SHELTER ISLAND YACHT BASIN
TOTAL MAXIMUM DAILY LOAD (TMDL) CONCEPTUAL MODEL REVIEW

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EXECUTIVE SUMMARY

This Total Maximum Daily Load (TMDL) Conceptual Model Review technical document presents findings to support updates to the Shelter Island Yacht Basin (SIYB) copper TMDL conceptual model. The TMDL Conceptual Model Review includes a comparative analysis of the 2005 TMDL Instantaneous Model and best available science life cycle conceptual model (Earley et al., 2013) for copper loading contribution calculations from copper antifouling paint leaching and in-water hull cleaning activities. Key findings suggest adaptive management measures to vessel hull cleaning frequency and adjustments to implementation practices may lead to copper load reductions and water quality improvements to meet SIYB TMDL requirements.

Vessel hulls are commonly coated with copper antifouling paints that release copper and inhibit growth of fouling organisms. Periodic hull cleaning occurs throughout a paint's life cycle to maintain smooth bottom surface. Environmental loading associated with continuous dissolution of copper antifouling paint and periodic cleaning activities result in copper levels that exceed water quality regulatory criteria in SIYB. Shelter Island Yacht Basin is subject to TMDL regulatory compliance requirements to reduce copper loading by 76% from the estimated 2005 loading level by the year 2022.

The TMDL conceptual model identified that passive leaching of copper antifouling paints account for up to 93% (2,000 kilograms/year [kg/yr]) of annual copper loading to SIYB (Regional Water Quality Control Board [Regional Board], 2005). An additional 5% (100 kg/yr) of annual copper loading was attributed to periodic hull cleaning events in the 2005 TMDL conceptual model. The TMDL conceptual model utilizes assumptions of instantaneous and static copper release closely correlated in time with hull cleaning events (hereafter, '2005 TMDL Instantaneous Model').

More recent technical analyses (Earley et al., 2013) suggest copper release rates following periodic hull cleaning events may provide greater than a 5% relative contribution to annual loading over an estimated three-year paint life cycle (hereafter, 'Life Cycle Dynamic Model'). Applicable *in situ* measurements indicate a volatile timeframe of increased and dynamic copper release in the 30 days following hull cleaning events. Data indicate an active phase of copper loading and toxicity following hull cleaning events due to increased release of bioavailable free copper ions. The Life Cycle Dynamic Model accounts for copper volatility spikes in the days following hull cleaning events that gradually decline to a steady state because of biofilm development and other processes.

Recent changes to the California Code of Regulations by the Department of Pesticide Regulation (DPR) establish a maximum allowable copper leach rate for copper antifouling paint products registered in California for use on recreational vessels (DPR Rule). Implementation of the DPR Rule includes registration and sales restrictions for paints that exceed the maximum allowable copper leach rate. Additional DPR copper mitigation strategies include in-water hull cleaning best management practices and frequency

limitations, product label updates, improved information for boater and boatyard awareness, and incentive programs for vessel hull paint conversion.

Key findings from this TMDL Conceptual Model Review technical document include:

- Comparative analysis of the 2005 TMDL Instantaneous Model and the Life Cycle Dynamic Model finds that the total and per-vessel loads are consistent between the models. In addition, when running the models using the 2018 SIYB TMDL Annual Report's vessel tracking data, the predicted annual copper load shows a less than 8% variation between the 2005 TMDL Instantaneous Model (1,152 kg/yr) and Life Cycle Dynamic Model (1,241 kg/yr) approach.
- The Life Cycle Dynamic Model suggests hull cleaning activities contribute greater than 5% of the annual copper loads to SIYB. Increased volatility and dynamic copper release for 30-day periods following hulling cleaning activity can vary the contribution of hull cleaning-related loading from 5% to more than 40% of annual copper load per vessel. A number of complex environmental processes may influence the copper dissolution rate, bioavailability, and toxicity of copper-based antifouling paint in the marine environment. This Life Cycle Dynamic Model best captures these processes, while concurrently providing the best representation of the boating practices and real-time use conditions observed in SIYB and other marina basins.
- Current loading estimates using recent SIYB vessel information suggest the final TMDL numeric copper loading target of 567 kg/yr may not be met by 2022 without modifications to vessel cleaning frequency.
- Low hull-cleaning frequency (twice per year or less) and implementation of the DPR Rule may reduce SIYB annual copper loading to below the final TMDL target. Given the increased loading attributed to hull cleaning as projected in the Life Cycle Dynamic Model, it is likely that water quality improvement will be observed with adjustments to hull cleaning frequencies.
- Additional feasibility analysis is needed to determine the operational viability of in-water hull cleaning frequency reduction strategies and other adaptive management measures.
- Ongoing water quality monitoring in SIYB is necessary to verify effectiveness of any hull cleaning frequency reduction measures and progress towards final TMDL numeric goals.

This TMDL Conceptual Model Review confirms that copper loading is associated with a continuous dissolution of copper antifouling paint and periodic cleaning activities to refresh the paint surface. This finding demonstrates that the recent Life Cycle Dynamic Model and the robust data analyses set forth within that model, provide total load calculations that are consistent with the TMDL and best represent real-time use conditions occurring in marina basins. As such, it stands to reason that the Life Cycle Dynamic Model developed by Earley et al. (2013) is appropriate and should be viewed as a scientifically credible and acceptable approach to update the 2005 TMDL Instantaneous Model.

At this time, it is recommended that the SIYB TMDL Conceptual Model be updated to (1) incorporate the loading assumptions provided in Earley et al. (2013)'s Life Cycle Dynamic Model, and (2) use the Life Cycle Dynamic Model moving forward for annually calculating copper loads for TMDL compliance and reporting purposes.

1.0 Introduction

Shelter Island Yacht Basin (SIYB) waters contain dissolved copper concentrations that have exceeded the dissolved copper numeric water quality objective (WQO) as well as the toxicity and pesticides narrative WQOs. These water quality conditions may threaten and impair the wildlife habitat and marine habitat beneficial uses in the basin (San Diego Regional Water Quality Control Board [Regional Board], 2005). Because of this exceedance, SIYB was placed on the list of impaired water bodies compiled pursuant to federal Clean Water Act (CWA) Section 303(d). As part of the Total Maximum Daily Load (TMDL) process, a conceptual model was developed to assign loading estimates to various copper sources in SIYB and resolve this impairment by requiring loading of dissolved copper into SIYB waters to be reduced. As stated in the TMDL, to achieve compliance by 2022, the copper load must be reduced to an annual load of 567 kilograms per year (kg/yr).

Recreational marine vessels moored in harbors and marinas are subject to biofouling that includes attachment and growth of aquatic organisms. Vessel hulls are commonly coated with copper-based paints that act as a toxicant to release copper and inhibit growth of fouling organisms. Periodic hull cleaning occurs throughout the coating life cycle to maintain smooth bottom surface. Environmental loading associated with continuous dissolution of antifouling paint and periodic cleaning activities to refresh the paint surface result in copper levels that exceed water quality regulatory criteria in SIYB.

The TMDL conceptual model (hereafter referred to as the '2005 TMDL Instantaneous Model') identifies that copper antifouling paint sources contribute the majority of dissolved copper loading to SIYB (Table 1-1). The greatest source of loading is the passive leaching of copper antifouling paint applied to the vessels moored in SIYB, accounting for approximately 93% (2,000 kg/yr of copper) of total loading. The TMDL conceptual model identifies that the in-water hull cleaning of the copper antifouling paints accounts for approximately 5% (100 kg/yr of copper) of loading (Regional Board, 2005). Other sources[1] were found to be nominal in the TMDL Conceptual Model.

[1] As stated in the Regional Board Technical Report, dissolved copper loading from urban runoff is marginal compared with loading from the other anthropogenic sources, at approximately 1% (30 kg/year) of the total load. In addition, copper is found naturally in seawater, and background loading accounts for approximately 1% (30 kg/yr). Direct atmospheric deposition was also determined to be a relatively insignificant contributor of dissolved copper, accounting for less than 1% (3 kg/yr) of the total load. Lastly, sediment was found to act primarily as a sink, rather than a source, of dissolved copper under current loading conditions to SIYB. This finding is of concern because of the likelihood of long-term contamination of sediment by copper (Regional Board, 2005).

Table 1-1.
SIYB Dissolved Copper Sources (Regional Board, 2005)

Source	Estimated Mass Load to SIYB (kg/yr)	Contribution to SIYB (Percent Dissolved Copper)
Passive Leaching	2,000	93
Hull Cleaning	100	5
Urban Runoff	30	1
Background	30	1
Direct Atmospheric Deposition	3	<1
Sediment	0	0
Total	2,163	100

Regional Board, 2005
Notes: kg/yr = kilogram(s) per year; SIYB = Shelter Island Yacht Basin

In addition, it has been further demonstrated that in-water hull cleaning can lead to sediment impacts. Previous reports have identified that a large amount of particle loading of copper occurs during hull cleaning and these particles can be deposited on the bay floor, even when in-water hull cleaning follows standard best management practice (BMP) protocols (Wood, 2019b; AMEC Earth & Environmental, 2006). Other studies (e.g., 2013 Regional Harbor Monitoring Program) have shown that sediments in marinas have elevated levels of copper that exceed the guideline values for sediment quality and that benthic communities are impacted as well (Amec Foster Wheeler Environment & Infrastructure, Inc., 2016). Although the current SIYB TMDL is for water quality only, other similar TMDLs in California, primarily in Newport Beach and Marina Del Rey, include copper load reductions for both water and sediment. Therefore, management strategies related to in-water hull cleaning of copper antifouling paints may result in an improvement of both water and sediment quality and could also reduce the potential for further copper-related sediment cleanups.

Per Investigative Order R9-2011-0036, the conceptual model for the TMDL should be refined and updated as new data becomes available. Recent scientific findings indicate that the current loading assumptions for in-water hull cleaning and passive leaching may need to be re-evaluated. This Total Maximum Daily Load (TMDL) Conceptual Model Review technical document presents findings to support SIYB TMDL conceptual model updates, as detailed herein.

Recently, a study conducted by the Navy Space and Naval Warfare Systems (SPAWAR) evaluated leach rates resulting from both the act of in-water hull cleaning and its residual effects following the active cleaning of the hull (i.e. the life cycle of a paint). This study entitled, *"Life Cycle Contributions of Copper from Vessel Painting and Maintenance Activities"* (Earley et al., 2013) (henceforth referred to as the Life Cycle Dynamic Model) utilized *in situ* data collection methods and best available science to evaluate copper loading and potential environmental impacts associated with in-water hull cleaning. This study measured copper release rates following periodic hull cleaning events to better understand the relative contribution of passive leaching and in-water hull cleaning to annual loading over an estimated three-year paint life cycle. It serves as the best available science to date.

The purpose of this TMDL Conceptual Model Review is to reassess the 2005 TMDL Instantaneous Model to determine whether the SIYB TMDL copper targets may be achieved by reducing or eliminating in-water hull cleaning while considering updated hull cleaning load contributions based on more recent scientific findings.

This TMDL Conceptual Model Review includes a comparative analysis of the 2005 TMDL Instantaneous Model and best available science from the Life Cycle Dynamic Model (Earley et al., 2013) for copper loading contribution calculations from copper antifouling paint leaching and in-water hull cleaning activities. This technical evaluation summarizes relevant findings from SIYB-related in-water hull cleaning studies, conducts a cross-comparison of loading allocations, and uses this information to model various in-water hull cleaning scenarios. Key findings suggest adaptive management measures to vessel hull cleaning frequency and adjustments to implementation practices may lead to copper load reductions and water quality improvements to meet SIYB TMDL requirements.

2.0 Copper Load Contributions

This section summarizes the copper load contributions and load allocations that have been presented in two separate load allocation approaches, the 2005 TMDL Instantaneous Model based on the TMDL technical analysis (Regional Board, 2005) and the Life Cycle Dynamic Model based on the Earley et al. (2013) study. The TMDL technical analysis provided the basis for the current copper load assumptions that identify the load allocations for each source category (Table 1-1) and are used to calculate the annual SIYB TMDL copper load (Wood, 2019a) The Earley et al. (2013) study was conducted in support of Assembly Bill 425 to provide scientific information to support the California Department of Pesticide Regulation's (DPR) setting of a maximum dissolved copper leach rate for copper antifouling paints.

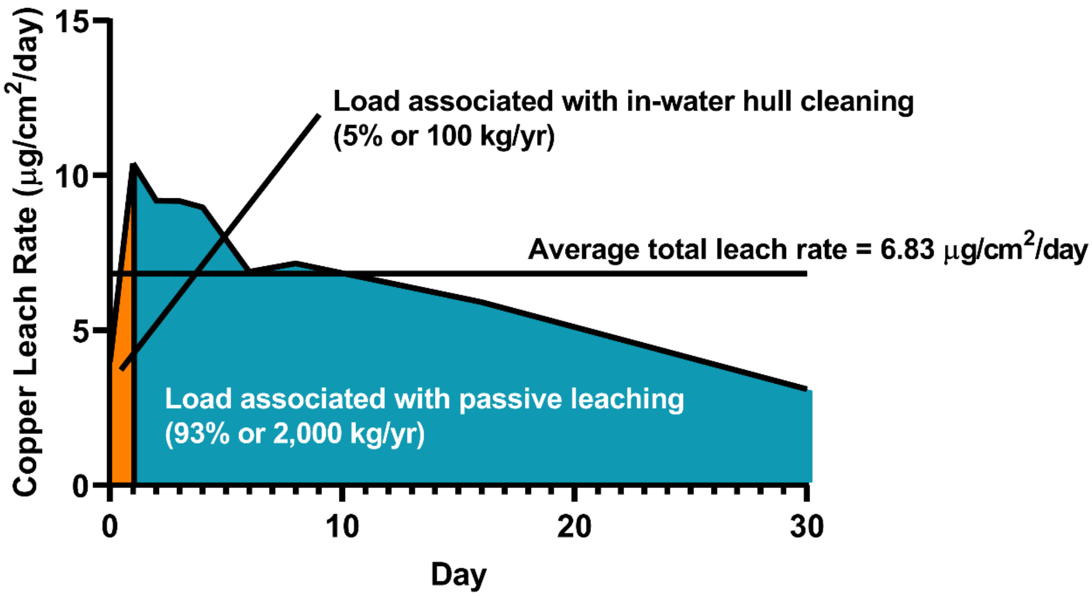
2.1 2005 TMDL Instantaneous Model (Regional Board, 2005)

The 2005 TMDL Instantaneous Model identifies a 2,163 kg/yr baseline load of dissolved copper to SIYB. A total of 98% of the load was attributable to (1) passive leaching of copper from copper antifouling paints on vessels, and (2) in-water hull-cleaning activities (Regional Board, 2005). Passive leaching was assumed to contribute 93% (2,000 kg/yr) in the 2005 TMDL Instantaneous Model, and hull cleaning events, considered static one day event(s) were assumed to contribute approximately 5% (100 kg/yr) of the total annual SIYB copper load (Figure 2-1). The average total leach rate was identified as 6.83 μg/cm^2/day (see Appendix A). Other sources, including urban runoff, background, and aerial deposition account for approximately 2% (63 kg/yr) of the total load and, as stated earlier, are not further examined as part of this comparative analysis.

2.1.1 Annual SIYB TMDL Monitoring and Report – Current Copper Load Calculation Methods

The SIYB TMDL annual copper load and load reduction efforts are currently assessed by tracking the number of vessel hulls painted with high-leach copper paint, lower copper paint (DPR Category I or low-copper), aged-copper paint, or non-copper paint, as well as vessel slip occupancy rates in SIYB. Several assumptions from the 2005 TMDL Instantaneous Model are particularly relevant to this annual load calculation: (1) the TMDL identified the number of vessels (or slips within SIYB) as 2,363; (2) vessel hull length is 12.2 meters, with a beam width of 3.4 meters; (3) 50% of all SIYB vessels are coated with epoxy copper-based paints and 50% are coated with copper-based vinyl paints; and (4) vessel hulls are cleaned using standard BMPs, i.e., 14 cleanings per year using BMP materials (Regional Board, 2005). Using this information, the TMDL identified an annual per-vessel copper load of 0.88 kg/yr, rounded to 0.9 kg/yr for high-leach copper paints.

Figure 2-1. Graphical Representation of 2005 TMDL Instantaneous Model



Note: Leach rate curve derived from Table 2 of Earley et al. (2013) (for epoxy paints using BMPs)

The TMDL also identified a transition to nontoxic and less-toxic hull paints as a potential management strategy to lower loading into the basin. The Port SIYB TMDL Implementation Plan (Weston Solutions, 2011) and the Regional Board in a letter dated July 26, 2013 (Regional Board, 2013) accepted that lower copper paints (those with less than 40% copper or low-leach copper paints, now referred to as DPR Category I paints) and aged paints (defined as paints applied to vessels without reapplication for a period of 3 years) would be given a loading calculation of half the amount of a full copper load (0.45 kg/yr) when calculating annual copper loading and assessing compliance with the TMDL.

The annual SIYB Dissolved Copper TMDL Monitoring and Progress Report includes an annual update of copper load in the basin using specific loading assumptions, as described above, and calculated based on the number of vessels reported, their occupancy rate, and the type of paint used on each vessel. Loading calculations from the 2018 report (Wood, 2019a) are provided in Table 2-1.

Table 2-1.
2018 SIYB Copper Load Using TMDL Assumptions

Vessel Hull Paint Category	Number per Category	Average Time Occupied	Copper Load per Vessel (kg/yr) [a, b]	Total Copper Load (kg/yr)
Copper or Unknown (Assumed Copper)	772	85.9%	0.9	597
DPR Category I (Low Leach)	672	93.3%	0.45	282
Low-Copper (Confirmed)	23	83.8%	0.45	8.67
Low-Copper (Unconfirmed)	12	94.0%	0.9	10.2
Aged-Copper Paint	541	90.3%	0.45	220
Non-Copper (Confirmed or Not Painted)	101	90.4%	0	0
Non-Copper (Unconfirmed)	8	91.1%	0.9	6.56
Vacant Slips (Yacht Clubs and Marinas) (Note: vacant slips are not included in the total vessel count below)	99	--	--	0
Port Fleet (Confirmed Non-Copper)	17	100%	0	0
Port Transient Dock (Assumed to be Copper)	28	61.8%	0.9	15.6
Port Weekend Anchorage (Copper or Unknown and Assumed to be Copper)	40	33.5%	0.9	12.1
Total Slips (All SIYB Vessels + Vacant Slips)	***2,313***	***--***	***--***	***1,152***

Notes:
% = percent; DPR = Department of Pesticide Regulation; kg/yr = kilogram(s) per year; SIYB = Shelter Island Yacht Basin
[a] Copper load per vessel is composed of the individual loads from passive leaching and hull cleaning used by the TMDL (2005).
[b] Wetted-hull surface area used was 35.3 m^2 (12.2-meter length and 3.4-meter beam width).

2.2 Life Cycle Dynamic Model (Earley et al., 2013)

The Life Cycle Dynamic Model is based on a study prepared for SPAWAR as part of the DPR copper paint re-evaluation that also analyzed contributions from in-water hull cleaning (Earley et al., 2013). The study evaluated the contributions of copper into the water from the painting and maintenance (i.e., in-water hull cleaning) that occur over an assumed 3-year paint life cycle.

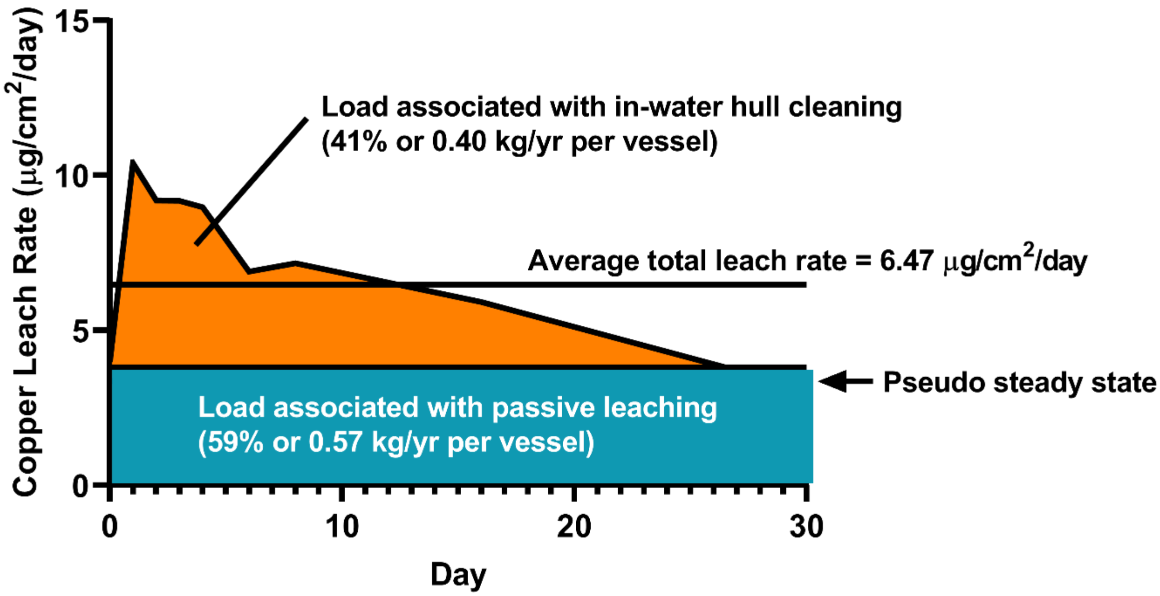
The study utilized *in situ* data collection methods to measure copper release following cleaning events. Study data indicated periods of volatile elevated copper release during the active phase of cleaning a vessel (i.e., instantaneous release) and in the two- to three day period following. Dynamic, elevated copper leach rates then slowly declined for a period of approximately 30 days post-cleaning or "surface refreshment". After approximately 30 days, the copper leach rate approaches a "pseudo steady state" (Figure 2-2). Earley at al. (2013) identified an average pseudo steady state leach rate of 3.36 micrograms per square centimeter per day ($\mu g/cm^2/day$) from day 30 continuing to the end of their assessment period (day 92). A critical difference between this study and the TMDL Technical Report was the foundational assumption that the loading resulting from a cleaning event is not entirely instantaneous, as suggested by the TMDL.

Without cleaning, the 3-year life cycle load is estimated to be 4,170 micrograms per square centimeter ($\mu g/cm^2$). With hull cleaning (according to the scenario[2] depicted in Figure 2-3), the Life Cycle Dynamic Model estimated the 3-year life cycle copper load per vessel[3] coated with high-leach copper paint is 7,084 $\mu g/cm^2$ over 1,095 days (or 6.47 $\mu g/cm^2/day$, see Appendix A), which equates to 0.97 kg/yr per vessel. In this Life Cycle Dynamic Model, approximately 0.40 kg/yr (41%) of the total annual copper load was associated with cleaning (including the cleaning event itself as well as the subsequent increase in post-cleaning leach rate), while approximately 0.57 kg/yr (59%) was attributed to passive loading. The Life Cycle Dynamic Model also identified the loading from the active cleaning event to be approximately 1% and 3% for BMP and non-BMP cleaning, respectively.

In addition to copper leach rate estimates, the Life Cycle Dynamic Model also addressed the potential for toxicity to be caused by increases in free copper ions associated with in-water hull cleaning activities. Earley et al. (2013) stated, "… in terms of the toxicity of copper as interpreted by the concentration of Cu^{2+}, cleaning appears to have more of an effect than initial paint exposure [IE], despite the lower dissolved copper release rates associated with cleaning vs IE." In addition, Earley et al. (2013) concluded, "The data show that copper released during CEs [cleaning events] can cause periodic toxicity that may persist until the free copper ion concentrations drop back down to ambient conditions."

[2] These scenarios include the initial exposure loading, 28- and 21-day life cycle loading and leach rate spikes as a result of cleaning activities (Earley et al., 2013).
[3] Assumes that the vessel hull (12.2-meter length and 4-meter beam width) is coated with copper-based epoxy paint and is cleaned using standard BMPs (i.e., 14 cleanings per year using soft-pile carpet).

Figure 2-2. Graphical Representation of Life Cycle Dynamic Model



Note: Leach rate curve derived from Table 2 of Earley et al. (2013) (for epoxy paints using BMPs)

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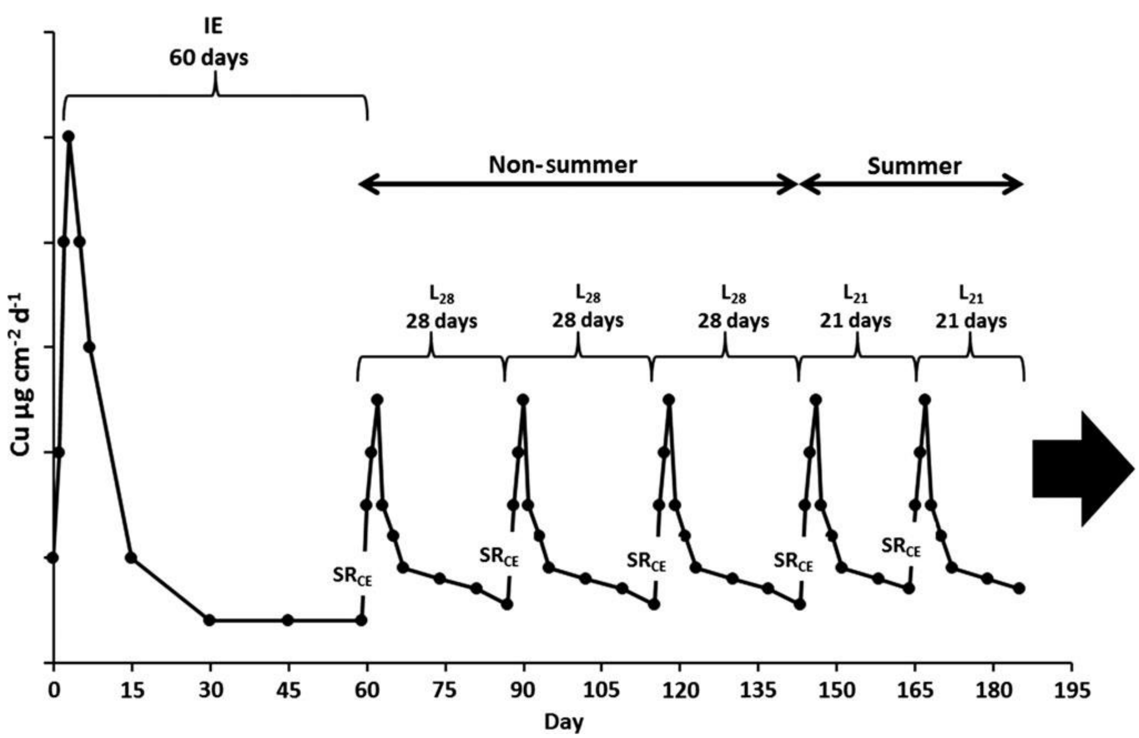
Figure 2-3. Earley et al. (2013) Leach Rates under Different Loading Scenarios (Initial Exposure [IE], 28 and 21-Day Life Cycle Loading)



Credit: Earley et al. (2013)

2.2.1 Projected 2018 SIYB TMDL Copper Load using Earley et al. (2013) Load Assumptions

For comparison purposes, this TMDL Conceptual Model Review evaluated the annual copper load derived from the Life Cycle Dynamic Model using the same process for calculating the SIYB TMDL copper loads annually. For this calculation, the Life Cycle Dynamic Model's per-vessel copper load of 0.97 kg/yr for high-leach copper paints was considered. Vessel data was taken from the 2018 report (Wood, 2019a). Loading calculations are provided in Table 2-2. The calculated total copper load using the Life Cycle Dynamic Model's assumptions is slightly higher (1,241 kg/yr) compared to the total copper load based on the TMDL Instantaneous Conceptual Model (1,152 kg/yr); however, this is to be expected given the difference between annual per-vessel copper loads (0.97 kg/yr for Earley et al. [2013] versus 0.9 kg/yr for the TMDL). Overall, the predicted total copper load shows a less than 8% variation between the two studies at 1,152 kg/yr (TMDL) and 1,241 kg/yr (Earley et al., 2013), respectively.

2.3 Comparisons between the TMDL Instantaneous Model and the Life Cycle Dynamic Model

The TMDL Instantaneous Model and the Life Cycle Dynamic Model both closely examine copper contributions from copper antifouling paints, namely from the cleaning and passive leaching phases of the paint. This TMDL Conceptual Model Review compares some of the foundational assumptions of these studies. Upon careful review, both the TMDL and Earley et al. (2013) analyses identify the actual load from the active cleaning to be relatively small (5% for the TMDL and 1% for the Earley et al. [2013] study[4]), and the total annual per-vessel load to be comparable (0.9 kg/yr and 0.97 kg/yr), respectively. In addition, both studies acknowledge the industry standard for cleaning to be 14 events per year (i.e., every 21 days during summer months and every 28 days during non-summer months). Appendix A presents a summary of leach rate and copper load calculations using information from the 2005 TMDL Instantaneous Model and the Life Cycle Dynamic Model.

Figures 2-1 and 2-2 present the loading projections described in the respective studies. Both figures similarly indicate the sharp increase in loading that occurs when a cleaning event occurs. Of greater importance, however, is ability of these figures to demonstrate the two models' different interpretations of the copper load attributed to in-water hull cleaning activities versus passive leaching. The 2005 TMDL Instantaneous Model identifies the cleaning-attributed load as an instantaneous event (Figure 2-1), while the Life Cycle Dynamic Model recognizes that cleaning is part of the entire life cycle; following the initial cleaning-associated load, a continuing increased load is experienced for a prolonged time period after each cleaning event (Figure 2-2).

[4] For cleaning events using BMPs on epoxy paints.

Table 2-2.
Projected 2018 SIYB Copper Load Using Earley et al., 2013 Assumptions

Vessel Hull Paint Category	Number per Category	Average Time Occupied	Copper Load per Vessel (kg/yr) [a, b]	Total Copper Load (kg/yr)
Copper or Unknown (Assumed Copper)	772	85.9%	0.97	643
DPR Category I (Low Leach)	672	93.3%	0.485	304
Low-Copper (Confirmed)	23	83.8%	0.485	9.35
Low-Copper (Unconfirmed)	12	94.0%	0.97	10.9
Aged-Copper Paint	541	90.3%	0.485	237
Non-Copper (Confirmed or Not Painted)	101	90.4%	0	0
Non-Copper (Unconfirmed)	8	91.1%	0.97	7.07
Vacant Slips (Yacht Clubs and Marinas) (Note: vacant slips are not included in the total vessel count below)	99	--	--	0
Port Fleet (Confirmed Non-Copper)	17	100%	0	0
Port Transient Dock (Assumed to be Copper)	28	61.8%	0.97	16.8
Port Weekend Anchorage (Copper or Unknown and Assumed to be Copper)	40	33.5%	0.97	13.0
Total Slips (All SIYB Vessels + Vacant Slips)	***2,313***	***--***	***--***	***1,241***

Notes:
% = percent; DPR = Department of Pesticide Regulation; kg/yr = kilogram(s) per year; SIYB = Shelter Island Yacht Basin
[a] Copper load per vessel is composed of the individual loads from passive leaching and hull cleaning used by Earley et al. (2013).
[b] Wetted-hull surface area used was 41.1 m^2 (12.2-meter length and 4-meter beam width).

Another key difference between the two models is the average beam width used to estimate the "wetted-hull surface area." The 2005 TMDL Instantaneous Model uses a beam width of 3.4 meters, while the Life Cycle Dynamic Model uses 4 meters. This factor is then applied to every vessel, resulting in annual per-vessel loads of 0.9 and 0.97 kg/yr, respectively. As such, the overall vessel size used in Life Cycle Dynamic Model will always yield a higher load per vessel due to the wider beam width used in the calculation. Because the "wetted-hull surface" area is such an integral component of the load calculation, this difference in wetted-hull surface area alone is enough to adjust the per-vessel load and address the variability between the two models.

Table 2-3 presents the total annual copper load into SIYB according to 1) the 2005 TMDL Instantaneous Model, and 2) the Life Cycle Dynamic Model using Earley et al. (2013)'s per vessel load value (0.97 kg/yr). A third column analyzes the TMDL per vessel load value (0.9 kg/yr) using the Life Cycle Dynamic Model's load assumptions. Each of these calculated loads assumes that vessels are cleaned according to the current industry-accepted cleaning frequencies (14 times per year; every 21 days during summer months and every 28 days during non-summer months) and that the number of vessels used is the same.

Table 2-3 shows that, while the interpretation of the copper load attributed to in-water hull cleaning and passive leaching varies greatly between the two models, the total annual copper loads attributable to vessels are similar. In addition, the third column highlights that when projecting the TMDL's overall copper load (0.9 kg/yr) into the Life Cycle Dynamic Model, the overall loading remains consistent, regardless of the model applied.

As discussed herein, copper loading is associated with a continuous dissolution of copper antifouling paint and periodic cleaning activities to refresh the paint surface. This repeated periodic hull cleaning occurs throughout the paint's life cycle to maintain a smooth bottom surface. The Life Cycle Dynamic Model accounts for the copper volatility spikes in the days immediately following hull cleaning events that gradually decline to a steady state because of biofilm development and other processes. This model realistically mimics the boating practices and conditions observed in SIYB and other marina basins.

This finding demonstrates that the recent Life Cycle Dynamic Model and the robust data analyses set forth within that model, provide total load calculations that are consistent with the TMDL and best represent real-time use conditions occurring in marina basins. As such, it stands to reason that the Life Cycle Dynamic Model developed by Earley et al. (2013) is appropriate and should be viewed as a scientifically credible and acceptable approach to update the 2005 TMDL Instantaneous Model.

Table 2-3. 2005 TMDL Instantaneous Model and Life Cycle Dynamic Model Comparisons of Passive and In-Water Hull Cleaning Copper Load Contributions to SIYB

Parameter/Calculation	Calculation	2005 TMDL Instantaneous Model	Life Cycle Dynamic Model (Earley et al., 2013)	Life Cycle Dynamic Model using TMDL TAL_v
Average wetted-hull surface area[a]	S	35.3 m^2	41.1 m^2	35.3 m^2
Number of vessels (using the 2018 SIYB TMDL Report Vessel Count)	N_v	2,214	2,214	2,214
Total annual per-vessel copper load	TAL_v = TAL / N_v = TL * S * 365 days/year / 10^9 µg/kg	0.9 kg/yr for high-leach copper paints 0.45 kg/yr for low-leach or low-copper paints	0.97 kg/yr for high-leach copper paints 0.485 kg/yr for low-leach or low-copper paints	0.9 kg/yr for high-leach copper paints 0.45 kg/yr for low-leach or low-copper paints
Annual passive load for all 2018 SIYB vessels	A_{PL} = (PL * S * N_v * 365 days/year) / 10^9 µg/kg	1,101 kg/yr	730.0 kg/yr	677.5 kg/yr
Annual IWHC load for all 2018 SIYB vessels	A_{IWHC} = (IWHC * S * N_v * 365 days/year) / 10^9 µg/kg	51.2 kg/yr	510.9 kg/yr	474.2 kg/yr
Total annual copper load for all 2018 SIYB vessels[b]	TAL = A_{PL} + A_{IWHC}	1,152 kg/yr	1,241 kg/yr	1,152 kg/yr

Notes:
[a]The average wetted-hull surface area during the 2018 monitoring year was 38.3 m^2. The TMDL uses an average wetted-hull surface area of 35.3 m^2, while Earley et al. (2013) uses 41.1 m^2.
[b]Includes average occupancy rate of approximately 88%.
A_{PL} = annual passive load; A_{IWHC} = annual in-water hull-cleaning load; IWHC = in-water hull cleaning leach rate; kg/yr = kilograms per year; m^2 = square meters; N_v = number of vessels; PL = passive leach rate; S = wetted-hull surface area; TAL = total annual copper load; TAL_v = total annual per-vessel copper load; TL = total average leach rate

3.0 Modeling Potential In-Water Hull Cleaning Scenarios

Because the Life Cycle Dynamic Model provides a realistic prediction of the anticipated loading from in-water hull cleaning over time, this process could be used to predict loading outcomes based on adjustments to cleaning frequencies and also to measure total loading for TMDL compliance purposes.

To evaluate how changes in the hull cleaning frequency may affect the copper load to SIYB, total annual copper loads were run through both model approaches and calculated for six different hull cleaning frequency scenarios, shown in Table 3-1.

Table 3-1. Hull Cleaning Frequency Scenarios

Cleaning Frequency	Number of Annual Cleanings Per Vessel
Current BMP cleaning frequency[1]	14
Monthly	12
Bimonthly	6
Quarterly	4
Semiannual	2
None	0

[1] Cleaning frequency identified in TMDL and Earley et al., (2013)

For this assessment, hull cleaning frequency scenarios were first run through the TMDL Instantaneous Model (i.e. static 93%:5% allocation for passive leaching and hull cleaning, respectively) to calculate annual loads associated with each cleaning frequency. Next, Equation 4 from the Life Cycle Dynamic Model was used to calculate the annual copper load for each hull cleaning frequency scenario. For the Life Cycle Dynamic Model, both the TMDL (0.9 kg/yr) and Earley et al. (2013) (0.97 kg/yr) total per-vessel load assumptions were evaluated for each hull cleaning frequency scenario.

Calculations were performed using, as a standard, the number of vessels and paint type distribution from the 2018 vessel tracking data provided in the 2018 SIYB TMDL Annual Report (Wood, 2019a). Further, it was assumed that each vessel was cleaned using standard BMPs (i.e., 14 cleanings per year using materials such as soft-pile carpet).

3.1 Copper Load Scenario Estimates using 2018 SIYB Vessel Data

The total annual copper load to SIYB was extrapolated for each hull cleaning frequency scenario using the per-vessel loads from each model and the 2018 vessel tracking and occupancy data[5] provided in the 2018 SIYB TMDL Annual Report (Wood, 2019a). These SIYB copper loading estimates are provided in Table 3-2 and depicted in Figure 3-1.

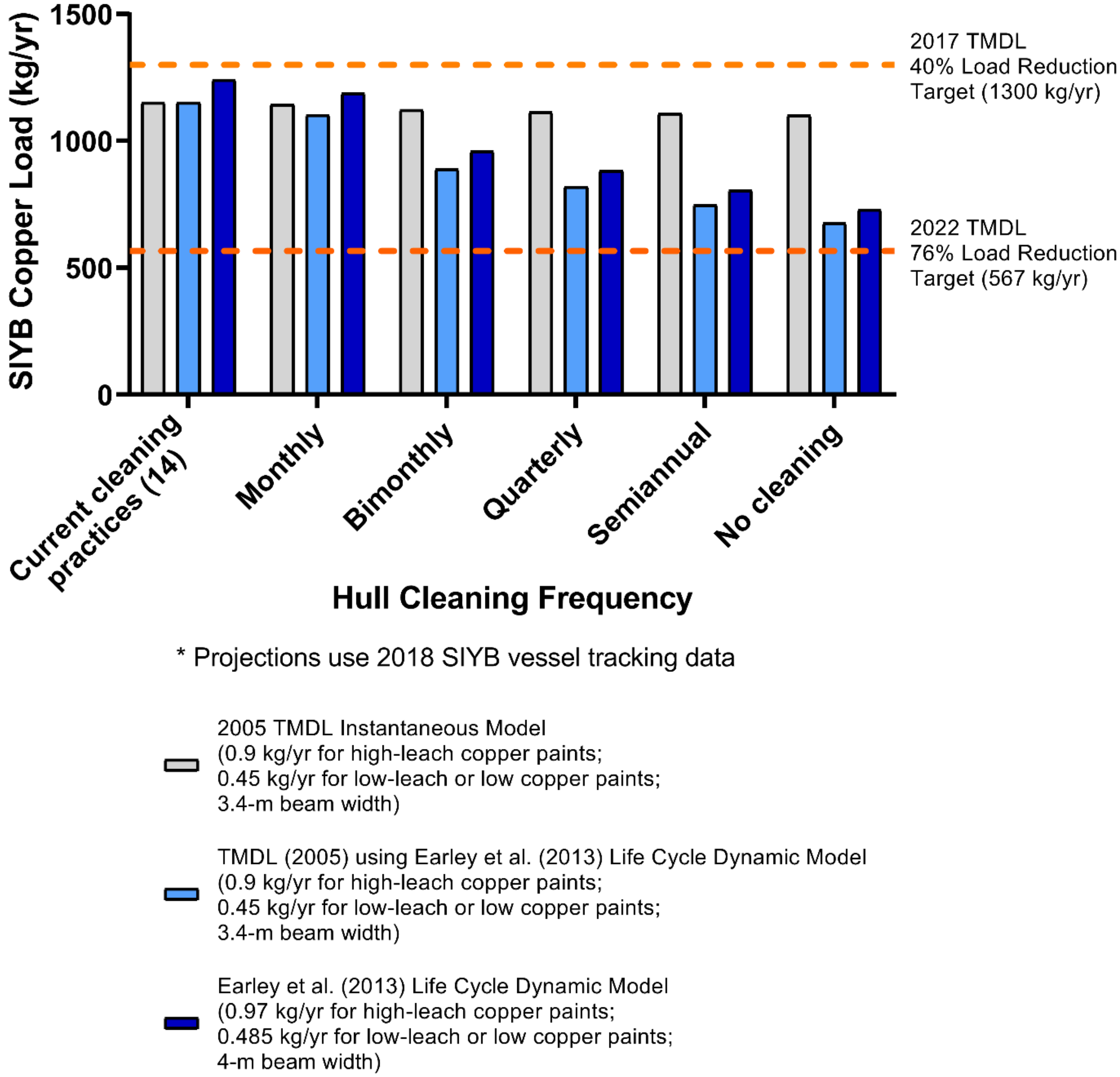
Table 3-2. Copper Loading Estimates for Various Hull Cleaning Frequencies Using the TMDL Instantaneous and Life Cycle Dynamic Models

Cleaning Frequency	Number of Annual Cleanings	2005 TMDL Instantaneous Model	Life Cycle Dynamic Model	
		TMDL Load of 0.9 kg/yr**	TMDL Load of 0.9 kg/yr**	Earley et al. (2013) Load of 0.97 kg/yr*
Current BMP cleaning frequency	14	1,152	1,152	1,241
Monthly	12	1,144	1,103	1,188
Bimonthly	6	1,122	890	959
Quarterly	4	1,115	819	883
Semiannual	2	1,108	748	806
None	0	1,100	677	730

Note:
*Uses an average wetted-hull surface of 41.1 m^2 (Earley et al., 2013).
** Uses an average wetted-hull surface of 35.3 m^2, as described in the TMDL (Regional Board, 2005).
The TMDL requires that copper loads be reduced to an annual load of 567 kilograms per year (kg/yr).
Bold values denote compliance with the TMDL load requirements.

[5] The 2018 SIYB TMDL Annual Report reported 2,214 vessels within SIYB and an average occupancy rate of 88%.

Figure 3-1. Copper Loading Estimates for Different Hull Cleaning Frequencies Using the 2005 TMDL Instantaneous and Life Cycle Dynamic Models*



3.2 Predicting Future Load Scenarios

On July 1, 2018, the DPR's adopted Section 6190 of Title 3, California Code of Regulations (DPR Rule) went into effect. This rule established a maximum allowable copper leach rate for copper-based antifouling paint products registered in California for use on recreational vessels. Assuming full realization of the DPR rule, all vessels in SIYB will be coated with low-leach copper paints (DPR Category I paints) or will have aged copper paint[6], both of which, for purposes of calculating copper loading, contribute a copper load equal to half the load of high-leach copper paints.

For the scenarios presented below, the total annual copper load to SIYB was extrapolated, assuming that all high-leach copper paints were phased out as a result of the fully-realized DPR Rule. As such, these calculations used the half-load copper allocation for each vessel that was accepted by the Regional Board (2013). Calculations were then performed using per-vessel half-loads from each study and the 2018 vessel tracking data (Wood, 2019a), following the same process as described in Section 3.1, above. Copper loading estimates for SIYB after full realization of the DPR Rule are provided in Table 3-3 and depicted in Figure 3-2.

The scenario modeling presented above quantifies (1) the annual copper load to SIYB using the 2005 TMDL Instantaneous Model and Life Cycle Dynamic Model, and (2) the load reduction that could be realized using various hull cleaning frequencies. As indicated in both Figures 3-1 and 3-2, reducing hull cleaning frequency using the Life Cycle Dynamic Model would provide a significant and more realistic copper load reduction compared to the TMDL's static assumptions. In particular, there appears to be a noted inflection point at which a greater reduction would occur with cleaning frequencies of every other month (bimonthly) or less often.

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[6] In the 2012 SIYB Monitoring and Progress Report, the Port recommended using a half-load calculation (0.45 kg/yr) for vessels with aged-copper paint for future loading calculations. This recommendation was based on numerous studies that show copper leaching rates are significantly diminished over the life cycle of hull paints. In a letter dated July 26, 2013, the Regional Board agreed with this concept, and stated, "To more accurately calculate the amount of copper loading to SIYB, allow the assumption that vessels with aged-copper AFPs have a copper release (i.e., leaching or loading) rate similar to low-copper AFPs (0.45 kg/yr) because the research (provided in Appendix E in the 2012 Shelter Island Yacht Basin TMDL Monitoring and Progress Report) indicates copper leach rates degrade over time, particularly after the first 2–3 years after application."

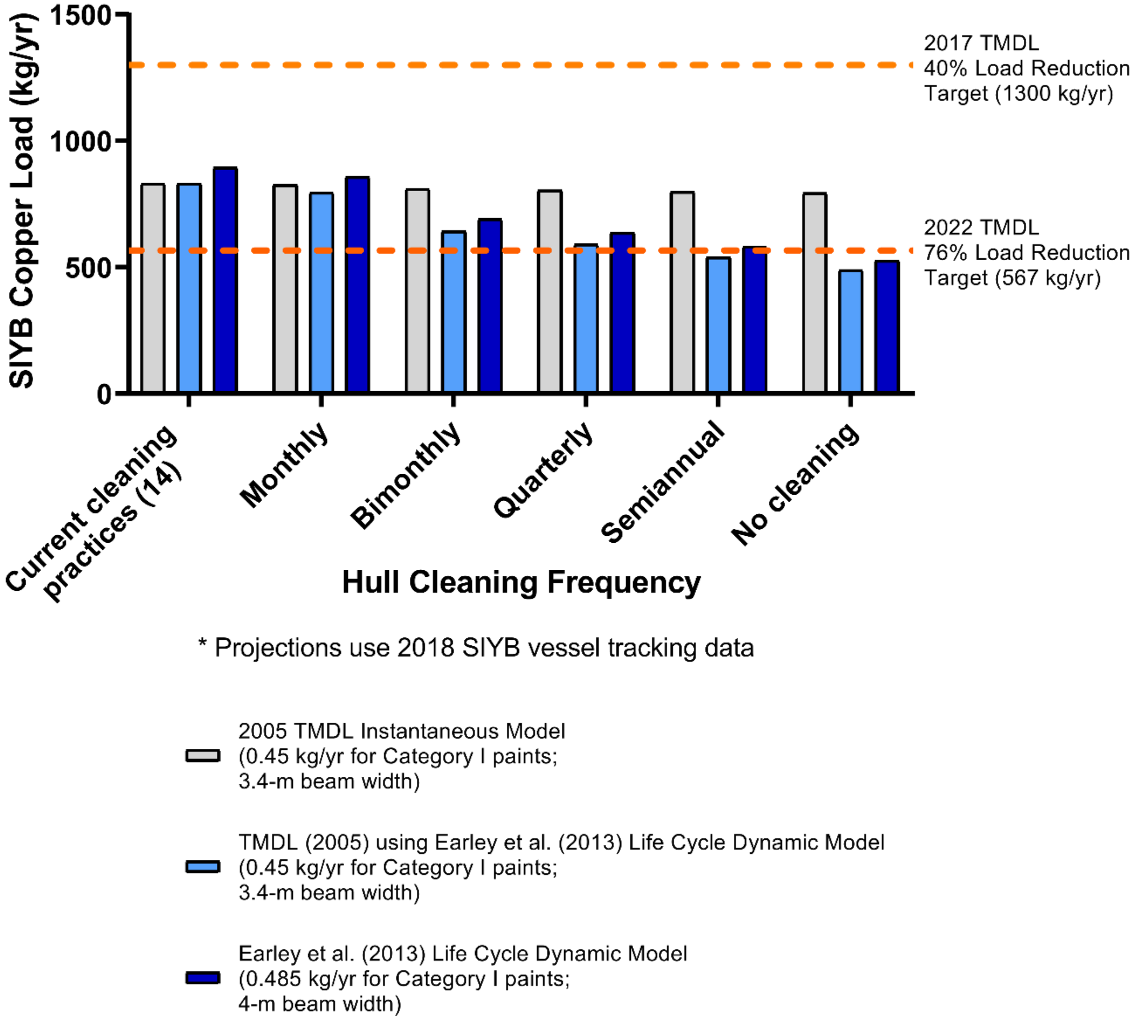
Table 3-3. Copper Loading Estimates for Various Hull Cleaning Frequencies Using TMDL Instantaneous and Life Cycle Dynamic Models after Fully-Realized DPR Rule

Cleaning Frequency	Number of Annual Cleanings	2005 TMDL Instantaneous Model	Life Cycle Dynamic Model	
		TMDL-Accepted Low Leach Load of 0.45 kg/yr**	TMDL-Accepted Low Leach Load of 0.45 kg/yr**	Earley et al. (2013) Low Leach Load of 0.485 kg/yr*
Current BMP cleaning frequency	14	831	831	895
Monthly	12	826	796	857
Bimonthly	6	810	642	692
Quarterly	4	805	591	637
Semiannual	2	799	**540**	582
None	0	794	**489**	**527**

Note:
Projections use 2018 SIYB TMDL vessel tracking data
*Uses an average wetted-hull surface of 41.1 m^2 (Earley et al., 2013).
** Uses an average wetted-hull surface of 35.3 m^2, as described in the TMDL (Regional Board, 2005).
The TMDL requires that copper loads be reduced to an annual load of 567 kilograms per year (kg/yr).
Bold values denote compliance with the TMDL load requirements.

The results also indicate that, by assuming full realization of the DPR Rule and reducing cleaning frequencies to either two cleanings per year or no cleanings per year, when looking at the life cycle of a vessel's copper paint, the 76% copper load reduction required by the TMDL compliance may be achieved (Figure 3-2). Based upon the refined copper load contributions presented in this evaluation, it appears the load reduction that may be realized by changes in hull cleaning frequency would likely have a more substantial reduction than originally anticipated using the TMDL Instantaneous Model, and an update to this model approach is necessary at this time. This finding raises the importance and value of addressing changes in hull cleaning practices as a key strategy to achieve the required load reduction needed to meet the SIYB dissolved copper TMDL final compliance target.

Figure 3-2. Copper Loading Estimates for Various Hull Cleaning Frequencies Using TMDL Instantaneous and Life Cycle Dynamic Models after Fully-Realized DPR Rule*



4.0 Conclusions, Additional Considerations, and Recommendations

This TMDL Conceptual Model Review technical document presents findings to support updates to the SIYB TMDL's Conceptual Model. The 2005 TMDL Instantaneous Model is based on source analysis and other data and information collected prior to 2005 that suggests the primary source of dissolved copper loads discharging to SIYB is associated with boat hulls coated with copper antifouling paints (Regional Board, 2005). The 2005 TMDL Instantaneous Model is static and assumes passive leaching contributes 93% of the total annual copper load directly into the water column with an additional 5% of the total annual copper load discharged during the active phase of in-water hull cleaning of boat hulls coated with copper antifouling paints.

SIYB TMDL-related technical report directives require the TMDL's conceptual model to be updated as SIYB characterization data becomes available (Regional Board, 2005). More recent and best available scientific technical analyses (Earley et al., 2013) support a conceptual model update to account for dynamic shifts in the relative contribution of passive leaching and hull cleaning that represent real-time conditions of annual copper loading in SIYB. Application of the Earley et al., (2013) Life Cycle Dynamic Model findings in SIYB suggest adaptive management measures to vessel hull cleaning frequency and adjustment to implementation practices may lead to copper load reductions and water quality improvements to meet TMDL requirements.

The robust comparative analyses that were completed in this TMDL Conceptual Model Review suggest consistent total and per-vessel annual load results between the 2005 TMDL Instantaneous Model and the Life Cycle Dynamic Model approach. Predicted annual copper loads show a less than 8% variation between the 2005 TMDL Instantaneous Model (1,152 kg/yr) and Life Cycle Dynamic Model (1,241 kg/yr), which is largely attributable to the difference in vessel dimensions used for the two models (i.e. beam width of 3.4 meters and 4.0 meters, respectively). However, the Life Cycle Dynamic Model approach suggests hull cleaning activities contribute greater than 5% of the annual copper loads to SIYB due to increased volatility and dynamic copper release for 30-day periods following hull cleaning activities. Hull cleaning-related loading can range from 5% to more than 40% of annual copper load per vessel in the Life Cycle Dynamic Model. A number of complex environmental processes may influence the copper dissolution rate, bioavailability and toxicity of copper-based antifouling paint in the marine environment. The Life Cycle Dynamic Model best captures these processes, while concurrently providing the best representation of the boating practices and real-time use conditions observed in SIYB and other marina basins.

Shelter Island Yacht Basin is subject to TMDL regulatory compliance requirements to reduce copper loading by 76% from the estimated 2005 loading level by the year 2022. Both the TMDL Instantaneous Model and the Life Cycle Dynamic Model suggest that controls to limit passive leaching and copper contribution from in-water hull cleaning of copper antifouling paint will be needed to meet the final TMDL 567 kg/yr copper load compliance target.

Recent changes by the California DPR establish a maximum allowable copper leach rate for copper antifouling paint products registered in California for use on recreational vessels. Restrictions for registration and sales of copper antifouling paints that exceed the maximum allowable copper leach rate are in place for phased implementation in California over the next few years. This will likely assist in reducing copper loads in SIYB. Additional copper mitigation strategies suggested by DPR such as in-water hull cleaning BMPs and frequency limitations, product label updates, improved boater and boatyard awareness and incentive programs for vessel hull paint conversion are all strategies that could be considered to meet the final TMDL numeric target (Department of Pesticide Regulation, 2014).

The Life Cycle Dynamic Model suggests programmatic in-water hull cleaning implementation adjustments may have a greater benefit than previously calculated as part of the 2005 TMDL Instantaneous Model. Low hull-cleaning frequency (twice per year or less) of copper antifouling paints may reduce SIYB annual copper loading to below the final TMDL target. Given the increased loading attributed to hull cleaning as projected in the Life Cycle Dynamic Model, it is likely that water quality improvement will be observed with step-wise adjustments to hull cleaning frequencies.

Further, while not analyzed as part of this TMDL Conceptual Model Review, it has also been demonstrated that in-water hull cleaning can lead to sediment impacts. Previous reports have identified that a large amount of particle loading of copper occurs and these particles can be deposited on the bay floor, even when in-water hull cleaning follows standard BMP protocols (Wood, 2019b; AMEC Earth & Environmental, 2006). Therefore, adjustments to in-water hull cleaning of copper paints may result in an improvement of both water and sediment quality and could also reduce the potential for copper-related sediment remediation.

Additional feasibility analyses will be needed to determine the operational viability of in-water hull cleaning frequency reductions in SIYB and other adaptive management measures. The Life Cycle Dynamic Model predicts that vessels cleaned outside of SIYB that are re-berthed shortly after a cleaning event may still contribute to copper loading due to increased volatility and dynamic release of bioavailable and toxic free copper ion processes post-cleaning. Further, feasibility studies for implementation of cleaning frequency management strategies are necessary to assess resource needs and enforcement capability.

Ongoing water quality monitoring in SIYB will be necessary to verify effectiveness of DPR Rule implementation, potential hull cleaning frequency reduction management measures, and progress towards final TMDL numeric goals. It is acknowledged that model-driven copper loading estimates may not linearly relate to concurrent changes in copper concentrations in field samples and improvements to water quality in SIYB. Accordingly, ongoing water quality monitoring can assess effectiveness of in-water hull cleaning frequency adjustments and other management measures to attain water quality objectives and meet the final TMDL numeric target.

This TMDL Conceptual Model Review confirms that copper loading is associated with a continuous dissolution of copper antifouling paint and periodic cleaning activities to refresh the paint surface. This finding demonstrates that the recent Life Cycle Dynamic Model and the robust data analyses set forth within that model, provide total load calculations that are consistent with the TMDL and best represent real-time use conditions occurring in marina basins. As such, it stands to reason that the Life Cycle Dynamic Model developed by Earley et al. (2013) is appropriate and should be viewed as a scientifically credible and acceptable approach to update the 2005 TMDL Instantaneous Model.

At this time it is recommended that the SIYB TMDL Model be updated to (1) incorporate the loading assumptions provided in Earley et al. (2013)'s Life Cycle Dynamic Model, and (2) use the Life Cycle Dynamic Model moving forward for annually calculating copper loads for TMDL compliance and reporting purposes.

5.0 Foundational Data Assumptions used in this Analysis

The following assumptions were made when performing calculations in this technical evaluation:

TMDL, 2005

- 50% of the boats painted with epoxy paints, 50% painted with hard vinyl
- Epoxy leaching rate (7.1 µg/cm^2/day) was obtained from U.S. Navy (Valkirs et al., 2003) and Southern California Coastal Water Research Project (SCCWRP) (Schiff et al., 2003) publications
- Vinyl paint leaching rate (5.9 µg/cm^2/day) estimated from the SCCWRP study only
- Average passive leaching rate = (7.1 µg/cm^2/day + 5.9 µg/cm^2/day)/2 = 6.5 µg/cm^2/day (annual load = 1,962 kg/yr)
- Hull cleaning assumed average dissolved copper emissions rate (both types of paint) = 8.5 µg/cm^2/day (annual load = 98.4 kg/yr) (Schiff et al., 2003)
- 14 cleanings per year (21-day/28-day cleaning routine)
- 50% of cleanings use BMPs
- Defines hull cleanings emissions as “instantaneous” one-day events
- Average boat beam width: 3.4 meters
- DPR Category I and low-copper paints assumed to have a half-load copper allocation for each vessel.

Earley et al., 2013

- 100% Epoxy copper paint, 100% BMP hull cleaning, 6.47 µg/cm^2/day back-calculated from 3-year life cycle (7,084 µg/cm^2/3yrs, Table 5 in report)
- BMP practices: soft carpet cleaning, 21-day/28-day cleaning pattern
- Average boat beam width: 4 meters
- DPR Category I and low-copper paints assumed to have a half-load copper allocation for each vessel

6.0 References

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Appendix A

Leach Rate and Copper Load Calculations for the 2005 TMDL Instantaneous Model and Life Cycle Dynamic Model

Appendix Table A-1. Dissolved Copper Load Estimates in Shelter Island Yacht Basin

Parameter / calculation	TMDL, 2005	Earley et al., 2013
PL = passive leach rate	6.5 µg/cm²/day, estimated from Valkirs *et al*., 2003 & Schiff *et al*., 2003	3.81 µg/cm²/day[a], Back-calculated from 3 yr life cycle (4,170 µg/cm²/3yrs, table 5)
IWHC = in-water hull cleaning leach rate	8.5 µg/cm²/event, estimated from Schiff *et al*., 2003; counted as a 1 day "instantaneous" event, equates to 0.33 µg/cm²/day assuming 14 cleanings/yr	2.66 µg/cm²/day[a], back-calculated from 3 yr life cycle (2,914 µg/cm²/3yrs, table 5)
TL = total average leach rate = (PL + IWHC)	6.83 µg/cm²/day	6.47 µg/cm²/day[a], back calculated from 3 yr life cycle (7084 µg/cm²/3yrs, table 5)
N_v = number of vessels	2,363, maximum number of vessels in SIYB, 100% occupancy assumed	-
L = average boat length	12.2 meters	12.2 meters
B = average beam width	3.4 meters	4 meters
S = wetted-hull surface area = L * B * 0.85	352,580 cm²	414,800 cm² [b]
A_{PL} = annual passive load = (PL * S * N_v * 365 days/yr)/10^9	1,977 kg/yr, rounded to 2,000 kg/yr in TMDL report	1,363 kg/yr [c] 1,159 kg/yr [d]
A_{IWHC} = annual IWHC = (IWHC * S * N_v * 365 days/yr)/10^9	100 kg/yr	952 kg/yr [c] 809 kg/yr [d]
TAL = total annual vessel load = A_{PL} + A_{IWHC}	2,000 kg/yr + 100 kg/yr = 2100 kg Cu/yr	2,315 kg/yr [c] 1,968 kg/yr [d]
TAL_v = Total annual per-vessel dissolved copper load = TAL / N_v = (TL * S * 365 days/yr)/10^9	0.88 kg/yr, rounded to 0.9 kg/yr in TMDL report	0.97 kg/yr [c] 0.83 kg/yr [d]

[a] Assume epoxy-based copper paint and BMP
[b] This value is rounded off. The value used in load estimate calculations in Section 3 above is 410,631 cm² (per Earley et al. (2013))
[c] Using TMDL N_v = 2,363 and Earley et al. 2013, Beam width = 4 meters.
[d] Using TMDL N_v = 2,363 and TMDL, Beam width = 3.4 meters.