

## EDITORIAL

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# Understanding health effects pathways and thresholds: filling a critical need to support microplastics management

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Microplastics are pervasive in the aqueous environment, having been reported in air, lakes, ocean, drinking water, sediment, snow, animals, and even humans [1–4]. Since plastic pollution was first documented in the marine environment in the 1970's [5], production has increased more than 10-fold [6], and inputs into the environment are expected to triple over the next ~20 years [7]. Since plastic degrades over extremely long timescales [8] and is ingested, inhaled, or absorbed throughout the food chain from microscopic organisms to humans [9–11], contamination is causing increasing concern for environmental managers. Many animals cannot distinguish microplastics from food, creating the potential for satiation challenges that can lead to decreased growth, reproduction, and survival [12]. Once microplastics enter food webs, they can be consumed by humans through seafood and other means [13]. Compounding the bioaccumulation challenge and toxicity of plastic particles by themselves is that plastics can serve as vectors for added chemicals [14–16] and attached pathogens [17, 18], creating a potential exposure pathway for multiple types of contaminants. Additionally, the smallest microplastics can penetrate the gut wall and accumulate in tissues that obstruct organ function [19–21].

The State of California has already taken robust management actions to reduce the amount of plastics in the environment and is developing additional long-term strategies [22]. Prominent among those was the first assignment of a water body to the federal 303(d) list as

impaired due to the presence of trash [23]. This action enabled water-quality agencies to issue a regulatory target for trash known as a total maximum daily load (TMDL), which compels entities that discharge runoff to reduce trash loading [24]. The California State Water Resources Control Board expanded on this by amending the master plans that govern management of California's coastal ocean and freshwater systems to include trash as a water-quality impairment, requiring agencies that discharge runoff to install storm drain inlet devices that to capture all particles larger than 5 mm, or develop an alternate plan for capturing trash at equivalent rates [25].

In addition to capturing plastic entering the marine environment, California has also been aggressive at reducing plastics at the source. For example, California voters approved in 2016 a statewide ban on carry-out plastic bags at grocery stores [26], and in 2021, passed a law prohibiting restaurants from distributing single-use plastic food ware to customers, except upon request [27]. To limit impacts of primary microplastics, California enacted regulations on facilities that manufacture, handle and transport pre-production plastic pellets that serve as the raw materials for plastic production [28], and is evaluating whether companies should be required to perform alternatives analyses for products that contain intentionally added microplastics through the state's green chemistry program [29].

To specifically address the risks of microplastics to humans and aquatic ecosystems, California passed two legislative mandates in 2018. Senate Bill 1263 requires the California Ocean Protection Council to adopt by 2022 a microplastics management strategy for assessing and mitigating ecological risks to coastal marine ecosystems

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[30]. Senate Bill 1422 requires the California State Water Resources Control Board to implement routine drinking water microplastics monitoring by 2021 [31].

Achieving these mandates requires addressing a number of scientific needs. First among those is agreeing on a definition of microplastics, which is a necessary first step toward management of these diverse particles. The California Water Resources Control Board adopted an intentionally broad regulatory definition in 2020 to ensure the broad range of potentially harmful plastic particles are considered [32, 33], which was based on converging definitions in the literature [34]. Next was the development of standard measurement methods, which California addressed through an inter-laboratory method comparison study that quantified effectiveness of various analytical techniques for measuring microplastics concentrations in water, sediment and tissue matrices [35]. Third, was identifying prevalence of microplastics in the environment and the sources that lead to that contamination, with the first exemplary monitoring in the state conducted in San Francisco Bay [36, 37].

However, the largest scientific need is understanding biotic effects pathways and abundance thresholds at which health effects manifest. Monitoring data allows for risk characterization when they are compared to concentrations at which health effects manifest. Such health effects thresholds are a primary driver in determining the urgency for imposing management controls, often forming the foundation for regulatory actions in California and other jurisdictions [38]. To help develop thresholds that support its legislative management needs, the State of California held a workshop that brought together experts from around the world. This special issue of the journal is dedicated to sharing the outcomes of that workshop.

The workshop focused on defining pathways of potential effect for microplastics and which particle characteristics, such as size, shape, polymer type, or additional factors most contribute to toxicity (Hampton et al. 2022 [39], “*Characterizing microplastic hazards: Which concentration metrics and particle characteristics are most informative for understanding toxicity in aquatic organisms?*”). The experts also identified management constructs that are responsive to legislative requirements and into which decision thresholds are embedded for aquatic ecosystems [40] and human health through drinking water (Coffin et al. 2022 [41], “*Development and application of a health-based framework for informing regulatory action in relation to exposure of microplastic particles in California drinking water*”). The risk assessment framework for ambient water was applied to monitoring data in San Francisco Bay, California to assess risks and inform management strategies (Coffin et al.

2022 [41], “*Risk Characterization of Microplastics in San Francisco Bay, California*”). While sufficient evidence was available to derive thresholds for aquatic ecosystems with a moderate-high degree of certainty, key information and data quality were lacking for quantitatively assessing risks to humans through drinking water exposure [42]. To increase confidence in future risk assessments, workshop participants identified knowledge gaps and recommended additional research to fill them (Hampton et al. 2022 [43], “*Research Recommendations to Better Understand the Potential Health Impacts of Microplastics to Humans and Aquatic Ecosystems*”) and developed an interactive open-source and open-data online tool (Toxicity of Microplastics Explorer - “ToMEx”) that allow researchers to rapidly query and upload microplastics toxicity data, visualize multi-variate relationships, and derive species sensitivity distributions using site-specific particle distribution data, species, and statistical parameters (Hampton et al. 2022 [44], “*A Living Tool for the Continued Exploration of Microplastic Toxicity*”).

In addition to serving as a key factor in regulatory decision-making for pathway interventions and cleanups, health effects pathways and thresholds also drive management strategies to prevent pollution from entering the environment. Microplastics are a diverse contaminant suite comprised of many polymer types, sizes, and shapes [45] with more than 10,000 added chemicals [46], of which some may drive toxicity in humans and in ecological receptors [47–49]. Understanding the relative toxicity of each of these components allows for strategies to reduce the input of the most harmful materials into the environment through safer-by-design regulatory frameworks as well as bans and reduction targets [50]. To inform these management efforts, Hampton et al. [39] performed a meta-analysis to identify physical characteristics of microplastics that are most important for toxicity, finding that size is a critical factor, and Peters et al. [51] used human physiological in vitro models in combination with analytical chemistry to identify hazardous chemicals associated with environmental microplastics.

Understanding health effects thresholds and pathways is also critical to developing effective monitoring programs. Numerous analytical techniques are available to quantify microplastics, with some being more appropriate and cost-effective for different sizes, shapes and polymer types [52]. For instance, visual microscopy might be used for particles larger than ~500 µm, Raman spectroscopy for particles larger than ~5 µm and electron microscopy for even smaller particles, each requiring different protocols and encompassing substantial cost differences [35]. Moreover, some techniques allow for estimation of the total mass of polymers (e.g. pyrolysis-gas chromatography/mass spectrometry)

without providing detailed information about the particles' sizes or shapes, while others can quantify particle counts in addition to these other parameters (e.g., Raman and infrared spectroscopy) [52]. Such analytical limitations have led to non-alignments between environmental monitoring data and laboratory toxicity data which can be accounted for through understandings of toxicity mechanisms and distributions of particle characteristics such as size, shape, and density [14]. While such estimation methods allow for assessments of risk ([40]; Coffin et al. 2022 [41] "*Development and application of a health-based framework for informing regulatory action in relation to exposure of microplastic particles in California drinking water*"), they may result in decreased confidence in risk characterizations (Coffin S, Weisberg SB, Rochman C, Kooi M, Koelmans AA: Risk characterization of microplastics in San Francisco Bay, California, submitted) "*Risk Characterization of Microplastics in San Francisco Bay, California*"), prompting the need for more holistic monitoring regimes. Additionally, understanding the thresholds at which effects are likely to begin manifesting is important to determining the appropriate water volume to sample (e.g., for drinking water; Coffin et al. "*Development and application of a health-based framework for informing regulatory action in relation to exposure of microplastic particles in California drinking water*"), as sampling too little water could lead to incorrect conclusions about a lack of risks.

Given these challenges and recent innovations, with this special collection we offer for the first time a cohesive and aligned series of articles covering all facets of microplastics risk assessment. Using a data-driven and quality-screening approach, we developed risk assessment and management thresholds for aquatic ecosystems, developed recommendations for further research to assess risks to humans, and performed meta-analyses to shed light on the complex multi-factorial interactions between plastic particles and biological systems.

#### Abbreviations

TMDL: Total maximum daily load; U.S. EPA: United States Environmental Protection Agency; ToMEX: Toxicity of Microplastics Explorer.

#### Acknowledgments

The authors would like to thank the participants of the Southern California Coastal Water Research Project's 2020-2021 microplastics health effects workshop for their contributions to manuscripts in this special collection. The authors would also like to thank Dr. Mark Gold and Kaitlyn Kalua from the Ocean California Protection Council for providing insights on state agency needs for managing risks from microplastics.

#### Authors' contributions

S.C. and S.B.W. conceptualized, wrote and reviewed the main manuscript. The author(s) read and approved the final manuscript.

#### Author's information

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any California State agency.

#### Funding

Funding for this work are from the California State Water Resources Control Board.

#### Availability of data and materials

Not applicable.

#### Declarations

#### Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Published online: 05 April 2022

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