To:	State Water Resources Control Board, Division of Water Rights, Instream Flow Unit
From:	Paradigm Environmental
CC:	SCCWRP
Date:	2/5/2025
Re:	Sub-Task 3.4: Technical Review of the Redwood Creek PRMS Hydrologic Model
Attachments:	IFU_PRMS_Model_Documentation_Comments.xlsx; AppendixA_Hydrology_Calibration.docx

Contents

Figures

Tables

1 INTRODUCTION

The California State Water Resources Control Board (Water Board), Division of Water Rights is supporting the development of a methodology to designate flow criteria and diversion schedules for streams in the North Coast Policy Area to support implementation of its Cannabis Policy. This effort involves the consideration of:

- Environmental water needs in a holistic manner, protecting natural hydrologic variability to support a diversity of aquatic and riparian species and overall ecosystem health
- Regulatory requirements and ongoing efforts to protect and manage sensitive aquatic species
- Non-ecological management goals including diversions for water users, primarily for cannabis cultivation, but also including other crop irrigation, municipal uses, and tribal and cultural practices, in consideration of existing water rights.

Necessary to this endeavor are both unaltered and (where applicable) altered daily volumetric flowrates across the region. However, the densely spaced, continuous records of altered and unaltered flows that are necessary for this project are impractical to measure. Therefore, a modeling approach has been adopted to provide estimates of these data.

The Instream Flow Unit (IFU) of the Water Board is developing hydrologic models for multiple North Coast watersheds, including the Eel River, Redwood Creek, Elk River, Mad River, and Little River watersheds. The purpose of these models is to provide daily flow time series appropriate for assessing ecohydrology at altered (i.e., subject to some degree of anthropogenic impact or water use) and unaltered locations and to allow evaluation of water allocations. This memo provides a technical review of the Redwood Creek watershed PRMS model.

The Redwood Creek watershed PRMS model review included examining model development from raw input data, the calibration approach, and documentation. Key hydrologic performance metrics presented by the IFU in the model report were verified, additional metrics and figures were created to aid the IFU team in further interpretation and analysis of model performance, and Functional Flow Metrics (FFMs) were calculated to provide additional information on performance. The main components of this review memo are described in the following sections:

1. Model Documentation: this section provides a critique of the IFU modeling report and provides recommendations on documentation improvements.
2. Calibration Procedure and Calibrated Parameters: this section provides a review of the calibration procedures documented in the IFU modeling report and the appropriateness of the calibrated parameters.
3. Evaluation of Hydrologic Performance: this section includes verification of hydrologic performance metrics presented in the IFU modeling report and provides additional metrics and figures to aid further interpretation and calibration efforts by the IFU team.
4. Evaluation of Functional Flow Metrics: this section provides a brief introduction to FFMs, which are less commonly known than the general hydrologic performance metrics, and the FFM aggregation methodology and results.
5. Conclusions and Recommendations: this section summarizes key recommendations from the above sections.

The Redwood Creek watershed PRMS model is based on a rapid development framework and is not intended to be an intensive watershed study. This approach is suitable for estimation of instream flows and allows for future model enhancements (e.g., higher resolution of climate data, groundwater model coupling, etc.) if deemed necessary. Given these considerations, the overall evaluation of the general hydrologic performance metrics and FFMs indicate the model performance is suitable for the intended purposes.

2 MODEL DOCUMENTATION

The Redwood Creek PRMS modeling report provided by the IFU team was reviewed for clarity and completeness. This included the description of input datasets and any processing that was carried out on them, as well as the calibration procedure and calibrated parameters (see Section 3). The inputs to configure, run, and calibrate the PRMS model include GIS datasets used to develop the gridded Hydrologic Response Units (HRUs), meteorological time series, and streamflow time series. All GIS datasets are from authoritative sources and the processes performed on them are generally described in sufficient detail.

Comments on model documentation are provided as an attachment to this memo in the "IFU_PRMS_Model_Documentation_Comments.xlsx" workbook. These are predominately aimed at providing a consistent level of detail and structure across the modeling reports developed for different watersheds.

3 CALIBRATION PROCEDURE AND PARAMETERIZATION

Defining a calibration framework and selecting appropriate parameters and observations based on a detailed conceptual model of water movements within a watershed is critical to develop a well calibrated and robust model. The Redwood Creek PRMS Model report provides a four-step process for calibrating the model, which is similar to the approach described in the PRMS guidance document (Markstrom et al, 2015, Appendix 3). Namely, calibrating solar radiation, potential evapotranspiration, streamflow volume, and streamflow timing in that order. The procedures and parameters discussed in the model report are reasonable and appropriately documented.

4 EVALUATION OF HYDROLOGIC PERFORMANCE

The assessment of a hydrologic model's performance is a key piece of the model development process, as it forms the basis for establishing the degree of uncertainty in model predictions and the reliability of the model as a basis for management decisions. The general hydrologic performance of the PRMS model was reviewed in two components: i) verification of the values presented in the IFU model report and ii) evaluation of additional metrics and plots that were created to allow for further evaluation of model performance by season and flow regime.

The IFU modeling report appendix presents several statistical performance metrics that were calculated for each gauge across the calibration/validation periods (Table 4-1). These metrics included:

- The coefficient of determination (R2): this metric describes the degree of collinearity between simulated and measured data. The correlation coefficient is an index that is used to investigate the degree of linear relationship between observed and simulated data. R2 describes the proportion of the variance in observed data that is explained by a model. Values for R2 range from 0 to 1, with 1 indicating a perfect fit.
- The Nash-Sutcliffe efficiency (NSE): this metric is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash

and Sutcliffe 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. Values for NSE can range between -∞ and 1, with NSE = 1 indicating a perfect fit.

Table 4-2 presents the comparison of the NSE and R2 between the IFU reported value from the model documentation and the verification value calculated for this review. There are no appreciable differences between IFU and PE calculated values.

Table 4-1. Streamflow stations used for model assessment

Station ID	Station Name	Type	Calibration		Validation/Assessment[1]	
			Start	End	Start	End
11481500	REDWOOD C NR BLUE LAKE, CA	Reference	10/1/1985	9/30/2010	10/1/2010	9/30/2022
11482500	REDWOOD C A ORICK CA	Impaired	--	--	10/1/1985	9/30/2022

[1] Note that impaired stations were used for general model assessment while validation was done for calibrated reference stations

Table 4-2. Verification of key flow metrics across the period of record for each station

Station ID	Station Name	PRMS Subbasin	Nash-Sutcliffe Efficiency		R squared	
			IFU[1]	PE[2]	IFU[1]	PE[2]
11481500	REDWOOD C NR BLUE LAKE, CA[3]	7	0.76/0.73	0.76/0.73	0.78/0.75	0.78/0.75
11482500	REDWOOD C A ORICK CA	2	0.77	0.78	0.79	0.80

[1] Instream Flow Unit
[2] Paradigm Environmental
[3] Calibration/Validation

To allow for further analysis of performance at each gauge, additional metrics and visualizations were created by season and flow regime. For statistical assessment of model performance, agreement between PRMS outputs and observed data was assessed using NSE, R2, and the percent bias:

- The percent bias (PBIAS) quantifies systematic overprediction or underprediction of observations. A bias towards underestimation is reflected in positive values of PBIAS while a bias towards overestimation is reflected in negative values. Low magnitude values of PBIAS indicate better fit, with a value of 0 being optimal.

Quantitative grading thresholds for PBIAS, R2, and NSE, as recommended by Moriasi et al. (2015), are shown in Table 4-3 and used as a weight of evidence approach to evaluate whether model performance is reasonable. These thresholds are considered highly conservative and "Satisfactory" or better is a significant outcome. The values for key hydrology metrics according to these thresholds for each gauge by season and flow regime is presented in Table 4-4. For reference stations, model performance was assessed for the validation period only, while impaired stations used the assessment period as listed in Table 4-1.

As documented in the IFU Redwood Creek modeling report, the model was calibrated to capture unimpaired flows with additional emphasis on spring recession flows (mid-March) and summer baseflows (after spring recession through September). The IFU team also preferred the model to slightly underpredict dry/low flows as a margin of safety when assessing water availability. For both stations, the model tends to underpredict flows when evaluated across all values or by season. Dry Season PBIAS is "Good" and underpredicted at the reference station (Redwood Creek near Blue

Lake) by 11%. This metric is underpredicted by 25% at the Redwood Creek near Orick station which is "Unsatisfactory" however, this is an impaired station and not the current focus for model calibration; this level of underprediction may be acceptable given the purposes of this model. Both stations have "Good" or "Very Good" seasonal R2 and NSE values, indicating a high level of agreement between the timing of modeled and observed flows.

Baseflow is an important condition for capturing dry season and low flow conditions in this region (e.g., after spring recession through September). The baseflow R2 and NSE metrics at both stations are "Very Good" and baseflow PBIAS is underpredicted by 12% and 17% at the reference and impaired stations, respectively. Figure 4-1 provides an example of the dry season flow and baseflow performance at the reference station for the 2014 severe drought year. The model captured the magnitude and trend of declining flows as the dry season progressed very well. The Low 50% metric, which the model generally had "Good" to "Very Good" performance on, represents a wide range of conditions (e.g., extreme drought with little to no streamflow, small to medium rain events in both the Wet and Dry season) and should be given less weight in this evaluation given the specific modeling objectives. A full suite of plots for each gauge that can aid additional performance assessment is available in Appendix A.

Table 4-3. Summary of qualitative performance thresholds

Performance Metric	Hydrological Condition	Performance Threshold for Hydrology Simulation			
		Very Good	Good	Satisfactory	Unsatisfactory
Percent Bias (PBIAS)*	All Conditions [1]	<5%	≥5% - <10%	≥10% -	>15%
	Seasonal Flows [2] Highest 10% of Daily Flow Rates [3] Lowest 50% of Daily Flow Rates [4] Days Categorized as Storm Flow Days Categorized as Baseflow [5]	<10%	≥10% - <15%	≥15% - ≤25%	>25%
R-squared (R2)	All Conditions [1]	>0.85	>0.75 – ≤0.85	>0.60 – ≤0.75	≤0.60
	Seasonal Flows [2] Highest 10% of Daily Flow Rates [3] Lowest 50% of Daily Flow Rates [4] Days Categorized as Storm Flow Days Categorized as Baseflow [5]	>0.75	>0.60 – ≤0.75	>0.50 – ≤0.60	≤0.50
Nash-Sutcliffe Efficiency (NSE)I	All Conditions [1]	>0.80	>0.70 – ≤0.80	>0.50 – ≤0.70	≤0.50
	Seasonal Flows [2] Highest 10% of Daily Flow Rates [3] Lowest 50% of Daily Flow Rates [4] Days Categorized as Storm Flow Days Categorized as Baseflow [5]	>0.70	>0.50 – ≤0.70	>0.40 – ≤0.50	≤0.40

* Thresholds apply to absolute PBIAS values

[1] All Flows considers all daily time steps in the model time series.

[2] Seasonal Flows considers daily flows during predefined, wet and dry periods. The Dry season included the months of May, June, July, August, and September. The Wet season included the months of October, November, December, January, February, March, and April.

[3] Highest 10% of Flows considers the top 10% of daily flows by magnitude as determined from the flow duration curve.

[4] Lowest 50% of Flows considers the bottom 50% of daily flows by magnitude as determined from the flow duration curve.

[5] Baseflows and Storm flows were determined from analyzing the daily model time series by applying the USGS hydrograph separation approach (Sloto & Crouse 1996)

Table 4-4. Summary of statistical performance metric results for flow by season and flow regime for the validation period/stations

Station ID	Hydrology Monitoring Locations	Performance Metrics (Seasonal)									Performance Metrics (Flow Regime)											
		PBIAS			R-squared			NSE			PBIAS				R-squared				NSE			
		All	Wet Season	Dry Season	All	Wet Season	Dry Season	All	Wet Season	Dry Season	Top 10%	Storms	Low 50%	Baseflow	Top 10%	Storms	Low 50%	Baseflow	Top 10%	Storms	Low 50%	Baseflow
11481500	REDWOOD C NR BLUE LAKE, CA	21%	22%	11%	0.75	0.71	0.87	0.73	0.68	0.86	29%	29%	-7%	12%	0.37	0.71	0.64	0.83	-0.11	0.67	0.34	0.82
11482500	REDWOOD C A ORICK CA	21%	20%	25%	0.80	0.77	0.86	0.78	0.74	0.81	26%	23%	7%	17%	0.54	0.76	0.64	0.86	0.31	0.74	0.55	0.83

Very Good | Good | Satisfactory | Unsatisfactory

- Overpredicts | + Underpredicts

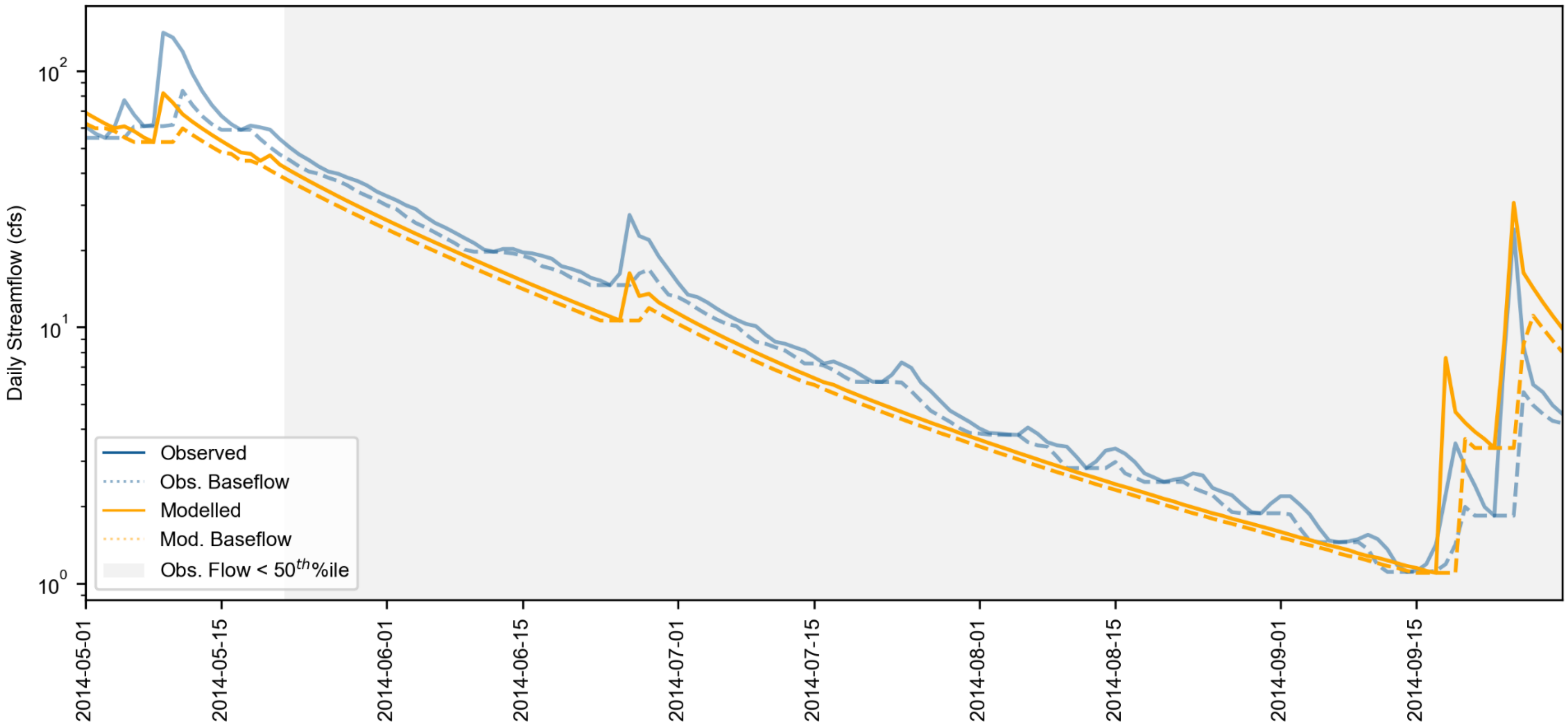


Figure 4-1. Water Year 2014 Dry season daily streamflow at Redwood Creek near Blue Lake (11481500). Observed and simulated baseflow are calculated with HYSEP; grey shading indicates observed flow is less than the 50th percentile.

5 EVALUATION OF FUNCTIONAL FLOW METRICS

Annual functional flow metrics (FFMs) for the periods and characteristics shown in Table 5-1 and Figure 5-1 were quantified for each gauge based on the modeled and observed data. FFM calculation used the Functional Flows Calculator API client package in R (version 0.9.7.2, https://github.com/ceff-tech/ffc_api_client), which uses hydrologic feature detection algorithms developed by Patterson, et al. (2020) and the Python functional flows calculator (https://github.com/NoellePatterson/ffc-readme).

Table 5-1. Description of Functional Flow Metrics (adapted from Table 1 in Grantham, et al. (2022))

Functional flow component	Flow characteristic	Functional flow metric
Fall pulse flow	Magnitude (cms)	Peak magnitude of fall season pulse event (maximum daily peak flow) in years when it occurs
	Timing (date)	Start date of fall pulse event
	Duration (days)	Duration of fall pulse event (# of days start to end)
Wet season baseflow	Magnitude (cms)	Magnitude of wet season baseflow and wet season median flow (10th and 50th percentile of daily flows, respectively, during the wet season)
	Timing (date)	Start date of wet season
	Duration (days)	Wet season baseflow duration (# of days from start of wet season to start of spring season)
Wet season peak flows	Magnitude (cms)	Peak flow magnitude (annual peak flows for 2-, 5-, and 10-years recurrence intervals)
	Duration (days)	Duration of peak flows over wet season (number of days in which a given peak flow recurrence interval is exceeded, in years when it occurs)
	Frequency	Frequency of peak flow events over wet season (number of times in which a given peak flow recurrence interval flow is exceeded, in years when occurs)
Spring recession flow	Magnitude (cms)	Spring peak magnitude (daily flow on start date of spring recession-flow period)
	Timing (date)	Start date of spring recession
	Duration (days)	Spring recession flow duration (# of days from start of spring to start of summer base flow period)
	Rate of change (%)	Spring recession flow rate (percent decrease per day over spring recession period)
Dry season baseflow	Magnitude (cms)	Dry season baseflow and high baseflow magnitude (metrics for the 50th and 90th percentile of daily flow, respectively, during the dry season)
	Timing (date)	Start date of dry season
	Duration (days)	Dry season baseflow duration (# of days from start of dry season to start of wet season)

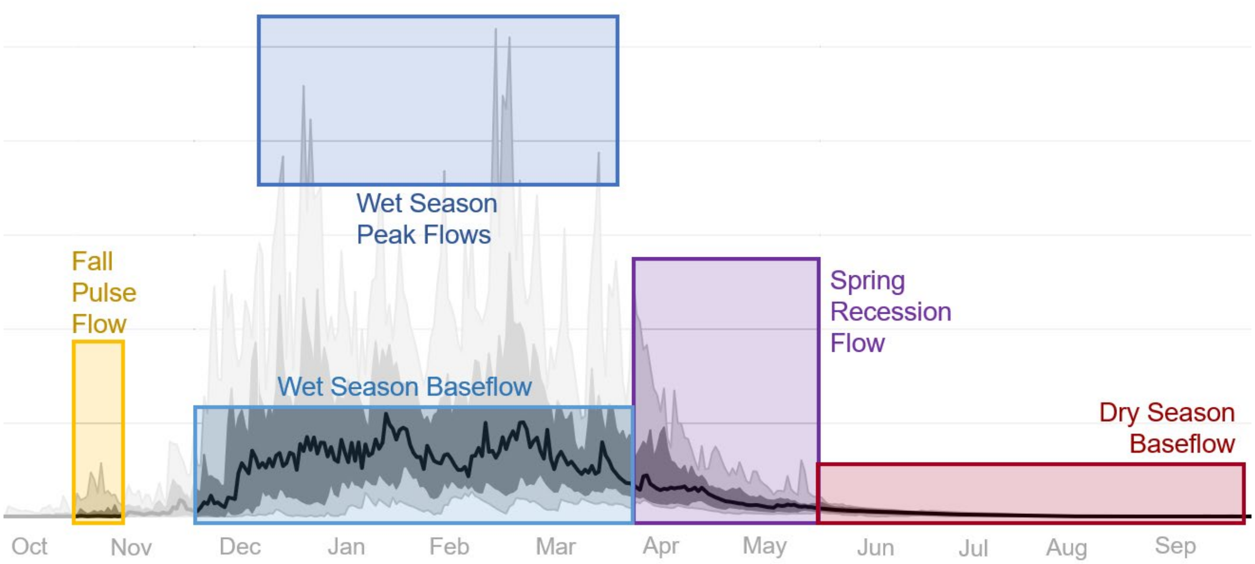


Figure 5-1. Periods of interest for calculation of functional flow metrics (after Yarnell, et al. (2020))

The FFMs were aggregated into normalized indices based on the methods of Grantham, et al. (2022) to allow for easier evaluation and comparison (Figure 5-2). This included calculating performance metrics for each gauge and flow metric that had at least 10 or more years of observations or flow metric values calculated. The performance metrics are as follows:

- Interquartile range (IQR): the percentage of observed values that fell within the predicted range between the 25th to 75th percentile values. It is expected that 50% of the observed flow metric values should fall within these ranges.
- Inter-80th percentile range (I80R): the percentage of observed values that fell within the predicted range between the 10th to 90th percentile values. It is expected that 80% of the observed flow metric values should fall within these ranges.
- Goodness-of-fit metrics typically used in hydrologic model performance (Eng et al. 2017; Moriasi et al. 2007) were calculated based on the annual values. Model performance for metrics that had less than 10 values calculated for the period of record, including peak flow magnitude metrics (i.e., 2-year, 5-year, and 10-year flood) were not calculated because only one value was calculated per gauge. The goodness-of-fit measures are:
    - Observed to expected ratio (O/E): the mean O/E across all years
    - Coefficient of determination (R2)
    - Percent Bias (PBIAS)
    - Nash-Sutcliffe Efficiency (NSE)

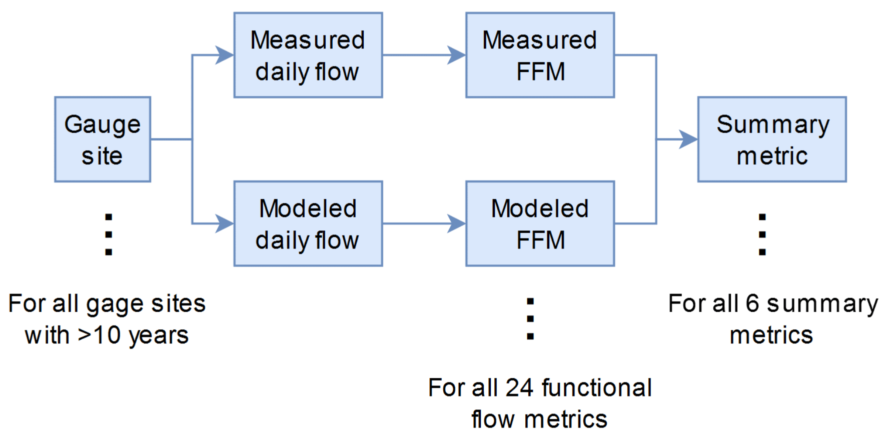


Figure 5-2. General workflow for calculating FFMs and summary metrics.

The aggregated FFM performance values were normalized between 0 (poor performance) and 1 (perfect performance) following Grantham, et al. (2022). The percentage in IQR was scaled by taking the absolute value from the difference between the calculated value and 50 divided by 50 and subtracted by 1. The same was done for the I80R, substituting 50 with 80. O/E was scaled for values greater than 1 by taking the inverse $\left(\frac{1}{O/E}\right)$. Percent bias was scaled by subtracting values from 100 and dividing by 100. NSE values greater than 0 were set to 0 and no changes were made to the R2.

A composite performance index was developed by averaging values of all six criteria. A dispersion composite performance index was also calculated by averaging values of percentage in IQR and percentage in I80R. The dispersion index provides a measure of how well the PRMS model captured the range of flow metric values at a given gauge. Qualitative ratings of model performance from Grantham, et al. (2022), following guidance from Moriasi, et al. (2007), were excellent (>0.9), very good (0.81–0.9), good (0.65–0.8), satisfactory (0.5–0.64), and poor (<0.5).

5.1 Functional Flow Metric Results

FFM performance was evaluated at reference gauges for the validation period only and was constrained to gauges and model nodes that had at least 10 or more years of observations or flow metric values calculated. For the Redwood Creek watershed only Redwood Creek near Blue Lake (11481500) was evaluated.

Note that there were not enough metric values calculated for fall pulse flow and peak flow metrics, so model performance related to these metrics was not assessed.

5.1.1 Average Composite Indices

Twelve functional flow metrics had at least ten years of concurrent observed and predicted values, providing sufficient data to assess performance criteria for annual flow metrics, overall composite performance, and composite dispersion index (Table 5-2). Overall, the PRMS model demonstrated satisfactory to very good performance in predicting all evaluated functional flow metrics, based on both the overall composite performance criteria. The PRMS model had satisfactory performance, based on composite index all, for the dry-season baseflow high magnitude and the spring recession flow rate of change, magnitude, and duration. The spring recession duration tended to be too long, and the rate of change was underpredicted compared to observed values (Figure 5-3).

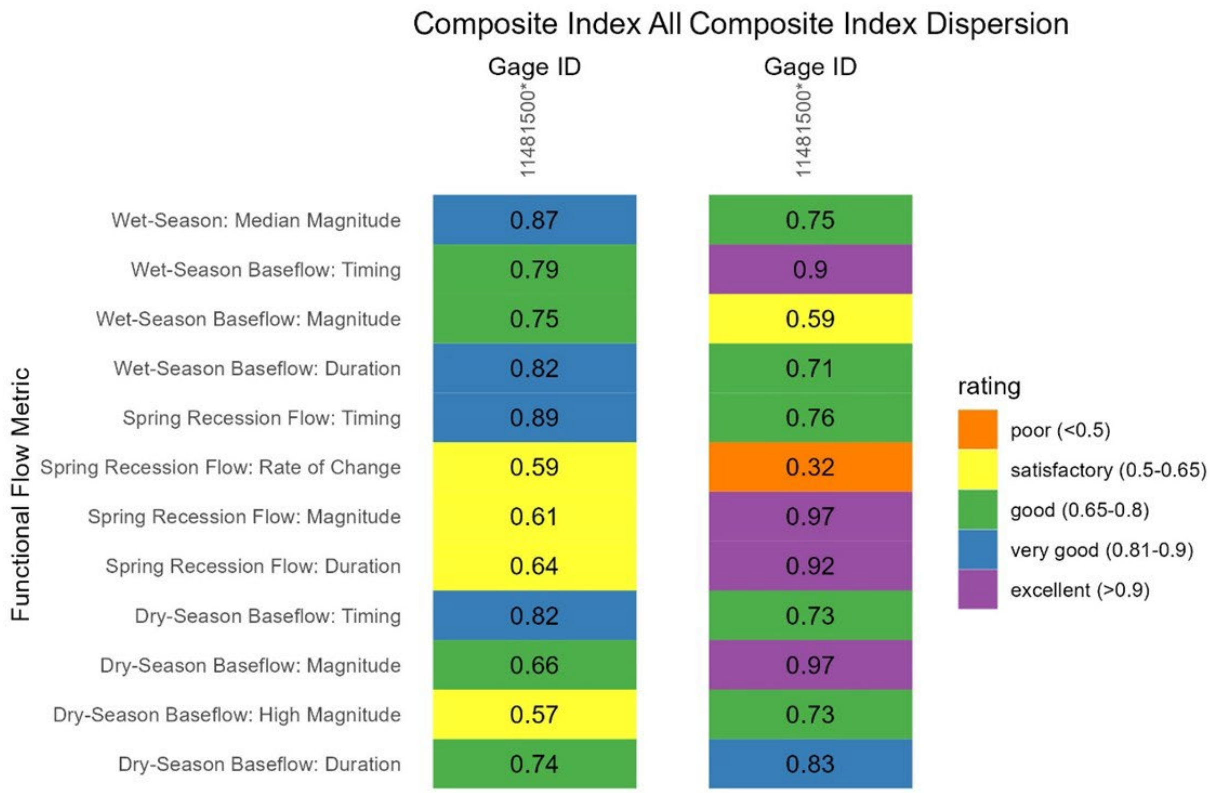
5.1.2 Dispersion Composite Indices

The model performed good to excellent in capturing the natural range of variation for all functional flow metrics evaluated, except for the wet-season baseflow magnitude (satisfactory) and spring recession rate of change (poor).

Supplemental visualizations were developed that compare the FFM values from gauged flow (observed) and modeled flow (predicted), including boxplots illustrating the range of metric values, scatterplots comparing concurrent annual metric values, and residual plots that illustrate potential bias in the annual flow metric value comparison. For more information on model performance at the functional flow metric level for Redwood Creek gages and by functional flow metric, please see supplementary data and plots provided below.

- Redwood Creek annual functional flow metric values for gages and model nodes: csv_results
- Redwood Creek summary of all performance metrics by gage and functional flow metric: performance results
    - Github repository for the functional flow metric performance evaluation: https://github.com/kristaniguchi/Cannabis_SWB.git
        - Functional flow calculator R script
        - Functional flow metric performance R script
- Supplementary plots of functional flow metric values calculated from gaged flow (observed) and associated model nodes (predicted):
    - Boxplots
    - Scatterplots
    - Residuals

Table 5-2. Composite and Dispersion performance indices by gauge and flow metric for reference (unimpaired) gauges used to calibrate the PRMS unimpaired model. Note that the composite index used all criteria while the dispersion index used only the percent in IQR and I80R.



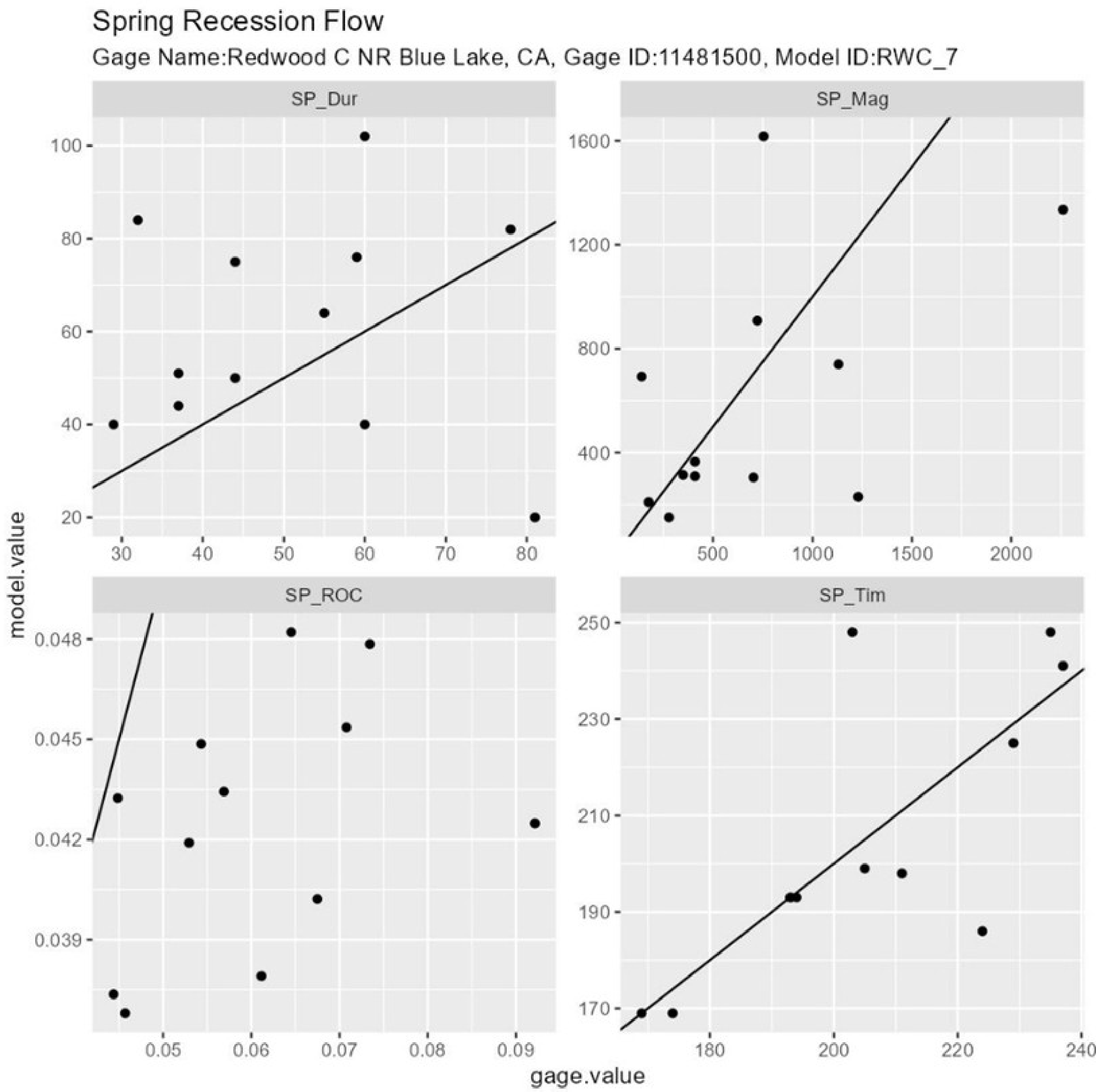


Figure 5-3. Scatter plots of functional flow spring recession metrics at the Redwood Creek near Blue Lake (11481500) reference calibration gauge.

6 CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this technical model review, the Redwood Creek watershed PRMS model represents observed streamflow well under most conditions and performs well in capturing the natural range of variation in functional flow metrics. Low flow conditions, which are particularly important for applications of this model and a focus of calibration, also had generally acceptable performance noting that underprediction is preferred. Model documentation should reference that additional refinements to model parameters may improve performance related to spring recession metrics.

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