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Exploratory Assessment of Risks from Drinking and Recreational Water Exposure to Children in the State of New Jersey

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Abstract: In this study, we conducted a worst-case risk assessment for children's health from ingestion exposure to water sources in two densely populated counties of the Piedmont province of New Jersey—Hunterdon and Mercer counties. Carcinogenic and non-carcinogenic health risk estimates for 19 contaminants, representing 3 different chemical classes—organic, inorganic and contaminants of emerging concern (CEC), for which environmental monitoring data are available—were generated. The three exposure scenarios examined were: (1) ingestion exposure to untreated groundwater from contaminated private wells; (2) recreational exposure through incidental ingestion of water from the Delaware River; and (3) ingestion exposure through fish consumption sourced from the Delaware River. The total health hazard posed by each contaminant across all the three exposure scenarios was compared to prioritize contaminants based on health risk potential. As a result of this analysis, arsenic and trichloroethylene in private well water were identified as key drivers of health risk and, hence, are proposed as the contaminants of primary concern for the target population. Significantly high total excess cancer risk of 2.13×10^{-3} from arsenic exposure was estimated, highlighting the need for testing and treating water sources as well as setting a framework for more detailed work in the future.

Keywords: risk assessment; water quality; human health; recreational exposure; cancer risk

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1. Introduction

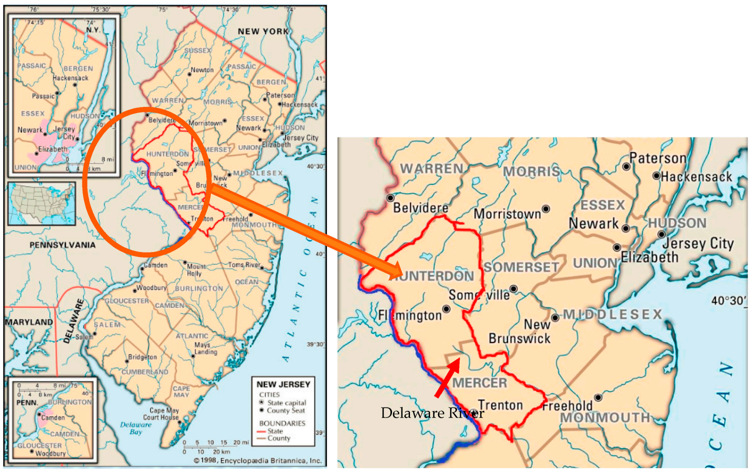
Water is an essential resource around the world, but providing clean, safe drinking water has always been a global challenge. In today's environment, with ever increasing human activities, meeting water quality challenges is becoming increasingly difficult. Residents living in the state of New Jersey face a number of environmental hazards that threaten water quality [1]. This includes exposure to many chemicals and compounds that are hazardous to human health. Sources of common contaminants range from natural leaching from bedrocks to discharge from chemical plants, factories, gas storage, landfills, and more [2]. In addition to the more well-known and examined contaminants, there are also many contaminants of emerging concern (CEC) that have been identified by the Delaware River Basin Commission (DRBC) that may also be an increasing threat to human health [3].

The federal government has established and placed limitations on the amount of contaminants that can be present in water sources. These limits, known as Maximum Contaminant Levels (MCLs), are established after extensive laboratory testing, observations, and analysis of both acute and chronic exposure dose-response. Individual states also have the power to impose stricter MCLs, which is the case with some compounds in New Jersey. In New Jersey, new MCLs were established with the passing of the New Jersey Safe Drinking Water Act in 2004. Any water source found to have concentrations of any contaminant in excess of the MCL is considered unsafe for human consumption and requires treatment before it can be used.

In addition to established MCL, other legislation can also play a significant role in protecting people from contaminant exposure. Private well use in New Jersey is common and widespread throughout the state. Over 400,000 privately owned wells provide drinking water to the citizens of New Jersey, and there are around 20,000 new private well permits provided each year [2]. In 2001, the New Jersey Private Well Testing Act (PWTA) was passed in response to a number of private well contamination issues reported throughout the state. The PWTA placed requirements for testing of groundwater by sellers of property with private wells and by landlords that provide private well water to their tenants. This is in addition to existing legislation that required testing of groundwater for newly constructed wells. Any well found to have an exceedance of contaminants is required to treat this water before consumption. Although legislation can have a very positive effect, it also has shortcomings that result in a large number of wells remaining untested. Additionally, the legislation only requires wells to be tested when the home is sold or well is built, or once every five years by landlords. Later, the responsibility is left to the homeowners or subject to individual county and municipality regulations. Water quality can change significantly in response to environmental influences, and not testing regularly can result in issues being missed and risks being imposed on humans.

It has been estimated that around 15% of the state's population obtains their drinking water from private wells, which have no federal regulations assuring water quality [4]. The New Jersey Department of Environmental Protection (NJ DEP) Division of Water Supply published the results of testing of private wells under the Private Well Testing Act over a period of five years, but noted that the majority of private wells (75–80%) remain untested [2]. Other research also highlighted the fact that serious challenges remain in reducing exposure, even in areas where testing has been conducted [5]. There is strong evidence in the literature regarding the presence of contaminants in well water [6–9], however, we found no study that quantified the associated cancer and non-cancer health risks to children, who represent a potentially sensitive subpopulation of the state. The association between gastrointestinal illnesses (GI)-related hospitalization in New Jersey (NJ) and heavy rainfall was tested to capture the effects of microbial contamination of drinking water supply in the state, which presented statistically strong evidence of increased threat to the communities served by surface water supply and private well water systems during wet weather periods [10]. This study also found that children under 5 years of age were at an increased relative risk of GI hospitalizations following heavy rainfall events than other age groups, emphasizing the need for a better understanding of potential health risks from containments and compounds present in the source water systems of the state. The major source of drinking water for the state is the Delaware River, which is also classified for other uses such as recreation, aquatic life maintenance, and fish consumption [11]. For a long period of time, the Delaware River has been known to have high levels of contaminants [3]. Over a period of decades, the Delaware River Basin Commission (DRBC) implemented programs to vastly improve water quality in the River. The DRBC continues to monitor and act on exceedances in river water, and has recently identified a set of contaminants of emerging concern (CEC). Although CEC concentrations are relatively low, they still have the potential to cause human health effects, and some have not yet been studied extensively enough. In addition to being present in water, the commission has also found measurable concentrations of CECs in fish tissues [3]. Hence, incidental ingestion of river water and recreational fishing can also be a potential exposure route to add to the burden of cancer and non-cancer risk for the children who are also exposed to high levels of contaminants via compromised private well water supply systems.

Human health risks vary greatly between contaminants and include several cancers, developmental effects, and immune system effects. The nature of some of the identified CECs also make them particularly harmful to children. The objective of this study was to assess the overall risk of both cancer and non-cancer effects on children due to oral exposure to a set of 19 contaminants outlined by the NJ DEP and the DRBC. A worst-case risk assessment for children's health in two densely populated counties of Piedmont province—Hunterdon and Mercer counties—was conducted to identify key drivers of risk for the target population. Both these counties are along the Delaware River, presenting direct opportunity for its residents for recreational water use (Figure 1). Hence, an exploratory risk assessment was conducted to estimate the potential for health risks to children from common recreational activities in the River. In order to capture the possible risk profiles across different exposure scenarios, three case studies were designed for analysis. These scenarios included: (1) ingestion exposure to untreated groundwater from contaminated private wells; (2) recreational exposure through incidental ingestion of contaminated water from the Delaware River during swimming, boating, and fishing activities; and (3) ingestion exposure through fish consumption sourced from the Delaware River. Default exposure factors and previously reported contaminant concentrations were used from published literature. Deterministic worst-case risk estimates were generated based on conservative assumptions to lay out a foundation for assessing children's health risk from water contaminants via multiple exposure scenarios. Limited by available data, calculations make use of either the upper bound of concentration ranges (Scenarios 1 and 3) or the average of a set of observations (Scenario 2) when determining risk.



(**a**) (**b**)

Figure 1. Site Map: (**a**) Full scale map of New Jersey (NJ) county boundaries with red highlighted study area; (**b**) Zoomed image with highlighted boundary for Hunterdon and Mercer counties and adjoining stretch of the Delaware River. Source: WordPress [12].

2. Methodology

2.1. Site Background

This study focused on the water ingestion risks for children from all sources in Hunterdon and Mercer Counties, located in the Piedmont Physiographic Province of NJ (area highlighted area in Figure 1). The water quality of private wells in this region has been of concern for the past few decades due to the underlying rock structure which contains elevated levels of inorganic contaminants, including arsenic. Contaminants from this geologic feature leach into the groundwater over time and in turn infiltrate the well water. Most of Hunterdon County and more than half of Mercer County, the area highlighted in red in Figure 1, are made up of Piedmont province rock beneath the surface. These two counties accounted for the majority of the state's test failures due to the exceedance of arsenic during the reporting period and beyond [2,13]. As a result, residents in this particular area are at greater risk of exposure to arsenic, which is a carcinogen that can also cause significant developmental harm to children.

In addition to well water exposure, people residing in these two counties, and this area in particular, have increased potential for recreational exposure to the Delaware River. Both counties share their western border with the Delaware River (Figure 1). There are also many parks and recreational areas established along the river in these counties. Because of the counties close proximity to the river, it would not be difficult for residents to travel to other recreational areas outside of the counties as well. Recreational activities can be wide ranging and include fishing, swimming, boating, and playing in small beach areas. As noted, the DBRC has identified and tested for many compounds, including a number of CECs, in the river for years. The study area is upstream from one of the U.S. Geological Survey (USGS) river stations (USGS 01463500) that collects water samples, and the assumption is made that the same concentrations will likely be found in the study area. The DBRC also provides data on contaminants found in fish tissue, which can be used to further assess risk from this additional route of exposure.

Lastly, these two countries are among the most densely populated in the state, with a combined estimated population of just under half a million people in 2016 [14,15]. Accounting for the area that is part of the Piedmont province, we estimated that around three hundred thousand people live in the risk area. The U.S Census Bureau also provides estimates of the percent of the population that is under the age of 5 years old; at its highest in the area, it is estimated at 5.9% [14,15]. This leaves a target population of around 17,000 children living in the area that may be exposed to elevated levels of contaminants.

2.2. Hazard Characterization

This study focused on nineteen main contaminants selected based on the potential severity of health effects. The contaminants span several categories of physical and chemical characteristics, including one inorganic (arsenic), one CEC—2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether (BDE-209) and seventeen Volatile Organic Compounds (VOCs). In Table 1, potential health hazards, oral slope factor, and reference doses proposed for these key contaminants are summarized. Oral slope factor values are defined as being an estimate of increased cancer risk due to chronic exposure to a compound over a lifetime and were used in this study for calculating final excess cancer risks associated with the target contaminants. Reference doses are estimates of daily oral exposure that are likely to be without significant health effects and were used in the calculations of non-cancer health effects. Also referenced are the no-observed-adverse-effect-level (NOAEL) and lowest-observed-adverse-effect level (LOAEL) values, when available. All the threshold benchmark values for hazard characterization of target compounds were obtained from the US EPA's Integrated Risk Information System (IRIS), which maintains a database of a large number of compounds and is reviewed regularly.

Table 1. Contaminant threshold values and health impacts [1].

Contaminants	NOAEL (mg/kg-Day)	LOAEL (mg/kg-Day)	Slope Factor $(mg/kg\text{-}Day)^{-1}$	Reference Dose (mg/kg-Day)	Major Health Effects	Reference
Arsenic	8×10^{-4}		1.5	3×10^{-4}	Cardiovascular, dermal and dermal cancers	[16–18]
Benzene		18	1.5×10^{-2}	4.0×10^{-3}	Immune, hematologic cancers	[19]
Trichloroethylene		0.048–0.37	4.6×10^{-2}	5×10^{-4}	Cardiovascular, developmental, immune, hematologic/hepatic/urinary cancers	[20–22]
Tetrachloroethylene		2.6–9.7	2.1×10^{-3}	6×10^{-3}	Neurological, ocular, hepatic cancers	[23]
Chlorobenzene	19	54.5	-	2×10^{-2}	Hepatic	[24]
1,2-Dichlorobenzene	85.7		-	9×10^{-2}	Cellular necrosis	[25]
1,2-Dichloroethane			9.1×10^{-2}	-	Hematologic cancers	[26]
Ethylbenzene	97.1		-	0.1	Hepatic, urinary	[27]
Naphthalene	71	142	-	2×10^{-2}	Cellular necrosis	[28]
Styrene	200	400	-	2×10^{-1}	Hepatic and hematologic	[29]
1,1,2,2-Tetrachloroethane		15	2×10^{-1}	2×10^{-2}	Hepatic and hepatic cancers	[30]
Toluene	223	446	-	8×10^{-2}	Urinary	[31]
1,2,4-Trichlorobenzene	14.8	53.6	-	1×10^{-2}	Endocrine	[32]
1,1,1-Trichloroethane		2155	-	2	Decreased body weight	[33]
1,1,2-Trichloroethane	3.9	44	5.7×10^{-2}	4×10^{-3}	Hematologic, immune, hepatic cancers	[34]
Vinyl Chloride	0.09	0.9	1.4	3×10^{-3}	Hepatic and hepatic cancers	[35]
Xylenes, Total	179	500	-	2×10^{-1}	Decreased body weight	[36]
Nitrates	1.6	1.8–3.2	-	1.6	Hematologic	[37]
BDE-209 [2]	2.22	20.1	7×10^{-4}	7×10^{-3}	Neurobehavioral, hepatic cancer	[38]

[1] NOAEL stands for No Observed Adverse Effect Level; LOAEL stands for Low Observed Adverse Effect Level.
[2] BDE-209 stands for 2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether.

2.3. Exposure Assessment

As mentioned, many contaminant sources were identified by the NJ DEP and the DRBC, ranging from leaching of natural contaminant from rock, to factory discharge and storage and landfill leaching. This study focused on analysis of three exposure scenarios to establish risk in the target area based on the environmental media that uptake contaminants from these sources. Groundwater, surface water in the Delaware River, and Delaware River Fish were identified as potentially contaminated media for these scenarios. Scenario 1 looked at the ingestion of untreated groundwater from contaminated private wells. Scenario 2 looked into recreational exposure through incidental ingestion of contaminated water from the Delaware River during swimming, boating, and fishing activities. Lastly, exposure through ingestion of contaminated fish sourced from the Delaware River was examined as Scenario 3. All exposure scenarios had assumptions to create worst-case conditions and were analyzed for risk from oral exposure pathways only.

2.4. Data Sources

For the well water exposure assessment, the concentrations of the contaminants were obtained from the published results of the Private Well Testing activity conducted by the NJ DEP. Results of PWTA testing varied greatly, often ranging from not detected (ND) or zero values all the way to concentrations that were multiple times greater than established MCLs. An average contaminant value was not able to be obtained from this report, as only ranges were provided. Hence, maximum reported concentration values were used in risk calculation, representing a worst-case scenario assessment. The state of New Jersey's Safe Drinking Water Act has established MCLs for many of the discussed compounds at values lower than federal levels. This may account for some of the many failures in well testing. This is important to note, but even though well test failures may be more inflated than they would be at the federal level, MCL is not used in our risk calculations. Therefore, the risk values calculated are valid even if MCLs are not exceeded in all cases. It is also important to note that decreases in concentrations within the body due to toxicokinetic processes are not accounted for in calculations. This was intentionally excluded to perform a worst-case scenario analysis. The ranges and values used for this study are shown in Table 2. For worst-case analysis and in the absence of average values, the upper bound concentration from these ranges were used in risk calculations (Scenario 1-Well water Exposure). It was further assumed that the private well water was the only source of drinking water for the children exposed under this scenario. Data for this scenario comes from a 2008 report, now about 10 years in the past, however, the Environmental Systems Research Institute (ESRI) testing results map published by the New Jersey DEP contains pass-fail results through 2014 that continue to show failures for arsenic and VOCs in the target area [13].

Delaware River surface water quality observations are taken periodically at a U.S. Geological Survey (USGS) site located slightly downstream from the target area in Trenton, NJ [25]. For the recreational exposure scenario (Scenario 2), the assumption was made that concentrations measured at this downstream site were the same as what would be found upstream at recreational areas. For this scenario, test results were published individually, and the average of concentrations obtained from these tests were used in calculations. Efforts made by the DRBC and in recent years to improve Delaware River water quality have been effective in reducing concentrations of contaminants to levels below federal MCLs. However, concentrations of arsenic still exceeded the state of New Jersey's reduced MCL recommendation. The concentrations of VOCs were below MCLs in this case, but still may have a significant cumulative effect in risk calculations.

In addition to the USGS, additional water quality monitoring is conducted by the Delaware River Basin Commission, particularly in the testing of contaminant levels in fish tissues. The DRBC has measured contaminant levels in catfish, perch, and smallmouth bass from the river. One of the fish testing sites used by the DRBC is located within the target area of this study in Hunterdon County [3]. USGS monitoring at Trenton, NJ also reports contaminant concentrations in fish tissue [39]. The arsenic data came from the Trenton USGS data (Inorganics ... Arsenic, biota, tissue, recoverable, dry weight, milligrams per kilogram) [39]. Many USGS entries did not distinguish between no data and zero or not detected values, so these points were omitted from our data range. Data from both the USGS and DRBC were used to calculate risk of exposure to (inorganic) arsenic and BDE-209 from fish ingestion. For this exposure (scenario 3), VOCs were not tested for and, therefore, are not reported in the table (Table 2).

Table 2. Contaminant concentrations across all three scenarios [a].

Contaminant of Concern	MCL (µg/L)	Scenario 1: Well Water Exposure [b]		Scenario 2: Recreational Exposure [c]		Scenario 3: Fish Consumption Exposure [d]	
		[C] Range (µg/L)	[C] Calculation (µg/L)	[C] Range (µg/L)	[C] Calculation (avg.) (µg/L)	[C] Range (mg/kg)	[C] Calculation (mg/kg)
Arsenic	5	0–254	254	0–6.4	1.199	0.3–1 [c]	1
Benzene	1	0–101	101	0.004–0.2	0.068	-	-
Trichloroethylene	1	0–550	550	0.009–0.2	0.066	-	-
Tetrachloroethylene	1	0–540	540	0.005–0.2	0.075	-	-
Chlorobenzene	50	0–15.8	15.8	0.016–0.2	0.067	-	-
1,2-Dichlorobenzene	600	0–5	5	0.02–0.2	0.073	-	-
1,2-Dichloroethane	2	0–31.3	31.3	0.06–0.2	0.136	-	-
Ethylbenzene	700	0–39.7	39.7	0.005–0.2	0.072	-	-
Naphthalene	300	0–22.9	22.9	0.18–0.4	0.222	-	-
Styrene	100	0–149.4	149.4	0.03–0.2	0.077	-	-
1,1,2,2-Tetrachloroethane	1	0–25.1	25.1	0.09–0.14	0.120	-	-
Toluene	1000	0–464	464	0.01–0.2	0.076	-	-
1,2,4-Trichlorobenzene	9	0–1.5	1.5	0.04–0.19	0.120	-	-
1,1,1-Trichloroethane	30	0–50.5	50.5	0.005–0.2	0.069	-	-
1,1,2-Trichloroethane	3	0–12.2	12.2	0.028–0.064	0.052	-	-
Vinyl Chloride	2	0–5.1	5.1	0.06–0.2	0.126	-	-
Xylenes, Total	1000	0–122.8	122.8	0–0.2	0.200	-	-
Nitrates	10,000	0–153k	153,000	23,000–37,000	30,000	-	-
BDE-209	ND	ND	-	ND	-	0.005–0.021 [d]	0.021

[a] [C] stands for concentration; MCL stands for maximum contaminant levels; ND stands for No Data. [b] Source of concentration data information: New Jersey DEP, 2008 [2]; [c] Source of concentration data information: U.S. Geological Survey, Delaware River at Trenton NJ [39]; [d] Source of concentration data information: Delaware River Basin Commission, 2009–2016 [3].

For scenario 2, recreational activities included boating, fishing, and swimming (Table 3). These were selected based on reported frequent water exposure activities as well as suggested designated water uses on the Delaware River [2,40]. The scenario assumed a full day of recreation that included all three activities. For a worst-case scenario, it was assumed that a full day of recreation occurred once every week for the full recreational season of the year (May–September, 5 months). Exposure duration statistics for fishing and boating were obtained from the study conducted by Sunger and co-authors that specifically observed recreational activities on the Delaware River [40]. However, for swimming, the United States Environmental Protection Agency (EPA) default exposure duration for children less than 6 years of age was considered [41]. Water ingestion rates accounted for fixed and incidental ingestion of water, where fixed intake refers to inhalation of mist and droplets via mouth and nose [42]. Using default ingestion rates and summing the results from each activity, as outlined in Table 3, it was found that children may incidentally ingest 0.078 liters of river water per day during a full day of recreation.

Table 3. Scenario 2—Recreational activity exposure factors.

Activity	Ingestion Rate	Exposure Duration	Conversion	Ingestion per Day
Boating	2 mL/h	2 h/day	1 L/1000 mL	0.004 L/day
Fishing	4 mL/h	2.11 h/day	1 L/1000 mL	0.0084 L/day
Swimming	50 mL/h	79 min/day	1 L/1000 mL	0.066 L/day
Sum				0.078 L/day

2.5. Risk Assessment

Calculations for Excess Cancer Risk (ECR) and Hazard Quotient (HQ) for non-cancer health effects were conducted for each assessed contaminant in all three scenarios. General formats for ECR and HQ were used, substituting appropriate ingestion rates for each scenario. ECR is defined as the lifetime average daily dose (LADD) multiplied by the oral slope factor value for the contaminant. Values of HQ was calculated by dividing the average daily dose value by the contaminant's reference dose value. The equations used for determining the health risk potential for each scenario are described below:

$$\text{ECR} = \frac{\text{Concentration} \times \text{IR} \times \text{EF} \times \text{ED}_c}{\text{BW}_c \times \text{LT}} \times \text{Oral Slope Factor}, \quad (1)$$

$$\text{HQ} = \frac{\text{Concentration} \times \text{IR}}{\text{BW}_c} \div \text{Reference Dose}, \quad (2)$$

where, IR = Ingestion Rate appropriate for each scenario from the EPA exposure factor handbook (child IR = 0.78 L/day of drinking water, Child fish intake rate IR = 4.08 g/kg-day), EF = exposure frequency appropriate for each scenario (350 days/year for case 1 and 3, 20 days/year for case 2), EDc = Child exposure duration of 6 years [41], BWc = child body weight of 15 kg [41], and LT = Lifetime (70-year period).

3. Results

Using appropriate default values for exposure variables under each scenario, risk, and hazard estimates were obtained for children under 6 years of age (Table 4). Results of the first scenario most strongly influenced total risk values due to high concentrations of contaminants observed in well water. Risks of exposure to eight contaminants were found to be higher than the acceptable limit in this study. Of these, arsenic and trichloroethylene were of highest concern for both cancer and non-cancer health effects. In addition to high concentration, high oral slope factor values and low reference doses contribute to higher risks. Other contaminants that could be prioritized for health-based screening, in the order of total cancer risk potential were Vinyl Chloride > Benzene > 1,1,2,2-Tetrachloroethane > 1,2-Dichloroethane > Tetrachloroethylene > 1,1,2-Trichloroethane.

Incidental recreational ingestion of Delaware River water was found to pose the least risk to children in the examined scenarios. Comparatively, contaminants were present at lower concentrations in river samples than other targeted media (well water, fish tissues) resulting in lower calculated risks. However, arsenic concentrations were still observed in amounts higher than the state's MCL. Due to this, arsenic was again the largest driver of risk in this scenario.

The ingestion of fish in scenario 3 also resulted in more than acceptable risk for exposure to arsenic. Results show that in the absence of VOC concentrations, arsenic was the only significant factor in fish ingestion risks. Present in only small concentrations, BDE-209 did not introduce significant health risks in this case. The total cancer risk posed to a receptor via an ingestion pathway is represented as the sum of risk from each individual exposure scenario. Similarly, the noncarcinogenic hazard estimates from the three exposure scenarios were summed up for each contaminant and the final estimates are presented in Table 4. Largely due to well water exposure, arsenic and trichloroethylene were the main drivers of overall risk.

Overall, we found that significant risks are present for both cancer and non-cancer effects. Risk ratio for cancer is defined as excess cancer risk divided by acceptable risk. In the United States, the EPA defines acceptable risk as 1 in one million (1.0×10^{-6}). This leaves us with a risk ratio of 2130 for arsenic and 108 for trichloroethylene, highlighting the fact that risks are much higher than what should be considered acceptable.

Table 4. Data summary table: results by scenario [a].

Contaminant of Concern [b]	Scenario 1: Well Water Exposure		Scenario 2: Recreational Exposure		Scenario 3: Fish Consumption Exposure		Cumulative Risk	
	ECR	HQ	ECR	HQ	ECR	HQ	ECR	HQ
Arsenic	1.63×10^{-3}	44.03	4.39×10^{-8}	0.02	5.01×10^{-4}	13.53	2.13×10^{-3}	57.67
Benzene	2.37×10^{-5}	1.31	9.12×10^{-11}	8.82×10^{-5}	-	-	2.37×10^{-5}	1.31
Trichloroethylene	1.08×10^{-4}	57.20	7.43×10^{-11}	6.88×10^{-4}	-	-	1.08×10^{-4}	57.20
Tetrachloroethylene	4.85×10^{-6}	4.68	3.82×10^{-12}	6.46×10^{-5}	-	-	4.85×10^{-6}	4.68
Chlorobenzene	-	0.04	-	1.75×10^{-5}	-	-	-	0.04
1,2-Dichlorobenzene	-	2.9×10^{-3}	-	4.23×10^{-6}	-	-	-	2.9×10^{-3}
1,2-Dichloroethane	1.22×10^{-5}	-	3.01×10^{-10}	-	-	-	1.22×10^{-5}	-
Ethylbenzene	-	0.02	-	3.73×10^{-6}	-	-	-	0.02
Naphthalene	-	0.06	-	5.77×10^{-5}	-	-	-	0.06
Styrene	-	0.04	-	2.00×10^{-6}	-	-	-	0.04
1,1,2,2-Tetrachloroethane	2.15×10^{-5}	0.07	5.84×10^{-10}	3.11×10^{-5}	-	-	2.15×10^{-5}	0.07
Toluene	-	0.30	-	4.96×10^{-6}	-	-	-	0.30
1,2,4-Trichlorobenzene	-	7.8×10^{-3}	-	6.26×10^{-5}	-	-	-	7.9×10^{-3}
1,1,1-Trichloroethane	-	1.3×10^{-3}	-	1.80×10^{-7}	-	-	-	1.3×10^{-3}
1,1,2-Trichloroethane	2.97×10^{-6}	0.16	7.24×10^{-11}	6.76×10^{-5}	-	-	2.97×10^{-6}	0.16
Vinyl Chloride	3.05×10^{-5}	0.09	4.31×10^{-9}	2.19×10^{-4}	-	-	3.05×10^{-5}	0.09
Xylenes, total	-	0.32	-	5.20×10^{-5}	-	-	-	0.32
Nitrates	-	4.97	-	9.75×10^{-6}	-	-	-	4.98
BDE-209	-	-	-	-	4.91×10^{-9}	1.22×10^{-2}	4.91×10^{-9}	1.22×10^{-2}

[a] ECR stands for Excess Cancer Risk; HQ stands for Hazard Quotient. [b] Bold highlighted contaminants presented total cancer risk higher than the acceptable risk value of 10^{-6}.

4. Discussion

This study assessed possible health risks to children in the target area of New Jersey from ingesting contaminated water from multiple sources. Results show that the highest risk of detrimental health effects on children came from the ingestion of untreated drinking water from private wells. However, higher than acceptable ECR and HQ values were found in two of the examined scenarios. A more in-depth review of these scenarios and others will be necessary to determine what actions, if any, will need to be taken to mitigate risks. It was found that arsenic is the highest risk contaminant in our scenarios, while the contaminant of emerging concern, BDE-209, showed the least risk.

The results of this study were limited by available data, assumptions, and scope of the project. Assumptions were made in the creation of exposure scenarios as well as in a select number of calculations. Future work should focus on narrowing exposure scenarios to make use of more realistic values during calculations. Follow-up studies should also work to include additional contaminants and routes of exposure. There was a total of 54 contaminants, including CECs, identified and measured by the NJ DEP and DRBC, while this study only focused on a subset of them. An analysis of inhalation and dermal exposure may also be necessary to expand on total risk calculations. For example, dermal exposure will occur during bathing, swimming, play in sand, as well as in other situations. Because of the number of VOCs present in the environment, it is also very likely that some risk will be introduced through the inhalation route. Lee and Park performed a similar risk assessment using additional exposure pathways and defined the most-likely exposure values in their analysis [43]. This study can further be used as a model for future work. It would also be important to consider toxicokinetic processes in the body for a more accurate estimate of health effects.

Additional future work may involve determining the correlation between well depth and the concentrations of arsenic observed in well water. As the main driver of risk in our scenarios, it would be helpful to discover the sources of the contaminant. As mentioned previously, the underlying geology through the target area, Piedmont Provence rock, is known to contain elevated amounts of natural arsenic. However, due to the lack of well depth information from the publicly available PWTA data, it is difficult to draw the conclusion that this rock is the source of the contaminant. Well depth data would help to identify possible sources of arsenic, and this information can then be used in future mitigation discussions. In a recent article, Jeen examines one of many treatment options for reducing arsenic in contaminated groundwater [44]. Based on future findings, many treatment options can be explored if needed. This data can also be used to attempt to identify sources of the other contaminants found in the groundwater as well.

Due to the age of the published well data, another future focus can be on performing testing and analysis on site and comparing the results to the PWTA report. This will provide the opportunity to see how water quality in the wells have evolved over time. Doing so will also provide researchers with a more manageable dataset and give them the opportunity to determine most-likely exposure values for the target area.

In the absence of a further focused analysis, this study does highlight the priority contaminants and underline the importance of regular testing and treatment of well water. The Private Well Testing Act in New Jersey, as well as the actions of the Delaware River Basin Commission, and many others have all made major contributions to water quality and awareness in this region. However, government protections and regulations should not always be treated as a failsafe against all risks. We have seen examples of how the State of New Jersey took steps to reduce risks through testing regulations, but we also know that well testing is not required under this act in most scenarios. There is still room for improvement to ensure all residents remain aware of these sorts of risk and take the initiative to test and treat when appropriate.

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