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Potential impact of the 2023 Lahaina wildfire on the marine environment: Modeling the transport of ash-laden benzo[*a*]pyrene and pentachlorophenol

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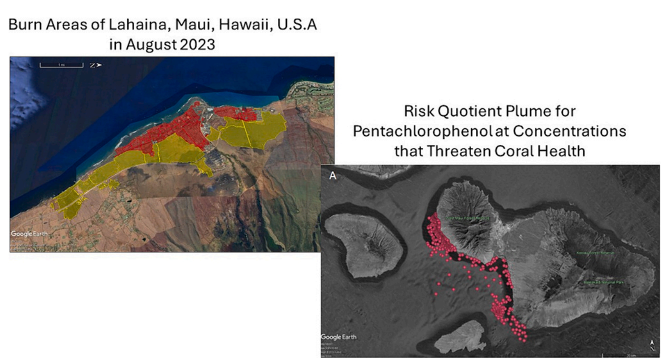
HIGHLIGHTS

- The Lahaina, HI fire event of 2023 is deadliest fire in the past century in U.S. history.
- Ash runoff in the first monsoonal rains mobilize pollutants into the coastal habitats.
- Modeled Risk Quotient plumes for benzo[*a*]pyrene and pentachlorophenol of coastline.
- Pentachlorophenol may pollute habitats as far south as the coral reefs of Molokini.

GRAPHICAL ABSTRACT



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ABSTRACT

The Lahaina urban/wildland fire event is considered the deadliest wildfire in the past century of U.S. history. This fire resulted in over 2200 building structures destroyed or damaged, approximately 4000 automobiles were incinerated and between 450 and 878 ha of grassland burned in areas adjoining the town of Lahaina, Maui County, State of Hawaii, U.S.A. One of the most abundant contaminants of both wildland and urban fires is the

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Pollution behavior
Risk assessment
Pentachlorophenol
Benzo[*a*]pyrene
Wildfire
Urban fire

incomplete combustion product, benzo[*a*]pyrene. Pentachlorophenol from burned and unburned utility poles/ residential burn sites enter into navigable waters, thus posing a serious risk to the water quality of coastal waters. The Risk Quotient Plumes for benzo[*a*]pyrene and pentachlorophenol, mobilized from Lahaina into coastal waters were calculated based on a hydrodynamic analysis and an integrated ecological risk assessment. This plume was simulated using rainfall events in November 2022 as a proxy for the first major rainfall event expected in Lahaina in 2024. The models indicated that the estimated levels of benzo[*a*]pyrene and pentachlorophenol posed a risk to near shore habitants within 2 km of Lahaina. The levels of pentachlorophenol were more widespread than benzo[*a*]pyrene and were predicted to pose a hazard to marine life as far away as Molokini Shoal Marine Life Conservation District and ʻĀhihi-Kīnaʻu Natural Area Reserve. Fisheries species captured near these areas should be tested for consumption safety.

1. Introduction

The Lahaina urban/wildland fire event is considered the deadliest wildfire in the past century of U.S. history. On August 7, 2023, according to laboratory meteorological models, a "downslope windstorm" (wind gusts exceeding 130 km/h) was formed from a strong high-pressure system north of the Island of Maui, Hawaii, (Businger, 2023). This meteorological phenomenon is the same process thought to have fueled many of the California wildfires (Mass and Ovens, 2019; Keeley and Syphard, 2021; LaDochy and Witiw, 2023). Coincidentally, the western side of Maui was experiencing drought conditions which resulted in dry grasslands along the western side of the West Maui Mountain range (Maui Komohana). On August 8, 2023, fires in the grasslands on the western slope of the West Maui Mountain range were sparked and are hypothesized to be a major driver for the Lahaina urban fire, though urban fires within the town may have arisen independently as a result of fallen electrical lines. This fire resulted in over 2200 building structures destroyed or damaged, approximately 4000 automobiles were incinerated and between 450 and 878 ha of grassland burned in areas adjoining the town of Lahaina (Dowd, 2023; Maui County, 2023; Fig. 1). Over 690 utility poles in the Lahaina area were damaged, and about half of the poles are to be completely replaced because of irreparable fire damage. This incident exemplifies the aftermath of a wildland-urban fire, laden with ash and combustion residues from urban and wildland combustion sources (USNAS, 2022).

Monsoonal rainfall in the Lahaina watershed usually begins in November and persists until April of the following year. Runoff from the burned areas into coastal waters poses a contamination event for the marine environment. The ash plume can carry an assortment of ash-laden contaminants onto Maui coral reefs, including asbestos, polyfluoroalkyl substances, dioxins, furans, benzo[*a*]pyrene and other polyaromatic hydrocarbons, as well as polychlorinated phenolic compounds, such as pentachlorophenol (NAS, 2022; Wang et al., 2022). During the first three months after the fire during discovery and recovery operations, dozens of cases of acute illnesses were being reported by workers, volunteers, and residents within the burn zone and adjacent to the burn zone within the atmospheric burn-plumes (e.g., personal communication by Maui County Council members). Many of these cases included symptoms consistent with exposure to polyaromatic combustion products and chlorinated-aromatic products (Bleiberg et al., 1964; Suskind, 1985; Tindall, 1985; Cole et al., 1986; Proudfoot, 2003; Zheng et al., 2015). Two compounds consistent with these symptoms are exposure to benzo[*a*]pyrene and pentachlorophenol (Booze et al., 2004; Chepelev et al., 2015; Bukowska et al., 2022). Besides posing as an ecotoxicological threat to Maui reef systems, exposure to either benzo[*a*]pyrene or pentachlorophenol can result in bioaccumulation of these two toxicants in marine fisheries, especially traditional Hawaiian subsistence fisheries including *Opihi* (*Cellana exarata*), *Limu* (marine macroalgae, e.g., *Ulva lactuca*, *Ahnfeltiopsis concinna*, *Grateloupia filicina*), *hawa'e maoli* (*Tripneustes gratilla*), and various reef fin-fish species (Carl, 2009; Hart et al., 2014; Grafeld et al., 2017; McCoy et al., 2018).

One of the most abundant contaminants of both wildland and urban

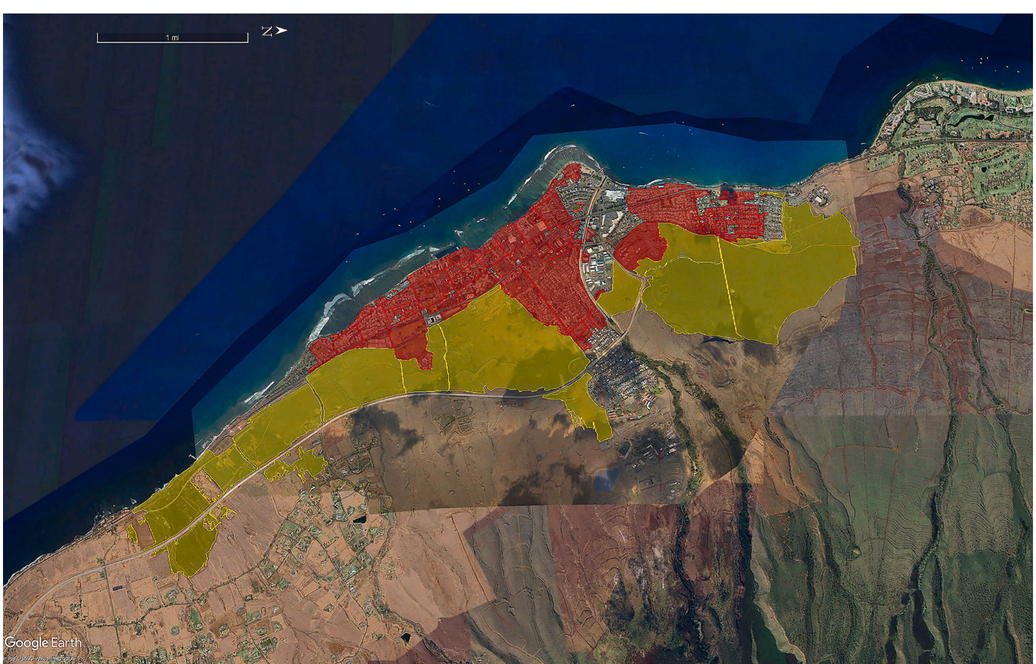

Fig. 1. Burn areas in Lahaina, County of Maui, State of Hawaii, U.S.A. on August 8, 2023. Urban-burned areas are shaded in transparent red. Grassland-burned areas are shaded in transparent yellow.

fires is the incomplete combustion product, benzo[*a*]pyrene (CAS# 50-32-8). Combustion sources such as wood (building structures and trees), grass, plastics, tires, and petroleum-based fuels can be sources for benzo[*a*]pyrene, with ash residues from these sources containing anywhere from 0.1 to 200 mg benzo[*a*]pyrene/kg of ash (Enell et al., 2008; Keith, 2014; Abel et al., 2015). Benzo[*a*]pyrene routes of exposure include inhalation, dermal absorption, and ingestion (Knafla et al., 2006; Wan et al., 2021; Bukowska et al., 2022). From a public health perspective, benzo[*a*]pyrene is carcinogenic, neurotoxic, a reproductive and developmental toxicant, causes epigenetic changes, and is both immunosuppressive and a viral-replicative stimulant - exposure to benzo[*a*]pyrene has been suggested as a possible virulence factor for COVID-19 (Collins et al., 1991; IARC, 2010; Chepelev et al., 2015; Bukowska and Sicińska, 2021; Bukowska et al., 2022). Benzo[*a*]pyrene's ecotoxicological consequences are far reaching and demand immediate attention and amelioration for environmental contamination, especially regarding coral reefs (Wu et al., 2011; Xiang et al., 2018). Benzo[*a*]pyrene can cause coral bleaching at concentrations of 10 μg/L while having an EC_{50} of around 2 μg/L for marine algal-growth inhibition (Djomo et al., 2004; Ozhan and Bargu, 2014; Xiang et al., 2019). The Lowest Observed Effect Concentration (LOEC) of benzo[*a*]pyrene to induce developmental arrest and deformities in sea urchins and bivalves is about 1 μg/L in a 48 h exposure (Hose et al., 1983; Steevens et al., 1999; Lyons et al., 2002; Guo et al., 2021). In fish, benzo[*a*]pyrene causes reproductive toxicity in adults with prolonged exposure. In fish embryos, the 48 h-LC_{50} and LOEC of benzo[*a*]pyrene range from 1 μg/L (LOEC) to 54 μg/L (LC_{50}) (Winkler et al., 1982; Hoffmann and Oris, 2006; Palanikumar et al., 2012; Nam et al., 2020; Sathikumaran et al., 2022).

Pentachlorophenol (CAS# 87-86-5) is a pesticide used to preserve wood products, such as utility poles, residential and commercial construction, and railroad ties (Carswell and Nason, 1938; Carswell, 1939; WHO, 1987; Kraševec et al., 2021). Pentachlorophenol was banned for use in residential lumber in the 1980s by the U.S. EPA, and is being completely phased out as a pesticide by 2027 (USEPA, 2023). Pentachlorophenol from burned and unburned utility poles/residential burn sites enters into waterways and navigable waters, thus posing a serious risk to the water quality of coastal waters (McKee et al., 1990; Beiras and Tato, 2018; Zheng et al., 2018; Young et al., 2021; Namit et al., 2022). Pentachlorophenol can bioaccumulate in a broad range of aquatic taxa, including fish, gastropods, bivalves, algae, and even mammals (El-Dib et al., 2000; Guerrero et al., 2001; Heinonen et al., 2003; Sun et al., 2014; Besser et al., 2016; Qi et al., 2023; Tran-Lam et al., 2023). In humans, pentachlorophenol can induce oxidative damage and genotoxic pathologies (Class 2B probable human carcinogen), hepatotoxicity, kidney disease, endocrine disruption along the thyroid axis, multi-generational lymphoma and hematopoietic neoplasms, as well as porphyria and chloroacne (Nyhan et al., 1969; Lui et al., 1976; Goldstein et al., 1977; Hughes et al., 1985; Seiler, 1991; Naito et al., 1994; Michałowicz, 2010; Guyton et al., 2016; Maheshwari et al., 2023). Pentachlorophenol poses a threat of immunotoxicity, mitochondria and metabolic disruption, genotoxicity and reproductive toxicity to aquatic organisms (Weinbach, 1956; Masini et al., 1985; Pavlica et al., 2000; Zheng et al., 2013; Zhang et al., 2022). It also can induce coral bleaching at levels around 100 ng/L (Zhang et al., 2024).

The goal of this study was to determine the ecotoxicological Risk Quotient (RQ) Plume distribution over a 96-hour period for pentachlorophenol and benzo[*a*]pyrene after two hypothetical rainfalls in the month of November 2023 (Doust et al., 2024). This RQ Plume model will indicate where ecological resources are being threatened, as well as what geographical areas are at potential risk and should be further investigated to determine contaminant loads in Hawaiian recreational and subsistence fisheries. The pollution plume was modeled using variables of current patterns and their velocities during tidal flushing and tidal slack, both in the larger bay area, as well as in the swash zone. A specialized approach combining hydrodynamic modeling with particle tracking was applied to analyze the behavior and distribution of benzo[*a*]pyrene and pentachlorophenol in the ocean. The predicted flow fields of these pollutants were mapped from simulations using 4-D hydrodynamic modeling previously demonstrated by Abbasian et al. (2023). This approach used Lagrangian particle-tracking for understanding the transit time and spread of pollutant particle from their sources; velocity fields to estimate trajectories of simulated particles for insights in oceanic dynamics at various scales; and time to map contaminant particle movement to their final destinations.

2. Materials and methods

The methodology described here is based on the application of numerical modeling for obtaining an estimate of the dispersion patterns of Lahaina wildfire ash within the surrounding marine environment. Numerical modeling includes a hydrodynamic model and a particle tracking algorithm to investigate different pollutant dispersion in order to obtain a desired approximation of the dispersion patterns and the possibility of vulnerable areas being affected.

2.1. Study area: Lahaina and Molokini Crater, Maui County, Hawaii

This study is concentrated on Lahaina (Fig. 2), situated alongside the west Maui Mountains, where geological and ecological aspects interact from the Kahoma stream's upper reaches to the coastal peripheries. The volcanic history of the region has sculpted a landscape of basaltic formations, rich in olivine, and carved into deep canyons by water runoff, resulting in a coastline uniquely shaped by sedimentary deposition. This area, spanning roughly 16 km^2 and recently affected by wildfires (Fig. 1), boasts a diverse range of habitats supporting both native and introduced species of plants.

The climate in Lahaina is semi-arid, characterized by modest annual rainfall but heavily influenced by seasonal variations and the prevailing northeast trade winds. These climatic factors contribute to the region's distinct environmental setting. Particularly notable is the coastal zone, where terrestrial and marine environments converge, characterized by sediment and basalt layers in the tidal areas with a thriving offshore coral reef (Swarzenski et al., 2012). However, this marine ecosystem is now threatened by sediment runoff from the land, potentially disrupting its ecological balance.

In August 2023, Lahaina region was hit by a large wildfire, which had unanticipated effects on the environment there, especially the river systems that feed into the coastal waters. In the scenario considered in this paper, it is assumed that the vast majority of the runoff is directed towards the main outfall channel, and the potential of a substantial contaminant load is mobilized. Adopting classic hydrological methods, a probable flood is estimated for the burnt areas, with a time base of 12 h, assuming that all the run-offs will wash the ash through the main channel sitting in the middle of the city and into coastal waters. Supplemental Fig. 1 provides a view of the watershed and sub-watersheds considered for this study.

This event could result in the entrainment and subsequent downstream transport of approximately 41,650 kg of pentachlorophenol and 71.84 kg of benzo[*a*]pyrene (Supplementary Table 1). The anticipated mass release curve, based on these hydrological and contaminant transport assumptions, is illustrated in Supplementary Fig. 2.

This research, focusing on Lahaina and the Molokini Crater in Maui County, Hawaii, includes an environmental risk assessment component, particularly in the wake of the devastating Lahaina wildfire in August 2023 (Fig. 2).

2.2. Hydrological modeling for runoff and material release scenarios

To build upon our hydrodynamic modeling framework, hydrological investigations are carried out to simulate surface runoff and the transport of materials, such as ash, into Lahaina's coastal waters. This approach, utilizing methodologies from the World Meteorological

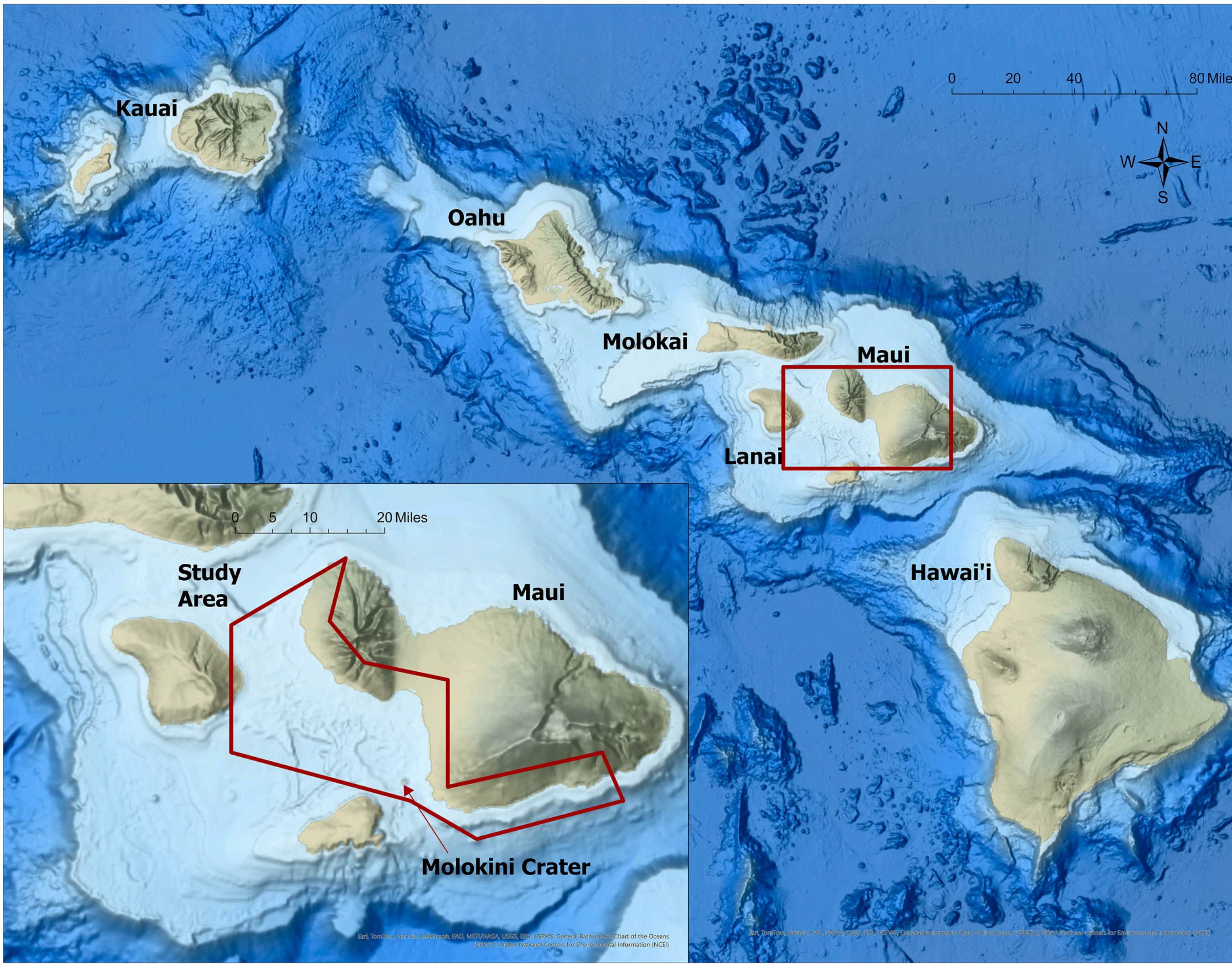

Fig. 2. Map depicting Maui, Hawaii, United States of America and surrounding islands. Study site is located on the northwest coast of Maui.

Organization (WMO) and adopting a runoff estimation formula presented by the Soil Conservation Service (SCS), translates rainfall data into runoff and then water and contamination hydrographs (Supplementary Fig. 2), taking into account a range of meteorological, hydrological, and geographical variables. The month of November is the beginning of the monsoon season, and where, historically the first significant rainfalls occur. The typical precipitation for the month of November is considered to be 80 mm for the hypothetical event with a typical runoff of 72 mm. The peak value of the flood hydrograph is calculated about 526.6 m^3/s, with a base time of 7.5 to 8 h.

The outputs from the hydrological estimations, particularly the data on generated flood hydrograph and associated material loads including the ash, are then fed into the hydrodynamic model. This integration enriches our existing framework, creating a comprehensive model that captures the full spectrum from watershed to reef, which is essential for addressing the complex environmental challenges in Lahaina.

2.3. Theoretical loading calculations for pentachlorophenol and benzo[a] pyrene

Theoretical loading calculations are best-effort estimates that are not actual measured amounts.

The calculations of the amount of benzo[*a*]pyrene produced from the Lahaina fires were based on estimates of amounts released from burned residential and commercial buildings, utility poles, gasoline from burned vehicles and grass fires (Supplementary Table 1). The amount of wood in burned buildings assumed an average 185 m^2 residential and conservatively 1000 m^2 commercial buildings. The amount of benzo[*a*] pyrene from burned utility poles was based on an average estimate of 1400 kg per pole. Gras et al. (2002) provided an estimate of 820 μg benzo[*a*]pyrene produced per kilogram of burned wood. The number of buildings and poles burned were based on news media reports and personal communications (Honore and Truesdale, 2023; Dowd, 2023). The estimate for the amount of benzo[*a*]pyrene produced from burned vehicles was based on gasoline combustion. A conservative estimate was made that each vehicle contained 25 L of gasoline and based on an estimated miles per liter that approximately 178.2 μg of benzo[*a*]pyrene was produced per incinerated vehicle (Williams and Swarin, 1979). The number of burned vehicles was based on reports by Dowd (2023). The amount of benzo[*a*]pyrene produced from the grass fires was based on the amount of benzo[*a*]pyrene per kilogram of ash produced from a kilogram of switchgrass (Austin, 1969; Kim et al., 2018; Harper et al., 2019). The acreage burned was based on news reports (O'Kane, 2023).

The amount of pentachlorophenol was estimated from downed and burned utility poles based on an average pole size in the area (1400 kgs) and each pole containing 9 % pentachlorophenol by weight which then was adjusted to account for chlorinated dioxin and chlorinated furans as contaminants of technical grade pentachlorophenol (ATSDR, 2022). The number of poles that were downed or burned was obtained from news reports and personal communications (Honore and Truesdale, 2023).

The details of the assumptions and calculations are found in Supplementary Table 1.

2.4. Hydrodynamic and particle tracking modeling

The release of chemicals into water bodies via rainfall events can be understood by integrating insights from hydrodynamics, pollutant behavior modeling, and urban runoff contexts. This integration aids in tracking pollutants from their origin to their eventual impact on larger ecosystems. Our choice of a numerical hydrodynamic model, which utilizes 3D Reynolds averaged Navier-Stokes equations on a flexible, unstructured grid (Fig. 3), is based on its capability to simulate complex fluid dynamics, including turbulence, which is vital in areas with significant changes in velocity (Mavriplis and Venkatakrishnan, 1996; Mintgen and Manhart, 2018). At the heart of our modeling approach is the advanced Particle Tracking Algorithm (PTA), which calculates runoff-release particle trajectories within fluid flows and consequence hotspots by solving their motion equations (Hunter et al., 2022), heavily influenced by the fluid's dynamic state as depicted by the hydrodynamic model used.

This interaction between the model and the PTA, which incorporates various forces such as advection and diffusion, is crucial for accurately simulating the behavior and movement of particles. Advection, in particular, plays a key role by aligning particle paths with the fluid flow, thereby connecting their trajectories to the velocity field of the fluid. This field, along with turbulence intensity and other factors, is determined by the hydrodynamic model based on the Navier-Stokes equations.

The use of interpolation techniques by the PTA to estimate fluid properties at particle locations ensures seamless integration with the hydrodynamic model. This integration is vital for realistic simulations of particle movement, enabling particles to dynamically respond to changing flow conditions (Vennell et al., 2021). Such a comprehensive approach, underscored by the inclusion of a Particle Tracking Module, is indispensable for simulating individual pollutant particles within overland flows. This capability is crucial for visualizing and predicting the pathways of pollutants, a point emphasized by recent research (Risk et al., 2021; Abbasian et al., 2023; Doust et al. (2024), and is particularly effective in illustrating the distribution and impact radius of materials released into water bodies, which is of paramount importance for our study focusing on the dispersal of chemicals derived from post-wildfire events and understanding their environmental impacts.

2.4.1. Model configuration

The configuration of our model involves covering the study area with triangular elements on an unstructured grid, optimizing resolution for shallow water regions and complex coastal features such as Lahaina's coastline and Molokini Crater. This grid configuration, which employs a paving method for uniform node distribution, along with a time step set at 300 s to adhere to the Courant-Friedrichs-Lewy condition, enhances the model's ability to accurately represent detailed environmental features (Yin and Seo, 2016). For modeling turbulent water flow, especially in areas with complex geometry, we utilized the Smagorinsky eddy viscosity model with a coefficient of 0.28, following the protocol described in Hassannezhad et al. (2011). This approach, combined with a finite difference method that employs explicit quadratic upstream interpolation for particle tracking, ensures the model's stability, mass conservation, and minimization of numerical dispersion, making it well-suited for simulating ocean currents, water levels, and particle concentrations, and providing a solid framework for understanding the behavior of pollutants in Lahaina's coastal waters and beyond towards Molokini Crater.

2.4.2. Data sources for bathymetry and boundary conditions

The initialization and driving of the model are supported by bathymetry data sourced from databases such as NOAA's National Centers for Environmental Information (NCEI) and the General Bathymetric Chart of the Oceans (GEBCO), with additional refinement from the International Hydrographic Organization (IHO) Data Center for Digital Bathymetry to enhance the bathymetric details of our study area (Supplementary Fig. 3). Atmospheric and ocean boundary conditions are derived from the Regional Ocean Modeling System (ROMS) provided by PacIOOS, supplemented by the HYbrid Coordinate Ocean Model (HYCOM) and the Weather Research and Forecasting (WRF) model for atmospheric data (Powell, 2015). Tidal predictions are obtained using Oregon State University's Tidal Prediction Software, which incorporates the TOPEX/Poseidon global inverse solution. This comprehensive integration of data sources ensures a detailed and accurate depiction of the initial and boundary conditions for our hydrodynamic model, facilitating precise simulations of ocean currents and the dispersion of pollutants in the study area.

2.5. Contaminant transport estimation

The study investigates the transport of pentachlorophenol (PCP) and benzo[*a*]pyrene chemicals introduced into the environment by burnt materials through a runoff event, using the described particle tracking algorithm (PTA). A comprehensive model has been developed to simulate the trajectory of these chemicals, which entered the water following a wildfire of August 2023. The objective was to elucidate the movement of these chemicals along the coastline of Lahaina and within the Molokini Marine Life Conservation District, influenced by tidal and oceanic currents. This analysis is pivotal in identifying patterns of pollutant dispersion in the waters of West Maui. For final simulations, it is assumed that there will be a possible flood that happens in November after a no rain period between August and November 2023. Using modeled current patterns for November 2022, two scenarios of current patterns are adopted, where northward and southward currents prevail nearshore along the Lahaina coastline on November 15 to the north and to the south on November 23.

The modeling of chemical behavior in water is complex, requiring different algorithms for different kinds of chemicals. Dispersed substances may be tracked using time-stepping concentration equations or point-source pollutants may be tracked using particle-tracking routines (Jiang et al., 2017). While pollutant concentration equations monitor changes over time and space, particle tracking follows pollutants throughout the study area (Supplementary Fig. 5).

The output of a pollution threshold analysis on various marine species using a hydrodynamic model assisted in identifying 'hot spots' where pollutant concentrations exceeded safe levels for different marine organisms at specific times following each release scenario. Our findings pinpoint specific areas where the environmental impact on marine life is most severe. Due to the embayment features around Molokini, a finer mesh grid was used for a detailed analysis that revealed this as a high-risk catchment for fire debris (Fig. 3C).

2.6. Risk quotient plume calculations for coral, algae, fish

As described in previous papers (Downs et al., 2022a, 2022b) and verbatim in Dowd, 2023, the European Commission guidance was used to calculate risk quotients (RQs) benzo[*a*]pyrene and pentachlorophenol in the water column (European Commission, 2003a, 2003b, 2003c; European Medicines Agency, 2006; Dussault et al., 2008; Hernando et al., 2006; Downs et al., 2022a, 2022b). The actual or measured environmental concentration (MEC) is compared to a derived or Predicted No-Effect Concentration (PNEC). The definition of a risk quotient is the "ratio of the potential exposure to a substance and the level at which no adverse effects are expected" (U.S EPA, 1998; Downs et al., 2022b). As mentioned in our previous papers, where the No Observed Effect Concentration (NOEC) was not known, but when the Lowest Observable Effect Concentrations (LOEC) was known, the LOEC was divided by two to calculate a predicted NOEC, as specified in ECHA

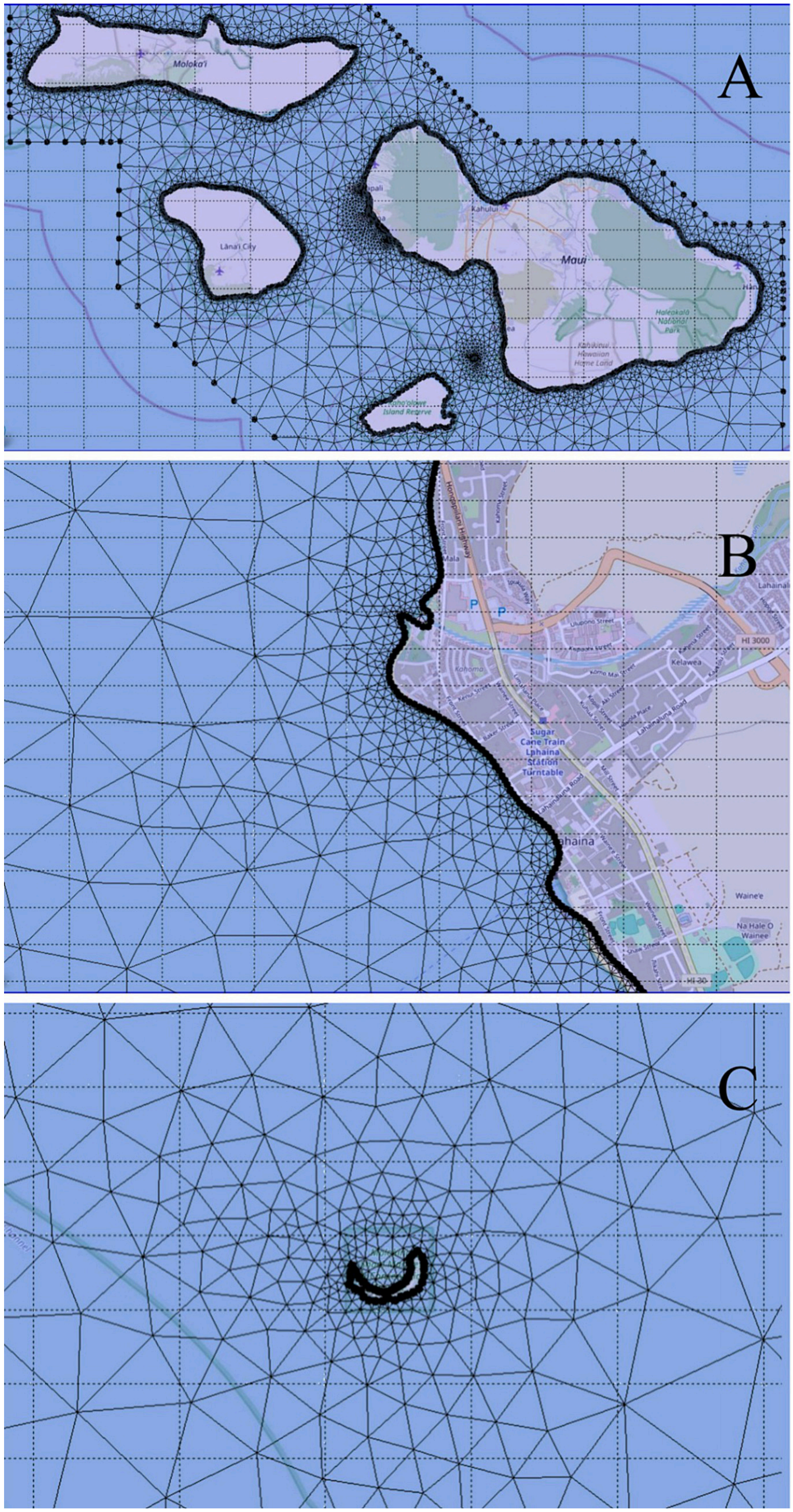

Fig. 3. Panel A - Computational grid. Panel B – Lahaina, Maui shoreline. Panel C -Molokini Marine Life Conservation District, south of Lahaina. Background map retrieved from https://planet.openstreetmap.org

(2008).

An assessment factor of 1000 was used to address differences between laboratory results and observed conditions in the wild to account for interspecies and intraspecies differences. It is argued to be standard practice to use an AF of 1000 for acute toxicity data and 100 for chronic toxicity data (Belanger et al., 2021). To calculate RQs, the following equation was used: RQ = (MEC)/(PNEC, NOEC, LC_{50} or EC_{50}) x 1000 (European Commission, 2003c; European Medicines Agency, 2006; Dussault et al., 2008). Toxicity reference values were obtained from the published literature as denoted in Table 1 (Chapman et al., 1998; Dussault et al., 2008; Environment Canada, 2013; Belanger et al., 2021; Jung et al., 2021). RQ values of 1 and higher are considered an unacceptable risk to the continuity of a population of a species when exposed to concentrations of a xenobiotic, e.g., benzo[*a*]pyrene and pentachlorophenol (Environment Canada, 2013).

For both benzo[*a*]pyrene and pentachlorophenol, calculations were made to determine concentrations at which their RQ = 1. The concentrations of these two compounds in the water column pose a hazard to relevant receptor or surrogate taxa at these toxicity reference values which can be found in Table 1a and Table 1b. The species included in this risk quotient assessment were chosen because they can be used as surrogates for Hawaiian subsistence fisheries. *Acropora* species in Hawaii are quite rare, but *Porites lutea* is endemic.

3. Results

3.1. Analysis of particle pathways

In Western Maui waters, the hydrodynamic model results, integrated with particle tracking, reveal two probable current patterns, which are primarily directed Southward (Supplementary Fig. 5A) and Northward (Supplementary Fig. 5B). The majority of particles drift south and southeast, with northward drifts occurring less frequently. Therefore, both benzo[*a*]pyrene and pentachlorophenol disperse in similar directions within the western Maui waters (Supplementary Fig. 4).

3.2. Dispersion analysis of benzo[*a*]pyrene

In a hypothetical 12-hour runoff scenario study, benzo[*a*]pyrene was released into the ocean in two separate events in November 2022, under

Table 1

Calculation of Risk Quotient for various species for Risk Quotient Plume construction. Toxicity reference values for either Lowest Observable Effect Concentration (LOEC) or Effect- and Lethal Concentration for 50 % (EC50, LC50) of the population for a specified exposure duration. Table 1A – Benzo[*a*]pyrene. Table 1B – Pentachlorophenol.

Table 1A

SPECIES	Benzo[*a*]pyrene toxicity endpoint		Toxicity Reference Value μg/L	Threshold μg/L	HQ value	References for Toxicity Reference Values
Coral						
Acropora formosa	bleaching	LOEC	10.00	0.01	1.00	Xiang et al., 2019
Acropora nasuta	bleaching	LOEC	10.00	0.01	1.00	Xiang et al., 2019
Algae						
Scenedesmus subspicatus	green algae - 7d growth inhibition	EC_{50}	1.48	0.00148	1.00	Djomo et al., 2004
Invertebrates						
Palaemonetes pugio	grass shrimp - mortality	LC_{50}	1.02	0.0010	1.00	Weinstein and Garner, 2008
Crassostrea gigas	larval development D-shell - 48 h (with UV)	LOEC	1.00	0.0010	1.00	Lyons et al., 2002
Lytechinus variegatus	4 cell development decrease with UVB light exposure	LOEC	1.00	0.0010	1.00	Steevens et al., 1999
Strongylocentrotus purpuratus	purple sea urchin developmental abnormalities -48 h	LOEC	1.00	0.0010	1.00	Hose et al., 1983
Fish						
Chanos chanos	Milkfish fingerlings mortality 96 h	LC_{50}	14.00	0.0140	1.00	Palanikumar et al., 2012
Oryzias javanicus	marine medaka embryos (F0) - mortality - 7d	LOEC	10.00	0.0100	1.00	Nam et al., 2020

Table 1B

SPECIES	Pentachlorophenol toxicity endpoint		Toxicity Reference Value μg/L	Threshold μg/L	HQ value	References for Toxicity Reference Values
Coral						
Porites lutea	bleaching-96 h	LOEC	1.00	0.0010	1.00	Zhang et al., 2024
Algae						
Skeletonema costarus	diatom - 96 h	EC_{50}	17.40	0.0174	1.00	U.S. EPA, 1980
Invertebrates						
Crassostrea virginica	Eastern oyster - 48 h	LC_{50}	40.00	0.0400	1.00	Borthwick and Schimmel, 1978
Penaeus aztecus	Brown shrimp	LC_{50}	195.00	0.1950	1.00	Schimmel et al., 1978
Paracentrotus lividus	sea urchin 48 h embryo development	EC_{50}	37.25	0.0373	1.00	Beiras and Tato, 2018
Fish						
Danio rerio	zebrafish yolk deformation/scoliosis 72 h	LOEC	0.10	0.0001	1.00	Cheng et al., 2015

varying ocean current conditions. The first release on November 15, 2022 occurred during northward flowing currents along the coastline, affecting marine ecosystems such as corals, brown shrimp, algae, fish, and sea urchins, particularly around the Lahaina coastal area (Fig. 4). This impact was primarily attributed to the limited quantity of benzo[*a*]pyrene entering this region and the initial direction of the northward currents. A second release on November 23, 2022 coinciding with dominant southern currents, led to a southern dispersion of benzo[*a*]pyrene, effectively flushing out most of the substance (Fig. 5). Despite the shift in the current direction, the majority of the identified impact hotspots were once again along the Lahaina coastline, indicating a consistent area of impact.

3.3. Dispersion analysis of pentachlorophenol

Considering a 12-hour runoff scenario, pentachlorophenol was released on two different days in November. The first release occurred on November 15, with the current pattern flowing along the coastline towards the north. In the analysis of this event, it was observed that various species including coral, brown shrimp, algae, fish, and sea urchin were impacted in different areas. This impact was primarily attributed to ocean currents which initially directed the pollutants northward, as evidenced in the particle tracking results (Supplementary Fig. 4), and subsequently dispersed them away from the Lahaina coastline towards the south, as depicted in Fig. 6.

The second release occurred on November 23, with the currents shifting towards the southern parts. With the predominance of southern currents over a 96-hour period, the dispersion pattern of the pollutants was oriented towards the south and southeast shores of West Maui, as illustrated in Fig. 7.

A "movie" (sequential time series) of the model that simulates the transport of pentachlorophenol and benzo[*a*]pyrene over one month is too large of a data size to be included in this manuscript but can be viewed at two websites, one that is hosted by https://climatheca.com/lahaina and the other hosted by the U.S. National Oceanic & Atmospheric Administration at https://coastalscience.noaa.gov/news/modeling-nearshore-contamination-risk-for-lahaina-hawaii-following-rainfall-events. The simulation includes two release scenarios on November 15 and November 23, based on typical November precipitation and runoff data. The flood hydrograph peaks at about 526.6 m^3/s, with a base time of 7.5 to 8 h for each release event. Thus, the duration of the model is one month, with specific focus on the events occurring for 8 h on the 15th and 23rd of November.

3.4. Risk quotient hot spot detection

In the West Maui waters, the distribution of detected hotspots for pentachlorophenol differs significantly from those of benzo[*a*]pyrene. The high concentration hotspots of benzo[*a*]pyrene, which exceed safe levels for the mentioned marine species, are predominantly concentrated along the Lahaina coastline (Figs. 4 and 5). This localized accumulation of benzo[*a*]pyrene poses a specific threat to the marine ecosystem in that region. In contrast, pentachlorophenol hotspots are scattered throughout the area, indicating widespread presence (Figs. 6 and 7).

Pentachlorophenol is also dispersed widely throughout the entire area, with its highest concentrations observed throughout. Pentachlorophenol is the only plume reaching the Molokini Crater, a State of Hawaii Marine Life Conservation District (Fig. 8; DLNR, 2023).

4. Discussion

4.1. Current flow aspects and particle dispersion patterns

Using a hydrodynamic model and a particle tracking algorithm, this study simulates the movement of debris from burnt structures as it is carried by floods, ocean currents, and tides. This model was designed to pinpoint areas along the coastline that are particularly susceptible to debris accumulation that threatens marine life and coastal ecosystems.

The Hawaiian Archipelago is a dynamically active zone from both oceanic and atmospheric points of view. When the North Equatorial Current meets the island of Hawaii, it splits into two branches, with bulk transport traveling around the southern-eastern part of the island, as the westward branch, and passing the island towards the west; meanwhile, the North Hawaiian Ridge Current follows the ridges of the other islands in the chain to the north. Both branches carry warm tropical waters, affecting the current fields around the islands. Winds from the northeast persist in the atmosphere, causing wind wakes in the lee of the peaks, particularly on Hawaii and Maui, when combined with the high terrain of the islands. This leads to high temperature gradients, a greater degree of seasonal variability, and the development of currents such as the Hawaiian Lee Countercurrent (HLCC) (Belmadani et al., 2013; and Hiroto et al., 2013). Maui, Lanai, and Molokai islands are affected by the interactions between NHRC and HLC currents. Long-term studies are required to determine possible current patterns in the area, however, over a one-month period in November 2022, two current patterns can be distinguished in the Maui-Lanai Channels (Auau Channel and Alalakeiki Channel).

Based on the hydrodynamic model results on Lahaina coastal waters, the currents can be classified into two categories: northward flowing currents and southward flowing currents. As the northward currents reach far from the shoreline of Lahaina, they are usually affected by regional southward currents and diverted southward, forming mostly local nearshore circular spots. Southward currents are more dominant in the study area. Supplemental Fig. 3 presents current patterns observed in model outputs. A mixing region can be observed in most cases near the source entrance at the channel outfall to the sea, where entrainment, turbulent mixing, and dilution take place, and farther downstream the concentration field gets wider as its concentration decreases. Local circulation near the entry inhibits the spreading of the plume to some extent, allowing lateral dispersion to dominate nearby. This locally mixed region generally follows the coastline and transports the plume northward up to a hundred meters, then collapses or fades, and the plume is carried away from the source area by the dominant current field.

4.2. Ecological risk and potential bioaccumulation

RQ Plume characterization can indicate which geographic coastal wildlife communities are at risk for toxic exposures. If the contaminant levels are high enough to elicit toxicity, then the contaminant is probably at a concentration to observe bioaccumulation, even if exposure is pulsed (short duration). Knowing which coastal habitats are impacted is of explicit value to wildlife conservation management. The issue of bioaccumulation is of value to public health management, because RQ plume distribution modeling can indicate fishery populations and their geographic distribution that may pose a threat to human consumption. Instead of randomly and erroneously sampling fishery populations not exposed to the plume (or not sampling and testing them at all), public health officials can sample specific geographies where retention and concentration levels could be hypothesized to be a potential hazard. Fisheries and public health management can more effectively use their limited financial resources to target contaminant chemistry testing. Fishery harvest may still continue in populations not exposed to the ash plume, while contaminant chemistry surveillance can be targeted to ash-plume impacted populations where retention levels in that area could be hypothesized to bioaccumulate.

Benzo[*a*]pyrene is a common pollutant generated from both urban and wildland fires. The concern is that it is of such high volume in ash materials that it poses a potential hazard, especially to marine habitats and human populations that consume contaminated wildlife (Wang et al., 2008; Sun et al., 2016; Sun et al., 2018; Jafarabadi et al., 2020). Its

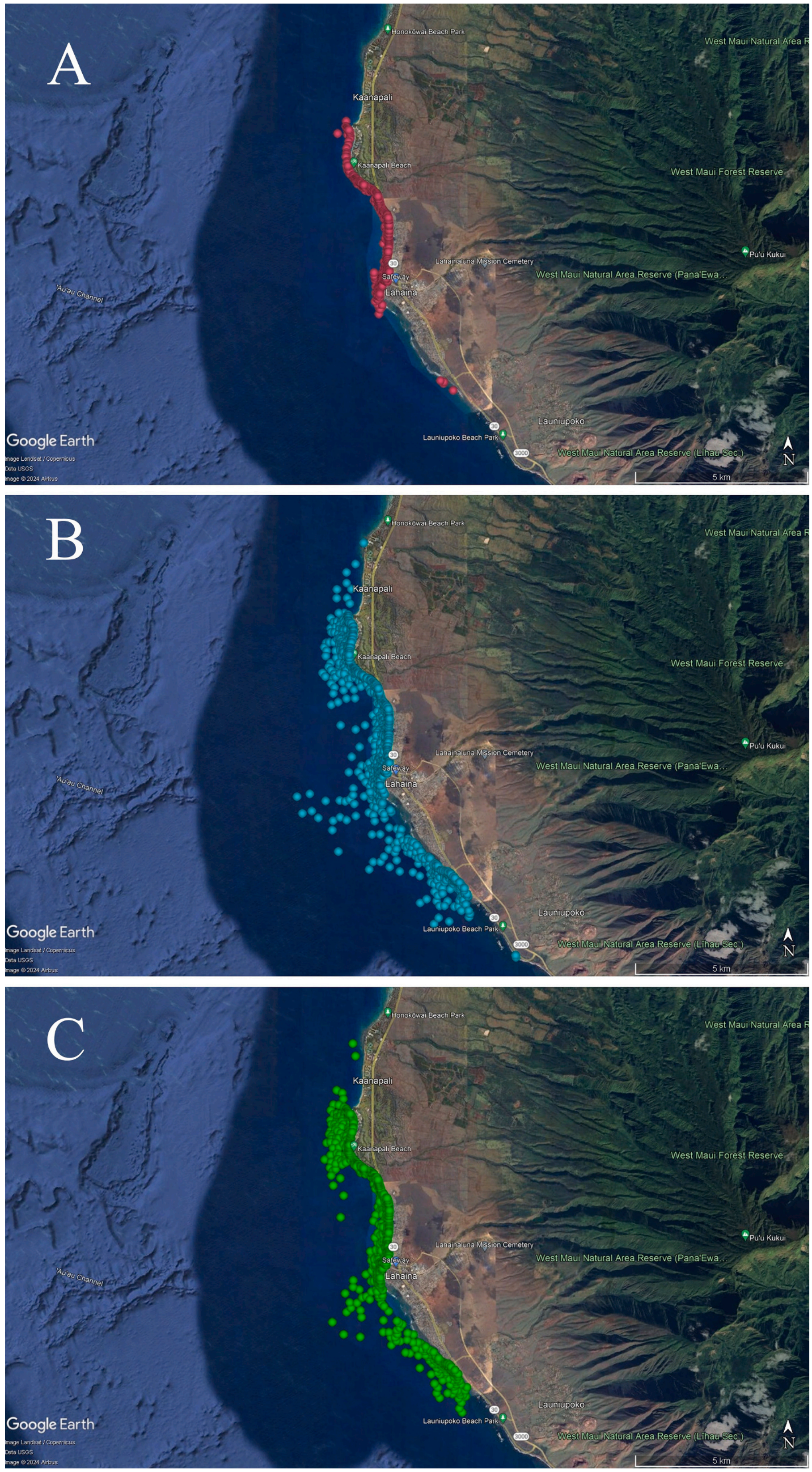

Fig. 4. Risk Quotient hot spot zones detected 96 h after benzo[*a*]pyrene release (Nov 15, 2022) using concentration fields. Panel A - Coral and Fish (threshold: 0.01 μg/L). Panel B - Invertebrates (threshold: 0.001 μg/L). Panel C - Algae (threshold: 0.002 μg/L).

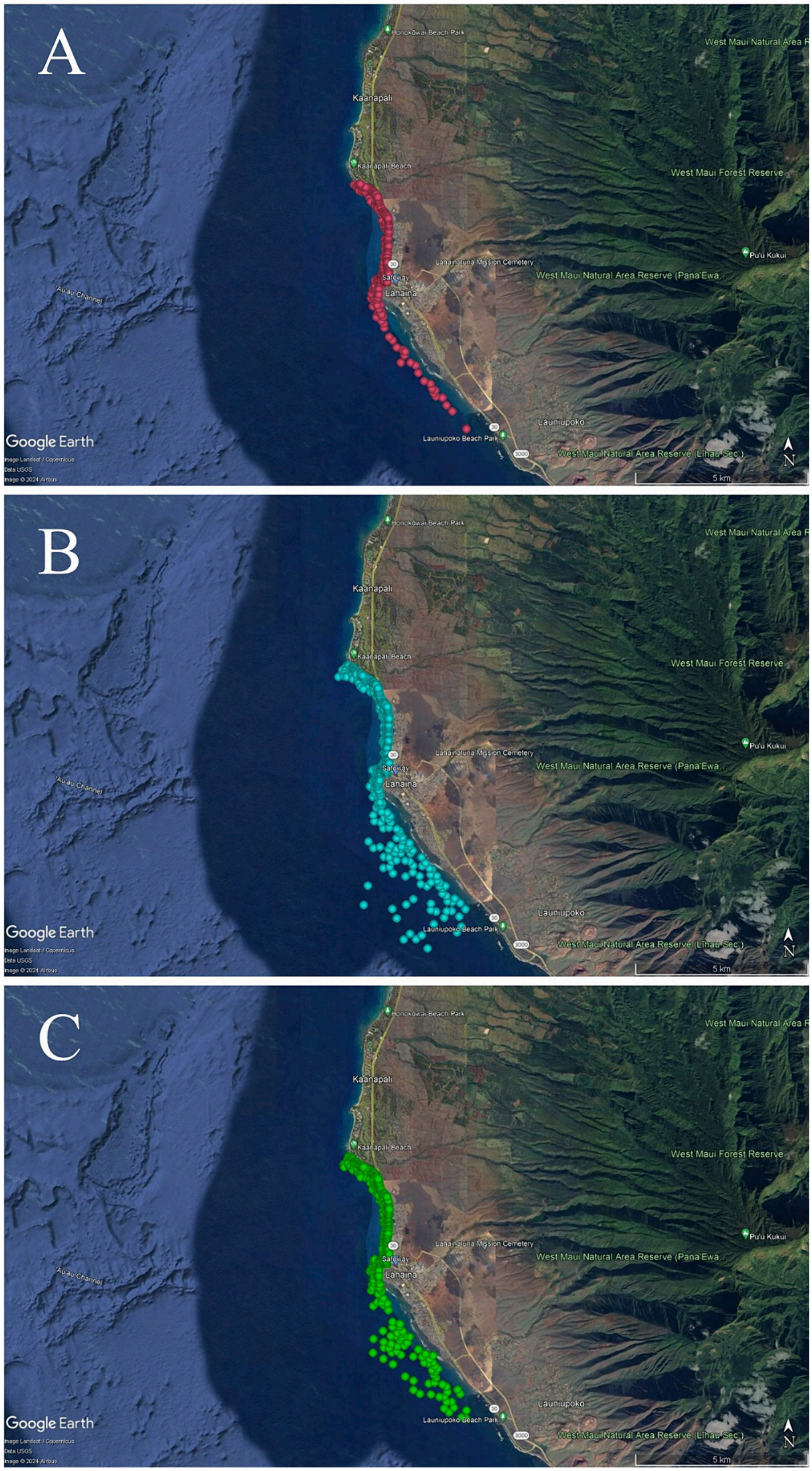

Fig. 5. Risk Quotient hot spot zones detected 96 h after benzo[*a*]pyrene release (Nov 23, 2022) using concentration fields. Panel A - Coral and Fish (threshold: 0.01 μg/L). Panel B - Invertebrates (threshold: 0.001 μg/L). Panel C - Algae (threshold: 0.002 μg/L).

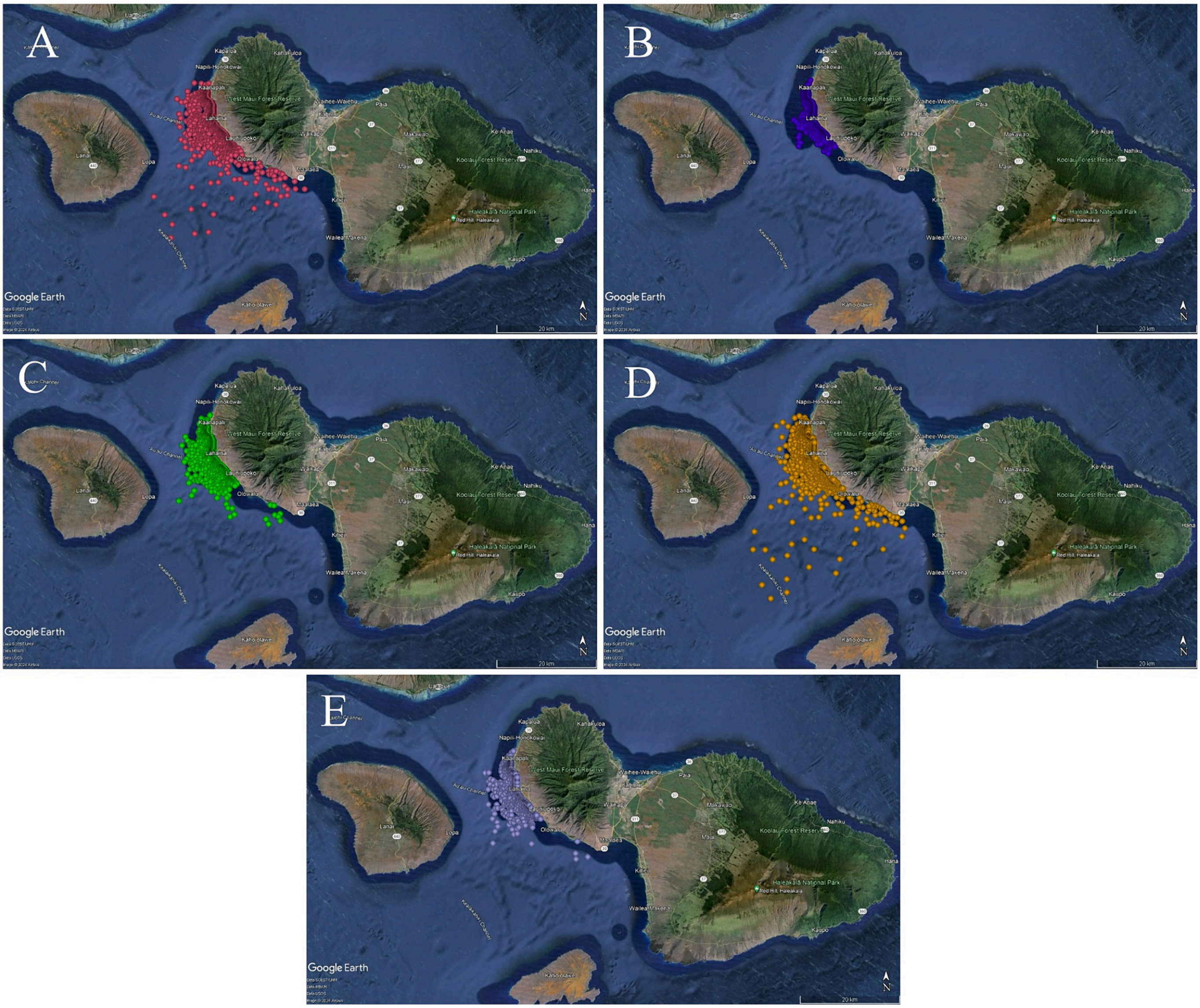

Fig. 6. Risk Quotient hot spot zones detected 96 h after pentachlorophenol release (Nov 15, 2022) using concentration fields Panel A - Coral (threshold: 0.0010 μg/L). Panel B - Brown shrimp (threshold: 0.1950 μg/L). Panel C - Algae (threshold: 0.0174 μg/L). Panel D - Fish (threshold: 0.0001 μg/L). Panel E - Sea urchin (threshold: 0.0373 μg/L).

wildlife toxicity ranges from being a known mutagen/carcinogen, induces porphyria and other metabolic pathologies, and is a demonstrated reproductive toxicant (Muzyka et al., 2002; Hoffmann and Oris, 2006; Uribe-Hernández et al., 2008; Wallace et al., 2020). Coral and fish exhibit a 10-fold lower toxicity to benzo[*a*]pyrene when compared to other invertebrates and algae (Table 1B). This manifests as reduced RQ plume risk of coral and fish compared to invertebrates and algae (Figs. 4 and 5). Benzo[*a*]pyrene is predominantly a threat to the near-shore coast line within Lahaina, while the RQ plume for non-coral invertebrates and algae pose a threat of over 2 km to offshore non-coral invertebrate populations (Fig. 4B). For both the November 15 and November 23 models, the RQ plume stays relatively close to the township border of Lahaina, with the southern limit being just north of Launiupoko Beach Park (Figs. 4 and 5). Benzo[*a*]pyrene may persist along this coastline for several weeks to months due to wave refraction and direction (Tubman and Suhayda, 1977; Santas and Santas, 2000; Guo et al., 2014). It can remain suspended in these areas during times of wave action and sediment resuspension (Onozato et al., 2016; Xiang et al., 2018; Habibullah-al-Mamun et al., 2019). Benzo[*a*]pyrene may be a good marker or surrogate for coral reefs impacted by wild/urban fire ash deposition since it was recently shown that wildfire ash emissions impair coral photosynthesis, causes a shift to heterotrophic feeding strategy which may increase the exposure to these fire pollutants, and inhibits coral calcification (Qin et al., 2024).

Pentachlorophenol is a persistent pollutant that is known to bioaccumulate in a number of fisheries (Trujillo et al., 1982; Guerrero et al., 2001; Mäenpää et al., 2004; Beiras and Tato, 2018; Rocha et al., 2018). In contrast to benzo[*a*]pyrene, pentachlorophenol contamination had a far more extensive distribution. For the November 15, 2022 model, pentachlorophenol RQ levels extended all the way to the Kealaikahki Channel (between the islands of Lanai and Kaho'olawe; Fig. 6). The November 23, 2022 model had RQ levels extending to the southern tip of the island of Maui, contaminating Molokini crater (a State of Hawaii Marine Life Conservation District) and ʻĀhihi-Kīna'u Natural Area Reserve (Fig. 7). Because pentachlorophenol bioaccumulates, it may pose a threat to coral populations in the affected areas during periods of high temperature, increasing their susceptibility to bleaching and mortality. These impacted areas may need to have their temperature-associated bleaching prediction models amended to show increased risk for bleaching (e.g., https://coralreefwatch.noaa.gov/satellite/bl

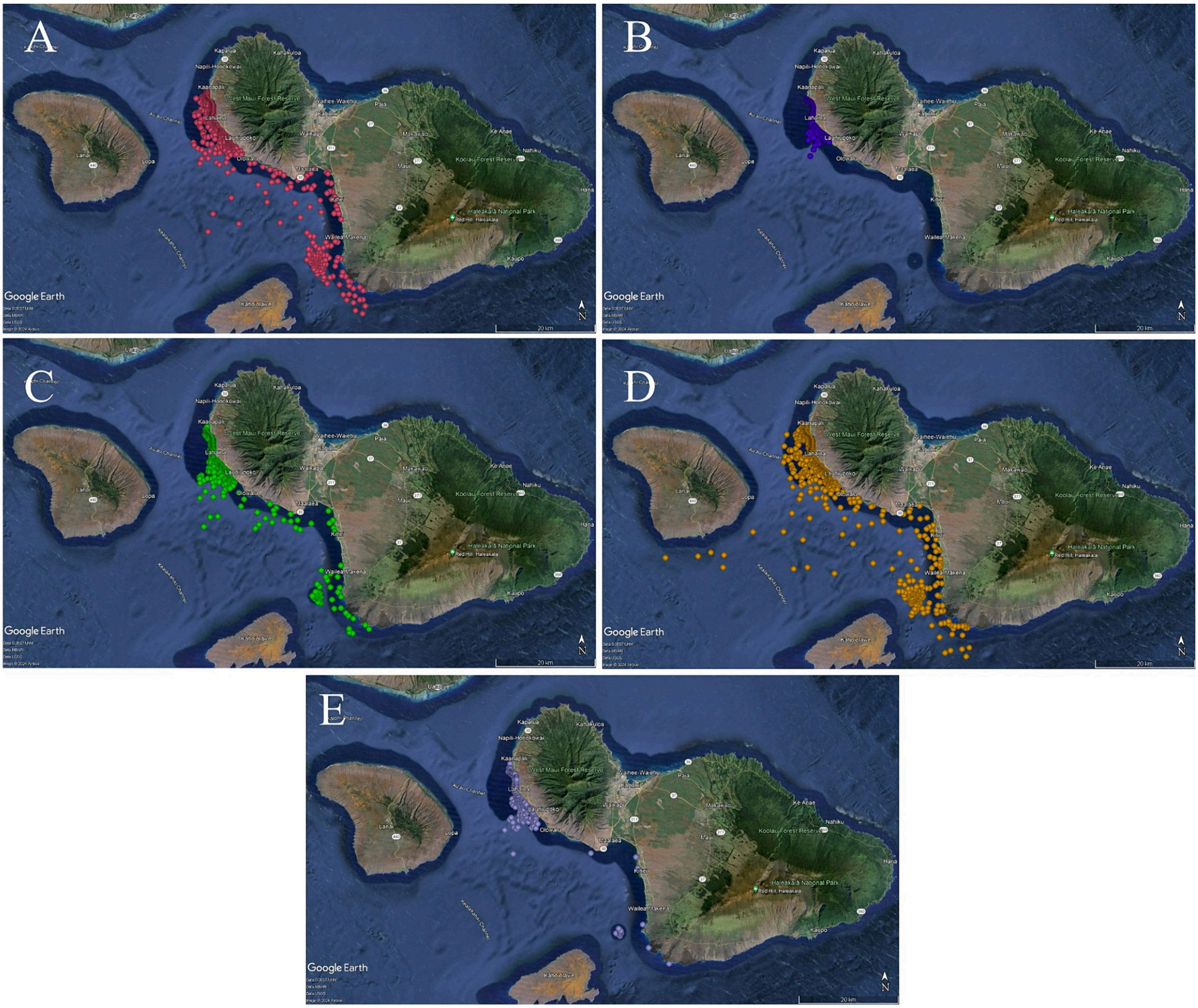

Fig. 7. Risk Quotient hot spot zones detected 96 h after pentachlorophenol after ash plume release event (Nov 15, 2022). Panel A - Coral (threshold: 0.0010 μg/L). Panel B - Brown shrimp (threshold: 0.1950 μg/L). Panel C - Algae (threshold: 0.0174 μg/L). Panel D - Fish (threshold: 0.0001 μg/L). Panel E - Sea urchin (threshold: 0.0373 μg/L).

eachingoutlook_cfs/index.php).

Pentachlorophenol-contaminated fisheries and *limu* (edible seaweed) potentially poses a health threat to local subsistence populations (Dougherty, 1978). Nearshore fisheries are often contaminated with pentachlorophenol, usually around 0.5–61 μg pentachlorophenol per kg of wet weight (ww) tissue in shrimp and fish (Ge et al., 2007). In 1977, the U.S. National Academy of Science (NAS) calculated an acceptable daily intake (ADI) for pentachlorophenol to be 3 μg/kg body weight per day, which was solely based on a feeding study in rats (U.S. EPA, 1988). In 1989, the World Health Organization released a report questioning the validity of the U.S. NAS ADI calculation because the "steady-state body burden is 10-20 times higher than the value extrapolated from rat pharmacokinetic data" (IPCS, 1989). This U.S. NAS calculation for ADI did not take into consideration carcinogenicity (e.g., hepatocellular carcinomas, adrenal pheochromcytomas, mesotheliomas, nasal squamous cell carcinomas, non-Hodgkin lymphomas) or reproductive and developmental toxicities (e.g., skeletal malformation, growth morbidities, fetal/neonatal mortality, decreased sperm counts) (IRIS, 2010; NTP, 2016; IARC, 2019; ATSDR, 2022). ADI's should be recalculated for demographics of subsistent consumers.

A significant caveat of this study's models is that it assumes the bulk of the source contamination is coming from the Kahoma stream/culvert. It does not account for direct source input of benzo[*a*]pyrene or pentachlorophenol from burn areas where the input is coming from surface runoff of grassland areas south of the road called Hokiokio Place. These benzo[*a*]pyrene ash contaminants would likely flow south to the Olowalu region. The choice of using the Kahoma stream watershed as the primary source is a conservative calculation assumption for the distribution of the ash plume along the Maui coastline.

A second caveat of this study is that the models do not account for residence time of the contaminant once it enters into an area. Based on wind/surf refractions, embayments that are contaminated may remain contaminated for a considerable amount of time. Swells and storms can cause resuspension of the contaminants, thereby increasing the length of exposure to contaminants.

Surveillance designs are usually conducted post-hoc of the calamitous event, as well as after events (e.g., storms) that transport the contaminants from the burn site to other locations. Knowing where these contaminants end up after a "transport" event is critical for knowing where to sample for both environmental impacts, and for assuring that

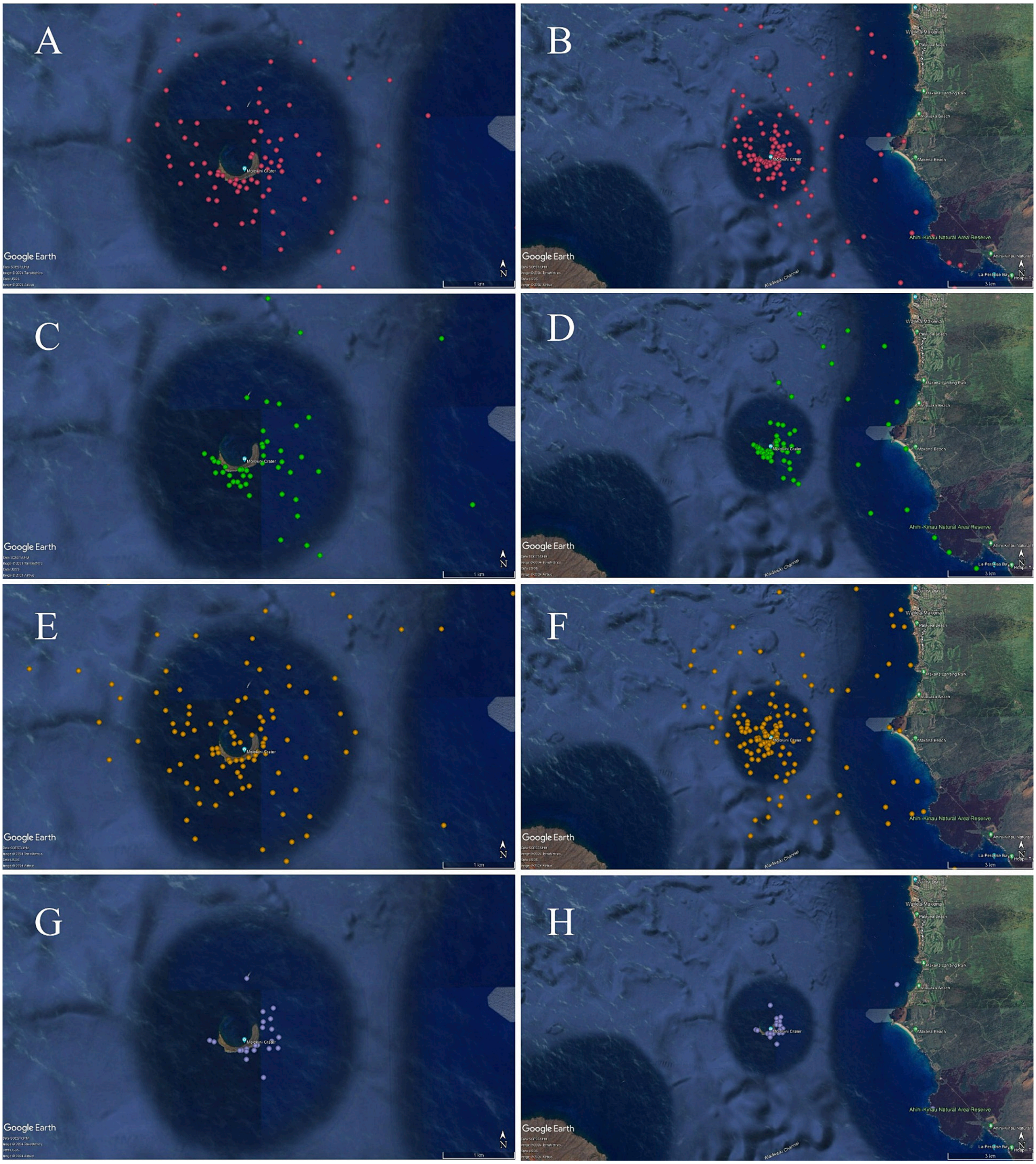

Fig. 8. Risk Quotient hot spot zones detected 96 h for pentachlorophenol after ash plume release event (Nov 23, 2022) for Molokini Crater Marine Life Conservation District to the Le Perouse Bay coastline immediately adjacent to ʻĀhihi-Kīnaʻu Natural Area Reserve. Panels A & B - Coral (threshold: 0.0010 μg/L). Panels C & D - Algae (threshold: 0.0174 μg/L). Panels E & F - Fish (threshold: 0.0001 μg/L). Panels G & H - Sea urchin (threshold: 0.0373 μg/L).

fisheries derived from specific localities are monitored.

4.3. Future studies

This foundational study was to create a model based on theoretical loading estimates on sequential historical rain events that would result in runoff and potential coastal contamination. A subsequent paper is being drafted that examines the accuracy of using this theoretical modeling against the first significant rainfall event in the Lahaina region after the urban/wildfire event in the week of January 8, 2024. Remote sensing of coastal water discoloration from watershed runoff is gathered along with water samples along the West Maui coastline to determine the level of accuracy and to identify factors that can generate corrections and improving the accuracy of the RQ Plume model methodology.

In addition to pollutants such as benzo[*a*]pyrene, dioxins, and pentachlorophenol, urban fires can produce significant amounts of microplastic debris (Luo et al., 2023). Plastic furniture, clothes, toys, curtains and wallpaper, PVC plumbing, and automobile components are some of the major sources of microplastics from urban fire events (e.g., Hale et al., 2022; Luo et al., 2024). Microplastics may even be formed from the weathering of the dust palliative from the plastic polymers used to secure the ash to the burn sites, especially when exposed to direct sunlight for months (Burrows et al., 2024). Microplastics from these sources will disburse into the marine environment with the arrival of the monsoon season (i.e. stormwater runoff) (Koutnik et al., 2022). RQ Plume modeling could also be used to determine if local fisheries are contaminated with these plastics and where the greatest contamination might take place. Sophisticated RQ Plume modeling may be needed to determine the dangers of pollutants adhering to plastics. Pesticides, petrogenically derived polycyclic aromatic hydrocarbons and even sunscreen chemicals adhere and are concentrated to microplastic marine debris, increasing their ecological threat (Pittura et al., 2018; Sharma et al., 2020; Lan et al., 2021; Concha-Graña et al., 2022).

5. Conclusion

This study provides the justification for regulatory agencies and community action groups to monitor subsistence fisheries along the West Maui coastline for the contamination of combustion-derived hydrocarbons and chlorinated hydrocarbons. Chlorinated dioxins and furan should especially be monitored in subsistence fisheries in these areas. The Maui medical community should also consider exposure of subsistence fishers or swimmers who frequent these potentially contaminated shorelines who seek medical attention if they have symptoms consistent with exposure to urban fires. Inhalation may not be the only route of exposure.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176346.

Disclaimer

The scientific results, conclusions, and opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of the U.S. National Oceanic & Atmospheric Administration or the U.S. Department of Commerce. The mention of any commercial product is not meant as an endorsement by the U.S. Federal government.

Access for viewing temporal model in its entirety. The models of the plume dispersion for both pentachlorophenol (PCP) and benzo[*a*]pyrene (BaP) can be viewed at these two websites: https://climatheca.com/lahaina and https://coastalscience.noaa.gov/news/modeling-nearshore-contamination-risk-for-lahaina-hawaii-following-rainfall-events.

CRediT authorship contribution statement

C.A. Downs: Writing – review & editing, Writing – original draft, Conceptualization. **Shadan Nasseri Doust:** Writing – review & editing, Methodology, Conceptualization. **S. Abbas Haghshenas:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Cheryl M. Woodley:** Writing – review & editing, Formal analysis. **Behzad Shirzad:** Formal analysis, Data curation. **E. Murphy McDonald:** Software, Data curation. **Ahad Nazarpour:** Methodology. **Aref Farhangmehr:** Formal analysis. **Hongwei Zhao:** Writing – review & editing, Methodology. **Elizabeth E. Bishop:** Writing – review & editing, Conceptualization. **Michael J. Risk:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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