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Camp Lejeune Marine Cancer Risk Assessment for Exposure to Contaminated Drinking Water From 1955 to 1987

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Abstract This study utilizes guidance from the United States Environmental Protection Agency (USEPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) to calculate the cancer risk to United States Marines who were exposed to carcinogens in drinking water at Marine Corps Base Camp Lejeune. Camp Lejeune is a 233-square-mile Marine Corps training facility in North Carolina. From 1953 to 1987, nearby dry cleaners, landfills, and underground storage tanks contaminated drinking water systems that served Camp Lejeune (ATSDR, 2017). Some of the most toxic contaminants found in the drinking water modeled by ATSDR include benzene, tetrachloroethylene (PCE), trichloroethylene (TCE), trans-1,2-dichloroethylene (DCE), and vinyl chloride (VC). ATSDR utilized MODFLOW and EPANET modeling software to determine the level of contamination in the three main drinking water systems at Camp Lejeune: Tarawa Terrace, Holcomb Boulevard, and Hadnot Point. This paper presents an application of methodology to quantify cancer risk for the Marines who lived and served at Camp Lejeune from 1953 to 1987 using ATSDR's health assessment, chemical contaminant modeling, and USEPA methodology. While VC and TCE were found to be the main risk drivers, benzene and PCE also contributed to the cumulative cancer risk. This analysis shows (1) That the cancer risk was greatest during the 1970s and 1980s and (2) that the inhalation exposure pathway had the greatest contribution to overall cancer risk followed by ingestion, with the smallest contribution from dermal absorption.

Keywords Camp Lejeune · Contaminated water · Risk assessment · Cancer risk · Camp Lejeune Justice Act · Marines

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Abbreviations

AT	Averaging time (LT (78 years) × 365 days)
ATSDR	Agency for Toxic Substances and Disease Registry
B	Ratio of the permeability coefficient of a chemical through the stratum corneum relative to its permeability coefficient across the viable epidermis (unitless)
BT	Total bathroom time (min/day)
BW	Body weight
CDC	Centers for Disease Control and Prevention
CF	Conversion factor
CSF_{ABS}	Absorption cancer slope factor
CSF_{oral}	Oral slope factor
Cw	Chemical concentration in water (µg/ L)
DAD	Dermally absorbed dose (mg/kg/day)
DCE	Trans-1,2-dichloroethylene
ED	Exposure duration (years)
EF	Exposure frequency (days/year)
EV	Event frequency (events/day)
FA	Fraction absorbed water (chemical specific)
Fw	Flow rate water (L/min)
HBWTP	Holcomb Boulevard water treatment plant
HPWTP	Hadnot Point water treatment plant
IARC	International Agency for Research on Cancer
IR	Water ingestion rate (L/day)
IUR	Inhalation unit risk
K	Constant for chemical volatilization
Kp	Chemical-specific permeability factor
ln Rmin	Inhalation rate (L/min)
lnRday	Inhalation rate (L/day)
LT	Lifetime (78 years)
NTP	National Toxicology Program
OEHHA	California Office of Environmental Health Hazard Assessment
OSF	Oral slope factor
PCE	Tetrachloroethylene
PHA	Public health assessment
RAGs	Risk assessment guidance
RCC	Renal cell carcinoma
RME	Reasonable maximum exposure
SA	Surface area (cm^3)
*t**	Time for chemical to reach steady-state
t event	Event time (h/event)
TCE	Trichloroethylene
Ts	Showering time (min)
TTWTP	Tarawa Terrace water treatment plant
USEPA	United States Environmental Protection Agency
Va	Volume of air in bathroom (L)
VOC	Volatile organic compounds
WHO	World Health Organization
WTP	Water treatment plant
τ	Lag time
τ event	Lag time per event (chemical specific)

1 Introduction

The US Marine Corps Base Camp Lejeune is located in North Carolina and was established in 1942 (ATSDR, 2014a). In 1982, the Marine Corps discovered that several drinking water distribution systems on the base were contaminated with volatile organic compounds (VOCs) from 1953 to 1987 that are hazardous to human health (ATSDR, 2014a). Since the late 1980s, the ATSDR has been modeling the pollution of Camp Lejeune's water systems to assess the health risks posed to over one million Marines and civilian residents who once lived or worked on the base (ATSDR, 2019b). The ATSDR has identified four specific VOCs present in the impacted zones of the water distribution systems and their website states:

> "It is ATSDR's position that past exposures from the 1950s through February 1985 to trichloroethylene (TCE), tetrachloroethylene (PCE), vinyl chloride, and other contaminants in the drinking water at the Camp Lejeune likely increased the risk of cancers (kidney, multiple myeloma, leukemias, and others), adverse birth outcomes, and other adverse health effects of residents (including infants and children), civilian workers, Marines and Naval personnel at Camp Lejeune." (ATSDR, 2014a)

While it is known that exposure to the VOCs present in drinking water at Camp Lejeune may cause cancers, birth defects, and other adverse health effects, risk has not yet been quantified for any individual who may have been affected by the Camp Lejeune contamination. This paper outlines a novel methodology, using risk assessment guidance published by the USEPA, to quantify cancer risk for

Marines who lived and worked on the base in the years defined by the Camp Lejeune Justice Act. The Camp Lejeune Justice Act "allows certain individuals to sue and recover damages for harm from exposure to contaminated water at Camp Lejeune in North Carolina between August 1, 1953, and December 31, 1987. This action is available only to individuals who were exposed to contaminated water for at least 30 days. The bill prohibits the US government from asserting specific immunity from litigation in response to such a lawsuit" (Rep. Cartwright, Matt, 2022).

While the ATSDR did publish a Public Health Assessment (PHA) in 2017 its final conclusions were limited spatially to which water treatment facility Marines received water from, averaged estimated concentrations by month and year for a 3-year period, and only considered a fixed 3-year residency period (ATSDR, 2017). Though the PHA references health effects of concern, it lacks cumulative cancer risk due to multi-contaminant exposure, temporally variable risk factors for differing residence periods, and variability in exposure pathways that this study hopes to address.

2 Background

2.1 Analysis of Drinking Water at Camp Lejeune

The three largest drinking water systems that served the Camp Lejeune base are the Hadnot Point Water Treatment Plant (HPWTP), the Holcomb Boulevard Water Treatment Plant (HBWTP), and Tarawa Terrace Water Treatment Plant (TTWTP) (see Fig. 1). The HPWTP began distributing finished water to Camp Lejeune residents in the early 1940s (Maslia et al., 2013). The HBWTP began servicing Berkeley Manor, Paradise Point, Watkins Village, and Midway Park in the summer of 1972. From June 1972 to December 1985, the HPWTP and HBWTP were occasionally interconnected during dry spring and summer months (Maslia et al., 2013). The TTWTP began treating and distributing water to the base between 1952 and 1953. These three contaminated water systems supplied approximately 75% of the base's water from 1942-2008 (Maslia et al., 2013).

The ATSDR completed its first public health assessment (PHA) in 1997 which enumerated several of the contaminants of concern at Camp Lejeune. In 2007, the ATSDR published results for the historical reconstruction of groundwater flow, contaminant fate and transport, and the distribution of drinking water from TTWTP. Drinking water distribution was not modeled at HBTWP and HPTWP because it was determined that TTWTP operated independently of the other plants, and modeling contamination for an individual plant was simpler because uniform mixing of water could be assumed for the plant prior to its delivery of water to residents in the service area. In 2013, the ATSDR published the *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas at Hadnot Point, Holcomb Blvd., and Vicinities, US Marine Corps Base Camp Lejeune, North Carolina* which included a similar analysis to the 2007 TTWTP report for the other two water treatment plants.

2.2 Health Effects from Toxic Chemicals at Camp Lejeune

Multiple public health agencies have provided evidence that links exposure to the chemicals found in Camp Lejeune drinking water to cancer (ATSDR, 2014b). In the past 15 years, the USEPA, the National Toxicity Program (NTP), and the International Agency for Research on Cancer (IARC) have all concluded that TCE is a human carcinogen (USEPA, 2011a; NTP, 2015; IARC, 2014). There is ample evidence that demonstrates TCE exposure can cause cancer, specifically renal cell carcinoma (RCC) (Raaschou-Nielsen et al., 2003; Radican et al., 2008; Scott et al., 2011 Karami et al., 2012). It has also been demonstrated that TCE increases the risk of non-Hodgkin's lymphoma (NHL) and its subtypes (Radican et al., 2008; Cocco 2013). Though the connection is recognized by the USEPA, NTP, and IARC, it should be noted that the evidentiary link between TCE and NHL is not as strong as the correlation between TCE exposure and RCC (USEPA, 2011a; NTP, 2015; IARC, 2014). Similarly, exposure to TCE has been shown to increase the risk of hepatobiliary cancer (Ritz et al., 1999; Raaschou-Nielsen et al., 2003), but public health entities view the evidence as less robust than the evidence linking TCE

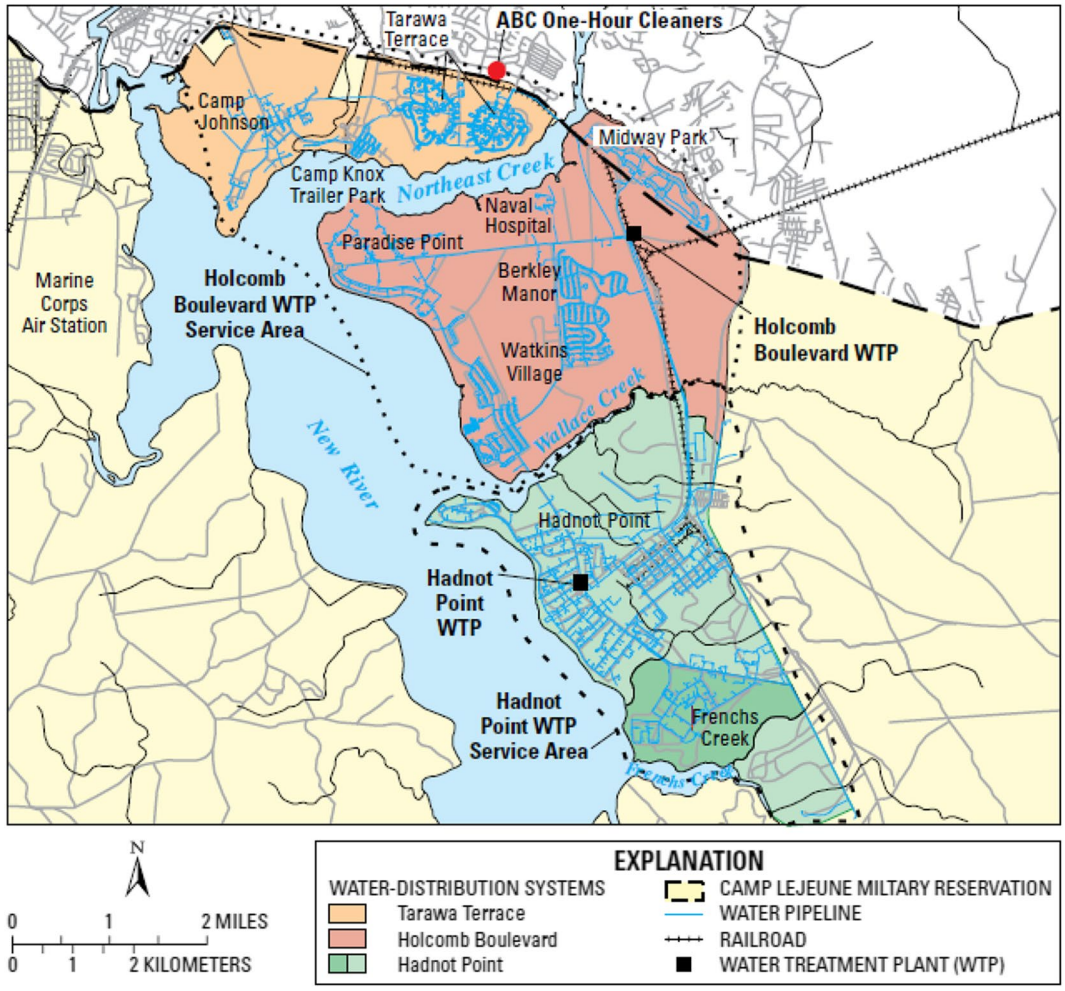

Fig. 1 2004 Camp Lejeune water distribution system diagram (Maslia, 2005)

exposure to kidney cancer (USEPA, 2011a; NTP, 2015; IARC, 2014). In recent years, epidemiological evidence has linked TCE to an increased risk of another hematopoietic cancer, multiple myeloma (Antilla et al., 1995; Blair et al., 1998; Wartenberg, 2000; Gold et al., 2011). The World Health Organization (WHO) currently classifies multiple myeloma as a "mature B-cell neoplasm" along with a variety of NHL subtypes (Swerdlow, 2016). In their evaluation of risk posed by exposures to TCE at Camp Lejeune, the ATSDR stated that epidemiological evidence was "equipoise and above" for the risk of multiple myeloma (ATSDR, 2017b).

Exposure to benzene has also been demonstrated to increase the risk of multiple cancers. Benzene exposure has long been recognized as leukemogenic in exposed human populations (Schnatter et al., 1993; Linet et al., 2015; Rhomberg et al., 2016). Studies have also linked benzene exposure to an increased risk of NHL (Steinmaus et al., 2008; Bassig et al., 2015; Rana et al., 2021; Liu et al., 2022). There is further evidence linking benzene to the development of multiple myeloma in humans (Infante, 2006; Georgakopoulou et al., 2021). In their evaluation of the risk posed by exposures at Camp Lejeune, the ATSDR stated that epidemiological evidence linking benzene to multiple myeloma was also considered "equipoise and above" (ATSDR, 2017b).

PCE exposure has been demonstrated to result in an increased risk of bladder cancer. Most evidence

predominantly stems from studies of occupational exposures to dry cleaning chemicals in which PCE is the primary contaminant (Pesch et al., 2000; Guyton et al., 2014; Vlaanderen et al., 2014). The IARC and USEPA have both determined that there is sufficient evidence from human and animal studies to determine a causal relationship between PCE exposure and bladder cancer (USEPA 2012; IARC 2014).

Vinyl chloride has been demonstrated to cause hepatobiliary cancers. Robust epidemiological evidence has shown that exposure to VC increases the risk of angiosarcoma of the liver as well as rates of hepatocellular carcinoma (CDC, 1997; Boffetta et al., 2003; Infante et al., 2009; IARC, 2012a).

Exposures to benzene, TCE, PCE, and VC at Camp Lejeune occurred simultaneously. The consequences of exposure to concurrent carcinogens are poorly studied despite countless scenarios where such exposure plays out. According to standard risk assessment methodologies, cancer risk from exposure to multiple carcinogens can be treated as additive (USEPA, 2000, 2005, 2009; NRC, 2009). Scientific literature suggests that the cumulative effect of independent exposures to carcinogens may be synergistic. The risk of lung cancer may become multiplicative when taking into account various independent exposures (Markowitz et al., 2013; Klebe et al., 2019). While this study will follow standard methodology and conservatively treat cancer risk from the four chemicals at Camp Lejeune as additive, an interaction greater than additive must be considered plausible.

2.3 Previous Health Studies Completed for Camp Lejeune

Several epidemiological studies have been conducted to understand the health impacts on children, Marines, and civilians working on base due to exposure to the contaminated drinking water.

In 2013, a case-control study was published by Ruckart, et al., that aimed to determine whether or not children born during 1968-1985 to mothers with residential exposure to the contaminated drinking water at Camp Lejeune contributed to higher incidences of childhood hematopoietic cancers, neural tube defects (NTDs), or oral clefts. The ATSDR collected residential information and utilized their monthly average estimates of modeled contaminant concentrations to estimate the quantity of contaminants in the drinking water serving the resident's location at the time of pregnancy (Ruckart et al., 2013). Magnitude of odds ratios (ORs) suggested there was an association between NTDs and drinking water contaminants (Ruckart et al., 2013). ORs suggested weaker association between drinking water contamination and childhood hematopoietic cancers (Ruckart et al., 2013).

In 2014, a cross-sectional study was conducted, "...to determine if maternal exposures to contaminants in drinking water at Camp Lejeune were associated with preterm birth and fetal growth retardation as measured by reduced mean birth weight (MBW), term low birth weight (TLBW), and SGA" (Ruckart et al., 2014). The study utilized water modeling, birth certificate, and housing data of residents living on the base for births between 1968 and 1985 to evaluate associations between exposure and health effects. Findings suggested associations between in utero exposures to TCE and adverse outcomes (SGA, TLBW, reduced MBW), in utero benzene exposure and TLBW, and in utero PCE exposure and preterm birth (Ruckart et al., 2014).

A 2014 retrospective cohort study evaluated the mortality of Marines and navy personnel at Camp Lejeune in comparison to a Camp Pendleton cohort (Bove et al., 2014). The study found slightly elevated standardized mortality ratios (SMR) of certain diseases associated with contaminated drinking water, such as kidney cancer, multiple myeloma, and cervical cancer (Bove et al., 2014). The same study found hazard ratios (HR) of certain cancers to be greater at Camp Lejeune than Camp Pendleton. For example, kidney cancer had an HR of 1.35 (95% CI: 0.84, 2.16), and liver cancer had an HR of 1.42 (95% CI: 0.92, 2.20) (Bove et al., 2014). In 2015 the ATSDR published a report on Camp Lejeune which found possible associations between development of breast cancer for men who worked at Camp Lejeune during the period of contaminated drinking water caused by exposure to PCE, DCE, and vinyl chloride (Ruckart et al., 2015). This study also found that an increased exposure to PCE contributed to higher cancer risk values.

The ATSDR published a PHA for Camp Lejeune in 2017 utilizing their modeled reconstructed drinking water contamination concentrations published in 2007 and 2013. The routes of exposure identified were ingestion, inhalation, and dermal absorption.

The PHA identified the highest contamination periods and drew several water treatment plant specific conclusions that provided helpful guidance for this study. The PHA utilized a "3-year running average of the concentrations provided by the historical reconstruction" for their exposure dose calculations and reasoned that "85% of the active-duty personnel had a tour of duty at MCB Camp Lejeune of fewer than 3 years" (ATSDR, 2017). The ATSDR considered marines with >3-year exposure to fall under the on base worker exposure scenario of 15 years (ATSDR, 2017). The PHA also supports that Marines who lived at Tarawa Terrace experienced the greatest excess cancer risk due to Vinyl Chloride exposure, with TCE and VC exposure being of greatest concern at Hadnot Point (ATSDR, 2017). The ATSDR determined that little risk can be attributed to exposure to drinking water contaminants at Holcomb Blvd (ATSDR, 2017). The ATSDR determined that TCE, VC, and PCE contributed to an increased risk of cancer or other adverse non-cancer health effects at Camp Lejeune with suggested next steps being the proposed Cancer Incidence Study (ATSDR, 2017). The limitations of the PHA can be mostly attributed to the 3-year and 15-year residency period assumptions used in the exposure dose calculations, the water system–specific conclusions that do not take into account multiple exposures from several different water systems, and the 3-year averaged water concentrations.

A 2018 ATSDR Morbidity Study of Marines and civilians at Camp Lejeune found that the drinking water was linked with increased risk for bladder cancer, kidney cancer, and kidney disease (ATSDR, 2018). There was a monotonic exposure-response relationship between kidney cancer risk and TCE/PCE exposure for Marines (ATSDR, 2018).

The previously mentioned case-study birth defect/childhood cancer, cross-sectional birth defect, morbidity, and mortality studies, while providing data-driven information about Camp Lejeune health effects, contained wide confidence intervals in their assessments. Such confidence intervals indicate a lack of precision in HR estimates, due to small numbers of specific causes of death (Bove et al., 2014). As a result, the actual magnitude of the effects of contaminated drinking on specific causes of death remains uncertain. Both the morbidity and mortality studies expressed the need for long-term medical monitoring in order to accurately assess impacts from the Camp Lejeune drinking water exposures. This knowledge gap necessitates the development and application of methodologies to proactively address the possible effects of contaminated drinking water until mortality data becomes available and the ATSDR completes its cancer incidence study (ATSDR, 2019). Many of the illnesses associated with Camp Lejeune drinking water exposure have long latency periods; a method of risk assessment for varying levels of exposures could assist in determining preventive health measures for at-risk populations that lived and worked at Camp Lejeune (IARC, 2014).

3 Methods

3.1 Review of ATSDR's Groundwater Flow Model Methodology and Camp Lejeune's Hydrologic and Hydrogeologic Assessment

A report regarding Camp Lejeune's Hydrologic and Hydrogeologic data was conducted by the USGS in 1989 and clarifies that the water supply wells that support TTWTP, HBWTP, and HPWTP "tap freshwater-bearing aquifers (sands and limestone), which are present at depths of about 50 to 300 ft (feet) below land surface" with saltwater found at further depths (Harned et al., 1989). The USGS report clarifies that hazardous waste disposal and spill sites sitting on land made of sand and natural or synthetic barriers led to the aquifers' contamination (Harned et al., 1989). At the time the report was written there were approximately 100 wells that had been drilled to satisfy the water demands of the base. The report's purpose was to discuss the attributes of the seven aquifers on the base and "provide the Marine Corps with information necessary to determine the best management practices so that the chances of further contamination of the aquifers can be minimized" (Harned et al., 1989).

The historical reconstruction of contaminant concentrations presented in the 2007 ATSDR paper utilized two different models in its analysis of the TTWTP drinking water distribution. The first model, MODFLOW-96, yielded results for a single contaminant dissolved in groundwater and uniformly mixed in the saturated zone, below the water table (Harbaugh & McDonald, 1996; Zheng & Wang, 1999; Maslia et al., 2007). A more accurate exposure to VOCs was

modeled with the second model, which looked at PCE and its degradation by-products, TCE, DCE, and VC, using a three-dimensional multi-species model called TechFlow MP which was more reflective of the contamination at Camp Lejeune (Maslia et al., 2007).

To reconstruct contaminant concentrations at HPWTP and HBWTP, the ATSDR utilized MODFLOW-2005 for transient groundwater-flow modeling, PEST-12 for parameter estimation, TechWellOp for historical water supply well operations, and a simulation of hydraulics and water quality of Holcomb Blvd.'s water distribution system using EPANET 2 (Maslia et al., 2013). Results from the simple mixing model presume that the concentrations in finished water at the WTPs are nearly equal to the concentrations of finished water at any location serviced by the WTPs. In 2007, Maslia et al. used the simple mixing model approach to reconstruct historical finished water concentrations for the TTWTP and later compared the mixing model approach to the EPANET 2 water distribution system model results. Maslia et al. (2007) demonstrated that after two weeks, spatially distributed concentrations throughout TTWTP computed using both models were identical (Maslia et al., 2013).

The 2013 ATSDR report documented the annualized daily average flow rates of raw water treated at both the HBWTP (Table S1.3) and the HPWTP (Table S1.2) (Maslia et al., 2013). Similarly, a brief summary of flow rate for raw water treated at the TTWTP was provided in *Chapter C: Simulation of Groundwater Flow* (Table C8) (Faye and Valenzuela, 2007). For years prior to 1975, in which data is not available, the "average rate of 116,200 ft^3/day determined for the period 1975–1986…was considered the average rate of total pumpage cumulative to all active Tarawa Terrace water-supply wells for the period January 1952–December 1974" (Maslia et al., 2007).

3.2 Development of a Cumulative Human Health Risk Model

In order to quantify annual risk for Marines living and working on base at Camp Lejeune, EPA's Risk Assessment Guidance for Superfund cancer risk methodology was used in conjunction with previously published data from the ATSDR. Similar to the ATSDR's 2017 PHA, this study's risk model utilizes historical reconstructed contaminant concentrations published by the ATSDR in 2007 and 2013. The raw historical reconstructed contaminant concentration data was summarized into annual maximum concentration values and utilized as the input parameters in the risk calculation.

Table 1 Inhalation unit risk and oral slope factor by chemical*

Analyte	IUR (ug/ m^3)$^{-1}$	OSF (mg/kg/day)$^{-1}$
TCE	4.10E-06	4.60E-02
PCE	2.60E-07	2.00E-03
Benzene	7.80E-06	5.5E-02
Vinyl Chloride	4.40E-06	7.2E-01

*All values from ATSDR's Public Health Assessment for Camp Lejeune (ATSDR, 2017) and the USEPA Integrated Risk Information System (IRIS)

Table 2 Chemical-specific dermal absorption parameters*

Analyte	*Kp* (cm/h)	τ	t*	*B*	*FA*
TCE	0.012	0.58	1.39	0.1	1
PCE	0.033	0.91	2.18	0.2	1
Benzene	0.015	0.29	0.7	0.1	1
Vinyl chloride	0.0056	0.24	0.57	0	1

*All values from USEPA Risk Assessment Guidance Part E (USEPA, 2004); *FA*, fractional absorption

The first input for the risk model is the duration each marine lived on the base. The duration calculation is as follows:

$$\text{Exposure duration (yrs.)} = \frac{\text{end date} - \text{start date}}{365} \tag{3.1}$$

Once duration of exposure is calculated, the model simultaneously pulls modeled contaminant concentrations and calculates risk for three exposure pathways. The respective equations utilized for risk by ingestion, dermal absorption, and inhalation are presented below. Table 1 summarizes the Inhalation Unit Risk values and Oral Slope factors by chemical as set by the USEPA and used in ATSDR's PHA. Table 2 lists the chemical-specific parameters used in the equations to quantify cancer risk for the various pathways. Table 3 outlines the default assumptions used to calculate a Marine's cancer risk based on values from ATSDR's

Table 3 Default assumptions for marines

Term	Definition	Marine	Reference
AT	Averaging time (days)	28470	(USEPA, 2009)
BT	Total time in bathroom (min/day) RME of Ts	120	(ATSDR, 2017)
BW	Body weight (kg)	80	(ATSDR, 2017)
EF	Exposure frequency (days/year)	350	(ATSDR, 2017)
IR	Water ingestion rate (liters per day) RME	4.334	(USEPA, 2019; ATSDR, 2017)
${}^{InR}day$	Inhalation rate-daily (m^3/day)	22.4	(ATSDR, 2017)
${}^{InR}min$	Inhalation rate-minute (m^3/min)	0.016	(ATSDR, 2017)
K	Constant for chemical volatilization	0.6	(ATSDR, 2017)
LT	Lifetime (years)	78	(ATSDR, 2017)
SA	Surface area of skin (cm^2)	24265	(ATSDR, 2017; USEPA, 2011d)
${}^{t}event$	Event duration (hr./event) RME	0.58	(USEPA, 2004)
${}^{T}s$	Time in shower (min) CT	20	(ATSDR, 2017)
${}^{V}a$	Volume of air for showering scenario (L)	44000	(ATSDR, 2017)
Fw	Flow rate water (L/min)	66	(ATSDR, 2017)

PHA and the USEPA's *Exposure Factors Handbook* (ATSDR, 2017; USEPA, 2011b, 2011c, 2011d).

3.3 Ingestion Risk Equation

The intake equation for ingestion in the risk model uses Equation 3.2, described below, from the USEPA's *Risk Assessment Guidance for Superfund Volume 1 Human Health Evaluation Manual (Part A)*. The risk calculation utilizes values from Table 1 and Equation 3.3 to quantify cancer risk due to ingestion of drinking water contaminants. The intake equation for ingestion is the same across all chemicals in the risk model.

$$\text{Intake (mg/kg/day)} = \frac{Cw \times CF \times IR \times EF \times ED}{AT \times BW} \tag{3.2}$$

(USEPA, 1989)

where

Cw= chemical concentration in water (µg/ L)

CF= conversion factor (1 *mg*/1000 *µg*)

IR= ingestion rate (L/day)

EF= exposure frequency (days/year)

ED= exposure duration (years)

AT= averaging time (LT (78 years) × 365 days)

BW= body weight (ATSDR, 2017; USEPA, 2011c)

$$Ingestion\ Risk = \text{Intake (mg/kg/day)} \times \text{CSF (mg/kg/day)}^{-1} \tag{3.3}$$

(USEPA, 1989)

where

CSF= USEPA Chemical Specific Cancer Slope factor or Oral Slope Factor $(mg/kg/day)^{-1}$

(See Table 1)

3.4 Dermal Risk Equation

The USEPA's *Risk Assessment Guidance Part E* outlines how to calculate the dermally absorbed dose (DAD) and shows the standard for calculating dermal risk (USEPA, 2004). The event duration is less than or equal to the time required for a chemical to reach steady state; therefore, Equations 3.4a–3.7e used.

$$DA\ event = 2\ FA\ x\ Kp\ x\ Cw \sqrt{\frac{6\tau\ event\ x\ t\ event}{\pi}} \tag{3.4a}$$

$$DA\ event\ (VC)^{*} = FA\ x\ Kp\ x\ Cw\ x \left(\left(\frac{ET}{1+b} \right) + 2\ x\ \tau\ event\ x \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right) \tag{3.4b}$$

$$DAD = \frac{DAevent\ x\ EV\ xED\ xEF\ xSA}{BW\ x\ AT} \tag{3.5}$$

$$CSF_{ABS} = CSF_{O}/ABS_{GI}\ * \tag{3.6}$$

*The fraction of contaminant absorbed in the gastrointestinal tract is generally >50% for all other

organics not listed in exhibit 4-1 of the USEPA Risk Assessment Guidance Part E (USEPA, 2004).

$$\text{Dermal cancer risk} = DAD \; x \; CSF_{ABS} \tag{3.7}$$

where

DAD= dermally absorbed dose (*mg/kg/day*)

DAevent= dermal absorption event

EV= event frequency(events/day)

Cw= chemical concentration in water (µg/ L)

τ *event*= lag time per event (chemical specific, see Table 3)

t*= time to reach steady state (chemical specific, see Table 2)

t event= event time (hr/event) (see Table 3)

CF= conversion factor $(1mg/1000\mu g)$ $(1L/1000cm^3)$

EF= exposure frequency (days/year)

ED= exposure duration (years)

AT= averaging time (LT (78 years) × 365 days)

SA= surface area (cm^3) (Marine specific, see Table 3)

BW= body weight (marine specific, see Table 3)

FA= fraction absorbed water (1, see Table 2)

Kp= chemical-specific permeability factor (*cm/h*) (see Table 2)

CSF_{ABS}= absorption cancer slope factor $(mg/kg/day)^{-1}$

CSF_{oral}= oral slope factor $(mg/kg/day)^{-1}$ (chemical specific, see Table 1)

ABS_{GI}= fraction of contaminant absorbed in the gastrointestinal tract is generally >50% for all other organics not listed in exhibit 4-1 of the USEPA risk assessment guidance (0.5)

3.5 Inhalation Risk Equation

For inhalation, the risk model uses equation 3.8 for benzene, PCE, and TCE to calculate inhalation for vinyl chloride. The inhalation calculation focuses on the inhalation of contaminants from drinking water that occurs during showering and time spent in the bathroom. Risk based on inhalation dose calculations uses equation 3.9 and USEPA's IUR factors to quantify cancer risk due to the inhalation pathway.

$$Inh.dose\left(mg/m^3\right) = \frac{Cw \times K \times Fw \times Ts \times CF \times lnRmin \times BT \times EF \times ED}{AT \times Va \times lnRday} \tag{3.8}$$

Inhalation Risk Equation for Benzene, PCE, and TCE (ATSDR, 2017)

where

Cw= chemical concentration in water (µg/L, see Table 3)

K= constant for chemical volatilization from water to air

Fw=flow rate water (L/min)

lnRmin = inhalation rate (L/min, see Table 3)

lnRday= inhalation rate (L/day, see Table 3)

Ts= showering time (min, see Table 3)

BT= total bathroom time (min/day, see Table 3)

Va= volume of air in bathroom (L, see Table 3)

EF= exposure frequency (days/year)

ED= exposure duration (years)

AT= averaging time (LT (78 years) × 365 days)

CF= conversion factor $(1mg/1000\mu g)$ $(1000L/1m^3)$

$$Inhalation\ Risk = Inh.dose\left(mg/m^3\right) \times IUR\left(mg/m^3\right)^{-1} \tag{3.9}$$

where

IUR = USEPA inhalation unit risk $(mg/m^3)^{-1}$(chemical specific, see Table 1)

The risk model then sums the maximum dermal, inhalation, and ingestion risk by each WTP. The basewide model creates a weighted average of risk by analyzing each water system's risk and average treated water (MGD) from the specified years each Marine lived at Camp Lejeune.

ATSDR provides equations for ingestion and inhalation pathways for vinyl chloride in Appendix C of the 2017 PHA (ATSDR, 2017). The equations presented in Appendix C for vinyl chloride were not used in this analysis, as the equations were left incomplete. ATSDR did not use such equations in Appendix C to calculate exposure dosage in Appendix B of the PHA. The equations presented in Appendix C would make the cancer risks higher for vinyl chloride, but to be conservative, they are not presented in this report.

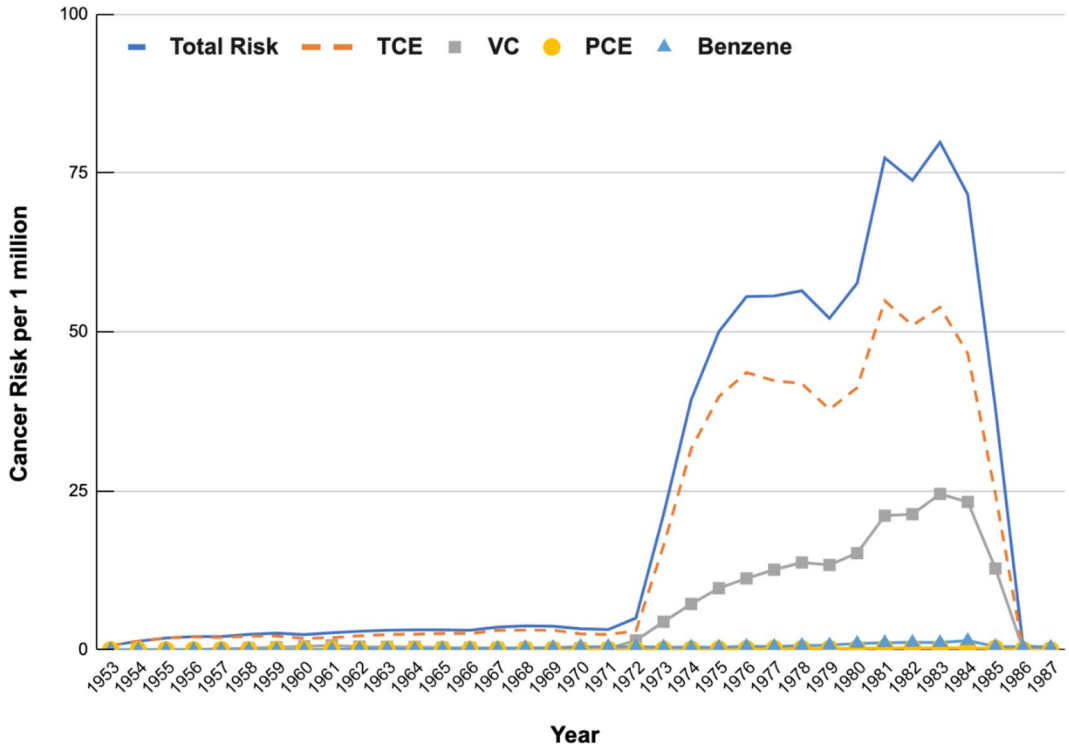

Fig. 2 Basewide cancer risk by chemical

4 Results

The results of an annual cancer risk analysis are presented in Figures 2, 3, 4, and 5. Figure 2 presents the annual basewide cancer risk by chemical. TCE and VC contributed to the highest cancer risk values from 1972 to 1985. This is most likely due to the degradation of PCE to TCE and VC via de-halogenated reductions (Vogel and McCarty, 1985). High VOC concentrations can be explained by the ABC One-Hour Cleaners' septic tank soil absorption system which was located half a mile away from the TTWTP and contaminated groundwater with PCE (Maslia et al., 2007). The septic tank was first constructed in the 1940s for ABC One-Hour cleaners with a floor drain leading to the septic tank later installed in the 1960s (Maslia et al., 2007). The ATSDR estimates, based on groundwater sampling locations and the concentrations at TTWTP's water supply wells from 1991 to 1993, that approximately 13 gallons of PCE per year from 1953 to 1985 contaminated the subsurface (Maslia et al., 2007).

Figure 3 presents each exposure pathways' contribution toward total cancer risk: ingestion, dermal exposure, and inhalation. On average, 59% of annual risk results from inhalation, 34% results from ingestion, and 5.5% from dermal absorption. Such results suggest that the inhalation exposure pathway poses a roughly 1.7 times greater risk than the ingestion pathway and almost 11 times greater than the dermal absorption pathway. These findings are consistent with peer-reviewed literature demonstrating that risk from inhalation exposure to indoor air may exceed exposure from ingestion (Andelman, 1985a; Andelman, 1985b; Giardino and Wireman, 1998; McKone, 1987; McKone and Knezovich, 1991).

Figure 4 presents the cancer risk from TCE and vinyl chloride. The USEPA Risk Assessment Guidance states anything above a 1 in a million-cancer risk is greater than *de minimis* risk (USEPA, 2021). Figure 4 demonstrates that, from 1980 to 1984, 1 month of working on the base could result in a greater than 1 in a million *de minimis* risk value. The TCE cancer risk peaked from 1983 to 1984 and the VC cancer risk peaked in 1980-1981. Also indicated by Figure 4, personnel working on the base for greater than or

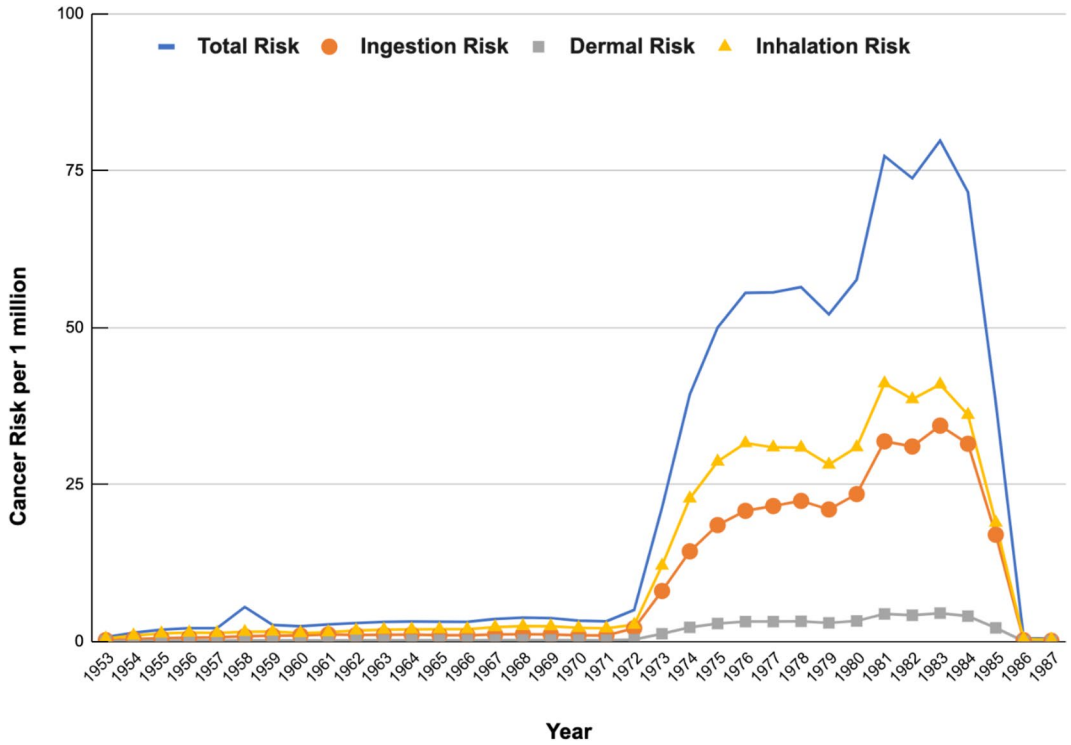

Fig. 3 Basewide annual total cancer risk by pathway of exposure

equal to 6 months experienced up to a 6-fold increase in cancer risk, compared to the 1-month exposure scenarios in the 1980s.

Figure 5 demonstrates that, from 1957 to 1972, TTWTP had the greatest contamination of the four chemicals modeled by ATSDR, thereby contributing the most toward annual basewide cancer risk. However, from 1972 until closure in 1986, HPWTP provided the most contaminated water to the base, causing it to be the greatest contributor toward overall annual cancer risk. Similar to the ATSDR's conclusions, HBWTP was found to contribute the least toward basewide cancer risk.

Given that the three WTPs have different concentrations of contaminants, a Marine's individual cancer risk is dependent on the specific WTPs that serviced the different areas of the base. HPWTP, TTWTP, and HBWTP. averaged treating 4.3, 0.85, and 1.06 million gallons of water a day, respectively. From 1953 to 1987, Hadnot Point, Tarawa Terrace and Holcomb Blvd. provided 80.7%, 12.4%, and 6.92% of the treated water to Marines at Camp Lejeune, respectively (Faye et al., 2007; Saunter et al., 2013; Maslia et al., 2013). After 1972, the HPWTP had the highest concentration of contaminated water on the base and was serving the most marines for approximately 13 to 14 years. This is consistent with the results of basewide risk being most similar to HPWTP's risk for each year of operation.

5 Discussion and Limitations

The methodology used in this study quantifies cancer risk for Marines who lived and worked on the base using raw historical reconstructed contaminant concentration data. While traditional epidemiologic studies can quantify health impacts from environmental exposures, they conventionally unfold over extended timelines (Caruana et al., 2015). Rather than providing an exact quantification of cancer cases like an epidemiological study, our methodology provides a method for risk assessment on shorter time scales.

Conventional epidemiological investigations require time-intensive data collection and analysis. Specifically, longitudinal studies aim to observe disease evolution and

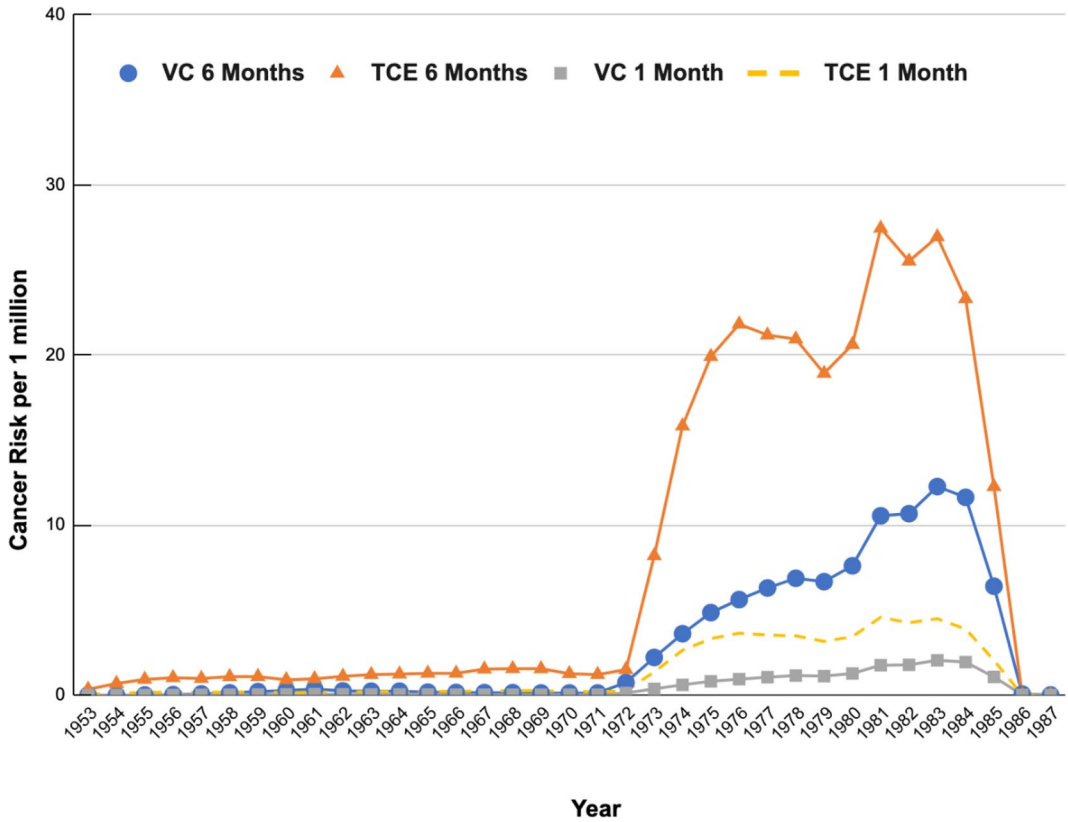

Fig. 4 Basewide cancer risk by chemical comparison of vinyl chloride and trichloroethylene

correlate with past exposures over the course of years or decades (Caruana et al., 2015). Furthermore, diseases like cancer, with prolonged latency periods, may remain dormant for years post-exposure, complicating timely risk assessment (IARC, 2014). This lengthy process often hinders timely actionable insights. Because the model outlined in this paper is based on reconstructed contaminant concentration data and variable pathway risk factors, it does not rely on health impact data that takes longitudinal studies years to obtain.

The methodology outlined here is based on guidance published by the USEPA for Superfund sites. Superfund sites are locations designated by the USEPA for cleanup and remediation due to the presence of hazardous materials, pollutants, or contaminants (USEPA, 2023). The requirements for a Superfund site designation are established in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), an act that established the trust fund for remedial action at such sites. While not every hazardous waste site qualifies as a Superfund site, the same methods can be applied for sites with similar contamination.

Specific exposure may be difficult to quantify, as some Marines stationed at Camp Lejeune are no longer living and others may not remember where they lived or worked, presenting a challenge in sourcing the origin of the water to which they were exposed. Additionally, all Marines traveled throughout the base and consumed water from various water systems making it inaccurate to draw assumptions of risk from a single water system. With this in mind, the model's estimate for basewide risk may be the most realistic tool of analysis given that it weighs contaminant concentration by flow rate at each respective treatment plant.

One limitation of this model is the reliance on standard assumptions such as duration, routes of exposure, variability of contaminant concentrations by area, by date, etc., mean that some degree of uncertainty will be inherent in the risk estimates for individuals. Even with such assumptions, however,

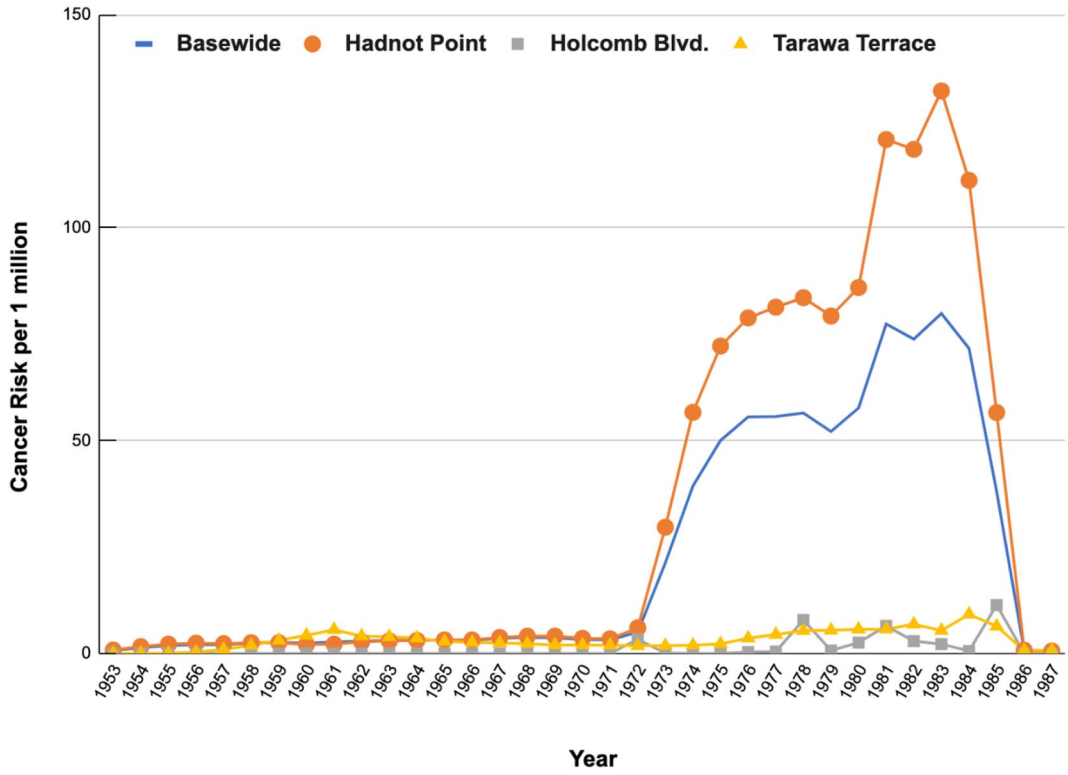

Fig. 5 Annual cancer risk based on water treatment plant

the risk assessment can be viewed as reasonable and offers conservative estimates for evaluating cancer risk to the community as a whole due to the use of modeled contaminant concentrations. Additionally, not all Marines living and working at Camp Lejeune sourced all of their water from the contaminated water treatment system. The three water systems discussed in this study account for approximately 75% of water served to the base from 1942 to 2008 (Maslia et al., 2013).

Even with considering the limitations of the study, applying this established health assessment modeling approach to the Camp Lejeune Marine Base can expedite the identification of potential health risks and recommend proactive health screenings to affected populations.

6 Conclusion

Using USEPA and ATSDR guidance, this model demonstrates that VC and TCE are the risk drivers, while benzene and VC also contribute to the cumulative cancer risk for Marines who lived and served at Camp Lejeune from 1953 to 1987. VC and TCE exposure for periods as short as 1 month can exceed a 1 in a million *de minimis* cancer risk value. Results presented in Figures 2, 3, 4, and 5 demonstrate that the highest cancer risk for Marines who lived and worked at Camp Lejeune occurred from 1972 to 1985.

Although use of the USEPA Risk Assessment methodologies is standard practice for assessing environmental contamination, this is the first application of the model to assess cancer risk for Marines at Camp Lejeune. It has the potential for use as a valuable public health tool for evaluating the extent of the risk conferred by the contamination. Strengths of this model include the use of published methodology to ensure the reliability of the results.

It can be reasonably concluded from the results and discussion that Camp Lejeune had significant enough water contamination to threaten the health of Marines living and working on the base. The cancer risk values

provide substantial evidence that diseases such as liver cancer, bladder cancer, kidney cancer, NHL, and multiple myeloma are a high risk to individuals who spent time on the base, especially during the years of greatest contamination in the late 1970s and 1980s. These health effects should be the primary focus in the ongoing cancer incidence study being prepared by the ATSDR, with further research conducted on the synergistic effects of these VOCs on human health. By applying USEPA risk assessment methodology originally created for superfund sites to areas with similar environmental contamination to Camp Lejeune, future studies can provide valuable insights into possible health implications and help identify the highest risk individuals that lived or worked in impacted areas.

Author Contributions PER introduced the concept for this paper, wrote the first outline, and contributed to the writing and editing throughout. KRS drafted text and oversaw content related to health effects. SJM, PER, and KRS conducted the literature search, analyzed cancer risk findings, and served as principal editors. PER, SJM, and SCW compiled the graphics. PER reviewed the guidance documents and constructed the risk assessment. PER, SJM, and SCW wrote the first draft sections of the paper. MSW assisted in drafting the final iteration of the manuscript. MFH drafted the groundwater section. All authors participated in revisions and read and approved the final manuscript. Alex E. Martin contributed greatly to the quality control of the risk calculations presented in this manuscript and provided useful editorial comments.

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Data Availability The data that support the findings of this study are provided as supplementary information with further data available on request from the corresponding author, PER.

Declarations

Competing Interests PER and KRS are both testifying experts in solvent exposure litigation. PER is also the co-founder of SWAPE LLC. All other authors have no conflicts of interest to declare.

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