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# Mixing zone and drinking water intake dilution factor and wastewater generation distributions to enable probabilistic assessment of down-the-drain consumer product chemicals in the U.S.

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## HIGHLIGHTS

- We derived distributions of "combined" dilution factors for U.S. WWTP mixing zones.
- Variability in flow, upstream loadings and in-stream decay was incorporated.
- Distributions were also derived for U.S. drinking water intakes.
- Variability in wastewater generation and treatment processes was also quantified.

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## ABSTRACT

Environmental exposure and associated ecological risk related to down-the-drain chemicals discharged by municipal wastewater treatment plants (WWTPs) are strongly influenced by in-stream dilution of receiving waters which varies by geography, flow conditions and upstream wastewater inputs. The iSTREEM® model (American Cleaning Institute, Washington D.C.) was utilized to determine probabilistic distributions for no decay and decay-based dilution factors in mean annual and low (7Q10) flow conditions. The dilution factors derived in this study are "combined" dilution factors which account for both hydrologic dilution and cumulative upstream effluent contributions that will differ depending on the rate of in-stream decay due to biodegradation, volatilization, sorption, etc. for the chemical being evaluated. The median dilution factors estimated in this study (based on various in-stream decay rates from zero decay to a 1 h half-life) for WWTP mixing zones dominated by domestic wastewater flow ranged from 132 to 609 at mean flow and 5 to 25 at low flow, while median dilution factors at drinking water intakes (mean flow) ranged from 146 to $2 \times 10^7$ depending on the in-stream decay rate. WWTPs within the iSTREEM® model were used to generate a distribution of per capita wastewater generated in the U.S. The dilution factor and per capita wastewater generation distributions developed by this work can be used to conduct probabilistic exposure assessments for down-the-drain chemicals in influent wastewater, wastewater treatment plant mixing zones and at drinking water intakes in the conterminous U.S. In addition, evaluation of types and abundance of U.S. wastewater treatment processes provided insight into treatment trends and the flow volume treated by each type of process. Moreover, removal efficiencies of chemicals can differ by treatment type. Hence, the availability of distributions for per capita wastewater production, treatment type, and dilution factors at a national level provides a series of practical and powerful tools for building probabilistic exposure models.



## 1. Introduction

The use of probabilistic approaches in environmental risk assessment is rapidly evolving into standard practice for informing the decision-making process (USEPA, 2007). Incorporation of variability and quantification of uncertainty by probabilistic-based assessment result in a more explicit risk characterization as well as improved risk communication. This is of particular importance when considering the challenge of risk assessment over large geographic scales (e.g., national-level), as more

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simplistic strategies that apply a single average value or worst-case scenario to extrapolate risk to a larger scale can significantly under- or over-estimate actual exposure and associated risk at the scale of interest. An approach that allows risk assessment over a large geographic scale is especially useful for assessing exposure to ingredients in personal care and other consumer products as well as pharmaceuticals and other contaminants that have wide and dispersive use. In the case of down-the-drain chemicals discharged from permitted wastewater treatment plant (WWTP) facilities, exposure and potential ecological or human health risk are influenced by wastewater volume into which the chemical is diluted, treatment efficacy, flow properties of receiving waters, and chemical fate and transport properties, all of which can have some degree of spatial and temporal variation. Whenever possible, the use of distributions in lieu of single values to represent influential parameters provides a robust approach for evaluating and characterizing exposure and potential ecological risk, for example by enabling the application of Monte Carlo-type analysis to simulate risk scenarios (e.g., Wind et al., 2004; Williams et al., 2009).

Down-the-drain chemicals for which probabilistic distributions of environmental concentrations have been used for risk assessment include triclosan (Lyndall et al., 2010), 1, 4, dioxane (Simonich et al., 2013), and the polycyclic musk HHCB (Federle et al., 2014). The latter two studies combined probabilistic distributions of chemical effluent concentrations (based on monitoring data) with probabilistic distributions of receiving water dilution factors, to generate probabilistic-based estimates of exposure and related risk. Dilution factors in these studies were generated using the iSTREEM® model, a national down-the-drain chemical exposure model for the U.S. sponsored by the American Cleaning Institute (www.istreem.org). Originally developed as the GIS-ROUT model (detailed in Wang et al., 2000, 2005), the current iSTREEM® model is comprised of 18,613 river reaches extracted from the USEPA Enhanced Reachfile "RF1" river network (ERF1 version 1, Alexander et al., 1999) which are further segmented based on spatial integration of WWTP locations (10,413 facilities from the 2004 Clean Watersheds Needs Survey "CWNS", USEPA, 2008), drinking water intakes (1700 drinking water intakes from the Safe Drinking Water Information System "SDWIS", USEPA, 2002), and depends upon user-based input parameters (per-capita loading, treatment process efficacy and in-stream loss for a given chemical of interest) to estimate chemical concentrations in influent, effluent and receiving waters at mean annual flow and low flow (ten-year seven-day, "7Q10") conditions. iSTREEM® utilizes established modeling algorithms (e.g. QUAL2E, Brown and Barnwell, 1987) for computing in-stream concentrations of point source discharges based on linkage to a river network, allowing the incorporation of cumulative upstream discharges in concentration estimates. Further information on model structure and specific algorithms employed by the model can be found in Wang et al. (2000, 2005). Similar exposure models include the GREAT-ER model in Europe (Feijtel et al., 1997) and the PhATE model in the U.S. (Koormann et al., 2005) which focus on specific watersheds. iSTREEM® works across a broader geographic scale by incorporating national-level data sources.

In-stream modeled concentrations reflect cumulative loading and dilution of effluent and are strongly driven by the flow of receiving waters. Therefore, an evaluation of the magnitude and variability in dilution is important to accurately characterize exposure for a given chemical. Dilution is quantitatively represented by the dilution factor, defined as the chemical concentration in effluent divided by the concentration in receiving waters at a given location (Nabholz, 1991). Using a river network-based model such as iSTREEM®, these dilution factors not only incorporate downstream hydrologic dilution of a chemical discharged from a WWTP, but also include cumulative upstream inputs of that chemical. Thus they not only account for dilution of effluent from the nearest upstream discharge but from all cumulative upstream discharges. For these reasons, the dilution factors considered in this study can be described as "combined" dilution factors, and have a practical application in risk assessment. The inclusion of upstream wastewater discharges provides a more conservative assessment of in-stream dilution across a river network. Rice et al. (2013) used a similar concept to characterize trends in de facto wastewater reuse by computing and comparing cumulative upstream discharges to average stream flow for drinking water intakes in 25 U.S. cities using the NHDPlus river network and stream gauge data.

Federle et al. (2014) used iSTREEM® to evaluate the aquatic environmental risk of the polycyclic musk (HHCB) in surface waters below U.S. WWTPs using a probabilistic exposure approach that combined statistical distributions of effluent concentrations for U.S. WWTPs with distributions of mixing zone (combined) dilution factors to estimate HHCB concentrations. These concentrations were then compared to various toxicity values. Measured concentrations of HHCB in effluent from a monitoring program of 40 WWTPs across the U.S. formed the basis for estimating environmental loadings. The dilution factors were derived from iSTREEM® following an approach similar to the approach used in this study (described in the Methodology section). The dilution factors used in Federle et al. conservatively assumed no in-stream losses of the HHCB. Based on a Monte Carlo analysis, the probability of HHCB concentrations being below the PNEC (predicted no effect concentration) for pelagic freshwater organisms was evaluated and found to be greater than 99.8%. This study also found that probabilistic estimates of HHCB exposure in WWTP mixing zones were consistent with measured concentrations in the literature at the time of publication. More recently, the USEPA (2014) TSCA Work Plan Chemical Risk Assessment of HHCB reported a mean measured surface water concentration (near outfalls) from USGS data (http//:waterdata.usgs.gov/nwis) of 1.08 μg/L and with a 95th percentile concentration of 2.30 μg/L. For comparison, Federle et al. predicted mean HHCB concentrations of 0.07 and 0.72 μg/L at mean and 7Q10 (low) flows, respectively while the predicted 95th percentile concentrations were 0.28 and 2.81 μg/L, providing further validation that this type of probabilistic exposure approach can accurately predict environmental exposures.

In a related but different application of this approach, Simonich et al. (2013) evaluated the risk at U.S. drinking water intakes from 1,4-dioxane in domestic wastewater treatment plant effluents using a probabilistic exposure approach that joined statistical distributions of effluent concentrations with distributions of (combined) dilution factors to estimate 1,4-dioxane concentrations in surface waters at drinking water intakes. Measured concentrations of 1,4-dioxane in effluent from 40 WWTPs across the U.S. were used to generate a distribution of effluent concentrations. iSTREEM® was used to generate drinking water dilution factors for 1323 drinking water intakes across the US assuming no in-stream loss of 1,4-dioxine. The results showed that at U.S. drinking water intakes, the probability of 1,4-dioxane concentrations exceeding the USEPA drinking water advisory concentration (before any treatment of the water for drinking use) was negligible.

While these previous studies focused on specific chemicals, the ready availability of probabilistic distributions of receiving water dilution factors is a valuable tool for any number of down-the-drain consumer product chemicals, with the main area of uncertainty being the influence of various rates of chemical in-stream loss on corresponding dilution factors. The Simonich et al. (2013) and Federle et al. (2014) studies used the most conservative approach by limiting the evaluation of dilution factors to a "no decay" scenario. However, in reality many down-the-drain consumer product chemicals undergo significant in-stream decay after the point of discharge due to biodegradation, sorption and volatilization, which has significant implications for exposure and associated risk from a probabilistic context (Sabaliunas et al., 2003). The objective of this study was to use the iSTREEM® model and associated data sources to develop a comprehensive reference base of data at the national-level (U.S.) for use in probabilistic assessment of down-the-drain chemicals (not specific to any one chemical). This analysis focused on the most recent (2014) version of the iSTREEM® model, for which the source data has been updated periodically throughout the history of the model since its origin as GIS-ROUT.