

Source water impact model (SWIM) – a watershed guided approach as a new planning tool for indirect potable water reuse

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Abstract The scope of this study was to develop a model to assess the impact of source water quality on reclaimed water used for indirect potable reuse. The source water impact model (SWIM) considered source water qualities, water supply distribution data, water use and the impact of wastewater treatment to calculate reclaimed water quality. It was applied for sulfate, chloride, and dissolved organic carbon (DOC) at four water reuse sites in Arizona and California. SWIM was able to differentiate between the amount of salts derived by drinking water sources and the amount added by consumers. At all sites, the magnitude of organic residuals in reclaimed water was strongly affected by the concentration of organics in corresponding water sources and effluent-derived organic matter. SWIM can be used as a tool to predict reclaimed water quality in existing or planned water reuse systems.

Keywords Indirect potable reuse; natural organic matter (NOM); residual DOC; salinity; soil-aquifer treatment; water reuse

Introduction

In 1998, the National Research Council published a report assessing the viability of augmenting drinking water supplies with reclaimed water. The report stated that planned indirect potable reuse is a viable application of reclaimed water, but concluded also that several issues remain unresolved regarding reclaimed water quality, quality assurance and health effects monitoring. To ensure the reliability of potable reuse systems, multiple barriers to contamination should be provided, including watershed protection programs, appropriate treatment technologies, and monitoring tools.

Following a watershed guided approach, the scope of this study was to investigate how quality assurance for total organic carbon (TOC) and total dissolved solids concentration (exemplary for selected anions and cations) can be established in indirect potable reuse systems. The watershed guided approach recognizes that origin of drinking water quality, water treatment processes, domestic and industrial water uses and water reclamation processes all influence the final product of water reuse systems. Previous studies conducted at water reuse field sites in Arizona showed that a significant amount of TOC in reclaimed water entering the groundwater was of drinking water origin (Drewes & Fox, 2000). Not only natural organic matter (NOM) from drinking water but also soluble microbial products (SMP) generated in the wastewater treatment process engrave their character on TOC in water reuse systems. Based on this approach, it was apparent that all water quality properties of source water characteristics, water use, and wastewater treatment are important determinants of reclaimed water quality.

Total dissolved solids concentration and residual organic carbon are of concern in groundwater recharge systems, infiltrating treated domestic effluents. Figure 1 illustrates how organic carbon is affected by different sources when considering indirect potable reuse via groundwater recharge. Despite the presence of identified and unidentified trace organics (anthropogenic organic compounds) in reclaimed water, most residual organics

are probably comprised of natural organic matter (NOM) already present in drinking water and effluent-derived organic matter generated in the wastewater treatment process (i.e. SMPs) (Amy *et al.*, 1987; Manka & Rebhun, 1982; Drewes & Fox, 2000). Whereas concentrations of anthropogenic trace organic compounds are on the order of a few micrograms per litre or less, concentrations of natural and effluent derived organic matter, consisting of compounds like humic and fulvic acids, are present at concentrations an order of magnitude higher. Further removal by biodegradation of natural organic matter is only possible to a specific extent, and it is currently believed that organic matter originated from wastewater might significantly influence groundwater TOC at the point of recovery.

This study was part of a tailored collaboration project funded in part by the American Water Works Association Research Foundation (AWWARF) and the U.S. Environmental Protection Agency entitled "Soil-aquifer treatment for sustainable water reuse" under the direction of the National Center for Sustainable Water Supply. The primary purpose of the study was to reduce uncertainties regarding the sustainability and effectiveness of SAT systems by investigating different water reuse field sites in Arizona and Southern California (Drewes *et al.*, 2000).

Methods

Field sites

Results reported here were focused on the City of Mesa (Arizona) Northwest Water Reclamation Plant (NWWRP), the Sweetwater Recharge and Storage Facility at Tucson (Arizona), the City of Riverside (California) Water Quality Control Plant, and the San Jose Creek East WRP and Whittier Narrows WRP operated by the County Sanitation Districts of Los Angeles County (CSDLAC). Treatment at the Mesa Northwest WRP consists of activated sludge treatment including nitrification/denitrification with disinfection and tertiary filtration. The plant receives sewage from the City of Mesa which receives a drinking water supply consisting mainly of surface water from the Salt River and Verde River (Salt River Project) (Table 1). Due to technical requirements and peak demands the city also uses Colorado River Water (Central Arizona Project) and local groundwater during specific times of the year. At the Tucson and Riverside sites, the drinking water supplies are derived from local groundwater only. Wastewater treatment at these sites consists of different biological processes: trickling filter treatment in Tucson, and activated sludge treatment with tertiary filtration in Riverside (including nitrification and partial denitrification).

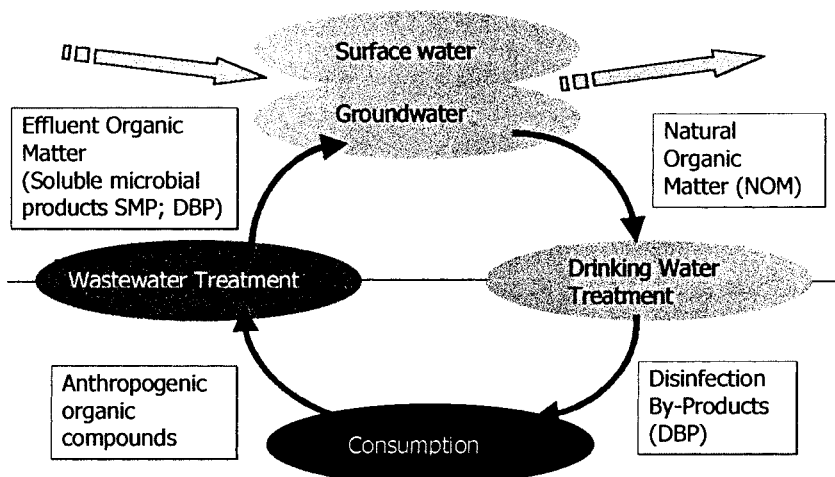


Figure 1 Sources of organic compounds in indirect potable reuse systems

Table 1 Investigated water reuse field sites in Arizona and California

Water reuse site	Watershed	Drinking water source	Wastewater treatment
NW Water Reclamation Plant Mesa (AZ)	City of Mesa (city zone)	a. groundwater b. Colorado River c. Salt River Project Salt River Verde River	activated sludge (nitrifying/denitrifying), disinfection, tertiary filtration
Sweetwater Recharge Fac., Tucson (AZ)	City of Tucson Pima County	Groundwater	secondary trickling filter, disinfection
San Jose Creek East Water Reclamation Plant (CA)	City of Azusa Covina Irrigation Company City of Glendora City of Industry Southern California Water Company San Dimas District Suburban Water Systems	a. Colorado River b. State Project Water c. groundwater	activated sludge (partly nitrifying), tertiary filtration, disinfection
Water Quality Control Plant Riverside (CA)	City of Riverside	Groundwater	activated sludge (nitrifying, partially denitrifying), tertiary filtration, disinfection

The San Jose Creek East WRP employs secondary treatment with partial nitrification, tertiary filtration and disinfection. Treatment at the Whittier Narrows WRP consists of nitrification, tertiary filtration and disinfection. The CSDLAC treatment plants receive wastewater originating from various purveyors in Los Angeles County that use local groundwater and imported surface water as drinking water sources. Table 1 contains an overview of the general water supply tributary for the San Jose Creek East WRP. Surface water is from the Metropolitan Water District of Southern California's (MWD's) Weymouth Filtration Plant (WFP). WFP exclusively receives Colorado River Water, except for the period of April through November, when 25% of the water originates from the State Water Project. On average, the San Jose Creek East WRP receives sewage which is based on 30% surface water and 70% groundwater. The mean source water qualities at the investigated sites are presented in Table 2.

Laboratory studies

To determine the biodegradability of effluents from different sites, an adapted soil-column system was used that simulated aquifer conditions using a series of four 1 m columns (diameter 0.14 m). The columns were operated under saturated, anoxic redox conditions. This system characterized TOC removal over periods up to 21 days. This was operationally defined as *short-term soil-aquifer treatment* (SAT). Water sample used in this system were applied over a study period of approximately two months.

Analytical methods

All samples were filtered using 0.45 μm cellulose nitrate membrane filter and stored at 4°C prior to analysis. The dissolved organic carbon was analyzed using a Dohrmann DC-180 TOC-analyzer (persulfate-ultraviolet method) with autosampler. UV-absorbance (UVA) was measured at a wavelength of 254 nm with a Hewlett Packard 8452A spectrophotometer (path length 1 cm). Anions were analyzed using a Dionex DX 500 ion chromatograph installed with an AS12A analytical column and combined with an AS 40 autosampler. Cations were determined using a Varian atomic absorption spectrometer.

Table 2 Drinking water quality at investigated water reuse field sites in Arizona and California

Water reuse site	Drinking water source	Source water quality average			
		DOC (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	TDS (mg/L)
NW Water Reclamation Plant Mesa, AZ	a. groundwater	a. < 0.5	260	50	690
	b. Colorado River	b. 2.45	92	250	360–560
	c. Salt River Project	c.			
	Salt River	2.0–3.6	180–330	77–140	340–510
Sweetwater Recharge Fac., Tucson, AZ	Verde River	1.6–3.4	40–110	80–140	170–360
	groundwater	< 0.3	17	48	310
San Jose Creek East and Whittier Narrows Water Reclamation Plants, CA	a. groundwater	a. < 0.5	20	49	280–330
	b. Colorado River	b. 2.3	93	269	600–700
	c. State Water Project	c. 2.4	54	55	215–300
Water Quality Control Plant Riverside, CA	groundwater	< 0.4	32	57	338

Results and discussions

Source water impact model (SWIM)

The quality of reclaimed water may vary due to the use of different drinking water sources, varying industrial discharges, temporary treatment of stormwater run-off, or variations in wastewater treatment operations. In order to address these various impact variables and to predict reclaimed water quality, a source water impact model (SWIM) was developed. SWIM considers the source water quality and the proportions of sources used in a facility's drinking water supply, the amount which is added during the use of water as well as the impact of the wastewater treatment process itself on reclaimed water quality. SWIM can be adapted to local conditions considering either daily or monthly data of water quality and water quantity. At the sites investigated in this study, SWIM was established for sulfate and chloride concentrations as well as for dissolved organic carbon concentration. However, SWIM is potentially applicable for any other parameter which might be of interest in water reuse projects, such as nitrogen, phosphorus, total organic halides (TOX), trace organics or others.

Some assumptions are necessary before SWIM can be applied. Only the service area of the city's or water agency's drinking water supply that is located within the drainage area of the reclamation plant is utilized to collect water quality and quantity data. In addition, information is needed on the industrial discharges tributary to the investigated reclamation plant in order to predict reclaimed water quality using SWIM. To assess whether variations in water quality regarding organics are caused by discontinuously discharging industries, daily samples including working days and weekends were collected for a defined period of time. For the Mesa site, standard deviations of daily DOC and UV absorbance results between weekend and working day effluents were only 3.43% and 3.22%, respectively (Drewes & Fox, 2000). CSDLAC estimated for San Jose Creek East and West Water Reclamation Facilities an industrial flow contribution of only 3.8%. No data on industrial flow contributions were available for the Tucson site.

Based on daily water quality data and water distribution data, the daily drinking water quality affecting the Mesa NWRP was calculated for a period of two years, assuming an average detention of 24 hours until water reaches the reclamation plant. Results of calculated drinking water DOC, measured tapwater and tertiary effluent DOC concentrations are presented in Figure 2 for a six-week period. The figure illustrates that during the period October 15, 1998 to November 26, 1998, there was a change in source water with a lower

DOC concentration. Although, it is generally difficult to grab a representative drinking water sample for an entire service area, the drinking water DOC calculated by SWIM was consistent with the measured drinking water quality analyzed from tapwater samples. The change of water source with a lower DOC caused a significant decrease in reclaimed water DOC. For the Mesa site, calculated drinking water concentrations were correlated with Mesa reclaimed water for daily data collected from May of 1995 to February of 1999. As expected, salt concentrations correlated very well ($R^2 = 0.9$), and higher salt concentrations in reclaimed water were caused by higher sulfate and chloride concentrations in drinking water (Drewes & Fox, 2000). For the WRPs at Riverside and Tucson, both based on groundwater supply only, the ion composition of reclaimed water stayed constant due to small variations of source water quality based on data provided by Riverside Public Utilities and Tucson Water. Water purveyors within the drainage area of San Jose Creek East WRP rely on drinking water sources that vary significantly in ion composition (see Table 2). Colorado River water contains a considerably higher sulfate and chloride concentration. Since local groundwater and State Water Project qualities were similar for sulfate and chloride concentrations and Colorado River water is exclusively used from November to March, SWIM was applied for this site on a monthly basis for the entire drainage area of San Jose Creek East WRP. Figure 3 presents the drinking water quality calculated by SWIM considering water distribution data of six water districts for a period of two years. Accordingly, the impact of higher salt concentrations using Colorado River water for the drinking water supply during winter months is obvious, and therefore will affect reclaimed water quality.

Increments of ions added during water use

According to the SWIM, Figure 4 represents the amount of selected anion and cation increments added by municipal water use at the investigated sites. Based on a comparison of all field sites, the portion of sulfate added during the use of water was on average 44 mg $\text{SO}_4^{2-}/\text{L}$, for chloride 75 mg Cl^-/L , and for sodium 74 mg Na^+/L not considering the Mesa watershed. These increments almost exactly confirm results of a survey of 22 U.S. cities reported by Snoeyink and Jenkins (1980).

The Mesa site showed significantly higher increments of chloride and sodium. Since the

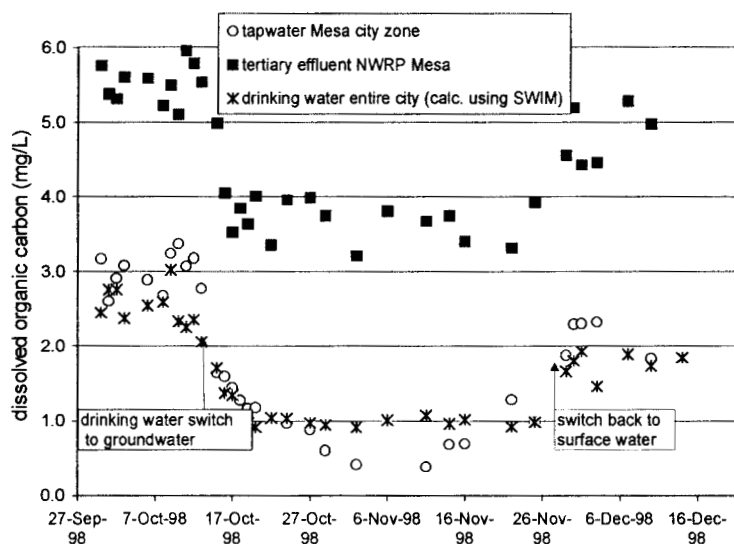


Figure 2 DOC in Mesa drinking water and reclaimed water during change of source water (9/98–12/98)

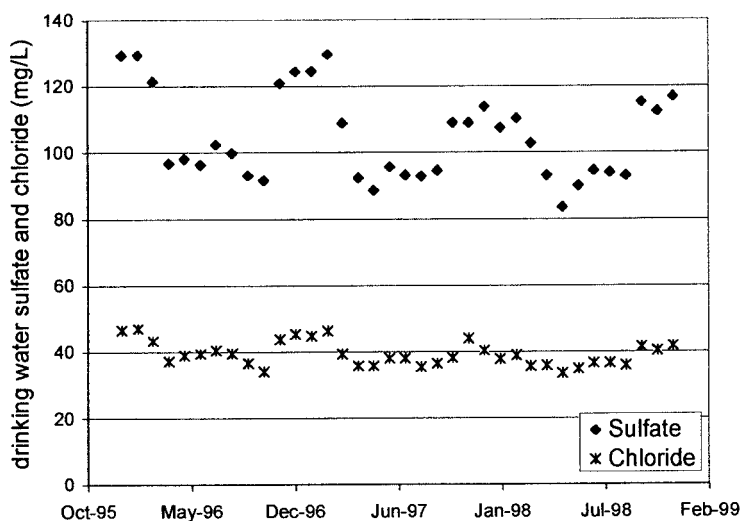


Figure 3 Predicted drinking water sulfate and chloride concentrations within the drainage area of San Jose Creek East (1/96–11/98) using SWIM

molar concentration of this additional portion is almost identical (~ 1.7 mmol/L) this additional increment may be caused by the widespread use of self-regenerating water softeners in the Phoenix metropolitan area releasing NaCl into the wastewater. For magnesium, water use led only to a slight increase in concentration, whereas for calcium no significant increase during water use was observed. Since only a minor increase of divalent ion concentration in drinking water occurred during water use and wastewater treatment, total hardness of reclaimed water seems to be a function of source water composition.

Addition of residual DOC due to water consumers and wastewater treatment

After an initial survey of drinking water sources and water treatments in watersheds of each investigated water reuse site, hydraulically corresponding drinking water and reclaimed water samples were collected. Since the reclamation facilities investigated employed different biological treatment processes, reclaimed water samples from each field site were infiltrated through the laboratory soil-column system. It was assumed that the drinking water DOC represents non-biodegradable organic matter. Drinking water samples with concentrations higher than 2.7 mg DOC/L were also percolated through the soil-column system to determine non-biodegradable residual drinking water DOC concentration. Figure 5 divides residual DOC (after soil column treatment) into drinking water DOC and DOC added during use or derived from the wastewater treatment process. Since this fraction is dominated by organic matter derived from the wastewater treatment process, it is referred to as *effluent-derived organic matter*. However, it still contains residual anthropogenic compounds added by consumers.

Based on six Mesa reclaimed water samples, which originate from different drinking water sources and thus resulted in significantly different residual DOC concentrations, up to 70% of reclaimed water DOC after simulated SAT was derived by drinking water DOC. At the Mesa site, the portion of DOC not related to drinking water varied between 0.8 and 1.4 mg/L. Tertiary effluent from Whittier Narrows WRP contained an effluent-derived organic matter concentration of 1.52 mg/L, and the average drinking water DOC of groundwater purveyors in the service area was 0.5 mg/L. A residual DOC of 1.59 mg/L was attributed to effluent-derived organic matter for the San Jose Creek East WRP. The DOC of

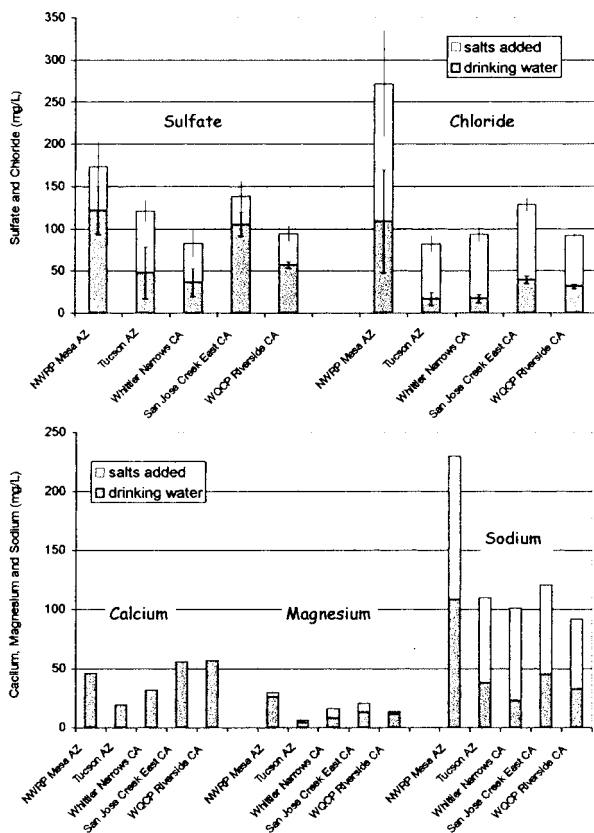


Figure 4 Comparison of selected anions and cations at different reuse sites for drinking water concentration and increments added during water use

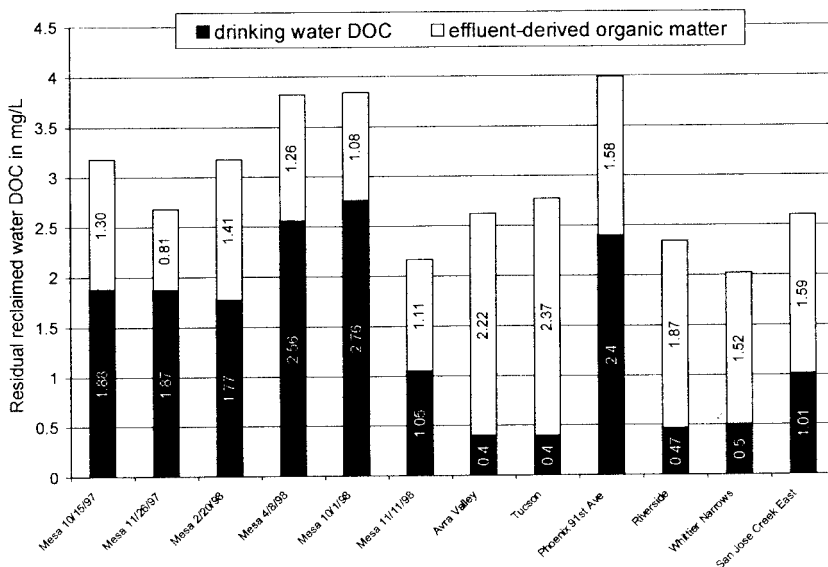


Figure 5 Residual DOC of reclaimed water after SAT for investigated field sites

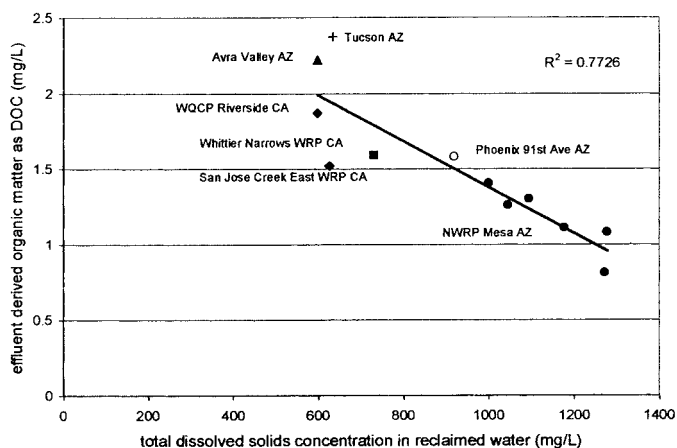


Figure 6 Correlation between effluent derived organic matter concentration and total dissolved solids (TDS) concentration for all investigated water reuse sites.

1.01 mg/L for the drinking water supply of the San Jose Creek East WRP represents an average based on SWIM calculations. Tucson and Riverside rely exclusively on groundwater supplies with DOC concentrations less than 0.4 mg/L. Figure 5 showed a substantially higher portion of effluent-derived organic matter for Tucson and Riverside effluents. Groundwater quality at Tucson and Riverside was not only characterized by low DOC concentrations but also by low TDS concentrations as compared to Mesa or San Jose Creek samples, where TDS concentrations were significantly higher. These findings may imply that the total ion composition of source water and wastewater may have a significant impact on effluent organic matter concentration in reclaimed water.

Impact of ion composition on effluent derived organic matter

A comparison of TDS concentration with effluent derived organic matter, which was determined as the difference between residual reclaimed water DOC after short-term SAT and drinking water DOC, revealed a positive correlation ($R^2 = 0.77$) (Figure 6). Water reuse sites with higher TDS concentration, generally considered as more critical due to their potential deterioration of groundwater quality by elevating salt concentrations, showed significant lower effluent derived organic matter concentrations. However, this impact was less evident for TDS concentrations of less than 700 mg/L, where the effluent derived organic matter concentrations of four different water reuse sites varied significantly. The presence of divalent cations has been demonstrated to interact with negatively charged biopolymers in activated sludge to change the structure of the flocs (Bruus *et al.*, 1992; Murthy and Novak, 1998). Monovalent cations such as sodium, potassium and ammonium tend to cause deterioration in settling and dewatering characteristics. However, divalent cations tend to retain biopolymers in the flocs leading to decreased SMPs and consequently lower residual DOC concentration in the treated effluent.

Conclusions

By gaining a better understanding of the interactions between source water, water treatment and reclaimed water quality, this work has established a foundation for assessing source water impacts on reclaimed water quality. Following a watershed guided approach, the scope of this project was to investigate the impact of drinking water sources and wastewater treatment processes on salt and residual DOC concentrations in indirect potable reuse systems. The developed Source Water Impact Model (SWIM) considered source water quali-

ties and distribution data. Data on water qualities and quantities necessary to run SWIM are often already generated by water utilities and therefore are readily available. SWIM was able to describe complex watersheds of reuse sites in Arizona and California. Higher levels of source water DOC clearly correlated with higher residual DOC concentrations in reclaimed water. According to these results, at all sites, the magnitude of organic residuals in reclaimed water was strongly affected by the concentration of organics in corresponding water sources and effluent-derived organic matter (soluble microbial products).

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