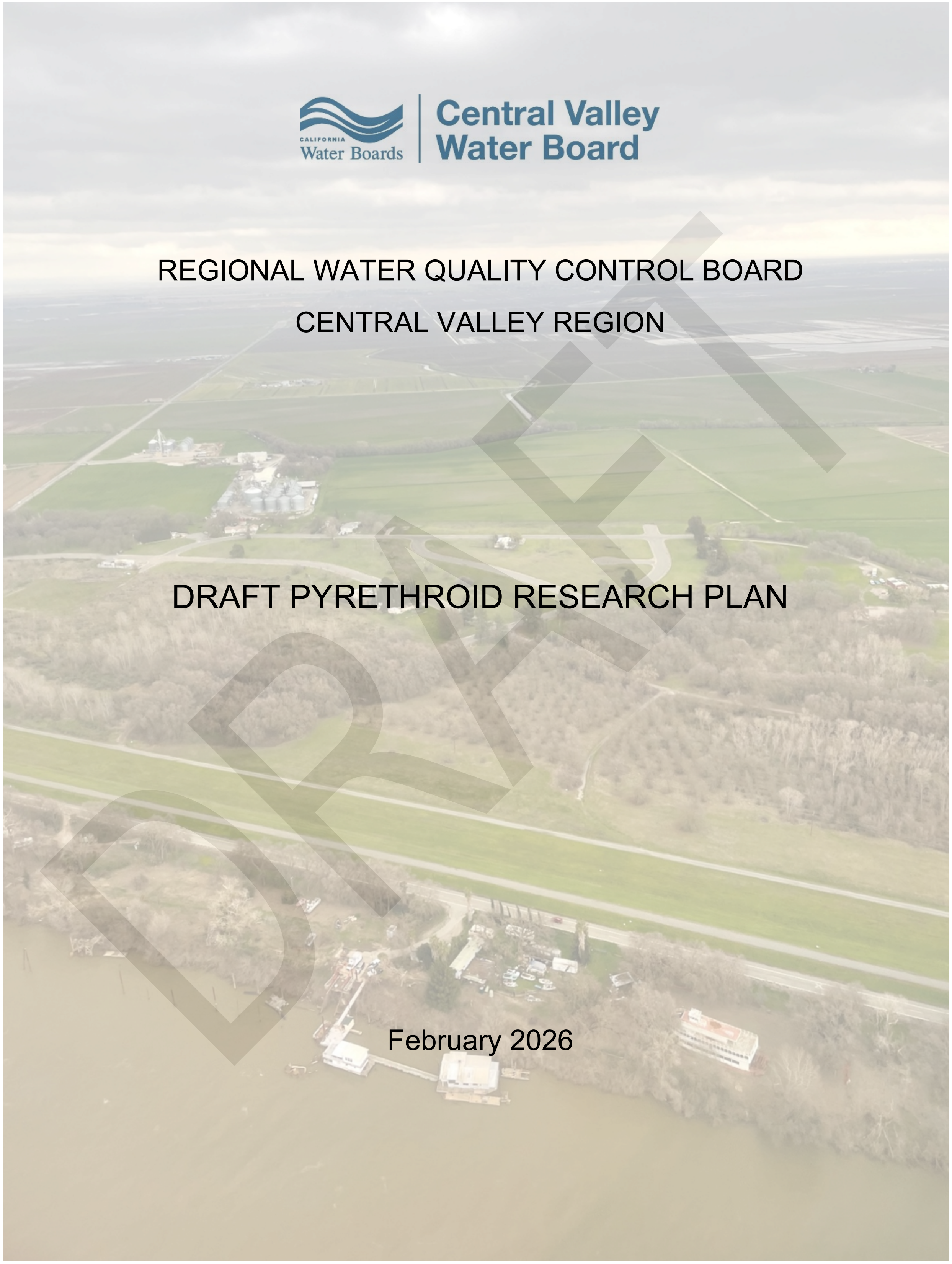

California Water Boards | Central Valley Water Board

REGIONAL WATER QUALITY CONTROL BOARD

CENTRAL VALLEY REGION

DRAFT PYRETHROID RESEARCH PLAN

February 2026

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PYRETHROID RESEARCH PLAN

FEBRUARY 2026

REGIONAL WATER QUALITY CONTROL BOARD
CENTRAL VALLEY REGION

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

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The cover photo of the Sacramento River was taken by Sajleen Phagura.

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Glossary:

Additive Toxicity: Toxic effects of two or more chemicals equal the sum of the effects of the chemical acting independently.

Adsorption: Physical and chemical attraction between two substances, such as binding of an organic compound to the surface of another compound. For example, binding to organic carbon.

Beneficial Uses: Designated uses of a waterbody. Beneficial uses are defined by State laws to protect against quality degradation and are critical to water quality management in California. Beneficial uses of the waters of the state that may be protected against quality degradation are listed in Chapter 2 of the Water Quality Control Plans for the Sacramento and San Joaquin River and Tulare Lake Basins.

Bioaccumulation: The concept that exposure to an organic chemical over an organism's lifespan results in higher concentration of that chemical in the organism as it ages. Bioaccumulation occurs when an organism absorbs a substance faster than it can be lost or eliminated by catabolism and excretion. Pyrethroids tend to accumulate in organism fat due to their lipophilic properties which also allow them to adsorb to soil organic matter.

Bioavailable: The fraction of a chemical that enters the organism and can have an effect. This is not always equivalent to organismal exposure to a chemical. The Pyrethroid Control Program assumes that pyrethroids bound to suspended solids or to dissolved organic matter have a much smaller toxic effect on aquatic organisms compared to pyrethroids that are freely dissolved.

Biomagnification: The process that occurs as a chemical transfers from lower trophic levels to higher trophic levels within a food web, resulting in a higher concentration in apex predators.

Biotransformation: Biochemical reactions by an organism that modify the chemical structure and activity of a compound that has entered the organism through an exposure pathway.

Concentration Addition Model (CA Model): Concentration Addition Model is a mixture toxicity concept that applies to chemicals with the same mode of action to produce a total effect in organisms equivalent to that caused by the total concentration from contributing chemicals. In short, the CA Model calculates toxicity in an organism exposed to a mixture of chemicals with the same mode of action. The model treats mixtures as one chemical with a concentration that is equivalent to the total concentration of the component chemicals. For example, 2A + 0.4B + 0.6C = 3 A or 3B or 3C, where A, B, and C have the same mode of action.

Co-stressor: A stressor co-occurring spatially and temporally with another stressor. The presence of a co-stressor may partly mitigate the adverse effects (i.e. antagonistic) of the other stressor, cause a predictable linear increase in effects (i.e. additive), or, in some cases, result in consequences more severe than those predicted from the summed effects of each stressor (i.e. synergistic).

Cold Freshwater Habitat (COLD) Beneficial Use: Uses of water that support cold water ecosystems, including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish, or wildlife, including invertebrates.

Desorption: The physical process by which adsorbed compounds are released from the surface of another compound.

Dissolved Organic Carbon (DOC): the fraction of organic carbon dissolved in the aqueous phase, operationally defined as that which can pass through a filter with a pore size typically between 0.22 and 0.7 micrometers.

Dissolved Organic Carbon-Water Partition Coefficient (K_{DOC}): The ratio of a chemical concentration adsorbed to DOC to that chemical concentration in the dissolved phase at equilibrium.

EC_x: The chemical concentration at which x% of a test group exhibits the toxicity endpoint (mortality, inhibition of growth, impaired reproduction, etc.) compared to the control group.

Enhancement: The interaction of two chemicals where one chemical increases the effect of the other, but their combined effect is not greater than the sum of the effects seen when exposed to each chemical alone.

Hydrophobic or Hydrophobicity: A chemical property that renders the chemical unable to dissolve in water. Pyrethroids are hydrophobic chemicals, meaning they have a strong tendency to bind to surfaces instead of being freely dissolved in water.

Independent Action Model (IA Model): Independent action model is a mixture toxicity concept that applies to chemicals with different modes of action at different target sites.

Integrated Report Category 4b: For an impairment listing, a total maximum daily load (TMDL) is not needed because other pollution control requirements are expected to result in the attainment of an applicable water quality standard (WQS) in a reasonable period. For example, the Pyrethroid Control Program numeric triggers are expected to be attained through waste discharge requirements of the Central Valley Water Board's Irrigated Lands Regulatory Program.

LC_x: The concentration of a chemical at which x% of the organisms in a test group are killed compared to a control group.

Partition Coefficient: The ratio of the concentration of a chemical in one medium or phase (C1) to the concentration in a second phase (C2) when the two concentrations are at equilibrium.

Particulate Organic Carbon (POC): the mass of carbon in the particulate organic material suspended but not dissolved in the aqueous phase. This fraction includes partially decomposed detritus and plant material, pollen, and other materials.

Potentiate or Potentiated: The ability of a chemical to increase the potency of another chemical. See “Synergists”.

Pyrethroid Numeric Trigger: Equivalent to the concentration goal unit of one (1) not to be exceeded more than once in a three-year period under either an acute (AGU) or chronic (CGU) exposure scenario. The AGUs and CGUs are calculated as the sum of individual freely-dissolved pyrethroid concentration-to-acute concentration goal or freely-dissolved pyrethroid concentration-to-chronic concentration goal ratios, respectively, as defined in the formula in Table 4-2 of the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins. Please see the Final Staff Report (Water Board, 2017) for more information regarding derivation of the pyrethroid numeric triggers.

Soil Organic Carbon-Water Partition Coefficient (K_{OC}): The ratio of a chemical concentration adsorbed to organic particles to that chemical concentration in the dissolved phase at equilibrium.

Suspension: A mixture of a liquid and solid particles where the particles do not dissolve but are dispersed throughout the liquid.

Synergists: A chemical that enhances the effectiveness (potentiate) of another chemical, i.e., the effect of piperonyl butoxide (PBO) on pyrethroids.

Synergy: The interaction of two or more chemicals when their combined effect is greater than the sum of the effects seen when exposed to each chemical alone.

Total Maximum Daily Load (TMDL): TMDLs are a “pollution budget” that define the maximum amount of a pollutant that a waterbody can receive while still meeting water quality targets. TMDLs are employed as a water quality control strategy to address waterbodies that are determined through the Integrated Report as not meeting water quality thresholds for a given pollutant. For the Pyrethroid Control Program, the TMDL numeric targets are equivalent to the pyrethroid numeric triggers.

Toxicodynamic: The quantitative description of the effects of a toxicant on a biological system. These effects include a range of endpoints and products, ranging from the molecular level, to cells, tissues, organ systems, and life-history traits.

Toxicokinetic: The life cycle of a chemical in an organism from exposure to excretion. This includes absorption, distribution, metabolism, and excretion of a chemical within an organism.

Ubiquitous: The state of being present everywhere.

Vicissitudes: A fluctuation of state or condition, typically one that is unfavorable.

Volatilize: The action of a chemical evaporating or dispersing in a vapor form.

Warm Freshwater Habitat (WARM) Beneficial Use: Uses of water that support warm water ecosystems, including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish, or wildlife, including invertebrates. WARM includes support for reproduction and early development of warm water fish.

Water Quality Objectives (WQOs): The limits or levels of water quality constituents or characteristics which are established for the reasonable protection of beneficial uses of water or the prevention of nuisance within a specific area (Water Code § 13050(h)).

Water Quality Standard: Provisions of State or Federal law which consist of a designated use or uses for the waters of the United States and water quality criteria for such waters based upon such uses. Water quality standards are to protect the public health or welfare, enhance the quality of water and serve the purposes of the Act (40 CFR 131.3(i)).

1. Introduction

Pyrethroids are synthetic pesticides widely used for pest control in residential, urban, and agricultural areas throughout the Central Valley. Sources of pyrethroids include runoff from urban and agricultural applications (Water Board, 2017). Pyrethroids have also been detected in municipal wastewater treatment plant (also known as publicly owned treatment works or POTW) effluent at levels of concern (Water Board, 2017).

Central Valley monitoring results from 2002 - 2011 identified pyrethroids at levels of concern for aquatic invertebrates in waters and sediments of the Sacramento and San Joaquin River watersheds (Water Board, 2017). Six pyrethroids have been identified as priority constituents due to their association with 303(d) listings and their high use rate in the Sacramento and San Joaquin River Basins on a mass basis. The six priority pyrethroids are bifenthrin, cyfluthrin, cypermethrin, esfenvalerate, lambda-cyhalothrin, and permethrin. To address pyrethroid impairments, the Central Valley Regional Water Quality Control Board (Central Valley Water Board or Board) established a Control Program for Pyrethroid Pesticide Discharges, including a conditional prohibition of discharge and a total maximum daily load (TMDL) for the nine urban water bodies on the 303(d) list for pyrethroid pesticides as of 2017.

A. Pyrethroid Control Program Overview

On 8 June 2017, the Central Valley Water Board adopted the Amendment to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins for the Control of Pyrethroid Pesticide Discharges (Pyrethroid Control Program). The State Water Resources Control Board (State Water Board) approved the Pyrethroid Control Program on 10 July 2018. The Office of Administrative Law (OAL) approved the Pyrethroid Control Program on 19 February 2019, enacting the conditional prohibition. Following U.S. EPA approval of the Pyrethroid Control Program on 22 April 2019, the TMDL became fully effective. More information can be found on the Central Valley Water Board website (https://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/resolutions/r5-2017-0057_res.pdf)

The Pyrethroid Control Program modified Water Quality Control Plan for the Sacramento River and San Joaquin River Basins (Basin Plan) Chapter IV (Implementation) to include a pyrethroid conditional prohibition for the Sacramento and San Joaquin River Basins and established a TMDL for six priority pyrethroid pesticides in nine urban water body segments and a TMDL alternative (Category 4b) in five waterbody segments receiving agricultural discharges (Basin Plan, Table 4-21 and Table 4-22, respectively). The Pyrethroid Control Program also modified Basin Plan Chapter V (Surveillance and Monitoring) to include monitoring and reporting requirements for agricultural, municipal stormwater, and municipal and domestic wastewater dischargers.

The Pyrethroid Control Program established aquatic life protection-based numeric triggers, which apply to all water bodies with aquatic life beneficial uses within the Sacramento and San Joaquin River Basins. The Pyrethroid Control Program prohibits discharges of six priority pyrethroids (bifenthrin, cyfluthrin, cypermethrin, esfenvalerate, lambda-cyhalothrin, and permethrin) at concentrations above the numeric triggers unless the discharger is implementing an approved management plan to reduce pyrethroid levels in their discharges. The Pyrethroid Control Program includes baseline monitoring requirements for both agricultural and municipal stormwater and wastewater dischargers to determine attainment of the numeric triggers. Under the conditional prohibition, dischargers are required to develop pyrethroid management plans with an adaptive management component if their discharges do not attain the numeric triggers. For stormwater and wastewater dischargers, management plans focus on education and outreach as these entities lack the authority to regulate pesticide use in their service areas. Trend monitoring, once implemented, will evaluate the effectiveness of these management plans. The Pyrethroid Control Program also contains provisions for monitoring and managing alternative insecticides to the six priority pyrethroids.

The Central Valley Water Board selected numeric triggers instead of water quality objectives (WQOs) due to insufficient information to satisfy California Water Code Section 13241 (Water Code 13241). Specifically, there was limited quantitative data on the effectiveness of available pyrethroid controls and the ultimate discharger costs to attain potential pyrethroid WQOs. For further details on the regulatory approaches considered and the associated rationales, please see Chapter 3 of the Final Staff Report (Water Board, 2017).

In recognition of the previously described uncertainties, the Pyrethroid Control Program was designed as a phased approach with a commitment to re-evaluate the Pyrethroid Control Program no later than 19 February 2034. A goal of the phased approach was to gather information to complete a full analysis of the Water Code 13241 factors when the Central Valley Water Board revisits the Pyrethroid Control Program so that the Board could then determine if, and at what level, pyrethroids WQOs are reasonable and necessary to protect beneficial uses. To this end, the surveillance and monitoring provisions established in the Pyrethroid Control Program enable determination of numeric trigger attainment in current discharges while collecting information to support consideration of the Water Code 13241 factors. Data collected will also identify whether source control actions are necessary to alleviate the impacts of pyrethroid and alternative insecticides. Additional studies and/or data collection efforts may be necessary to compile the needed information to properly consider the Water Code 13241 factors for the re-evaluation of the Pyrethroid Control Program.

B. Pyrethroid Research Plan Development

During the synthesis of the Final Staff Report (Water Board, 2017), Board staff recognized that the data used to evaluate the potential for registered pyrethroid products to cause or contribute to water quality concerns contained considerable knowledge gaps. In recognition of this, the Pyrethroid Control Program includes a provision that identifies the following as topics that required further study:

1. potential refinement of partition coefficients (K_{OC}, K_{DOC});
2. further assessing the need to incorporate temperature effects in toxicity relationships;
3. consideration of synergists and potential mixture effects with other commonly occurring contaminants on pyrethroid toxicity;
4. consideration of the need for chronic toxicity values for taxa for which data are not currently available;
5. evaluation of sublethal effects;
6. fate and transport of particulate-bound pyrethroids;
7. consideration of monitoring and laboratory methods for both pyrethroid chemistry and toxicity testing and inter-laboratory comparison.

This provision, found in Basin Plan section 4.5.5.1(8), states that the Central Valley Water Board will work with stakeholders to develop a Pyrethroid Research Plan (Plan) that will describe research and other special studies to inform future iterations of the Pyrethroid Control Program (e.g., potential objectives, program refinement). The provision requires the Central Valley Water Board to coordinate and consult with the Delta Science Program, Delta Independent Science Board, Delta Stewardship Council, Department of Fish and Wildlife, and Delta Regional Monitoring Program, as appropriate, and seek to implement the Plan through available funding mechanisms.

Since the adoption of the Pyrethroid Control Program, the Central Valley Water Board has provided resources to inform some knowledge gaps and conducted a scientific literature review to determine if recent studies were sufficient to fill the identified knowledge gaps (see items 1 - 7 above). The Central Valley Water Board allocated discretionary contract funds to investigate site-specific partition coefficients (to inform item 1) as well as staff resources to coordinate laboratory method development for pyrethroid water column chemistry (to inform item 7). Board staff performed the literature review in 2023 using the search engine Google Scholar to identify scientifically peer-reviewed articles with relevance to the knowledge gaps using the following key words: “pyrethroids”, “toxicity”, “aquatic”, “sublethal”, “chronic”, “temperature”, “microplastics”, and “mechanism”. Board staff reviewed and summarized the relevant journal articles in the Plan.

The scientific literature review determined that, while further research had been conducted related to the previously identified knowledge gaps, overall, the additional information identified was neither sufficient to fill the knowledge gaps nor to re-evaluate the implementation of the Pyrethroid Control Program. The research conducted since the publication of the Final Staff Report (Water Board, 2017) served to identify additional knowledge gaps that Board staff deemed appropriate for informing future iterations of the Pyrethroid Control Program including:

8. pyrethroid bioaccumulation
9. salinity as a co-stressor,
10. microplastics as both a stressor and a vector that could affect bioavailability,
11. urban insecticide use patterns, specifically non-professional applications, including replacement or alternative insecticides, and
12. availability and effectiveness of management practices.

C. Statement of Purpose

As outlined in Basin Plan section 4.5.5.1(8), the purpose of the Plan is to identify knowledge gaps where research and studies are needed to inform future iterations of the Pyrethroid Control Program. As noted in Section 1. A, the Basin Plan commits the Central Valley Water Board to re-evaluate the Pyrethroid Control Program by 2034. Specifically, Basin Plan section 4.5.5.2(4), stipulates that the Central Valley Water Board will review the pyrethroid pesticides prohibition, the pyrethroid pesticides total maximum daily load allocations, the numeric pyrethroid triggers, and the implementation provisions for pyrethroid pesticide discharges in the Basin Plan no later than 19 February 2034 as part of the Triennial Review process or other processes.

The scope of the re-evaluation as described above requires a combination of data collected through the implementation of the current Pyrethroid Control Program as well as research information not obtainable through regulatory channels. The intent of the Plan is to identify existing knowledge gaps that will enhance the understanding of pyrethroid environmental impacts and behavior. Any resulting research findings will be used to supplement data to inform the re-evaluation of the Pyrethroid Control Program. Therefore, the scope of the Plan is limited to areas of scientific uncertainty, as identified during the Pyrethroid Control Program adoption and expanded by Board staff in 2023, that may be addressed by the research community.

The Plan documents the relevant Research Questions and Knowledge Gaps, including those identified in the scientific literature or by interested persons and Native American Tribes, since the adoption of the Pyrethroid Control Program. Once approved by the Central Valley Water Board, the scientific community may reference the Plan as a justification for grant proposals or other funding opportunities, while research and funding agencies can reference the Plan in their requests for proposals. The Central Valley Water Board will, as resources allow, seek to fund some studies pursuant to the

Plan; however, most of the remaining study needs will need to be fulfilled by research and funding agencies.

The Plan does not articulate the practical and logistical steps (e.g. study methodologies, designs, etc.) for meeting the data and research needs as this is outside Board staff expertise and may limit researchers in developing proposals for funding. Rather, the Plan focuses on the broader research needs to ensure longevity and flexibility for researchers to innovate.

The Plan does not outline or include any uncertainties directly related to regulatory actions or requirements, such as consideration of Water Code 13241 factors needed to develop WQOs. Development of WQOs is not an express goal of the Plan. The Water Code 13241 factors required for the development of WQOs are a regulatory requirement and are therefore outside the scope of a research plan directed toward the scientific community.

The re-evaluation of the Pyrethroid Control Program will be conducted through the Basin Plan amendment process. This process will include opportunities for public engagement throughout, including identification of outstanding data or information needs during initial scoping. As described in Section 1.A, the Pyrethroid Control Program collects data that support the re-evaluation, and staff will continue to collate this data as implementation of the Pyrethroid Control Program progresses. Additional data may be needed to supplement implementation data, and Board staff are committed to working with interested persons, agencies, environmental interest groups, Tribes, and permittees, to gather this information during the development of the Pyrethroid Control Program re-evaluation proposal. This information may include, but is not limited to, updated costs and feasibility of attaining current trigger levels or potential WQOs, data on alternative insecticides, available management and/or treatment practices, etc. As established in the Basin Plan, re-evaluation of the Pyrethroid Control Program will occur using the data available, including that generated pursuant to the Plan.

D. Uses, Sources, and Fate of Pyrethroid Pesticides

Pyrethroid contamination in the Sacramento River and San Joaquin River basins is attributed to runoff from both urban and agricultural applications (Weston and Lydy, 2010) and wastewater treatment plant (WWTP) effluents (Weston and Lydy, 2010, 2012; Parry and Young, 2013; Weston *et al.*, 2013; Weston, Ramil, and Lydy, 2013; Markle *et al.*, 2014). Pyrethroid insecticides, authorized for use in California for urban pest control and landscape management, and agricultural pest control, are persistent in the environment and have been detected in sediments and surface waters (Domagalski *et al.*, 2010; Kuivila *et al.*, 2012; Palmquist *et al.*, 2012; Parry and Young, 2013; Weston *et al.*, 2013; Lu *et al.*, 2019; Budd *et al.*, 2020; Hall and Anderson, 2020).

Organic carbon-water partition coefficients (K_{OC}) are ratios of the amount of a given chemical that, in water, will associate with the carbon fraction (particulate or dissolved). A high K_{OC} indicates that a chemical will preferentially bind to carbon sources in water or sediments. Due to low solubility, low vapor pressure, and high K_{OC}, pyrethroid pesticides have a strong tendency to adsorb to organic matter and are not likely to volatilize. In soils, pyrethroids can be transformed by hydrolysis, microbial degradation, and photolysis, and enter surface water via runoff. Due to pyrethroids' tendency to adsorb to organic matter, they tend to move off crops, soil, and other surfaces and into surface water via organic particles in runoff from rainfall and irrigation (Gan, Bondarenko and Spurlock, 2008; Ng *et al.*, 2008; Werner and Moran, 2008; Weston *et al.*, 2008; Sy *et al.*, 2022). In water, pyrethroids can be transformed by hydrolysis, photolysis, and microbial degradation, and sorb to particles or dissolved organic matter. Pyrethroid degradation is influenced by pH, temperature, salinity, and other water quality parameters. In general, pyrethroids degrade more rapidly in alkaline water than neutral or acidic waters, and the rate of hydrolysis of aqueous pyrethroids increase with high pH (Strachan, Glooschenko and Maguire, 1982; Laskowski, 2002).

Pyrethroids can be toxic to aquatic life, acting as nerve agents that induce paralysis in invertebrates following acute exposures (Haya, 1989; Werner and Moran, 2008; Fojut, Palumbo and Tjeerdema, 2012; Heim *et al.*, 2018; Ullah *et al.*, 2019; Schulz *et al.*, 2021). Aquatic organisms are inherently more sensitive to pyrethroids because they can affect an enzyme used in osmoregulation (Antwi and Reddy, 2015; Farag *et al.*, 2021; Segarra *et al.*, 2021). Sublethal effects caused by pyrethroids include reduced growth (Goedkoop, Spann and Akerblom, 2010), disruption of reproductive functions (Moore and Waring, 2001; Farag *et al.*, 2021; Xie *et al.*, 2022), and impaired swimming performance (Gutiérrez *et al.*, 2017; Wang *et al.*, 2020; Wu *et al.*, 2020). Pyrethroid sublethal effects observed in the fish and invertebrates of the Sacramento-San Joaquin Delta include general stress, effects on various physiological systems, osmoregulation, necrosis/apoptosis, growth and development, deformities, and reproductive output (Fong *et al.*, 2016). Effects reported in the studies summarized in this paragraph were observed in the laboratory or mesocosms and not in the environment.

2. Research Questions

The aim of the Central Valley Water Board is to use pyrethroid research to inform science-based pyrethroid management in the Sacramento and San Joaquin River Basins, thereby protecting beneficial uses and addressing impairments. Research conducted to fill the Knowledge Gaps identified in the Plan will help answer pyrethroid Research Questions. Table 1 outlines the connection between the Research Questions and Knowledge Gaps. The Research Questions that apply to pesticide-related issues identified in the Sacramento and San Joaquin River Basins are listed below.

1. What are the urban use patterns for pyrethroids and alternative insecticides? What are the ecological impacts of these insecticides?

The Basin Plan stipulates that trend monitoring should be designed to determine if monitoring and reporting programs are needed for alternative insecticides, including pyrethroids not covered by the Pyrethroid Control Program. There is no State requirement for reporting private urban pesticide applications; therefore, there is limited data available on the most used formulations and active ingredients. Additional research is needed to identify common urban alternative insecticides and any associated ecological impacts.

This Research Question will be informed by the fulfillment of the Synergistic and Additive Toxicity and Urban Insecticide Use Knowledge Gaps.

2. Are alternative pyrethroid management practices needed to protect beneficial uses now and in the future?

Data collected under the Pyrethroid Control Program indicates a high occurrence of pyrethroid numeric trigger exceedances despite implementation of widely-used management practices. As more is understood about the fate and transport of pyrethroids, there is a need for additional cost-effective and feasible strategies to complement and improve existing integrated pest management strategies.

This Research Question will be informed by the fulfillment of the Fate and Transport of Pyrethroids and Alternative Pyrethroid Management Practices Knowledge Gaps.

3. Are there disproportionate impacts of pyrethroid or alternative insecticide discharges in disadvantaged and Tribal communities?

Many environmental pollutants are known to have disproportionate effects on Black, Indigenous, and People of Color (BIPOC), as well as communities of low-income and wealth (Donley *et al.*, 2022). On 8 December 2022, the Central Valley Water Board adopted its Regional Racial Equity Resolution (Resolution R5-2022-0067), affirming its commitment to State Water Board Resolution No. 2021-0050 and establishing water quality program goals in support of racial equity. As the Central Valley Water Board refines the Pyrethroid Control Program, it will look for research that supports the evaluation of pyrethroid and alternative insecticide impacts on beneficial uses in BIPOC and economically disadvantaged communities.

This Research Question will be informed by the fulfillment of the Urban Insecticide Use Knowledge Gap.

4. What further specifications or modifications are necessary to standardize and/or improve the analytical methods for pyrethroid chemistry?

At the time of its adoption, the Pyrethroid Control Program required analytical reporting limits that were lower than standardized and commercially available methods for pyrethroid analysis. Three laboratories participated in a Central Valley Water Board method validation effort and developed performance-based analytical methods that could achieve the lower concentration goals required to assess compliance with the Pyrethroid Control Program. These laboratories received Central Valley Water Board validation and Environmental Laboratory Accreditation Program (ELAP) accreditation for these methods. Further method development is needed to standardize these lower limit methods to ensure uniform implementation across laboratories and improve method performance to capture the Pyrethroid Control Program's chronic concentration goals.

This Research Question will be informed by the fulfillment of the Pyrethroid Chemistry Methodology Knowledge Gap.

5. What factors affect bioavailability of pyrethroids?

Due to high organic partition coefficients, the processes of adsorption and desorption control the bioavailability of pyrethroids. Therefore, any factor that impacts these processes will affect pyrethroid bioavailability. Some factors that impact pyrethroid adsorption and desorption are physicochemical properties of pyrethroids, the quality and quantity of dissolved and particulate organic matter, particle sizes of sediment, aging, and salinity (Delgado-Moreno, Wu and, Gan, 2010; Cui, and Gan, 2013; Lu *et al.*, 2019). Understanding bioavailability and factors that influence it will serve to either refine or substantiate the existing methods for calculating the dissolved pyrethroid concentrations under the Pyrethroid Control Program.

This Research Question will be informed by the fulfillment of the Partition Coefficients (K_{OC} and K_{DOC}), Temperature, Salinity, and Microplastics Knowledge Gaps.

6. What other taxa may be affected by pyrethroids in surface water and sediments in the Central Valley Region? What are the sublethal and/or chronic effects?

There are uncertainties regarding regulation of endpoints that are most protective of the aquatic life beneficial uses in the Central Valley. While *Hyalella azteca* is considered the most sensitive species using lethality as an endpoint, effects on *H. azteca* and its role in aquatic ecology may not capture the sublethal and chronic effects of pyrethroids on other taxa. Without additional research, it is difficult to determine if the numeric triggers established under the Pyrethroid Control Program are protective of other endpoints such as survival, growth, and reproduction in *H. azteca* and other taxa.

This Research Question will be informed by the fulfillment of the Evaluation of Sublethal Effects, Chronic Toxicity in Other Taxa, and Pyrethroid Bioaccumulation Knowledge Gaps.

7. How will co-stressors affect pyrethroid toxicity?

Pyrethroid toxicity to aquatic species is exacerbated by the condition or characteristics of the water such as salinity, temperature, and presence of microplastics. There is a negative correlation between water temperature and mortality for aquatic species, and a positive correlation between both salinity and microplastics mortality for aquatic species. Shifting temperature and hydrologic patterns due to climate change could affect these water properties and how they interact with pyrethroids present in the surface water. Future iterations of the Pyrethroid Control Program may need to incorporate effects of co-stressors to adequately protect aquatic life beneficial uses.

This Research Question will be informed by the fulfillment of the Temperature, Salinity, Microplastics, and Synergistic and Additive Toxicity Knowledge Gaps.

A. Research Question – Knowledge Gap Linkage

Table 1 outlines the connection between the Research Questions and Knowledge Gaps. This information can also be found in Section 2 under each Research Question description and Section 3 at the end of each Knowledge Gap summary.

Research Questions	Knowledge Gaps
1. What are the urban use patterns for pyrethroids and alternative insecticides? What are the ecological impacts of these insecticides?	• Urban Insecticide Use • Synergistic and Additive Toxicity
2. Are alternative pyrethroid management practices needed to protect beneficial uses now and in the future?	• Fate and Transport of Particulate-Bound Pyrethroids • Alternative Pyrethroid Management Practices
3. Are there disproportionate impacts of pyrethroid or alternative insecticide discharges in disadvantaged and Tribal communities?	• Urban Insecticide Use
4. What further specifications or modifications are necessary to standardize and/or improve the analytical methods for pyrethroid chemistry?	• Pyrethroid Chemistry Methodology

5. What factors affect bioavailability of pyrethroids?	• Partition Coefficients (K_{OC} and K_{DOC})
	• Pyrethroid Co-Stressors:
	  o Temperature
	  o Salinity
	  o Microplastics

6. What other taxa may be affected by pyrethroids in surface water and sediments in the Central Valley Region? What are the sublethal and/or chronic effects?	• Evaluation of Sublethal Effects • Chronic Toxicity in Other Taxa • Pyrethroid Bioaccumulation

7. How will co-stressors affect pyrethroid toxicity?	• Pyrethroid Co-Stressors:
	  o Temperature
	  o Salinity
	  o Microplastics
	• Synergistic and Additive Toxicity

Table 1. Linkage between Research Questions and Knowledge Gaps

3. Knowledge Gaps

As previously stated, the Central Valley Water Board initiated efforts to address two Knowledge Gaps identified in the Pyrethroid Control Program, namely the refinement of partition coefficients and pyrethroid chemistry analytical methods. The sections below summarize the Knowledge Gaps identified in the Basin Plan and the scientific literature review as well as the Central Valley Water Board actions to date.

A. Partition Coefficients (K_{OC} and K_{DOC})

Pyrethroids have high K_{OC} values and can be present in three distinct forms in water: freely dissolved and thus potentially bioavailable, associated with dissolved organic carbon (DOC), or sorbed to suspended particulate organic carbon (POC). In the latter two categories, the pyrethroid residues are not directly bioavailable without further desorption (Laskowski, 2002; Gan, Bondarenko and Spurlock, 2008; Parry and Young, 2013; Yang, Wu and Wang, 2018). Studies have shown that sediment characteristics of black carbon and percent fines positively corresponded to increased bioavailability of pyrethroids (Yang *et al*., 2009; Fuller *et al*., 2022a).

The freely dissolved concentration of each pyrethroid pesticide in a sample may be directly measured or estimated using partition coefficients. The Central Valley Water Board selected the latter approach as the default for the Pyrethroid Control Program out of consideration for discharger resources. Under the Pyrethroid Control Program, the freely dissolved concentration of a pyrethroid pesticide can be estimated using partition coefficients, by calculating the amount of pyrethroid bound to POC and DOC using the following equation (Basin Plan, Table 4-2):

$$C_{dissolved} = \frac{C_{total}}{1 + (K_{OC} x[POC]) + (K_{DOC} x[DOC])}$$

Where:

$C_{dissolved}$ = freely dissolved concentration of pyrethroid pesticide

C_{total} = total concentration of an individual pyrethroid pesticide in water

K_{OC} = organic carbon-water partition coefficient for the individual pyrethroid pesticide

[POC] = concentration of particulate organic carbon in the water sample, which can be calculated as [POC]=[TOC]-[DOC]

K_{DOC} = dissolved organic carbon-water partition coefficient
[DOC] = concentration of dissolved organic carbon in the sample

Inputs for the equation are obtained through monitoring for pyrethroid whole water concentrations, and TOC and DOC concentrations. Additionally, this calculation requires partition coefficients, K_{OC} and K_{DOC}, the determination of which are based on the measured freely dissolved and whole-water concentrations of known quantities of pyrethroids that have been spiked into prepared sediment suspensions. Due to lack of site-specific partition coefficients, the Pyrethroid Control Program's default K_{OC} and K_{DOC} values (Basin Plan, Table 4-2) were based on a study conducted by Chickering (2014) that met all the data acceptability criteria.

Studies determining partition coefficients for both ambient and wastewater matrices report variability in partition coefficients across samples (Parry and Young, 2013; Chickering, 2014). The Final Staff Report (Water Board, 2017) recommended that the partition coefficients be refined to reflect site-specific K_{OC} and K_{DOC} as organic carbon present in the environment can vary widely in binding capacity depending on the physicochemical properties of the organic matter, which primarily develop based on the source and aging of the material. Site-specific K_{OC} and K_{DOC} may also vary with season and timing of sample collection because aquatic ecosystems are not static and new sources of material may be introduced due to changes in the surrounding environment.

In November 2018, the Central Valley Water Board contracted with Dr. Thomas Young of University of California, Davis (UCD) to determine pyrethroid K_{OC} and K_{DOC} for sediment samples collected from watersheds throughout California using solid phase microextraction (SPME). The Young laboratory used 19 sediment samples collected for the State Water Board's Stream Pollution Trends Monitoring (SPoT) Program representing varying conditions in California, particularly the organic carbon content of the sediment. The sediment samples were spiked with bifenthrin, cyfluthrin, cypermethrin, esfenvalerate, lambda-cyhalothrin, and permethrin to determine the K_{OC} and K_{DOC} for each analyte in ambient water.

Board staff released the UCD Draft Report for public comment in 2023 and submitted all comments received to the Young Lab for consideration while completing the Final Report. The Young Lab completed the Final Report and a response to public comments in summer 2025. The Final Report and response to comments document can be requested via instructions on the Pyrethroid Control Program webpage (https://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/pyrethroid_control_program/).

Any interpretation of, or action based on, the findings of the Final Report constitutes a regulatory determination, which is outside of the scope of this Plan. The Final Report may provide additional insight to inform future directions or actions of the Central Valley Water Board during the re-evaluation of the Pyrethroid Control Program as required by Basin Plan 4.5.5.2(4). The Central Valley Water Board recognizes the complexity of partition coefficient determination and that a single study is insufficient to comprehensively characterize the varied factors that influence partitioning across the universe of Central Valley sediments. Therefore, the Central Valley Water Board welcomes additional studies to supplement any reassessment of the default partition coefficients or support use of site-specific partition coefficients in the Pyrethroid Control Program.

Similar to refinement of ambient partition coefficients, there is a need to reassess pyrethroid partition coefficients in wastewater effluents. Current default wastewater partition coefficients were developed based on a study by Parry and Young (2013). The study used samples from Sacramento Area Sewer District to determine K_{OC} and K_{DOC} for bifenthrin, lambda-cyhalothrin, cypermethrin, and permethrin. As partition coefficients for wastewater effluents were not available for cyfluthrin and esfenvalerate, the default partition coefficients for ambient waters were used in place of wastewater partition coefficients for these two analytes. Due to the differences between the two matrices, the Final Staff Report (Water Board, 2017) recommended using partition coefficients specific to municipal and domestic wastewater effluents as available for these compounds.

Wastewater treatment facilities in the Central Valley process their wastewater through different treatment processes, including secondary, advanced secondary, and tertiary treatments. Given that most wastewater treatment plants subject to the Pyrethroid Control Program use tertiary treatment, the current defaults, partially derived from a secondary wastewater treatment system, may not represent the matrix characteristics of tertiary treatment facilities. Additional evaluation is needed to determine whether default partition coefficients are affected by treatment level and technologies. Any further study of partition coefficients in the wastewater effluent matrix should include all six pyrethroid analytes of the Pyrethroid Control Program to remedy the lack of wastewater effluent default partition coefficients for cyfluthrin and esfenvalerate.

Fulfillment of this Knowledge Gap will inform Research Question # 5 regarding pyrethroid bioavailability.

B. Pyrethroid Chemistry Methodology

The Pyrethroid Control Program set low concentration goals for six priority pyrethroids in discharge and receiving waters, requiring lower analytical reporting limits for compliance monitoring than were commercially available. To address stakeholder concerns about availability and reliability of analytical methods at these low levels, Board staff initiated a method validation process for new or modified analytical methods for the pyrethroid analytes under the Pyrethroid Control Program.

Board staff organized a work group comprised of members of the Environmental Laboratory Technical Advisory Committee (ELTAC), the State Water Board Quality Assurance Officer, Environmental Laboratory Accreditation Program (ELAP) staff, and Board staff. The work group developed the method validation framework, including the minimum reporting levels (MRLs), performance criteria, laboratory questionnaire, and validation package solicitation.

Participating laboratories were required to complete and return a questionnaire to indicate their intent to participate in the method validation process. The Central Valley Water Board solicited ELAP-certified laboratories to submit performance-based method validation packages for analytical methods that achieved specified MRLs for pyrethroids in whole water (unfiltered) samples from surface waters and wastewater effluent. All submitted validation packages were required to be prepared in accordance with U.S. EPA guidance for review and validation of alternative or new methods (USEPA, 2018a; 2018b).

The Central Valley Water Board has authority to validate methods for five of the six pyrethroid analytes included in the Pyrethroid Control Program. Title 40, Part 136 of the Code of Federal Regulations (40 CFR 136) is the U.S. EPA's governing publication for establishing test procedures for pollutants. Because 40 CFR 136 identifies specific methods allowed for determining Clean Water Act (CWA) compliance for permethrin, U.S. EPA approval via the CWA Alternative Test Procedure (ATP) was required for any new or modified method developed through the Central Valley Water Board method validation process.

Board staff received validation packages from four laboratories, three of which were approved: McCampbell Analytical, Physis, and Caltest. Upon approval, the submitting laboratory was required to obtain ELAP accreditation for that method. Laboratories were subsequently instructed to pursue U.S. EPA approval for the permethrin ATP to participate in CWA compliance monitoring for the Pyrethroid Control Program.

The Pyrethroid Control Program method validation process is ongoing, and Board staff will review additional validation packages as they are received. Information, including a list of approved laboratories can be found on the Central Valley Water Board's Central Valley Pyrethroid Control Program webpage.
(https://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/pyrethroid_control_program/#analyticalmethods)

Currently, the approved methods for the Pyrethroid Control Program are limited use methods unique to the individual laboratories. Per the Knowledge Gaps identified in the Basin Plan, there is an outstanding need for an inter-laboratory calibration effort and statewide pyrethroid method development to increase the reliability and availability of pyrethroid analytical services.

To prevent further delays to implementation of the Pyrethroid Control Program, acute-based MRLs were accepted on an individual analyte basis if chronic-based MRLs could not be achieved by laboratories. Currently, none of the approved methods are sensitive enough to capture the Pyrethroid Control Program's chronic concentration goals for all six pyrethroid analytes. Therefore, further work is needed to improve the capability of existing methods or develop alternative methods that can achieve the chronic MRLs needed to determine compliance with the Pyrethroid Control Program's chronic numeric triggers.

C. Fate and Transport of Particulate-Bound Pyrethroids

The fate and transport of pyrethroids in both urban and agricultural environments are governed by partitioning and transformation processes, which are dependent on pyrethroid chemical properties and environmental factors such as temperature and the presence of water, light, particles, organic matter, and/or microorganisms. Based on multiple studies, pyrethroid fate is dominated by adsorption to organic matter due to its high K_{OC} values, low water solubility, and low Henry's Law constants (Gan *et al.*, 2005; Budd *et al.*, 2007; Gan, Bondarenko and Spurlock, 2008; Weston *et al.*, 2009; Li *et al.,* 2017).

Although pyrethroids are predominantly applied near the perimeter of structures in urban settings, detections in urban waterways indicate off-site transport of pyrethroids. The transport of pyrethroids occurs mainly through the movement of particulate matter containing sorbed pyrethroids that is either suspended in irrigation or precipitation runoff or suspended in the air due to wind or traffic (Jiang and Gan, 2016; Jiang *et al.*, 2016). Research has shown that the majority of the pyrethroids in runoff were associated with solid particles greater than 0.7 µm in diameter (Jiang and Gan, 2012; Jiang *et al.*, 2012). Weston *et al.* (2009) conducted a study quantifying pyrethroids in storm drains during both dry and wet seasons in Sacramento. The results from dry season samples showed detections of bifenthrin, cyfluthrin, permethrin, and cypermethrin, most likely due to lawn irrigation runoff. Bifenthrin was detected at concentrations above LC_{50} values for *H. azteca*. Concentrations of cyfluthrin, permethrin, and cypermethrin increased during the wet season, with cyfluthrin and cypermethrin detected at concentrations above LC_{50} values for *H. azteca* (Weston *et al*., 2009).

There is some uncertainty on the fate of pyrethroids after they enter waterbodies, specifically, the rate of degradation and how labile pyrethroids are after they adsorb to sediments. Review of data on the persistence and partitioning of pyrethroids in sediment by Gan, Bondarenko, and Spurlock (2008) show that the bioavailable concentrations of pyrethroids decrease in sediment due to an aging effect, suggesting diminishing toxic potential over time.

Arkles, Sinche, and Lydy (2023) investigated the influence of organic carbon, aging time, and temperature on bifenthrin bioavailability. Results indicated an inverse relationship; meaning that bifenthrin bioavailability decreased with increasing organic carbon content in the sediment, holding time of the sediment samples, and temperatures under which the extraction was conducted. These findings support the mitigating effects of organic carbon on pyrethroid bioavailability as well as the importance of holding times for pyrethroid sediment chemistry analysis. The study showed that bifenthrin adsorption to sediments sequestered the parent compound and decreased both degradation of bifenthrin and the concentration of bifenthrin that was available for uptake. The study results suggest that the exposure risk of bifenthrin to aquatic species is greatest immediately after it enters a waterbody. The researchers concluded that the toxicity of bifenthrin to aquatic species increases in areas where sediments have a low organic content and in areas or seasons where water temperatures are colder (Arkles, Sinche, and Lydy, 2023). This study on the fate of pyrethroids in sediments and aging effect on toxicity was conducted in a laboratory setting using select sediments and pyrethroid analytes. There is a need to further understand the behavior of all six Pyrethroid Control Program analytes in the varied environmental conditions of the Central Valley Region.

A study measuring levels of bifenthrin and permethrin in runoff from consecutive precipitation events from 1 to 89 days after application showed that 90% of the pesticide runoff occurred 1 day after application. Surprisingly, detection of both pyrethroids continued to occur in runoff from concrete even 89 days after application despite four previous precipitation events (Jiang *et al*., 2012). In a comparison of pyrethroid transport pathways, a model revealed pyrethroid runoff concentrations results similar to the measured values (Jiang *et al.*, 2016) but also showed evidence of pyrethroid transport through association with dust particles. A study in China showed that pyrethroid concentrations associated with dust varied seasonally based upon application patterns and occurred within the same range in both urban and agricultural areas (Li *et al.*, 2014). Another study conducted by Richards *et al.* (2016) in Southern California determined dust on hard surfaces is a significant source of pyrethroids by evaluating spatial and seasonal distribution patterns of current-use insecticides around residences. Researchers found that pyrethroids were uniformly distributed in areas adjacent to houses, suggesting significant redistribution, and were detected in dust from the driveway, curb gutter, and street. Dust-associated pyrethroids decreased in the wet season, suggesting rainfall as a major mechanism that moved pyrethroid residues offsite. Fine dust particles have a higher mobility/are more likely to be transported by rainfall runoff than coarse particles. Therefore, pyrethroids adsorbed to fine dust particles have a higher chance of being transported offsite by rainfall runoff (Richards *et al.*, 2016).

Some uncertainty exists regarding the occurrence of dust particle-bound pyrethroids in California urban and agricultural environments, and how dust becomes contaminated by pyrethroids, but the studies described previously have shown definitive evidence that the major pathway for off-site transport of particle-bound pyrethroids is via runoff. Transport from their application source and the partitioning of pyrethroids are strongly dependent on their half-life; however, release from urban and agricultural areas eclipses any degradation in waterways or sequestration in sediments (Bhatt *et al.*, 2019; Arkles, Sinche, and Lydy, 2023). While identified as a Knowledge Gap in the Final Staff Report (Water Board, 2017), additional research on transport of particulate-bound pyrethroids would not further inform the Pyrethroid Control Program because the dominant pathways are already addressed. However, further research is needed to evaluate the fate of particle-bound pyrethroids once they enter the waterbodies and how their bioavailability is affected by environment variables such as particle size, sediment organic matter characteristics and sediment age and source.

Fulfillment of this Knowledge Gap will inform Research Question # 2 regarding the need for development of alternative pyrethroid management practices.

D. Pyrethroid Co-Stressors

1. Temperature

Climate change models predict hydrological changes that include reduced future flows in rivers and streams coupled with increased intermittent flow from flash floods following heavy rainfall as well as increased length of dry periods followed by flash floods. These climate change impacts contribute to increased erosion and geomorphological degradation, thereby threatening endangered fish populations and freshwater and estuarine ecosystems downstream (Tanner *et al*., 2022).

Temperature changes predicted by global climate change trends may exacerbate the detrimental biological effects of pesticide exposure, further impacting the threatened Chinook populations of the Sacramento River watershed (Derby *et al*., 2021). Fuller *et al*. (2022b) determined the occurrence and distribution of current-use pesticides in two important habitats in the Central Valley for threatened juvenile Chinook salmon populations. Across both floodplain and riverine habitats, significant increases in the detection frequency of fipronil and pyrethroids were observed in a flood year as compared to drought conditions, suggesting a role of hydrological conditions in determining pesticide exposure of resident biota (Fuller *et al*., 2022b).

Decreasing aquatic temperatures increase pyrethroid toxicity to aquatic species (Hasenbein, Poynton, and Connon, 2018). Studies show that decreased temperatures affect both organism biology and pyrethroid biotransformation thereby increasing duration of exposure to the parent compound (Derby *et al.*, 2022). Colder water temperatures affect organism biology by increasing the stability of sodium channels, resulting in greater cellular excitation. Pyrethroids produce the same effect on sodium channels in aquatic organisms; therefore, pyrethroid exposure in cold water exacerbates organismal stress (Salgado, Herman and Narahashi, 1989; Carle *et al.*, 2009; Harwood, You and Lydy, 2009; Jiang and Bloomquist, 2021).

Furthermore, as biotransformation of pyrethroids results in a less toxic metabolite, decreased biotransformation rates at lower water temperatures result in increased concentration of the more toxic parent compound (Harwood, You and Lydy, 2009; Weston *et al*., 2009; Brander *et al.*, 2016; Akinwande, Arotiowa and Ete, 2021). Weston *et al* (2009) and Harwood, You and Lydy (2009) observed a dual temperature effect of pyrethroids on *H. azteca* and *Chironomus dilutus*, respectively, where neurons were exposed to an increased concentration of the more toxic parent compound but also were more sensitive to the resulting stimulation, which resulted in a three-fold increase in pyrethroid toxicity at 13°C compared to 23°C.

Water temperature varies geographically, seasonally, and due to climate change factors, such as rainfall, rising temperatures, flooding, and heat waves. Additional research is needed to understand the impact of climate change and seasonal variability on pyrethroid toxicity. As discussed above and in the Final Staff Report (Water Board, 2017), it has been established that pyrethroids can be more toxic at lower temperatures. However, temperature effects for pyrethroids were not accounted for during the development of the Pyrethroid Control Program numeric triggers because sufficient data was not available for multiple species for each pyrethroid compound to quantify this effect and develop temperature-dependent criteria. Based on the literature review performed for the development of this Plan, incorporation of temperature effects in pyrethroid toxicity relationships is an outstanding need.

Fulfillment of this Knowledge Gap will inform Research Question # 5 regarding pyrethroid bioavailability, and Research Question # 7 regarding effects of co-stressors on pyrethroid toxicity.

2. Salinity

Research demonstrates that the salinity of a given waterbody affects pyrethroid bioavailability. Salinity has been shown to decrease the water solubility of organic pesticides with a direct correlation between degree of hydrophobicity and impact of salinity (Segarra *et al*., 2021; Derby *et al*., 2022). As pyrethroids are highly hydrophobic, increased salinity results in decreasing pyrethroid solubility. Decreased water solubility would correspondingly increase chemical adsorption, thereby decreasing bioavailability of pyrethroids in the aqueous phase (Yang *et al*., 2016; Saranjampour, Vebrosky and Armbrust, 2017).

Research investigating co-exposure of pyrethroids and salinity on Silversides, which are present throughout Central Valley waterways, showed toxicity decreased as salinity increased for all pyrethroids except permethrin (Hutton *et al*., 2023). Greater salinity causes increased pyrethroid adsorption to sediments thereby increasing exposure to benthic organisms. In a laboratory experiment, Hladik (2020) found that in the absence of suspended sediments, the fraction of pyrethroid insecticides in the aqueous phase increases with increasing salinity. Further work is needed to determine if this correlation is also observed outside the laboratory, specifically in waterbodies with less suspended sediment.

Climate change may increase seasonal salinity stress in the future (Tanner *et al*., 2022). In California, as surface and groundwater supplies become scarcer, and as wastewater streams become more concentrated, salinity impairments occur with greater frequency and magnitude. The 2022-2024 Integrated Report lists 49 Central Valley waterbodies impaired for salinity. California is additionally impacted by climate change-related vicissitudes where increased duration and frequency of drought periods reduces the freshwater entering estuaries; coupled with sea level rise, this allows for intrusions of higher-salinity water from the ocean, pushing the low-salinity zone further upstream (Kimmerer, MacWilliams and Gross, 2013; Quinn and Oster, 2021). To combat salinity and nitrate impairments, the Central Valley Water Board has adopted a Salt and Nitrate Control Program under Resolution R5-2018-0034 (CV-SALTS).

Impacts of salinity were not considered in the derivation of the pyrethroid numeric triggers or their application under the Pyrethroid Control Program. While the CV-SALTS program aims to address salinity impairments, the Plan aims to address the knowledge gap of how salinity impacts pyrethroid bioavailability, and the geographic extent to and environmentally relevant concentrations at which pyrethroids and salinity co-occur. Additionally, examining the effect of salinity on the toxicity of pyrethroids is essential in assessing the risk that pyrethroids pose to beneficial uses, especially during sensitive stages of organismal development.

Fulfillment of this Knowledge Gap will inform Research Question # 5 regarding pyrethroid bioavailability, and Research Question # 7 regarding effects of co-stressors on pyrethroid toxicity.

3. Microplastics

Microplastics are defined as fragments of plastic less than 5mm in length (NOAA Marine Debris Program, 2023). While anthropogenic in origin, microplastics are found ubiquitously in nature. As microplastics are emerging pollutants, there are many unknowns regarding their behavior in the environment and their effects on exposed organisms. This section discusses the literature relevant to the interactions of microplastics with pyrethroids and other organic compounds, as well as constraints on analytical methods for microplastics characterization.

Research has also shown microplastics induce stress in some aquatic organisms, which can result in increased toxicity when organisms are co-exposed to microplastics and pyrethroids (Amelia *et al.*, 2021; Lin, Chiu and Kuo, 2021; Varg *et al.*, 2021). A study investigating the influence of microplastics on the ecotoxicity of pyrethroids found that combined exposure to deltamethrin and microplastics had a synergistic effect on survival, brood number, and number of neonates per surviving female of *Daphnia magna*. The researchers observed a 46% reduction in brood number and a 51.1% reduction in number of neonates per surviving female when the organism was co-exposed to deltamethrin and microplastics (Felten *et al.*, 2020).

Similar to particulate and dissolved organic matter, research demonstrates that microplastics adsorb other toxic pollutants, and when ingested, these toxic substances may then aggregate in biota (Rainieri *et al.*, 2018; Fu *et al.*, 2021; Yang, Lim and Song, 2021). Studies have shown that the most common mechanism by which organic compounds adsorb to microplastics is through hydrophobic interactions. However, there are multiple other bonding mechanisms through which organic pollutants adsorb to microplastics, such as electrostatic interaction, hydrogen bonds, ionic bonds, halogen bonds, and Pi-Pi interactions (Hai *et al.*, 2020; Amelia *et al.*, 2021). With large octanol-water partitioning coefficients, pyrethroids are highly organic compounds, and may also adsorb to microplastics via these mechanisms (Sharom and Solomon, 1981; Teuten *et al*., 2007; Horton *et al*., 2018; Nelms *et al,* 2018; Ziajahromi *et al.*, 2019; Felten *et al*., 2020).

The ability of microplastics to adsorb organic pollutants is affected by microplastic particle size, specific surface area, aging, crystallinity, functional groups, and polarity. Similarly, the hydrophobicity, number of chlorine atoms, and charge of organic pollutants affect their ability to adsorb to microplastics. Additionally, environmental conditions, such as pH, temperature, and ionic strength, affect the interactions of microplastics and organic pollutants (Ziajahromi *et al.*, 2019; Hai *et al.*, 2020; Fu *et al.*, 2021).

Asmonaite *et al.* (2020) compared the tendency and relative importance of different microplastics (polystyrene and polyethylene) and silica glass particles to adsorb common hydrophobic organic contaminants, specifically 17α-ethinylestradiol, chlorpyrifos and benzo(α)pyrene. The study also compared the degree to which the contaminants accumulated in fish tissue following ingestion to determine the vector capacity of the microplastics versus glass particles. Results demonstrated that both microplastics and glass particles adsorbed and transferred each of the contaminants into fish tissue. While microplastics mediated higher contaminant transfer and tissue accumulation than silica glass, the overall difference was found to be very low. The researchers noted greater adsorption of contaminants onto polystyrene versus polyethylene. This work suggests that contaminant adsorption, desorption, and subsequent transfer in vivo depends on multiple interconnected factors, including physicochemical properties of microplastics and contaminants. As discussed previously, adsorption is affected by the physicochemical properties of both the microplastic and the organic contaminant; therefore, more research is needed to evaluate the adsorptive and vector capacity of other commonly occurring microplastics in addition to polystyrene and polyethylene.

Ziajahromi *et al.* (2019) conducted a study investigating the effects of polyethylene microplastics on the acute toxicity of bifenthrin to midge larvae (*Chironomus tepperi*) in synthetic and river water. Results demonstrated that in synthetic water bioassays, the presence of microplastics reduced the toxicity of bifenthrin (LC_{50} 1.3 µg/L) compared to bifenthrin alone (LC_{50} 0.5 µg/L). Conversely, in the river water bioassays, the presence of microplastics did not have a significant effect on bifenthrin toxicity (LC_{50} 1.4 µg/L) compared to bifenthrin alone (LC_{50} 1.3 µg/L). A comparison of the LC_{50} of bifenthrin in the synthetic water + microplastics bioassay and the LC_{50} of bifenthrin in the river water bioassay reveals that, in synthetic water (absent background dissolved organic carbon), microplastics function similarly to dissolved organic carbon, serving as a sink for bifenthrin. The researchers concluded that bifenthrin preferentially adsorbed to the dissolved organic carbon in the river water, eliminating the mitigating effect of microplastics observed in synthetic water (Ziajahromi *et al.*, 2019).

The studies discussed in this section were predominantly conducted in laboratory settings and, therefore, may not be representative of interactions between pyrethroids and microplastics and the effects thereof under environmental conditions. Mixing with naturally-occurring concentrations of suspended sediments, dissolved and particulate organic matter, algal cells, etc., may impact interactions of pyrethroids and microplastics, and any resulting potential toxic effects on aquatic organisms. More research is required to further examine the adsorption and desorption kinetics of pyrethroids to and from different microplastics under environmentally realistic conditions and should not only focus on the adsorption of single pollutants by microplastics, but also on investigating adsorption with multiple coexisting pollutants.

Investigation of microplastics in California has only been conducted in select waterbodies (Kashiwabara *et al*., 2021; Nava *et al.,* 2023; Dronjak *et al*., 2024; Singh *et al*., 2025). Information about the type, distribution, and abundance of microplastics in freshwater and freshwater sediments in the Central Valley Region is needed. To address this Knowledge Gap, there is a need to develop standardized analytical methods for quantification and identification of microplastics in ambient water and sediments. Currently, the State Water Board has only approved two particle size-based methods for determination of microplastics in treated drinking water, which were developed through an interlaboratory study (State Water Resources Control Board, 2022; State Water Resources Control Board, 2021a; State Water Resources Control Board 2021b). A similar method development effort is needed for ambient water and sediments; however, this process may prove more challenging as these matrices are more complex and variable than treated drinking water.

Fulfillment of this Knowledge Gap will inform Research Question # 5 regarding pyrethroid bioavailability, and Research Question # 7 regarding effects of co-stressors on pyrethroid toxicity.

E. Synergistic and Additive Toxicity

Chemicals have additive toxicity when their combined effect equals the sum of each chemical's individual toxicity and synergistic toxicity when their combined effect is greater than the sum of each chemical's individual toxicity. The Pyrethroid Control Program numeric triggers account for the additive toxicity of the six priority pyrethroids but not the likely additive toxicity of other pyrethroids. Due to the high use of pesticides in California, ambient receiving waters may contain a mixture of chemicals that may have additive or synergistic effects on pyrethroid toxicity to aquatic organisms. Therefore, the additive and/or synergistic effects of other pyrethroids and contaminants present in aquatic systems require further study.

In general, pyrethroids are more toxic than their metabolites, which form via oxidation, ester cleavage, and conjugation (Mikata, Isobe and Kaneko, 2012). Pyrethroid toxicity to nontarget aquatic species is potentiated when co-exposed with another chemical that inhibits pyrethroid biotransformation. Chemicals such as piperonyl butoxide (PBO), azole fungicides, and organophosphates act as substrates in the pyrethroid biotransformation pathways, increasing the exposure duration to the pyrethroid parent compound, thereby increasing pyrethroid toxicity (Martin *et al.*, 2021).

PBO–pyrethroid mixtures demonstrate both additive and synergistic toxicity (Amweg and Weston, 2007). In a study where *H. azteca* were exposed to PBO and pyrethrin both separately and in different mixtures, Giddings, Gagne, and Sharp (2016) found that PBO was less toxic than pyrethrin alone. The researchers noted that at and less than 1.7 µg PBO/L in PBO-pyrethrin mixtures, no synergy or enhancement was observed. Doses at and greater than 3.5 µg PBO/L resulted in both synergism and enhancement. The threshold for synergism of pyrethrin toxicity exists between these specific PBO doses, and increasing the dose of PBO beyond 3.5 µg/L did not significantly affect the synergism between these two chemicals (Giddings, Gagne, and Sharp, 2016).

Similar to PBO, azole fungicides, commonly used to manage fungi in crops and pets, also act as a substrate for the oxidation metabolism pathway in aquatic species. Bjergager *et al* (2012) designed a study to investigate synergistic potential of prochloraz on esfenvalerate toxicity on *D. magna*. The researchers defined synergy as either a >2-fold decrease in EC_{50} or a >2-fold increase in the fraction of organisms displaying impaired mobility. The results showed synergy between prochloraz and esfenvalerate in both laboratory and outdoor aquatic microcosm settings. Increasing the exposure duration to the mixture decreased the EC_{50}. In a later study, Bjergager *et al.* (2017) investigated the synergistic interaction between cypermethrin and three azole fungicides (prochloraz, propiconazole or epoxiconazole). The study showed similar synergistic interactions as with esfenvalerate and a threshold below which synergy doesn't occur. Both studies demonstrate that synergy between these chemicals and the dose at which it is observed is a function of exposure duration.

The enzyme carboxylesterase, which is responsible for detoxification (amongst other functions) in all living organisms, metabolizes both pyrethroids and organophosphates via cleavage of the ester bond on these chemicals (Cao *et al.*, 2021). Denton *et al.* (2003) studied toxic effects of diazinon and esfenvalerate mixtures on fathead minnows (*Pimephales promelas).* While only diazinon significantly inhibited carboxylesterase activity, the observed toxicity of the mixture was synergistic. Similar results were observed by Zhang *et al.* (2010) who studied effects of binary mixtures of permethrin, tetramethrin, bifenthrin, and etofenprox with either dichlorvos or phoxim. The authors found synergistic effects when zebrafish (*Danio rerio)* were exposed to a combination of pyrethroid and organophosphate, with some binary mixtures having a higher toxic effect compared to others.

Given the infinite possible contaminant mixtures to which organisms are exposed in the environment, scientists rely on two main predictive models to estimate the environmental impact of pesticide mixtures: the independent action model (IA) and the concentration addition model (CA). The IA predicts toxicity for mixtures of pesticides with unique modes of action while the CA predicts toxicity for mixtures of pesticides with a shared mode of action. Belden and Lydy (2006) investigated the joint toxicity of esfenvalerate and chlorpyrifos mixtures on *P. promelas* and *Chironomus tentans* and compared these results to those of IA and CA models for the same mixtures. In the initial study, the researchers exposed both species to equipotent mixtures of the two insecticides. The researchers also performed a second study evaluating the effects of low levels of chlorpyrifos on esfenvalerate toxicity. In both studies, the researchers observed greater toxicity in *P. promelas* than was predicted by either model; however, the EC_{50} were within a factor of two of those predicted by the CA model. The CA model more closely approximated the observed toxicity in *C. tentans*, where the observed and predicted EC_{50} were similar in both studies. The researchers hypothesize that the disagreement between the observed and model-predicted toxicity likely resulted from a toxicokinetic interaction between the insecticides (Belden and Lydy, 2006). These results reinforce the additive toxicity of organophosphates and pyrethroids as they have a shared mode of action and suggest that the CA model is a reasonable predictor of such additive toxicity.

Currently, compliance with the Pyrethroid Control Program's numeric triggers is determined by calculating the sum of the ratios of the freely dissolved concentrations and the corresponding concentration goals for all six priority pyrethroids. According to the Final Staff Report (Water Boards, 2017), the consideration of additive toxicity of pyrethroids was only possible for the six pyrethroids for which the UCD-derived concentration goals. Additionally, the Final Staff Report (Water Boards, 2017) discusses that pyrethroids also exhibit additive and synergistic effects with other pesticides and adjuvants, such as organophosphates and PBO. These additive and synergistic effects could not be included in the concentration goal derivations since the effects could not be quantified across multiple species. Research is needed to identify potential additive and/or synergistic chemicals, including other pyrethroids, that are relevant to the Central Valley Region, and their associated concentration and exposure durations in receiving waters and sediments. All this information is necessary to evaluate the occurrence and severity of additivity and synergy under environmental conditions.

Fulfillment of this Knowledge Gap will inform Research Question # 1 regarding identification of alternative insecticides used in urban areas and their ecological impacts, and Research Question # 7 regarding effects of co-stressors on pyrethroid toxicity.

F. Evaluation of Sublethal Effects

Sublethal effects occur at exposure levels below the concentrations that cause lethality and may arise from both acute and chronic exposure scenarios. There are various ecotoxicological tests that measure and quantify sublethal biological responses at the sub-organismal, whole-organismal, and population/community levels (Schuijt *et al*, 2021; Gandara *et al*, 2024). However, current USEPA methods to evaluate sublethal effects of growth, reproduction, and behavior only exist for chronic exposure scenarios (USEPA, 1994). Therefore, further work is needed to develop approved methods to monitor and evaluate sublethal effects on aquatic organisms under acute exposure scenarios.

Sublethal toxic effects can have severe impacts to reproductive success and survival of aquatic organisms that may lead to population-level effects. Studies have shown that sublethal biological responses include behavioral, growth, immune system, reproductive/endocrine, and histopathological effects (Moore and Waring, 2001; Werner and Moran, 2008).

In 10-day exposure studies, Hasenbein *et al.* (2015) assessed motility and growth as endpoints for sublethal effects in *C. dilutus* and *H. azteca* exposed to bifenthrin, permethrin, cyfluthrin, and chlorpyrifos. While motility was identified as the most sensitive sublethal endpoint at low concentrations for both species, growth was a good indicator of toxicity for all four pesticides for *H. azteca*. Montaño-Campaz *et al.* (2022)

observed that immature *Chironomus columbiensis* exposed to LC_1 concentration of deltamethrin showed reduced fecundity and variations in wing morphology. Reduction in fertility rates were observed in larvae exposed to LC_{10} concentrations. While fecundity was restored by 80% after one recovery generation, two subsequent recovery generations were not sufficient to fully restore fecundity. Recovery from variations in wing morphology was observed in adults after two consecutive generations without deltamethrin (Montaño-Campaz *et al.*, 2022). Al-Ghanim *et al.* (2020) showed that exposure to sublethal concentrations of fenvalerate induced metabolism impairment with increase in aspartate amino transferases and alanine amino transferases indicating liver damage in *D. rerio*. Variations in stress enzymes were also seen indicating mitochondrial disruption and tissue damage. *Astacus leptodactylus* exposed to sublethal concentrations of permethrin showed hyperplasia in the gill lamella and degenerations of the hepatopancreas tissues (Günal *et al.*, 2021).

Adverse impacts, such as metabolomic profile alterations that regulate inflammatory responses and cell death, have been documented in juvenile Chinook salmon exposed to sublethal concentrations of bifenthrin (Magnuson *et al*.,2020). Fuller *et al.* (2021) detailed the impacts of juvenile Chinook salmon dietarily exposed to cypermethrin (200 and 2000 ng/g), noting altered expression of homeostatic genes including fatty acid synthase and ATP citrate lyase in fish livers which are crucial for energetic processes. Endocrine and olfactory system effects have also been documented in studies examining the effects of pyrethroids on juvenile salmonids (Crago and Schlenk, 2015; Maryoung *et al*., 2015). Such effects alter the behavior of juvenile Chinook salmon, which may lead to detrimental population-level effects (Giroux *et al.*, 2019; Magnuson *et al.*, 2020).

According to the Final Staff Report (Water Board, 2017), studies on some non-resident species such as the amphipod *Gammarus* species and Atlantic salmon have documented sublethal effects of pyrethroids at low concentrations, but these effects were not included in UCD's concentration goal derivation since they were not directly linked to survival, growth, or reproduction, and effect concentrations were not quantified due to detection limits.

While it's often difficult to establish direct links of sublethal responses to higher-level effects, these toxic effects can have far-reaching consequences in the aquatic environment where organisms are often simultaneously exposed to many different stressors. There is a need for more extensive research to identify low-level pyrethroid and alternative insecticide concentrations that may cause ecological effects. Integration of sublethal endpoints into pesticide control programs, including the Pyrethroid Control Program, could provide broader protection to aquatic ecosystems.

Fulfillment of this Knowledge Gap will inform Research Question # 6 regarding effects of pyrethroid on other taxa.

G. Chronic Toxicity in Other Taxa

H. azteca has been identified as the most sensitive species when lethality is defined as the endpoint. However, chronic toxicity in other taxa was proposed as a Knowledge Gap in the Basin Plan Section 4.5.5.1(8) to address concerns about chronic effects and endpoints other than lethality on aquatic species other than *H. azteca*. Chronic studies have higher resolution identifying toxic effects which may include several endpoints such as growth and development, reproduction, nerve function, motility, and behavior.

Limited studies investigating the chronic toxicity of pyrethroids in other aquatic taxa pre-date the Final Staff Report, leading to the inclusion of chronic toxicity as a Knowledge Gap in the Pyrethroid Control Program (Water Board, 2017). One chronic toxicity study predating the Final Staff Report investigated *D. magna* exposed to *cis*-bifenthrin for 21 days. The study showed decreased longevity, brood size, and number of young per female at concentrations greater than or equal to 0.02 µg/L. Decreased reproduction onset was observed in females exposed to 0.04 µg/L of *cis*-bifenthrin. Decreased population growth was also observed as a result of decreased longevity (Wang *et al.*, 2009).

Moran *et al*. (2017) assessed the sediment chemistry of 99 streams across the Midwestern United States and detected bifenthrin in nearly half of the sites. The sediments were tested for toxicity with the amphipod *H. azteca* (28-d exposure), the midge *C. dilutus* (10-d), and, at a few sites, with the freshwater mussel *Lampsilis siliquoidea* (28-d). While the sediment concentrations, normalized to organic carbon content, infrequently exceeded benchmarks for aquatic health, bifenthrin, both in mixture and individually, was significantly related to observed sediment toxicity.

Another study investigated the effect of cypermethrin on progeny of adult *D. rerio* exposed to various concentrations of the chemical for 28 days. The researchers observed a negative relationship between fecundity and fertility and concentration of cypermethrin in adults. Cypermethrin was shown to accumulate in the parental *D. rerio* during high-dose exposure but the concentration of cypermethrin in the progeny was below quantifiable levels. Despite the non-detection of cypermethrin in progeny, the study showed that cypermethrin decreased both heart rate and swim bladder development in the progeny (Han *et al*., 2024).

Given the limited available studies on chronic toxicity of pyrethroids in species other than *H. azteca*, extensive research is needed to address both water column and sediment exposure and toxicity to aquatic species at all trophic levels. Addressing these gaps will better inform future pyrethroid control strategies.

Fulfillment of this Knowledge Gap will inform Research Question # 6 regarding effects of pyrethroid on other taxa.

H. Pyrethroid Bioaccumulation

Widespread pesticide contamination in aquatic ecosystems is of critical concern due to the potential for bioaccumulation in higher trophic level species, leading to adverse effects in individuals or negative ecological interactions affecting food webs (Hela *et al.*, 2005; Chiu, Hunt, and Resh, 2016; Fong *et al.*, 2016). Fish and lower trophic level prey may be exposed to pesticides via gills, dermal exposure, and diet (Clasen *et al.*, 2018; Werner *et al.*, 2002). Due to their hydrophobicity, pyrethroids bioaccumulate in non-target organisms, serving as a pathway for trophic transfer of pyrethroids (Corcellas, Eljarrat and Barceló, 2015).

Investigation of pesticide presence in juvenile Chinook salmon and prey in the Sacramento River watershed by Anzalone, *et al.* (2022) showed detections of pyrethroids in all prey, with a significant increase in detection frequency and concentrations in zooplankton compared to macroinvertebrate prey. The researchers note that pesticide occurrence and concentrations in zooplankton may have been influenced by the presence of suspended solids of similar size within a sample, but as juvenile Chinook salmon are unlikely to differentiate between zooplankton and particulates, the data obtained for zooplankton in the study remains relevant for predatory fish feeding in the pelagic zone. Pyrethroids were detected in the juvenile Chinook salmon the same number of times in both the Sacramento River and the Yolo Bypass; however, significantly fewer pyrethroid detections and lower pyrethroid concentrations were observed in drought conditions compared to flood conditions.

Inland silverside was used by Derby *et al.* (2021) to investigate the impacts of temperature and salinity on pyrethroid bioaccumulation via trophic transfer from resistant *H. azteca*. The study showed that silversides bioaccumulated permethrin across all treatments of salinity and temperature. While no statistically significant effect of temperature was found on total bioaccumulation, there was a negative relationship observed between salinity and bioaccumulation. Most bioaccumulation was observed in the least saline treatment, with bioaccumulation decreasing with increased salinity. The study also showed that permethrin bioaccumulation and the interaction with temperature and salinity elicited significant transcriptional responses in genes relating to detoxification, growth, development, and immune response.

There are several uncertainties associated with bioaccumulation assessment. Currently, bioaccumulation is calculated using bioavailability which may not be universally applicable as this formula has only been developed for specific invertebrates. Using bioavailability to calculate bioaccumulation can also be problematic as it disregards biotransformation of pyrethroids. Modeling and lab experimentation is highly recommended before field validations of methods are performed (Lu *et al.*, 2019). Sole measurement of water or sediment levels of pyrethroid can be an inaccurate representation of exposure, especially for organisms at higher trophic levels because it does not account for the potential for biomagnification. Biomagnification of pyrethroids may result in toxicity in sensitive higher trophic organisms (Aznar-Alemany and Eljarrat, 2020a; Anzalone *et al.*, 2022). It is also possible that pyrethroid toxicity would alter test organism behavior and thus affect bioaccumulation (Aznar-Alemany and Eljarrat, 2020b). A study analyzing pyrethroid levels in 19 species of fish found that pyrethroid accumulation varied more based on species rather than geographic distribution, with carnivorous fish containing higher concentrations of pyrethroids in their muscles compared to omnivorous and phytophagous fish (Xie *et al.*, 2022).

The Pyrethroid Control Program does not currently account for bioaccumulation due to the above-mentioned uncertainties and issues. Further study and understanding of pyrethroid bioaccumulation will inform what other taxa may be affected by pyrethroids in surface water and sediments as well as the sublethal and/or chronic effects on these organisms.

Fulfillment of this Knowledge Gap will inform Research Question # 6 regarding effects of pyrethroid on other taxa.

I. Urban Insecticide Use

Pesticide contributions in municipal stormwater and wastewater discharges result predominantly from urban use by homeowners, pest management professionals, government agencies, nurseries, and urban agriculture. Meftaul *et al.* (2020) asserted that herbicides, insecticides, fungicides, rodenticides, etc. are frequently not applied according to label instructions, resulting in unintentionally higher application concentrations in small urban areas such as lawns, gardens, and impermeable surfaces. Consequent to their extensive and intensive use in urban areas, pesticide contamination poses a serious threat to non-target organisms (Meftaul *et al.,* 2020).

California Code of Regulations 3, sections 6624 – 6628 require pesticide use reporting for agricultural and commercial structural pest control applications, allowing for the identification of use amounts and patterns of pyrethroids and alternative pesticides in those application scenarios (CDPR, 2024a). In a study comparing use data from the California Department of Pesticide Regulation (CDPR) Pesticide Use Reporting Database (PUR) and commercial sales data, Xie *et al.* (2021) identified fipronil, imidacloprid, bifenthrin, permethrin, cypermethrin, deltamethrin, cyfluthrin, lambda-cyhalothrin, and esfenvalerate as insecticides with a high potential for indoor down-the-drain transport. Building on that study, Budd *et al.* (2023) monitored both wastewater influent and effluent within a single catchment, showing detections of fipronil, imidacloprid, and pyrethroids in influents, but only fipronil and imidacloprid detections in wastewater effluents.

There is no State requirement for reporting private urban pesticide applications; therefore, there is limited data available on the most used formulations and active ingredients. To determine the presence of pesticide in urban runoff and surface waters, CDPR's Surface Water Protection Program (SWPP) initiated a statewide urban monitoring program in 2008 (CDPR, 2007; CDPR, 2008). Using the Surface Water Prioritization Model, SWPP monitors specifically for 24 insecticides. CDPR's webpage hosts the [Surface Water Prioritization Model](https://www.cdpr.ca.gov/docs/emon/surfwtr/sw_models.htm) (https://www.cdpr.ca.gov/docs/emon/surfwtr/sw_models.htm).

SWPP Study Reports from the past five years show the ten most detected insecticides as imidacloprid, bifenthrin, fipronil, permethrin, chlorantraniliprole, deltamethrin, lambda cyhalothrin, carbaryl, clothianidin, and cyfluthrin (CDPR, 2024b, 2023a, 2023c). To investigate pyrethroid occurrence and distribution throughout an urban drainage system, a study collected samples of water, sediment, algae, and biofilm from catch basins, open channels, and outfalls in Los Angeles County, California, during the dry season. The study detected pyrethroids in 89% of the water samples, and all sediment, algae, and biofilm samples, with bifenthrin and cyfluthrin being the most frequently detected (Sy *et al*., 2024).

Studies have shown that both fipronil and neonicotinoids induce toxicity in aquatic organisms (Yamamuro *et al.*, 2019). Fipronil degrades via photolysis, oxidation, pH-dependent hydrolysis, and reduction to form four principal metabolites: desulfinylfipronil (desulfinyl), fipronil sulfone (sulfone), fipronil amide (amide), and fipronil sulfide (sulfide). These metabolites tend to be more stable and persistent than fipronil (Miller *et al*., 2020). Multiple studies demonstrate that fipronil and its metabolites are toxic to aquatic non-target species (Bownik and Szabelak, 2021; Miller *et al*., 2020; Monteiro *et al*., 2019; Al-Badran *et al*., 2018).

Neonicotinoids are systemic pesticides that are effective on a wide range of invertebrate pests. Due to their water solubility, neonicotinoids have become contaminants of concern in surface water and have shown aquatic toxicity in multiple trophic levels (Miles *et al.*, 2017; Buszewski *et al.*, 2019; Mörtl *et al.*, 2020). In addition to the lethal effects, many studies point to sublethal impacts such as reduced reproductive capacity, initiation of downstream drift of organisms, reduced ability to eat, or a change in feeding strategies (Mukherjee *et al.,* 2022; Picone *et al.,* 2022; Strouhova *et al.*, 2023)

The insecticides identified in the previously described studies have been shown to impose toxicity to aquatic organisms in both the sediments and water column. Sublethal effects of individual insecticides and the cumulative effects of contaminant mixtures and/or multiple stressors may reduce individual fitness and negatively affect populations of non-target species, potentially disrupting complex ecological systems and possibly leading to a decline of fish abundance (Baldwin *et al.,* 2009; Watson *et al.,* 2020; Werner, Berndt, and Mansfield*,* 2021). There is limited understanding of the fate and ecological effects of pesticides and their residues in urban settings due to variable soil physio-chemical properties (Meftaul *et al*., 2020). There is a need to understand the extent to which urban insecticide use is impacting subsistence and cultural practices of Tribal and disadvantaged communities.

The Pyrethroid Control Program requires stormwater and wastewater permittees to conduct trend monitoring to determine the effectiveness of management practices implemented to reduce pyrethroid discharges to levels that comply with the numeric triggers. The Basin Plan stipulates that trend monitoring should also be designed to determine if monitoring and reporting programs are needed for alternative insecticides, including pyrethroids not covered by the Pyrethroid Control Program. If an alternative insecticide is identified as appropriate for monitoring, monitoring shall be performed by the discharger to determine whether alternatives to pyrethroid pesticides are being discharged at concentrations with the potential to cause or contribute to exceedances of applicable numeric or narrative water quality objectives. Additional research is needed to identify common urban alternative insecticides and any associated ecological impacts. Furthermore, more research is needed to understand the ecological impacts and potential environmental justice impacts of pyrethroids and alternative insecticides in urban environments.

Fulfillment of this Knowledge Gap will inform Research Question # 1 regarding identification of insecticides used in urban areas and their ecological impacts, and Research Question # 3 regarding impacts of pyrethroids and pyrethroid regulation in disadvantaged and Tribal communities.

J. Alternative Pyrethroid Management Practices

Due to their broad-spectrum action, pyrethroids pose a risk to aquatic invertebrates and fish (USEPA, 2019). Best management practices are needed to protect aquatic organisms while considering economic factors, availability, technical feasibility, ability to implement, and effectiveness. The Pyrethroid Control Program requires dischargers to develop pyrethroid management plans to mitigate aquatic contamination if pyrethroid concentrations in their discharges exceed the numeric triggers. Available management practices or mitigation strategies vary based on discharger type, with municipal stormwater and wastewater dischargers being largely limited to education and outreach efforts as they have limited source control.

Conversely, since agricultural dischargers can control their applications, there are more strategies available. Currently, agricultural coalitions employ, among others, the following widely-used management practices to curtail pesticide runoff: recirculation – tailwater return systems, sedimentation ponds, berms between fields and waterways, setbacks, and modified application strategies according to weather conditions.

Initial data collected under the Pyrethroid Control Program indicates pyrethroid numeric trigger exceedances in both urban and agricultural settings. Until trend monitoring is implemented for municipal stormwater and wastewater dischargers, there is no way to evaluate the effectiveness of the Pyrethroid Management Plan education and outreach practices. If these practices are not effective, there will be a need to identify true source control-based actions.

Agricultural coalitions, however, perform regular monitoring of pyrethroids, revealing recurring numeric trigger exceedances despite implementation of management practices. This demonstrates that current widely-used management practices may be inadequate at attaining the low pyrethroid concentrations set to prevent aquatic toxicity, requiring development of updated management practices. Other factors such as failure to adhere to label instructions, human error, equipment error, or insufficient label requirements may also contribute to the continued exceedances of the pyrethroid numeric triggers. If the aforementioned factors are identified as the cause of exceedances, the Central Valley Water Board will coordinate with the Coalitions and other relevant regulatory agencies.

Dischargers and regulatory agencies have a shared interest in developing effective management practices for reducing pesticide discharges and associated water quality impacts. There is an ongoing effort by CDPR to integrate safer, more sustainable pest control practices through its Sustainable Pest Management Roadmap. Work done in support of this Roadmap will complement, or possibly address, the needs identified in this Knowledge Gap.

Fulfillment of this Knowledge Gap will inform Research Question # 2 regarding the need for development of alternative pyrethroid management practices.

4. Conclusion

The Basin Plan stipulates that the Plan is required to identify existing knowledge gaps that will enhance the understanding of pyrethroid environmental impacts and behavior, and any resulting research findings will be included in the re-evaluation of the Pyrethroid Control Program. The scope of the Plan is limited to areas of scientific uncertainty that can be addressed by the research community. Therefore, the Plan does not outline any uncertainties directly related to regulatory actions or requirements, such as consideration of Water Code 13241 factors needed to develop WQOs. However, as stated in Section 1.C, Board staff is committed to working with interested persons, agencies, environmental interest groups, Tribes, and permittees, to gather any additional information that would inform the consideration of the Water Code 13241 factors or other aspects of the Pyrethroid Control Program re-evaluation.

The Plan contains an updated literature search of research relevant to the Knowledge Gaps identified during the development of the Pyrethroid Control Program as well as Knowledge Gaps identified since its adoption. The Plan documents the Board’s pyrethroid-related Research Questions and needs to support the re-evaluation of the Pyrethroid Control Program.

The Knowledge Gaps identified by Board staff include:

- partition coefficients;

- pyrethroid chemistry methodology;
- fate and transport of particulate-bound pyrethroids;
- co-stressors: temperature, salinity, microplastics;
- synergistic and additive toxicity;
- evaluation of sublethal effects;
- chronic toxicity in other taxa;
- pyrethroid bioaccumulation;
- urban insecticide use;
- alternative pyrethroid management practices;

Filling the scientific Knowledge Gaps will require a combination of new monitoring, laboratory studies, and computer modeling. Addressing many of the Knowledge Gaps discussed in this Plan will require years of study. While steps were taken by the Central Valley Water Board to address some of the Knowledge Gaps, these efforts are ongoing.

The Plan may be referenced by the scientific community as a justification for grant proposals or other funding opportunities, while research and funding agencies can reference the Plan in their requests for proposals. The Central Valley Water Board will, as resources allow, seek to fund some studies pursuant to the Plan; however, most of the remaining needs will be fulfilled by research and funding agencies.

The Central Valley Water Board is committed to a formal re-evaluation of the Pyrethroid Control Program by 19 February 2034. At such time, research in support of the Knowledge Gaps identified in the Plan could inform the review of the pyrethroid pesticides prohibition, the pyrethroid pesticides TMDL allocations, the numeric pyrethroid triggers, and the implementation provisions for pyrethroid pesticide discharges in the Basin Plan.

Historically, pesticide control programs result in reduced or eliminated use of the relevant pesticides, but increased reliance on replacement pesticides. Pyrethroids may be obsolete by the time some of the Knowledge Gaps have been addressed and the Central Valley Water Board formally re-evaluates the Pyrethroid Control Program. In recognition of shifts in pesticide use trends, the Central Valley Water Board welcomes more holistic pesticide research that has broader applicability to new and replacement products. As an agency, the Central Valley Water Board seeks to modify its management approach from single-class or active ingredient control programs to a more comprehensive approach that will allow adaptation to the ever-changing pesticide market and ultimately more dynamic protection of beneficial uses.

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Appendix:
Pyrethroid Research Plan Stakeholder Engagement

Pyrethroid Control Program Development and Adoption
As referenced in Section 1.B, the Pyrethroid Control Program was adopted as an amendment to the Basin Plan with a provision (Basin Plan section 4.5.5.1(8)) to develop a Pyrethroid Research Plan (Plan).

The development and adoption of any Basin Plan amendment involves a robust stakeholder engagement process governed by legal requirements, which includes a public process, public noticing for meetings and the release of documents, formal written comment periods, and meeting opportunities. The Pyrethroid Control Program development and stakeholder engagement process took place over the course of five years, from 2013 – 2017. During this time, Board staff actively engaged with individuals, groups, and organizations that had an interest in or would be affected by the developing regulations of the Pyrethroid Control Program. Stakeholders involved in the development process included municipal stormwater and wastewater dischargers, agricultural dischargers and their representatives, representatives of the pyrethroid manufacturers, conservation groups, researchers, and state and federal agencies.

In addition to numerous meetings with stakeholders, the Board held three publicly-noticed Board Workshops where stakeholders provided oral feedback to the Board members on the Pyrethroid Control Program's scientific approach, proposed regulatory options, implementation provisions, etc. Comments identified factors and topic areas requiring further study. Board staff incorporated these identified information gaps in detail in the draft Staff Report. Board staff used the feedback obtained from the stakeholders during previous meetings to draft the Staff Report. Board staff publicly released the draft Staff Report and the proposed Basin Plan amendment language for public comment. During the written comment period, Board staff presented an information item at a Board Meeting where members of the public, stakeholders, and representatives of other agencies could provide oral comments on the proposed Basin Plan amendment and the draft Staff Report. Board staff reviewed and considered all comments in the final version of the Pyrethroid Control Program and maintained the information gaps and areas requiring further study in the final version.

The Board adoption hearing served as another opportunity for stakeholders to comment. In response to comments provided during the Board adoption hearing, Board staff added a late revision to the Pyrethroid Control Program, to develop a Pyrethroid Research Plan to address seven specified areas requiring further study. Additionally, the late revision included specific named organizations or entities that should be consulted on the Plan including the Delta Science Program, Delta Independent Science Board, Delta Stewardship Council, Department of Fish and Wildlife, and Delta Regional Monitoring Program.

Pyrethroid Research Plan Development

Board staff used the seven Knowledge Gaps identified in the Basin Plan (4.5.5.1(8)) and in the Final Staff Report (Water Board, 2017) as a starting point for the draft Plan. Additionally, in 2023, Board staff conducted a review of scientifically peer-reviewed publications and incorporated five additional Knowledge Gaps based on research developments since the adoption of the Pyrethroid Control Program. Board staff compiled this information and developed an initial draft of the Plan. Board staff provided an advanced preview of the draft Plan to the stakeholders identified in the Basin Plan, as well as the Pyrethroid Working Group, with the intent to solicit feedback prior to the public release. Board staff received largely editorial comments during this period, with one exception regarding the scope of the Plan, specifically pertaining to Water Code 13241 considerations for developing water quality objectives. Board staff revised the initial draft according to the editorial comments and publicly released the draft Plan in July 2023.

Outreach and engagement with disadvantaged and tribal communities

Board staff sought to engage with disadvantaged and tribal communities with the goal of identifying additional needs from those communities that could be added to the Plan. Board staff solicited input on how to best engage with disadvantaged communities from regulated community and industry representatives for the MS4 and wastewater dischargers and pyrethroid manufacturers. Board staff coordinated with Larry Walker Associates, who represent a large contingent of MS4 Phase II stormwater permittees in the Central Valley, to organize a meeting with permittees, specifically those representing small and/or disadvantaged communities. On 16 August 2023, Board staff, in partnership with Larry Walker Associates, hosted a virtual meeting with stormwater permittees. Forty-two representatives from 25 Phase I and Phase II stormwater dischargers attended the meeting. The hour-long meeting consisted of a condensed presentation covering an overview of the draft Plan followed by a 45-minute question and answer period. Following the meeting, Board staff provided a copy of the presentation as well as staff contact information for follow-up questions or to arrange additional meetings.

Board staff also contacted representatives of Environmental Justice (EJ) groups. As the Central Valley region is home to communities with varying resources, Board staff sought to engage community outreach groups such as EJ groups, tribes, and discharger organizations, specifically those serving disadvantaged communities. Board staff coordinated with the Central Valley Water Board's Community Engagement and Tribal Coordinator to distribute the public notice of opportunity to comment on the draft Plan to 32 EJ groups and 144 Tribes.

Board staff also coordinated with the Board's Irrigated Lands Regulatory Program (ILRP) staff to share information about the draft Plan with ILRP's EJ and Coalition stakeholders. On 26 July 2023, Board staff presented at the ILRP Quarterly Stakeholder

Meeting, providing a brief overview of the draft Plan, information about the August 2023 staff workshop, the deadline to comment, Board contact address, and instructions on how to access the draft Plan.

Public Outreach

Board staff posted the notice of opportunity to comment on the draft Plan on the Central Valley Water Board's Public Notices website in English and Spanish. To announce the initiation of the 63-day comment period (17 July 2023 – 18 September 2023), Board staff issued a GovDelivery bulletin to the Pyrethroid Control Program subscription list notifying subscribers of the opportunity to comment and the upcoming staff workshop to discuss the draft Plan.

On 1 August 2023, Board staff hosted a hybrid staff workshop at the Rancho Cordova office to discuss the draft Plan. Twenty-seven participants attended the workshop. Participant affiliations included the regulated community, consultants, scientific community, state regulatory agencies, and industry. Board staff collected verbal feedback at the workshop and encouraged participants to submit written comments. Following the workshop, Board staff distributed a digital copy of the presentation and attendance list to all participants.

After the public comment deadline, staff reviewed all comments and drafted preliminary responses to comments. Several commenters raised similar concerns over the following three topics: the scope of the Plan, and by extension, the appropriateness of the Management Questions; the relationship between the Knowledge Gaps and Management Questions; and request for prioritization of the Knowledge Gaps. On 12 March 2024, Board staff hosted a second hybrid staff workshop to discuss the proposed revisions intended to address the feedback received during the public comment period. Twenty-six participants attended the workshop. Participant affiliations included the regulated community, consultants, scientific community, state regulatory agencies, and industry. Following the workshop, Board staff distributed a digital copy of the presentation and attendance list to all participants.

During the 12 March 2024 workshop, several attendees advocated strongly for the prioritization of research identified in the Plan, so Board staff proposed holding an additional meeting where interested groups could provide their group's prioritization proposals for inclusion in the revised Plan. Board staff organized a meeting on 29 July 2024 so that interested organizations could present their respective prioritization proposals. Board staff offered to include any submitted prioritization schemes for individual stakeholder groups as an appendix to the Plan. Board staff have not received requests for additional meetings nor identified a clear Plan for prioritization.