**Estimating Bifenthrin Concentration in Urban Runoff Using PWC Model**

**Abstract**

The Sacramento-San Joaquin River Delta provides critical habitat for many fish and invertebrate species and is impacted by pyrethroid use and associated polluted urban storm runoff. We modeled the concentration of the pyrethroid bifenthrin for four storm drain outlets associated with two creeks using the Pesticide in Water Calculator (PWC; version 1.59), with a simulation period of January 2009 to December 2014. We used PCO data to estimate the total mass of bifenthrin applied at the county level in Sacramento and Placer County. We estimate that approximately 1.5% to 1.88% of bifenthrin reaches Pleasant Grove Creek creeks in Roseville and Alder Creek in Folsom through runoff and drift, with runoff accounting for more than 80% of the mass loss. Simulated daily bifenthrin concentrations were greatest in Alder Creek due to its high urban influence and associated application. The modeled Estimated Environmental Concentrations (EEC) results for 1-day and 4-day (acute) averages are over an order of magnitude higher than the EPA Office of Pesticide Program’s aquatic life benchmarks. Compare to 21-d and 60-d (chronic) concentrations. Monitoring data indicate that Alder Creek reached maximum concentrations of 73.2 ng/l bifenthrin and Pleasant Grove Creek reached a maximum bifenthrin concentration of 44.8 ng/l. Monte Carlo and sensitivity analysis results. Overall, the model demonstrated good performance in capturing the application patterns and concentration of bifenthrin at the modeled sites. We demonstrate that with careful application, the model can be appropriately used for pyrethroid simulation and can efficiently support water resource management decisions.

***Keywords****:* Pesticide in Water Calculator, Pyrethroid, Bifenthrin, Urban runoff, Estimated Environmental Concentration

# Introduction

Rivers and streams receiving urban runoff have been shown to be toxic to aquatic species (e.g. *H. azteca*) due to the presence of pyrethroids (Budd et al., 2007; Weston and Lydy, 2010; Weston et al, 2014). The pyrethroid bifenthrin is highly toxic to aquatic species, with acute mortality possible at even low concentrations of 1 ng/L (Weston et al., 2008; Weston et al., 2010), yet urban runoff regularly contains concentrations greater than 20 ng/L (Weston and Lydy, 2012). Generally, bifenthrin is widely used by professional pest control applicators for landscape application or as perimeter treatments to keep pests out of structures in most urban environments. In the urban environment, runoff often contains a considerable amount of bifenthrin after a storm event (Weston et al. 2009). The Sacramento-San Joaquin River Delta, one of the main water bodies in California, receives urban runoff after rainfall events. Studies have shown that the Sacramento–San Joaquin Delta is habitat for many aquatic species of concern, including the delta smelt, threadfin shad, San Francisco longfin smelt, and striped bass, whose decline has been associated with the presence of high bifenthrin concentration (Sommer and Mejia, 2013).

Werner et al. (2010) estimated that toxicity from bifenthrin can be as high as 117 ng/L, about 10 times the acute toxicity level for loss of motion to most aquatic threatened and endangered species in the Sacramento-San Joaquin River Delta. To reduce pyrethroid runoff to a safe level in the Delta, there is a need to monitor upstream urban rivers and creeks for the presence of these pesticides. Modeling data is needed in combination with pesticide monitoring data to evaluate the effectiveness and mitigate pesticide runoff and determine whether observed concentrations in water bodies are at continued risk (Hoogeweg et al., 2011). The use of exposure models is an effective mode of estimating pesticide concentration in water bodies (Luo et al, 2011). For environmental fate and transport modeling, water quality models are typically combined with field-scale models to predict exposure concentrations and screen for pesticide registration (Guo et al., 2004). Additionally, the data outputs from these models can be used to aid in the development of effective management and mitigation strategies, such as in the development of Best Management Practices (BMPs) for reducing pesticide fluxes in water bodies (Moore et al., 2002; Cho and Mostaghimi, 2009).

The Pesticide in Water Calculator (PWC) is an environmental fate and transport model developed by the United States Environmental Protection Agency (USEPA) Office of Pesticide Program (OPP) as a regulatory tool for risk assessment. The model simulates pesticides concentration in surface water for aquatic exposure assessments (USEPA, 2016b) and contains two main simulation engines: The Pesticide Root Zone Model (PRZM5 version 5.02), and the Variable Volume Water Model (VVWM version 1.02) (PWC Manual, 2015). The model accommodates specific characteristics of the pesticide of interest and includes site-specific information pertaining to the application method and impact of local daily weather on the treated site for long-term simulations (typically 30 years or more). PRZM5 is a continuous simulation model, which uses multiple years of rainfall data to cover year-to-year variability in runoff; secondly, PRZM5 predicts daily edge-of-field loadings of pesticides in both dissolved (in runoff water) and adsorbed forms (sorbed to sediment) (USEPA, 2016b). The VVWM is an updated model of the EXposure Analysis Modeling System (EXAMS; Burns, 2000). Unlike EXAMS, which assumes constant water volume and does not allow the water bodies within the watershed to vary in response to precipitation, runoff, evaporation, and overflow (USEPA, 2016b), VVWM also simulates daily variations in water body volume due to runoff, precipitation, overflow, and evaporation for the USEPA standard water bodies (USEPA, 2016b).

Although PWC has many advantages compared to other exposure models such as FIRST (FQPA Index Reservoir Screening Tool) and GENEEC (GENeric Estimated Environmental Concentration) (Parker et al. 1995, USEPA, 2016b), the PWC model has not been thoroughly evaluated for its modeling capability to simulate pesticide concentrations from urban uses. Studies evaluating the use of the model in simulating pesticide concentration in surface water for risk assessment are just now emerging (e.g., Sinnathamby et al. 2019; Argentina study). In this study, PWC was used to simulate the acute and chronic bifenthrin EECs in storm drain outfalls in Pleasant Grove Creek Watershed and Folsom Watershed within Placer and Sacramento Counties, respectively. Storm drain outfalls are the main source of pyrethroid wash-off into the urban creeks which, eventually ends up in large rivers and streams. We evaluated bifenthrin because it is among the highest-use pyrethroids in the region (CDPR Database, 2014) and most often contributes to the increased toxicity in the study area urban creeks (TDC, 2010; Amweg et al., 2005), which eventually end up in the Sacramento-San Joaquin River and Delta. Additionally, monitored bifenthrin concentrations are available for the model evaluation. The specific objectives of this study are to: (1) evaluate how accurately the PWC model predicts daily and longer term EEC of bifenthrin in urban runoff at the sampling outlets; and (2) compare the model-derived acute and chronic EECs at the urban sites to the reported 2011 CALFED aquatic Threatened and Endangered Species values, which provide useful information for exposure-related decision making and management.

# Materials and Methods

## PWC Model and Aquatic Exposure Risk Assessment

Since PRZM5 and VVWM are the two main engines of the PWC, a brief introduction of PRZM5 and VVWM is provided below. In the PWC model, PRZM5 is dynamically (file transfer-) linked to the VVWM for the estimation of pesticide concentrations in surface waters for aquatic ecosystem exposure assessments. PRZM5 is a one-dimensional hydrology, heat and solute transport model, developed for pesticide simulations in unsaturated soil systems within and underneath the root zone of plants (Young and Fry, 2016). PRZM5 model simulates descending movement of water by a tipping bucket concept, where water is always moving downward. It is designed to evaluate the influence of climate, soil properties, and management practices on pesticide transport and transformation processes (e.g., surface runoff, leaching, erosion, and volatilization). The model has the capacity to simulate up to three chemicals as separate chemicals or as a parent and daughter mixes and allows the simulation to be conducted using multiple years of rainfall data to cover year-to-year climate variability. This added feature gives the user the alternative to observe the impacts of various chemicals without making extra runs, or the capacity to enter a mass change component from a parent chemical to daughter chemicals.

The PRZM5 model calculates runoff based on the Natural Resources Conservation Services (NRCS) Curve Number (CN) method (NRCS, 2003). In using the CN method, irrigation water, and snowmelt is treated as having the same effect as precipitation (rain). Hence, precipitation in the above equations is the sum of rain, snowmelt, and irrigation. The CN used to compute daily runoff is adjusted on a daily basis according to the soil moisture (Young and Fry, 2016). PRZM5 has two options for erosion calculation (Young and Fry, 2016); the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and the Small watershed version of MUSLE (MUSS) (Kinnell, 2004).

In PRZM5, chemicals are simulated through the vertical movement of water in the soil compartment (Young and Fry, 2016). The soil water content in the water column, at any point of the simulation, is first calculated from the amount of infiltrating water from the layer above. At any point, if the soil water content exceeds the field capacity, the excess water is used as flow into the next compartment for the chemical simulation that compartment. This process continues throughout the soil column chemical simulation with the aid of precipitation, irrigation and snowmelt infiltration.

The VVWM simulation engine of the PWC model, the successor of the EXAMS model (Burns, 2000), is an important water quality model used to assess the fate, transport, exposure, and persistence of pesticides in aquatic systems (Xie, 2014). In the VVWM model, the receiving water body is divided into two parts – the littoral zone and the benthic zone, which are coupled by completely mixing with dispersive and advective transports and first-order mass transfer process (Burns, 2000; Young, 2014). Classic processes, such as pesticide adsorption and desorption, photolysis, hydrolysis and redox, biolysis, and volatilization are involved in the VVWM model. The model allows users to define custom water bodies within their study area. The main difference between the VVWM model and the EXAMS model is based on the assumption of the volume of the receiving water body in the region of study. That is, the EXAMS model assumes constant water volume whereas the VVWM model allows the water volume to vary in response to precipitation, runoff, evaporation, and overflow.

The advantages of the VVWM coupled with the ability of PRZM5 to simulate relevant processes of pesticide transport, and its use by regulatory agencies in their pesticide exposure assessments (USEPA, 2010) aided in the selection of the PWC for this study. In addition, California has also developed urban scenarios to aid in the application of the PWC model in aquatic risks assessment (CALFED Report, 2011). These scenarios specify the urban land application site percentages (pervious and impervious) for structural, landscape maintenance, and other urban land uses, and soil properties.

To assess the risks to aquatic species, the PWC model in this study estimated acute and chronic EEC of bifenthrin in the surface runoff. These EECs were obtained from the PWC model as 1 and 4-day average concentration in the 1-in 10 -year return simulation period. The model’s estimated acute and chronic concentrations were compared to the 2011 CALFED report established benchmark for bifenthrin. The 2011 CALFED report benchmark was obtained as 1/10th of the USEPA benchmark for aquatic species (CALFED, 2011). This comparison was in-line with the proposed toxicology threshold established in the 2011 CALFED Report for Threatened and Endangered Species.

## Study Area

Sacramento and Placer Counties in California have experienced increased population growth, and within the past few years, thousands of homes have been built on land that was initially grassland (Weston et al., 2012). The cities of Roseville and Folsom are two of many such urban communities that are made up of numerous single-family homes, most of which are less than 20 years old. Roseville and Folsom were selected because they contain active water monitoring sampling sites of the California Department of Pesticide Regulation (CDPR), at which bifenthrin has been detected (Budd et al., 2020). In addition, the sites are urban areas with no agricultural land use upstream of the sites (Fig. 1). The sites themselves are upstream of the Sacramento–San Joaquin Delta and a contributor to water quality in the Delta.

This study area focuses on the two HUC-12 watersheds that Roseville and Folsom are located within (Pleasant Grove Creek watershed and Folsom watershed, respectively). Each watershed contains two storm drains of interest which receive runoff from residential neighborhoods in Roseville and Folsom (Fig. 1).

Of the two storm drains located in the city of Folsom, Sacramento County (Folsom watershed), one storm drain is located near open fields at Brock Circle (CDPR-FOL002) with a drainage area of 0.26 km2 and the other storm drain is located near an outfall at Marsh Hawk Drive between Donnelly Circle Widgeon Court (CDPR-FOL003) with a drainage area of 0.11 km2. These storm drains serve approximately 295 and 91 single-family homes, respectively. Discharge water from both storm drains lead into Alder Creek. The area is mostly characterized by a dry season from May through October with an average annual high temperature of 23.8o C and low temperature of 9.9o C. Precipitation mostly occurs from November through April resulting in an annual average of 625 mm.

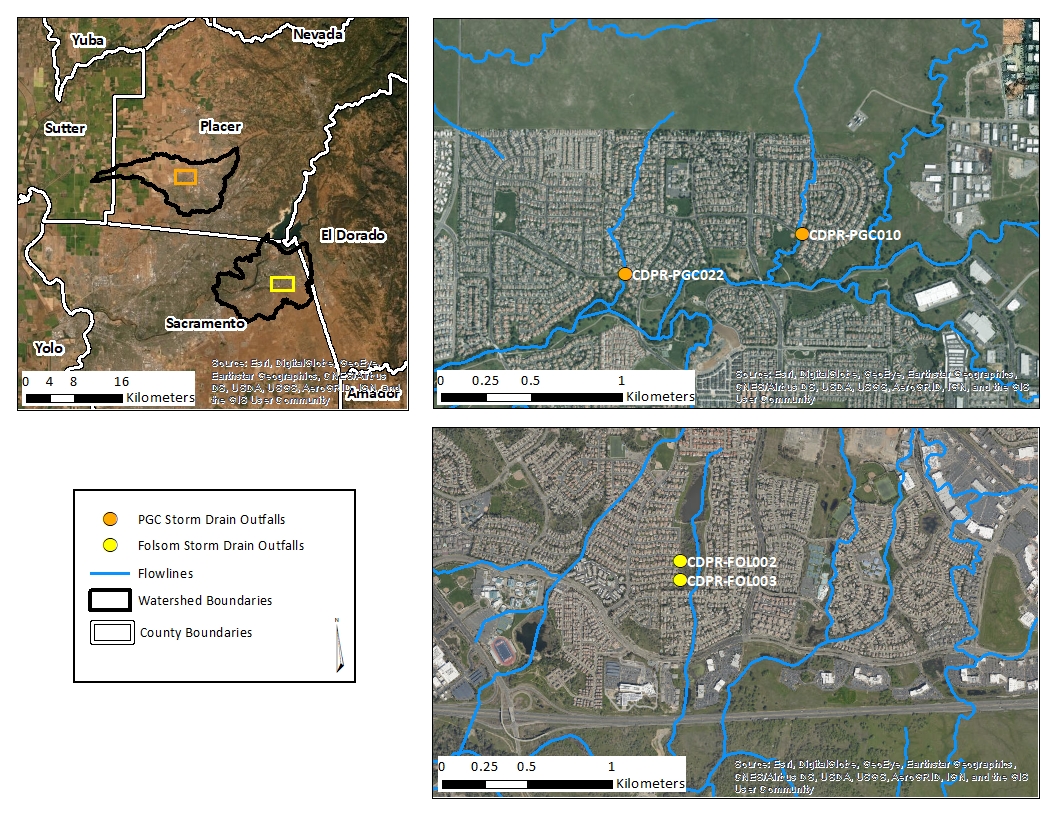


Fig. 1. Reference map of Folsom watershed storm drains and Pleasant Grove Creek watershed storm drains. Located upstream of the Sacramento-San Joaquin Delta.

Two storm drains are located in Roseville, Placer County (Pleasant Grove Creek watershed) (Fig. 1). Both storm drains connect to Kaseberg Creek, one of the watershed’s main tributaries to the Sacramento–San Joaquin delta. One storm drain is located in Dugan Park on Diamond Woods Circle (CDPR-PGC010) and has a drainage area of 0.23 km2.The second storm drain is located at Opal and Parkside Way (CDPR-PGC022) with a drainage area of 0.45 km2. These sites serve about 250 and 375 single-family homes, respectively. Precipitation usually occurs between November and March with an annual value of about 711 mm. With almost similar climatic conditions, the primary source of water to the drains is runoff from residences during storm events and over-irrigation of landscapes and lawns during the summer.

These four storm drains are actively monitored by the CDPR’s Surface Water Protection Program for bifenthrin concentrations from urban water bodies due to high urban pesticide usage. The CDPR’s Surface Water Protection Program collected water samples from storm drain outfalls from 2009 to 2018 (Budd et al., 2020). Samples were generally collected four times per year with two collected during precipitation-induced storm water events during the wet season (Oct. – Mar.) and two collected during irrigation-induced events during the dry season (June – Sept.). The program attempted to collect a sample during the first and last major storm events during the wet season. Between this study’s time span of 2009 – 2014, the following number of water samples were collected: 21 for CDPR-FOL002, 17 for CDPR-FOL003, 27 for CDPR-PGC010, and 14 for CDPR-PGC022. These observed concentrations were compared to model outputs and used to assess model performance.

Table 2. Parameters Required for Defining the Receiving Water Body.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | CDPR-FOL002 | CDPR-FOL003 | CDPR-PGCO10 | CDPR-PGC022 |
| Watershed and Water Body Dimensions | **User Defined** | **User Defined** | **User Defined** | **User Defined** |
| Field Area (m2) | 1.4310e+8 | 1.4310e+8 | 1.2144e+8 | 1.2144e+8 |
| Water Body Area (m2) | 35000 | 35000 | 32000 | 30000 |
| Initial Depth (m) | 2 | 2 | 2 | 2 |
| Maximum Depth (m) | 2 | 2 | 2 | 2 |
| Hydraulic Length (m) | 2400 | 2400 | 2000 | 2000 |
| Water Body Physical Parameters – Water Column | **USEPA Pond** | **USEPA Pond** | **USEPA**  **Pond** | **USEPA Pond** |
| DFACa | 1.19 | 1.19 | 1.19 | 1.19 |
| Water Column SSb (mg/L) | 30 | 30 | 30 | 30 |
| Chlorophyll (mg/L) | 0.005 | 0.005 | 0.005 | 0.005 |
| Water Column FOCc | 0.04 | 0.04 | 0.04 | 0.04 |
| Water Column DOCd (mg/L) | 5 | 5 | 5 | 5 |
| Water Column Biomass (mg/L) | 0.4 | 0.4 | 0.4 | 0.4 |

*Table edited from Young, 2014.*

*aDFAC = VVMM-defined distribution factor associated with photolysis*

*bWater Column SS = Concentration of suspended sediment in water column*

*cWater Column FOC = Fraction of organic carbon in water column*

*dWater Column DOC = Concentration of dissolved organic carbon in water column*

## Data Collection and Input Preparation

The main PWC model components are the land phase (simulated by PRZM5) and the water phase (simulated by VVWM). Daily weather data required by PRZM5 are rainfall, temperature, wind speed, and solar radiation. PWC requires weather inputs consisting of daily rainfall, temperature, wind speed, solar radiation, and evapotranspiration (\*.wea file). Weather station daily averages for 2008 – 2014 were available from the National Center for Environmental Prediction Reanalysis and the NOAA Climate Prediction Center Unified Rain Gauge Analysis at 0.25 x 0.25-degree latitude/longitude resolution (Fry et al., 2016). The grid centroids were used to identify the weather station closest to the storm drain; this was performed for each of the four storm drains. Other PRZM5 parameters, including soil physical properties and USLE parameters, were determined using the CALFED 2011 Report and the Soil Survey Geographic (SSURGO) databased (USDA-NRCS, 2009). Soil property input values used for the deterministic simulations are shown in Table 1. Because FOL002 and FOL003, and PGC010 and PGC022 are located within the same watershed, input values were the same for the two storm drain pairings.

For VVWM, three modeling scenarios are available: the USEPA standard farm pond for aquatic ecosystem risk assessment, the USEPA standard index reservoir for drinking water exposure assessment, and a “User Defined” scenario (PWC Manual, 2015). The “User Defined” water body (Table 2) was used for simulation in this study. Water body dimensions were derived from GIS analysis (ArcGIS 10.4) of the study site, with water body physical parameters based on USEPA OPP default values (Table 2).

Table1. Environmental Properties Used in The PRZM5 Deterministic Simulation.

|  |  |  |
| --- | --- | --- |
| **Parameter** | **FOL002, FOL003** | **PGC010, PGC022** |
| Potential evapotranspiration adjustment factor | 0.77 | 0.77 |
| Min. depth from which evapotranspiration is extracted | 17.5 | 17.5 |
| USLE soil erodibility factor | 0.35 | 0.35 |
| USLE topographic factor | 0.37 | 0.37 |
| USLE practice factor | 1.0 | 1.0 |
| USLE cover factor | 0.06 | 0.06 |
| Land slope (%) | 2.5 | 2.5 |
| Hydraulic length (m) |  |  |
| Runoff curve number 2 | 84 | 67 |
| Manning’s roughness coefficient | 0.07 | 0.07 |
| Bulk density of first soil horizon (g/cm3) | 1.3 | 1.3 |
| Field capacity; maximum capacity | 0.284 | 0.284 |
| Wilting point; minimum capacity | 0.144 | 0.144 |
| Organic carbon in the horizon (%) | 0.29 | 0.29 |
| Dissolved phase pesticide decay rate | 0.004283931 | 0.004283931 |

Table 2. Parameters Required for Defining the Receiving Water Body



2.3.1 Bifenthrin Input Parameters

The physicochemical properties of bifenthrin are the governing factors for pesticide runoff potential in both dissolved and absorbed phases (Goss, 1992; Luo and Zhang, 2010). Input values used in the deterministic simulations were determined using the CALFED 2011 report, the EPA chemistry dashboard, and values found in the literature (Table 3). Degradation of pesticides in soil involves processes such as hydrolysis, photolysis, and microbial decay and are simulated by PRZM5 based on a combined single decay rate and assumes first-order kinetics (Luo and Zhang, 2009).

Professional bifenthrin application data were downloaded from the California Pesticide Information Portal (CALPIP), maintained by CDPR (CDPR, 2016). CALPIP reports all daily agricultural and non-agricultural (excluding homeowner) uses of registered pesticides by active ingredient at the county level. Because this study modeled bifenthrin concentrations at the watershed-scale, the county-level application data were downscaled to the watershed-scale using methodology provided by the CDPR’s Surface Water Protection Program (Luo, 2015). For this study, “structural pest control,” “regulatory pest control, “landscape maintenance,” “rights-of-way,” and “buildings and structures (non-ag outdoor)” sites for bifenthrin in Placer, Sacramento, El Dorado, and Sutter counties from 2009 – 2014 were downloaded from the CALPIP. For each year in each county, the daily pounds of applied bifenthrin was summed to compute monthly totals and then converted to kilograms. Homeowner use is not recorded in the CALPIP but it has been estimated to be approximately 25% of the recorded amount (site this). As a result, an additional 25% of the reported CALPIP bifenthrin usage was added to the monthly totals. Sub-county division population density data was used to aggregate the CALPIP data to the watershed-scale (Fig. 2). The population in the watershed was calculated by summing the product of each sub-county division’s population density with the area of the watershed intersecting the sub-county division, for all sub-county divisions intersecting the watershed belonging to the same county. The population in the watershed was then divided by the total population in the county. These fractions, one for each of the counties intersecting the watershed, was multiplied by monthly applications (kg) that were previously computed. To obtain the application rates (kg/ha), applications (kg) were divided by the area of urban landcover in the watershed (ha). Urban landcover area was calculated using the NLCD 2016 landcover raster (USGS NLCD, 2016) in ArcMap (ArcGIS, version 10.7). An in-depth display of the calculations are shown in Tables A – B.

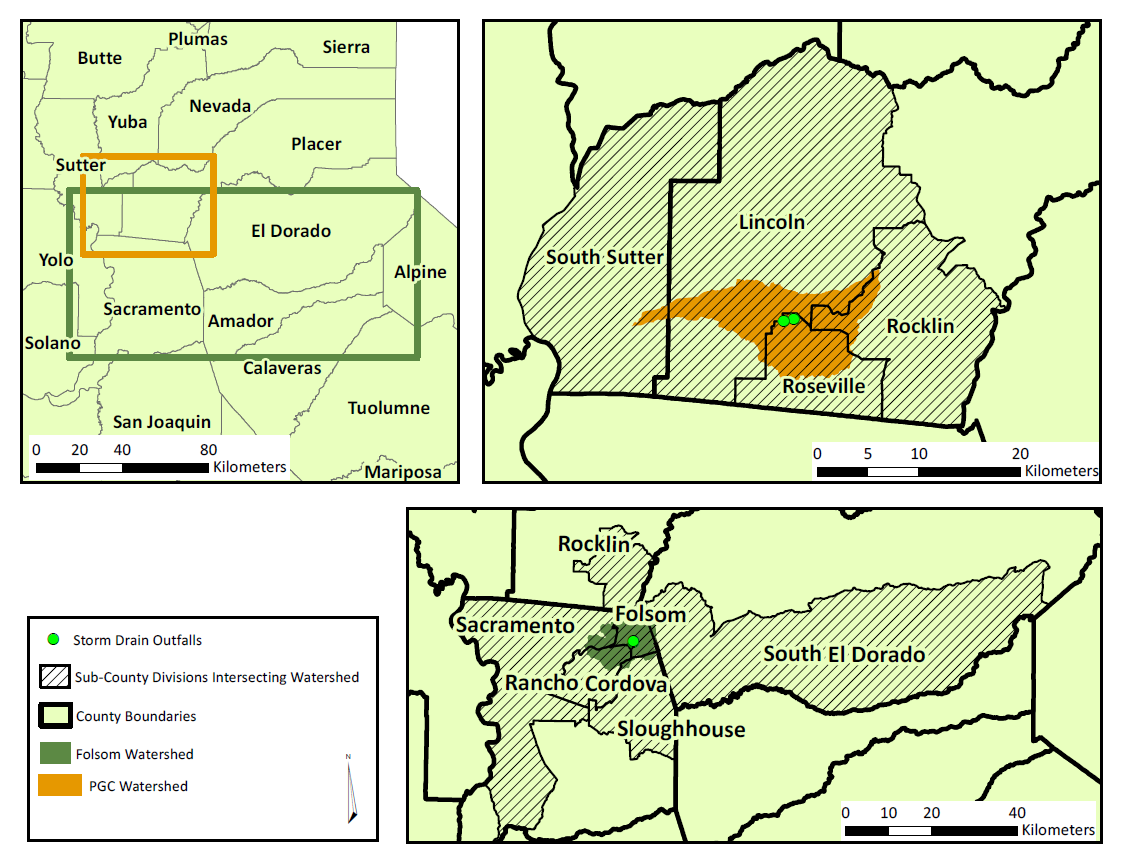


Fig. 2: Reference map for aggregating urban pesticide use data to the watershed-scale.

Monthly application rates were divided by the number of days in the month to obtain daily application rates. A 30-day moving average was then calculated to avoid relatively drastic changes between months. The PWC graphical user interface only allows up to 50 application rates, so in order to run the simulation, the 2,191 daily applications rates were directly entered into the PWC input files (.inp). Application efficiency and drift were set to 99% and 1% for all simulations (CALFED Report, 2011).

Table 3. Bifenthrin Properties



|  |  |
| --- | --- |
| **Bifenthrin Properties** | **Input Value** |
| Dissociation coefficient (mL/g) | 3570 |
| Water column degradation half-life (days) | 323.6 |
| Water column reference temperature (C) | 20 |
| Benthic degradation half-life (days) | 647.2 |
| Benthic degradation reference temperature (C) | 20 |
| Photolysis half-life (days) | 365 |
| Photolysis reference latitude | 40 |
| Hydrolysis half-life (days) | 365 |
| Soil half-life (days) | 161.8 |
| Soil reference temperature (C) | 20 |
| Molecular weight (g/mol) | 422.9 |
| Vapor pressure (torr) | 1.80e-3 |
| Solubility (mg/L) | 0.000014 |
| Henry’s Constant (m3/mol) | 7.2e-3 |

## Deterministic Simulation Design

A deterministic simulation for each storm drain (CDPR-FOL002, CDPR-FOL003, CDPR-PGC010, CDPR-PGC022) was performed to provide a single concentration estimate over the studied time period of 2009 - 2014. Deterministic simulations do not incorporate a random component. A single set of input values are used to model the output rather than considering a range of possible values for each input parameter. The input values used in the deterministic simulations are shown in Tables 1 – 3.

PWC model outputs are time series concentrations at a daily scale, reported as 1-day and 4-day average EEC of bifenthrin in the urban waters. In order to evaluate the performance of the PWC deterministic simulations, deterministic model outputs were compared to the CDPR SWPP observed concentrations as well as the probabilistic simulation predictions for the corresponding storm drain.

## Probabilistic Simulation Design

The probabilistic simulation uses the deterministic simulation’s set of input parameters and assumptions. However, the probabilistic simulation utilizes pre-determined distributions for each input parameter to allow for variability across the simulations. This approach randomly draws input variables from their respective distribution during each simulation to yield x model outputs (where x is the number of probabilistic simulations). A probabilistic sensitivity analysis (SA) then searches the entire parameter space to identify critical parameters on the model output. The SA can also aid in reducing overall model variation and uncertainty by focusing efforts on the critical input parameters.

The probabilistic SA included 5000 simulations and 38 input parameters. Input parameters were sampled using the Latin Hypercube technique with the “lhs” R package (Carnell, 2016). The Latin Hypercube technique samples parameters evenly across their distribution range. Table 4 displays the sampled PWC input parameters, their descriptions, their distribution ranges, and the sources used to determine these ranges. The partial correlation coefficient (PCC) statistic was computed with the “sensitivity” R package to quantify the parameters’ impact on the model output, therefore serving as the primary sensitivity analysis metric (Pujol et al., 2017). The PCC statistic measures the strength of the linear relationship between the model output and each input parameter while accounting for changes in all other input parameters. It ranges from -1 to +1 with the sign denoting a negative or positive relationship, respectively, between the model output and input parameter. A Monte Carlo shell wrapper was developed using R version 3.6.1 to execute PRZM and VVWM (PWC version 1.59), conduct the Latin Hypercube technique, and assess parameter sensitivity using the partial correlation coefficient statistic (RStudio Team, 2018). The shell wrapper consisted of several R scripts each with a specific and sequential task. The scripts were written to: set up the local environment; parameterize PWC inputs with the Latin Hypercube technique and create 5000 sets of model inputs, load initial PRZM and VVWM input files, insert the Latin Hypercube sampled input parameter values into the PRZM and VVWM input files according to each simulation; execute PWC by executing PRZM and VVWM for each simulation; and write out PWC input/output files for each simulation (Figure 3). PWC output variables from all simulations were consolidated into .RData packages to be used in the subsequent PCC computations and analyses. The results from the probabilistic simulation design are discussed in section \_\_\_.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Description** | **Range** | **Source** | **Notes** |
| PFAC | Potential evapotranspiration adjustment factor | 0.72 – 0.78 | Young and Fry, 2014 | Figure 3.4 |
| ANETD | Minimum depth from which evapotranspiration is extracted | 15 – 20 | Young and Fry, 2014 | Figure 3.1 |
| uslek | Universal Soil Loss Equation (K) of soil erodibility | 0.1 – 0.49 | USDA-NRCS Web Soil Survey | K factor (rock free, whole soil) |
| uslels | Universal Soil Loss Equation topographic factor | 0.01 – 5 | Author’s Judgement |  |
| uslep | Universal Soil Loss Equation practice factor | 0.1 – 1 | Young and Fry, 2014  Author’s Judgement |  |
| slp | Land slope (%) | 0.001 – 50 | USDA-NRCS Web Soil Survey |  |
| hl | Hydraulic length (m) | 2000 – 5000 | Author’s Judgement |  |
| CN\_c | Runoff curve number, condition 2 | 51 – 98 | USDA-NRCS Web Soil Survey  SDCHM, 2003  Author’s Judgement |  |
| uslec\_c | Soil loss cover management factor | 0.001 – 1 | Young and Fry, 2014 | Page 26 |
| MNGN | Manning’s roughness coefficient N | 0.006 – 0.47 | Suarez, 2005 |  |
| bd1 | Bulk density of first soil horizon (g/cm3) | 1.3 – 1.65 | USDA-NRCS Web Soil Survey | Bulk density, 1/3 bar |
| fc | Field capacity in the horizon (cm3 cm-3) | 0.001 – 0.16 | USDA-NRCS Web Soil Survey | Available water capacity |
| WP | Wilting point in the horizon (cm3 cm-3) | 0.1 – 0.3 | PRZM Manual  USDA-NRCS Web Soil Survey | Figure 5.11 |
| OC | Organic carbon in the horizon (%) | 0.01 – 2 | USDA-NRCS Web Soil Survey |  |
| app\_rate | Application rate (kg/ha) | 0.5 – 2 | CALPIP |  |
| DWRATE | Dissolved phase pesticide decay rate (day-1) | 0.00274 – 0.2 | Author’s Judgement |  |
| DSRATE | Absorbed phase pesticide decay rate (day-1) | 0.00274 – 0.2 | Author’s Judgement |  |
| kd | Dissociation constant (mL/g) | 882 – 5910 | Laskowski, 2002 | Table 16 |
| aer\_aq | Water column degradation half-life (days) | 5 - 365 | CALFED, 2011  Author’s Judgement | Table 4 |
| temp\_ref\_aer | Reference temperature for water column degradation (C) | 20 – 25 | CALFED, 2011 | Table 4 |
| anae\_aq | Benthic degradation half-life (days) | 5 – 730 | CALFED, 2011  Author’s Judgement | Table 4 |
| temp\_ref\_anae | Reference temperature for benthic degradation (C) | 20 – 25 | CALFED, 2011 | Table 4 |
| photo | Photolysis half-life (days) | 96.9 – 416 | Fecko, 1999  Laskowski, 2002 | Fecko, 1999 (p. 2)  Laskowski, 2002 (p. 52) |
| RFLAT | Reference latitude for photolysis | 40 | CALFED, 2011 | Table 4 |
| hydro | Hydrolysis half-life (days) | 0.1 – 365 | CALFED, 2011  Laskowski, 2002 | Table 4 |
| SOL | Solubility (mg/L) | 0.000241 – 0.744304 | EPA Comptox |  |
| benthic\_depth | Depth of benthic region (m) | 0.01 – 1 | Author’s Judgement |  |
| porosity | Porosity of benthic region | 0.1 – 0.8 | Author’s Judgement |  |
| bulk\_density | Bulk density of benthic region (g/mL) | 0.86 – 1.76 | Author’s Judgement |  |
| FROC2 | Fraction of organic carbon on sediment in benthic region | 0.001 – 0.03 | FOC guide |  |
| DOC2 | Concentration of dissolved organic carbon in benthic region (mg/L) | 0.01 – 60 | Author’s Judgement |  |
| BNMAS | Areal concentration of biosolids in benthic region (g/m2) | 0.001 – 5 | Author’s Judgement |  |
| SUSED | Suspended solids concentration in water column (mg/L) | 0.005 – 80 | Author’s Judgement |  |
| CHL | Chlorophyll concentration in water column (mg/L) | 0.001 – 1.5 | Author’s Judgement |  |
| FROC1 | Faction of organic carbon on suspended sediment in water column | 0.001 – 0.14 | D’Andrea, 2020 | Table 1 (Supplementary Material) |
| DOC1 | Concentration of dissolved organic carbon in water column (mg/L) | 0.1 – 15 | Author’s Judgement |  |
| PLMAS | Concentration of biosolids in water column (mg/L) | 0.001 – 10 | Author’s Judgement |  |
| bf | Provides an additional constant flow through the waterbody (m3/s) | 0 – 0.001 | Author’s Judgement |  |

Table 4: Probabilistic Simulation Input Parameter Ranges

**Results**

**Modeled Pesticide Concentrations for Deterministic and Probabilistic Simulations**

Figures X – X and Y – Y show the modeled bifenthrin concentrations in the water column and benthic zone, respectively, from 2009 – 2014 for CDPR-FOL002. The figures display the CDPR SWPP observed bifenthrin concentrations, the deterministic model output, as well as the median, first, second, and third standard deviations of the probabilistic model output. The deterministic simulation is primarily contained within the second standard deviation when estimating bifenthrin concentration in the water column and benthic zone. Across the entire time period, the deterministic model output is more conservative compared to the median probabilistic model output. Apart from the observed concentrations in 2009, the observed concentrations fall within the probabilistic second standard deviation and the deterministic model output. Overall, the bifenthrin concentration in the water column peaks on the first day of the month and directly following sizable rainfall events. The concentration of bifenthrin in the benthic column predominately accumulates over the time interval and surges immediately after sizable rainfall events.

**Sensitivity Analysis**

Sensitivity analysis revealed the input parameters with the greatest impact for determining the bifenthrin concentrations in the PWC model.  Figures X - Z display the partial correlation coefficient (PCC) between input parameters and the concentration of bifenthrin in the pool water column, benthic zone, and surface runoff.  The PCC was used as the sensitivity analysis metric. While 38 input parameters were incorporated in the model, only those with |PCC| > 0.05 are shown. A positive PCC indicates the input parameter and model output have a positive correlation; a negative PCC indicates the input parameter and model output have a negative correlation. A PCC closer to ± 1 expresses a stronger relationship between the input parameter and model output.

As shown in Figures X – Z for CDPR-FOL002, the curve number was among the most sensitive.  The curve number for antecedent moisture condition (CN) serves as a metric for the runoff properties of soil and land cover based on soil hydrologic group, land use, and hydrologic condition.  Low CN values represent soil and land cover with an increased ability to retain rainfall and therefore reduce runoff, while high CN values represent soil and land cover with minimal absorption abilities which lead to a substantial amount of rainfall runoff.  The PCC figures display that higher CN values indicate a higher bifenthrin concentration in the water column, benthic zone, and runoff. CN was the most sensitive input parameter to the bifenthrin concentration in runoff as designated with a PCC of 0.94.  Field capacity (fc) and wilting point (WP) were also sensitive parameters to bifenthrin concentration in runoff with a PCC of 0.52 and -0.30 respectively. Field capacity denotes the maximum water capacity in the soil and land cover whereas wilting point indicates the minimum water capacity in the soil and land cover required by plants to not wilt.  Both input parameters consider soil and land cover properties including content of organic matter, soil texture, bulk density, soil structure, as well as accounting for salinity and rock fragments. The sensitivity of these input parameters provides additional evidence to assume that the soil and land cover’s ability to absorb water and limit the amount of water available for runoff is critical to the bifenthrin concentration in runoff.

Along with CN, the dissociation constant (kd) was also a sensitive parameter for determining bifenthrin concentration in the water column and benthic zone. Kd measures the inclination of the chemical to separate into smaller components when placed in a solution. Smaller kd values indicate a lower propensity to separate into smaller components, and vice versa. Figures X and Y reveal a negative correlation between kd and bifenthrin concentration in the water column and benthic zone. Additionally, the application rate has a positive correlation to bifenthrin concentration in the water column and the benthic zone as shown by PCC values of 0.13 and 0.055, respectively. The sensitivity of the application rate to bifenthrin concentration in the water column and benthic zone is not surprising as it stands to reason that higher quantities of applied bifenthrin would correlate to higher measurements of bifenthrin concentration. The benthic region (benthic\_depth) is another sensitive parameter to bifenthrin concentration in the benthic zone. It is negatively correlated with bifenthrin concentration, indicating a deeper benthic zone might have the capacity to incorporate or breakdown bifenthrin concentration to result in lower bifenthrin concentration measurements in the benthic zone.

Daily times series of parameter sensitivity values are shown in Figures E - F and can be used to examine changes of parameter sensitivity over time. PCC values between sensitive parameters and bifenthrin concentration in the benthic zone sees little change over time as PCC values are primarily constant during the time period. PCC values between sensitive parameters and bifenthrin concentration in the water column do fluctuate over the time period. Fluctuations appear to occur immediately following rainfall events as PCC values spike.   ….

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# Discussion

# Results and Discussion

## Deterministic Findings

### Runoff Evaluation

Researchers have often cited runoff as the main mode of pesticide transport from urban areas (Wittmer et al., 2011; Weston et al., 2012). One of the factors which influence runoff is precipitation. At the study sites, high annual precipitation of 1304 mm and 1209 mm for 2010 and 2011, respectively; and annual low of 210 mm was recorded for the 2013 period (Fig. 2). Average annual precipitation for both sites throughout the entire study period, 2009-2014, was 934 mm.

The CN, another factor that influences runoff, reflects the impermeability of a given land-use based on soil type and hydrologic conditions. For the modeled urban sites in this study, the CN used ranges from 92 to 98 (CALFED Report, 2011) because of the high amount of impervious surfaces (Buildings, pavements, etc.). A higher CN means a higher runoff potential and vice versa.

Fig. 2 and 3 shows simulated runoff from the Folsom and Roseville study site and the observed runoff at the USGS gauging station at Arcade C NR Del Paso Heights, which are about 10 miles and 16 miles from the Roseville and Folsom sites, respectively. Runoff simulated by the PWC accurately tracked the monthly precipitation trends during the study period. The average simulated annual runoff was 614 and 674 mm for Folsom and Roseville sites, respectively, while the average simulated runoff was 540 mm at the USGS gauging station at Arcade C NR Del Paso Heights. The runoffs from the modeled sites closely match that of the modeled USGS site in both trend and magnitude. Both closely follows the annual trend in precipitation. The slight variation in the magnitude of runoff at the USGS site compared to that of the study sites may be due to differences in land cover composition of the sites. That is, impervious surface percentage associated with the study sites may be more than impervious surface percentage associated with the USGS site since the study sites were made up entirely of urban land use and the USGS site composition is 90% urban and 10% agricultural as stated in the study area description. The high amount of runoff from the urban sites may result in high annual flows at the respective storm drain outlets (DPR-FOL002, DPR-FOL003, DPR-PGC010 and DPR-PGC022). With the model simulated runoff of 614 mm and 674 mm for the Folsom and Roseville storm drains, respectively, the possibility of pesticides reaching the Sacramento-San Joaquin River, downstream of the modeled sites, is high.

Fig. 2 Total annual precipitation and simulated runoff at the USGS 11447360, Folsom, and Roseville study sites

Fig. 3. Monthly precipitation, simulated runoff at USGS 11447360, Roseville, and Folsom Sites.

### Bifenthrin Simulation

High bifenthrin concentrations were modeled in all the sites. The highest concentrations were dominant at the Folsom sites compared to the Roseville sites. The simulated bifenthrin concentrations peaked in 2011and 2014, which is a reflection of the high amount of bifenthrin used during those periods (Fig. 4). For example, the predicted peak bifenthrin concentrations of 55.2 ng/L, 41.8 ng/L, and 43.4 ng/L on 11 March, 2011, 10 October 2011, and 3 December, 2014, respectively, for DPR-FOL002 storm drain outlet (Fig. 2) reflected individual PUR database entries of about 3.2, 2, and 2.6 kg recorded for the same period. TheseThese peak values demonstrate the sensitivity of the PWC model to individual entries in the PUR database. Similar relationship between the simulated peaks of bifenthrin and individual used amount entries was also obtained by Jorgenson et al. (2012).

1. DPR-FOL002
2. DPR-FOL003
3. DPR-PGC010
4. DPR-PGC022

Fig. 4. The observed and simulated daily bifenthrin concentrations at four sites from 2009 to 2014.

Graphically, the patterns of simulated bifenthrin concentrations were generally consistent with the observed bifenthrin concentration pattern (Fig. 4). Across the four study sites, mean and maximum measured concentrations were between 10.6-12.3 ng/L and 21.4-48.6 ng/L, respectively, and the simulated mean and maximum concentrations were between 3.74-13.8 ng/L and 19.3-41.6 ng/L, respectively. With respect to the simulated bifenthrin concentrations, the Pleasant Grove site (DPR-PGC022) had a maximum of 33.4 ng/L in comparison to the maximum value of 21.7 ng/L obtained at the DPR-PGC010. The higher concentration at the DPR-PGC022 may be due to the higher bifenthrin use amount associated with higher number of residential units. For the Alder Creek sites in Folsom, the simulated maximum bifenthrin concentration at the DPR-FOL003 outlet was 21.4 ng/L compared to the maximum value of 48.6 ng/L at the DPR-FOL002 outlet. Like the Roseville site, the number of residential units that drain to the DPR-FOL002 is more than that drains into the DPR-FOL003 outlet.

Table 5. Urban Site Observed and Simulated bifenthrin concentration from 2009 to 2014

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | | **Observed Bifenthrin** | | | **Simulated Bifenthrin** | | | **T-Test** |
| **Site** | Monitored Outlets | Number of Observed Data | Mean  Conc. (ng/L) | Median  Conc. (ng/L) | Max.  Conc. (ng/L) | Mean  Conc.  (ng/L) | Median  Conc.  (ng/L) | Max.  Conc.  (ng/L) | p = 0.05 |
| **Pleasant**  **Grove**  **Creek** | DPR-PGC010 | 21 | 5.55 | 3.27 | 21.7 | 3.74 | 0.67 | 23.56 | 0.24 |
| DPR-PGC022 | 11 | 12.27 | 9.60 | 33.4 | 8.81 | 8.64 | 23.37 | 0.15 |
| **Alder**  **Creek** | DPR-FOL002 | 19 | 16.3 | 14.4 | 48.6 | 13.8 | 11.2 | 41.6 | 0.27 |
| DPR-FOL003 | 16 | 10.60 | 11.30 | 21.40 | 9.33 | 8.34 | 19.32 | 0.25 |

In general, the PWC model output performed well in simulating bifenthrin concentration at the four storm drain outlets. With the exception of one measurement observed in three sites in 2011, the results show a close match between the simulated and observed bifenthrin data (Fig. 4 and Table 5). The slight variability between the simulated and the observed data may be due to expected variability associated with environmental measurements. The statistical evaluation revealed a strong to moderate correlation between the simulated and observed concentrations. This is evident in the R2 values of 0.67, 0.54, 0.85, and 0.70 for the DPR-FOL002, DPR-FOL003, DPR-PGC010, and DPR-PGC022, respectively, when the same day observed and simulated bifenthrin concentration values were plotted (Fig. 5). There was not much difference when the means and median of the same day observed and simulated concentrations were plotted (Fig. 6). The T-Tests of equality of means (Table 5) also indicated that no statistically significant difference between the observed and simulated bifenthrin data. Overall, the PWC model was able to simulate bifenthrin concentration with reasonable accuracy. This suggests that the PWC model is capable of being used to generate bifenthrin concentration values in areas where there is limited to no data when needed for analysis.

(DPR-FOL002) (DPR-FOL003)

(DPR-PGC010) (DPR-PGC022)

Fig. 5. Scatterplot of observed vs. simulated bifenthrin concentration at the four sites

(DPR-FOL002) (DPR-FOL003)

(DPR-PGC010) (DPR-PGC022)

Fig. 6. The same day observed vs. simulated bifenthrin mean and median concentration at the four sites

### Bifenthrin Application Mass Loss

Results from the PWC model shows that a substantial mass of the bifenthrin applied at the urban sites were transported to the water bodies with runoff being the main mode of transport in comparison to drift, the other mode of off-site transport (Table 6). At the Folsom sites, a mass of 0.84% (232kg) and 0.78% (310kg) of the total applied bifenthrin were transported by combined effects runoff and drift to the urban creek at the DPR-FOL002 and DPR-FOL003 sites, respectively, for the entire simulation period (Table 6). Out of these, runoff alone accounted for 76% (176 kg) at the DPR-FOL002 and 60% (186 kg) at the DPR-FOL003 site. For the urban sites in Roseville, 1% (72kg) and 0.56% (72kg) of total bifenthrin applied were transported to the urban creek at DPR-PGC010 and DPR-PGC022 with runoff alone accounting for 85% and 92% of the mass loss at the respective sites. In the study area, the dominant land use is impervious surfaces and lawns which generate a substantial amount of runoff during storm events and results in washing off the applied bifenthrin to the urban creeks. While the total mass of bifenthrin lost are greatest at the Folsom sites than at the Roseville sites, the mass loss is a proportional representation of the mass applied in both counties. This outcome indicates that the total amount of bifenthrin lost by transport is substantial enough to increase surface water pollution and its associated toxicity to aquatic species in the urban creeks and the receiving Sacramento-San Joaquin River Delta downstream of the urban sites.

Table 6. Mode of Relative Transport of Pesticide Mass

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | County | Sacramento | | Placer | |
|  | Urban Storm drain outlets | DPR-FOL002 | DPR-FOL003 | DPR-PGC010 | DPR-PGC022 |
| Bifenthrin | Percentage of runoff as main mode of transport | 76 | 60 | 85 | 92 |
| Percentage of drift as transport mechanism (%) | 24 | 40 | 15 | 8 |
| Percentage of mass transported to the urban creek by Runoff +Drift (%) | 0.84 | 0.76 | 1 | 0.56 |
| Mass applied transported to the urban creeks by Runoff +Drift (kg) | 232 | 310 | 72 | 72 |
| Mass applied transported by Runoff (kg) | 176 | 186 | 61 | 66 |
| Mass applied transported by Drift (kg) | 56 | 124 | 11 | 6 |

### Predicted Bifenthrin Toxicity in the Water Column

Bifenthrin is toxic to aquatic species at even low concentrations (Solomon et al., 2001; Feo et al., 2010). The California State Water Resources Control Board has numerous water bodies in the state that are listed as being impaired due to pyrethroids and thereby the need to mitigate the sources and runoff pathways. - At the Folsom sites used in this study, the daily mean concentrations of bifenthrin during the simulation period were between 0.66 ng/L to 17.0 ng/L at DPR-FOL002 and between 0.41 ng/L to 9.18 ng/L at DPR-FOL003. At the Roseville sites, mean bifenthrin concentration at DPR-PGC010 ranged from 0.25 ng/L to 6.44 ng/L and that at DPR-PGC022 ranged from 0.10 ng/L to 12.27 ng/L. Maximum concentrations of bifenthrin were predicted at all the urban sites for the 2011 period (Table 7) which is also the year of maximum bifenthrin application for both Sacramento and Placer County.

Table 7. Daily mean and maximum urban creek concentration in ng/L predicted by the PWC model

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Site | Outlets | DPR-FOL002 | | | | | | DPR-FOL003 | | | | | |
| FOLSOM | **Year** | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| **Mean** | 1.1 | 9.54 | 17.0 | 4.69 | 2.95 | 0.66 | 0.98 | 4.95 | 9.18 | 3.51 | 2.83 | 0.41 |
| **Max** | 7.32 | 53.1 | 55.2 | 20.3 | 19.8 | 44.1 | 5.2 | 28.9 | 25.2 | 10.8 | 24 | 26.1 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| ROSEVILLE | **Outlets** | **DPR-PGC010** | | | | | | **DPR-PGC022** | | | | | |
| **Year** | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| **Mean** | 0.39 | 3.36 | 6.44 | 1.35 | 0.54 | 0.25 | 0.54 | 6.48 | 12.27 | 2.29 | 0.10 | 0.44 |
| **Max** | 3.58 | 19 | 21.9 | 7.9 | 5.74 | 20.8 | 6.86 | 32.4 | 44.8 | 16 | 0.58 | 29.2 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |

Simulated daily bifenthrin concentrations show that high peak values mainly occur during the wet season (October to April) (Fig. 4). These increased peaks may be due to the washing of accumulated bifenthrin that was applied during the dry season, in addition to flow and low dilution capacity. This is consistent with urban surface water pyrethroid concentration observed by Jorgenson et al. (2012).

### Comparison between Simulated Bifenthrin EEC and CALFED 2011 Values

CALFED (2011) reported acute and chronic threatened and endangered species benchmarks for bifenthrin as 7.5ng/L and 1.3ng/L respectively. The acute benchmarks are equivalent to 1/10th the lowest acute USEPA benchmark for bifenthrin (CALFED, 2011). The USEPA benchmarks, developed by the OPP, are derived from the evaluation of toxicity data for a pesticide active ingredient (A.I.) or metabolite and include acute and chronic toxicity values for fish, invertebrates, vascular and nonvascular plants and other organisms within the aquatic ecosystem (USEPA, 2016a). To be consistent with the benchmark values, the PWC derived 1-day and 4-day EECs averages to determine acute and chronic risk of bifenthrin to the urban creeks.

For the four storm drain outlets for which bifenthrin concentrations were modeled, outflow into Alder Creek presents a greater risk to aquatic threatened and endangered species than Pleasant Grove creek with acute EEC values between 29 ng/L and 55 ng/L compared to the 7.5 ng/L benchmark reported in the CALFED report (2011). This was expected because of the high amount of bifenthrin usage in Sacramento County as reported in the PUR database during the 2009 to 2014 period. This is not to say the Pleasant Grove Creek sites, DPR-PGC010 and DPR-PGC022, are safe for aquatic species existence since their 1-day average EECs are also higher (22 ng/L to 43 ng/L) than the CALFED (2011) benchmark.The modeled results show that bifenthrin EECs in the urban creeks exceeded the CALFED (2011) benchmark. This is of major concern at the Folsom and Roseville area since concentrations of this magnitude pose risk to a wide variety of macro benthic taxa, as indicated by the sensitivity of *H. azteca* to bifenthrin.

Table 8. EEC of Bifenthrin in ng/L

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| City of Folsom | | | City of Roseville | | |
| Outlets | **EECs** | **EEC** | **Outlets** | **EECs** | **EEC** |
| DPR-FOL002 | Acute | 55 | **DPR-PGC010** | Acute | 22 |
| Chronic | 51 | Chronic | 20 |
| DPR-FOL003 | Acute | 29 | **DPR-PGC022** | Acute | 43 |
| Chronic | 25 | Chronic | 39 |

Though the urban creek runoffs contained a high concentration of bifenthrin, the risk to aquatic species is not limited to the urban creeks receiving run-off, but can also affect the main receiving waters downstream of these urban creeks such as the Sacramento-Joaquin River Delta. The predicted EECs of bifenthrin, obtained in this study, can also be compared to that seen in other urban rivers and streams in northern California (Weston and Lydy, 2012; Weston et al., 2014).

# Conclusion

We used the PWC environmental fate and transport model to predict the surface water concentration of bifenthrin in the Alder and Pleasant Grove Creeks in tFolsom and Roseville, respectively. Results show that the model predicted an acceptable level of same day concentration in comparison to observed concentration at the four urban study sites. Predicted acute and chronic EEC for the modeled pesticides in the urban creeks were higher than the derived CALFED benchmark for aquatic threatened and endangered species (invertebrates and fish).

These findings suggest that bifenthrin may indeed present a risk to aquatic communities at the sites modeled as well as in other urban watersheds throughout the United States where intensive lawn maintenance and pest control practices are common. Furthermore, the results strengthen concerns that bifenthrin poses a significant environmental risk since current use patterns and practices allow bifenthrin to be applied to urban landscape and structures, which then lead to off-site transport via runoff. causing impairments in downstream water bodies such as the.

Bifenthrin is commonly used in treating outside areas of buildings in California for the control of pest, mainly ants and rodents. Its application is either done by homeowners, who obtain the products from retail stores, or by professional pest controllers who have a maintenance contract with residents for regular treatment of their property (Weston et al., 2009). Because the study area is an urban environment, it is assumed environmental concentrations of bifenthrin occurred as a result of homeowner usage and professional pest control applications. Hence, an inference can be made from the usage application. A survey conducted by TDC Environmental (2010) on homeowner and professional applicators usage provides insight into the origin of these pesticides in the urban waters (CALFED 2011). It was assumed in this study that professional applications of bifenthrin in residential areas was 80% of all use, with homeowner application of bifenthrin estimated at 25% of professional use (20/80=0.25). In most situations, liquid bifenthrin is used as barrier treatments around the perimeter of structures through spraying and solid granulated bifenthrin is broadcasted on lawns and similar features throughout the year. In 2014, out of the 78,379 kg and 18,605 kg of pyrethroid active ingredients used in Sacramento County and Placer County for structural pest control and landscape maintenance, bifenthrin accounted for about 9263(12%) and 1297kg (7%) (CDPR Database, 2014).

The predicted concentrations as modeled in this study along observed monitoring data demonstrates the strength of combined environmental risk of urban bifenthrin application limited these An region can be more closely studied as an indicator of other similar urban environments.locations. For aquatic risk assessment, it is suggested that regular monitoring of pesticides in surface water is conducted, including detailed market trends in pesticide use. Modeling data can be used in combination with monitoring data, especially when observed data is limited due to resources, and site accessibility; in order to more effectively predict or limited resourcesmodeled EECsprovideexposure assessment to aid in determing the fate of pesticides in urban waters.

Some main assumption made in the PWC modeling conducted in this study is that bifenthrin applied for structural pest-control and landscape maintenance was outside of buildings and aboveground. To effectively reduce the increased presence of bifenthrin in urban runoffs, protocol modifications may have to focus on professional applicators since they account for about 80% of the bifenthrin applications in the study area. A citizen-science initiative could also be put in place to involve homeowners in tracking their use of pesticide to obtain more information about pesticide types and frequency of use to refine the modeling effort. Also, application amounts could be reduced in rainy conditions and the timing of lawn irrigation could be integrated into the model where the pesticides are used on grass and shrubs. Additionally, future analysis of seasonal variation in precipitation (dry versus wet conditions) and timing of pesticide applications may show preferred time intervals for applications. For examples, focus applications when dry conditions in forecast to allow more time for degradation before runoff occurs.

Although this study was focused on the urban sites sampling outlets within the cities of Roseville and Folsom, they are representative of urban sites in the CA Central Valley and areas in similar climatic zones. In summary, the PWC modeling system used in this study holds a great promise as a predictive tool to estimate bifenthrin concentrations to evaluate pesticide fate and transport in an urban setting.

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