ASSESSING THE IMPACT OF WATER REUSE ON WATER QUALITY IN THE LOS ANGELES RIVER

By:

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ABSTRACT

Water reuse through water reclamation plants (WRPs) is an approach used by Los Angeles to reduce dependence on imported water. Three WRPs in the Los Angeles River (LAR) watershed, located in southern California, contribute up to 70% of the river discharge during dry weather periods. Increasing water reuse will lead to flow reductions in-stream, which could affect water quality. The purpose of this research is to identify the impact of water reuse on loads and concentrations of copper, zinc, lead, total suspended solids (TSS), and total dissolved solids (TDS) in the LAR. First, an empirical water quality data analysis was accomplished by collecting concentration data from monitoring programs and evaluating the relationships between pollutants and discharge. A water quality module was then added to a calibrated EPA-SWMM hydrologic model for water years 2011 to 2017 on a daily time-step, which was developed in prior work. Land use characteristics, event mean concentrations, urban baseflow concentrations, and WRP effluent data were added to the model. The model was then calibrated at four locations along the river mainstem. Water reuse scenarios were applied to the calibrated model and the simulated daily loads and concentrations were assessed using water quality regulatory compliance. Results show that TSS and metals are strongly correlated with each other and that discharge is a moderate predictor of pollutant concentration. Median daily loads for all pollutants generally decrease under scenarios of varying WRP flow reduction, but median daily concentrations either increase or decrease depending on the major sources for each pollutant. Copper, zinc, and lead regulatory compliance are not greatly impacted by WRP flow reduction, but TDS compliance is degraded. The results from this study will help inform regional water managers of potential impacts of flow reductions on water quality in the LAR and help aid decisions on water recycling policies.

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LIST OF ABBREVIATIONS

BMP	Best Management Practices
CWA	Clean Water Act
DMR	Discharge Monitoring Reports
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
EWMP	Enhanced Watershed Management Plan
GIS	Geographic Information Systems
LA	Los Angeles
LACDPW	Los Angeles County Department of Public Works
LAR	Los Angeles River
LARB	Los Angeles River Basin
LFD	low flow diversions
MS4	municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination
NSE	Nash Sutcliffe Efficiency
PET	potential evapotranspiration
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Storm Water Management Model
TDS	total dissolved solids
TMDL	Total Maximum Daily Loads
TSS	total suspended solids
USGS	United State Geological Survey
Water IRP	Water Integrated Resources Plan
WRP	wastewater reclamation plant

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CHAPTER 1

INTRODUCTION

The world's population jumped from one billion persons in 1800 to 7.7 billion today, and is expected to reach eleven billion by 2100 [1]. There has been a gradual shift from rural to urban living as the population grows. Currently 55% of the population is living in urban areas and this number is expected to increase to 68% by 2050 [2]. As urban areas expand to accommodate population growth, the natural landscape is transformed into an impervious landscape with artificial drainage networks, which causes changes to flow regimes and runoff timing [3]. The generation of runoff on these urban surfaces also carries a range of contaminants, such as heavy metals, nutrients, sediment, and trash, known as nonpoint-source pollution [4][5]. The rate of transport and magnitude of nonpoint-source pollutants are accelerated by human activities and an increase in impervious surfaces and connectivity [6]. Point-source pollution is defined as pollution with a single identifiable source, like wastewater reclamation plants. The contributions of nonpoint-source and point-source pollution degrade in-stream water quality in a river and other receiving bodies of water, causing risk to human health and aquatic life. To address water quality issues, the Clean Water Act (CWA) was established to set a federal standard for pollution in the nation's waterways. The act enforces regional water boards to determine water quality targets for impaired waterbodies listed on the CWA's 303(d) list that are under their jurisdiction [7].

The Los Angeles River Basin (LARB) was once a densely vegetated floodplain rich with wildlife, but over three centuries the population grew rapidly. The area developed into a dense, urbanized city that heavily relied on the river, groundwater basin, and imported water for their needs. Catastrophic floods were frequent, so in the 20th century the Los Angeles River (LAR) was straightened, lowered, and widened in response. The channels were lined with concrete, and dams and debris basins were constructed. This permanently altered the hydrology, ecology, and water quality of the LAR [8]. All reaches and tributaries in the LARB have been listed as impaired on the 303(d) list, and water quality targets were established by the Los Angeles Regional Water Quality Control Board to reduce water quality degradation and assess compliance [9]. Additionally, interest grew in the early 2000's to increase the City of LA (City)'s water portfolio resiliency in the LARB.

The City began its effort to integrate plans for wastewater, recycled water, and stormwater in 1999 with the development of the City's Water Integrated Resources Plan (Water IRP). The challenges that motivated the initiation of the Water IRP were a growing population, aging water infrastructure, pollution in waterways, dependence on imported water from Northern California and the Colorado River, and a shortage of funding to address these issues [10]. The plan was implemented in 2006 with the hope to expand planning in 2020. Droughts, new stormwater regulations, and climate change triggered problems for the Water IRP so the City initiated the One Water LA 2040 Plan in 2018 [11]. One Water LA aims to improve water quality by achieving 100% of compliance for metals by 2028 in the upper LARB using stormwater management. It also aims to strengthen the urban water cycle by increasing reuse and stormwater capture to reduce dependence on imported water. The plan highlights that water reuse will be a critical approach to meet the goal of sourcing 50% of the City's water supply locally by 2035. In recent years, LA County uses up to 85% of imported water if local water supplies are limited by drought [12].

California has been on the forefront on formalizing comprehensive water reuse regulations since 1987 with the goal to make urban water portfolios in cities more resilient. Policies are set up in the City to support infrastructure that will expand water reuse [13]. However, increasing water reuse in the LARB will lead to reductions in streamflow that will impact the hydrology, ecology, water quality, and recreational uses in the LAR. The State Water Resources Board and the Regional Water Quality Control Board (known collectively as the California Water Boards) are responsible for ensuring flows in-stream will sustain a variety of beneficial uses, so they must approve or disapprove wastewater change petitions under California Water Code Section 1211 that seek to reduce discharge. The wastewater reclamation plants (WRPs) are responsible for demonstrating that a reduction in discharge will not negatively impact the aquatic ecosystem in the river. The City of Burbank and City of Glendale WRPs submitted wastewater change petitions and flow studies that concluded the reductions in flow will not have a major impact on habitat or humans [14][15]. Due to a lack of protocol or approach to determine the minimum amount of flow required to sustain the ecosystem in the river, commenters encouraged a robust environmental flows study so that a toolset could be created to evaluate flow reduction scenarios in the LAR. Water quality, among other beneficial uses, need to be assessed in the LARB under various flow reduction scenarios to aid flow management decisions made by the California Water Boards and regional water managers. The current research attempts to quantify impacts of water reuse on water quality in the LAR by applying water reuse scenarios to a calibrated water quality model in EPA SWMM.

There have been several studies in the LARB that explore water quality and water management. Stein and Ackerman (2007) estimated dry weather loading sources for several constituents in the LARB and adjacent basins by sampling for dry weather pollutants and simulating wet weather loads using a GIS-based stormwater runoff model. They found that WRPs are a major source of copper and zinc and storm drains are a major source of lead. They also concluded that dry weather loading during a dry year can make up a major part of total annual loading. The study demonstrated that dry weather loadings are important to total annual loading, so water managers should incorporate dry weather loads, not just wet weather loads, into their water quality plans [16]. A study by Tariq et al. (2017) looked at how climate stress and changes in land use would impact an Enhanced Watershed Management Plan (EWMP) in the Tujunga subbasin, acknowledged for its degraded water quality and TMDL exceedances. They used the Los Angeles County Flood Control District's Watershed Management Modeling System modeling tool, the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), to model zinc loads and best management practices (BMP) load reductions. After applying climate and land use change scenarios, they found that climate change could decrease the ability of the EWMP to meet water quality goals, but increasing permeable surfaces could offset non-compliance scenarios [17]. Read et al. (2019) looked at how flow regimes would change in the LAR with the installation of stormwater BMPs to achieve water quality compliance using Storm Water Management Model (SWMM) to simulate the hydrology and SUSTAIN to simulate BMP scenarios. The authors found that annual minimum flows decreased by 45% with the future BMP scenario. They also found that if 100% of WRP discharge was diverted, along with stormwater BMPs implemented, then annual minimum flows would approach zero [18]. Read et al. (2019) highlights that there is a gap in the research to quantify impacts of future management decisions on ecology and other beneficial uses due to changes in the flow regime. The water quality assessments conducted in the LARB are often focused on stormwater management for water quality compliance, but there is a need to consider how changes in flow will impact water quality in the LAR.

The goal of the current study is to assess the impact of wastewater discharge flow reductions on water quality in the LAR. This was achieved by answering the following questions: (1) What is the relationship between concentrations of heavy metals, total suspended solids, total dissolved solids, and discharge in the LAR? (2) What spatial and temporal patterns for pollutant loads and concentrations exist in the LAR? (3) How do pollutant loads and concentrations respond to reductions of treated wastewater discharge in the LAR? and (4) How do reductions of treated wastewater discharge impact water quality regulatory compliance?

CHAPTER 2

DATA AND METHODS

2.1 Study Site

The Los Angeles River Basin (LARB), located in Los Angeles County, California, has an area of 2,165 square kilometers (836 square miles), presented in Figure 2.1. The LARB terrain includes mountains, valleys and coastal plains. The basin area is an estimated 37% impervious [19]. The LARB is considered highly urbanized, with around 36% of the basin residential, 20% transportation, 16% industrial and commercial, and only 22% parks and undeveloped spaces [20]. The slopes vary from 0.1% near the coast to 18% near the mountainous regions [21]. The climate is described as semi-arid, where nearly all precipitation occurs in December through March. Precipitation in the summer is infrequent and long periods of antecedent dry days are common. On average, it rains 14 inches/year in the coastal plains and 26 inches/year in the mountainous regions [22]. The Los Angeles River (LAR) headwaters are in the western side of the basin in the San Fernando Valley and water flows through predominantly concrete-lined channels for 51 miles until discharged into the Pacific Ocean. The river is divided into six reaches on the mainstem based on water quality compliance locations (Figure 2.1) and six tributary reaches; most notably Burbank Western Channel, Compton Creek, and Rio Hondo. Eight major dams and several spreading grounds are located throughout the basin. One hundred twenty seven storm drain outfalls [23] and three Wastewater Reclamation Plants (WRPs) named the Los Angeles-Glendale WRP (Glendale WRP), Burbank WRP, and Donald C. Tillman WRP (Tillman WRP) contribute to river discharge and pollutant concentrations in the LAR.

2.1.1 Water Quality Regulations

Point-source discharges from WRPs, municipal separate storm sewer system (MS4s), and illegal dumping, as well as nonpoint-source discharges from atmospheric deposition and irrigation from agriculture, contribute to metal, fecal indicator bacteria, trash and nutrient loads in the LAR and its tributaries [24]. Currently all six reaches and six tributaries in the LARB are listed as impaired on the CWA 303(d) list for these parameters, shown in Figure 2.1 [25]. The name of each impaired reach is listed in Figure A.1. Regional programs and actions are in place to address impairments and improve water quality [24][26]. Loading capacities, referenced as a load-based Total Maximum Daily Load (TMDL), and numeric targets, referenced as a concentration-based TMDL, were developed in 2008 and revised in 2015 for copper, lead and zinc, the metal constituents used in this study, in each impaired reach (Table A.1 and Table A.2) to address high pollution levels in dry and wet weather [9]. A dry weather day is defined as a day when the maximum daily flow does not exceed 14.2 cms (500 cfs), and this method is used to identify dry and wet weather days in this study. If a metal exceeds its load or concentration-based TMDL on a dry or wet weather day, then the receiving water is considered out of compliance. The concentration-based TMDL are expressed in terms of concentration of total recovered metals. Dry weather load-based TMDL are reach-specific concentration-based TMDLs multiplied by reach-specific critical dry flows, whereas wet weather load-based TMDLs are calculated by multiplying daily storm volumes by the wet weather concentration-based TMDLs for each metal. MS4 and National Pollutant Discharge Elimination System (NPDES) permittees are currently responsible for monitoring progress with load and concentration-based target compliance [9]. Currently, there are dry weather compliance points for copper and lead at the bottom of each impaired reach. Note that the only dry weather compliance point for zinc is on the Rio Hondo tributary, which is not impacted the WRPs discharge and therefore not assessed in this study. There is one wet weather compliance location for all three metals in the LARB, which is located at gauge F319.

No TMDLs have been established for TDS and TSS. However, water quality standards for inland surface waters for TDS were established by the Los Angeles Regional Water Quality Control Board in 1990 to address levels of chloride and other indicators of salinity levels and protect fish, wildlife, and recreation [27]. In the LARB, the TDS standard for the segment of river between the Sepulveda Flood Basin and gauge F57C is 950 mg/L, while the standard between gauge F57C and F319 is 1,500 mg/L. TSS does not have a defined water quality standard regionally. The U.S. Environmental Protection Agency's *Quality Criteria for Water* states that TSS should not impact photosynthesis by 10% from the norm for aquatic life by reducing the depth of the compensation point, and does not present any specific concentration target [28]. In the LARB, TSS is monitored often with other targeted pollutants because of its impact on aquatic life.

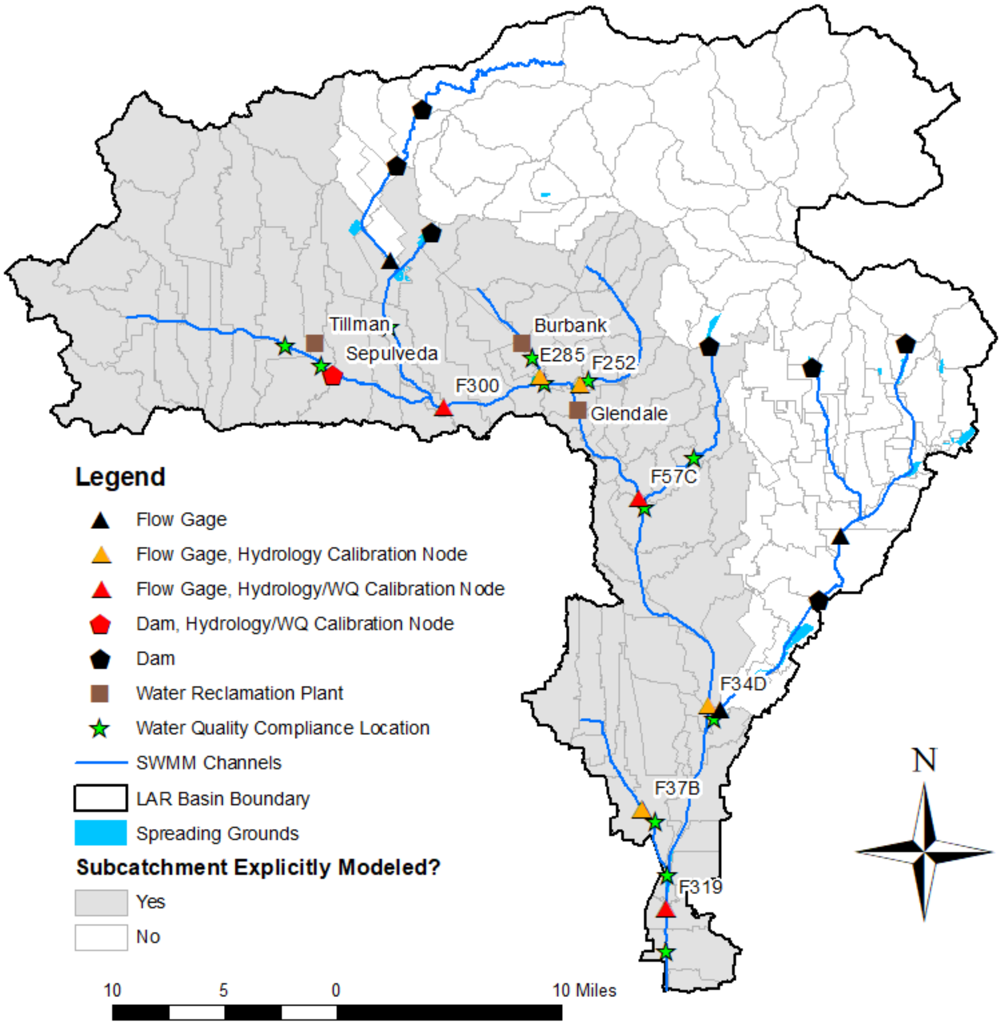

Figure 2.1 Map of LAR Basin model domain. Dams, spreading grounds, water quality compliance locations, flow gauges (labeled), and WRPs (labeled). Sepulveda is also described as gauge 11092450.

2.2 Water Quality Database

Observed water quality data were collected from the California Environmental Data Exchange Network, Mass Emissions Stations, Los Angeles River Watershed Monitoring Program, MS4 Reports, and Stormwater Multiple Application and Reporting Tracking Systems [29][30][31][32] and compiled into a single database. Constituents data-mined include various physical, chemical, and biological parameters. The database was reduced to focus on the following water quality parameters relevant to the research scope: total copper, zinc, and lead; total dissolved solids (TDS); and total suspended solids (TSS). Most of the samples were grab samples, collected at one time and at one location, but roughly 20% of samples were composite samples. Any samples measured outside of the river channel or at outfalls were removed. Left censored data, or data that is non-detected because the concentration falls between zero and the reporting limit or method detection limit, were included in the database. Methods of handling non-detects were followed using Helsel (2012) [33].

2.2.1 Empirical Data Analysis

An analysis was conducted on the observed water quality database using RStudio Version 1.1.463 [34]. The relationships were explored between the concentrations of total metals, TSS, TDS and average daily flow, measured on the same day, by computing correlation coefficients (ρ) using the Spearman Rank-Order Correlation test. The Spearman test was picked as it is non-parametric, can handle outliers, and does not assume normality of variables [35]. Spearman's correlation coefficients determine the strength and direction of the monotonic relationship rather than the linear relationship. A monotonic relationship can be described as doing one of the following: as one variable value increases, so does the other; or as one variable value increases, the other decreases [36]. The coefficients were computed in a correlation matrix to investigate dependence between multiple variables at the same time. The correlation matrix includes density plots for each variable, bivariate scatter plots with a fitted line, and significance levels, and were created using the PerformanceAnalytics package in RStudio [37]. Data for this analysis was used at gauge F319 near the estuary (Figure 2.1).

A change point analysis was additionally conducted to investigate changes in observed concentrations over the modeled period (water years 2011–2017). A change point analysis aims to identify a change in the mean of a variable and acts as a tool to analyze historical data. A change point analysis can be difficult to apply to irregular timed data, such as water quality samples, but the bcpa package in RStudio finds significant break points in any time-stamped movement data [38]. The behavioral change point analysis in this package uses a likelihood-based method to determine the most likely changepoints.

2.3 Hydrologic Model

A hydrologic model of the LARB was created in EPA SWMM. The model was previously created and calibrated, with detailed methods found in Stein et al. (2021) [39]. The LARB was delineated into 147 catchments that were merged together from 1,001 sewersheds downloaded from the LA County Watershed Management and Modeling System [40]. Seventy-seven catchments were explicitly modeled in the LARB.

The explicitly modeled area was bounded by observed data from seven dams, spreading grounds, and one flow gauge located on the Rio Hondo tributary to complete the study area.

Physical data was collected to characterize the 77 explicitly modeled catchments. The average slope and total imperviousness for each catchments were estimated based on a Digital Elevation Model from the US Geological Survey (USGS) 3D Elevation Program at 1/3 arcsecond resolution [21] and from the National Land Cover Database [19], respectfully. Soils data was retrieved from the Natural Resources Conservation Service, United States Department of Agriculture Soil Survey Geographic Database [41]. Green-Ampt infiltration parameters were estimated by matching Natural Resources Conservation Service hydrologic soil groups and established values.

Precipitation data was retrieved from 72 of the Los Angeles County Automatic Local Evaluation in Real Time rain gauges. Using kriging interpolation, precipitation was spatially interpolated for each catchment. Potential evapotranspiration (PET) data was downloaded from the California Irrigation Management Information System [42]. The inverse-distance square weighting method was used to combine nine PET datasets into one for the centroid of the basin and was applied to all catchments throughout. Hourly discharge data for Tillman and Glendale WRPs were retrieved from the City of Los Angeles. Discharge data for Burbank WRP was retrieved from the State Water Resources Control Board [43]. Inflow and outflow dam data was retrieved from the Los Angeles County Department of Public Works (LACDPW) and USGS [44][45]. Data for spreading grounds, large basins that recharge groundwater with a mix of imported, recycled, and stormwater, were retrieved from the LACDPW [46]. Hourly flow gauge datasets were retrieved from the LACDPW and the USGS [47][45].

The USGS hydrograph separation program was utilized to separate baseflow from observed discharge [48] and disaggregated between each flow gauge based on contributing area. Groundwater upwelling and channel evaporation, both estimated and assumed constant, were separated from baseflow in the Glendale Narrows area to account for upwelling from its natural river bottom and losses from evaporation.

The hydrologic model was calibrated using an automated calibration tool [49] for mean daily discharge at seven gauges in order of upstream to downstream. The automated calibration tool optimized the calibration parameter set with 500 runs. Nash Sutcliffe Efficiency (NSE), percent bias, and R^2 were calculated and the best parameter set was picked based on maximizing NSE and minimizing percent bias. Calibration parameters included catchment width, hydraulic conductivity, depression storage, Manning's roughness, and percent directly connected impervious area. The model was calibrated for water years 2011 through 2013 and validated for water years 2014 through 2017. Calibration and validation were generally very good [50] with NSE ranging from 0.66 to 0.94 and percent bias from -19.9 to 17.3. For full details on the calibration and validation methods of the hydrologic model, see Stein et al. (2021) [39].

2.4 Water Quality Model

A water quality module was added to a calibrated hydrologic model with an hourly time step in SWMM to simulate water quality in the LARB. The model was set up to account for three types of pollutant sources: stormwater runoff, dry weather discharge, and WRP effluent discharge. Steps to simulate water quality associated with dry weather discharge and stormwater runoff include establishing pollutants to be simulated, defining land use types that generate pollution, assigning the percentage of each land use type to each catchment area, and setting the pollutant concentration and EMC for urban baseflow and stormflow, respectively. The model produces hourly flow and concentration timeseries and was used to determine a model baseline. Water reuse scenarios were applied to the calibrated hydrologic model and impacts on water quality loads and concentrations assessed. Figure 2.2 presents the workflow associated with creating the water quality model.

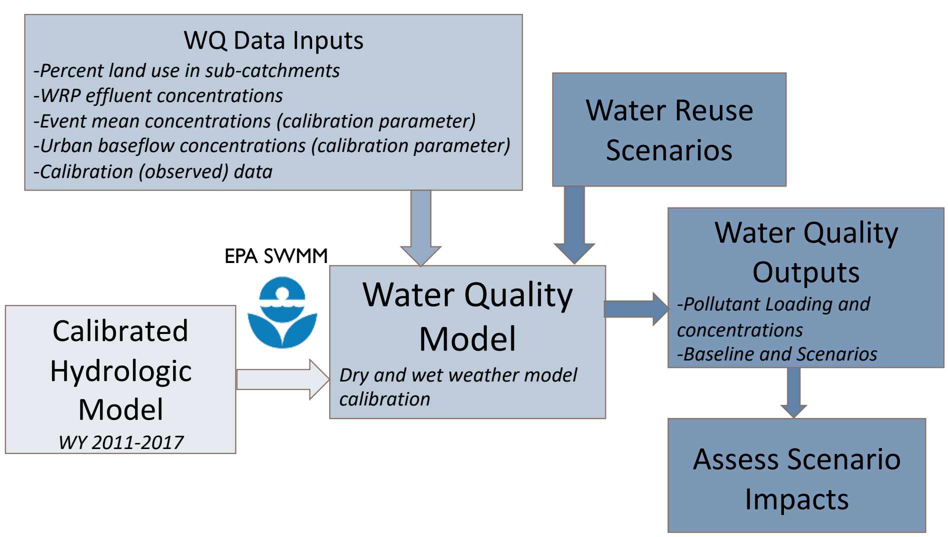

Figure 2.2 Model workflow, starting with a calibrated hydrologic model. WQ data inputs are added into the model and calibrated. Reuse scenarios are applied and modeled outputs are assessed.

2.4.1 Input Data

Land use for Los Angeles and Ventura counties were downloaded from the Southern California Association of Governments [20]. The shapefiles were combined and aggregated into 11 land-use classifications (Figure A.2). The percent land use in each catchment was determined by totaling the area of each land use in each catchment using the Tabulate Area tool in ArcGIS and calculating the percentages.

The event mean concentration (EMC) method was used to simulate pollutant wash off during storm events as opposed from the buildup/wash off method. An EMC is a flow weighted average concentration, which is an estimate of the total mass of a pollutant divided by the total storm flow volume. The EMC method was utilized due to the lack of data on antecedent dry conditions in Los Angeles needed to calibrate buildup/wash off method equations, another water quality method supported by EPA SWMM. Each of the 11 distinct land use types used in this study have an estimated EMC, or a discrete pollutant runoff concentration, associated with it. Constituents were sampled at discrete land uses by the LA County Department of Public Works' Stormwater Modeling Program between 1994–2001 and the Southern California Coastal Water Research Project's Watershed and Land Use Storm Water Pollutant Loading Data study between 2000–2005 [51]. Data was compiled from both data sources and the median EMC was initially used for each of the 11 land use types to simulate wet weather loads.

Baseflow timeseries at each model node were assigned a concentration to simulate in-stream pollutant concentration from dry weather discharge, such as water from car washes or lawn irrigation [52]. Mean concentrations computed from measurements sampled at storm drain outfalls during dry weather in the LARB [16] were used for metals and TSS as initial calibration values. The average dry weather concentration for TDS was taken from the observed data since no dry weather samples at storm drains outfalls were taken for the constituent.

Discharge monitoring report (DMR) datasets for fiscal years 2009–2020 were downloaded from the U.S. EPA's Enforcement and Compliance History website for Burbank, Tillman, and Glendale WRPs [53], which are all considered major NPDES dischargers in the LARB [54]. The DMR datasets, which report monthly averages measured at the outfall for all constituents in this study, were aggregated by month and the median was calculated, presented in Table 2.1. Only 6–36% of the total samples were detected for TSS and lead (Table 2.1), thus non-detected data samples were assumed to equal half of the detection limit.

Table 2.1 Median monthly WRP concentrations for model input

	WRP Concentration														
	Tillman					Glendale					Burbank				
Month	**Total Copper (ug/L)**	**Total Lead (ug/L)**	**Total Zinc (ug/L)**	**TSS (mg/L)**	**TDS (mg/L)**	**Total Copper (ug/L)**	**Total Lead (ug/L)**	**Total Zinc (ug/L)**	**TSS (mg/L)**	**TDS (mg/L)**	**Total Copper (ug/L)**	**Total Lead (ug/L)**	**Total Zinc (ug/L)**	**TSS (mg/L)**	**TDS (mg/L)**
1	11.6	0.25	65.5	1	547	6.56	0.25	47	0.5	686	8.5	0.25	60.5	0.5	626
2	11.6	0.25	66.6	1	568	8.51	0.25	48.9	0.5	676	10	0.25	56	0.5	625
3	10.8	0.25	55.3	1	557	7.42	0.25	48	0.5	673	14	0.25	80	0.5	628
4	11.8	0.25	51.9	1	592	7.19	0.25	48	0.5	658	11.5	0.25	57	0.5	642
5	9.48	0.25	57.3	1	577	8.41	0.25	49.2	0.5	670	12	0.25	68.5	0.5	658
6	10.9	0.25	60.5	0.5	546	7.19	0.25	48	1	686	12	0.25	70	0.5	660
7	13	0.25	57.3	1	540	8.69	0.25	46	1	654	9.5	0.25	65	0.5	664
8	10.8	0.25	57.3	0.5	534	7.52	0.25	45.4	0.5	652	9.4	0.25	67.5	0.5	638
9	10.9	0.25	57.3	0.5	520	9.63	0.25	52.8	1	682	10	0.25	64.5	0.5	634
10	12	0.25	57.3	0.5	545	7.65	0.25	47.5	1.1	699	10.2	0.25	59.5	0.5	662
11	11.5	0.25	57.3	0.5	547	8.8	0.25	54.6	1.2	692	10.8	0.25	59.5	0.5	642
12	9.83	0.25	57.6	0.75	563	7.85	0.25	48	0.75	665	10.5	0.25	71.5	0.5	612
Percent Detected	96%	6%	100%	29%	100%	88%	7%	100%	36%	100%	100%	31%	100%	23%	100%
N = Total Samples	142	109	13	139	138	137	137	50	137	137	137	110	30	137	137
N = Detected Samples	137	6	13	40	138	121	9	50	49	137	137	34	30	32	137
N = Samples not required to be monitored	0	0	88	0	0	0	0	87	0	0	0	0	88	0	0

2.4.2 Calibration and Validation

The water quality model was calibrated manually for daily pollutant loads at four gauges starting with the furthest upstream gauge (11092450) and ending with the furthest downstream gauge (F319). Water quality could not be calibrated at all seven flow gauges due to the limited number of observed samples at some locations. Table 2.2 summarizes where each parameter was calibrated and validated and if the location was calibrated for dry weather or wet weather based on the number of available measurements. The compiled water quality database was used to calibrate and validate model outputs in multiple locations throughout the basin. The model was calibrated using only detected samples due to the uncertainty of non-detected measurements, which made up only 2% of the entire calibration dataset.

Table 2.2 Water quality calibration and validation methods

Gauge	Constituent	Number of Dry Weather samples	Number of Wet Weather samples	Calibrated for Dry Weather / Wet Weather?	Validated for Dry Weather / Wet Weather?	Reported statistics for
11092450	Copper	23	1	YES / NO	NO / NO	Dry Weather only[1]
	Lead	12	1			
	Zinc	18	1			
	TSS	34	3			
	TDS	18	1			
F300	Copper	7	6	YES / YES	NO / NO	Dry and Wet Weather together[2] and Dry Weather only[1]
	Lead	6	6			
	Zinc	7	6			
	TSS	20	8			
	TDS	0	0	NA	NA	NA
F57C	Copper	19	7	YES / YES	NO / NO	Dry and Wet Weather together[2] and Dry weather only[1]
	Lead	16	6			
	Zinc	12	6			
	TSS	34	7			
	TDS	11	3			
F319	Copper	21	32	YES / YES	YES / YES	Dry and Wet Weather together[2] and Dry Weather only[1]
	Lead	21	31			
	Zinc	21	32			
	TSS	14	59			
	TDS	12	26			

[1] See Table A.3 and Table A.5 for reported statistics.
[2] See Table 3.1 and Table A.4 for reported statistics.

Daily dry weather loads were calibrated by adding an estimated urban baseflow concentration to each separated baseflow timeseries and adjusting the parameter until the statistics were optimized. Daily wet weather loads were then calibrated by adjusting EMCs. Statistics were optimized for wet weather loads by including the calibrated dry weather loads because of the limited number of wet weather samples at most locations (Table 2.2). The best calibration run was picked based on minimizing percent bias and matching modeled max, mean, and median daily loads to observed loads.

Initial and final calibrated values are presented in Table 2.3. Initial urban baseflow concentrations were scaled down from estimated values for most constituents except for lead and TDS. Since the initial values are estimated from storm drain outfall measurements, the in-stream concentrations are likely to be lower because of water dilution capacities. The median EMC values were found to underpredict pollutant loads when compared to observed loads for every constituent except TDS. Higher EMC percentiles were needed to better predict metal loads, which is supported by past water quality calibration efforts for metal loading in the LAR [55]. After the model was calibrated, model validation was performed for each constituent at the lowest downstream gauge F319 for wet and dry weather. Observed sample days were split randomly in half for calibration and validation. For example, 16 random wet weather samples for copper were selected for calibration at F319 and 16 random wet weather samples were selected for validation. Once calibration and validation of daily pollutant loads were completed, additional statistics were calculated to assess model performance for simulated in-stream concentrations.

Table 2.3 Calibration parameters for water quality

Calibration Parameter	Constituent	Initial Value	Final Value at Gauge			
			11092450	F300	F57C	F319
Urban baseflow concentration (mg/L)[1]	Copper	0.0250	0.0085	0.0025	0.0000	0.0143
	Zinc	0.1220	0.0290	0.0000	0.0000	0.0610
	Lead	0.0020	0.0040	0.0025	0.0077	0.0017
	TSS	208.0	120.0	31.20	0.0000	104.0
	TDS	662.0	1158	-	1721	695.1
Event Mean Concentration (percentile)[2]	Copper	50	-	86	80	93
	Zinc	50	-	81	32	92
	Lead	50	-	76	67	99
	TSS	50	-	96	94	68
	TDS	50	-	-	50	Min

[1] Initial values from Stein and Ackerman, 2007 except for TDS, which is estimated from observed data
[2] EMC percentiles from LA County and SCCWRP data. 50 corresponds to the median.

2.5 Reuse Scenarios

Los Angeles plans to increase water reuse, which means diverting WRP treated discharge for non-potable uses and recharging groundwater basins [56]. However, the LAR is considered an effluent dominated river. WRP discharge can make up as much as 70% of the total dry weather flow volume in some years [57], so there will be impacts to the river when the effluent discharge is reduced. Water reuse scenarios were applied to the calibrated hydrologic and water quality model by scaling the historical WRP discharge data in the modeled period. All three WRP discharges were scaled 100%, 75%, 50%, 25%, and 0%. The 100% scenario represents all WRP discharge flowing into the LAR and no water reuse. The 0% scenario represents no WRP discharge in the river and 100% is reuse. Note that when one WRP was scaled, the other two WRPs were also scaled by the same percentage. For example, if Tillman WRP was scaled to 50%, then Glendale and Burbank WRPs were also scaled to 50%. Results were assessed at multiple reaches in the LAR; thus, some locations may be influenced by only one or two WRPs. Reach 4, dictated by its dry weather TMDL location, is impacted by Tillman and Burbank WRP's discharge but not by Glendale WRP. A reduction in WRP discharge may consequently reduce pollutant loadings contributing into the river and affect dilution capacities in-stream. By applying the reuse scenarios, this study can assess how WRP flow reductions effect overall water quality in the LAR.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Empirical Data Analysis

A correlation matrix comparing relationships between total metals, TSS, TDS, and flow at the gauge F319 is presented in Figure 3.1. The observed concentrations and flow data are consistently positively skewed in their data distribution, which means the median of the data is lower than the mean. It is expected that hydrologic and pollutant data are positively skewed and are approximately lognormal in shape. This is due to a lower bound of zero and high data outliers [35], such as a spike in flow from a large storm. The exact process that explains why pollutant concentrations are approximately lognormal in shape is still unclear, but Ott (1990) successfully demonstrated that random dilution processes that occur in the environment could explain why concentration data appears this way [58].

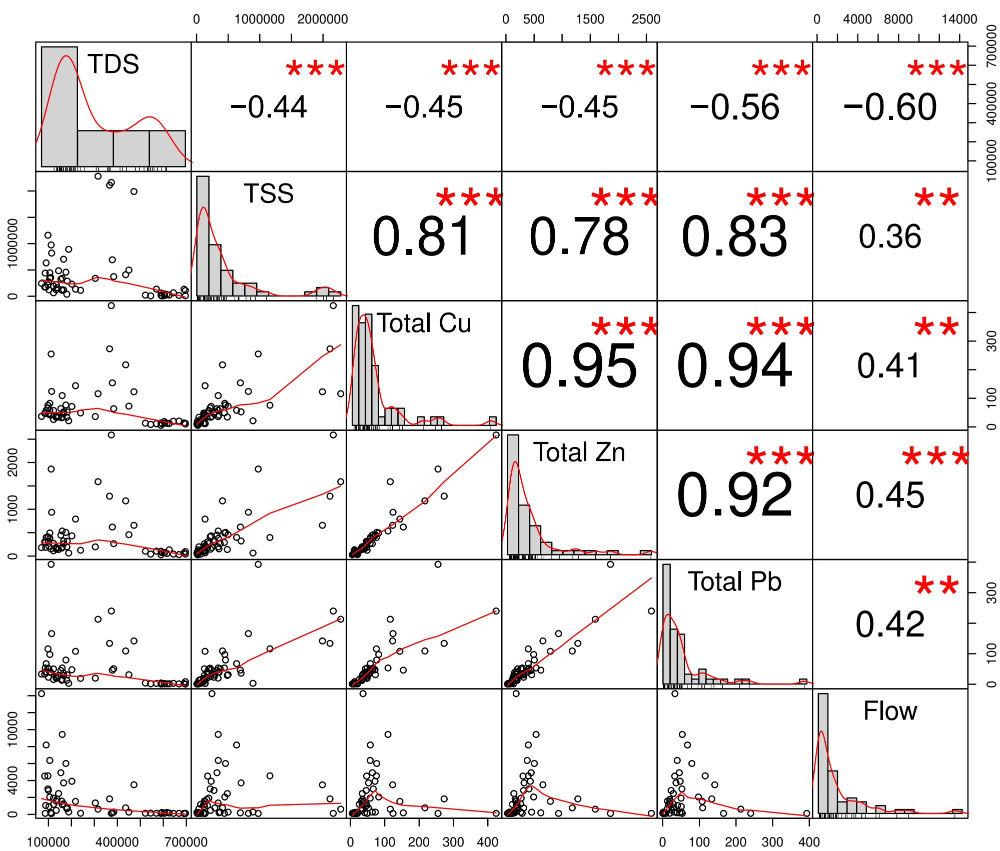

Figure 3.1 Correlation matrix for data at F319 (N = 56). Distribution of each variable is shown on the diagonal. Bivariate scatter plots with a fitted line are below the diagonal. The correlation coefficients and significance values represented by stars (*** = p-value<0.001, ** = p-value<0.01) are above the diagonal. (Cu = Copper, Zn = Zinc, Pb = Lead).

The strength of Spearman's correlation is interpreted using Gogtay and Thatte (2017), which classifies a strong correlation in the range of 0.5 to 1.0 in the positive direction or -0.5 to -1.0 in the inverse direction [59]. A correlation that is statistically significant (p-value < 0.01) indicates that there is less than a 1% chance that the association occurred by random chance. Copper, lead, and zinc share a statistically significant, strong, and positive association with TSS ($\rho = 0.81, 0.78, 0.83$, respectfully and p-value < 0.01) due to the nature of heavy metal ions adsorbing onto sediments. This finding suggests that copper, lead, and zinc could be reasonably estimated using TSS. On the other hand, lead shares a significant, strong, and inverse correlation with TDS ($\rho = -0.56$ and p-value < 0.01). No other metals are strongly correlated with TDS. TSS and TDS also do not share a strong correlated relationship.

Streamflow against total metals, TSS and TDS are weakly correlated except for a significant, strong, and inverse association with TDS ($\rho = -0.60$ and p-value < 0.01), so streamflow is generally not a good predictor of pollutant concentration. This finding contradicts Nagorski et al. (2003), which found a significant, strong and positive association between flow and TSS, and some total recoverable metals, in both a stream unburdened by development and a river impacted from mining operations [60]. Physical mobilization of TSS during high flow events occur because of high river stage and velocity that erode, scour, and re-suspend sediment [61], which affects sediment transport and dispersion of pollutants. Studies have shown that concentrations tend to increase and peak during the rising limb of a storm hydrograph, particularly in an basin with high impervious cover [62][61]. The “flushing” phenomenon was also observed on the bivariate scatter plots in Figure 3.1. These plots show that concentrations are relatively low during high flow events, but high during low-to-mid range flows. This supports the idea that peak concentrations do not occur at peak storm flow. While there is less flow available during low flows, pollutants are less diluted, and concentrations will spike.

Sources of metals, TSS and TDS in the LARB originate from WRPs and pollution generation on land surfaces. Because the LARB is characterized as heavily urbanized, the excess of automobile brake pads, tires, and building siding are identified as key sources for copper, lead, and zinc. Atmospheric deposition is another nonpoint-source considered important for all three metals [63]. The sources of TSS originate from suspended particles transported from eroding hillsides or other pervious surfaces and buildup on impervious surface during dry weather from atmospheric deposition [64]. TDS varies based on ions released from the geology and soil of the LARB, which may come from rocks, soil, fertilizers or salts [65]. Groundwater upwelling could possibly be a contributor to TDS in the LAR due to the few natural-bottomed segments of the river. Groundwater in the LA Basin is reported by USGS to have moderate TDS levels (between the recommended level and upper limit) in 47% of the entire groundwater basin [66]. However, there is only an estimated volume of 3,000 acre-feet per year of groundwater upwelling in the Glendale Narrows, the largest soft bottom reach. Further, groundwater makes up roughly 1% of the total river annual flow volume, so it is not likely a significant source of TDS in the LAR [65].

Change point analysis results (Figure 3.2) show temporal trends of pollutant concentration. Dry weather concentrations are observed at F319 and significant change points identified, reflected by the purple vertical line. All study pollutants were tested except for TDS because no significant change point could be identified. Average copper, lead and TSS concentrations in dry weather changed by a rate of -48%, -71%, and -68% respectfully after the detected change-point in 2014, while after 2015 the average concentration of zinc changed by -73%. Copper, zinc, lead and TSS concentrations were assessed in wet weather (Figure A.3), but the averages minimally changed after the detected change point (-16%, -13%, -4%, and -16% respectfully). In 2010, California passed a law to eliminate copper brake pads [67] which may explain the concentration reduction for copper. This law additionally prohibited the sale of other brake pads that contained harmful pollutants like lead in 2014. In 2015 the amount of copper found in new brake pads reduced by 22% since the law passed, but loads are not expected to be noticeably reduced until the 2020s [67]. Water conservation practices are another possible explanation for the observed concentration reductions in dry weather. In 2014 and 2015 Los Angeles enforced mandatory water use restrictions in response to a persistent drought in Southern California [68]. This suggests that restricting outdoor residential water use, like watering lawns or washing cars, reduces nonpoint-source pollution in dry weather. However, the detected change-point timing and the trend of concentration reduction are not similar between F319 and upstream locations (Figure A.4). The concentrations at F319, the furthest downstream monitoring location, could be responding differently because of the densely developed land uses and higher wash off concentrations that are characterized in the lower LARB, indicated by higher EMCs calibrated in the lower sub-catchments in Table 2.3. The results from this analysis are limited by the number of observed samples. Consistent monitoring would improve a change-point analysis to determine whether concentrations are being reduced near the estuary.

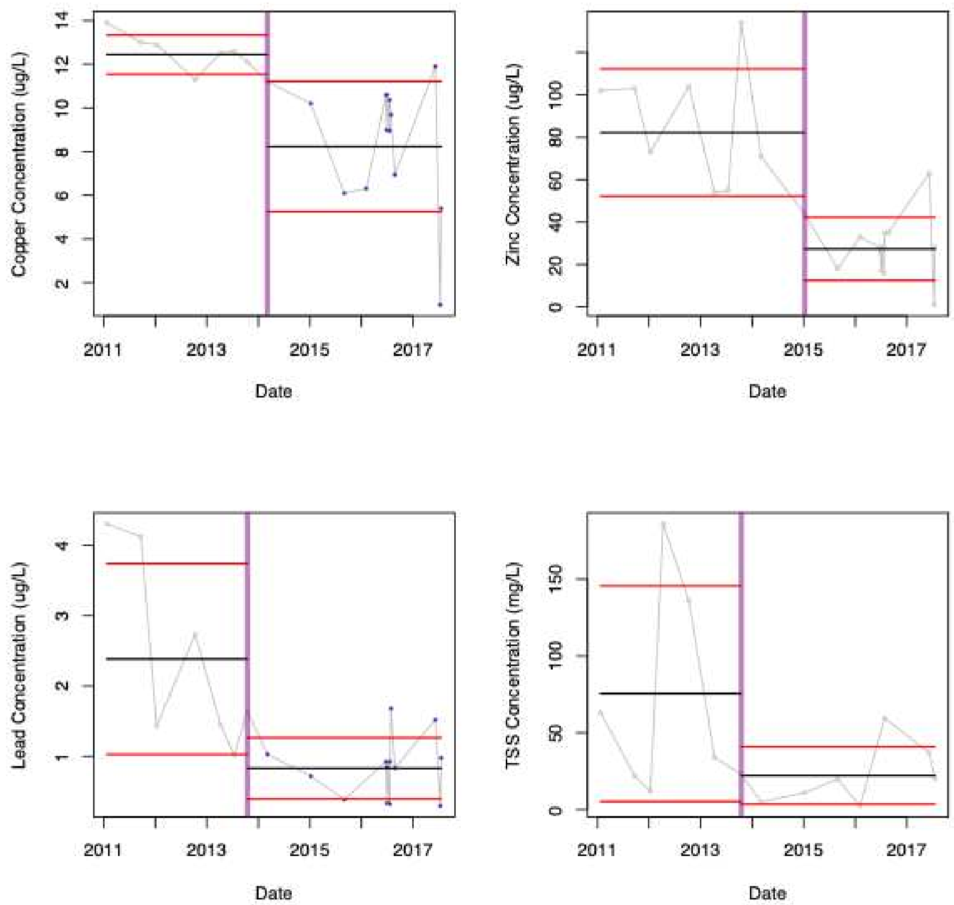

Figure 3.2 Change point analysis for dry weather concentration at F319. Vertical purple lines represent the significant break line. Horizonal black lines represent the mean and red lines represent the standard deviation.

3.2 Calibration and Validation

Water quality calibration and validation results are presented in Table 3.1, where percent bias and observed and modeled mean, median and max loads for dry and wet weather combined were computed. Table A.3 presents results for dry weather only load calibration, and Table A.4 and Table A.5 presents results for concentrations. Percent bias, the statistic minimized while calibrating, ranged from 0.016% to 16% in load calibration, which resulted in -36% to 21% for concentrations. The model performed poorly predicting high pollutant loads and concentrations in both wet and dry weather. The average and median loads were either well matched or slightly over predicted, which indicates that the model can replicate conditions during most storm events and dry weather flows reasonably well. Validation of the model at F319 shows that the final calibrated parameters caused the model to underpredict some pollutants when compared to the randomized observed data picked for validating, and the percent bias ranged from -32% to 12.5% for loads and -36% to 17% for concentrations. Calibration and validation are determined to be very good based on performance ratings by Moriasi et al. (2007), where a "very good" goodness-of-fit is equivalent to a percent bias less than or greater than 15% for sediment pollutants [50]. There is inherent uncertainty in water quality modeling due to the complexity of physical processes that represent the generation and transport of pollutants, but calibrating parameters can improve model performance [69].

Table 3.1 Dry and wet weather load calibration and validation results

Load - Dry & Wet Weather combined calibration results										
Gauge	**Location**	**Constituent**	**Percent Bias (%)**	**Observed Mean (kg)**	**Modeled Mean (kg)**	**Observed Median (kg)**	**Modeled Median (kg)**	**Observed Max (kg)**	**Modeled Max (kg)**
F300	Tujunga Avenue	Copper	0.851	18.4	18.5	1.54	1.45	94.2	70.8
		Zinc	2.11	88.3	90.0	6.46	7.88	463	342
		Lead	3.11	7.33	7.54	2.06	1.81	37.8	29.0
		TSS	2.79	7.63E+04	7.83E+04	1.90E+03	2.14E+03	9.71E+05	6.67E+05
F57C	Glendale Narrows	Copper	0.501	10.5	10.6	1.83	1.96	108	103
		Zinc	0.979	52.9	53.8	9.71	10.2	458	433
		Lead	0.898	5.33	5.38	0.166	0.209	47.9	43.8
		TSS	1.43	6.38E+04	6.46E+04	1.94E+03	2.16E+03	1.67E+06	1.13E+06
		TDS	2.17	1.61E+05	1.65E+05	1.68E+05	1.54E+05	1.85E+05	2.45E+05
F319	Between Willow Street and Wardlow Road	Copper	3.53	245	254	62.5	75.0	1.28E+03	2.30E+03
		Zinc	6.69	1.37E+03	1.46E+03	325	475	7.42E+03	1.23E+04
		Lead	3.57	224	233	65.8	82.9	1.29E+03	2.03E+03
		TSS	2.48	1.25E+06	1.28E+06	5.04E+05	8.79E+05	6.42E+06	4.83E+06
		TDS	16.3	5.83E+05	6.79E+05	4.50E+05	6.00E+05	2.07E+06	1.98E+06
Dry & Wet Weather combined validation results									
F319	Between Willow Street and Wardlow Road	Copper	-21.4	273	215	97.5	94.6	1.16E+03	1.18E+03
		Zinc	-32.0	1.74E+03	1.18E+03	592	5.17E+02	7.96E+03	6.67E+03
		Lead	-5.94	195	184	43.8	48.3	1.35E+03	1.16E+03
		TSS	10.7	7.04E+05	7.79E+05	3.13E+05	3.83E+05	5.38E+06	4.00E+06
		TDS	12.5	3.05E+04	3.43E+04	2.16E+04	2.98E+04	9.58E+04	1.15E+05

The observed water quality samples were limited in sample size, where some pollutants were sampled only a handful of times a year at upstream locations. This limited the ability to calibrate the water quality model by timing and matching peak concentration with observed and modeled data. Because of the generally small sample sizes, the distribution of modeled data is important to match to the distribution of observed data. Figure 3.3 presents boxplots of modeled and observed copper loads at each location for dry and wet weather. The distributions of data show similar patterns at each location for all five pollutants, so the model is successful at predicting the distribution of pollutant loads for dry and wet weather conditions. Concentration distributions for zinc, lead, TSS and TDS can be observed in Figure A.5 through Figure A.8.

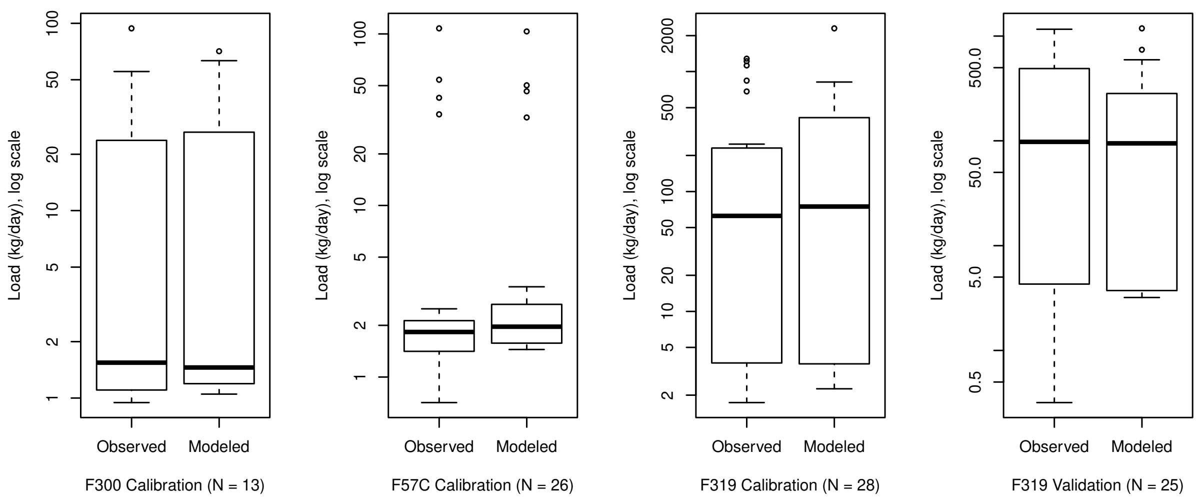

Figure 3.3 Copper calibration and validation results, comparing observed daily loads vs. modeled daily loads in dry and wet weather.

3.3 Simulated Water Quality Baseline

Baseline modeled outputs are used to observe spatial and temporal water quality patterns to better understand the LAR system. Modeled concentration timeseries for all constituents and modeled flow timeseries at five gauges, which are located and labeled in Figure 2.1, are used to establish current loading and concentration conditions in the LAR. Figure 3.4 presents boxplots for copper that display daily loads and concentrations grouped by month and gauge. Figure A.9 through Figure A.12 present results for zinc, lead, TSS and TDS, respectfully. Over the course of a year, the median of daily loads decreases slightly in drier months compared to wetter months and daily concentrations stay relatively constant or increase in the drier months, due to lack of dilution capacities. The data distribution becomes much smaller in the summer and early fall months compared to the distribution of data in other seasons. Outliers are prominent in the wetter months and are caused by greater flows and concentrations due to stormwater runoff.

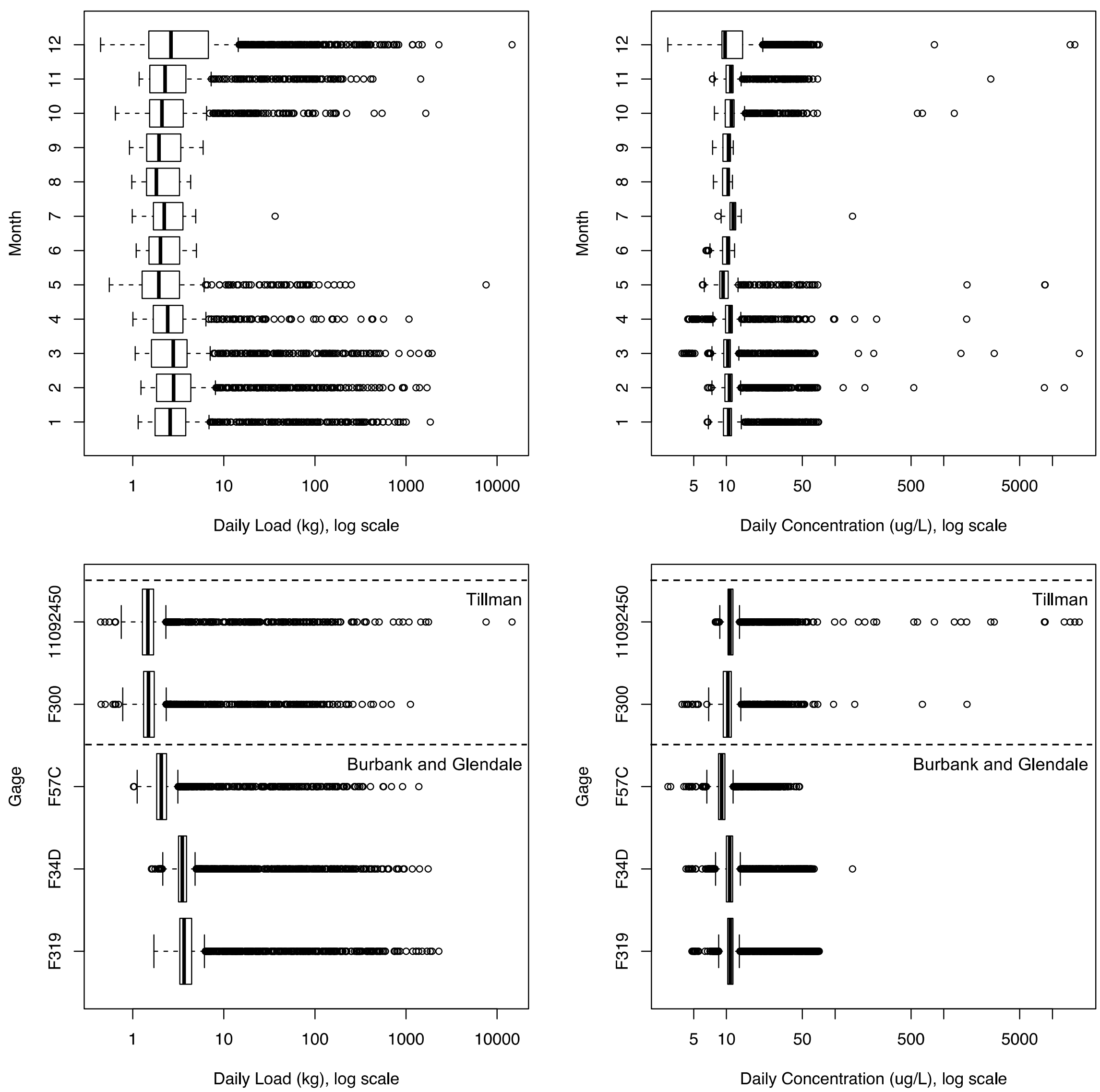

Figure 3.4 Copper with modeled baseline conditions for load (left) and concentration (right) grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Y-axis on gauge plots correspond to relative position in the LAR (upstream to downstream).

Every constituent shows a pattern of increasing *load* as pollutants are transported downstream after Burbank and Glendale WRPs discharge into the LAR. This suggests that the input of flow from the

WRPs have an impact on pollutant loading downstream. On the other hand, the median and data distribution of daily *concentrations* decrease slightly or stay relatively constant directly after Burbank and Glendale WRPs, with the exception of TDS. This finding indicates that WRP discharge is diluting pollutant concentrations. A possible reason why TDS slightly increases in concentration is because of other pollutant sources contributing to concentration, such as industrial dischargers or dry weather urban runoff. Except for TDS, the median of the daily concentrations increases slightly downstream of the WRPs, likely because of the accumulation of nonpoint-source pollution in the lower sub-catchments added into the LAR via MS4s.

Pollutant sources during dry weather days, characterized when the maximum flow at gauge F319 does not reach 14.2 cms (500 cfs), are assessed using the baseline modeled outputs. Figure 3.5 presents WRP load and non-WRP load contribution in the LAR on any given dry weather day. The WRP load contribution for zinc, copper, TDS, lead and TSS may account to roughly 47%, 43%, 39%, 4% and 1% of total dry weather load in the LAR, respectfully. WRPs are not a major source of TSS and lead, which is suggested by the observed WRP data from Table 2.1. TSS and lead concentrations at each WRP are consistently low or non-detected every month. On the other hand, the WRPs contribute to the copper, zinc and TDS load into the river and are considered a major pollutant source during dry weather. These findings are supported by past conclusions made to quantify dry weather pollutant sources in the LAR [23] [16].

Dry and wet weather loads contributing toward total loads in the LAR are also assessed (Figure 3.6). Dry weather loads for TDS, copper, zinc, TSS, and lead make up 63%, 17%, 16%, 11%, 6% of total loads, respectfully. Wet weather loading (i.e. stormwater runoff) is a major contributor to copper, zinc, lead, and TSS loading. The exception is TDS; the final calibrated EMCs were either the median values or minimum values for TDS (Table 2.3), which indicates nonpoint-source pollution from stormwater runoff is not a major contributor for TDS loading. Overall, dry weather loading only accounts for the minority of the total load for copper, zinc, lead and TSS.

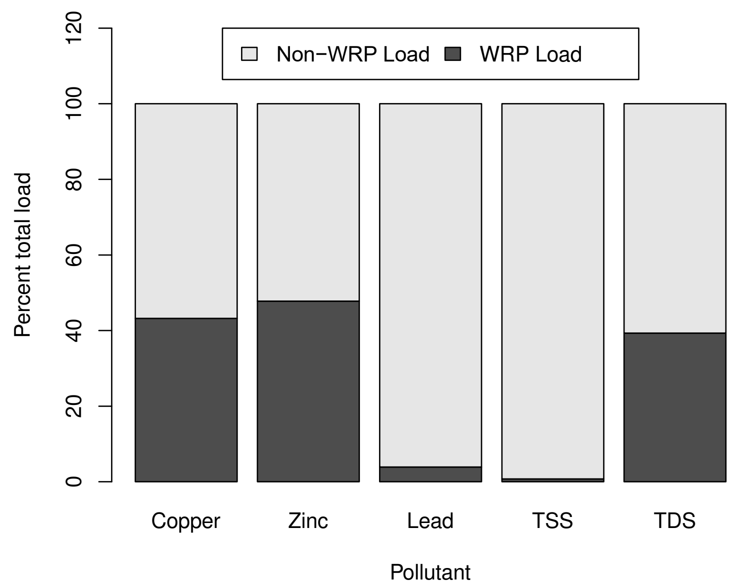

Figure 3.5 Load source contribution (percent) during dry weather for various pollutants. (WRP = Wastewater Reclamation Plant).

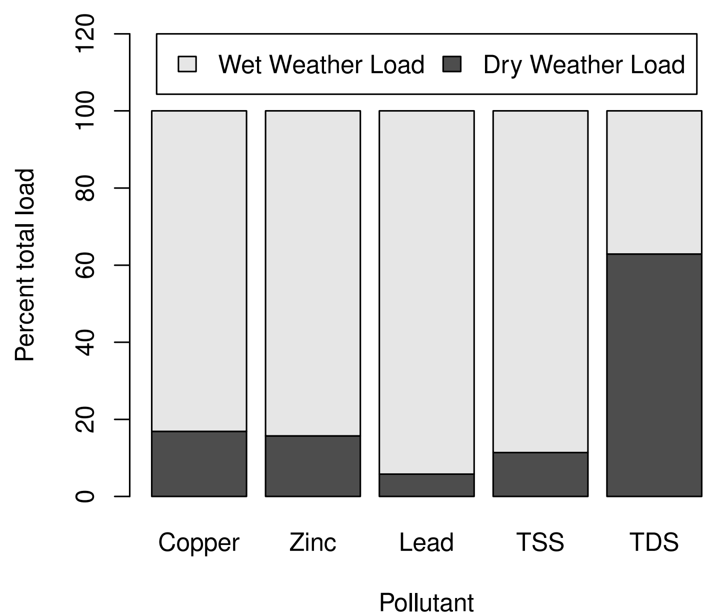

Figure 3.6 Percent of dry and wet weather loads in the LAR for various pollutants.

3.4 Water Reuse Impacts

Loads generally decrease in both space and time for every constituent (Figures 3.7-3.9 for copper, lead, and TDS, respectfully, and Figures A.13 and A.14 for zinc and TSS, respectfully). Pollutant loads are flow-dependent, so loads consequently decrease when flow is reduced. Each scenario at each gauge and month decreases at a constant rate because the WRP scenarios are varied at a constant rate. Therefore, flow reductions will lead to load reductions for copper, lead, zinc, and TDS in the LAR. However, TSS loads did not change by a considerable amount in both space and time. The largest percent change of TSS load between baseline and the most severe scenario is 11%, which is lower compared to percent change of load for other pollutants. For example, the average percent change for copper load between the same scenarios is roughly 70%.

Median concentrations decrease or increase with a reduction of WRP discharge depending on the pollutant. Unlike loading responding with a constant rate, concentrations respond non-linearly for every pollutant. For example, copper median daily concentration in October begins at 11.1 ug/L in the baseline scenario, increases to 11.0 ug/L in the 75% scenario, 10.9 ug/L in the 50% scenario, 10.5 ug/L in the 25% scenario, and finally 7.99 ug/L in the 0% scenario. There is a consistent pattern of varying differences between concentrations under each scenario, especially between the 25% WRP scenario and 0% WRP scenario. This can be explained using a plug flow reactor mass balance equation that assumes well-mixed media, steady-state, and no chemical reactions (Equation 3.1), where initial load in the river ($Q_{\text{initial}}\ C_{\text{intial}}$) and WRP load ($Q_{\text{WRP}}C_{\text{WRP}}$) equals the final load in the river ($Q_{\text{final}}C_{\text{final}}$). Assuming that flow is balanced (Equation 3.2), the final concentration in the river can be determined after rearranging Equation 3.1 (see Equation 3.3).

$$Q_{\text{final}}C_{\text{final}} = Q_{\text{WRP}}C_{\text{WRP}} + Q_{\text{initial}}\ C_{\text{intial}} \tag{3.1}$$

$$Q_{\text{final}} = Q_{\text{WRP}} + Q_{\text{initial}} \tag{3.2}$$

$$C_{\text{final}} = \frac{Q_{\text{WRP}}C_{\text{WRP}}}{Q_{\text{WRP}}+Q_{\text{initial}}} + \frac{Q_{\text{initial}}C_{\text{initial}}}{Q_{\text{WRP}}+Q_{\text{initial}}} \tag{3.3}$$

Using constant initial flow, initial concentration, and WRP concentration, the calculated final concentration responds exponentially with changing WRP flow values. This simple mass balance model, the mechanism behind simulating concentrations in SWMM, supports the response of pollutant concentrations to changing WRP discharge scenarios occurring. Additionally, median concentrations are converging under each scenario as pollutants travel downstream. This finding suggests that flow increasing downstream mutes WRP flow reduction impacts on pollutant concentrations.

Copper and zinc loads are 43% and 47%, respectfully, sourced by WRP loading during dry weather, but dry weather loading only makes up roughly 15% of total loading, based on Figures 3.5 and 3.6. These pollutants share similar load and concentration responses to various flow reduction scenarios (Figure 3.7 for copper and Figures A.13 for zinc). Median daily concentrations decrease considerably in each month and at each gauge, except for gauges F34D and F319 for copper. Concentrations increase with reductions of WRP discharge at these two locations, despite decreasing upstream. Because this research separately examined monthly and spatial trends, the results are limited to definitively demonstrate that concentrations are increasing or decreasing under reuse at a specific gage at a specific time. A deeper analysis that looks at monthly or seasonal trends at each gauge would be useful and provide better details to impacts on concentrations and loads. Overall, reductions in WRP discharge decrease the daily median concentrations and loads for copper and zinc because WRP loading is a considerable pollution source. WRP discharge is reduced which effectively decreases copper and zinc concentrations and improves current water quality conditions in the LAR.

WRP loading is not a major pollutant source for lead or TSS, so most dry weather loading is due to by dry weather urban runoff and industrial discharges. Because these pollutants do not have WRP discharges as a major pollution source, they share similar concentration responses to scenarios (Figure 3.8 for lead and Figure A.14 for TSS). Median daily concentrations increase with reductions of WRP discharge because their dilution capacities are reduced. This finding suggests that lead and TSS depend on WRP discharge for concentration dilution, and reductions in flow degrade current water quality conditions.

For TDS, WRP loads make up 39% of dry weather loading and dry weather loading makes up 63% of total loading in the LAR. This pollutant is unique compared to the other study constituents because wet weather loads do not make up most of the total loading, indicating that WRPs, dry weather urban runoff, and industrial dischargers are major sources of pollution for TDS. Median daily TDS concentrations increase under WRP discharge scenarios (Figure 3.9). Even though WRPs is a source of pollution for TDS, other dry weather pollution sources are still majorly contributing to TDS pollution in the LAR. Like lead and TSS, reducing WRP discharge reduces TDS dilution and consequently increases concentrations and degrades current conditions.

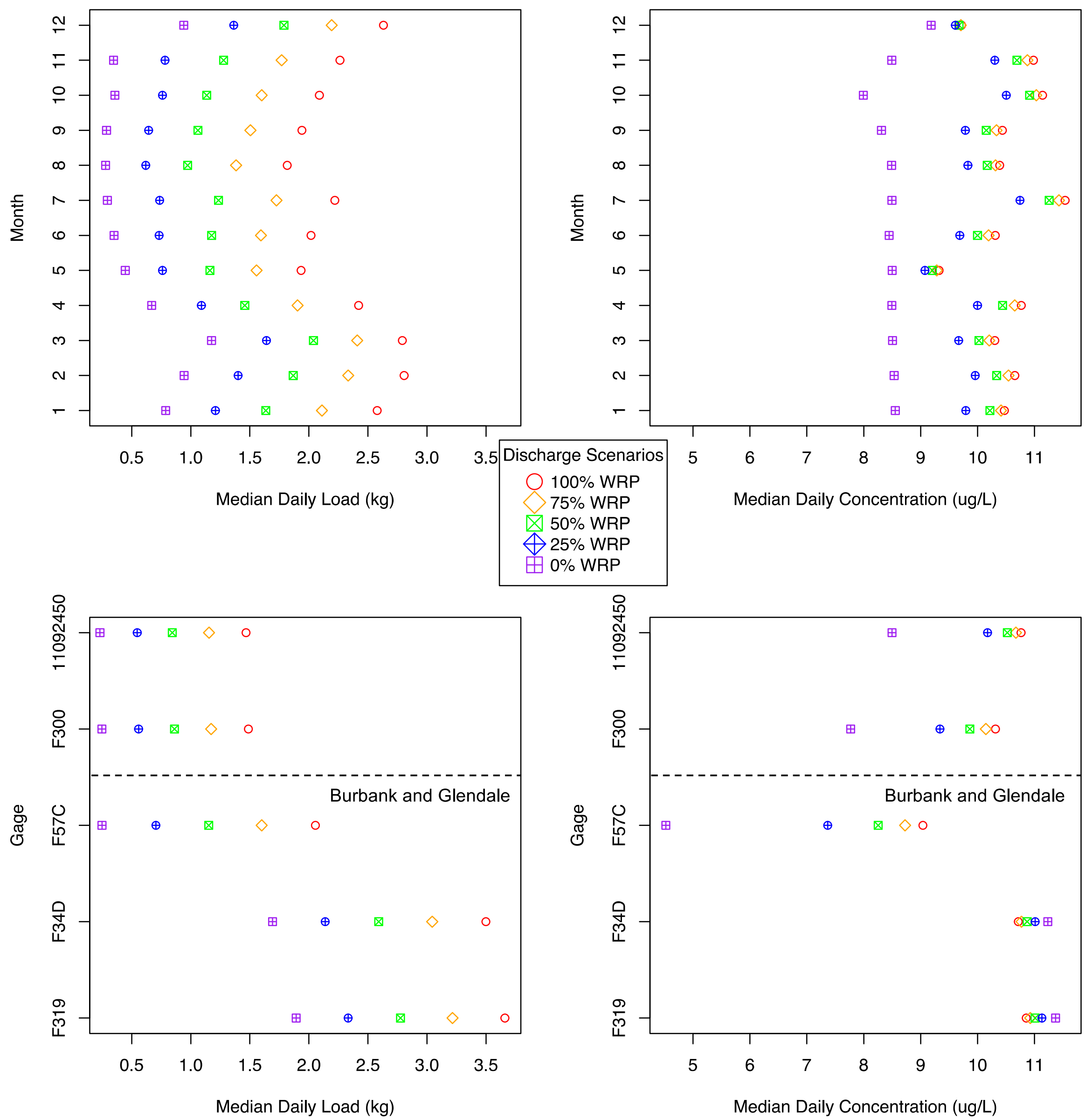

Figure 3.7 Copper median daily loads (left) and concentrations (right) for each water reuse scenarios, grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Tillman WRP is located above gauge 11092450. Y-axis correspond to relative position in the LAR (upstream to downstream). 100% WRP discharge scenario = 0% reuse, represented by a red circle and 0% WRP discharge scenario = 100% reuse, represented by a purple square.

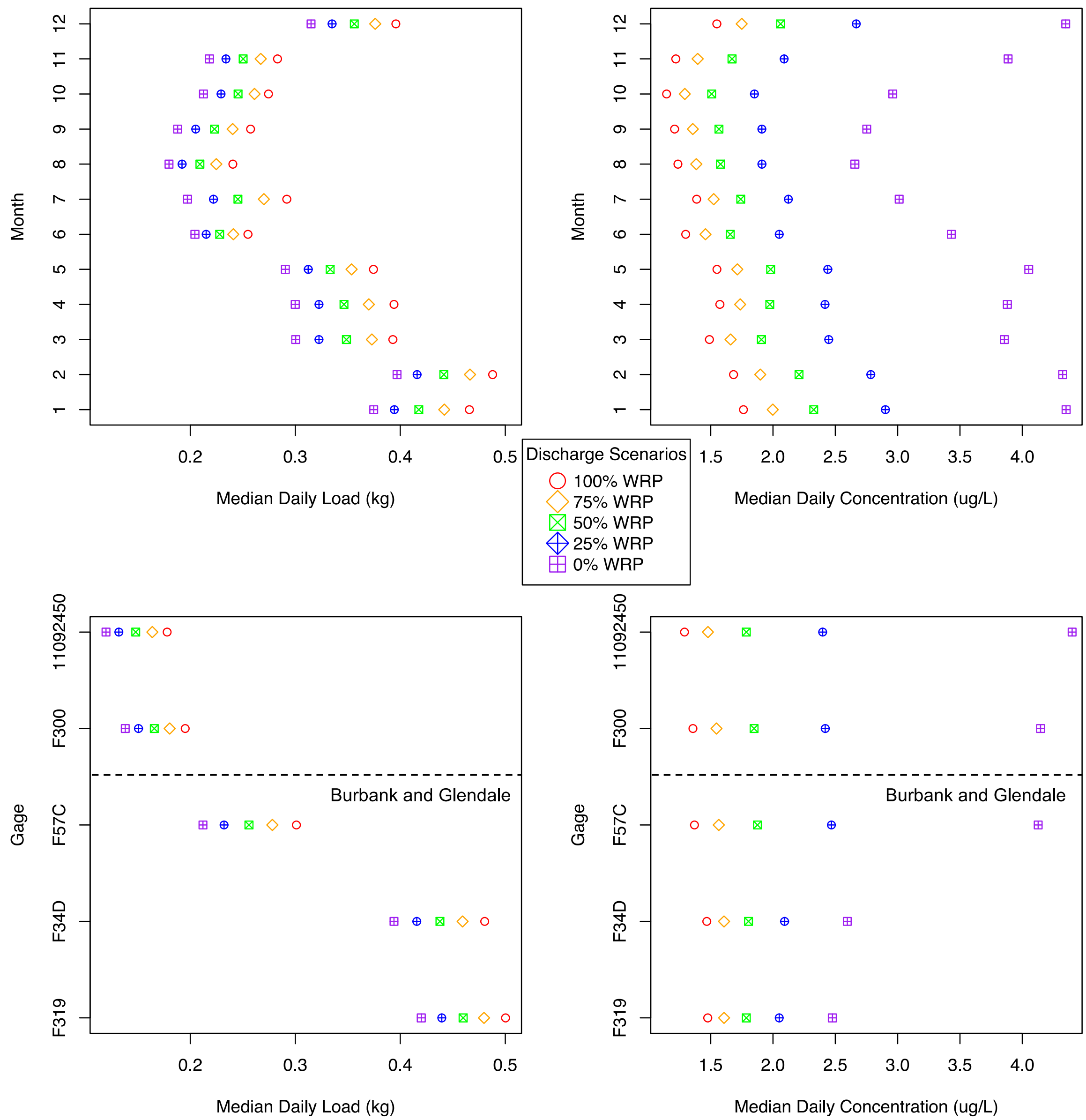

Figure 3.8 Lead median daily loads (left) and concentrations (right) for each water reuse scenarios, grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Tillman WRP is located above gauge 11092450. Y-axis correspond to relative position in the LAR (upstream to downstream). 100% WRP discharge scenario = 0% reuse, represented by a red circle and 0% WRP discharge scenario = 100% reuse, represented by a purple square.

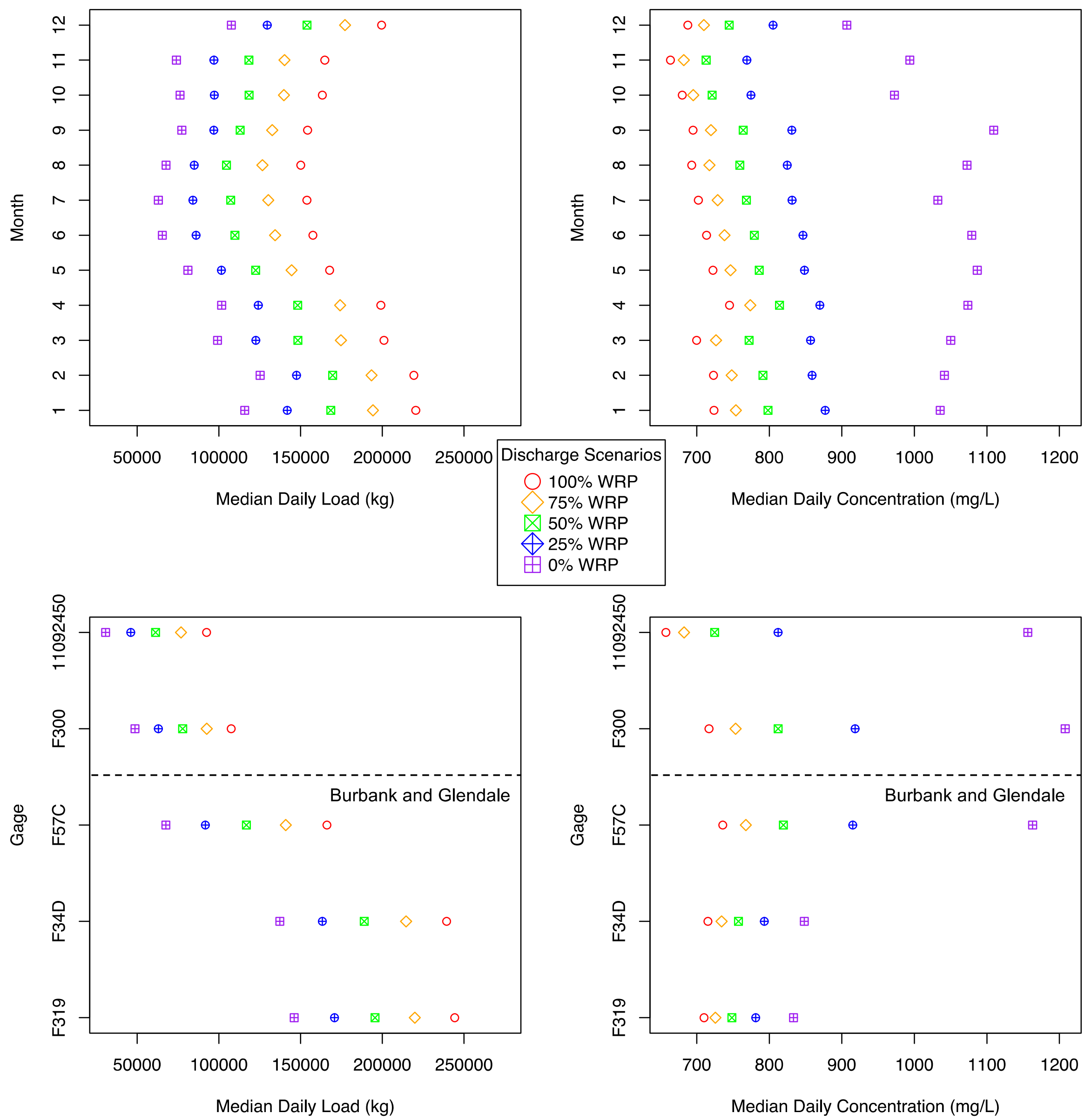

Figure 3.9 TDS median daily loads (left) and concentrations (right) for each water reuse scenarios, grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Tillman WRP is located above gauge 11092450. Y-axis correspond to relative position in the LAR (upstream to downstream). 100% WRP discharge scenario = 0% reuse, represented by a red circle and 0% WRP discharge scenario = 100% reuse, represented by a purple square.

3.5 Compliance with Water Quality Regulations

The wastewater reuse scenarios do not greatly impact load or concentration- based TMDLs in the LAR (Table 3.3 and Table A.6, respectfully). The modeled baseline complies almost 100% of the time for copper and lead during dry weather. Zinc averages 22 exceedances per year in wet weather and has no dry weather compliance locations. It is important to note that while the modeled baseline is mostly in compliance, this study only assesses reaches impacted by WRP discharge. Other reaches and tributaries are likely out-of-compliance. In a comprehensive stormwater quality modeling study in the LARB, the majority of dry weather load-based TMDL exceedances were found in Compton Creek, Rio Hondo, Tujunga, and Reach 5 and very few in Reaches 1-4 and Burbank Western Channel for copper and lead [70].

Dry weather load and concentration-based TMDLs comply under WRP flow reductions for copper and lead. This is because median daily loads decrease under scenarios, as shown in Figure 3.7 and Figure 3.8, respectfully, despite an increase in concentrations for lead. This suggests that even when concentrations are increasing, the change in concentration and load under each scenario are not enough to trigger dry weather exceedances.

For wet weather load and concentration-based TMDL compliance, exceedances increase slightly with an increase in flow reduction for copper. Copper compliance from the baseline to the 0% scenario decreases from 100% to 88%. This finding highlights that copper concentrations increase during wetter months under WRP reuse scenarios, which explains the logic behind daily median concentrations increasing in downstream gauges in Figure 3.7. Consequently, the number of wet weather exceedances per year increase for copper under each scenario. Zinc exceedances per year only increase by one day, but is the most out-of-compliance between all three metals. To improve wet weather compliance, stormwater Best Management Practices (BMPs) have been shown to reduce zinc load and concentration in the LARB and effectively increase compliance [71]. Lead has no wet weather exceedances. Note that load-based TMDL exceedances correspond to days where the numeric target is also exceeded.

The number of dry weather days and wet weather days change by one day between the 75% WRP discharge and 50% WRP discharge scenario. WRP discharges make up a small amount of overall flow during wet weather so reductions in WRP discharge will not reduce peak stormwater flows enough to change the number of dry and wet weather days at gauge F319. However, the current TMDL documentation uses median flows from 1988–2000 to designate dry weather days and critical flows used to calculate dry weather TMDLs [9].

Table 3.2 Load-based TMDL exceedances/yr and percent compliance for each scenario in each impaired reach impacted by WRP discharge. WW = wet weather and DW = dry weather.

Impaired Reach	Scenarios	DW days/yr	Dry weather TMDL exceedances/year (TMDL Compliance[%])					WW days/yr	Wet weather TMDL exceedances/year (TMDL Compliance[%])					
			Copper		Lead		Zinc		Copper		Lead		Zinc	
Burbank Western Channel	Baseline (WRP 100%)	331	0	(100%)	0	(100%)								
	WRP 75%	331	0	(100%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 4	Baseline (WRP 100%)	331	1	(99.7%)	0	(100%)								
	WRP 75%	331	0	(99.7%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 3	Baseline (WRP 100%)	331	0	(100%)	0	(100%)								
	WRP 75%	331	0	(100%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 2	Baseline (WRP 100%)	331	0	(100%)	0	(100%)								
	WRP 75%	331	0	(100%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 1	Baseline (WRP 100%)	331	0	(100%)	0	(100%)		34	0	(100%)	0	(100%)	22	(35%)
	WRP 75%	331	0	(100%)	0	(100%)		34	2	(94%)	0	(100%)	23	(32%)
	WRP 50%	332	0	(100%)	0	(100%)	-	33	2	(94%)	0	(100%)	23	(30%)
	WRP 25%	332	0	(100%)	0	(100%)		33	3	(91%)	0	(100%)	23	(30%)
	WRP 0%	332	0	(100%)	0	(100%)		33	4	(88%)	0	(100%)	23	(30%)

Flow in the LAR has increased due to WRP discharges, outdoor residential use, and implementation of stormwater BMPs, which has altered the historic flow regime since 1988 [18]. The TMDL standards created in the 2000 documentation may need to be changed based on future management decisions to accurately reflect realistic water quality goals.

TDS exceedances increase under WRP discharge scenarios (Table 3.3). In the upstream reach at F57C, compliance drastically falls from 95% to 15% between baseline and the 0% WRP discharge scenario, while compliance barely changes in the downstream reach at F319. The water quality standard is more stringent upstream (950 mg/L) compared to downstream (1,500 mg/L), which is likely why there are more exceedances upstream. Additionally, while median daily concentrations increase under WRP scenarios, TDS concentrations are lower in magnitude at gauge F319 compared to F57C and further support the results found in Table 3.3. The upstream reach is degraded heavily under the scenarios, which could have environmental implications. Changes in TDS concentrations can be harmful to aquatic life. If levels are too high or low, it may limit growth of aquatic plants and animals. High concentrations may also reduce water clarity [64]. While TSS does not have any water quality standards in the LAR, concentrations also increase under scenarios. The implication of high TSS, like TDS, may also limit growth of animals and plants and reduce water clarity, which will slow down photosynthesis, reduce dissolved oxygen, and increase surface temperatures [64]. There has been a suggested level of TSS concentrations greater than 100 mg/L that cause definite health effects and poor conditions for fish habitat [72]. Under the 0% WRP flow scenario, median daily concentrations approach 100 mg/L for TSS (Figure A.14), so mitigation should be done to protect fish and aquatic health when increasing water reuse. One solution to prevent potential habitat degradation from high TDS and TSS is to use low flow diversions facilities (LFD), which divert dry weather flow to treatment facilities and either recycle flows or return flows back into the river. The City of LA has implemented a LFD program successfully for a watershed adjacent to the LARB [73] and there are plans to build these facilities in the LARB [74]. This approach will additionally improve water quality for other pollutants and regulatory compliance in tributaries.

Table 3.3 TDS concentration exceedances per year and percent compliance for wastewater reuse scenarios at two locations along the mainstem in the Los Angeles River.

Reach	Scenario	TDS exceedances/year (Compliance [%] out of 365 days)	
Upstream of Gauge F57C	Baseline (WRP 100%)	17	(95%)
	WRP 75%	29	(92%)
	WRP 50%	73	(80%)
	WRP 25%	159	(56%)
	WRP 0%	311	(15%)
Between Gauge F57C and F319	Baseline (WRP 100%)	1	(99%)
	WRP 75%	1	(99%)
	WRP 50%	1	(99%)
	WRP 25%	2	(99%)
	WRP 0%	2	(99%)

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

This research conducted a water quality assessment to quantify the impacts of water reuse on water quality in the LAR. Relationships between copper, lead, zinc and TSS concentration were found to have strong and significant correlations among each variable while discharge was not a strong predictor of pollutant concentrations. The calibrated modeled outputs were used to establish a baseline of temporal and spatial patterns of pollutant loads and concentrations, where loads increased, and concentrations diluted with an input of WRP discharge. Additionally, WRPs were found to be a major pollution source in dry weather for copper, zinc, and TDS, but not a large source for lead or TSS. Wet weather loading was a major source for zinc, lead, and TSS compared to dry weather loading, but dry weather loading was a major source for TDS. Under WRP flow reduction scenarios, loads decreased but concentrations increased or decreased, depending on whether WRPs were a major source of pollution or a pollutant depended on WRPs for dilution in the river. WRP flow reduction scenarios did not greatly impact load or concentration-based TMDL compliance for copper, lead or zinc, despite an increase in concentration in lead. TDS and TSS concentrations increased under WRP flow reduction scenarios, which could have negative environmental impacts on the aquatic life in the river.

The results from this study signify that water reuse could improve or degrade water quality in the LAR, depending on the pollutant and its pollution source. Regional water managers need to be aware of impacts to water quality when it comes to making decisions for water management, such as increasing water reuse. Low flow diversions and stormwater BMPs, discussed in the One Water LA Plan, will also impact water quality, so studies are needed to quantify their combined impact with water reuse. An ecological study should be conducted to quantify impacts of increasing TSS and TDS concentrations on aquatic habitat. Additional analyses could also be done to assess water reuse impacts on more pollutants, such as contaminants of emerging concern.

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APPENDIX A

ADDITIONAL FIGURES AND TABLES

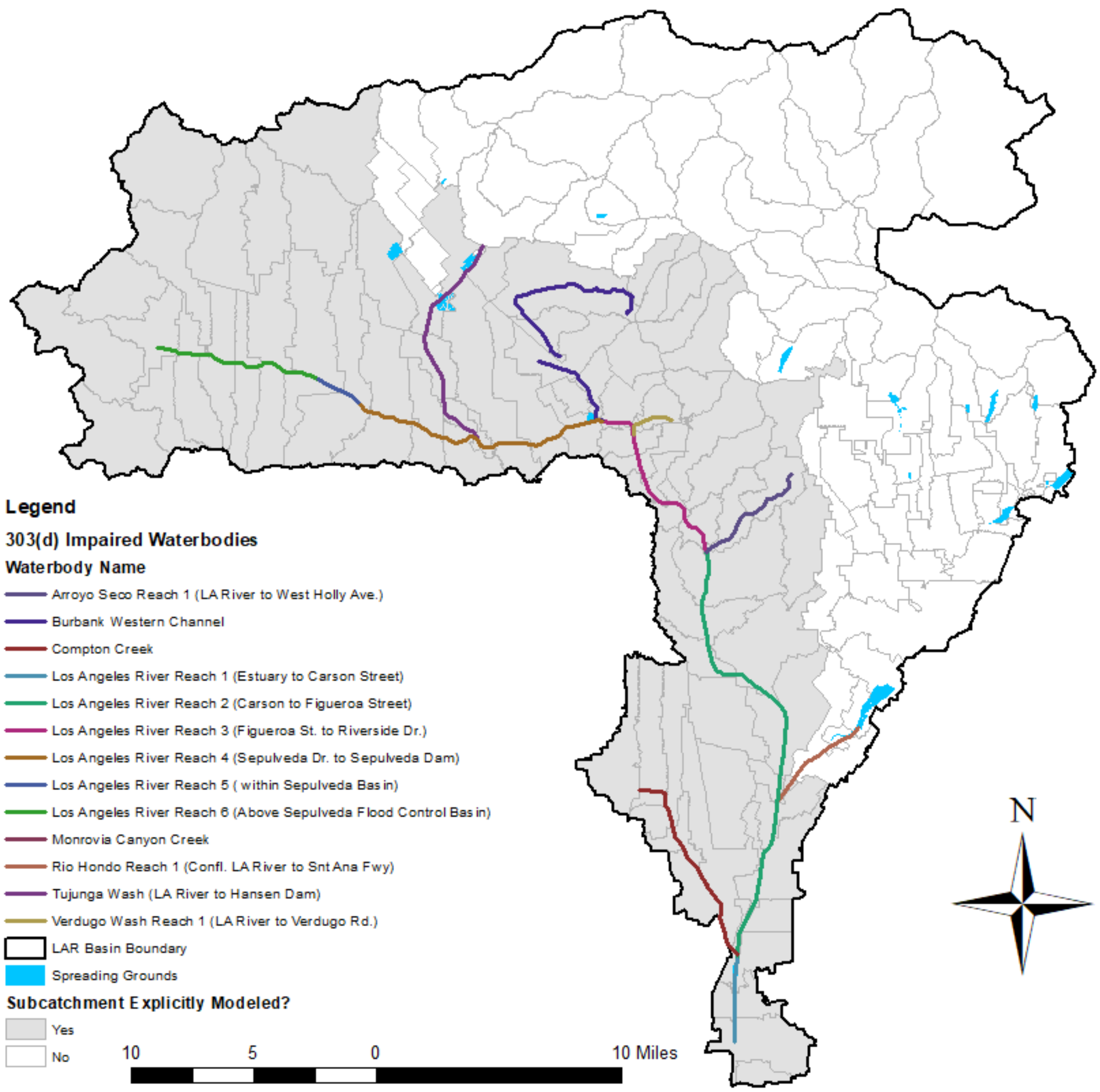

Figure A.1 Map of impaired waterbodies listed on the 303(d) List

Table A.1 Reach specific concentration-based TMDL for dry and weather (ug/L) [9]

		Copper	Lead	Zinc
Dry Weather	Burbank Channel	WER^3 x 19	WER^1 x 75	-
	Reach 4	WER^2 x 26	WER^1 x 83	-
	Reach 3	WER^2 x 26	WER^1 x 100	-
	Reach 2	WER^2 x 22	WER^1 x 94	-
	Reach 1	WER^2 x 23	WER^1 x 102	-
Wet Weather	-	WER^2 x 17	WER^1 x 94	WER^1 x 159
[1] Default WER of 1.0 [2] Approved WER of 3.97 [3] Approved WER of 4.75				

Table A.2 Reach specific load-based TMDL for dry and wet weather (kg/day) [9]

		Copper	Lead	Zinc	Critical Flow (cfs)
Dry Weather	Burbank Channel	WER^3 x 0.8	WER^1 x 3.2	-	17.3
	Reach 4	WER^2 x 8.1	WER^1 x 26	-	129.13
	Reach 3	WER^2 x 2.5	WER^1 x 9.6	-	39.14
	Reach 2	WER^2 x 0.24	WER^1 x 1.02	-	4.44
	Reach 1	WER^2 x 0.14	WER^1 x 0.64	-	2.58
Wet Weather[4]	-	WER^2 x 17	WER^1 x 94	WER^1 x 159	-
[1] Default WER of 1.0 [2] Approved WER of 3.97 [3] Approved WER of 4.75 [4] Multiply by daily storm volume (L) and daily concentration (ug/L) to get wet weather TMDL (kg/day)					

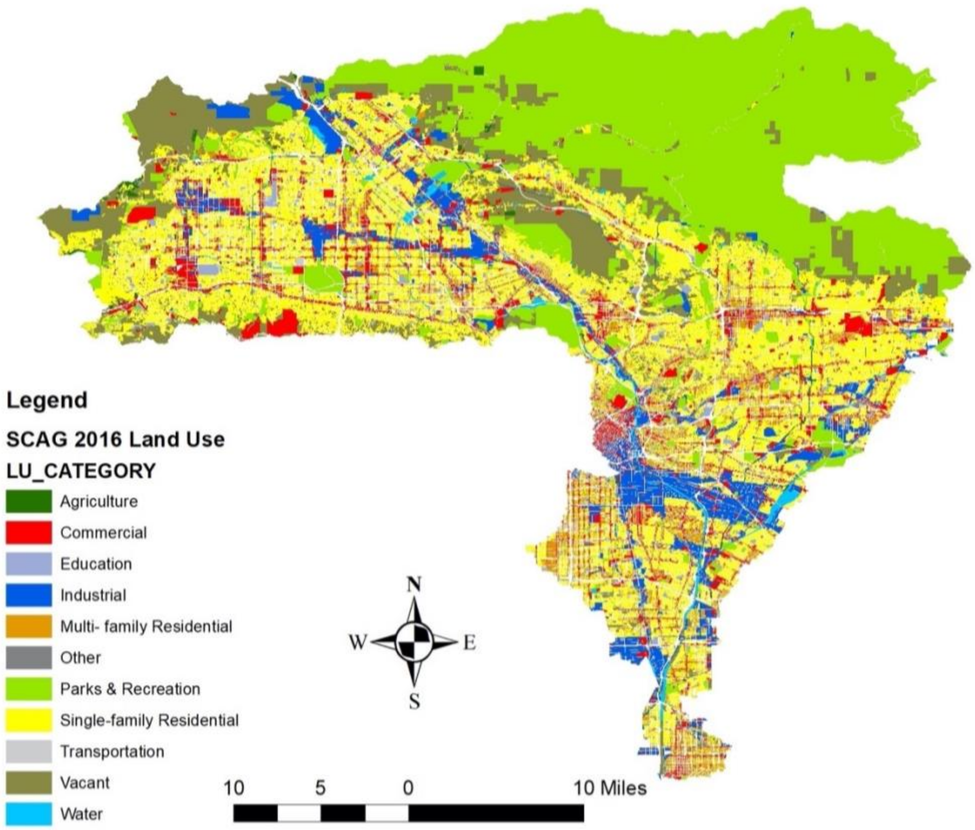

Figure A.2 Map of land use in LARB. SCAG = Southern California Association of Governments

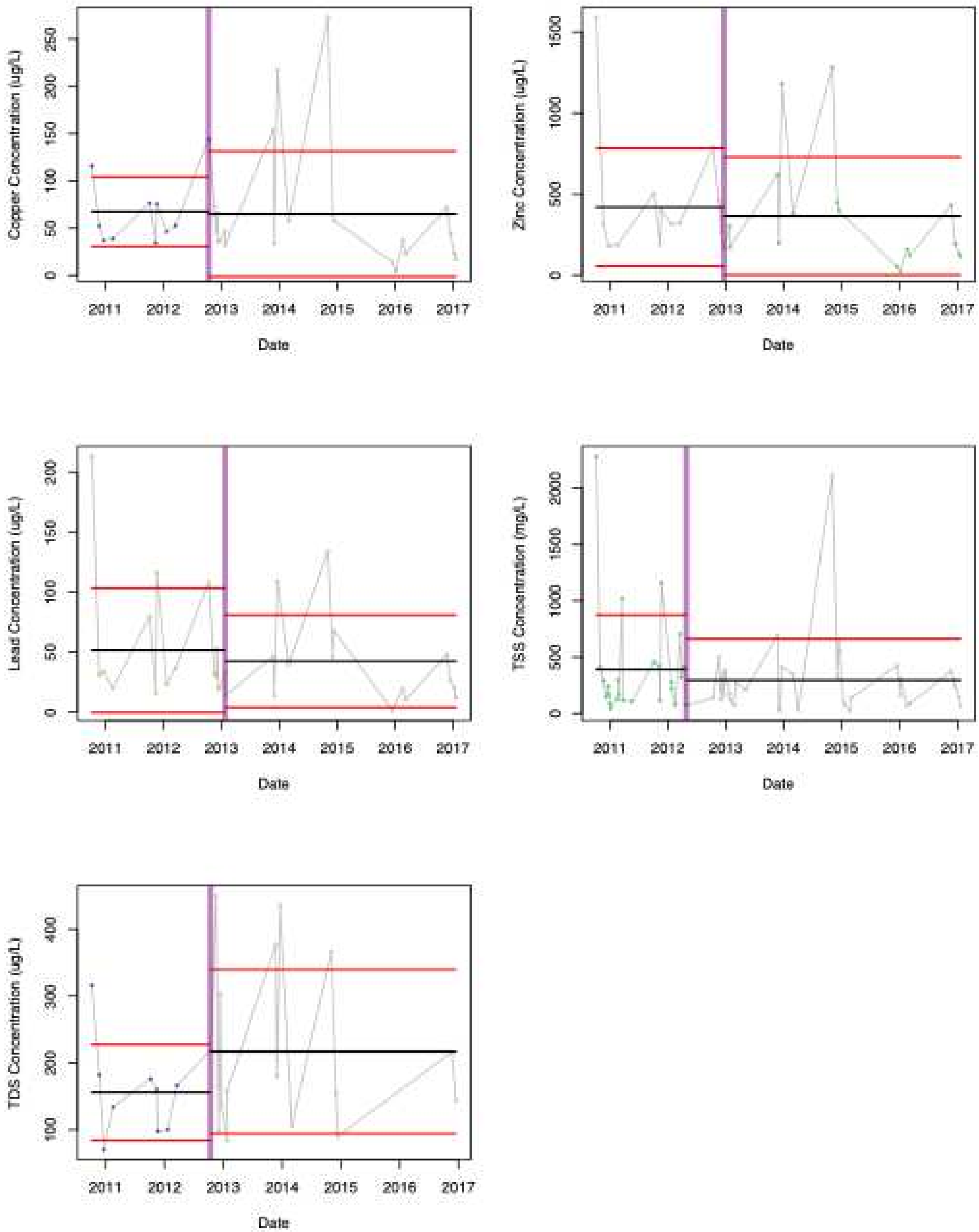

Figure A.3 Change point analysis for wet weather concentration at F319. Vertical purple lines represent the significant break line. Horizonal black lines represent the mean and red lines represent the standard deviation.

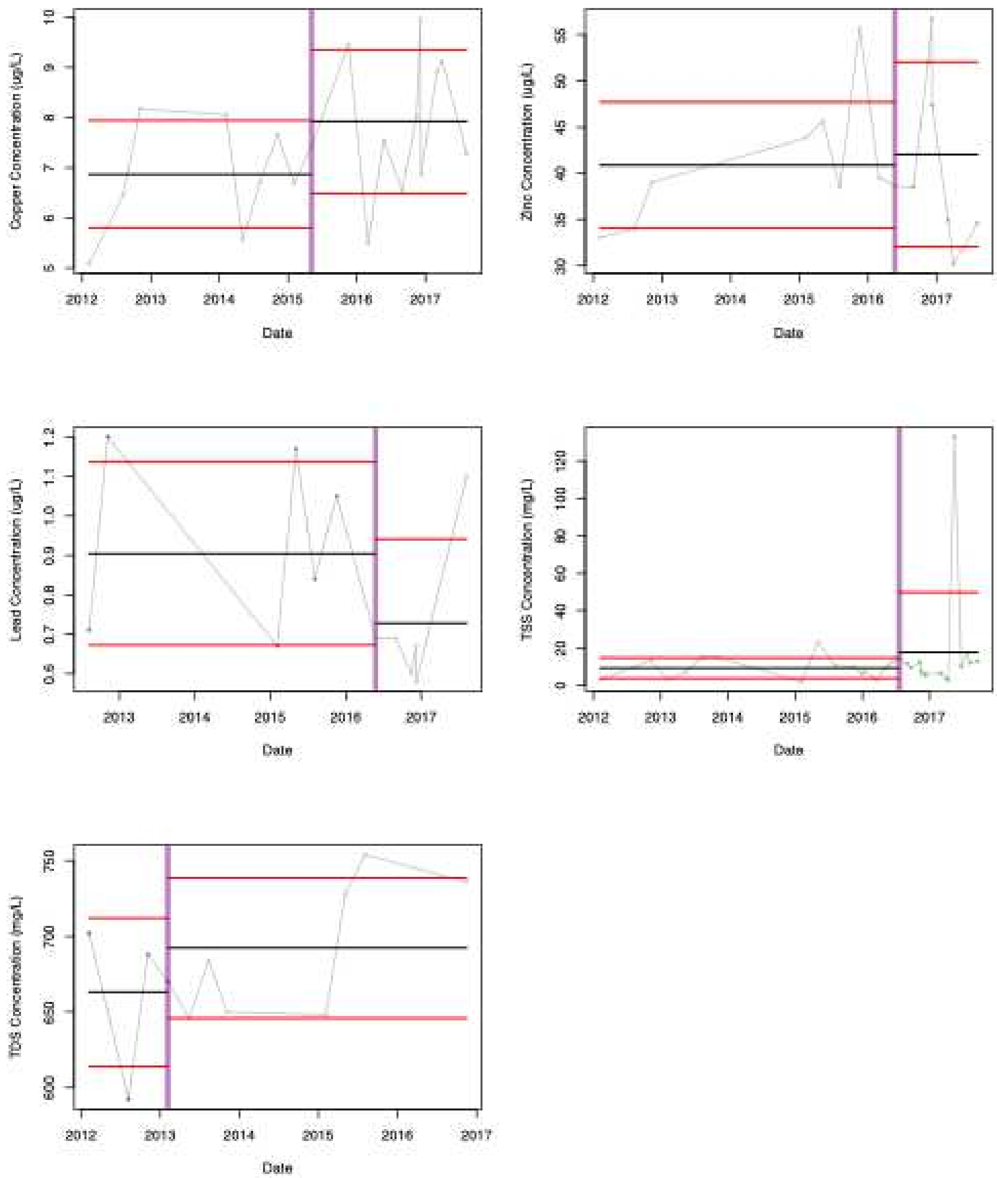

Figure A.4 Change point analysis for dry weather concentration at F57C. Vertical purple lines represent the significant break line. Horizonal black lines represent the mean and red lines represent the standard deviation.

Table A.3 Dry weather load calibration and validation statistics

Gauge	Location	Constituent	Percent Bias (%)	Observed Mean (kg)	Modeled Mean (kg)	Observed Median (kg)	Modeled Median (kg)	Observed Max (kg)	Modeled Max (kg)
Load - Dry Weather Calibration results									
11092450	Sepulveda	Copper	0.016	1.39	1.39	1.23	1.32	3.44	2.82
		Zinc	0.012	6.75	6.75	6.54	6.63	18.21	11.58
		Lead	1.79	0.093	0.094	0.075	0.099	0.233	0.165
		TSS	5.15	1.92E+03	2.02E+03	1.78E+03	1.60E+03	4.79E+03	7.21E+03
		TDS	0.94	9.75E+04	9.83E+04	9.38E+04	8.25E+04	1.68E+05	2.89E+05
F300	Tujunga Avenue	Copper	1.26	1.20	1.22	1.10	1.19	1.54	1.45
		Zinc	12.4	5.63	6.33	5.88	6.29	6.46	7.88
		Lead	0.506	0.089	0.089	0.073	0.085	0.145	0.136
		TSS	1.73	1.87E+03	1.90E+03	1.60E+03	1.81E+03	6.04E+03	6.88E+03
F57C	Glendale Narrows	Copper	14.3	1.65	1.89	1.61	1.81	2.50	3.36
		Zinc	6.11	9.21	9.79	8.92	9.33	12.5	14.9
		Lead	0.12	0.177	0.177	0.150	0.169	0.298	0.260
		TSS	9.83	2.47E+03	2.71E+03	1.79E+03	1.88E+03	2.08E+04	2.00E+04
		TDS	0.789	1.67E+05	1.68E+05	1.71E+05	1.58E+05	1.85E+05	2.45E+05
F319	Between Willow Street and Wardlow Road	Copper	0.982	3.50	3.54	3.10	3.60	7.04	4.46
		Zinc	2.23	16.9	17.3	11.0	17.5	34.2	19.6
		Lead	0.717	0.496	0.500	0.260	0.500	1.41	0.921
		TSS	3.07	1.34E+04	1.38E+04	8.38E+03	1.46E+04	4.42E+04	2.31E+04
		TDS	0.084	2.54E+05	2.54E+05	2.12E+05	2.53E+05	3.46E+05	3.40E+05
Dry Weather Validation results									
F319	Between Willow Street and Wardlow Road	Copper	3.37	3.65	3.78	3.31	3.54	7.25	4.79
		Zinc	-2.08	17.8	17.5	14.9	16.0	40.0	21.3
		Lead	-5.98	0.471	0.442	0.546	0.425	1.37	0.679
		TSS	-1.12	1.58E+04	1.56E+04	9.46E+03	1.41E+04	5.13E+04	3.11E+04
		TDS	2.10	9.79E+03	1.00E+04	9.83E+03	1.14E+04	1.33E+04	1.19E+04

Table A.4 Dry and wet weather concentration calibration and validation results

Gauge	Location	Constituent	Percent Bias (%)	Observed Mean (mg/L)	Modeled Mean (mg/L)	Observed Median (mg/L)	Modeled Median (mg/L)	Observed Max (mg/L)	Modeled Max (mg/L)
Concentration Dry & Wet Weather combined calibration results									
F300	Tujunga Avenue	Copper	-36.7	2.47E-02	1.56E-02	1.30E-02	1.14E-02	7.87E-02	2.74E-02
		Zinc	-31.8	1.14E-01	7.78E-02	5.43E-02	5.95E-02	3.18E-01	1.32E-01
		Lead	-38.7	7.44E-03	4.56E-03	4.56E-03	3.24E-03	2.51E-02	1.12E-02
		TSS	-22.05	70.8	55.2	13.5	16.7	416	257
F57C	Glendale Narrows	Copper	-8.04	1.21E-02	1.11E-02	7.85E-03	9.14E-03	4.81E-02	2.67E-02
		Zinc	-9.60	6.27E-02	5.66E-02	4.18E-02	4.93E-02	1.98E-01	1.12E-01
		Lead	-22.7	3.64E-03	2.81E-03	9.45E-04	1.09E-03	1.58E-02	1.13E-02
		TSS	-15.7	42.6	35.9	10.0	11.1	410	290
		TDS	5.109	678	712	682	711	754	854
F319	Between Willow Street and Wardlow Road	Copper	-36.5	0.300	0.190	0.188	0.231	1.590	0.407
		Zinc	-8.54	0.219	0.200	0.134	0.217	1.280	0.410
		Lead	15.9	0.027	0.031	0.020	0.035	0.134	0.074
		TSS	-17.6	270	223	163	278	2.28E+03	402
		TDS	17.4	400	470	436	434	882	858
Dry & Wet Weather validation results									
F319	Between Willow Street and Wardlow Road	Copper	-36.5	0.300	0.190	0.188	0.231	1.590	0.854
		Zinc	-8.54	0.219	0.200	0.134	0.217	1.280	0.407
		Lead	15.9	0.027	0.031	0.020	0.035	0.134	0.410
		TSS	-17.61	270	223	163	278	2280	74
		TDS	17.4	400	470	436	434	882	402

Table A.5 Dry weather concentration calibration and validation statistics

Gauge	Location	Constituent	Percent Bias (%)	Observed Mean (mg/L)	Modeled Mean (mg/L)	Observed Median (mg/L)	Modeled Median (mg/L)	Observed Max (mg/L)	Modeled Max (mg/L)
Concentration Dry Weather calibration results									
11092450	Sepulveda	Copper	7.84	9.90E-03	1.07E-02	9.48E-03	1.07E-02	1.31E-02	1.17E-02
		Zinc	8.64	4.83E-02	5.24E-02	4.64E-02	5.30E-02	6.60E-02	5.72E-02
		Lead	2.29	7.18E-04	7.35E-04	5.90E-04	7.87E-04	1.69E-03	1.10E-03
		TSS	1.97	14.6	14.9	12.9	13.5	49.0	43.9
		TDS	1.63	662	672.8	660	654	984	953
F300	Tujunga Avenue	Copper	3.51	1.01E-02	9.77E-03	9.59E-03	9.34E-03	1.30E-02	1.14E-02
		Zinc	5.84	4.81E-02	5.10E-02	5.05E-02	5.36E-02	5.43E-02	5.95E-02
		Lead	-10.6	7.83E-04	7.01E-04	6.50E-04	6.88E-04	1.29E-03	1.02E-03
		TSS	-6.37	15.2	14.2	12.3	14.0	47.0	39.4
F57C	Glendale Narrows	Copper	20.8	7.42E-03	8.96E-03	7.42E-03	8.91E-03	9.96E-03	9.93E-03
		Zinc	14.6	4.14E-02	4.74E-02	3.88E-02	4.85E-02	5.67E-02	5.54E-02
		Lead	10.6	8.31E-04	9.19E-04	7.00E-04	9.21E-04	1.20E-03	1.35E-03
		TSS	-12.2	13.1	11.5	9.60	9.75	133	52.7
		TDS	8.10	682	737	684	733	754	854
F319	Between Willow Street and Wardlow Road	Copper	8.05	1.01E-02	1.09E-02	1.04E-02	1.10E-02	1.39E-02	1.23E-02
		Zinc	6.26	4.89E-02	5.19E-02	3.50E-02	5.37E-02	1.03E-01	5.60E-02
		Lead	-0.01	1.46E-03	1.46E-03	9.25E-04	1.42E-03	4.30E-03	2.32E-03
		TSS	8.09	36.9	39.8	22.5	41.6	136	59.9
		TDS	11.2	648	721	594	711	882	858
Dry Weather Validation results									
F319	Between Willow Street and Wardlow Road	Copper	6.1	1.27E-03	1.34E-03	1.03E-03	1.36E-03	4.12E-03	1.60E-03
		Zinc	17.58	4.44E-02	5.22E-02	4.04E-02	5.32E-02	1.04E-01	5.53E-02
		Lead	6.1	1.27E-03	1.34E-03	1.03E-03	1.36E-03	4.12E-03	1.60E-03
		TSS	-17.3	51.3	42.4	23.0	45.3	186	65
		TDS	13.2	646	732	606	727	882	791

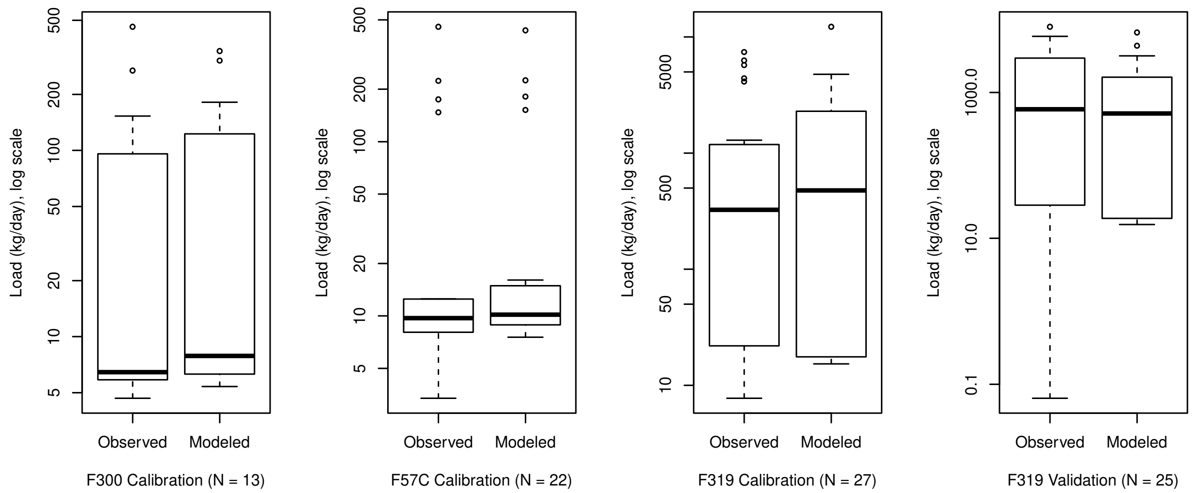

Figure A.5 Zinc calibration/validation for dry and wet weather, comparing observed daily loads vs. modeled daily loads in dry and wet weather

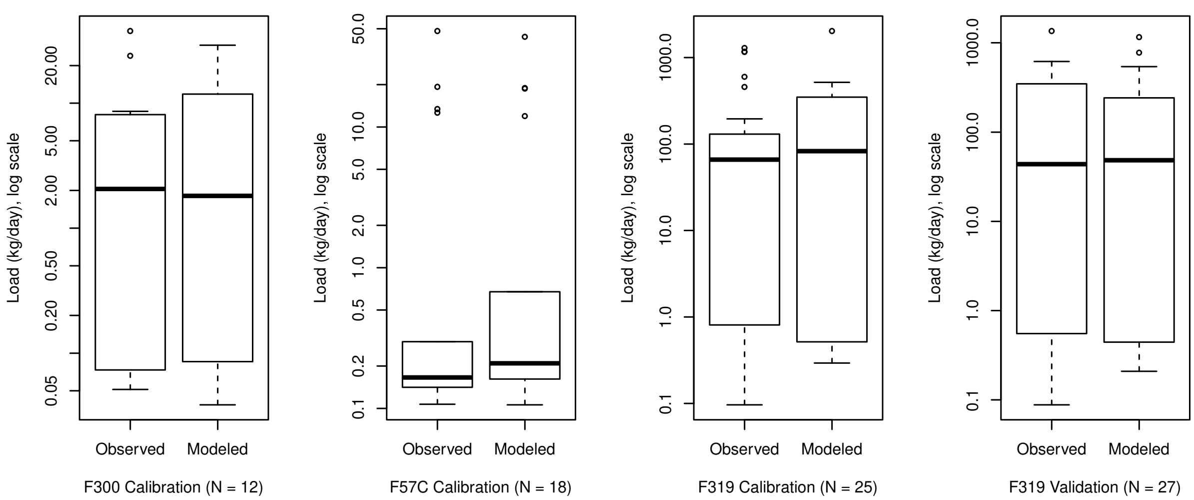

Figure A.6 Lead calibration/validation for dry and wet weather, comparing observed daily loads vs. modeled daily loads in dry and wet weather

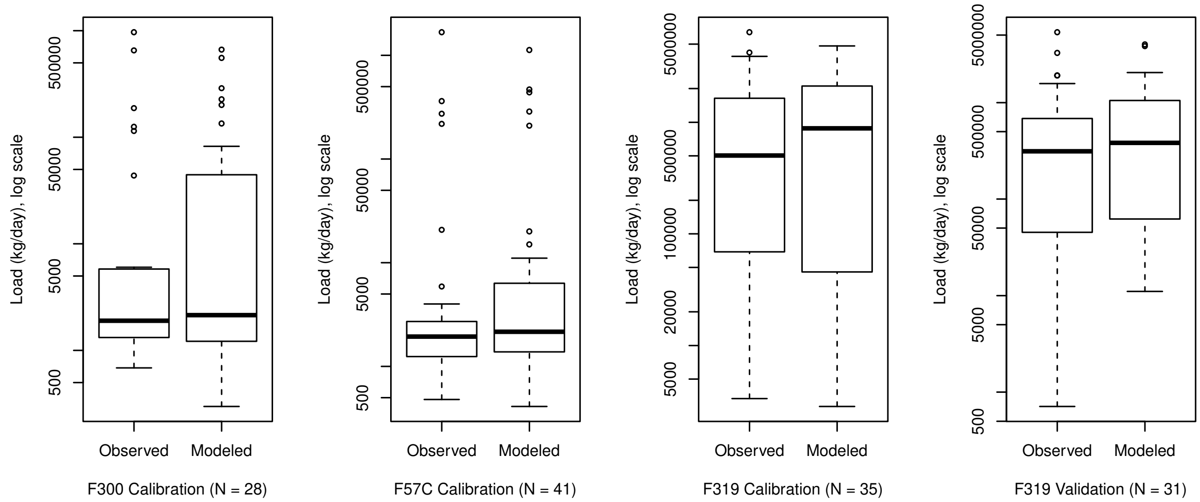

Figure A.7 TSS calibration/validation for dry and wet weather, comparing observed daily loads vs. modeled daily loads in dry and wet weather

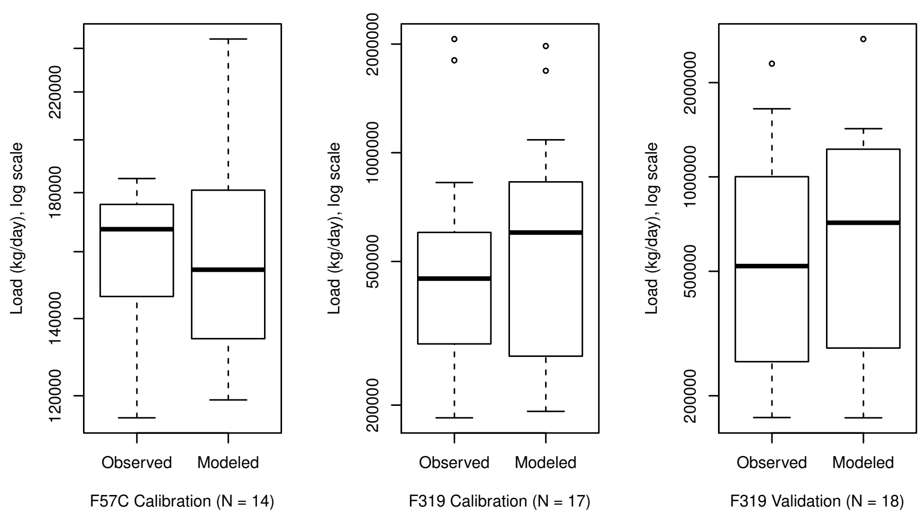

Figure A.8 TDS calibration/validation for dry and wet weather, comparing observed daily loads vs. modeled daily loads in dry and wet weather

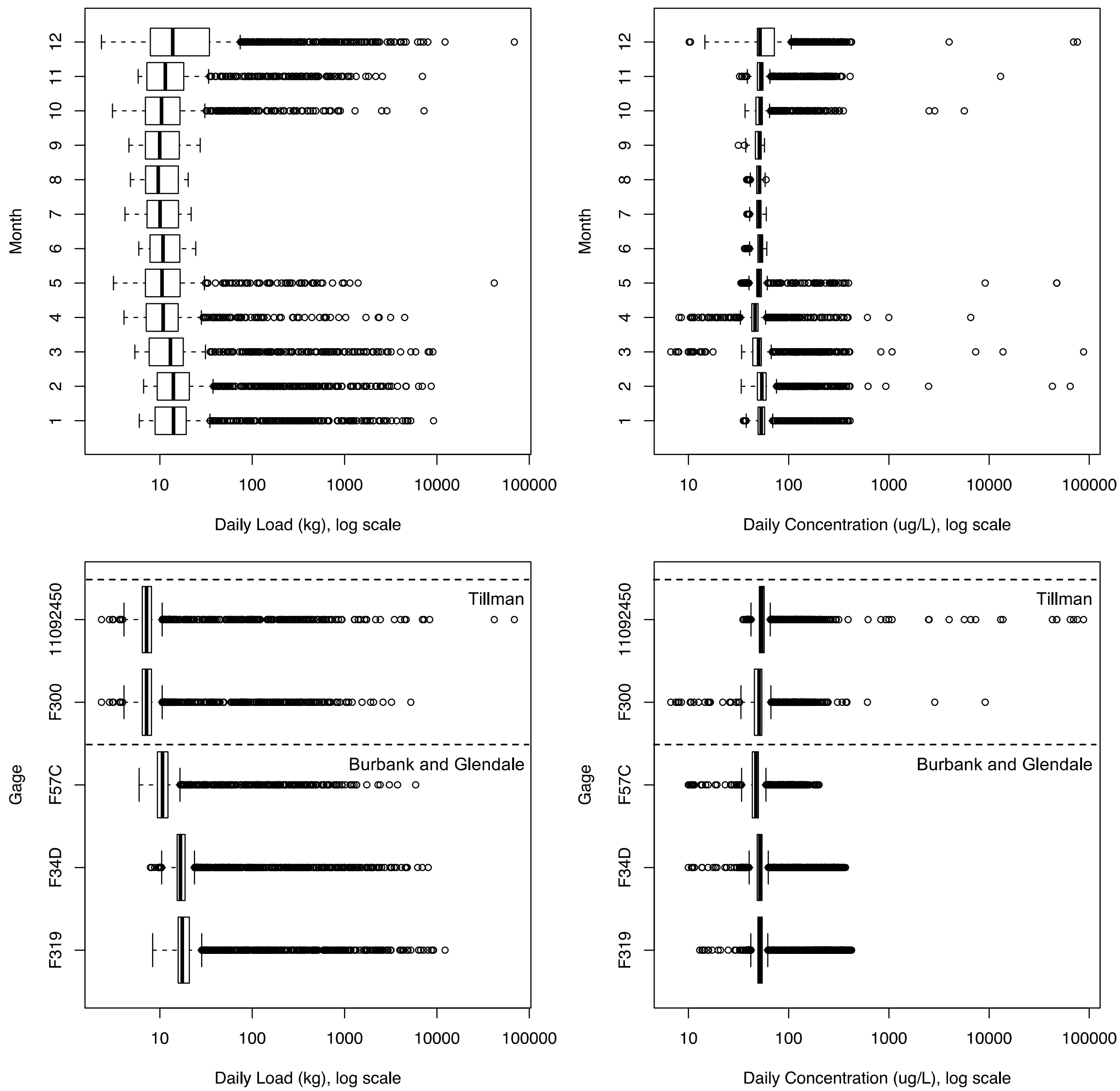

Figure A.9 Zinc with modeled baseline conditions for load (left) and concentration (right) grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Y-axis on gauge plots correspond to relative position in the LAR (upstream to downstream).

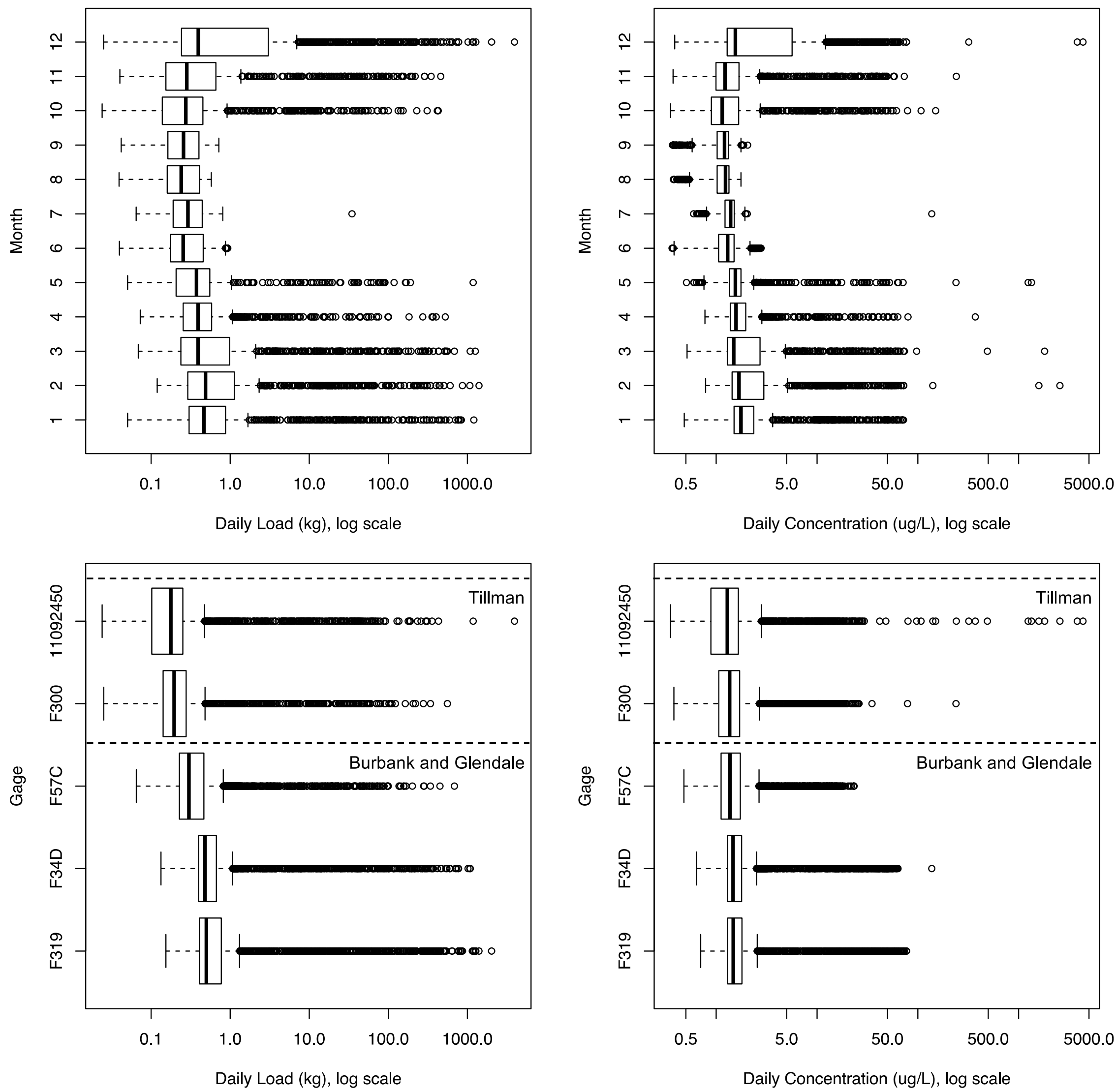

Figure A.10 Lead with modeled baseline conditions for load (left) and concentration (right) grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Y-axis on gauge plots correspond to relative position in the LAR (upstream to downstream).

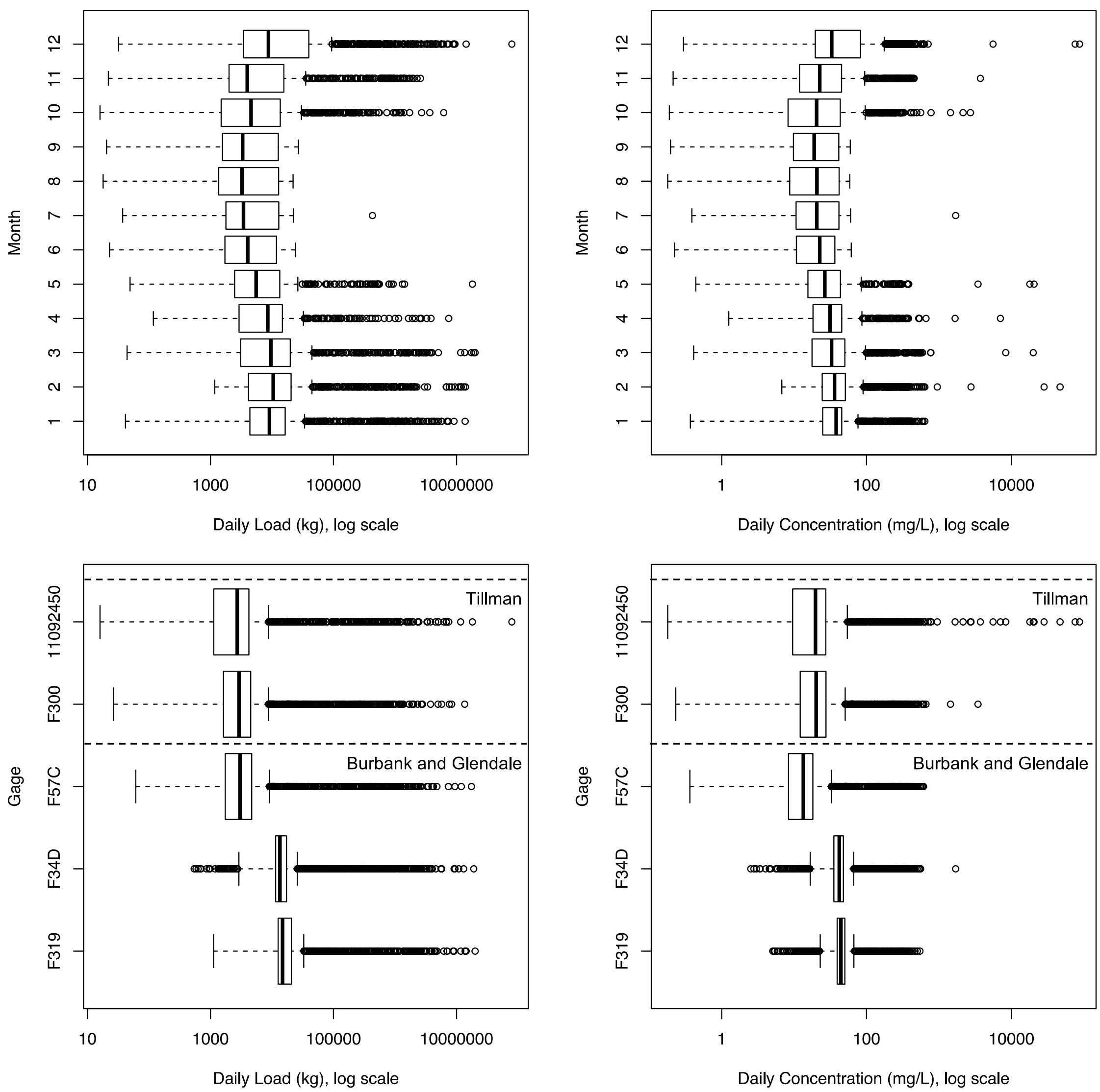

Figure A.11 TSS with modeled baseline conditions for load (left) and concentration (right) grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Y-axis on gauge plots correspond to relative position in the LAR (upstream to downstream).

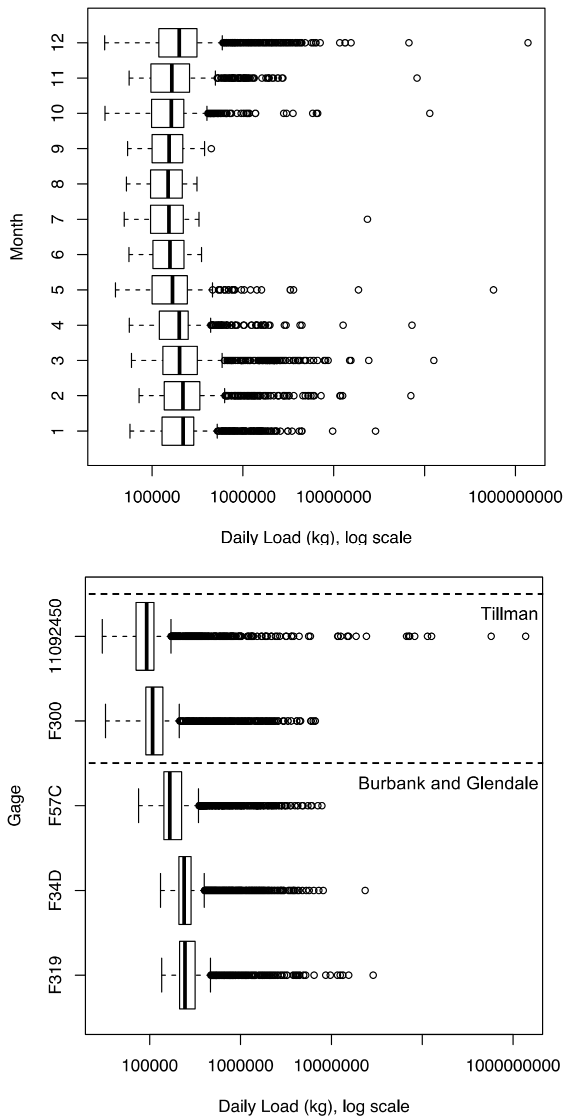

Figure A.12 TDS with modeled baseline conditions for load (left) and concentration (right) grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Y-axis on gauge plots correspond to relative position in the LAR (upstream to downstream).

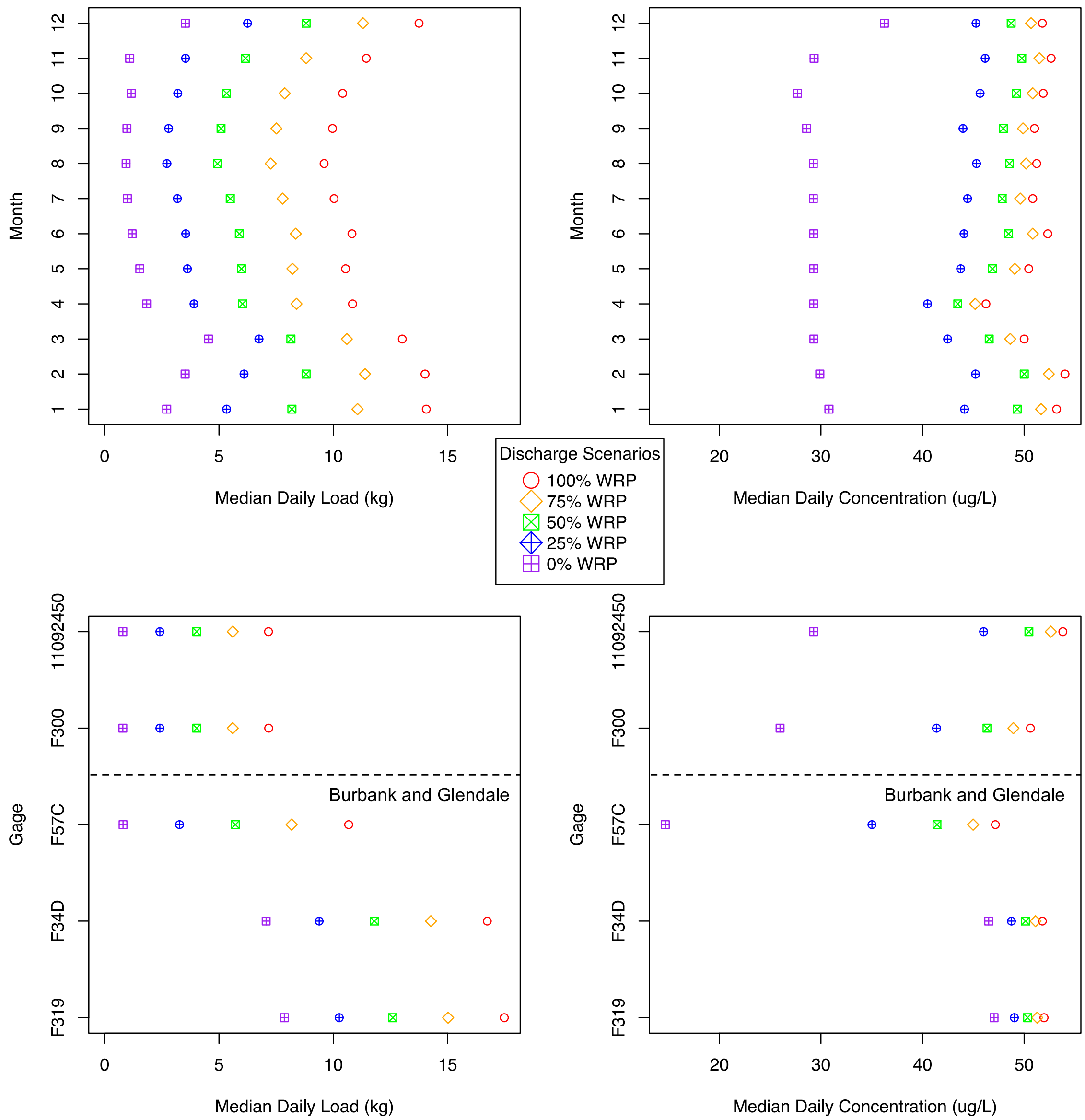

Figure A.13 Zinc median daily loads (left) and concentrations (right) for each water reuse scenarios, grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Tillman WRP is located above gauge 11092450. Y-axis correspond to relative position in the LAR (upstream to downstream). 100% WRP discharge scenario = 0% reuse, represented by a red circle and 0% WRP discharge scenario = 100% reuse, represented by a purple square.

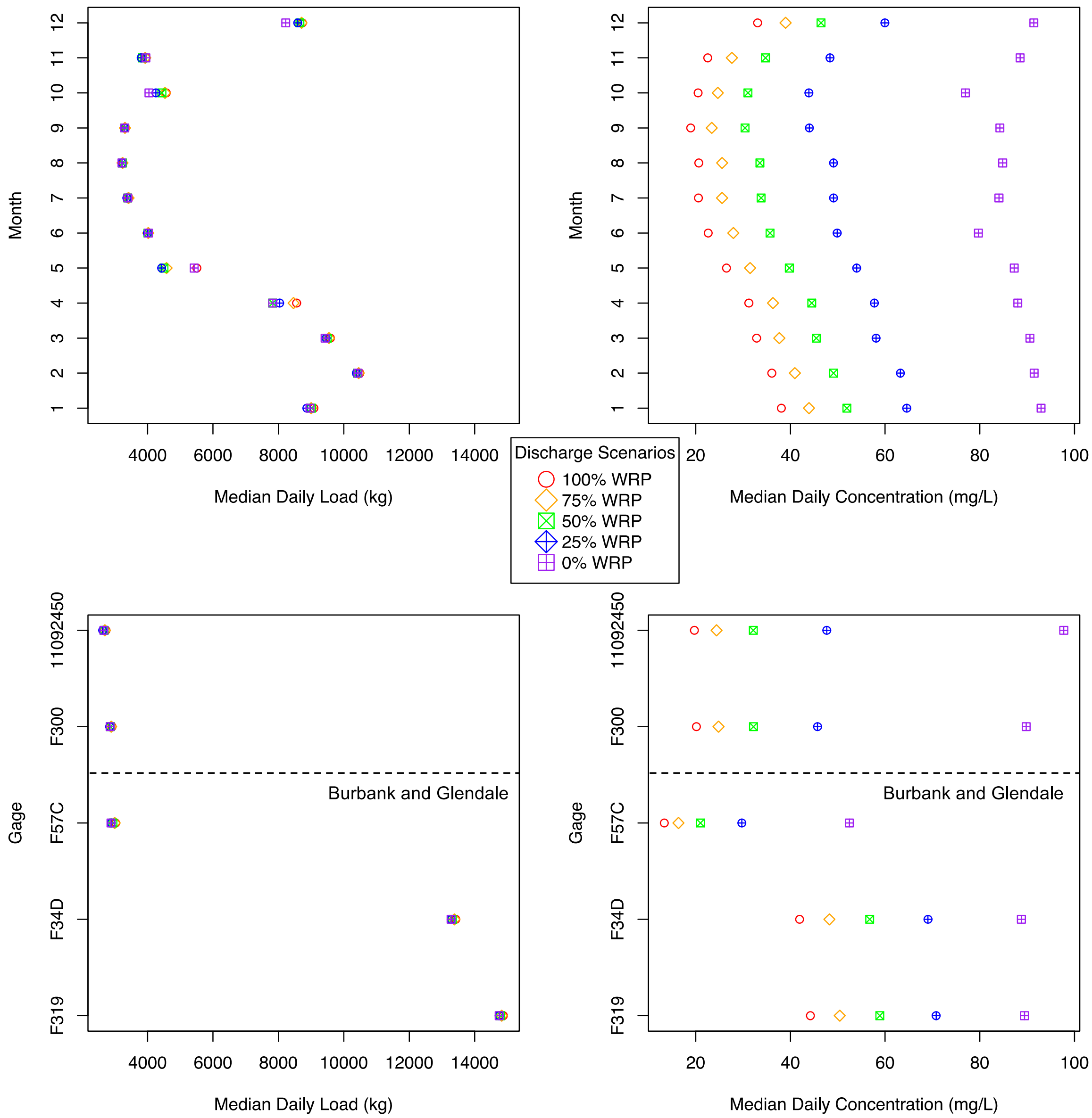

Figure A.14 TSS median daily loads (left) and concentrations (right) for each water reuse scenarios, grouped by month and gauge. Horizontal dotted line represents wastewater reclamation plant discharge input. Tillman WRP is located above gauge 11092450. Y-axis correspond to relative position in the LAR (upstream to downstream). 100% WRP discharge scenario = 0% reuse, represented by a red circle and 0% WRP discharge scenario = 100% reuse, represented by a purple square.

Table A.6 Concentration-based TMDL exceedances/yr and percent compliance for each scenario in each impaired reach impacted by WRP discharge. WW = wet weather and DW = dry weather.

Impaired Reach	Scenarios	DW days/yr	DW Numeric Target exceedances/year (Numeric Target Compliance[%])					WW days/yr	WW Numeric Target exceedances/year (Numeric Target Compliance[%])					
			Copper		Lead		Zinc		Copper		Lead		Zinc	
Burbank Western Channel	Baseline (WRP 100%)	331	0	(100%)	0	(100%)								
	WRP 75%	331	0	(100%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 4	Baseline (WRP 100%)	331	1	(99.7%)	1	(99.7%)								
	WRP 75%	331	1	(99.7%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 3	Baseline (WRP 100%)	331	0	(100%)	0	(100%)								
	WRP 75%	331	0	(100%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 2	Baseline (WRP 100%)	331	0	(100%)	0	(100%)								
	WRP 75%	331	0	(100%)	0	(100%)								
	WRP 50%	332	0	(100%)	0	(100%)	-	-	-		-		-	
	WRP 25%	332	0	(100%)	0	(100%)								
	WRP 0%	332	0	(100%)	0	(100%)								
Reach 1	Baseline (WRP 100%)	331	0	(100%)	0	(100%)		34	0	(100%)	0	(100%)	22	(35%)
	WRP 75%	331	0	(100%)	0	(100%)		34	2	(94%)	0	(100%)	23	(32%)
	WRP 50%	332	0	(100%)	0	(100%)	-	33	2	(94%)	0	(100%)	23	(30%)
	WRP 25%	332	0	(100%)	0	(100%)		33	3	(91%)	0	(100%)	23	(30%)
	WRP 0%	332	0	(100%)	0	(100%)		33	4	(88%)	0	(100%)	23	(30%)