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Tapwater-contaminant mixtures and risk in a biofuel-facility impacted private-well community

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We assessed private-well drinking water (DW) at the point of use (*i.e.*, tapwater, TW) within a rural Nebraska community around a state-closed biofuel facility, which used pesticide-treated corn seed as feedstock for ethanol production. Organic (485), inorganic (34), and microbial (13) analytes were assessed at 15 locations in June 2022, to evaluate the relative contribution of facility-consistent pesticides (seed-treatment fungicides and insecticides) to overall TW-contaminant exposures and predicted human-health risks. Thirty-three organics (12 pesticides) and 28 inorganics were detected, the former including the fungicide sedaxane, insecticide chlorantraniliprole, and multiple neonicotinoid insecticides/degradates, all consistent with seed treatment and respective biofuel-facility waste. Assessment of pesticides only at extant point-of-use (POU) treatment taps at three sites demonstrated complete elimination of all TW-pesticide detections. Based on detection of maximum pesticide concentrations in a home located downstream along a creek capturing facility runoff, pesticides only were assessed in January 2023 again at this home and at three adjacent locations, confirming results at the former and documenting decreasing TW-pesticide concentrations, including neonicotinoids, with increasing distance from the creek. Human-health DW benchmarks are not available for many detected pesticides, including the detected fungicide and insecticides, but precautionary screening levels were exceeded frequently due to multiple inorganics. The results indicate that exposures to multiple (median: 4.5; range: 1–7) co-occurring TW contaminants of potential human-health concern are common, warranting consideration of point-of-entry or POU treatment(s) throughout the community to reduce or eliminate unrecognized exposures to TW contaminants, including facility-associated pesticides in down-gradient locations. More broadly, results emphasize the importance of continued characterization of private-TW exposures, employing a environmentally informative analytical scope, to identify and mitigate risks of unrecognized exposures in private-well-dependent rural communities.

Water impact

Private-well-dependent rural agricultural communities incur elevated risks of unrecognized tapwater exposures and human-health effects of agrochemical and naturally occurring contaminants, due to owner-dependent and generally limited private-well monitoring. A broad-analytical-scope assessment around a state-closed biofuel facility illustrates the importance of private-well monitoring and precautionary tapwater treatment to reduce cumulative risks of a range of unrecognized contaminant exposures.

1 Introduction

Drinking water (DW) safety and sustainability are priorities in the United States (US) and globally,[1–5] given the biological prerequisite for water[6–8] and consequent role as an increasingly vulnerable route of potential human exposures to numerous environmental contaminants, including a wide range of inorganic (*e.g.*, nutrients) and organic (*e.g.*, pesticides) chemicals associated with contemporary agricultural practice,[3–5,9] such as pesticide seed-treatments to

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improve corn and soybean crop production.[10] DW-agrochemical contamination has long been a public-health concern,[11–13] notably in agriculturally-intensive areas like US midwestern states and China,[14–19] due to prolific use,[20–22] landscape-scale sources and routes to ground and surface DW resources,[15,17,19,23–27] and well-documented DW exposures.[11,14,15,28–32] Associated DW-organic exposure concerns[14,33] include pesticide links to cancers,[34–39] Parkinson's disease,[40] endocrine disruption,[41] reproductive[42] and cardiovascular toxicities,[43] and developmental neurotoxicity,[44] while example DW-inorganic concerns[14,33] include nitrate-nitrogen (NO_3–N) links to infant (<6 months) methemoglobinemia[45] and, more recently,[46,47] cancers,[48–53] thyroid disease,[54,55] and neural tube defects.[56]

Pesticides and NO_3–N have been documented in all three primary point-of-use (POU) DW supplies (private-well tapwater [TW], public-supply TW, and bottled water).[5,11,15,57] The risk of unrecognized exposures, however, is notably higher for private-well TW (private-TW) due to a comparative lack of information on associated contaminant exposures.[5,58] The US Environmental Protection Agency (EPA) is not authorized to regulate or monitor private-TW,[59] and about 14% of the US population relies on private wells,[60–62] with concomitant homeowner-monitoring/-maintenance burdens.[59] High analytical costs, limited technical training/awareness, and conflation of safety and aesthetic quality severely undermine homeowner private-well monitoring;[5] accordingly, TW data, where available, typically comprise only a few analytes (*e.g.*, microbial).[63–65] The resultant TW-contaminant-exposure data gap in private-well-dependent remote/rural locations, including in agriculturally-intensive regions, undermines individual and community DW-risk-management decision making[5,65] and contributes to water insecurity[66,67] and attendant physical- and mental-health burdens.[68,69]

An ongoing, unusual agrochemical-contamination "hotspot/hot event"[70] at and around a bioenergy plant in Mead, Nebraska has raised water insecurity concerns for the largely private-well-dependent community.[71–77] In operation from 2015 until closed under state order in February 2021,[78,79] the facility utilized unused, expired pesticide-treated corn seeds as feedstock for ethanol production, resulting in onsite accumulation of wastewater and "wet cake" (estimated at 67 000 m^3 and 77 000 metric tons, respectively, at site closure) highly contaminated with fungicides and insecticides, including neonicotinoids. Field applications in the surrounding area during 2017–2019,[73] combined with aerial (*e.g.*, windblown dust) and hydrologic (*e.g.*, digester tank and storage-lagoon breaches to surface-water and groundwater systems, respectively[75,78,79]) transport offsite, have raised notable environmental[73,75,76,80] and human[73,74,77,81] exposure concerns, including through private-TW.

Addressing TW insecurity requires extensive inorganic/organic/microbial characterization of respective exposures and cumulative-risks, to disentangle perceived *versus* actual risks and support community and individual-consumer risk-mitigation actions. The U.S. Geological Survey (USGS) partners with communities, universities, Tribal Nations and colleges, state and federal agencies, utilities, and others to inform DW-exposure data gaps by assessing TW inorganic/organic/microbial contaminant mixtures and associated distal (*e.g.*, ambient source water) and proximal (*e.g.*, premise plumbing, point-of-entry [POE]/POU treatment) drivers in a range of US socioeconomic and source-water-vulnerability settings.[5,18,82–90]

In 2022, USGS partnered with University of Nebraska Lincoln, University of Nebraska Medical Center, and the community of Mead to assess exposures to a broad suite of potential inorganic/organic/microbial TW contaminants in 15 locations surrounding and downgradient of the facility. Research goals included 1) assessing contaminant-mixture exposures and cumulative risks to human health[91–93] in private-TW, 2) quantifying TW exposures and relative risks attributable to biofuel-facility, seed-coat pesticides, and 3) continued expansion of the national perspective on contaminant mixture exposures at the TW point of use by maintaining the same general sampling protocol and analytical toolbox employed in previous studies across the US.[5,18,82–89]

TW exposures were operationally represented as concentrations of 485 organics, 34 inorganics, and 13 microbial indicators in private-TW samples, for this study. Potential human-health risks of individual and aggregate TW exposures were screened[5,94–96] based on individual and cumulative benchmark-based toxicity quotients (TQ and $\sum_{TQ}$, respectively)[84,97] and supported by cumulative exposure-activity ratio(s) ($\sum_{EAR}$),[84,98] as described previously.[5] Due to the limited availability of organic benchmarks (*e.g.*, *circa* 100 in Safe Drinking Water Amendments [SDWA] National Primary Drinking Water Regulations [NPDWR][45,99]) relative to organic chemicals in global commercial use,[100] potential human-health risks of individual TW exposures also were explored based on detections/concentrations of designed-bioactive chemicals (*e.g.*, pesticides, pharmaceuticals).[101] In line with published results by this research group,[5,18,82–89] and by others,[9,64,102–106] simultaneous exposures to multiple organic, inorganic, and microbial constituents of potential human-health interest were hypothesized to occur in private-TW. Specific hypotheses addressed herein included:

I. Human exposures to insecticide(s) and fungicide(s) consistent with pesticide-treated-seed feedstock occurred *via* private-TW in the vicinity and downgradient of the biofuel facility.

II. Systematic TW-organic-contaminant exposures of potential human-health concern comprised primarily co-occurring agricultural pesticides, including fungicides and neonicotinoid insecticides, with detections of other organic classes generally limited and sporadic.

III. Extant POU treatments effectively removed pesticide contaminants from private-TW samples.

IV. Co-occurring inorganic exposures of potential human-health concern were common in private-TW samples.

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V. Due to limited human-health DW-pesticide benchmarks, private-TW cumulative risk was driven primarily by co-occurring inorganic exposures.

2 Methods

2.1 Site selection and sample collection

Mead, Nebraska, and the closed biofuel facility (Fig. 1) are located within Saunders County in the Todd Valley, an abandoned channel of the Platte River.[107,108] The facility lies within the drainage basin of Clear Creek, which flows southeast, discharging in turn to Wahoo Creek, Salt Creek, and the Platte River near the southeast corner of Saunders County.[107] The unnamed, intermittent, tributary network, draining the Eastern Nebraska Research, Extension and Education Center (ENREEC) south of the facility, includes a branch (labelled previously[75] and herein as ENREEC creek) that headwaters within the biofuel-facility grounds, combines into a single streamflow, and passes through a run-of-stream pond near site 4, shortly before the confluence with Clear Creek. Groundwater flow through the Todd Valley, including in the unconfined surficial Quaternary alluvial aquifer, likewise, is generally northwest to southeast toward the Platte River.[79,107,108]

Fifteen private-well sample locations in the area surrounding the biofuel facility, including upgradient [northwest] of Mead and downgradient [southeast] of the facility on ENREEC creek, were selected for broad-scope organic/inorganic/microbial analysis (Fig. 1; Table S1).[109] Sites 1 and 2 were facilities with on-site chlorine disinfection of the respective private-well TW. Kitchen taps (cold water) were sampled for broad-analytical-scope assessment once each in June 2022. Because three of these private-TW locations had POU treatment installed in parallel to the kitchen tap (reverse osmosis [RO]: site 1; under-sink carbon filter: sites 4 and 6), pesticide samples also were collected from the POU-treatment fixture, at the request of the study participants, to assess the efficacy of pesticide-contaminant removal. Samples were collected at the participant's convenience throughout the day, without pre-cleaning, screen removal, or lead and copper rule stagnant-sample requirements.[110,111] Based on maximum observed pesticide concentrations, including insecticides and a fungicide consistent with biofuel-facility feedstock, in a private-TW sample location (site 4) downgradient on ENREEC creek, this and three additional nearby homes (sites: 17, 19, 20), located north (sites 19, 20) and south (site

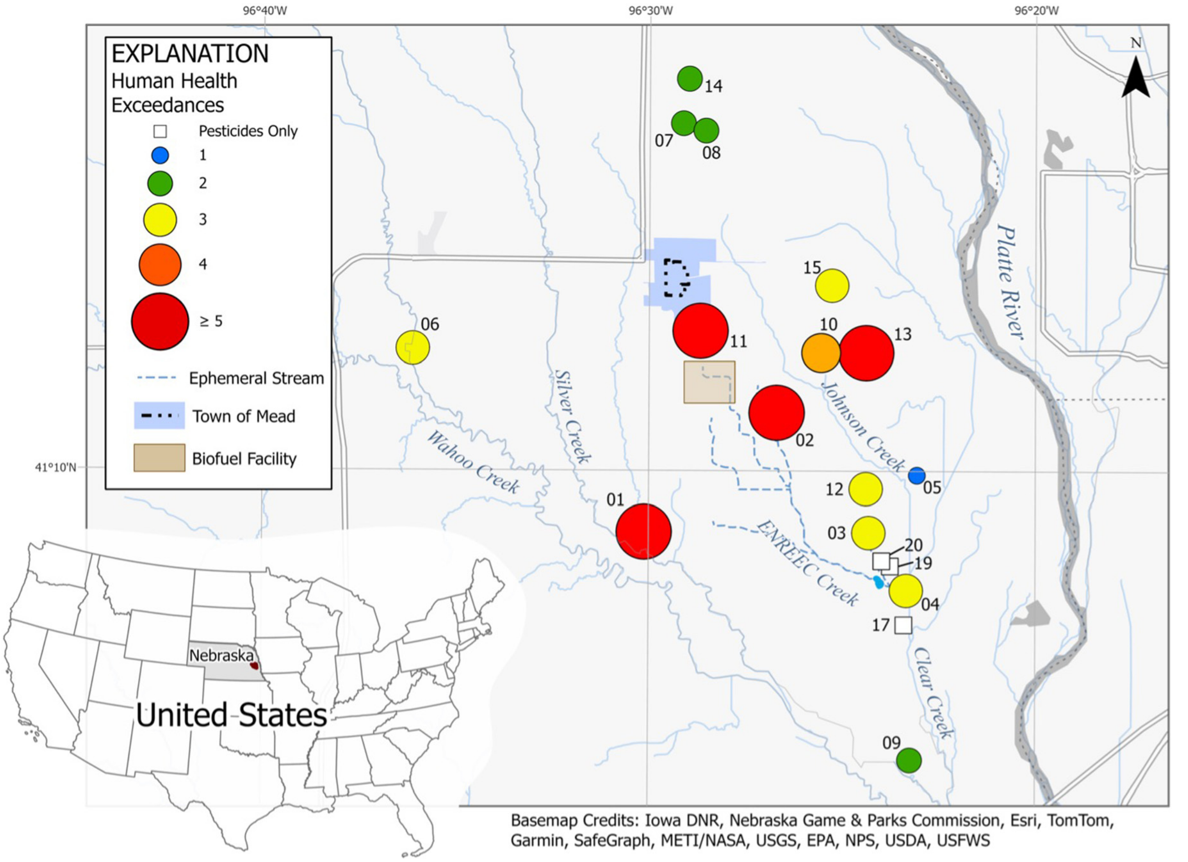

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Fig. 1 Map of study area near Mead, Nebraska, United States, showing private-TW locations sampled for broad-scope organic/inorganic/microbial analysis in June 2022 (color circles; sites: 01–15) and for pesticides only in January 2023 (empty squares; sites: 17, 19, 20). Number next to symbol indicates site number in Table S1. Size and color of circles indicate number of exceedances of human-health benchmarks for detected analytes. Sample locations are anonymized.

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17) of Site 4 and orthogonal to the general flow of ENREEC creek (Fig. 1) and presumptive southeast groundwater flow direction from facility,[79] were resampled/sampled for pesticides only in January 2023, to provide insight into potential pesticide-contaminant hydrologic-transport mechanisms. Complete sampling details are provided elsewhere.[109,112]

2.2 Methods, quality assurance, and statistics

Briefly, TW samples were analyzed by USGS using 8 organic (7 classes; 499 total/485 unique analytes), 6 inorganic (34 ions/trace elements), 13 microbial (13 indicators), and 2 field (3 parameters) methods (Table S2), as discussed.[5,82–84,86,112,113] Organic analytes included cyanotoxin, disinfection byproduct(s) (DBP), pesticide, per/polyfluoroalkyl substance(s) (PFAS), pharmaceutical, semi-volatile organic compound(s) (SVOC), and volatile organic compound(s) (VOC) classes; additional method details and links to source publications are in the SI (Table S2). All results are in Tables S3a–S6 and in Meppelink *et al.*[109] Quantitative (≥limit of quantitation, ≥LOQ) and semi-quantitative (between LOQ and long-term method detection limit, MDL[114,115]) results were treated as detections.[114,116,117] Quality-assurance and quality-control included analyses of one field blank and laboratory blanks, spikes, and stable-isotope surrogates. No organic or inorganic analytes or microbial indicators were detected in blanks at concentrations in the range observed in TW samples (Table S6). The median surrogate recovery (Table S4c) was 92.6% (interquartile range: 78.5–104%).

2.3 Individual and cumulative contaminant risk assessments

Individual-contaminant private-TW exposures were compared to public-supply-applicable NPDWR maximum contaminant level(s) (MCL)[45,99,118] as a frame of reference for exposures of potential concern for the general-consumer population (*i.e.*, not sensitive subpopulation(s)). However, because the EPA MCL rule-making process includes technical and financial considerations,[45,118] the potential for apical human-health effects of individual contaminant exposures was screened based on health-only MCL goal(s) (MCLG), "the maximum level of a contaminant in drinking water at which no known or anticipated adverse effect on the health of persons would occur, allowing an adequate margin of safety", when considering sensitive (infants, children, elderly, immune- or disease-compromised) subpopulations,[118] and other similar federal, state, and international health-only DW advisories.

A human-health-only, DW-benchmark-based precautionary screening of cumulative organic/inorganic contaminant risk was conducted consistent with World Health Organization/International Programme on Chemical Safety [WHO/IPCS] framework tier 1 hazard index risk screening,[94] European Food Safety Authority tier 1 reference point index (RPI) risk screening,[95] and 2023 EPA[96] guidance, as described previously.[5] The toxEval version 1.4.0 package[119] of the open source statistical software R[120] was used to sum (broadly applicable non-interactive concentration/dose addition model[121–126]) the TQ (ratio of detected concentration to corresponding health-based DW benchmark) of individual detections to estimate sample-specific cumulative TQ ($\sum_{\mathrm{TQ}}$).[5,97] Departures from approximate concentration addition (*e.g.*, ref. 127–130) are uncommon, limited in magnitude, and increasingly improbable with increasing mixture complexity.[125,131,132] The most protective human-health DW benchmark (*i.e.*, lowest benchmark concentration) among the following was employed, for each detected analyte: NPDWR MCLG,[45,133] EPA Drinking-Water Health Advisory(ies) (DWHA),[134] WHO guideline value (GV),[135] state MCL or DWHA (*e.g.*, ref. 136), or USGS Health-Based Screening Level (HBSL) or Human Health Benchmarks for Pesticides (HHBP).[137] EPA sets MCLG at "zero" for DW contaminants (*e.g.*, bromodichloromethane, lead [Pb]), which "may cause cancer" and for which "there is no dose below which the chemical is considered safe", including for sensitive (infants, children, elderly, immune- or disease-compromised) subpopulations.[45,118,133] For this $\sum_{\mathrm{TQ}}$ assessment, MCLG values of "zero" were set to 0.1 $\mu\mathrm{g\ L}^{-1}$ for metals (arsenic [As], lead [Pb], uranium [U]), DBP, and VOC, as described.[5] $\sum_{\mathrm{TQ}}$ results and respective health-based benchmarks are summarized in Table S7a and b.

Potential molecular-level effects of mixed-organic contaminant exposures also were explored, using an exposure-activity ratio (EAR) approach based on Toxicity ForeCaster (ToxCast)[138,139] high-throughput data.[140] In contrast to the human-health DW-concentration benchmarks employed in the mathematically-analogous $\sum_{\mathrm{TQ}}$ assessment above, ToxCast metrics are *in vitro* estimates of chemical-specific exposure-response relations at the site of molecular activity. The approach herein and previously[5,18,82–87,141] assumes that the measured TW concentration provides a reasonable first-level estimate of *in vivo* molecular-level exposure. Accordingly, the R package[120] toxEval version 1.4.0 (ref. 119) was employed to sum (approximate concentration addition model[121–126]) individual-contaminant EAR (ratio of the detected contaminant concentration to the contaminant-specific "activity concentration at cutoff" for a positive response (ACC) metric from ToxCast[140]) to estimate sample-specific cumulative EAR ($\sum_{\mathrm{EAR}}$).[5,98] ACC data in the toxEval v1.4.0 employed in the present study were from the September 2023 invitroDBv4.1 release of the ToxCast database.[142] Non-specific-endpoint, baseline, and unreliable response-curve assays were excluded.[82,83,98] $\sum_{\mathrm{EAR}}$ results and exclusions are summarized in Table S8a–c. Approximate contaminant-specific equivalency of the widely-employed TQ = 0.1 screening-level threshold of concern and EAR = 0.001 has been reported.[97] Thus, EAR (and $\sum_{\mathrm{EAR}}$) = 0.001 was employed to screen for potential concern (*i.e.*, for additional investigation and characterization) but not necessarily apical health risk, the latter due to uncertainties in *in vitro* to

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in vivo extrapolation[143,144] and the fact that measured bioactivities are not necessarily adverse and may, in some cases, reflect adaptive (*e.g.*, activation of xenobiotic metabolism[145]) responses.

3 Results and discussion

3.1 Target-analyte TW exposures

Multiple regulated and unregulated chemical (organic, inorganic) and microbial analytes were routinely detected in private-TW samples collected in 2022 (Fig. 1–3; Tables S3, S4a and S5). At least one detection of potential human-health concern was observed in every sample, with 2–7 in 93% (14/15) of samples.

TW samples were screened for 4 cyanotoxins, 22 DBP, 186 pesticide, 34 PFAS, 111 pharmaceutical, 55 SVOC, and 73 VOC analytes (Fig. 2; Table S2). Of these 485 unique organic analytes, 33 (7%) were detected at least once (Fig. 2), including 4 organics observed at concentrations of human-health concern with analyte-specific concern-level exceedance frequencies ranging 7% (tetrachloromethane, trichloroethene) up to 20% (tribromomethane) of all samples (Table S4a). Among the 33 organic analytes detected during the June 2022 broad-analytical-scope assessment, 16 (49%) were detected only once (Fig. 2; Table S4a). Nineteen (51%) were detected only once, when including the January 2023 pesticide-only follow-up sampling (Table S4b). At least one organic contaminant was detected in every TW-sample location (median: 5; IQR: 2.5–6.5; range: 1–15), with more than one detected in 80% (12/15) of locations (83% or 15 of 18 locations, including 2023 pesticide-only sampling). Analyte-specific detection frequencies for organics ranged up to 53% (deethylatrazine [CIAT], desmethyldiltiazem). No pesticides were detected in any TW samples collected from POU-treatment taps at sites 1, 4, and 6, indicating effective removal.

Fungicide (sedaxane) and insecticide (chlorantraniliprole, clothianidin, thiamethoxam) or degradate (thiamethoxam degradate CGA-355190) analytes consistent with facility seedcoat feedstock were observed only in the private-TW sample location (site 4) downgradient along ENREEC creek. These feedstock-consistent site 4 detections were confirmed at approximately 2–4 times higher concentrations in January 2023, along with additional neonicotinoid-insecticide detections of imidacloprid and its degradate (Table S4b). During the January 2023 sampling, single detections of feedstock-consistent neonicotinoids also were observed at sites 17 (clothianidin) and 19 (imidacloprid), located adjacent to site 4 and orthogonal to the general southeastern orientation of the ENREEC creek drainage and presumptive groundwater flow.

Twenty-eight (82%) of 34 inorganic analytes were detected at least once (Table S3a). Ten inorganics were detected at concentrations of human-health concern with analyte-specific concern-level exceedance frequencies ranging 7% (single detections for boron [B], fluoride [F], manganese [Mn], strontium [Sr]) up to 100% (U) of samples.

Microbial results included commonplace detections of general heterotrophic bacteria (*i.e.*, heterotrophic plate counts [HPC]) but no detections of total coliforms or *Escherichia coli* (Table S5). However, growth on putative-pathogen selective media indicated possible human-health concern in several sample locations.

3.2 Individual contaminant screening: MCL comparison

Concentrations equivalent to the respective NPDWR MCL (frame of reference only; not enforceable in federally unregulated private-TW) were exceeded for four inorganics, comprising nitrate-nitrogen (NO_3–N), arsenic (As), copper (Cu), and uranium (U) (Table S3). The MCL-equivalent concentration for NO_3–N was exceeded in three samples (sites: 1, 6, 10), with single MCL-equivalent exceedances for As, Cu, and U. MCL-equivalent exceedances in private-TW samples in this study are consistent with prior findings,[5] reemphasize the inherent risks of unrecognized contaminant exposures in federally-unregulated and rarely-monitored private-TW,[5] and illustrate the potential benefits of systematic private-TW monitoring[65] with a broad analytical scope that credibly reflects extant environmental-contaminant complexity,[26,101,105,146,147] to mitigate unrecognized adverse exposures. While MCL-equivalent exceedances indicate exposures of concern for general consumers, the emphasis hereafter is on human-health-only DW advisories like MCLG, which identify a maximum contaminant level below which no adverse health effect is known or anticipated, allowing an adequate margin of safety for sensitive (infants, children, elderly, immune- or disease-compromised) subpopulations.[118]

3.3 Individual contaminant health-risk screening: organics

TW-sample DWHA exceedances were observed for four VOC, of which two are typically associated with chlorine-based DW disinfection (*i.e.*, DBP; Table S4a). All four (bromodichloromethane, tribromomethane (bromoform), tetrachloromethane [carbon tetrachloride], trichloroethene) have no known safe level of exposure for vulnerable subpopulations and corresponding MCLG of "zero".[45] Other notable, organic detections of potential human-health concern owing to designed-bioactivity were multiple pesticides and associated degradates (median: 1 per sample; IQR: 0–3.5; range: 0–12) and pharmaceutical contaminants (Table S4a).

Detected concentrations of regulated pesticides (atrazine, bentazon, metolachlor, prometon) and degradates (deisopropyl atrazine [CEAT], CIAT) were well-below corresponding DWHA, and human-health DW benchmarks are lacking for many of the detected pesticides, including seed-coat-associated fungicides (sedaxane) and insecticides (chlorantraniliprole, chlothianidin, imidacloprid, thiamethoxam). However, pesticide links to multiple adverse outcomes,[34–44] multiple pesticide detections per sample, and growing concerns for neonicotinoid-insecticide health effects (*e.g.*, cancers,[148]

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diabetes,[149] developmental neurotoxicity[44]) raise concerns for potential adverse effects of long-term TW-pesticide exposures.[31,74,150]

The diltiazem metabolite, *N*-desmethyldiltiazem, was detected in 53% (8/15) of locations at near-detection-limit concentrations (median: 0.006 μg L^{-1}; range: 0.004–0.007 μg L^{-1}). Diltiazem is a calcium-channel-blocker cardiovascular pharmaceutical, prescribed to treat high blood pressure and angina.[151] The lipid-regulating cardiovascular drug fenofibrate was detected in 13% (2/15) of private-TW locations (detected concentration range: 0.008–0.012 μg L^{-1}). Increasing detections of fenofibrate and other cardiovascular drugs and metabolites (*e.g.*, desmethyldiltiazem) in environmental waters[151] and DW,[152] are ascribed to growing global use, concomitant wastewater discharge, environmental stability, and poor removals in DW treatment.[153–155]

The results demonstrate that TW-organic exposures of human-health concern for vulnerable subpopulations occur in the Mead community, notably downgradient of the facility on ENREEC creek. These organic results are consistent with those in northeast Iowa[18] and emphasize the importance of private-TW monitoring in agriculturally-intensive areas with an analytical scope that realistically reflects the respective environmental organic-contaminant complexity.[26,101,105,146,147]

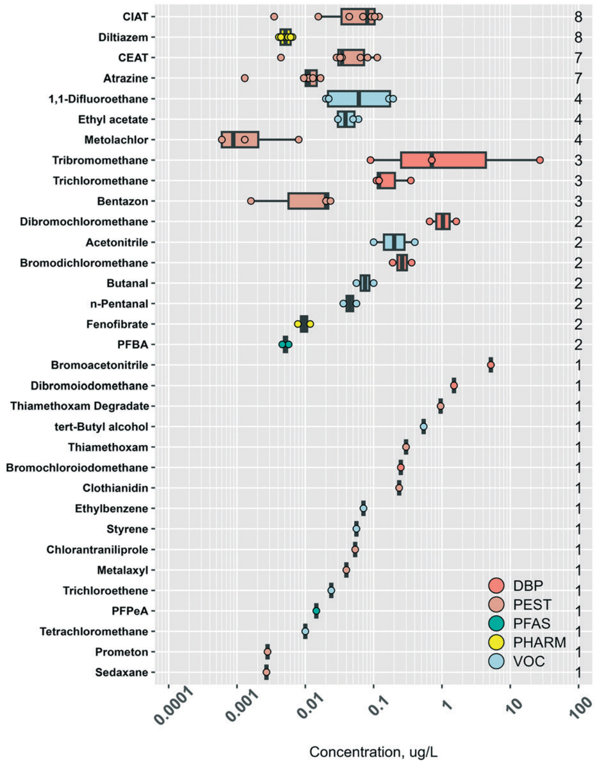

Fig. 2 Detected concentrations (μg L^{-1}) and number of sites (right axes) for 33 organic analytes (left axis, in order of decreasing total detections) detected in private-well tapwater samples collected during 2022 in the vicinity of the state-closed biofuel facility near Mead, Nebraska. Circles are data for individual samples. Boxes, centerlines, and whiskers indicate interquartile range, median, and 5th and 95th percentiles, respectively. DBP, PEST, PFAS, PHARM, and VOC indicate disinfection byproducts, pesticides, per/polyfluoroalkyl substances, pharmaceuticals, and volatile organic chemicals, respectively.

3.4 Individual contaminant health-risk screening: inorganics

DWHA exceedances were observed for multiple inorganics (Fig. 3, S1; Table S3), consistent with previous private-TW results in agriculturally-intensive northeastern Iowa[156] and with hypothesis I. Among these, As, lead (Pb), and U have no known safe level of exposure for vulnerable subpopulations (MCLG of "zero").[45] Additional TW-inorganic exceedances (in order of discussion) of human-health benchmarks include non-zero MCLG (NO_3–N) and other human-health-only advisories (boron [B], hexavalent chromium [Cr(VI)], fluoride [F], manganese [Mn], strontium [Sr]).

Geologically-derived (geogenic), redox-reactive, As was detected (*de facto* MCLG exceedance) in 5 (33% of sites) private-TW samples (Fig. 3, top right; Table S3). Tasteless and odorless, DW As has been linked with various cancers,[157,158] organ toxicity,[157] cardiovascular disease,[159,160] diabetes,[159,160] adverse pregnancy outcomes,[161] and mortality.[161,162] Concern for adverse effects at concentrations below the 10 μg L^{-1} EPA MCL[157,159,163,164] prompted New Jersey and New Hampshire to establish a 5 μg L^{-1} MCL,[165,166] a level exceeded in three samples (20% of sites) in the current study. Maximum TW-As concentrations observed in the current study were consistent with elevated C horizon As profiles[167] and groundwater As concentrations[168] documented in eastern Nebraska.

Redox-reactive, geogenic U was detected (*de facto* MCLG exceedance) in every TW sample in this study (Fig. 3, middle left; Table S3), including at a concentration more than double the MCL-equivalent 30 μg L^{-1} at one location (site 11: 74 μg L^{-1}). U concentrations >3 μg L^{-1} (common method detection limit for public-supply compliance monitoring) or >10 μg L^{-1} were observed in 40% (6/15) and 13% (2/15) of private-TW samples, respectively. Widespread detections of U concentrations, including sporadic detections at elevated concentrations are consistent with elevated C horizon U contents documented in southeastern Nebraska.[167] DW U is linked to a range of adverse human-health impacts, including nephrotoxicity[169–173] and osteotoxicity,[171,172,174] thyroid cancer,[175] inhibition of DNA-repair *in vitro*,[176] estrogen-receptor effects in mice,[177] reproductive endpoints in humans,[171,172,178] and elevated prediabetes[179] and type-2 diabetes risks.[180,181]

Lead was observed (*de facto* MCLG exceedance) sporadically (33%) in private-TW samples (Fig. 3, top left; Table S3). Three sites (11, 13, 14) had concentrations greater than the American Academy of Pediatrics[182] suggested upper DW-exposure limit of 1 μg L^{-1}, also a common method detection limit for public-supply compliance monitoring.[183] Elevated (>1 μg L^{-1}) DW-Pb concentrations are generally attributed to legacy (pre-1986) use in distribution-system and premise-plumbing infrastructure.[184] In this study, plumbing-derived TW-Pb exposures may be substantially underestimated, because same-day prior use was common and flushing decreases plumbing-derived contaminant

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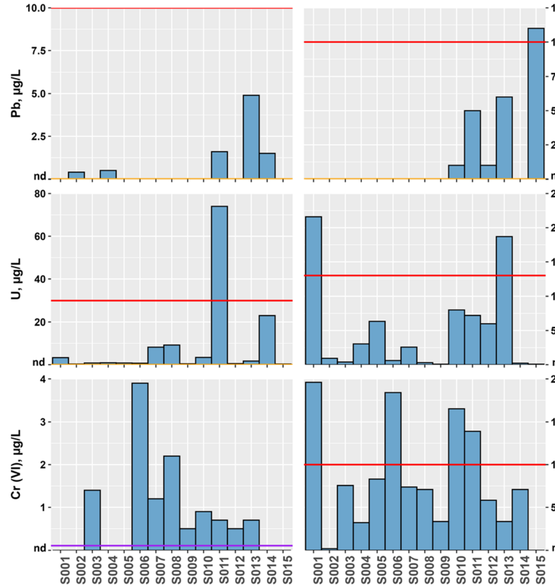

Fig. 3 Detected concentrations (*y*-axis) by site (*x*-axis) for lead (Pb µg L^{-1}, upper left), arsenic (As µg L^{-1}, upper right), uranium (U µg L^{-1}, middle left,), copper (Cu µg L^{-1}, middle right), hexavalent chromium (Cr(VI) µg L^{-1}, lower left) and nitrate–nitrogen (NO_3–N mg L^{-1}, lower right) detected in private-well tapwater samples collected during 2022 in the vicinity of the state-closed biofuel facility near Mead, Nebraska. Red lines (Pb, As, U, Cu, NO_3–N), indicating the public-supply maximum contaminant level (MCL), are frame-of-reference only for federally unregulated private-well tapwater. Health-only MCL goals (MCLG, orange lines) are 'zero' for Pb, As, and U. Purple line indicates EPA risk screening level for Cr(VI).

concentrations.[184,185] DW-Pb exposures primarily are concerns for potential impacts on infant/child neurocognitive development.[182,184]

MCLG-/MCL-equivalent exceedances were observed for Cu in two (13%) locations in this study (Fig. 3, middle right). The EPA MCLG/MCL for Cu in public-supply DW (1.3 mg L^{-1}) and the WHO GV (2.0 mg L^{-1}), were promulgated to protect against gastrointestinal distress from short-term exposure and potential liver and kidney damage from long-term exposure.[186–189] Excluding rare autosomal regulatory disorders (*e.g.*, Wilson's disease) that may result in serious health consequences even at normal exposure levels, there is little evidence of liver toxicosis at twice the WHO GV, including for bottle-fed infants.[190] Although elevated DW-Cu concentrations are generally attributed to distribution and premise-plumbing infrastructure and often associated with low DW pH,[184] elevated C horizon Cu concentrations have been documented in southeastern Nebraska.[167]

Well-documented throughout Nebraska,[168,191] elevated (*i.e.*, >1 mg L^{-1}) private-TW NO_3–N concentrations were common (87% of samples) in the study area (median: 7.1 mg L^{-1}), with the MCL-/MCLG-equivalent (10 mg L^{-1}) concentration exceeded in three (20%) sample locations (Fig. 3, bottom right; Table S3). The NO_3–N MCL/MCLG was promulgated to prevent methemoglobinemia in bottle-fed infants (<6 months).[45] However, associations with other adverse health outcomes,[46,47] including cancer,[48–53] thyroid disease,[54,55] and neural tube defects,[56] drive recent concerns for long-term consumption of TW-NO_3–N at less than MCL concentrations. Regionally intensive crop agriculture, widespread TW detections of agricultural pesticides (Table S4a and b), and lack of multiple, co-occurring human-waste indicators (*e.g.*, human-use pharmaceuticals [Table S4a], fecal bacteria indicators [Table S5]) are consistent with agricultural surface treatment (*e.g.*, inorganic/organic fertilizers) as presumptive source of elevated NO_3–N concentrations in groundwater[168,191] and private-TW samples (Table S3) and indicate that human-waste infrastructures (septic systems) were not primary contributors.

No MCL/MCLG currently exists for B, and no private-TW sample in this study exceeded the EPA 6000 µg L^{-1} life-time DWHA[134] (Fig. S1, middle right; Table S3), based on male reproductive effects (*i.e.*, testicular lesions).[192,193] However, in 2017, the Minnesota Department of Health lowered its respective risk assessment advice value (previously 2000 µg L^{-1} B; pregnant women sensitive population) to 500 µg L^{-1} B due to uncertainties concerning bottle-fed infant exposures and toxicity,[136,194] a value exceeded in a single private-TW sample (7% of locations).

Consistent with elevated C horizon contents reported previously in southeastern Nebraska,[167] TW-Cr was detected in TW samples, primarily as Cr(VI) (Fig. 3, bottom left; Table S3). While TW-Cr(total) concentrations were well below the NPDWR MCL (100 µg L^{-1}), which addresses Cr(VI) as a component,[45,99] and TW-Cr(VI) concentrations were below the recent California MCL (10 µg L^{-1}),[195] Cr(VI) is classified as "likely to be carcinogenic" *via* oral exposure.[196] About 60% of private-TW locations in this study exceeded the USGS cancer HBSL (0.04 µg L^{-1})[137] and the EPA Regional Screening Level (RSL)[197] for one-in-one million (10^{-6}) cancer risk applied previously,[5,198] with one sample (site 6: 3.9 µg L^{-1}) *circa* the one-in-ten thousand (10^{-4}) cancer risk HBSL (4 µg L^{-1}).[137] These observations raise concerns for elevated risk of stomach cancer from long-term TW-exposures in the study area.[158,199]

All TW-F concentrations (Fig. S1, top left; Table S3) were less than the EPA MCL (4 mg L^{-1}) for protection against bone fragility and skeletal fluorosis.[45,133] However, the F concentration (1.55 mg L^{-1}) in one TW sample (site 2) exceeded the WHO GV (1.5 mg L^{-1}) established to prevent dental fluorosis[135] and, critically, adopted in the recent National Toxicology Program review to mitigate the risks of neurodevelopmental and cognitive effects in children.[200] This result raised concern for TW-F exposures to children within the study area. Consistent with groundwater across the US[201,202] and corresponding dental-health concerns in private-well-dependent children,[203] TW-F concentrations in all but two samples were below the US Public Health Service[204] optimum of 0.7 mg L^{-1} to prevent dental caries.

In response to increasing concerns for cognitive, neurodevelopmental, and behavioral effects of long-term TW-Mn exposures in children and especially in bottle-fed infants,[205,206] WHO established a Mn provisional GV of 80 µg L^{-1}, to prevent neurological effects in bottle-fed infants.[207]

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This value was exceeded in one private-TW sample (site 15: 212 $\mu g\ L^{-1}$) in the current study (Fig. S1, middle left). Co-occurring elevated iron (258 $\mu g\ L^{-1}$) and negligible NO_3–N concentrations indicate occurrence of reducing redox conditions in the private-well groundwater at the time of sample collection. No MCL/MCLG has been promulgated for Mn, but EPA issued a 300 $\mu g\ L^{-1}$ life-time DWHA (assumes 100% exposure from drinking water).[134]

A TW-Sr concentration (3950 $\mu g\ L^{-1}$) of potential human-health concern also was observed in only one sample (site 2) in this study (Fig. S1, bottom right; Table S3). Sr is widely detected in US groundwater.[208] TW-Sr human-health concerns, primarily in children, are driven by potential replacement of bone calcium and resultant abnormal bone development with long-term elevated exposure.[209,210] In 2014, EPA published a preliminary determination to regulate DW-Sr,[211] but to date no MCL/MCLG has been promulgated. The site 2 TW-Sr concentration was more than double the 1500 $\mu g\ L^{-1}$ Health Advisory Level (HAL) established by the state of Wisconsin for bone effects in children.[212]

The results demonstrate that TW-inorganic exposures of human-health concern for vulnerable subpopulations also occur in the Mead community, notably downgradient of the facility on ENREEC creek. The results, combined with those for organics above, emphasize the importance of private-TW monitoring with an analytical scope that realistically reflects the documented complexity of environmental contamination.[26,101,105,146,147]

3.5 Individual contaminant health-risk screening: microbial

Microbial detections (HPC) were common (92% or 12 of 13 sites; not available for sites 14 and 15) in private-TW samples (median: 6100 most probable number per 100 mL [MPN 100 mL^{-1}]; IQR: 4000–6400 MPN 100 mL^{-1}; range: 0–7000 MPN 100 mL^{-1}) (Table S5). No HPC were detected in the site 2 sample, which had detectable VOC indicative of chlorine disinfection (*i.e.*, DBP). HPC bacteria are ubiquitous in the environment, common in DW, and not inherent health concerns but practical indicators of system maintenance,[45,134] which includes routine disinfection in private wells.[59] Total coliform bacteria and *E. coli* were not detected in any sample in this study. However, growth on selective media for microorganisms of potential human-health concern was observed in several samples.

Detections of *Salmonella* (7 or 47% of samples) and *Campylobacter* (2 or 13%) spp., common causes of food-/water-borne enteric diseases,[213–215] and the opportunistic premise-plumbing (biofilm-related) pathogens[215–217] *Pseudomonas aeruginosa* (8 or 53%), *Legionella* spp. (8 or 53%), and *Mycobacterium* spp. (1 or 7%) raise concerns for adverse TW microbial exposures in the study area.[215] Growth on oxacillin-resistant staphylococci selective media for 3 samples, indicates the potential presence of antibiotic-resistant microorganisms, a growing public-health[218] and DW-quality concern.[219]

Among these, detections of biofilm-related[215] *Pseudomonas aeruginosa* and *Legionella* spp. in more than half of samples and often co-occurring are notable concerns (Table S5). *Legionella* was identified as the leading and increasing cause of biofilm-related disease outbreaks in the US during 2015–2020.[215] The maximum detection of *Legionella* spp. observed in this study was 989 MPN 100 mL^{-1} in the site 15 sample (Table S5). The MCLG for *Legionella* is "zero".[45] *Salmonella* spp., *Campylobacter* spp., and staphylococci are well-documented in livestock/poultry wastes[220] and acknowledged human-exposure concerns in nearby private wells,[221,222] due to infiltration from waste storage lagoons[223] and agricultural-land applications.[224] These results reiterate the inherent challenge of unmonitored private-TW[63,64,102,202] and support systematic monitoring,[65] including for microbial contamination.

3.6 Precautionary human-health-benchmark $\sum_{TQ}$ screening

Pervasive, co-occurring inorganic/organic exposures of human-health concern suggest potential cumulative TW risk within the private-well-dependent community, at a minimum to the health of the most vulnerable (infants, children, elderly, immune- or disease-compromised) subpopulations.[45,118,133] We screened for cumulative TW risk using a $\sum_{TQ}$ approach that informs apical-human-health effects of inorganic/organic co-exposures but is notably constrained to available human-health DW benchmarks. Regarding the latter, 62% (16 inorganic; 22 organic) of the 61 total detected analytes (28 inorganic; 33 organic) in this study, had available human-health benchmarks focused on risks to presumptive most-vulnerable populations (Table S7a). Among these, all but one organic analyte had at least one exposure resulting in an individual TQ ≥ 0.00001 and were included in the $\sum_{TQ}$ assessment. All broad-scope-analysis TW samples (*i.e.*, not including 2023 pesticide-only samples) exceeded $\sum_{TQ} = 1$ (Fig. 4; Table S7b), indicating high probabilities of cumulative risks to sensitive subpopulations, when accounting for inorganic-/organic-contaminant exposures.

Every location had at least one individual TQ ≥ 1 (median: 3; IQR: 2–4.5; range: 1–6), comprising, in decreasing detection frequency, U (15/15 sites), Cr(VI) (9/15), As (5/15), Pb (5/15), NO_3–N (4/15), tribromomethane (bromoform, 2/15), bromodichloromethane (2/15), Cu (2/15), Mn (1/15), B (1/15), and Sr (1/15) (Fig. 4; Table S7b). Frequent exceedances of $\sum_{TQ} = 1$ and co-occurring exceedances of TQ = 1 in TW samples from unregulated and generally unmonitored private-wells in this and previous studies[18,83–85,141] emphasize the intrinsic human-health vulnerability of unrecognized exposures in private-well-dependent communities[63–65,90,102,202] and reinforce previous recommendations for systematic private-well monitoring,[65,225–228] with a broad analytical scope reflective of the range of environmental-contaminant mixtures.[5,101,105]

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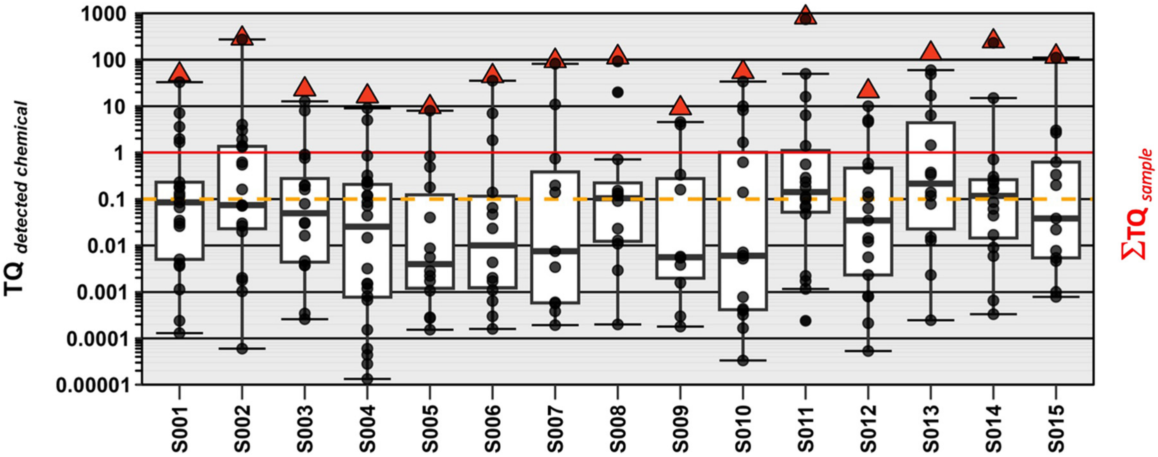

Fig. 4 Individual (circles) and cumulative (red triangles) health-only toxicity quotients (TQ) for private-well tapwater samples collected in the vicinity of the state-closed biofuel facility near Mead, Nebraska. Red (upper) and orange (lower dashed) lines indicate benchmark equivalent exposure (TQ or $\sum_{TQ} = 1$) and screening-level of concern (TQ or $\sum_{TQ} = 0.1$), respectively. Boxes, centerlines, and whiskers indicate interquartile range, median, and 5th and 95th percentiles, respectively. *X*-Axis labels are sample site numbers.

3.7 Human-health-benchmark $\sum_{EAR}$ screening

Bioactivity-weighted EAR and $\sum_{EAR}$ were calculated to identify organic-contaminant drivers of molecular-level human-relevant bioactivities and potentially identify additional concerns not addressed by existing human-health benchmarks. The screening approach employed here specifically assumes that measured private-TW exposures are reasonable first-level estimates of *in vivo* molecular-level exposures. ACC data were available for about 48% (16) of the 33 detected organics (Table S8b), of which 13 (39% of detected) had at least one individual EAR ≥ 0.00001 and were included in the $\sum_{EAR}$ assessment. Within the 485 organic-contaminant analytical space, only two organics (6% of detected) exceeded the EAR = 0.001 screening-level for potential molecular-level effects[97] at least once and only 4 (26% of locations) TW samples had $\sum_{EAR}$ greater than the 0.001 screening level (Fig. S3). Based on EAR-screening-level exceedance, the post-emergent herbicide bentazon was the only additional potential TW-exposure concern identified, beyond those identified by benchmark-based $\sum_{TQ}$ screening above.

3.8 TW-pesticide transport lines of evidence

Agricultural-pesticide use and occurrence in groundwater resources are well-documented throughout the US Corn Belt,[11,25,29,229] including Nebraska[168,191,229,230] and specifically the Platte River valley.[231] Consistent with commonplace historical and ongoing use in corn and soybean agriculture,[232] including within the study area,[231] the herbicide/herbicide-related atrazine and degradates (8 sites), metolachlor (4 sites), and, to a lesser extent, bentazon (3 sites) were commonly detected in TW throughout the study area, including upgradient of the facility (Fig. 1; Table S4a and b) and in areas with no known facility wet-cake or wastewater applications.[75,78]

However, the results also document greater detections and concentrations, including facility-feedstock-consistent pesticides, in TW southeast of the facility downstream on ENREEC creek and downgradient along the general southeast groundwater flowpath reported for the shallow alluvial aquifer in the Todd Valley of Saunders County.[78,107,108] Due to high reported pesticide use (crop application and treated seeds); including the detected chlorantraniliprole, chlothianidin, imidacloprid, sedaxane, and thiamethoxam; in the Todd Valley and throughout Nebraska,[20,232] corresponding detections in private-TW samples cannot be attributed unequivocally to a facility source. However, these detections are consistent with previously hypothesized mechanisms for facility-feedstock-pesticide transport offsite to private-well groundwater supplies, including possible surface-water transport *via* ENREEC creek, groundwater transport from the facility along the reported southeast shallow groundwater flowpath, or land application of contaminated "wet cake".[75,78,79]

Among these hypothetical pathways from the facility, multiple lines of evidence support proximity to ENREEC creek as the primary driver of facility-consistent TW-pesticide exposures observed in this study. Nearby land application of facility "wet cake" was reported by several study participants, including upgradient of the facility,[75,78,79] without corresponding TW detections of feedstock-consistent pesticides, suggesting that these surface applications were not a primary mechanism of the private-TW contamination observed in this study. In contrast, detections of sedaxane fungicide and elevated concentrations of multiple insecticides, including chlorantraniliprole and neonicotinoids/degradates, at the site 4 location were consistent with containment losses of facility waste, with subsequent hydrologic transport from the facility to the corresponding private-well directly *via* groundwater[79] or indirectly *via* ENREEC creek,[75] the latter followed by

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infiltration to the private-well groundwater source. Declining volume within the inactive northwest lagoon after facility closure in 2021 combined with comparable pesticide composition and concentrations in lagoon wastewater and underlying shallow groundwater confirmed lagoon leakage to the shallow groundwater system.[79] In February 2022 a burst pipe for a 15 000 m^3 digester released process wastewater to ENREEC creek,[75] resulting in elevated water (water grab, polar organic chemical integrative samplers [POCIS]) fungicide and insecticide concentrations in ENREEC creek,[75,76,233] and acute exposures to fish and wildlife in and around the creek pond at site 4.[71,76,233] Downstream-flow attenuation within the pond would favor preferential infiltration of surface water and corresponding contaminants into the site 4 private-well groundwater source.

To further inform the relative importance of the two hypothesized hydrologic transport mechanisms, three additional sites, located adjacent to site 4 but further from ENREEC creek orthogonal to surface-water and presumptive groundwater flow (Fig. 1), were assessed for pesticides only in 2023 along with repeat sampling at site 4. Consistently high detected concentrations of multiple facility-consistent pesticides (chlorantraniliprole, chlothianidin, sedaxane, thiamethoxam and degradates) at site 4, contrasted with single neonicotinoid detections of notably lower concentrations at adjacent sites 17 and 19, are most readily reconciled with preferential surface-water transport to the site 4 pond, a hydrologic setting which would delay further downstream transport and favor infiltration of surface-water and associated contaminants into the shallow alluvial aquifer supply for the site 4 private-well. Importantly, the distinctive pesticide signature of chlorantraniliprole, chlothianidin, sedaxane, thiamethoxam and degradates observed in site 4 TW aligned well with results for surface-water samples collected within ENREEC creek and the corresponding site 4 pond during a separate March to July 2022 multi-matrix ecological assessment of pesticide concentrations and impacts in area streams.[76,233]

3.9 Study limitations

Several interpretive limitations warrant consideration. As noted previously,[5] the extensive target-analyte scope employed herein is only a fractional indicator of the estimated 350 000 anthropogenic chemicals in commercial production[100] (not including environmental transformation products/degradates) and, thus, potentially in ambient DW-supplies; the current exposure and risk results may be orders-of-magnitude underestimates. Individual (TQ) and cumulative risk ($\sum_{\mathrm{TQ}}$) estimates are limited by available weighting-factors (human-health benchmarks and ToxCast ACC, respectively), which are notably lacking for many of the pesticides detected in this study. The employed cumulative risk ($\sum_{\mathrm{TQ}}$) and molecular-level-bioactivity ($\sum_{\mathrm{EAR}}$) approaches estimated mixture effects assuming approximate concentration addition,[121–126] potentially underestimating or overestimating cumulative effects in the event of synergism/potentiation or antagonism, respectively;[234] documented[127–130] departures from approximate concentration addition are uncommon[125,131,132] due in part to uncertainties in quotient denominator point-of-departure estimates,[235,236] increasingly unlikely with increasing number of mixture components,[125] and typically within one order of magnitude.[125,131,132] The employed cumulative risk ($\sum_{\mathrm{TQ}}$) screening assumed equivalent lifetime consumption (*i.e.*, no differences in individual and daily consumption). To provide a precautionary lower-bound estimate of *in vivo* adverse-effect levels, EAR was estimated across all ToxCast endpoints (*i.e.*, not constrained by recognized modes of action),[237] a useful screening and prioritization approach but not necessarily reflective of apical health effects.[98,238] MCLG values of "zero" were set to 0.1 $\mu g\ L^{-1}$ for metals, DBP, and other VOC, but this approach may not sufficiently protect for molecularly-triggered, self-propagating toxicities, such as carcinogenicity and endocrine-/immune-disruption. The June 2022 spatial-synoptic (one-time sample) broad-scope exposure and the January 2023 pesticide-only exposure assessments were not intended to capture temporal variability, including potential seasonal effects on water quality and groundwater/surface-water contaminant transport. Finally, the extensive analytical scope employed in this study provided actionable insight into TW-contaminant exposures to inform exposure-mitigation decision-making at household and community levels and preliminary information on potential contaminant sourcing, but the pilot-scale sample scope (n = 15) was not intended to capture the full range of spatial, groundwater-source, and premise-plumbing drivers of TW-exposures in the study area.

3.10 TW treatment and exposure mitigation

Contaminant-specific TQ ≥ 1 at every location and commonplace co-occurrence (per site median: 3; IQR: 2–3.5; range: 1–5) demonstrate the benefit of effective multi-contaminant POE-/POU-treatment options to mitigate unrecognized private-TW contaminant exposures in the study area.[239,240] Complete elimination of pesticide detections in the three locations with extant POU-treatment (reverse osmosis [RO]: site 1; under-sink carbon filter: sites 4 and 6) confirms this conclusion, at least for pesticides, the most common organics detected in the study. Several POE-/POU-treatment technologies are effective in reducing all inorganic and organic TW-contaminant exposures identified in this study,[239] with treatment efficacy dependent on selection of suitable filtration technologies for exposures of concern, timely maintenance, and routine performance monitoring. In light of common co-occurring inorganic- and organic-contaminant exposures throughout the study area, broadly effective treatment technologies, such as RO, or multi-stage/multi-filtration

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systems (sediment filter, redox media, activated carbon, ion exchange, UV disinfection) may be more appropriate.[239]

4 Conclusions

The biological essentiality of water[6–8] makes it an especially vulnerable human-exposure pathway (human-health risk vector) for a vast range of environmental chemical/biological hazards.[5,102,198,227] Consequently, in private-well-dependent communities, DW is a critical leverage point for individual and community-level contaminant-risk mitigation through cognizant chemical use/disposal, improved well/premise-plumbing infrastructure installation and maintenance, well-head/source-water protection, and POE/POU treatment. In general, financial resource, water-quality expertise, and contaminant-exposure data limitations at the household-scale are fundamental obstacles to private-TW decision-making and risk-mitigation actions.[65,84,90] Analytically extensive datasets like this study, which are intended to support household and community-level decision-making and, more broadly, enhance scientific understanding of the role of DW in human-health outcomes, remain rare because extensive TW-contaminant assessments are not routinely conducted at the point-of-exposure in the US or worldwide.

The results of this and previous[82–85] studies highlight the human-health vulnerability inherent to unmonitored TW[63–65,102,202] and the potential value of systematic private-well monitoring[65] with an analytical scope that reasonably reflects the breadth of environmental contamination.[26,101,105,146,147] This study demonstrated elevated human-health risk from simultaneous exposures to multiple TW contaminants throughout the study area, emphasizing the need for improved understanding of the adverse human-health implications of long-term exposures to inorganic-/organic-contaminant mixtures in private-TW. The results illustrate the importance of well-maintained POE/POU treatment as prudent protection against unrecognized simultaneous exposures to multiple contaminants in private-TW.[84,241] These findings confirm the importance of continued characterization of private-TW exposures and increased availability of resultant health-based data, including at concentrations below technically-/economically-constrained public-supply standards (*e.g.*, MCL), to support community engagement in source-water protection and inform household POE/POU treatment decisions in the study area and throughout the US.

Author contributions

PMB: conceptualization, methodology, sampling, data curation, formal analysis, project management, funding, writing – original draft, writing – review & editing. SMM: sampling, data curation, writing – review & editing. KMR: methodology, data curation, formal analysis, visualization, writing – review & editing. MLS: writing – review & editing. KLS: methodology, formal analysis, project management, funding, writing – review & editing. SLB-H: conceptualization, methodology, sampling, writing – review & editing. BKD: writing – review & editing. SEG: visualization, writing – review & editing. KAL: formal analysis, funding, writing – review & editing. RBM: formal analysis, writing – review & editing. EGR: conceptualization, writing – review & editing. DLR: writing – review & editing. DDS: conceptualization, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

Supplementary information: All data are available in the SI. See DOI: **https://doi.org/10.1039/D5EW00490J**.

Data discussed in this paper are summarized in SI Tables S1–S8c and in the USGS data releases cited.[109]

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