus (NHDPlus) for each streamline in the network; NHDPlus derives streamflow by the enhanced runoff method that includes a gauge adjustment step. Due to the gauge adjustment process being restricted by limitations in the number of stream gauges throughout the network, it was assumed that the average flows did not include municipal wastewater inputs. Therefore, de facto reuse equals the accumulated wastewater flow divided by the sum of the average stream and accumulated wastewater flows. Scenarios 2, 3, 4, and 6 were limited by the number of USGS stream gauges located in close proximity to DWTP intake locations, when matched by NHD reach code.

Scenarios 3 and 4 utilized a low flow index (Q95) to determine the sensitivity of de facto reuse to low flow conditions. Q95 represents the flow that is exceeded 95% of the time (which corresponds to the fifth percentile (P5) streamflow), and has an estimated recurrence time of 15 years.[35] Given greater availability of Q95 data, it can be used to calculate the percent of de facto reuse at a larger number of sites. Previous studies have shown Q95 to have higher streamflow values as compared to the 7-day, 10-year low flow (7Q10), which is often used in National Pollutant Discharge Elimination System (NPDES) permits for WWTP discharges, and are intended to protect aquatic ecosystems. A current limitation of NHDPlus is the inability to predict low-flow estimates, which were instead obtained from USGS stream gauges.

The low flow analysis was completed in two stages. First, intake sites located on the same reach of the stream as a USGS stream gauge were identified (Scenario 3). Second, additional sites were selected in geographic areas underrepresented in the first stage, and estimates for Q95 were obtained using the USGS Streamstats web application (Scenario 4). Ungauged sites were estimated using eq 1 (adapted from Ries, 2006[36]), where the estimated flow statistic (Q_u) is calculated by the drainage areas of the ungauged (A_u) and gauged (A_g) sites, drainage area exponent given by a regression equation (b), and flow statistic at the gauged station (Q_g).[36] The lack of streamflow data near DWTP intakes currently limits broader analysis of streamflow variations. However, the subset of streams selected for investigation span a range of Strahler Stream Orders, which emerge as a useful tool for understanding streamflow variations on de facto reuse.

$$Q_u = \left[\frac{A_u}{A_g}\right]^b Q_g \tag{1}$$

In an effort to assess the potential future impacts of climate change, de facto reuse was assessed in two additional scenarios. Scenario 5 takes into account additional sites in the western U.S., where average streamflow conditions are estimated to decrease by 30%.[18] For Scenario 6, historic streamflow percentiles are used to assess de facto reuse across a range of streamflow conditions, from 1[st] to 99[th] percentile.

RESULTS AND DISCUSSION

De Facto Reuse Occurrence under Average Flow Conditions (Scenarios 1 and 2). Figure 1 gives the number and percentage of DWTPs impacted by upstream WWTP discharges categorized by USGS hydrologic regions. De facto reuse has a high frequency of occurrence (nearly 50%) in DWTP systems serving greater than 10 000 people across the U.S. Under average flow conditions 756 of 1210 DWTP facilities (1017 of 2056 DWTP intakes), are impacted by upstream discharges of treated municipal wastewater. Each hydrologic region in Figure 1 corresponds to a drainage basin and naturally accounts for the connectivity of DWTP intakes within the same network. The percentage of impacted DWTP intakes range from a frequency of only 5% in Region 1 (New England) to 100% in Region 9 (Souris Red-Rain). The high percentage of Region 9 is partially due to having only 9 intakes. Region 12 (Texas Gulf) had the second highest frequency of de facto reuse at 90% of DWTP intakes.

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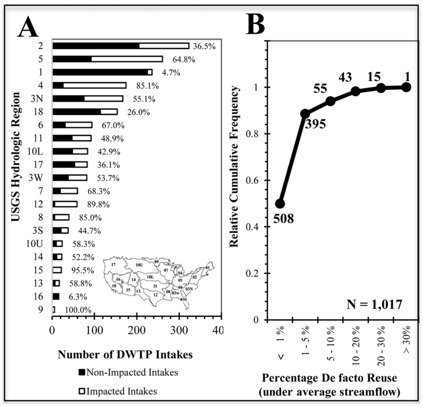

Figure 1. (A)The frequency of de facto reuse occurrence at DWTP intakes across the U.S. under average flow conditions (Scenario 1). The percentage of DWTPs impacted by upstream WWTP discharges is identified for each region. DWTPs are grouped by USGS hydrologic region (shown in insert). (B) Relative cumulative frequency for DWTP intakes impacted by de facto reuse. (Scenario 1).

In contrast to the high frequency of occurrence, the magnitude was lower for de facto reuse under average flow (Figure 1). Fifty percent (50%) of impacted intakes had less than 1% of accumulated upstream treated municipal wastewater impacts. Eighty-nine percent (89%) of the DWTPs had less than 5% treated wastewater in their source water, and 94% of the intakes exhibited less than 10% de facto reuse. Only 21 intake sites have de facto reuse greater than 15%, with only 16 sites greater than 20% de facto reuse. Figure 2 depicts the 25

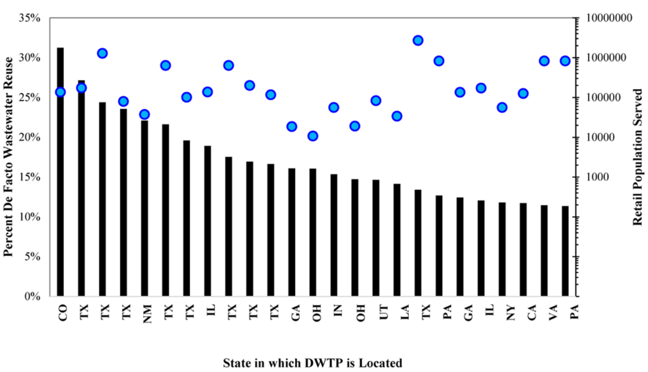

Figure 2. The 25 intakes with the highest estimates of de facto reuse under average flow conditions. The *X*-axis is labeled for discretion and referred to only by the state. The secondary *Y*-axis represents the number of customers served by each DWTP (depicted by blue dots). (Scenario 1).

intake sites with the highest levels of de facto reuse limited to include the intake with the highest estimate for DWTPs with multiple intakes, ranging from 11 to 31% de facto reuse. Sixteen (16) of the sites serve greater than 100 000 people (categorized by EPA as "very large systems"), and highlights the potential exposure to higher levels of de facto reuse by impacted DWTPs in highly populated areas.

Figure 3 shows the sites impacted by upstream treated wastewater; a bar and whisker plot indicate the percentage of de facto reuse across the hydrologic regions. De facto reuse ranges were up to 4 orders of magnitude within each hydrologic region. Median values for de facto reuse were generally consistent across geographic regions, with the notable

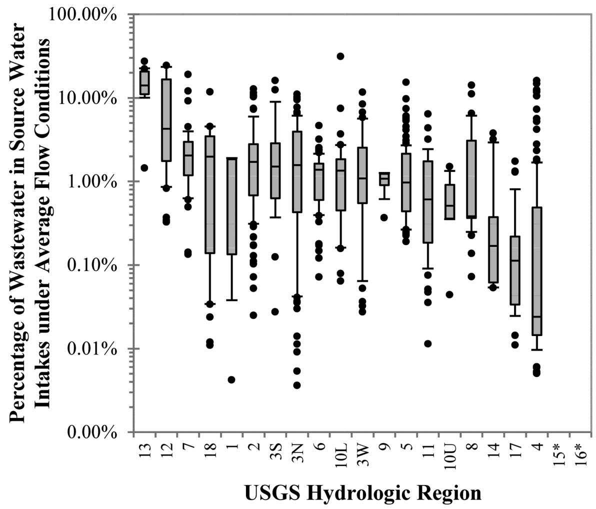

Figure 3. Statistical summary of the percentage of treated wastewater present at DWTP intakes across USGS hydrologic regions (key given in Figure 1). Regions with an asterisk do not have enough data points to be plotted. Top and bottom of box = 75th and 25th percentiles, respectively; the top and bottom of whisker = 90th and 10th percentiles, respectively; line across inside of box = median (50th percentile). (Scenario 1).

exceptions of regions 4, 14, and 17. Figure 4 spatially illustrates 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 semiarid landscapes influence the wastewater contributions from highly populated upstream cities.

De facto reuse was estimated based upon USGS stream gauge data for median streamflow (Scenario 2), and compared to de facto reuse estimates from Scenario 1 based on average streamflows. The estimates based on the gauged median flow were consistently higher. 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 are clustered toward 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 streamflow conditions rather than average flow, 9 of the 37 sites were greater than 20% de facto reuse and 5 sites were greater than 50% treated wastewater, which are higher than de facto reuse under average conditions from NHDPlus (see SI Figure SI-2). This shows the variability in calculating de facto reuse based upon the methodology selected to serve as a representative streamflow for dilution of wastewater. Thus, national levels of de facto reuse are likely higher than levels shown in Figure 1 (average streamflow), under median streamflow conditions.

De Facto Reuse Estimates under Drought Conditions (Scenarios 3 and 4). Reduced streamflow during dry periods of the year has the potential to increase de facto reuse. Here, we consider Q95 as the low flow condition. The extent of de facto reuse greatly increased under low flow periods, as displayed in Figures SI-3a,b. During low flow conditions (Scenarios 3 and 4), 23 of the 80 investigated DWTP intakes had the potential to contain 100% de facto reuse. This infers that during drought conditions, upstream municipal discharges are the sole input to

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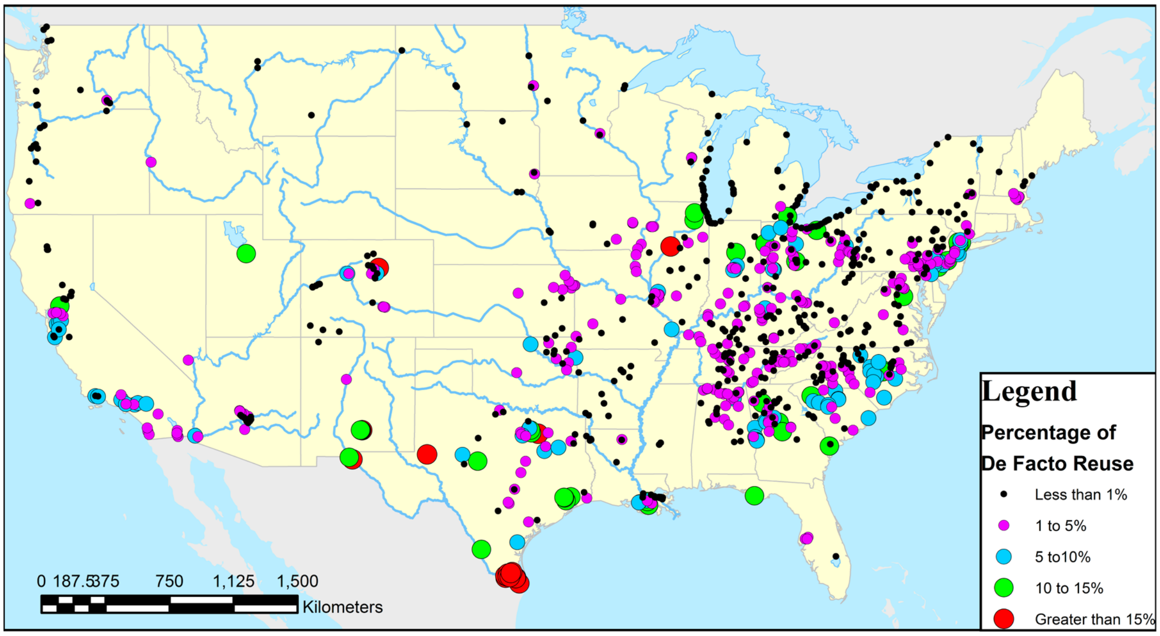

Figure 4. Magnitude of de facto wastewater reuse occurrence in large drinking water surface intakes across the U.S. (Scenario 1).

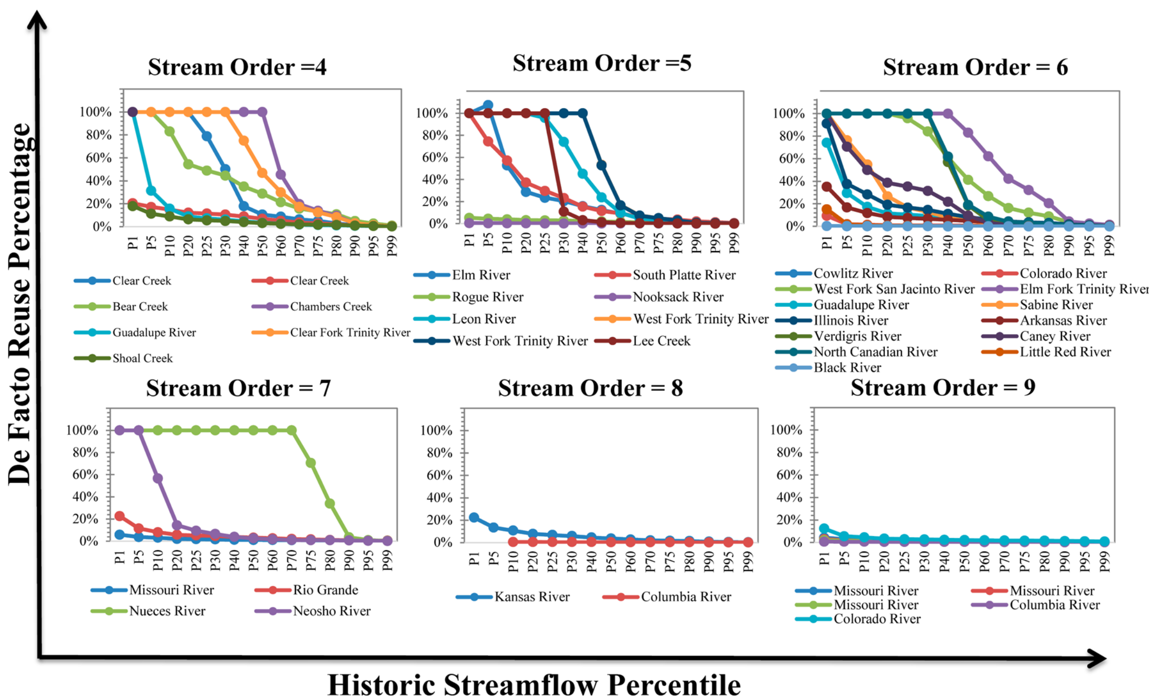

Figure 5. De facto reuse under temporal variation (modeled by historic streamflow percentiles) and grouped by Strahler Stream Order with DWTPs from Scenario 6. (The *X*-axis gives the streamflow correlating to the N^{th} percentile, indicating the percent of historical streamflow that is equal to or less than it.)

the stream's source waters. Thirty-two (32) of the 80 sites have greater than 50% treated wastewater during low streamflow conditions. Overall, the average percentage of de facto reuse across the sites increased from 3.6% under mean flow to 46% under low flow conditions. Figure SI-4 compares de facto reuse using Q95 against 7Q10 streamflows. For sites where 7Q10 data are available from ungauged USGS Streamstat estimates, the level of de facto reuse is higher under 7Q10 streamflow conditions than under Q95.

De Facto Reuse under the Potential Impacts of Climate Change (Scenarios 5 and 6). De facto reuse estimates for Scenario 5 included 131 DWTP intake sites in the states of Arizona, California, Colorado, Nevada, New Mexico, Oregon, Utah, and Washington. We assumed a 30% decrease in streamflow (Scenario 5), causing de facto reuse to linearly increase. The amount of increase is dependent upon the contribution of wastewater discharges to total streamflow. Overall de facto reuse slightly increased from 7.1 to 8.0%. The majority of the sites (111 of the 131) increased by less than 1 percentage point. Notable exceptions include 14 DWTP intakes that increased between 1and 5 percentage points, and 6 intakes that increased by greater than 10 percentage points. It is

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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. Strahler Stream Order defines stream size based on hierarchy of tributaries. Seventy-six (76) of the 131 sites were from water sources with Strahler Stream Order classifications greater than 5. We believe this to be due to DWTPs of larger design capacity as more likely to utilize streams of higher stream order (because of higher average flows needed to meet demand requirements).

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. 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.[37] For a group of 37 intakes, Figure 5 illustrates levels of de facto reuse for DWTPs (Scenario 6), as a function of both Strahler Stream Order and distribution of streamflows. 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% (average values of 2 to 9%). In contrast, DWTP intakes from water sources classified as a stream order 2 were an order of magnitude higher, with a median value of 52% treated wastewater. De facto reuse in higher order streams was less sensitive to flow variations (i.e., even low flow conditions allowed significant dilution of WWTP discharges). However, the extent of de facto reuse, and reliance of a sustainable water supply due to upstream wastewater discharges, was more variable for lower order streams.

The importance of stream order is further demonstrated in the Columbia and Missouri rivers (Figure 5), which held some of the largest values of accumulated treated wastewater, with DWTP intake sites impacted by greater than 2.8 m^3/s (100 cfs; 64.6 MGD) treated wastewater. Despite the amount of treated wastewater present, de facto reuse remains less than 10% during low flow conditions (Q95). In some cases, the accumulated wastewater in the higher order streams was an order of magnitude higher than that in lower stream orders, but the capacity of the streams offered higher dilution potential. This was evident in the case of the Mississippi River Basin, where sites in the downstream segments of the river yielded the highest accumulated flows by treated wastewater, but remained less than 10% de facto reuse under drought conditions.

Our current analysis calculated Q95 for only 80 (Scenarios 3 and 4) of the 2056 intakes considered under average flow (Scenario 1) due to lack of readily available statistical USGS data on the other streams. On the basis of the analysis related to Figure 5, lower order streams are influenced more by de facto reuse. Therefore, the stream order was assessed for all intake sites impacted by treated wastewater (Figure SI-5), limited to sites with Strahler Stream Order data ($N = 916$). Stream order was plotted against de facto reuse under average streamflow (i.e., from Figures 2−5), and the number of customers served by each DWTP (retail population). The previous trend of higher de facto reuse impacts on lower order streams under temporal variation (Figure 5) does not carry over when the analysis was performed using average streamflow conditions (Figure SI-5). Nevertheless, de facto reuse values are more sensitive to climate-related streamflow variation within streams that have Strahler Stream Orders less than 6; more than 70% ($N = 656$ of 916) of the impacted DWTP intakes fall into this category.

Implications. 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. In addition, this paper contributes to the assessment of the magnitude of potential exposure. The NAE report stated that de facto reuse with 5% treated wastewater posed higher risks from wastewater contaminants than planned potable reuse schemes. On the basis of this 5% de facto reuse level and 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 (assuming each intake is the sole source of water). For DWTPs under below average streamflow conditions (Scenario 6), de facto reuse increases disproportionally more for DWTPs on lower order streams. 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 work also corroborates the notion for a holistic approach toward the protection of human health from contaminants of emerging concern (CECs). Contrary to the U.S., Germany has set precautionary drinking water target levels of pesticides and pharmaceuticals to 0.1 μg/L.[38,39] This modeling work can aid current policy initiatives for CEC's in the U.S., by playing a role in CEC sampling and health studies for influence of indirect reuse. Geographic locations identified in this paper also 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. Updating the model to incorporate decay coefficients will facilitate its ability to estimate CECs that are present prior to drinking water treatment. Future analysis can be performed in a similar manner to those completed in England and Wales, where estimates of wastewater contributions to drinking water sources are used to evaluate potential exposures to CECs.[40] Outside of the U.S., similar modeling efforts of wastewater also echo the importance of streamflow conditions and can potentially benefit by integrating Strahler Stream Order into ongoing work.[40−42] Although our analysis currently covers 82% of the U.S. population, future work is aimed at quantifying de facto reuse for drinking water treatment plants serving fewer than 10 000 people. We believe many of these intakes are at lower order streams and may be more susceptible to de facto reuse.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional results of the model validation and Scenarios 1−4. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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