2024

Redwood Creek Watershed Hydrologic Water Supply Model using the Precipitation Runoff Modeling System

DIVISION OF WATER RIGHTS, CANNABIS INSTREAM FLOWS SECTION

STATE WATER RESOURCES CONTROL BOARD

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1 The Redwood Creek Watershed

1.1 Background

The Redwood Creek watershed encompasses a drainage area of 280 square miles that mainly consists of forested, steep mountainous terrain. The watershed is completely located in Humboldt County and is surrounded by the Mad River basin to the west and the Klamath River drainage to the east. The lower portion of the watershed and part of the estuary falls within Redwood National and State Parks, which includes about 41 percent of the watershed. Private lands make up approximately 56 percent of the watershed area, while the Bureau of Land Management and United States Forest Service owns about 3 percent of the land. The small town of Orick is located near the outlet of the river, close to the Pacific Ocean, and is the only main development in the watershed. The river provides recreational, agricultural, and industrial water supply for the community of Orick and is also a key habitat for endangered species. Redwood Creek has a presence of Chinook salmon, coho, steelhead and coastal cutthroat trout, which are federally listed species under the Endangered Species Act (2014). Cold freshwater habitat in the river is important for fish migration and spawning. The Redwood Creek watershed is listed on the Section 303(d) List for impairment or threat of impairment to water quality associated with sediment and temperature, based on the technical Total Maximum Daily Load (TMDL) established by the U.S. Environmental Protection Agency (1998). The Redwood Creek watershed PRMS model was developed to run for the period from October 1st, 1981, to February 28, 2023. However, model calibration was conducted for the period of October 1st,1985 to September 30th, 2010. The Redwood Creek model was then validated for the period from October 1st, 2010 to September 30th, 2022 to check on the model performance for a set of data that was not used during calibration. The purpose of this model is to provide daily unimpaired flow simulations needed for the allocation of water for water diverters and ecohydrology to support a diversity of aquatic and riparian species to maintain overall ecosystem health. An unimpaired flow gauge, alternatively referred to as a reference gauge, was utilized to calibrate the model to estimate unimpaired flows throughout the basin. The calibration approach outlined in this report provides daily flow estimates that are not impaired by water diversions and upstream impediments such as dams and water barriers.

1.2 Redwood creek streamflow gauges

Redwood Creek – HUC 1801010201 is a HUC10 watershed that can be further represented by six HUC12 watersheds. USGS 11482500 Redwood C A Orick CA is the most downstream gauge within the watershed and is an active monitoring location that represents a drainage area of 277 square miles. USGS 11482468 Little Lost Man C A Site No 2 nr Orick CA is a historical gauge within the Prairie Creek tributary and represents a small drainage area of 3.46 square miles. USGS 11482200 Redwood C at S Park Boundary nr Orick CA is a historical gauge at the mainstem that represents a drainage area of 185 square miles. USGS 11482130 Coyote C nr Orick CA is a historical gauge located at the outlet of the Coyote Creek tributary and represents a drainage area of 7.78 square miles. USGS 11482125 Panther C nr Orick CA is another historical gauge located at the outlet of the Panther Creek tributary and represents a drainage area of

6.07 square miles. USGS 11482120 Redwood C AB Panther C nr Orick CA is a historical mainstem gauge that represents a drainage area of 150 square miles. USGS 11482110 Lacks C nr Orick CA is a historical gauge located at the outlet of the Lacks Creek tributary and represents a drainage area of 16.9 square miles. USGS 11481500 Redwood C nr Blue Lake CA is the most upstream gauge within the watershed and is an active monitoring location that represents a drainage area of 67.7 square miles.

Figure 1 shows a location map of the Redwood Creek watershed, HUC12 sub watersheds, and gauge IDs labeled. All current and historical USGS streamflow gauges within the model period of record are shown on the map. USGS 11481500 Redwood C nr Blue Lake CA was used as the reference calibration and validation site, since it is the least subject to upstream water diversions and impediments. Visual assessment at the most downstream gauge was conducted as part of this analysis to confirm general model agreement, although the model was not validated at impaired gauges since the purpose is to develop unimpaired flow estimates. Additional details on gauge selection, calibration and validation periods, and evaluation metrics is further discussed in the model calibration and model evaluation sections of this report.

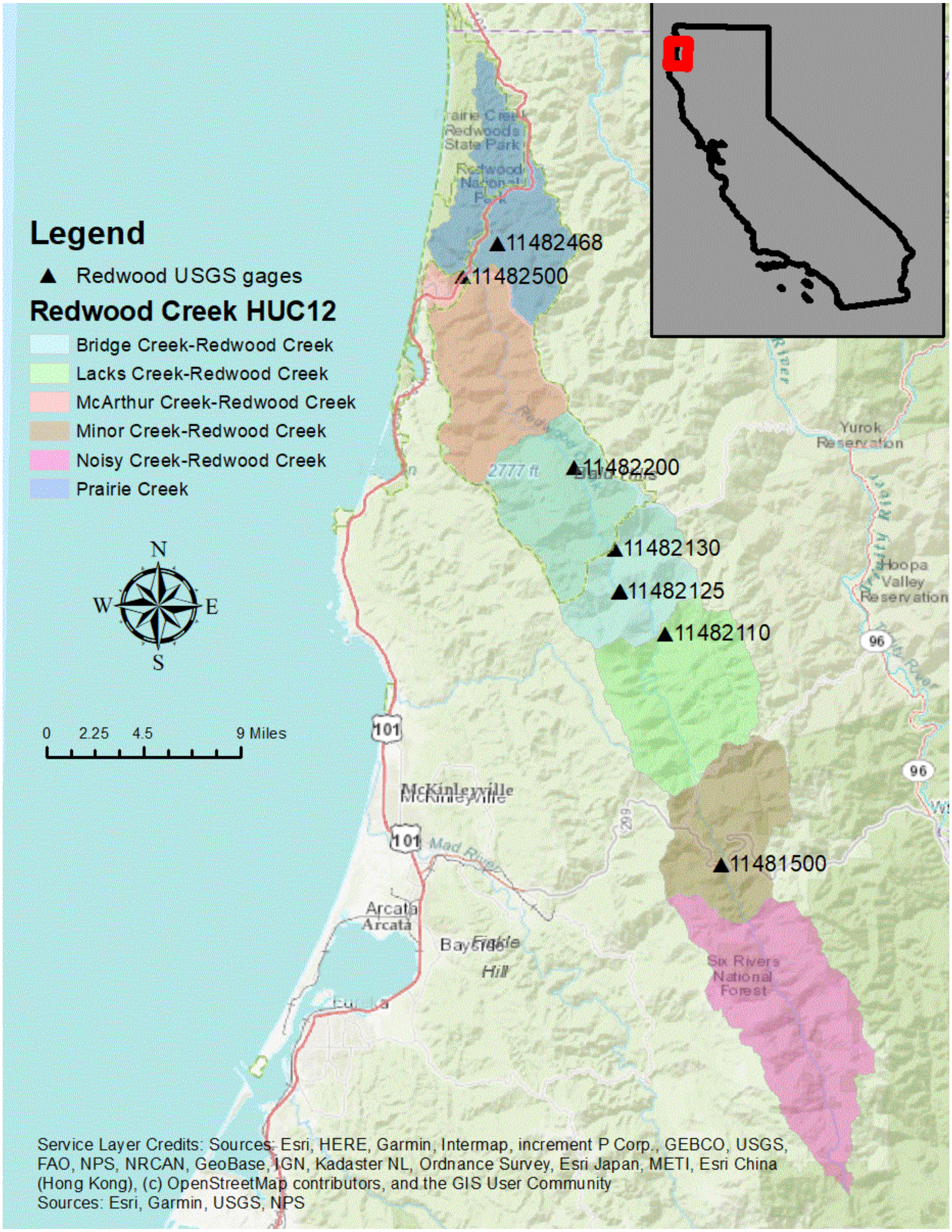


Figure 1. Redwood Creek watershed and all current and historical USGS gauges

2 USGS Surface Water Model and Python Tools

2.1 Precipitation Runoff Modeling System (PRMS)

Computer aided hydrologic models use computer software applications to simulate the hydrologic cycle of watersheds to help assess geology, variability in climate, biota, flow, and water availability. The Precipitation Runoff Modeling System (PRMS) is a spatially distributed physical-based model that uses terrain (i.e., elevation and slope), vegetation/land use, and meteorological data to simulate hydrological processes of a watershed, such as surface and groundwater flow, evapotranspiration, soil moisture dynamics, and streamflow. Inputs for PRMS include precipitation in the form of rain and snow, minimum and maximum temperature, and short-wave solar radiation. Temperature and solar radiation inputs influence the process of evaporation, transpiration, sublimation, and snowmelt. These processes impact water loss from the watershed, which in turn impacts the amount of water left for runoff and storage. A watershed model domain in PRMS is represented by a grid that consists of square shaped cells that are more technically known as hydrologic response units (HRUs). An HRU is designated as either land, lake, swale, or inactive. Each HRU holds hydrologic and physical inputs, such as surface elevation, slope, and aspect; vegetation type and cover; land use; distribution of precipitation, temperature, and solar radiation; soil morphology and geology; and flow direction. Hydrologic and physical inputs are publicly available datasets that are discretized to the HRU model grid using python and Environmental Systems Research Institute's (ESRI) Geographic Information System (GIS).

After water loss from evapotranspiration is simulated, the remaining water available to the watershed is modeled by PRMS through three conceptual soil zones: preferential flow, capillary, and gravity reservoirs. Simulation of water through these conceptual soil zones is determined by the inputs that are supplied to the model and PRMS modules. PRMS modules include complex physical equations and predefined approaches used to generate parameters and simulate various hydrologic processes. Parameters are values that define various characteristics of the watershed and are generated through raw inputs and PRMS modules. After model development, parameters can be modified through calibration to achieve better simulations of hydrologic processes such as streamflow volume, rate, and timing. Developing PRMS inputs and parameters is a complex process, but readily available reproducible tools allow to develop them efficiently and effectively.

Each module used by the PRMS is well documented by Markstrom and others (2008) from the United States Geological Survey in the PRMS IV user manual. The manual, installation instructions, and the source code can be found at the following location:

https://www.usgs.gov/software/precipitation-runoff-modeling-system-prms

2.2 Python based model development tools

USGS developed model input processing tools using python Jupyter® notebooks that semi automate the development of inputs for PRMS and MODFLOW. MODFLOW is the groundwater component of the coupled GSFLOW model. The python-based tools were used to develop surface water models only (PRMS component), which accounts for some groundwater contributions and losses to surface flows from geologic, soils, and land use data, but lacks the comprehensive long term groundwater modeling components of a MODFLOW model. The USGS python-based tools were selected because they are reproducible, well documented, and allows for base inputs to develop a MODFLOW model with the same resolution as the PRMS grid for future considerations of a coupled/integrated GSFLOW model. PRMS alone provides flow estimates that have been deemed adequate to make decisions related to water availability and drought preparedness; however, certain areas of the state may benefit from the integrated GSFLOW model, particularly where there is high groundwater interaction. Considering time and resources, a coupled GSFLOW model might be considered but may not be possible to develop for every watershed of the state. The model development tools are formally known as pyGSFLOW and the associated documentation is titled "Rapid Model Development for GSFLOW with Python and pyGSFLOW" by Joshua D. Larson and others from USGS. Past PRMS hydrologic models such as the Eel River Watershed Model were developed using the existing anaconda-based tools (GSFLOW-ArcPy), while Redwood Creek was developed using the latest version of pyGSFLOW. The modules of pyGSFLOW are all discussed in this report as part of the model development process are well documented in the pyGSFLOW links referenced above. Any future surface water hydrologic PRMS models will be developed using pyGSFLOW as well, since the tools are currently maintained and supported by USGS while the legacy GSFLOW-ArcPy tools are no longer maintained.

3 Redwood Creek Model Inputs

3.1 Coordinate system determination

The python-based model development tools are set up with the NAD83 Universal Transverse Mercator projected coordinate system (UTM). The state of California is characterized by either UTM Zone 10 or 11. ESRI has an online tool that allows you to determine your watershed's appropriate UTM coordinate system. Using the tool, it was determined that the Redwood Creek watershed is within NAD83 UTM Zone 10.

3.2 Watershed boundary shapefile

The SWRCB's GIS database was used to obtain the Redwood Creek watershed boundary polygon shapefile. The Redwood Creek watershed boundary includes six HUC12 watersheds. The boundary is important in defining the model extent and development of the model grid. The 'project watershed' toolbox in ArcGIS was used to set the spatial projection of the watershed boundary shapefile. All input raster datasets, shapefiles, pour points and datasets used in the python code were projected to the NAD 83 UTM Zone 10 projected coordinate system as a requirement for pyGSFLOW.

3.3 Digital elevation model (DEM)

A Digital Elevation Model (DEM) covering the Redwood Creek watershed boundary is required for the python modeling tools. The input DEM resolution needs to be smaller than the designated model grid resolution. Raw DEMs often contain sinks and need to be filled before they can be used as model inputs. A sink is a cell or set of spatially connected cells that cannot be assigned a flow direction. They can occur when all neighboring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop. In a digital elevation model, a sink can occur through elevation rounding errors to integers during sampling. Sinks need to be filled to create a proper delineation of the basin and streams. If they are not filled, the resulting basin delineation may be discontinuous. A raw DEM can be hydrologically conditioned through a series of GIS processing steps using ArcHydro to fill the sinks and establish realistic drainage paths. The SWRCB's GIS database has a readily available hydrologically conditioned DEM by USGS, which has the sinks filled and drainage paths established using the Watershed Boundary Dataset (WBD) and National Hydrography Dataset (NHD) flowlines. The hydrologically conditioned DEM was obtained, clipped and projected to the UTM Zone 10 projected coordinate system for use with pyGSFLOW to develop the Redwood Creek PRMS model.

3.4 HRU cell size and model grid generation

An HRU is each square shaped polygon cell that makes up the model grid. The model resolution is determined by specifying the size of an HRU. Desired model resolution is determined by the objectives of modeling. For the purposes of decisions related to water rights management, the scale needs to be fine enough to represent critical nodes in the stream network to effectively evaluate how diverters may impact one another in a water availability analysis. Finer resolutions provide more HRUs in the watershed model, which also allows for more flexibility in subbasin delineations. Smaller HRU cell sizes provide finer model resolution at the sometimes-significant cost of prohibitively longer model run times. By conducting an analysis on model resolution and model run time through inspecting different HRU cell sizes, it was determined that a 300m x 300m HRU cell size was sufficient to balance desired resolution and runtime efficiency. All input raster datasets including DEM, vegetation, soils, climate, and impervious area get resampled to the model grid resolution. The first step in the model development process is to specify the model grid cell size of 300m x 300, specify the Redwood Creek watershed boundary shapefile file path location, and then run the first python script in pyGSFLOW to generate the model grid. The script takes the built in GenerateFishnet class within pyGSFLOW to develop the model grid, as shown in Figure 2.

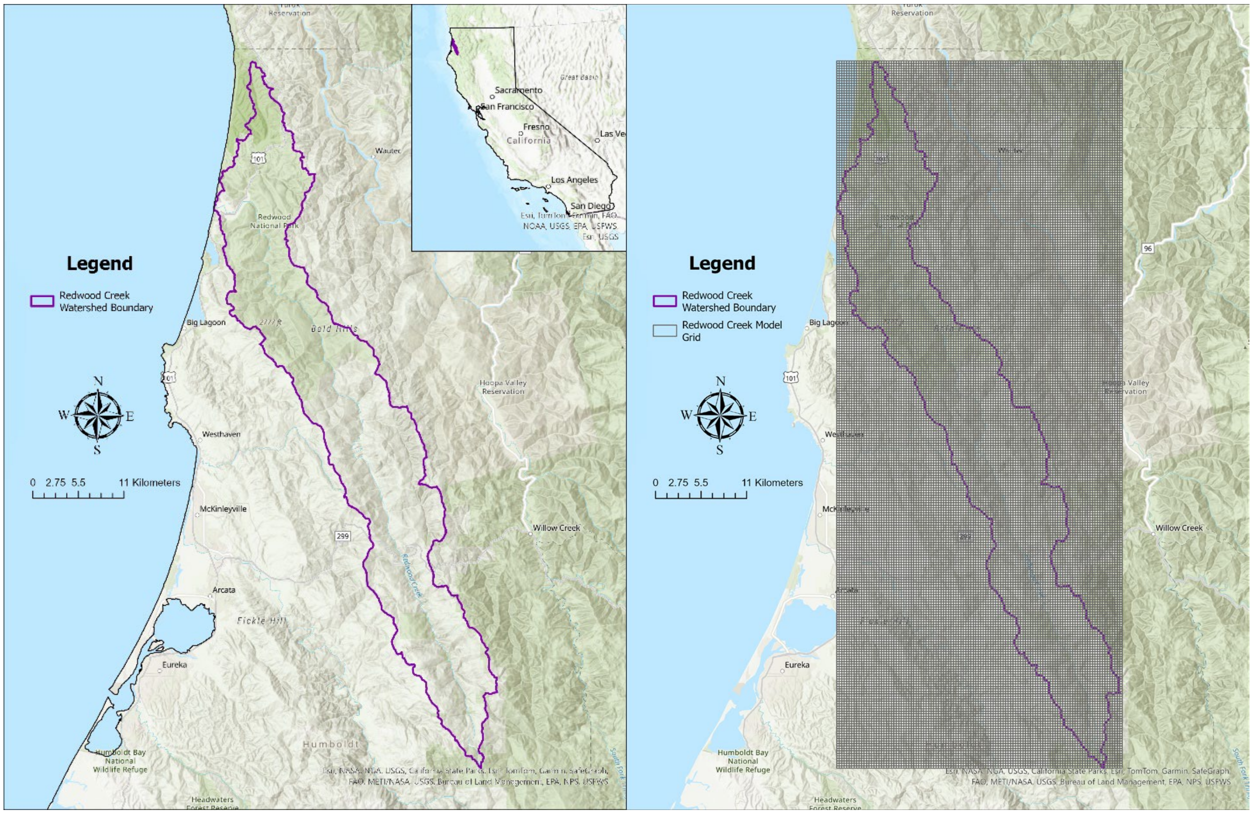


Figure 2. Redwood Creek watershed boundary conditions and 300m x 300m model grid

3.5 Resampling DEM to model grid resolution

After generating the model grid, the Raster class in pyGSFLOW was used to resample the 30m hydrologically conditioned DEM to the 300m x 300m model grid resolution. Raster class is part of FlowPy's utility for cropping, sampling and resampling raster data. Because Redwood Creek is a coastal watershed that generally has very little variations in elevations near the coastal area, the minimum method in raster resampling was used to resample the DEM to the model grid resolution. The minimum method better computes downward drainage slopes to prevent discontinuous streams from being generated during the subsequent flow direction and accumulations steps in the modeling process. After running this script, the resampled elevation is calculated and populated for each HRU in the model grid. Eventually the HRU elevation gets written to the PRMS parameter file after successful execution of the last python modeling script in the model development process. Figure 3 provides a graphic of how a hydrologically conditioned DEM gets resampled to the model grid resolution to generate modeled elevations. The resampled elevations in the model grid are used in subsequent scripts to generate the streamflow routing, cascade, and other computations such as temperature distribution that rely on elevation, slope and aspect values in PRMS. Figure 3 shows the original 30m hydrologically conditioned DEM and an inset that showcases the resampled elevations to the 300m x 300m model grid resolution for the Redwood Creek watershed model.

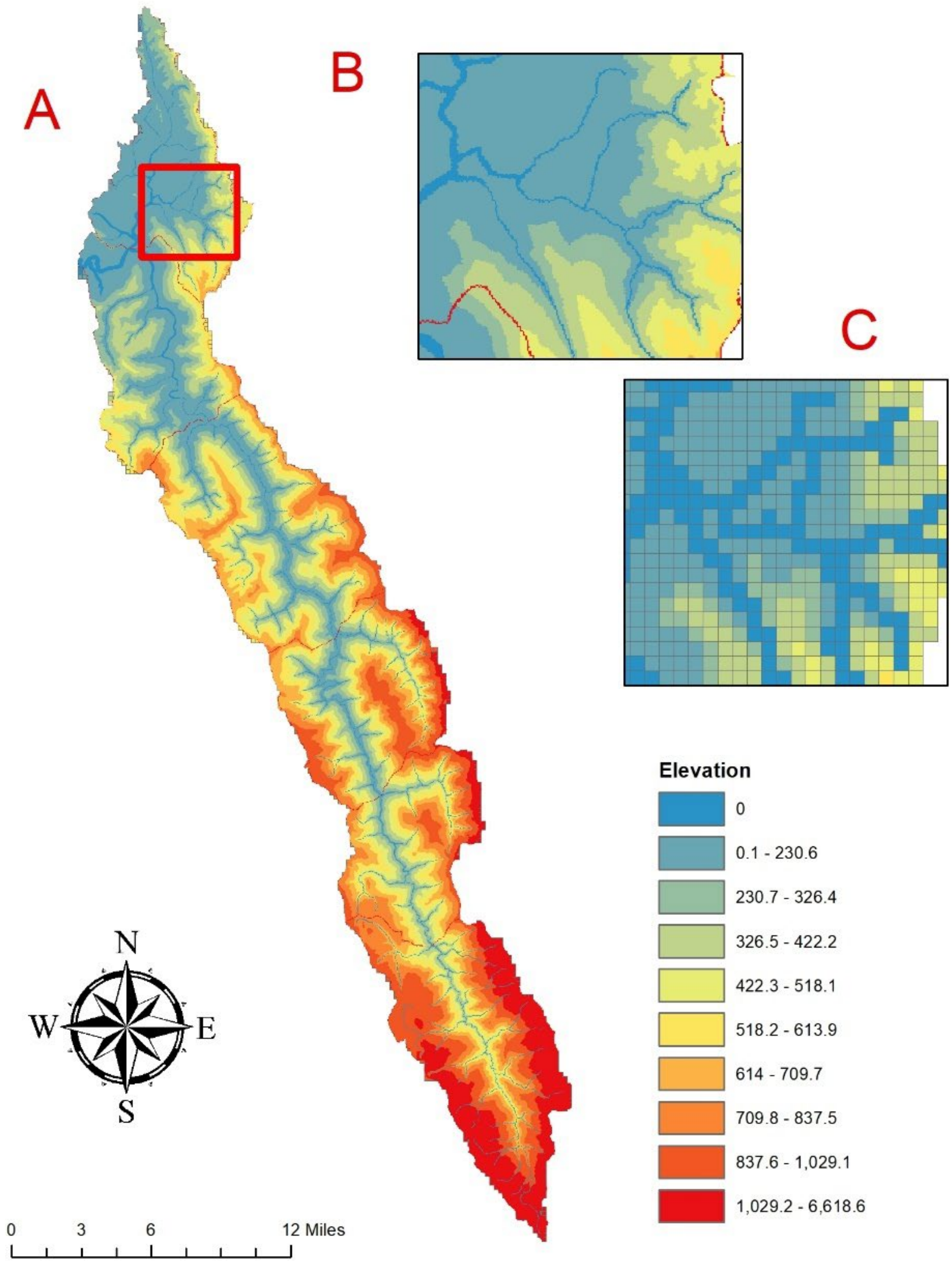


Figure 3. A) Original 30m hydrologically conditioned DEM for the Redwood Creek watershed, B)

inset of 30m hydrologically conditioned DEM area, and C) same inset showing DEM resampled to the 300m x 300m model grid.

3.6 Flow direction and flow accumulation

The FlowAccumulation class in pyGSFLOW includes the flow_direction and flow_accumulation methods to generate the direction and accumulation of flow needed to model streamflow routing, subbasins and calculate associated drainage paths. The flow_direction method in this class calculates the D8 flow method, which models flow direction to its steepest downslope neighboring HRU based on the calculated model grid elevations. The D8 method in pyGSLFOW specifies the direction of an HRU's flow to one of eight possible adjacent or diagonal neighbors with the steepest downward slope. Next, the flow_accumulation method takes the flow direction results to ultimately generate the flow accumulation raster at the model grid resolution, as shown in Figure 4. Flow accumulation is a calculation that determines how many cells flow into a given cell in a raster. From the image shown, it is evident that the mainstem and major streams generally have more accumulation of flow as compared to the smaller tributaries in the Redwood Creek watershed, which is a good representation of realistic drainage paths.

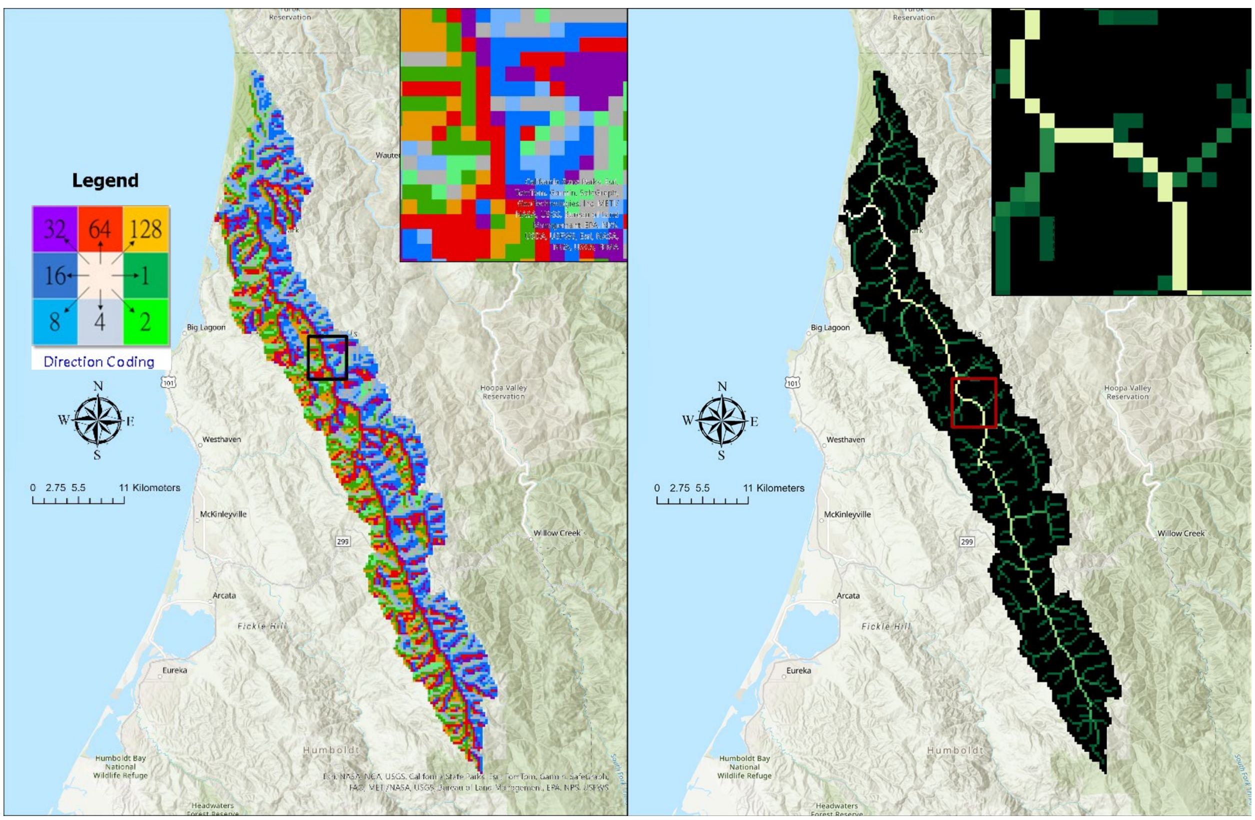


Figure 4. Flow direction and flow accumulation at the model grid scale

3.7 Development of Subbasin outlet points

Subbasins were developed using HUC12 boundaries as well as USGS streamflow gauge locations. Subbasins outlet points, also known as pour points, are developed through ArcGIS by manually creating points at desired outlet locations. The attribute table is also populated to indicate whether the point is a subbasin point or the main outlet of the watershed. A total of 8 pour points were developed considering HUC12 locations and streamflow gauge locations for calibration and downstream visual assessment. All pour points are subbasin points, and subbasin 1 represents the outlet of the watershed to the Pacific Ocean. PRMS has a subbasin module that allows flow simulation outputs at all designated subbasin points. The module allows cumulative flows as well as individual flow contributions from each delineated subbasin at temporal scales ranging from monthly to daily in metric or imperial units. The outputs specified for this model are at a daily time scale with average daily cfs time series available for each modeled subbasin outlet point.

3.8 Subbasin delineation, streamflow routing and cascades

The define _watershed and define_subbasin methods, as part of the flow accumulation class, takes the manually created subbasin points shapefile to generate the watershed and subbasin delineations. The HRUs outside of the model boundary are designated as HRU type=0, which is considered inactive, while the active HRUs get assigned subbasin numbers based on the attributes from the subbasin points shapefile.

The stream network routine uses the flow direction and flow accumulation arrays to define HRUs that need to be designated as streams. The make_streams method in the flow accumulation class takes the flow direction, flow accumulation, and threshold to classify and route streams. The threshold is the accumulated area threshold, which is the minimum number of cells for defining streams. The next step involves using the get_cascades method, which takes the generated stream network, pour points and model grid file to create cascades for PRMS. The get_cascades method ensures smooth and continuous downward slopes along streams by filling undeclared swales and populates cascade parameters that define the direction and proportion of overland and shallow subsurface flow routing used to calculate lateral flows from HRU to HRU, and HRU to streams, lakes, and model pour points. Figure 5 shows the modeled subbasins and pour points with an inset at a location to display a more focused view with the model grid.

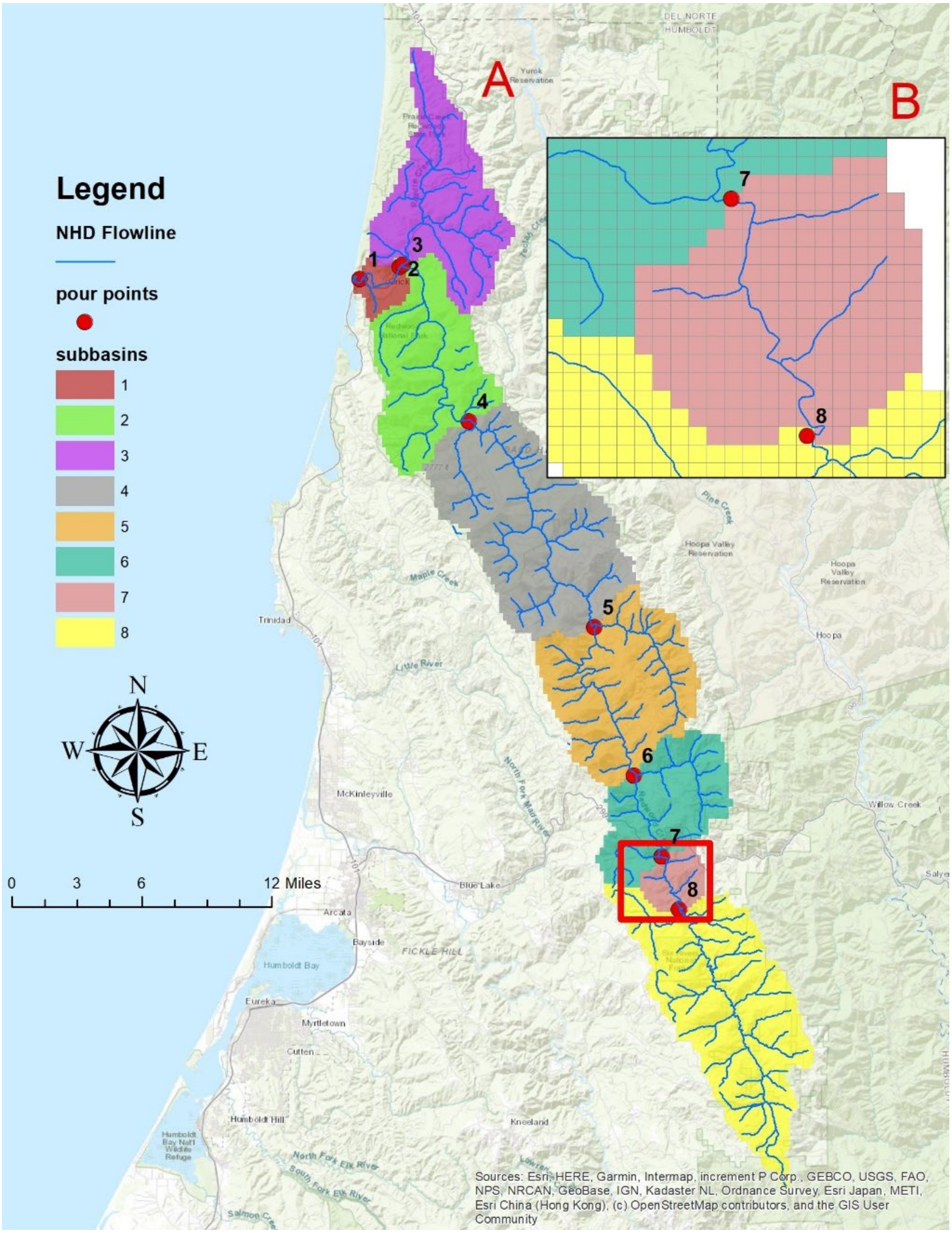


Figure 5. A) subbasin delineations with pour points. B) inset at a subbasin scale showing the model grid and pour points 7 and 8.

3.9 Vegetation input data

Raw vegetation raster datasets include Existing Vegetation Cover (EVC) and Existing Vegetation Type (EVT), available from the LANDFIRE data distribution site. The rasters are readily available at a 30m pixel resolution. The downloaded rasters were projected to the NAD83 UTM Zone 10 projected coordinate system and then resampled to the model grid resolution using the pyGSFLOW code. The builder_utils module in pyGSFLOW takes the resampled vegetation rasters and remap files to calculate PRMS vegetation parameters. Remap files are lookup files that translate LANDFIRE dataset codes to values that PRMS will accept. PRMS only accepts five types of vegetation including bare, grasses, shrubs, deciduous trees, and coniferous trees. As an example, remap files will take LANDFIRE vegetation type “California coastal redwood forest” from the resampled EVT raster and translate it to vegetation type 4, which is considered conifer in PRMS code. Figure 6 shows the EVT raster with the available vegetation type names directly from the LANDFIRE source. The code also takes the EVC raster to compute summer and winter vegetation cover densities. All PRMS vegetation parameters that get generated include covtype, covden_sum, covden_win, rad_trncf, snow_intcp, srain_intcp, and wrain_intcp. Additionally, at this stage of model development the pyGSFLOW code calculates the rooting depth for use with computing soil parameters. The flow direction that was computed in previous steps is used to calculate the hru_aspect and hru_slope parameters required by PRMS. The most up to date LANDFIRE vegetation data available was used for development of the Redwood Creek watershed model and updated remap files were obtained from USGS to translate the most recent LANDFIRE 2020 (LF 2.2.0) datasets.

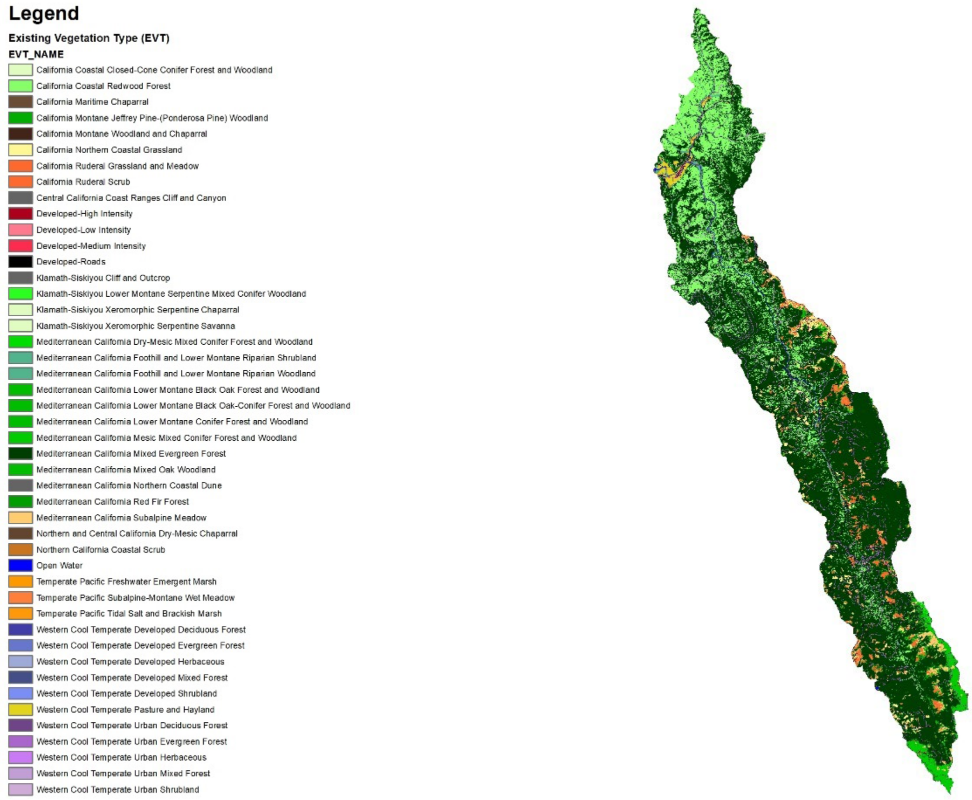


Figure 6. Raw Existing Vegetation Type (EVT) 30m raster from the LANDFIRE data distribution website

3.10 Soils input data

Raw input data related to soil properties was obtained from the Soil Survey Geographic Database (SSURGO) and State Soil Geographic (STATSGO2) datasets by the United States Department of Agriculture (USDA)'s Natural Resources Conservation Services (NRCS). Soil data is available as a large geodatabase for the state of California, so the Soil Data Development Toolbox was used in ArcGIS to extract raster datasets needed to develop soil zone parameters. Input raster datasets needed for pyGSFLOW include percent sand, percent clay, available water capacity (awc), and saturated hydraulic conductivity (ksat). All raw soil raster datasets were acquired and prepared using the Soil Data Development Toolbox (toolbox). Figure 7 shows raw awc and ksat rasters at the 30m resolution obtained from the toolbox prior to resampling to the Redwood Creek model grid. The prepared rasters were projected to the NAD83 UTM Zone 10 projected coordinate system and then resampled to the model grid resolution using pyGSFLOW. The builder_utils module in pyGSFLOW takes the resampled soil rasters, previously calculated rooting depth, hru_aspect and hru_slope to calculate PRMS soil parameters. PRMS soil parameters include soil type, soil_moist_init, soil_moist_max, soil_rechr_init, soil_rechr_max, ssr2gw_rate, slowcoef_lin, and slowcoef_sq.

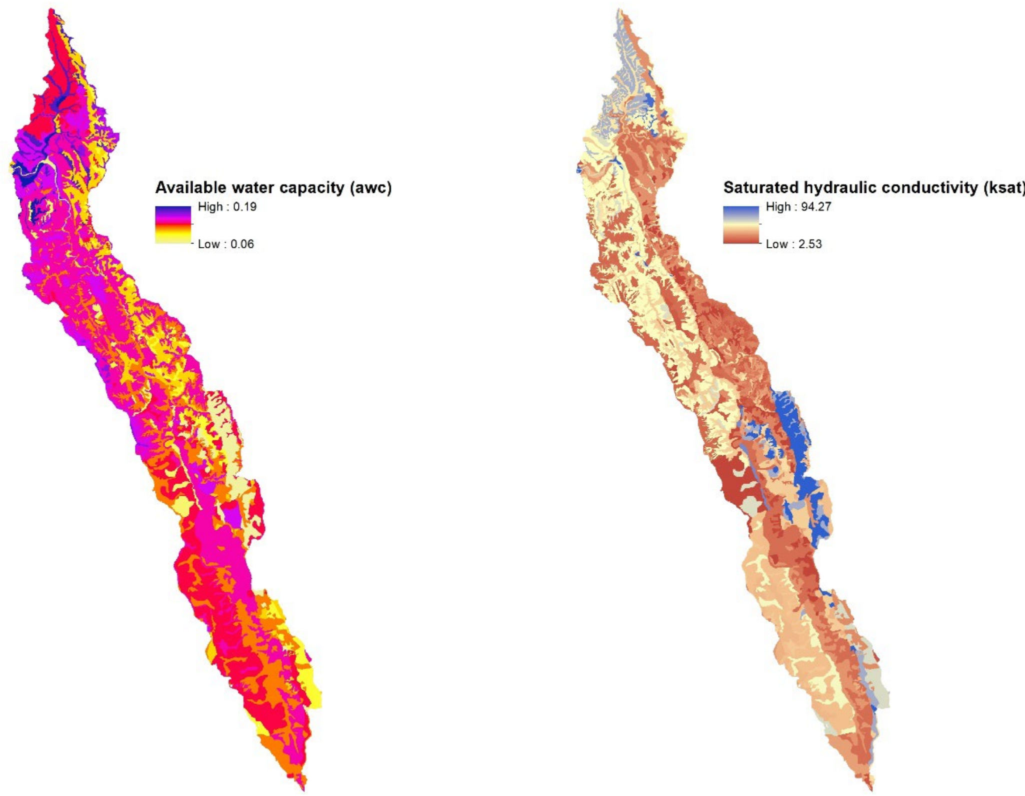


Figure 7. Available water capacity (awc) and saturated hydraulic conductivity(ksat) 30m raster datasets from NRCS, extracted using the Soil Data Development Toolbox

3.11 Impervious cover raster

The National Land Cover Database (NLCD) provides datasets on land cover and land cover changes at a 30m resolution and includes classification systems. The NLCD percent imperviousness raster is needed for pyGSFLOW to populate PRMS parameters related to impervious coverage. The downloaded raster was projected to the NAD83 UTM Zone 10 projected coordinate system and then resampled to the model grid resolution using pyGSFLOW. The builder_utils module in the code then takes the resampled percent impervious raster to calculate PRMS impervious coverage parameters, which include hru_percent_imperv and carea_max. As shown in Figure 8, the Redwood Creek watershed mainly consists of previous area except for roadways and the city of Orick.

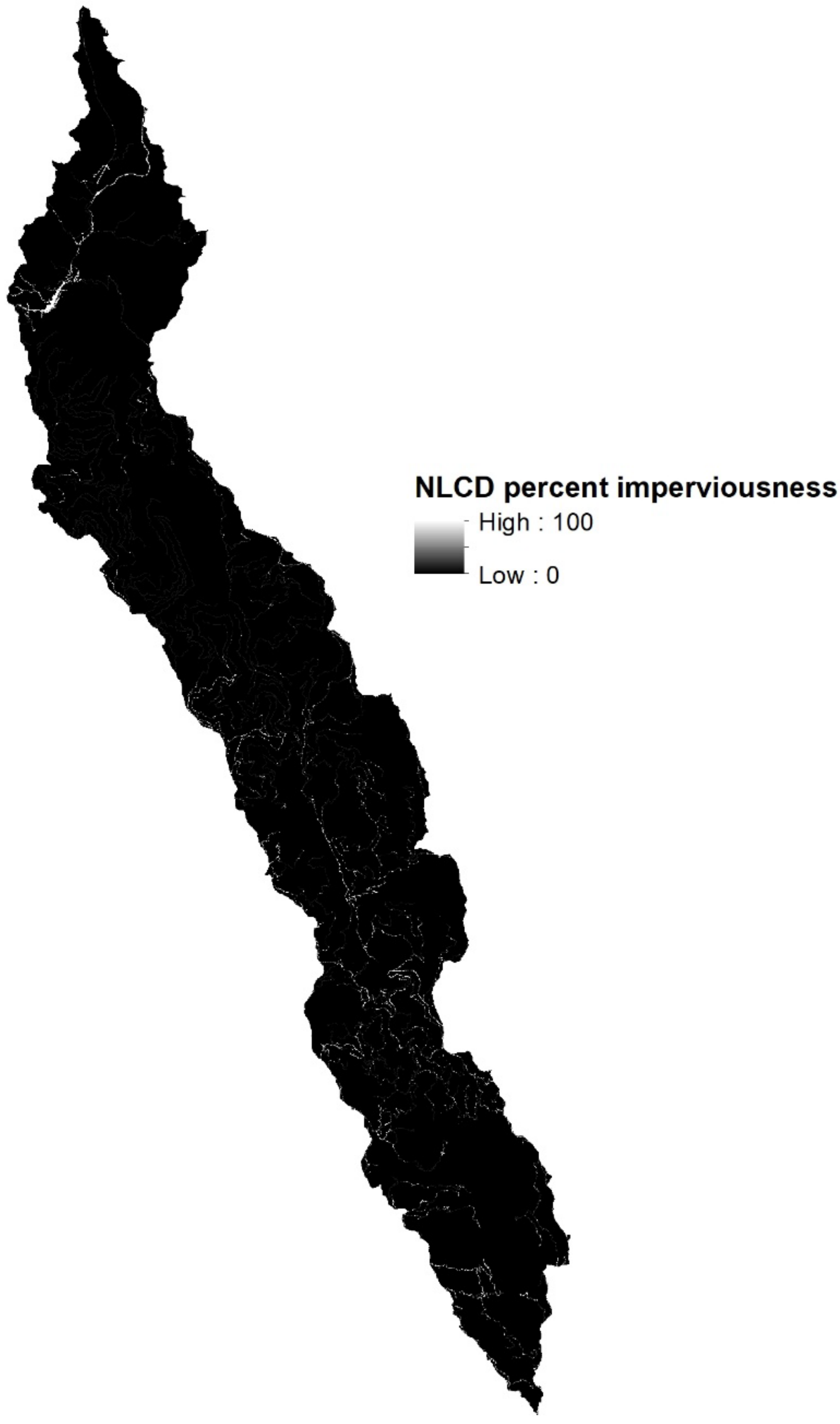
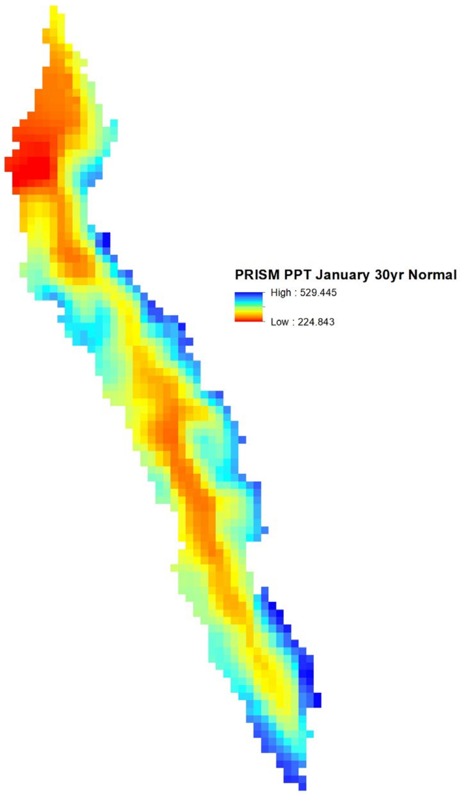


Figure 8. Percent imperviousness 30m raster obtained from the NLCD website

3.12 Baseline precipitation and temperature

Oregon State University (OSU) has a Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate group that provides advanced climate dataset models at various temporal scales ranging from daily to monthly time series. The advanced models are developed based on climate observations from a wide range of networks, incorporate sophisticated quality control measures, and are publicly available as open-source data products. Long term climate conditions are also modeled through data products more formally known as climate 30-year Normals. Normals are monthly average precipitation values spatially distributed at an 800m resolution and provide a baseline to determine precipitation variability throughout the watershed, based on the last 30 years of records. Normals are required for pyGSFLOW and include a maximum and minimum temperature along with a total precipitation value for each month. PRISM 800m Normals rasters were downloaded for each month as inputs to the python modeling tools. As an example, Figure 9 shows the 30-year Normals for the months of January and April for the Redwood Creek watershed boundary. The pyGSFLOW code takes the PRISM Normals rasters and resamples them to the model grid resolution. The builder_utils module in the code calculates the PRMS parameters rain_adj and snow_adj for each HRU by dividing the mean monthly PRISM Precipitation Normals by the mean monthly Precipitation from the station shown in Table 1. The ratio is used to spatially distribute the daily precipitation to each HRU. For instance, there may be a specific HRU that shows the long term 30-year normal precipitation for January as 216 mm while the mean monthly January precipitation at the observation may be 180 mm. The rain_adj factor for that specific HRU would be 1.2 for the month of January (216 divided by 180). This factor is multiplied by the daily precipitation that occurs in January at the observation station for that specific HRU. This computation is calculated for all HRUs for each month of the calendar year, allowing a more realistic distribution of precipitation. The rain_adj factor is a calibration parameter that can be adjusted during the streamflow volume calibration stage to increase or decrease the amount of water available to the watershed model, as discussed later in this report.



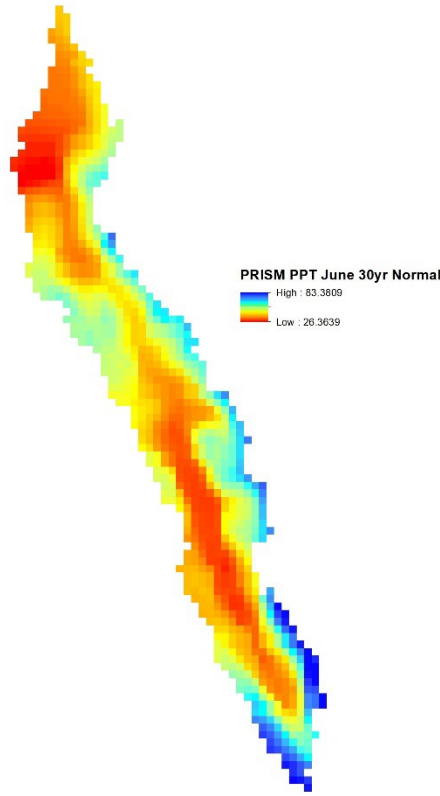


Figure 9. PRISM 30-year 800m resolution Precipitation Normals for January and June for the Redwood Creek watershed

3.13 Daily precipitation and temperature stations

Daily precipitation and temperature observation station metadata was first downloaded from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information website. The results were plotted alongside the watershed boundary shapefile, stream network and subbasin delineations to get an idea of the spatial distribution of climate stations. Additionally, stations from the Western Regional Climate Center website were also downloaded and plotted. The model's start and end times are from October 1, 1981 to February 28, 2023, respectively. Stations with a period of records prior to the model's start time were eliminated since it is not possible to use them in model development.

Observation climate stations may have data gaps that need to be filled prior to using those stations to develop a model. Data gaps can occur from missing observation records due to various reasons including, but not limited to, periods of service/maintenance, periods of deactivation/reactivation, and/or permanent deactivation. To fill data gaps correctly, a degree of certainty with high confidence needs to be established between stations of missing data and the alternative data source that is used for gap filling. For this purpose, OSU's PRISM was used as the alternative gap filling source. PRISM provides a spatial distribution for daily precipitation and temperature data at 4 km resolution. The latitude and longitude of observation stations with data gaps were used to determine appropriate PRISM locations for each precipitation station. A regression analysis was then developed between observation stations and corresponding PRISM daily values to ensure that there is a good fit with a high correlation (i.e., high R^2 factor). A high correlation ensures a certain level of certainty in PRISM data being a reliable alternative source to fill gaps in the observed data. Another objective for developing statistical models for precipitation and temperature stations is that if a station becomes inactive in the future, there will be a high level of certainty in using PRISM as an alternative data source to compensate for missing data for future model updates. After conducting a regression analysis, the list of precipitation stations available to use for the model was narrowed down to those with the highest R squared values. The most recent release of PyGSFLOW is set up to accept one precipitation station, so the station was selected based on proximity, how well the station represents precipitation in the watershed, and a high R squared value between PRISM 4k daily values. The data gaps in the observations station were filled using PRISM 4km daily values at the equivalent lat/long. Figure 10 shows the locations of the climate stations and *Table 1* summarizes station metadata along with the R squared correlation value against PRISM 4km daily values.

Figure 10. PRMS Precipitation, Base and Lapse rate Temperature Stations designated for the Redwood Creek watershed PRMS model

Table 1. PRMS meteorological station designations for the Redwood Creek model.

PRMS Station	Station ID	Latitude	Longitude	Elev (m)	Station Period of Record	R^2 vs. PRISM Daily 4km Point	Station Name and Link
PRECIP	US1CAHM0047	40.658	-123.925	745.5	9/22/2000 - 11/08/2020	0.92	HYDESVILLE 11.4 NE, CA US
Base TMAX/ TMIN	USC00046498	41.362	-124.019	48.8	05/01/1937 - 10/31/2012	0.76	ORICK PRAIRIE, CA US
Lapse TMAX/ TMIN	USR0000CSHH	41.138	-123.906	804.7	01/04/2001- active	0.72	SCHOOL HOUSE, CA US

Temperature is distributed to HRUs using a base observation station and a lapse rate observation station. The base station is at the lower elevation, while the lapse rate station is designated as the higher elevation station. For Redwood Creek, the base and lapse rate stations are shown in Table 1. For temperature distribution in the model, the base station and lapse rate station selection criteria was based on elevation, proximity, how well the station represents overall temperature in the watershed, and a high R squared value. The following formula from the PRMS modeling computation is used to determine the lapse rate for each month, and the same calculation is repeated for TMIN:

$$TMAX_{Laspe\ Rate} = \frac{\text{Mean Monthly } TMAX_{Laspe\ station} - \text{Mean Monthly} TMAX_{Base\ Station}}{Elevation_{Lapse\ station} - Elevation_{Base\ station}} * (1000)$$

The temp_1sta module in PRMS takes the computed temperature lapse rate to distribute temperature to HRUs based on their elevations. For each increase in 1000 elevation units, the temperature of the base temperature station is adjusted by the lapse rate and set as the HRU temperature. This computation provides a more realistic spatial distribution of temperature throughout the model domain.

The builder_utils module also takes the mean monthly TMAX and TMIN values from the observation station along with the model grid to calculate the PRMS parameter jh_coef for all HRUS, which is used to estimate the spatial potential evapotranspiration for the model. Finally, the climate parameters are written in the parameter file, and the pandas python package is used to establish the correct formats before writing the daily observation climate station time series to the PRMS data file. The last step of the development process involves writing the entire model, including the control, parameter, and data files to the output folder location.

4 Model calibration

4.1 Stepwise, multi-objective calibration approach

A stepwise, multi-objective calibration approach is more effective in capturing more realistic hydrologic modeled processes. Hydrologic processes are interdependent, so it is important to calibrate a model using a stepwise approach. The approach involves calibrating hydrologic process including solar radiation, potential evapotranspiration (PET), streamflow volume, and streamflow timing in the order listed. Solar radiation is the first step in the stepwise approach because it impacts every other hydrologic process either directly or indirectly. The solar radiation hydrologic process calculates the total amount of energy available from the sun, which has a direct impact on the amount of water loss that can occur from PET. Calibrating for PET is the second step in the multi objective stepwise process. Modeled PET determines watershed losses after precipitation events, which has a direct impact on the amount of water left in the basin for runoff and storage. The last step involves calibrating streamflow volume at a monthly and daily scale, adjusting model parameters to better capture the monthly and daily streamflow rate/timing.

4.2 Solar radiation

The National Renewable Energy Laboratory (NREL) has a National Solar Radiation Database (NSRDB) that can be used to obtain gridded solar radiation. The values are spaced at 4km and are a result of an advanced model developed by NREL. There are not many solar radiation measurement stations to obtain observed data for calibration, although point source observations should be utilized where available. Global Horizontal Irradiance (GHI) is the observed variable while the simulated solar radiation is defined by the PRMS output variable basin_orad. Note that GHI is reported in $W/m^2/hour$ while the PRMS variable basin_orad is reported in Langley/day. GHI was converted to Langley/day for a successful calibration. GHI in $W/m^2/hour$ was obtained for the Redwood Creek watershed boundary from the NSRDB viewer. An R script was written to convert GHI from $W/m^2/hour$ to Langley/day, and daily values averaged to mean monthly values. Solar radiation was simulated in PRMS by the ddsolrad module. The parameters dday_intcpt and dday_slope are the two coefficients that were adjusted during calibration. Parameter values were adjusted through a trial-and-error process until simulated potential solar radiation was optimized against observed GHI values. Calibration results for solar radiation are shown in Figure 11.

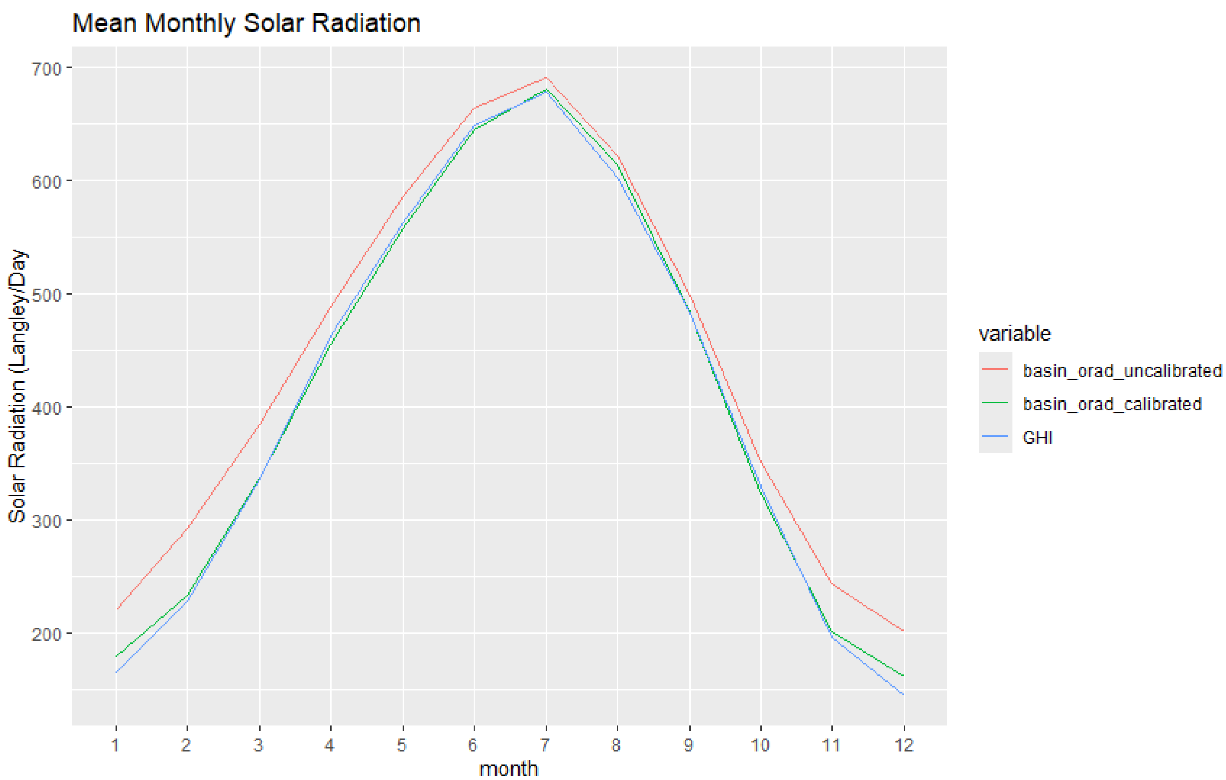


Figure 11. Solar radiation calibrated on a mean monthly scale using GHI from NREL's NSRDB

4.3 Potential evapotranspiration

The second step in the stepwise multi-objective calibration process is to calibrate potential evapotranspiration (PET). PET is a measure of the amount of water loss from the system and it directly impacts other hydrologic processes such as water budget and streamflow volume. Reference values were obtained from the California Irrigation Management Information System (CIMIS) Reference ETo zones chart. The Redwood Creek watershed completely falls into Reference Evapotranspiration (Eto) zone 3, which is defined as "Coastal Valleys & Plains & North Coast Mountains." The values are reported in inches/month and are used as the observed monthly values, while simulated PET is defined by the PRMS output variable pot_et. Daily pot_et was converted to mean monthly values for a successful calibration. Potential evapotranspiration was simulated in PRMS by the potet_jh module, which is a formulation of a procedure developed by Jensen and Haise (1963). The parameter jh_coef is the coefficient in the Jensen-Haise equation that was adjusted. The parameter was adjusted through trial and error until simulated potential evapotranspiration was optimized against referenced ETo values. Calibration results for potential evapotranspiration are shown in Figure 12.

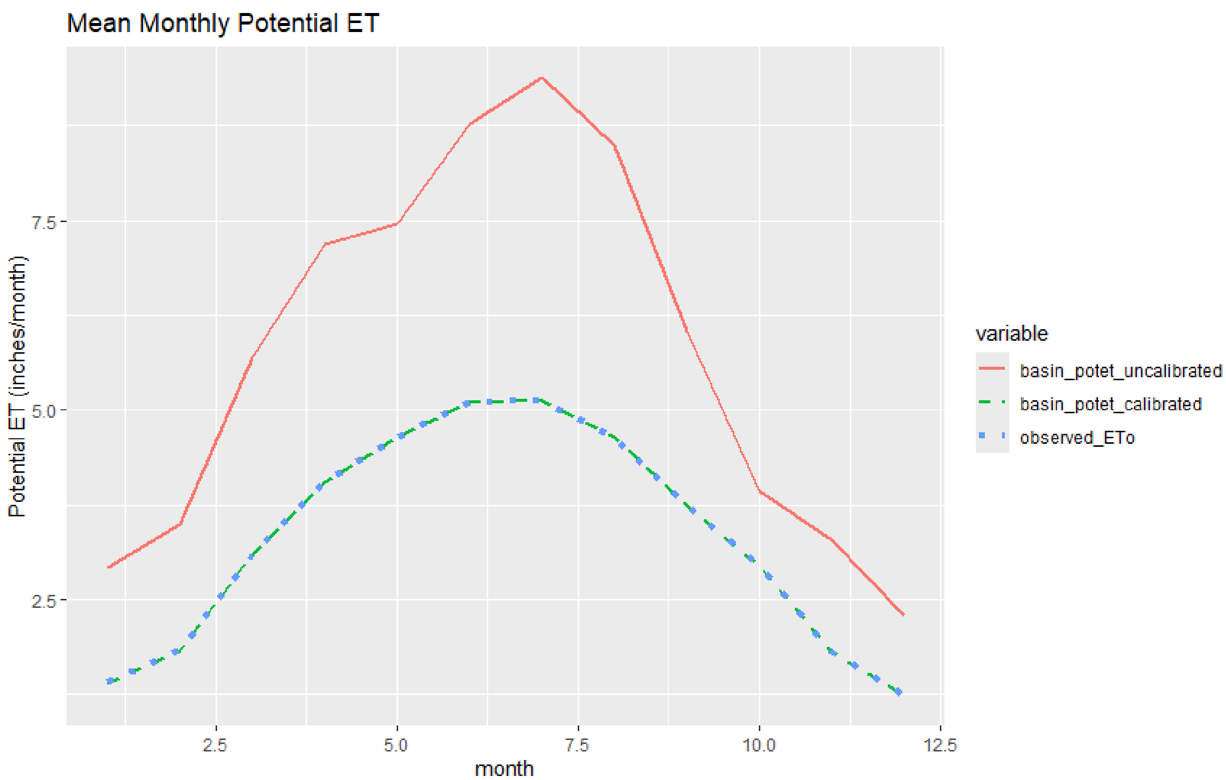


Figure 12. PET calibrated on a mean monthly scale using reference ETo from CIMIS

4.4 Streamflow volume and timing/rate

The first two steps of the calibration process gave us a greater level of confidence in the simulation of water loss from the basin through potential evapotranspiration. The unknown/uncertain values remain to be streamflow volume and timing. To adjust the model for streamflow volume, the initial simulated hydrograph was first examined against the observed streamflow calibration gauge at Redwood C NR Blue Lake Ca.

The most upstream gauge, USGS 11481500 Redwood C NR Blue Lake, was selected as the reference calibration and validation gauge. For the Redwood C NR Blue Lake, CA gauge, the first 2/3rd of the period of record from water years October 1, 1985 to September 30, 2010 was used for model calibration and the last 1/3rd of the period from water years October 1, 2010 to September 30, 2022 was used for model validation. The most downstream gauge in the watershed is USGS 11482500 Redwood C a Orick CA, and it was not used to validate model performance since it is subject to most upstream water diversions in the Redwood Creek watershed. Redwood C a Orick Ca was plotted against associated modeled flows (outlet of subbasin 2) at various temporal hydrographs for the sole purposes of visually assessing model agreement. Because the intent is to calibrate the model to estimate unimpaired flows, the most upstream and unimpaired gauge was used to calibrate and validate the model and general model agreement was verified through visual analysis at the downstream gauge.

Parameters that were evaluated include soil_moist_max, sat_threshold, slowcoef_lin, slowcoef_sq, ssr2gw_rate, gwflow_coef, gwsink_coef, pref_flow_den, and fastcoef_sq, soil2gw_max, and rain_adj. Soil_moist_max is the water holding capacity of the soil profile for each HRU, and has a major impact on all other parameters. Sat_thrshold is the water holding capacity of the gravity and preferential flow reservoirs; difference between field capacity and total soil saturation for each HRU. Both soil_moist_max and sat_threshold have a higher degree of impact on high flows, although intermittent flow and low flows are also impacted depending on the watershed. Slowcoef_lin and slowcoef_sq are coefficients in equation to route gravity reservoir storage down slope for each HRU, and they impact all range of flows. Soil_rechr_max is the maximum amount of storage for soil recharge zone, which is the upper part of the capillary reservoir model zone where losses occur as both evaporation and transpiration. Ssr2gw_rate is the coefficient in equation used to route water from the gravity reservoir to the groundwater reservoir (GWR) for each HRU. Gwflow_coef is a coefficient in equation to compute groundwater discharge for each GWR, and gwsink_coef is used to compute outflow to the groundwater sink for each GWR. Pref_flow_den is the top layer of the soil fraction where preferential flow and fast interflow occur for each HRU. Fastcoef_lin and fastcoef_sq are coefficients in equation to route preferential-flow storage down slope for each HRU. Soil2gw_max is the water in the capillary reservoir zone that is routed directly to GWR for each HRU. A more detailed description of all PRMS parameters and the physical based equation used to compute hydrologic flow computations is provided in the PRMS manual and training videos, which is publicly available through the USGS website.

The model was optimized for the dry season and wet season, separately in two parts. The first optimization better captures the spring recession and summer base flows, which includes the dry season from May to the end of September. The second optimization better captures flows for the rest of the season, which covers the wet season from October to April. Parameters were adjusted and the unimpaired gauge was analyzed against the associated drainage area until flows were optimized. For both optimizations, the calibration period is from October 1, 1985 to September 30, 2010 and validation from October 1, 2010 to September 30, 2022. The optimized flows were evaluated for both the calibration and validations periods using objective function metrics as discussed in the model evaluation section of this report.

For the first optimization, dry season flows were optimized from the spring recession and summer base flow season from May to the end of September. The water holding capacity of the soil zone was generally increased by multiplying soil_moist_max by 2 times the original values because initial values produced hydrological responses that were greater than what the unimpaired gauged flows showed. Sat_threshold was optimized by setting the initial spatial values to soil_moist_max and then multiplying by three. Pref_flow_den is the capacity of the top layer of the soil where preferential flow and fast interflow occur. Preferential flow was increased by setting the parameter pref_flow_den to 0.05. Fastcoef_sq was set to a value of 0.2 to decrease the fast interflow routing storage downslope for each HRU, which decreased unnecessary spikes (noise) from the summer base flows. Soil2gw_max was optimized by increasing the value to 0.15, increasing the capillary reservoir excess water routed directly to the GWR reservoir, decreasing summer base flows. Gwsink_coef was also increased to 0.043 to get the dry season summer bases flows low enough, particularly during the dryest months. Ssr2gw_exp and ssr2gw_rate are parameters that are associated with the saturated hydraulic conductivity of the soil zone. Through trials ssr2gw_exp was kept at the default optimized value of 1.0 and the original ssr2gw_rate was multiplied by a factor of 0.0035. Gwflow_coef was one of most sensitive parameters for this watershed, and it was increased to a value of 0.045 to optimize and increase the flow routing to streams during the spring recession to the transition into the dry season summer base flows.

For the second optimization, the wet season was optimized to better capture flows from October to April. Soil_moist_max, sat_threshold, slowcoef_lin, slowcoef_sq, ssr2gw_exp, pref_flow_den, and fastcoef_sq were left unchanged from the first optimization. Gwsink_coef was increased by setting the value to 0.028 to increase wet season baseflows. Gwflow_coef was also increased to 0.05 to optimize the flow routing to streams for flows during the wet season. Soil2gw_max was decreased slightly by setting the value to 0.1 to increase intermittent and peak flows during the wet season. Soil_rechr_max decreased to 0.5 of the original values to reduce the amount of water in the soil recharge zone available for evapotranspiration, which further optimized the wet season baseflows. Ssr2gw_rate was optimized by multiplying the original values by 0.0025 to increase intermittent and peak flows during the wet season. Finally, rain_adj was slightly decreased to 90% of original values for the months of December and January. Table 2 provides a summary of the scaling factors or parameter values that were adjusted for the final calibration of the Redwood Creek watershed PRMS model.

Table 2. PRMS calibration parameters adjusted for both Optimization 1: May-Sep and Optimization 2: Oct-Apr

Parameter	**optimization1_May_to_Sep**	**optimization2_Oct_to_Apr**
Rain_adj	-	x0.9 for Dec and Jan
soil_moist_max	x2	x2
sat_threshold	x3	x3
soil_rchr_max	-	x0.5
slowcoef_lin	-	-
slowcoef_sq	-	-
ssr2gw_rate	x0.0035	x0.0025
ssr2gw_exp	-	-
gwflow_coef	0.045	0.05
gwsink_coef	0.043	0.028
pref_flow_den	0.05	0.05
fastcoef_lin	-	-
fastcoef_sq	0.2	0.2
soil2gw_max	0.15	0.1

5 Model Evaluation

5.1 Hydrostats and HydroErr Python Packages

Hydrostats is a python-based hydrology package used to evaluate model performance. It allows for daily, mean monthly, and seasonal flow performance evaluations with access to dozens of objective functions. The package's source code contains an example Jupyter notebook, and the documentation contains details on how to set up certain functions to produce evaluation metrics, charts, and output files. HydroStats has a package dependency called HydroErr which allows access to over 70 objective functions and helps deal with NAN, negative, and inf values. Hydrostats python code was modified by SWRCB staff to include seasonal evaluation metrics since the focus of this calibration effort was to optimize flows for wet season (Oct-Apr) and dry season (May-Sep) separately. The modified scripts were utilized to generate seasonal hydrostats plots and objective function metrics as discussed in the next section.

5.2 Redwood creek model evaluation metrics

The Redwood Creek watershed PRMS model was developed to run for the period from October 1st, 1981, to February 28, 2023. However, model calibration was conducted for the period of October 1st,1985 to September 30th, 2010. The Redwood Creek model was then validated for the period from October 1st, 2010 to September 30th, 2022 to check on the model performance for a set of data that was not used during calibration. The appendix includes a full set of plots and summaries of calibration results for solar radiation, PET, seasonal flow daily time series, monthly mean cfs, mean monthly cfs, R squared, and seasonal water year averages for each optimization. Optimization 1 is for the dry season period from May to September and optimization 2 captures the wet season period from October to April. The hydrographs in the appendix have objective function metrics displayed on the charts for each optimization and relative seasonal period. Table 3 provides a summary of key objective function metrics of observed versus simulated flows as the gauges indicated for both seasonal optimizations. When examining results, it is important to note that California has experienced severe droughts since 2012. The California Palmer Drought Severity Index reports thirteen of the most 30 driest months on record occurring from 2012 to 2016, and drought conditions persisting largely through 2021 to 2022.

Table 3. Summary of Objective Function Metrics for both Optimization 1: May-Sep and Optimization 2: Oct-Apr

Gauge ID	Gauge Name	Type/Use Case	PRMS Subbasin	NSE		R^2		NRMSE	
				May-Sep	Oct-Apr	May-Sep	Oct-Apr	May-Sep	Oct-Apr
11481500	Redwood C NR Blue Lake, CA	Calibration 1985 to 2010	7	0.80	0.75	0.82	0.75	0.79	0.69
		Validation 2010 to 2022	7	0.86	0.72	0.87	0.73	0.63	0.72
11482500	Redwood C a Orick CA	Impaired 1985 to 2022	2	0.81	0.77	0.86	0.77	0.78	0.69

6 Limitations

The Redwood Creek watershed PRMS model was developed using the pyGSFLOW workflow, which is a rapid watershed model development process. The current version of pyGSFLOW is set up to develop rapid watershed models with only one precipitation station designation. Future releases of the tools may include the ability to incorporate more precipitation zones; however, the internal calculation of the rain_adj parameter in PRMS does account for spatial variability of precipitation throughout the model domain. The Redwood Creek PRMS model does not take diversion data or water use data into account, so any water availability analysis would need to be conducted using external supplemental resources such as the Demand QA/QC Methodology, Drought Water Rights Allocation Tool (DWRAT), and/or the Water Evaluation and Planning System (WEAP).

7 Conclusion

The Redwood Creek watershed hydrologic PRMS model was developed using python-based tools called pyGSFLOW. The model grid resolution was set to 300m x 300m, with subbasin pour points set at the HUC12 scale along with one unimpaired calibration gauge and one downstream impaired gauge location. Modeling input raster and climate datasets were acquired from open-source, publicly available resources. Gaps in climate precipitation and temperature stations were filled using PRISM daily data. The model was calibrated using a stepwise, multi-objective calibration approach that takes solar radiation, PET, streamflow volume and streamflow timing/rate into consideration in the order listed. A stepwise, multi-objective approach is more effective in capturing realistic hydrologic processes to ensure watershed losses are properly accounted for first before adjusting parameters values related to streamflow volume and timing/rate. The most unimpaired gauge (11481500) was used to calibrate the model from water years 1985 to 2010 and validate performance from water years 2010 to 2022. The most downstream gauge was used to visually assess model agreement, although it was not used as calibration/validation gauge because it is subject to upstream water diversions from the Redwood Creek watershed. D.N Moriasi and others (2007) conducted an in-depth analysis of industry wide metrics used to assess model performance and provide opinions on the most statistically significant metrics and commonly accepted values to deem a model satisfactory. In general, model simulation can be judged as satisfactory if NSE > 0.50 and RSR < 0.70, and if PBIAS =25% for streamflow. Overall, the Redwood Creek model has a performance rating ranging from satisfactory to good. The model was calibrated to capture unimpaired flows with two optimizations, one for the dry season (May to Sep) and the other for the wet season (Oct to Apr). Because PRMS is a modular and open-sourced modeling system, users can acquire the model and recalibrate parameters to better capture certain seasons or flows to meet flow objectives for specific applications. The Redwood Creek watershed PRMS model is available through the following GitHub repository:

https://github.com/CAWaterBoardDataCenter/Redwood-Creek-PRMS-Hydrologic-Model.git

8 References

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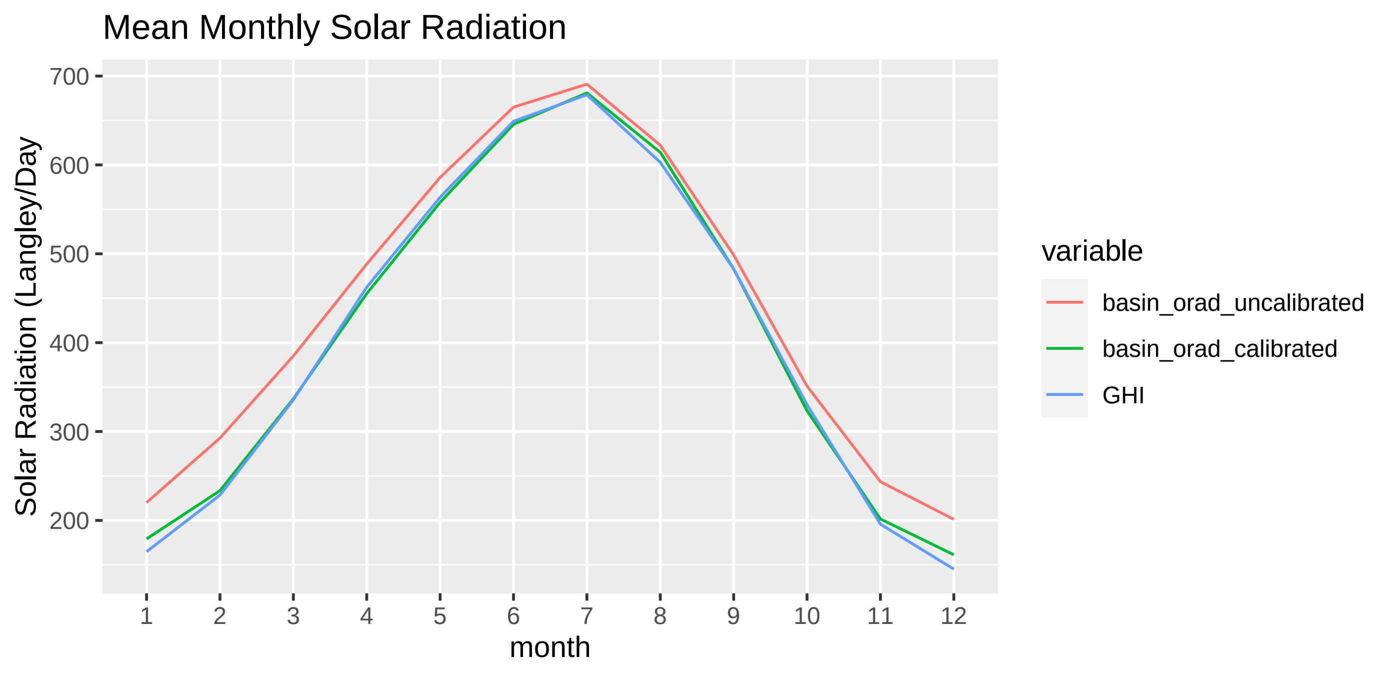
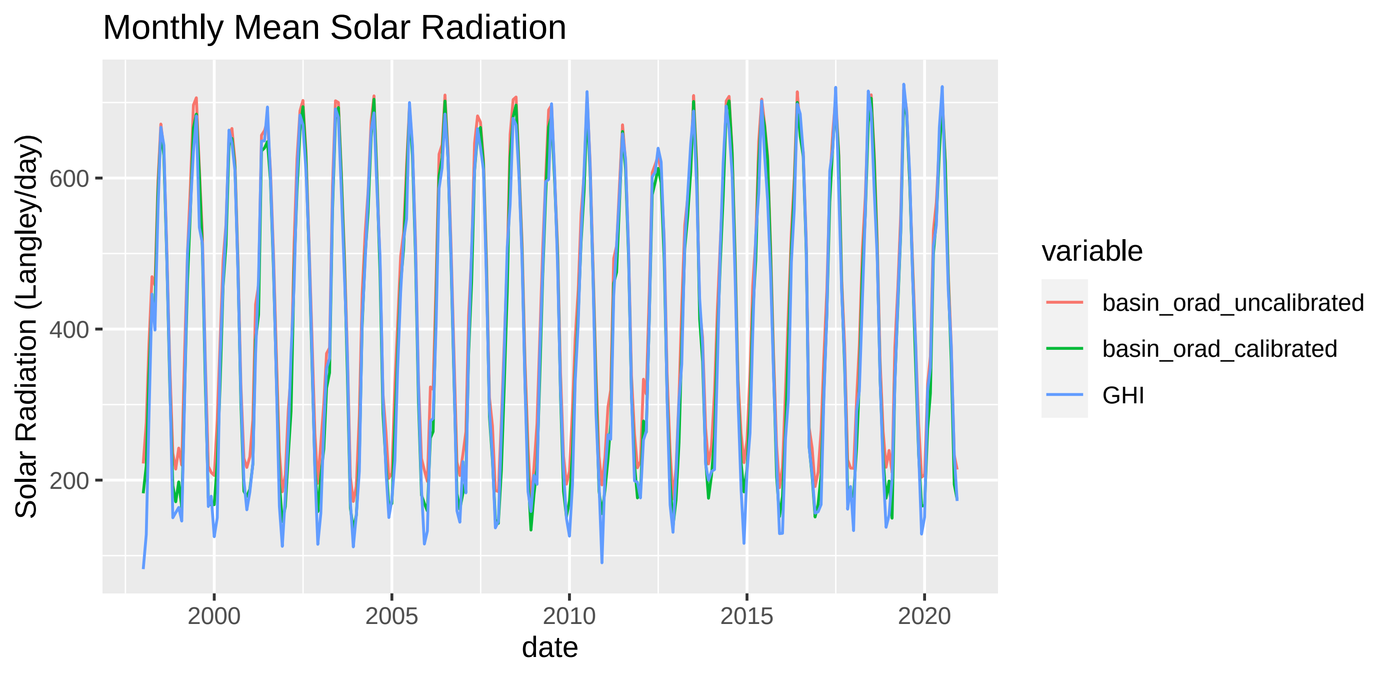
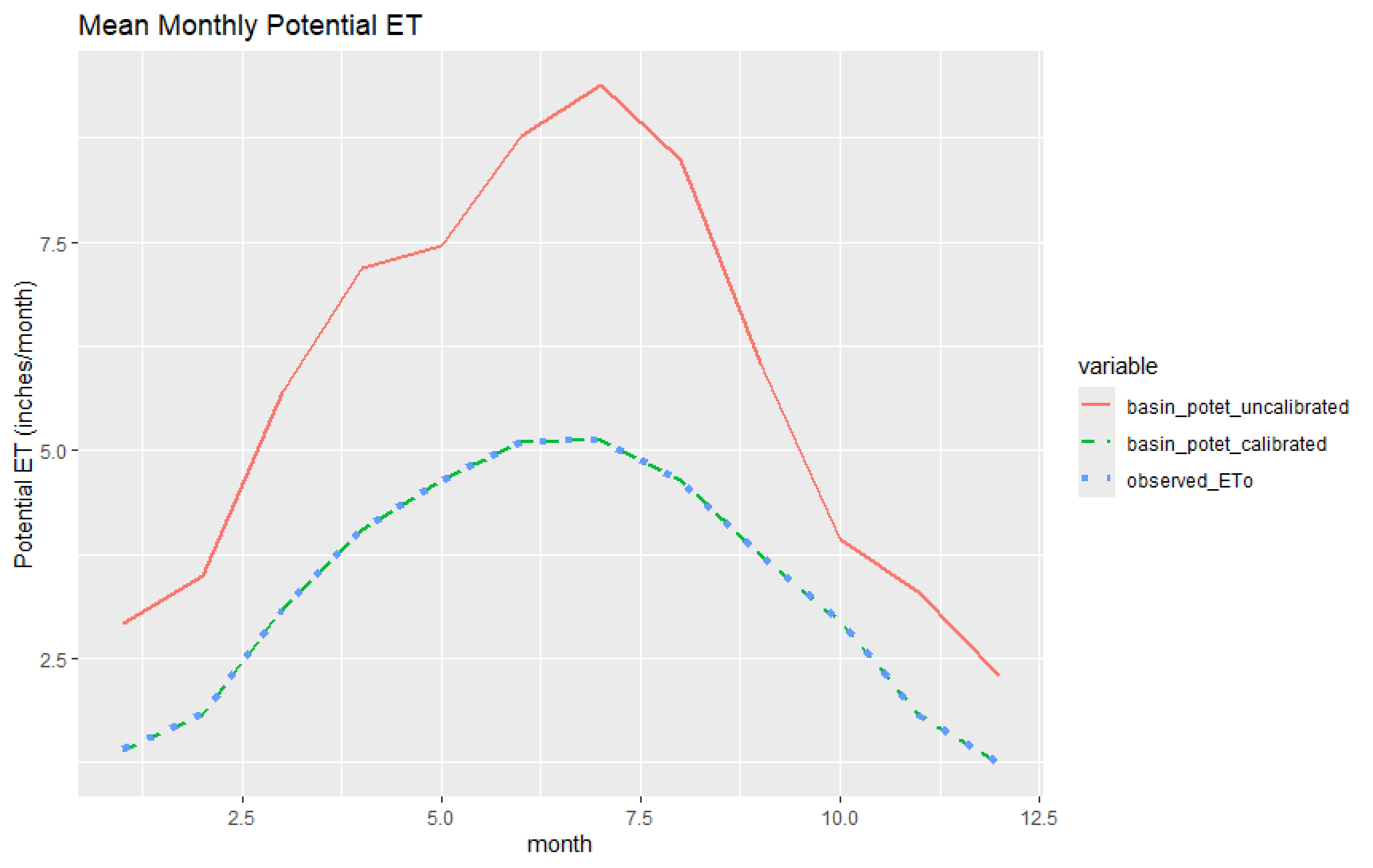
Appendix


Mean Monthly Solar Radiation
Solar Radiation (Langley/Day
700
600
500
400
300
200
1
2
3
4
5
6
7
8
9
10
11
12
month
variable
basin_orad_uncalibrated
basin_orad_calibrated
GHI



Monthly Mean Solar Radiation
Solar Radiation (Langley/day)
600
400
200
2000
2005
2010
2015
2020
date
variable
basin_orad_uncalibrated
basin_orad_calibrated
GHI



Mean Monthly Potential ET
Potential ET (inches/month)
7.5
5.0
2.5
2.5
5.0
7.5
10.0
12.5
month
variable
basin_potet_uncalibrated
basin_potet_calibrated
observed_ETo

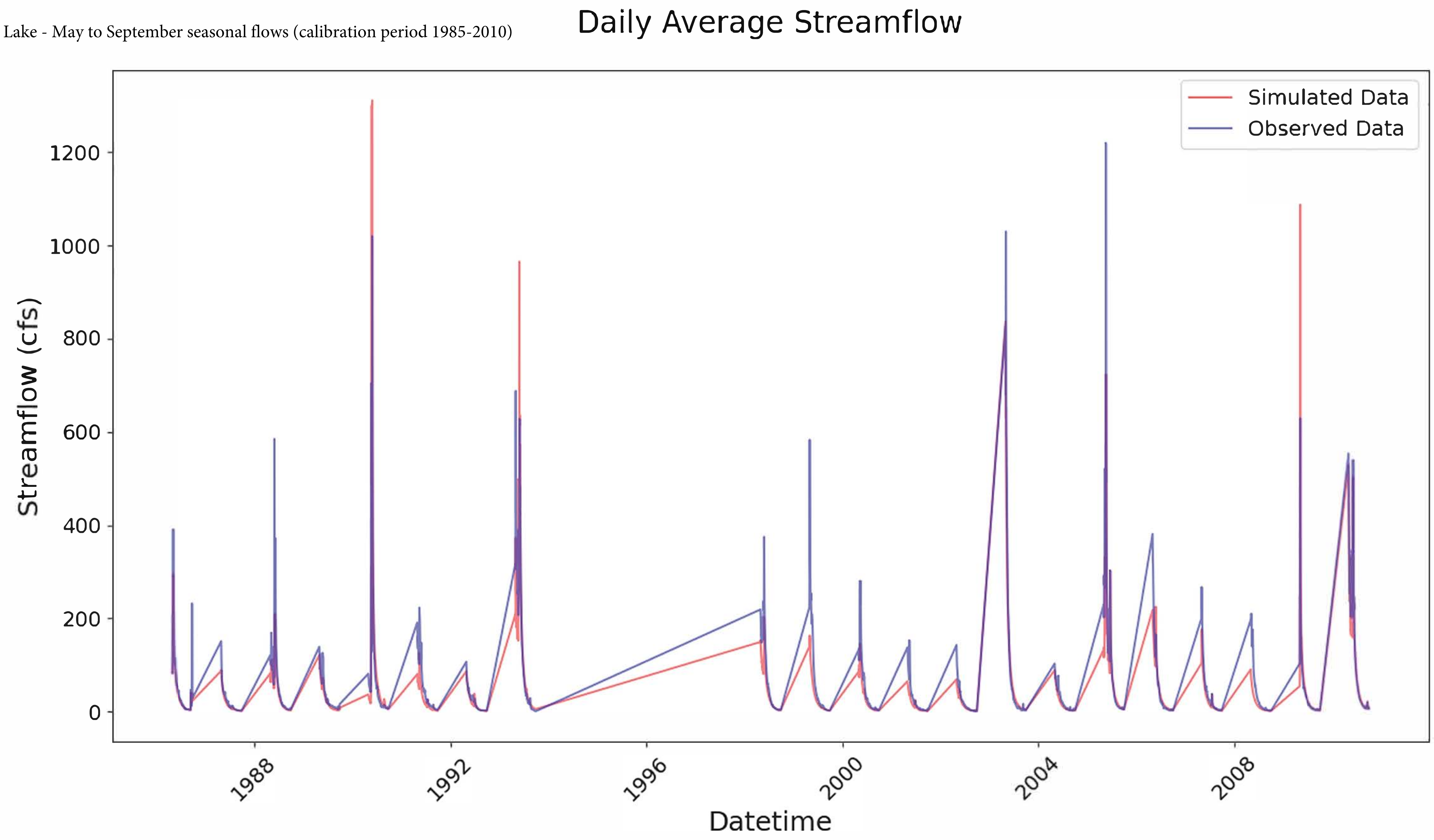
Redwood C nr Blue Lake Ca (11481500)

Calibration period: 1985 to 2010

Validation period: 2010 to 2022

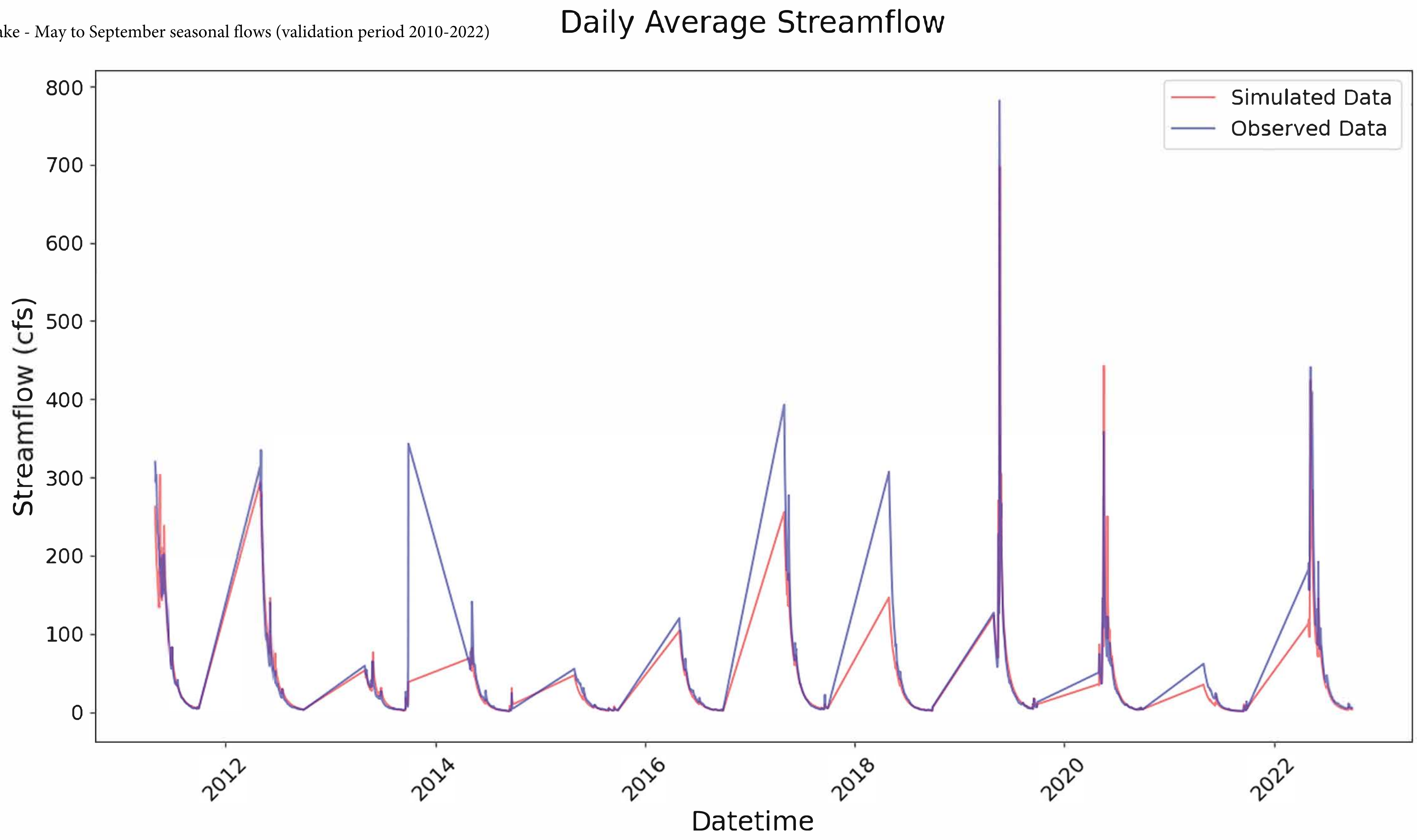
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal flows (calibration period 1985-2010)

ME=-11.733
MAE=18.001
NSE=0.802
r2=0.817
d=0.941
NRMSE (Mean)=0.786
RMSE=44.482



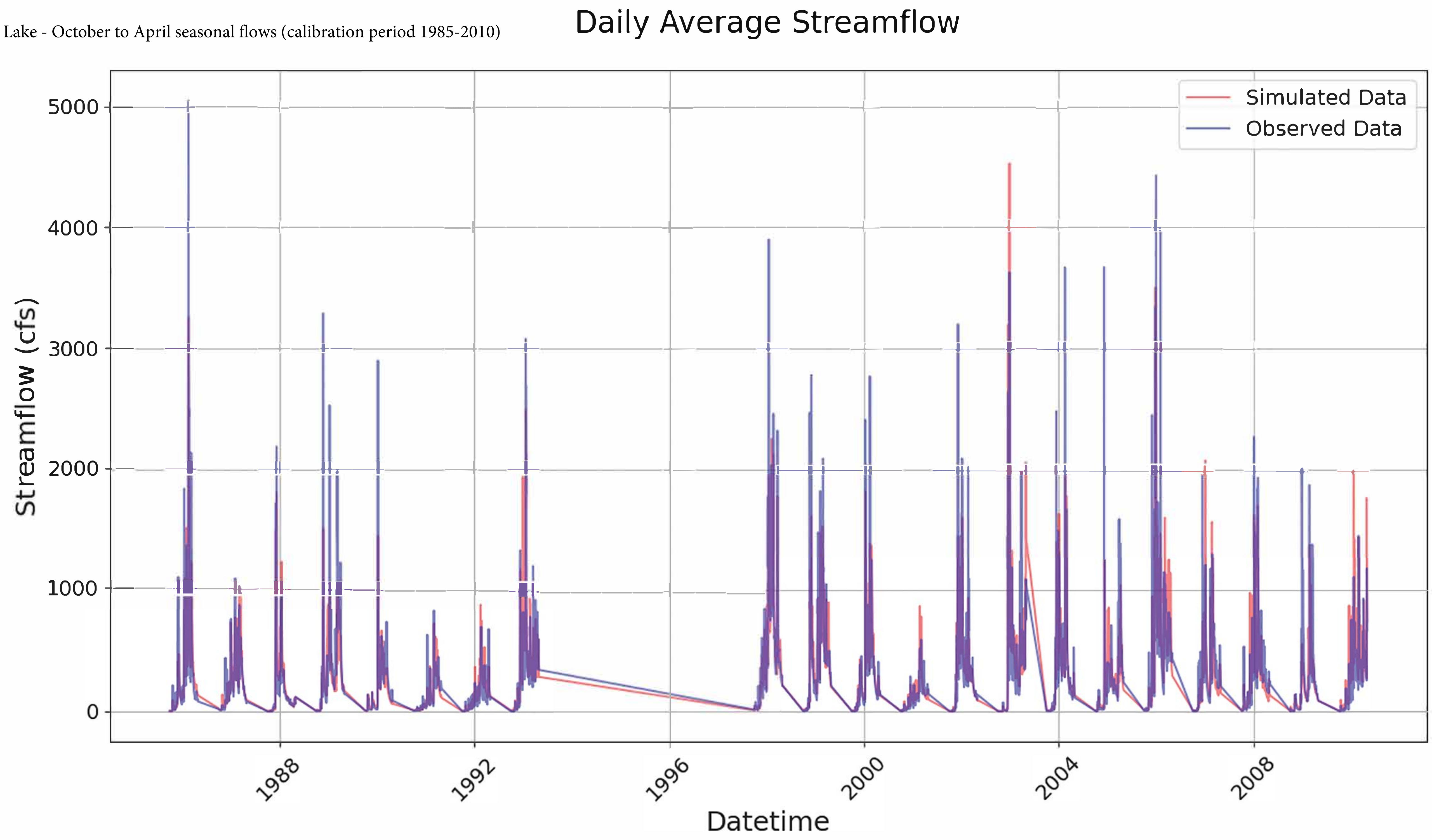
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal flows (validation period 2010-2022)

ME=-4.26
MAE=8.943
NSE=0.857
r2=0.872
d=0.956
NRMSE (Mean)=0.633
RMSE=25.234



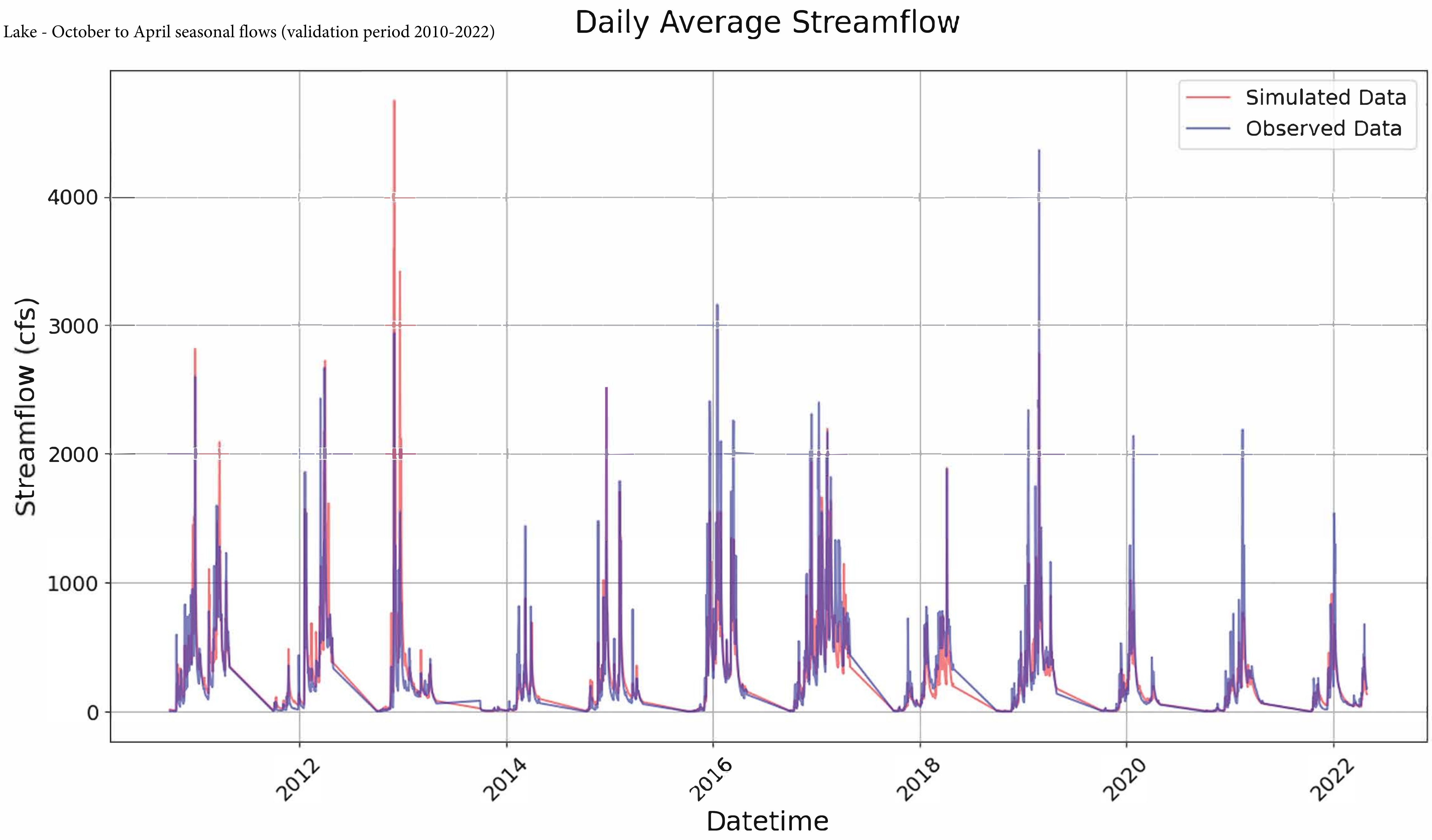
Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal flows (calibration period 1985-2010)

ME=2.627
MAE=99.591
NSE=0.747
r2=0.747
d=0.922
NRMSE (Mean)=0.693
RMSE=207.483

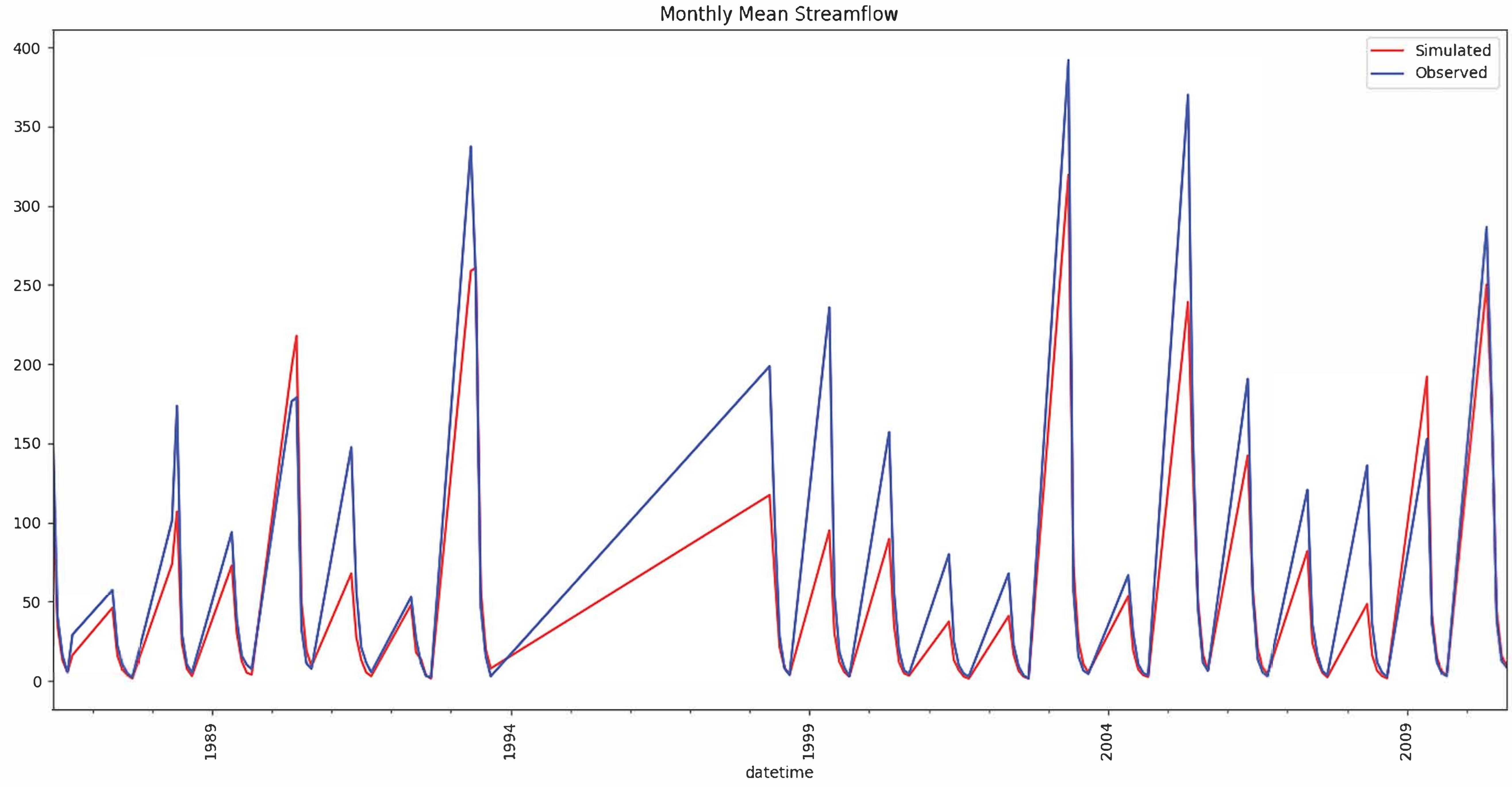


Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal flows (validation period 2010-2022)

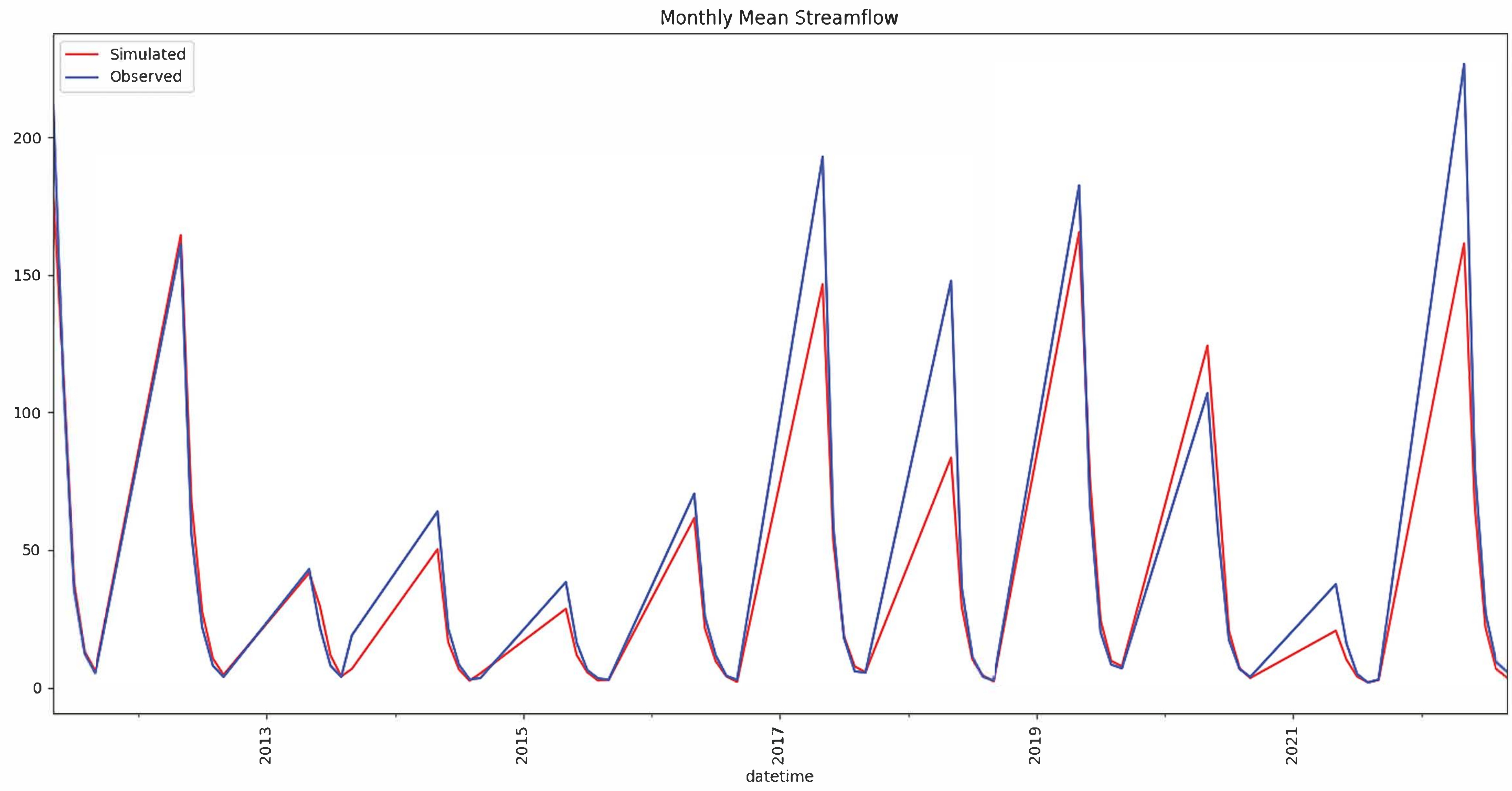
ME=-20.987
MAE=97.628
NSE=0.723
r2=0.727
d=0.917
NRMSE (Mean)=0.716
RMSE=207.219



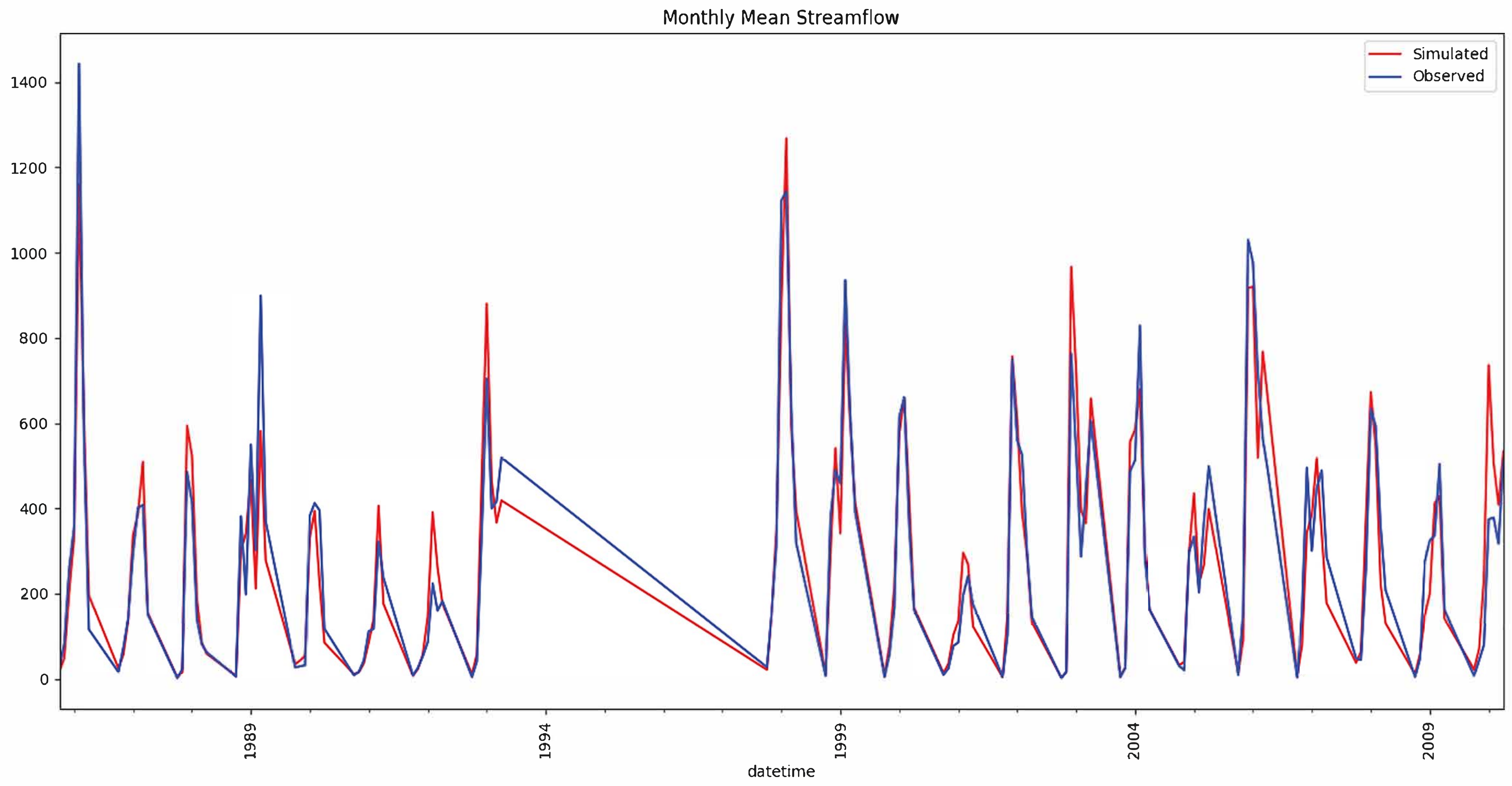
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal monthly mean cfs (calibration period 1985-2010)



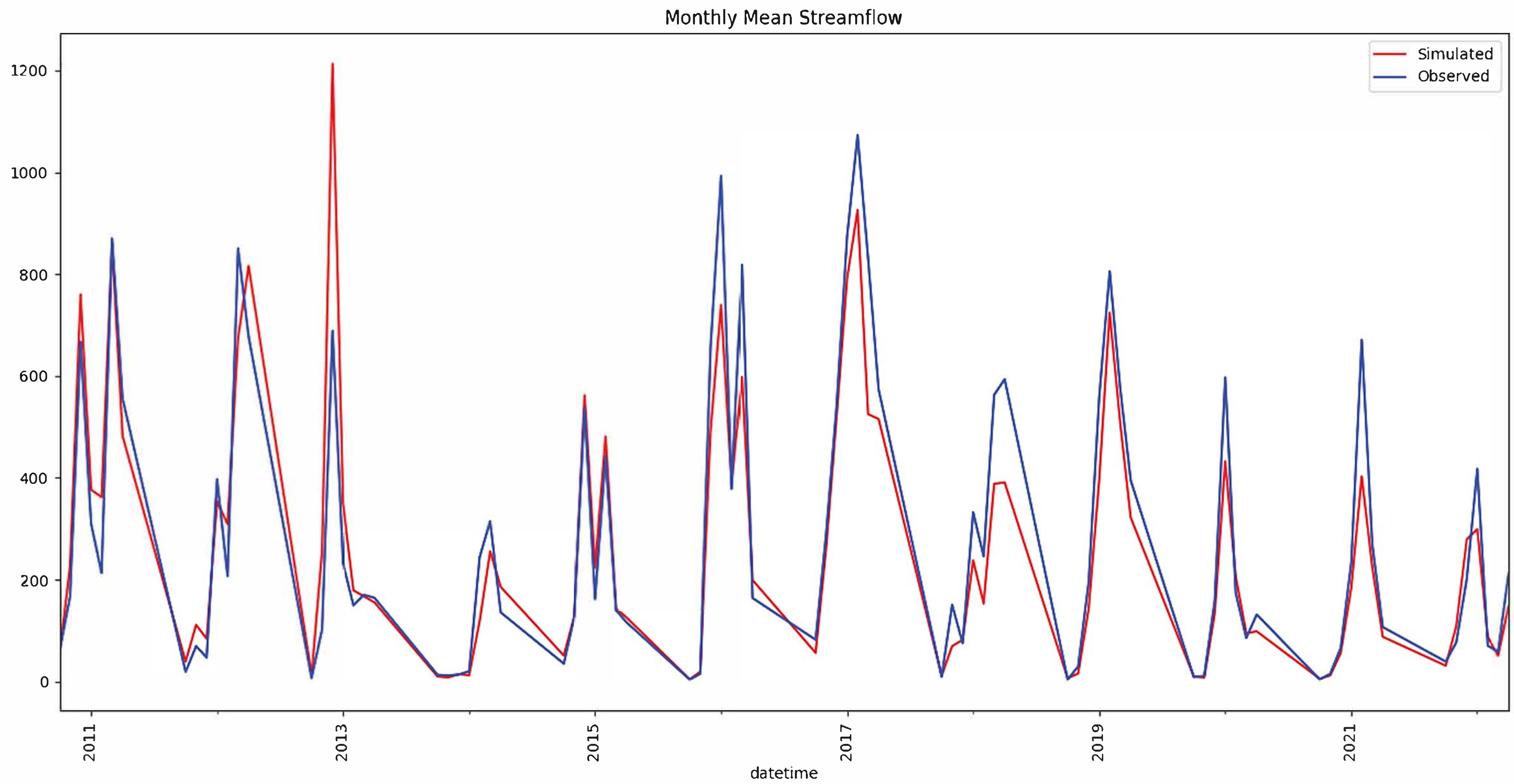
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal monthly mean cfs (validation period 2010-2022)



Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal monthly mean cfs (calibration period 1985-2010)

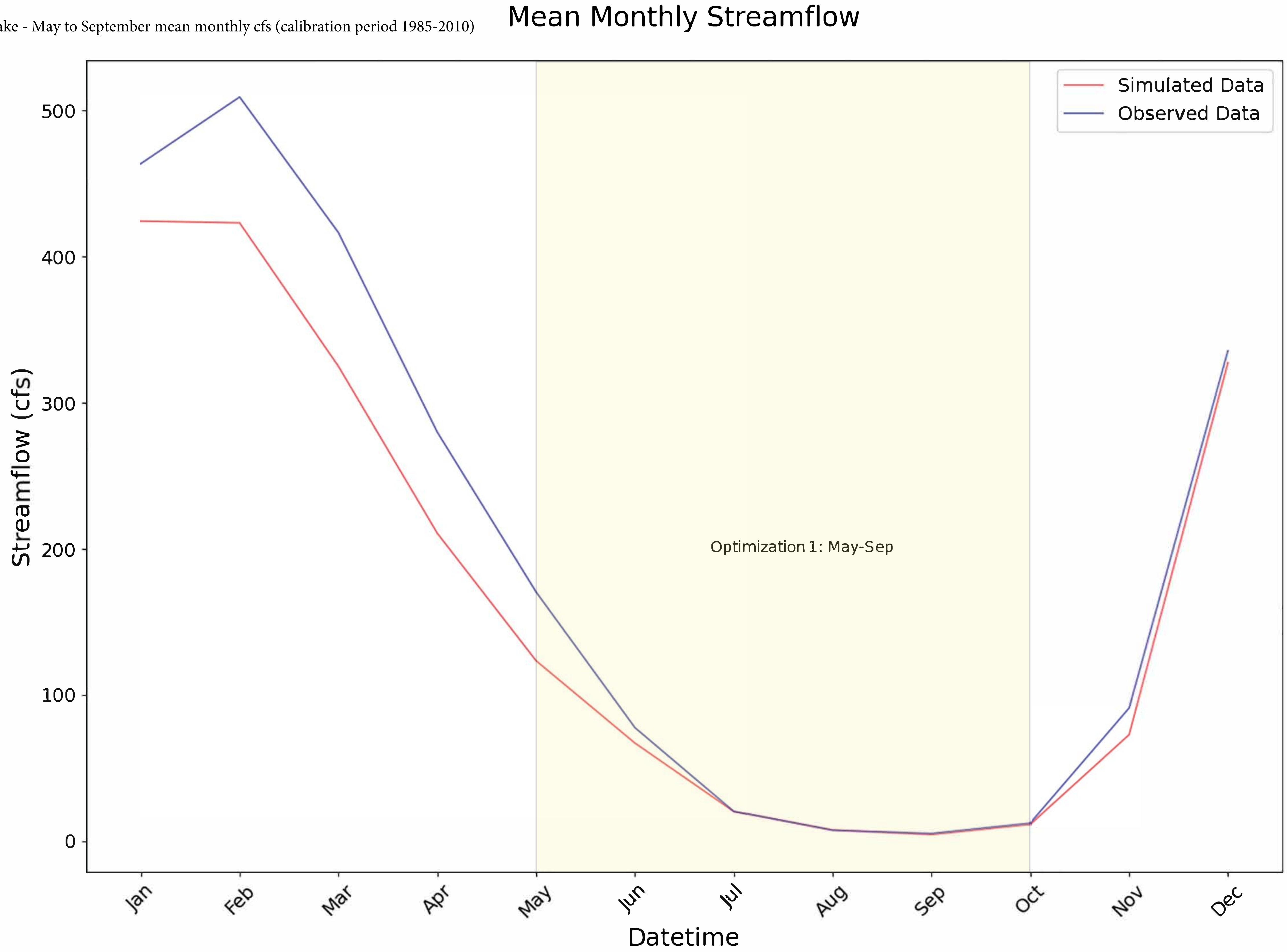


Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal monthly mean cfs (validation period 2010-2022)



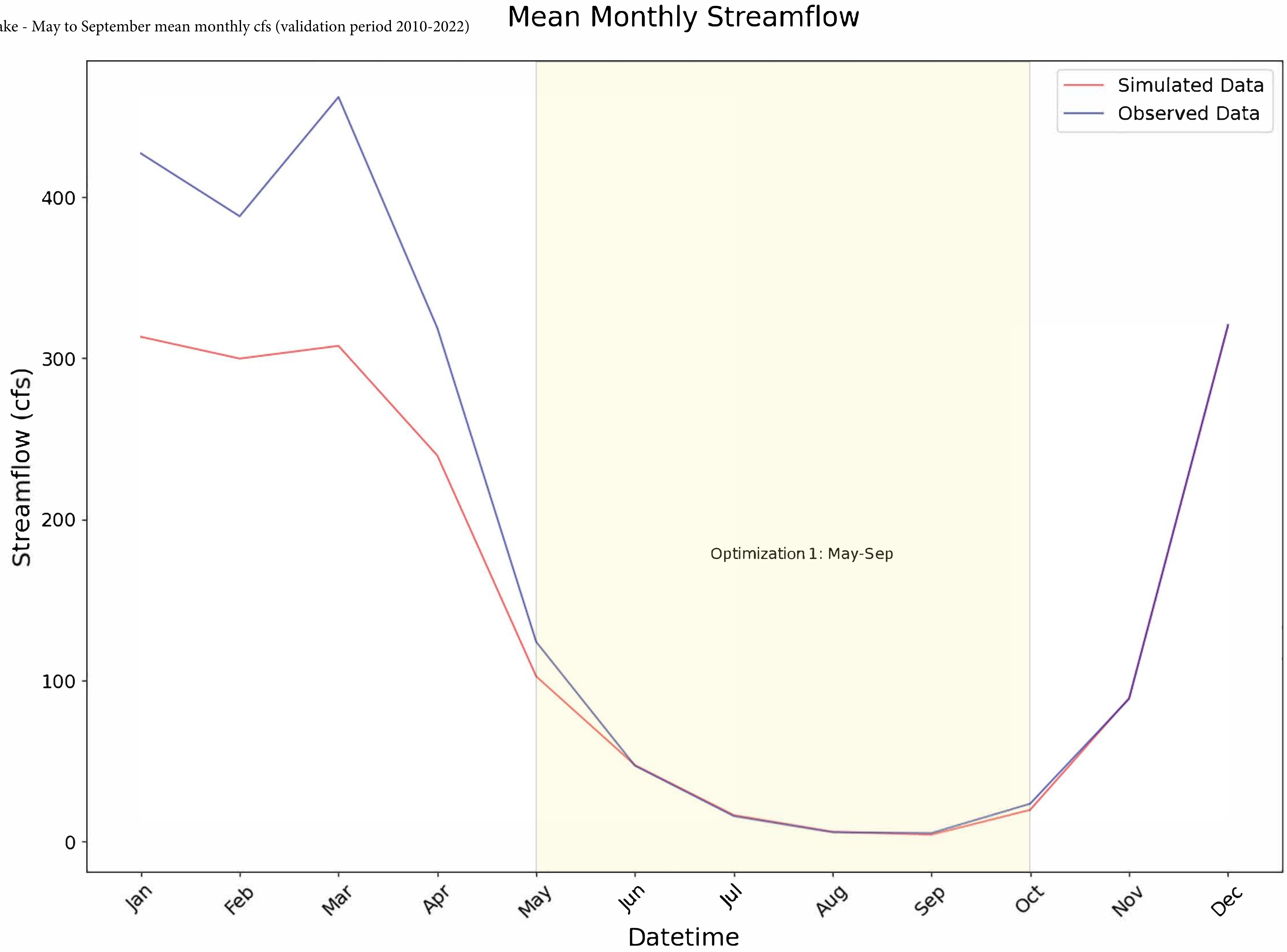
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September mean monthly cfs (calibration period 1985-2010)

ME=-30.96
MAE=30.988
NSE=0.939
r2=0.984
d=0.982
NRMSE (Mean)=0.228
RMSE=45.452



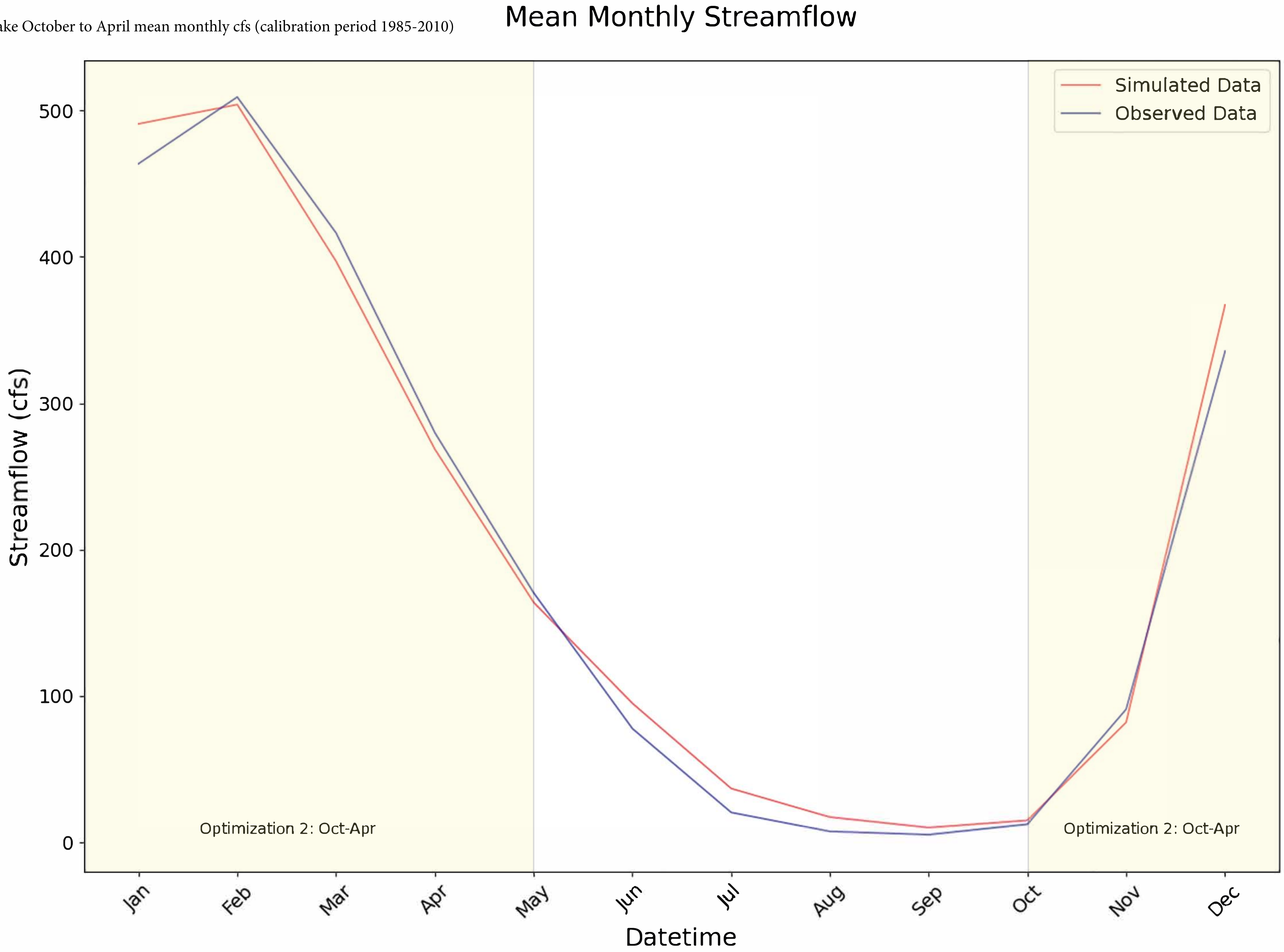
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September mean monthly cfs (validation period 2010-2022)

ME=-38.365
MAE=38.659
NSE=0.859
r2=0.961
d=0.954
NRMSE (Mean)=0.352
RMSE=65.38



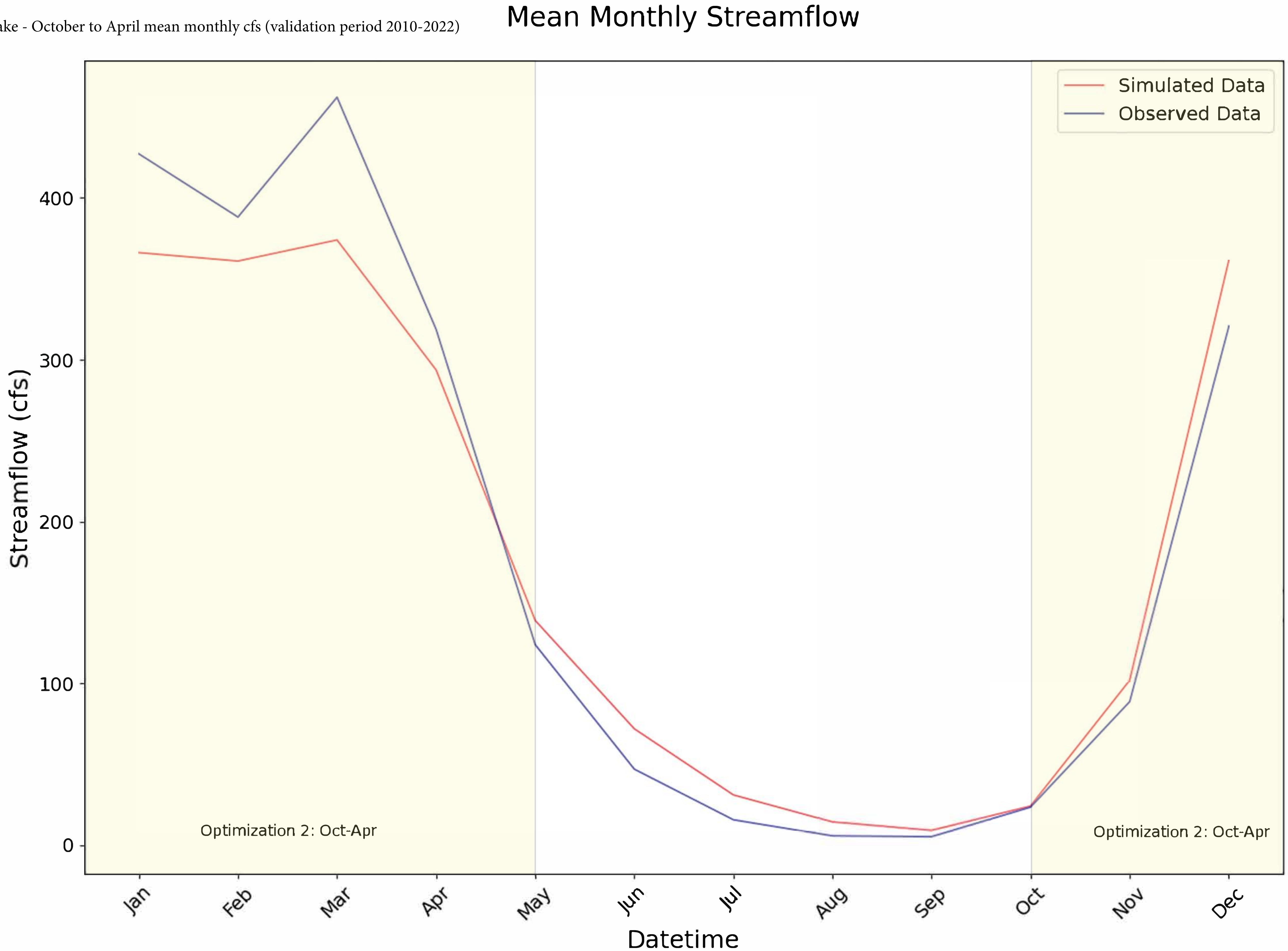
Optimization 2: Wet Season - Redwood C nr Blue Lake October to April mean monthly cfs (calibration period 1985-2010)

ME=4.883
MAE=13.415
NSE=0.992
r2=0.993
d=0.998
NRMSE (Mean)=0.081
RMSE=16.037



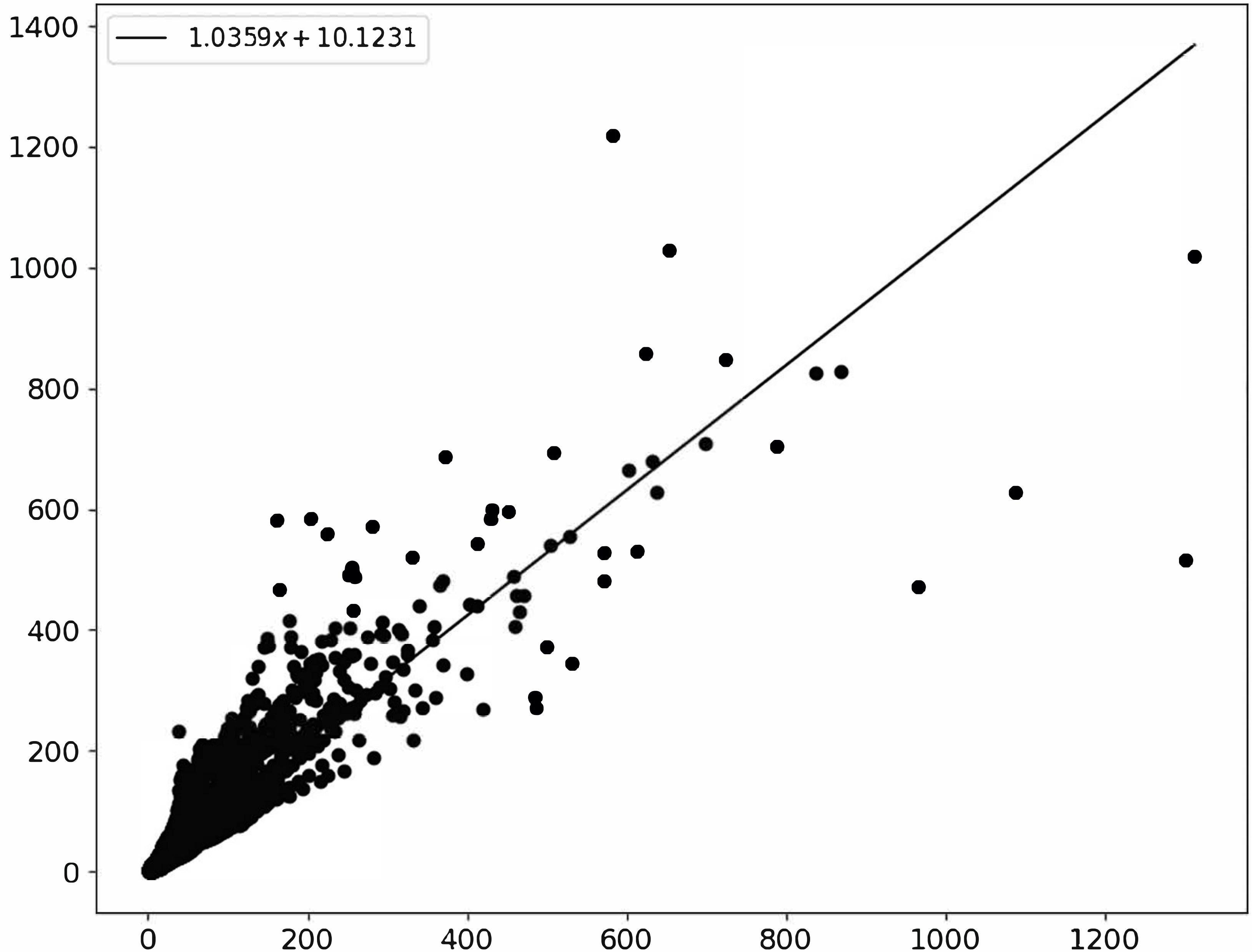
Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April mean monthly cfs (validation period 2010-2022)

ME=-6.56
MAE=26.985
NSE=0.956
r2=0.972
d=0.987
NRMSE (Mean)=0.196
RMSE=36.361



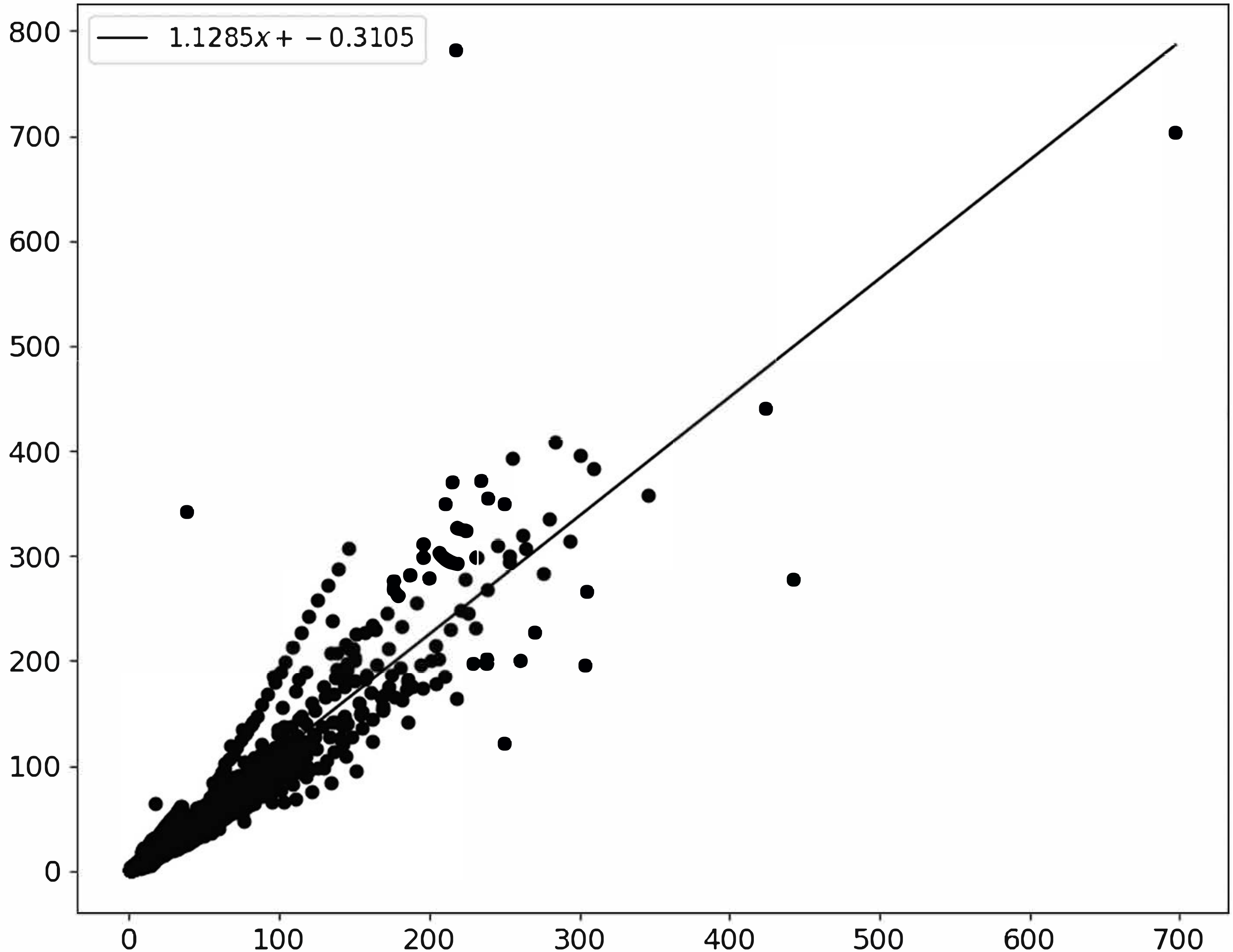
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal flows R squared (calibration period 1985-2010)

r2=0.817



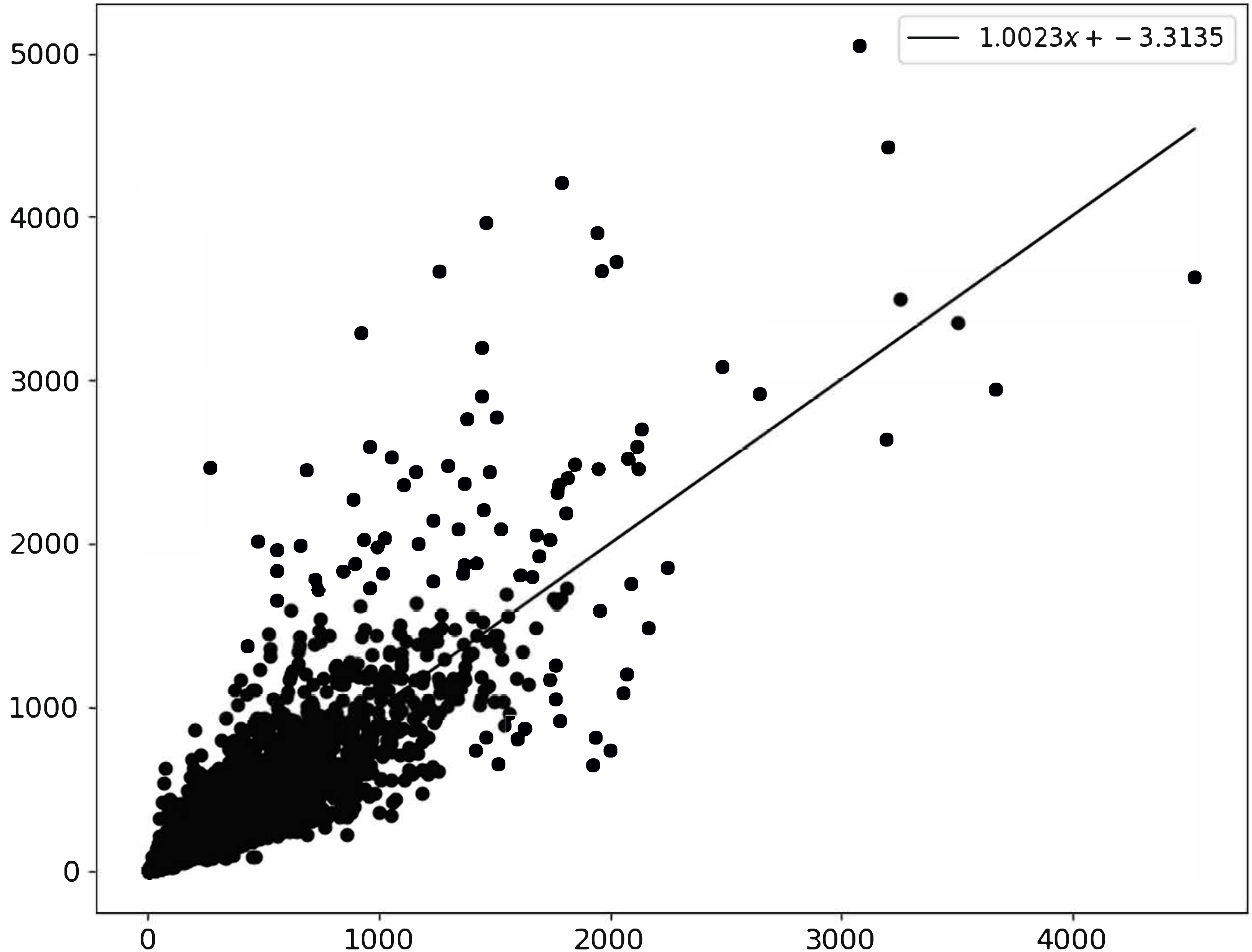
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal flows R squared (validation period 2010-2022)

r2=0.872



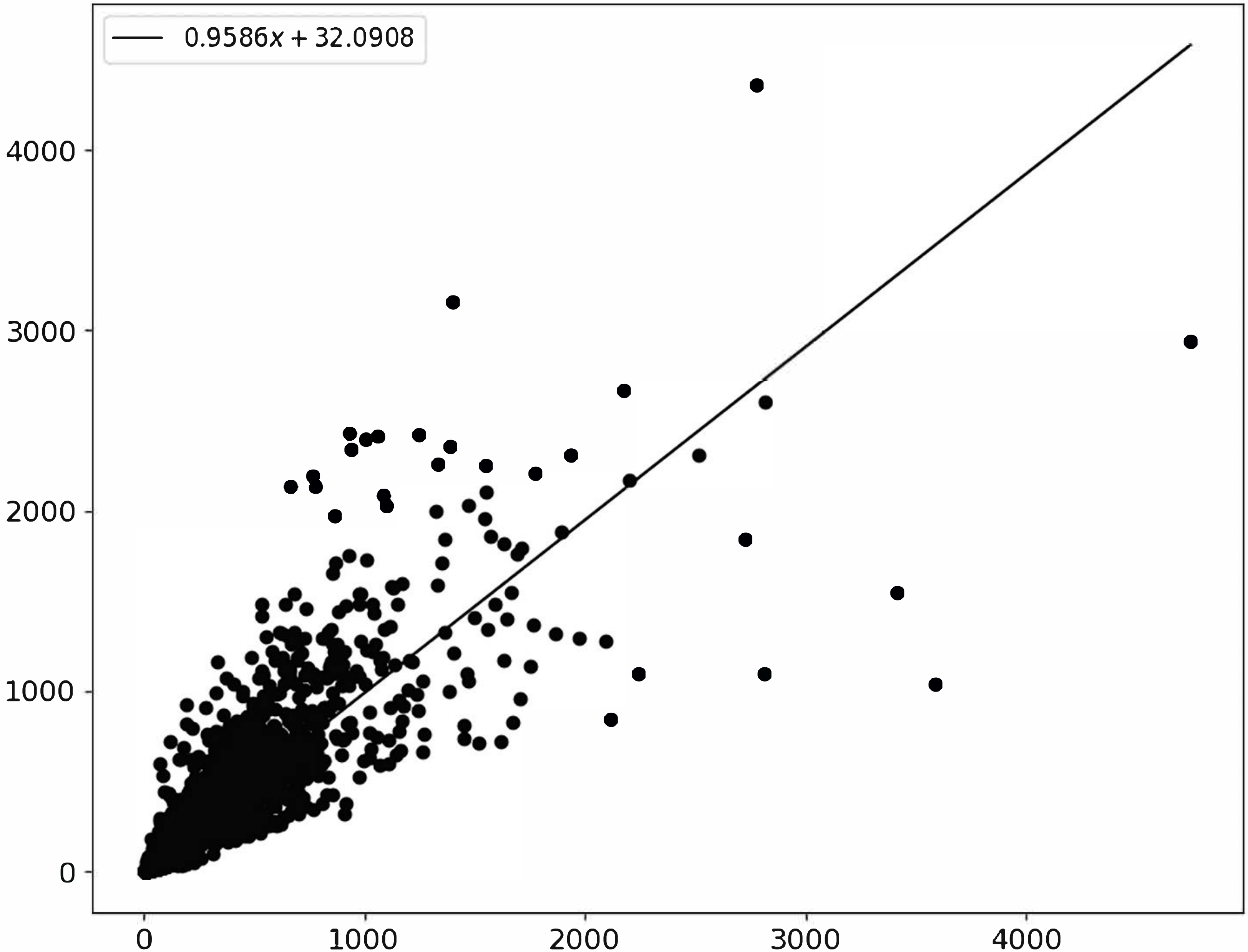
Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal flows R squared (calibration period 1985-2010)

r2=0.747

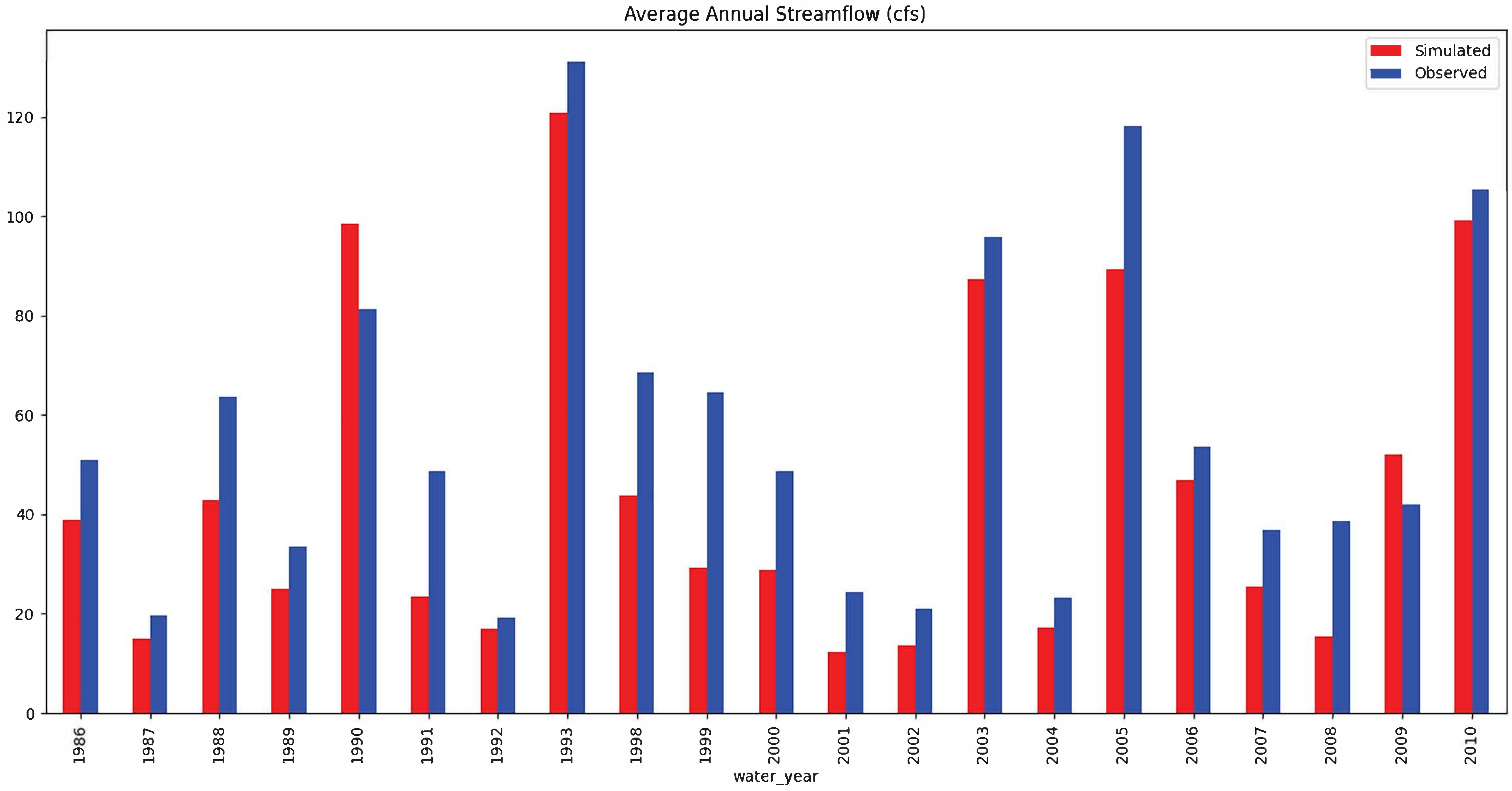


Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal flows R squared (validation period 2010-2022)

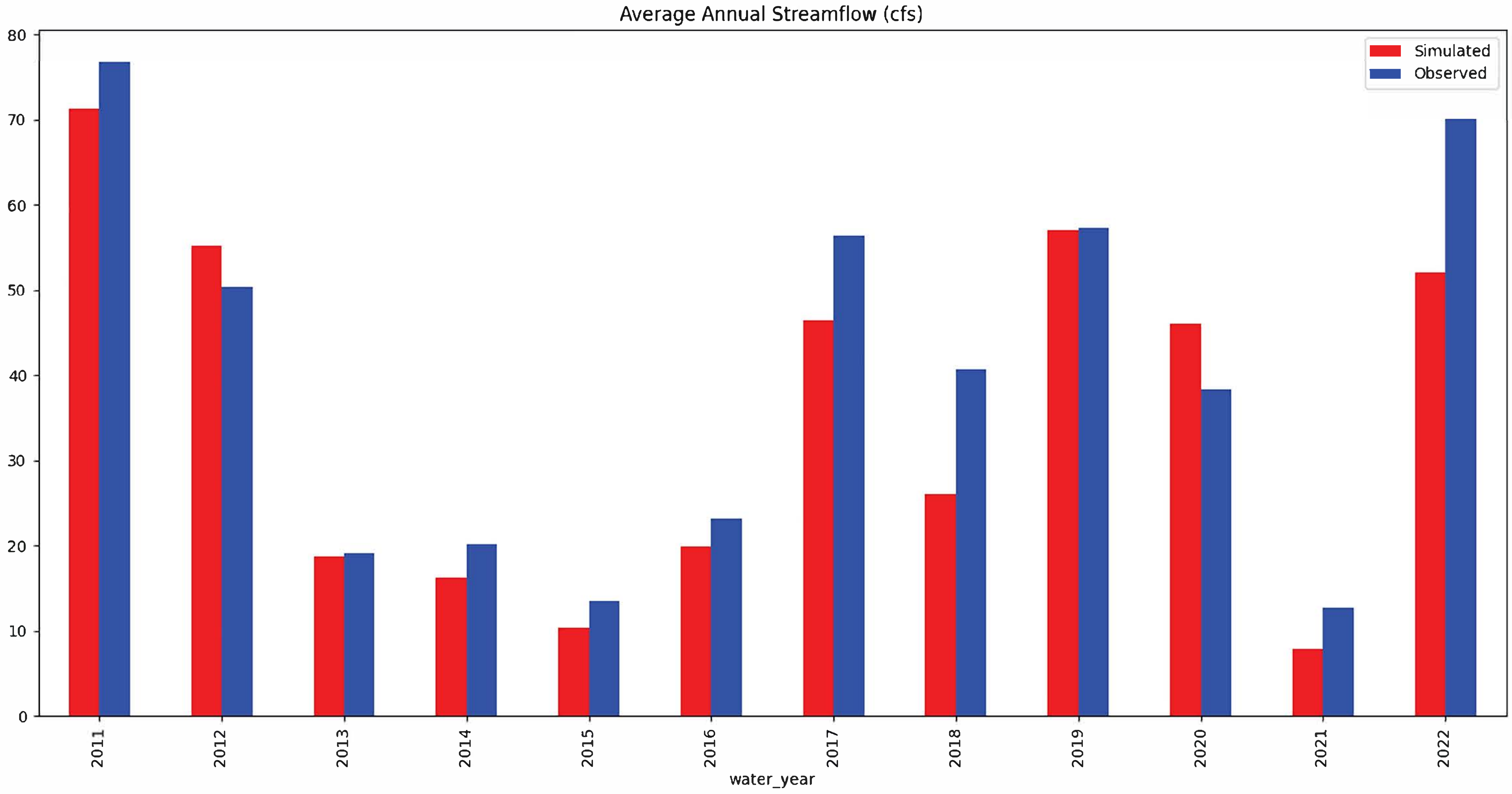
r2=0.727



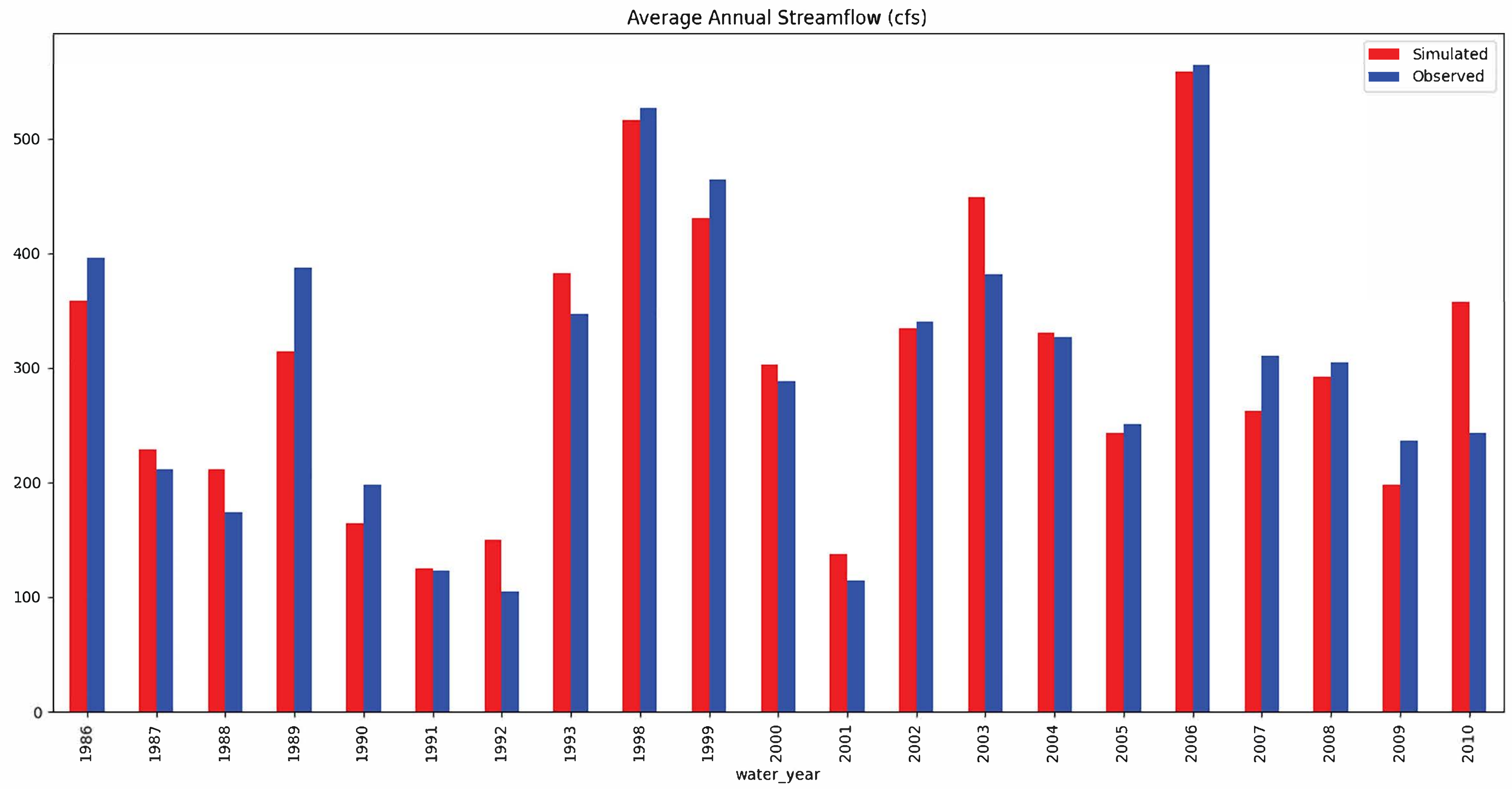
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal water year average cfs (calibration period 1985-2010)



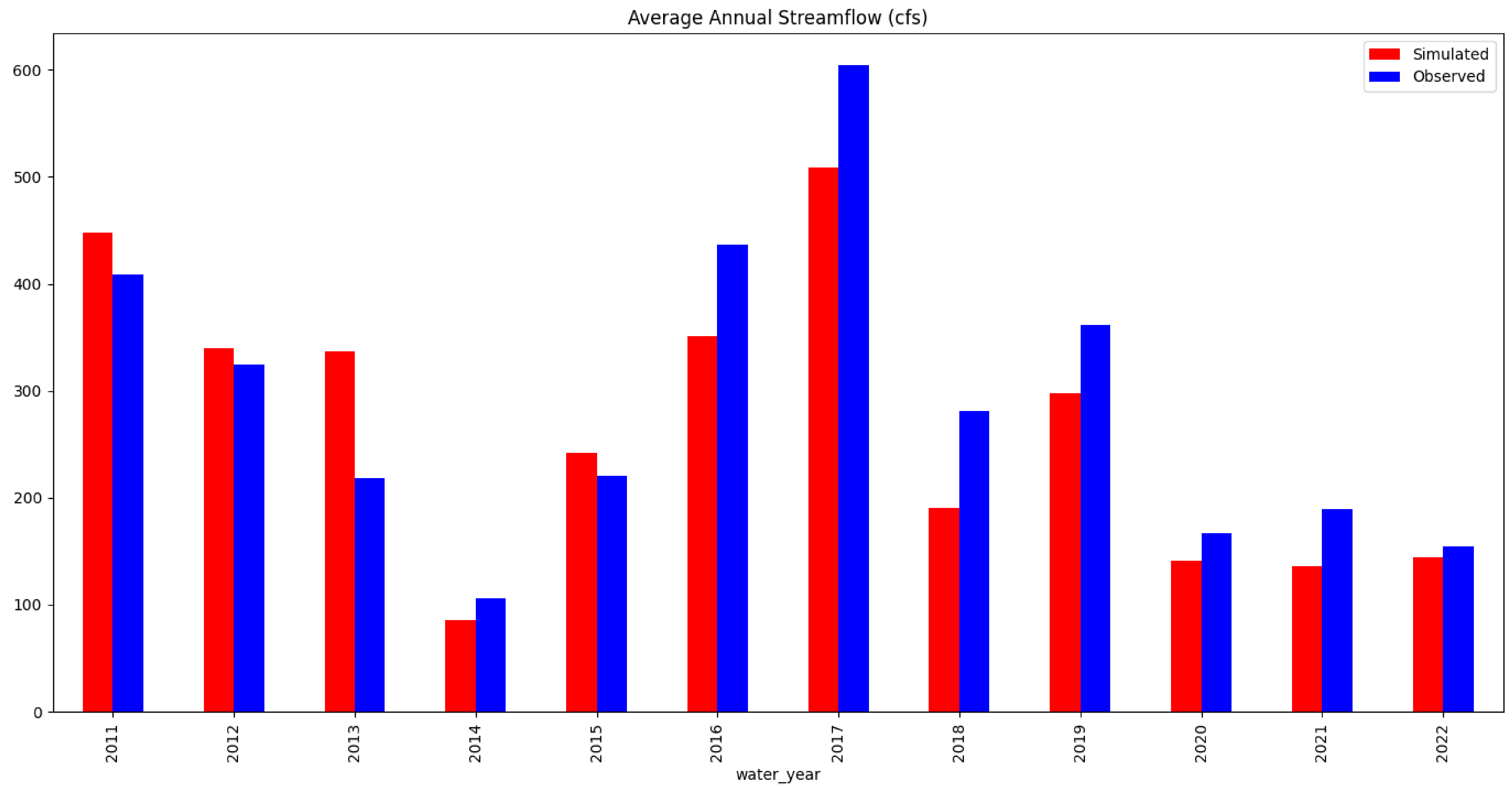
Optimization 1: Dry Season - Redwood C nr Blue Lake - May to September seasonal water year average cfs (validation period 2010-2022)



Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal water year average cfs (calibration period 1985-2010)



Optimization 2: Wet Season - Redwood C nr Blue Lake - October to April seasonal flows (validation period 2010-2022)



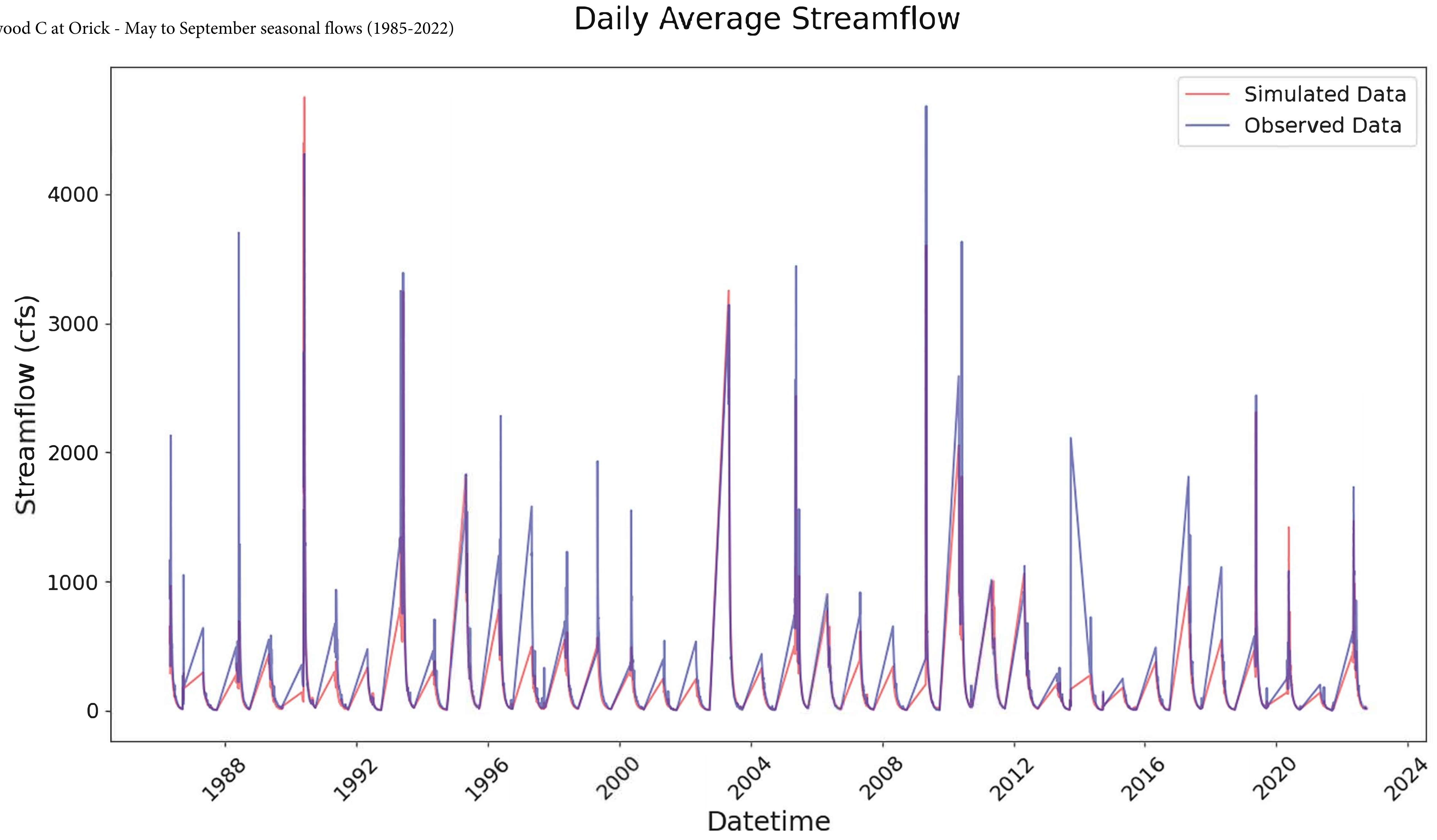
Redwood C a Orick Ca (11482500)

Impaired Gage (visual assessment)

1985 to 2022

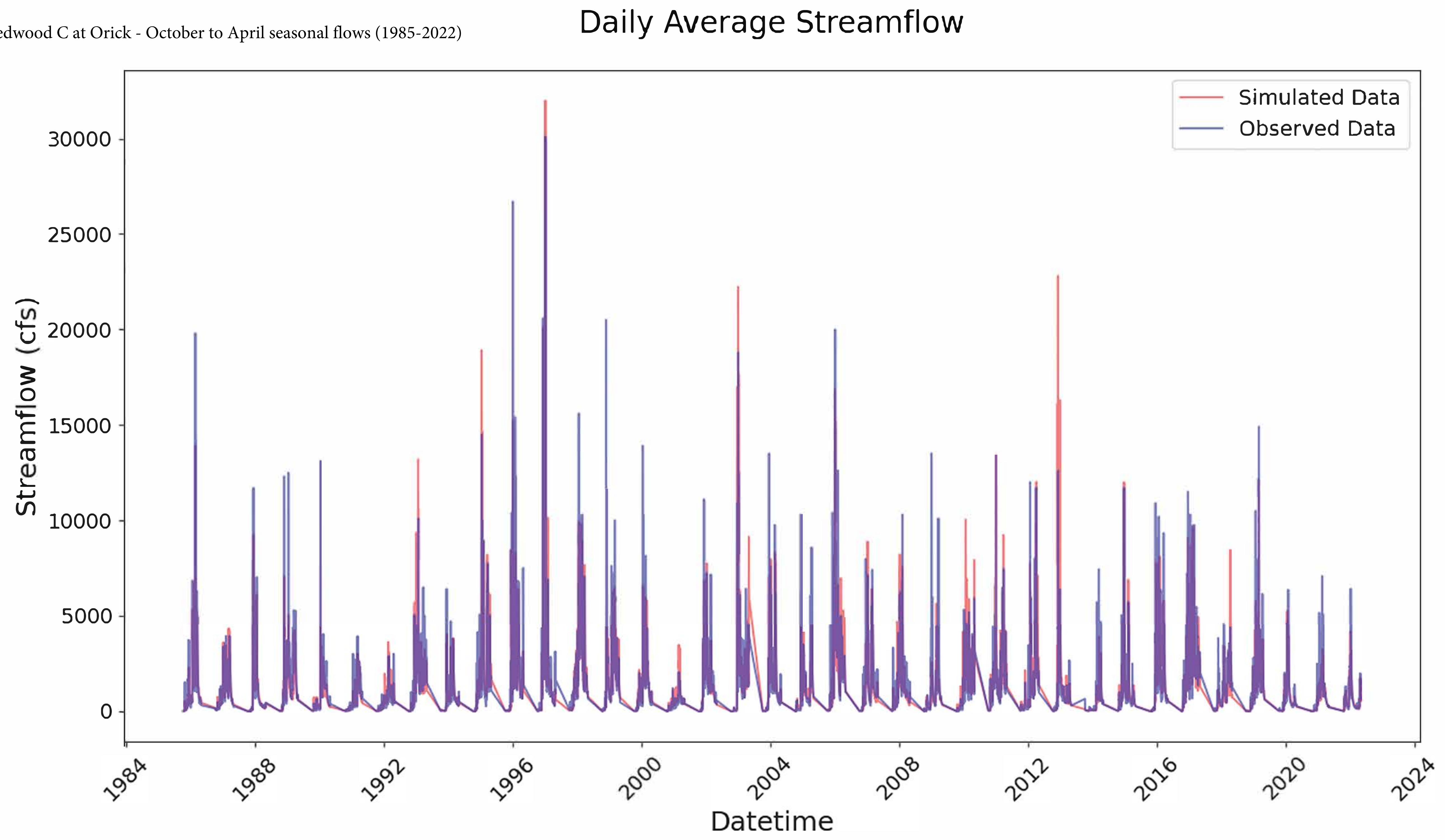
Optimization 1: Dry Season - Impaired gage Redwood C at Orick - May to September seasonal flows (1985-2022)

ME=-50.59
MAE=60.312
NSE=0.806
r2=0.857
d=0.935
NRMSE (Mean)=0.777
RMSE=155.784

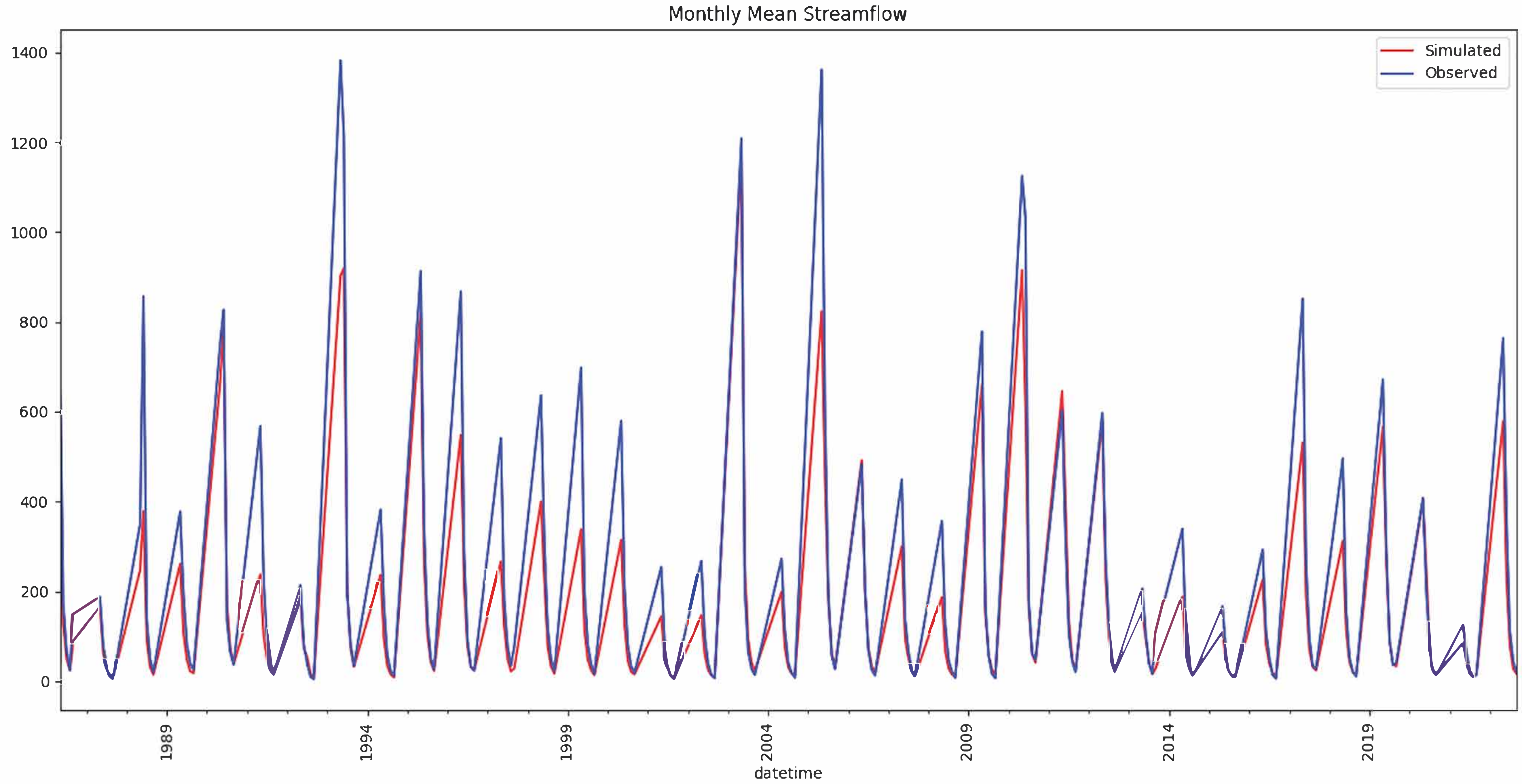


Optimization 2: Wet Season - Impaired gage Redwood C at Orick - October to April seasonal flows (1985-2022)

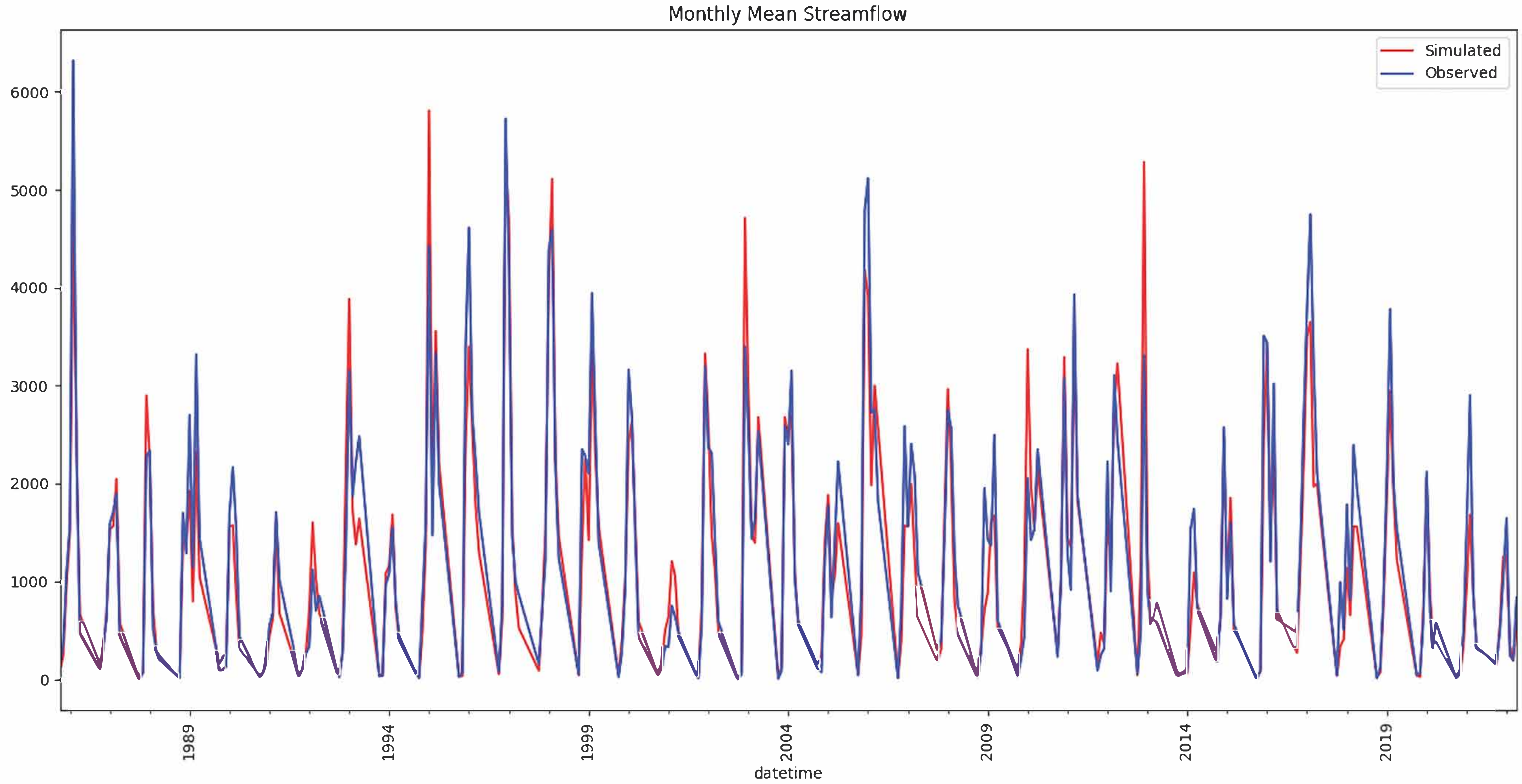
ME=-82.046
MAE=416.142
NSE=0.768
r2=0.771
d=0.932
NRMSE (Mean)=0.685
RMSE=917.338



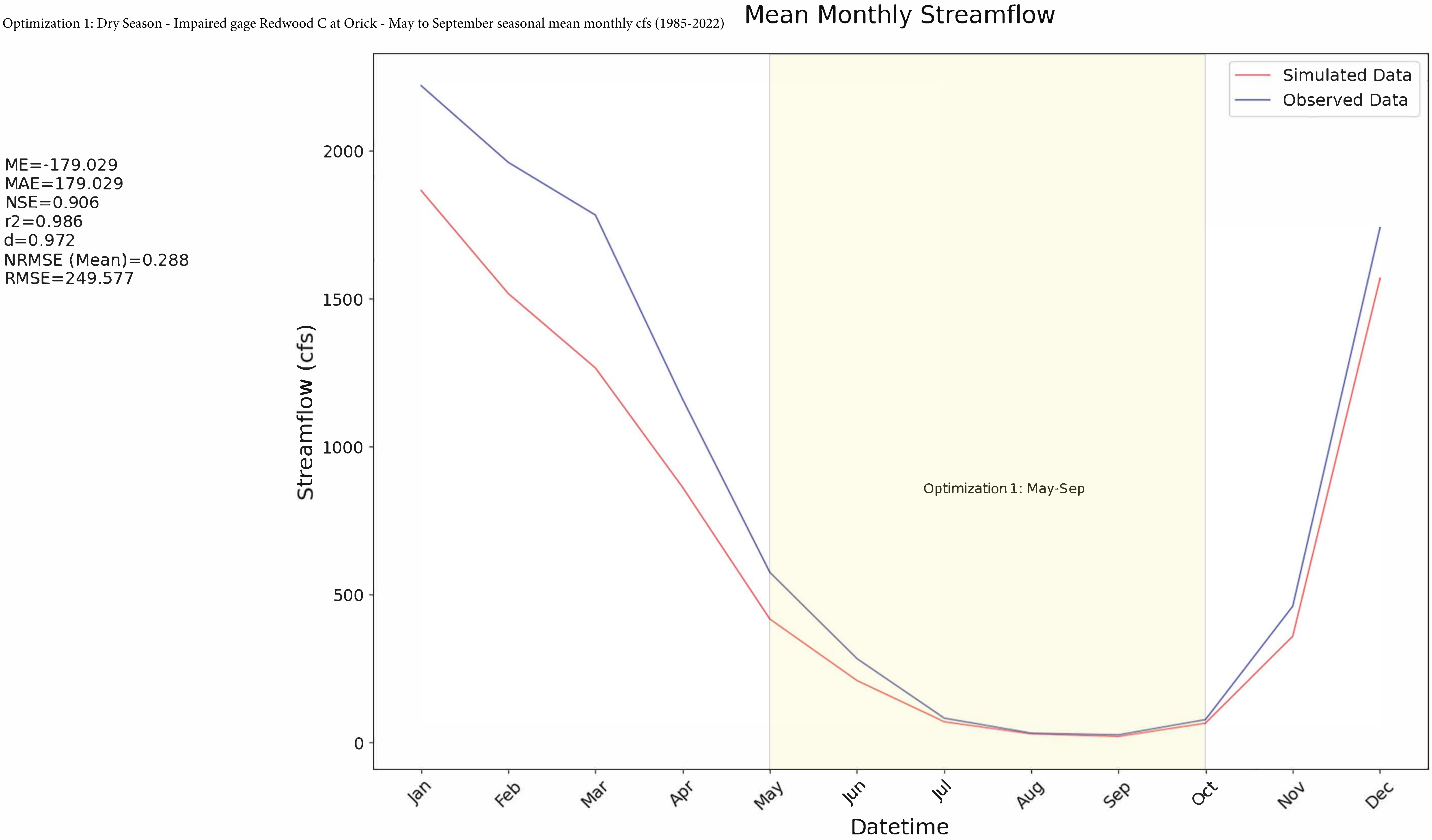
Optimization 1: Dry Season - Impaired gage Redwood C at Orick - May to September seasonal monthly mean cfs



Optimization 2: Wet Season - Impaired gage Redwood C at Orick - October to April seasonal monthly mean cfs

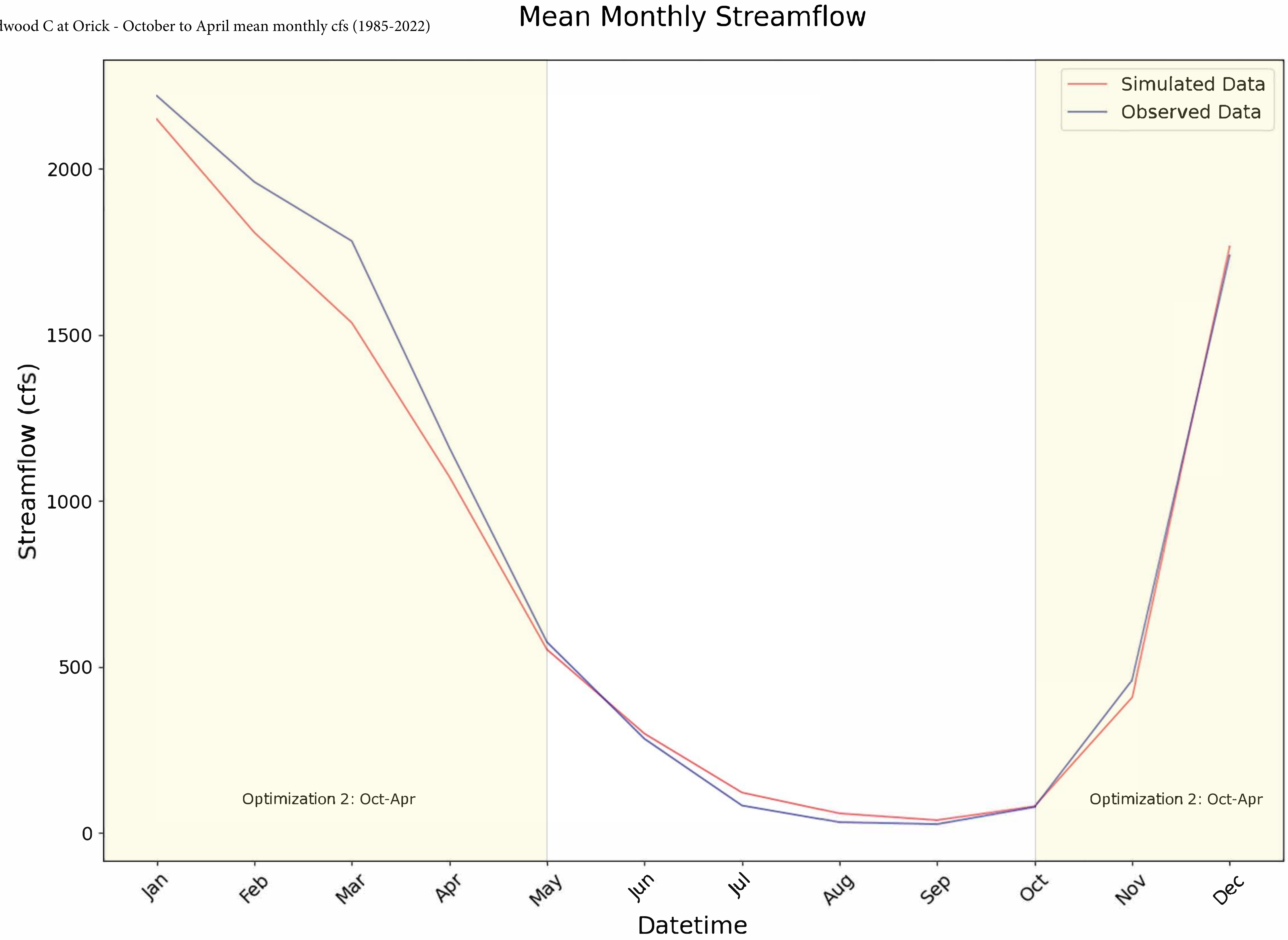


Optimization 1: Dry Season - Impaired gage Redwood C at Orick - May to September seasonal mean monthly cfs (1985-2022)



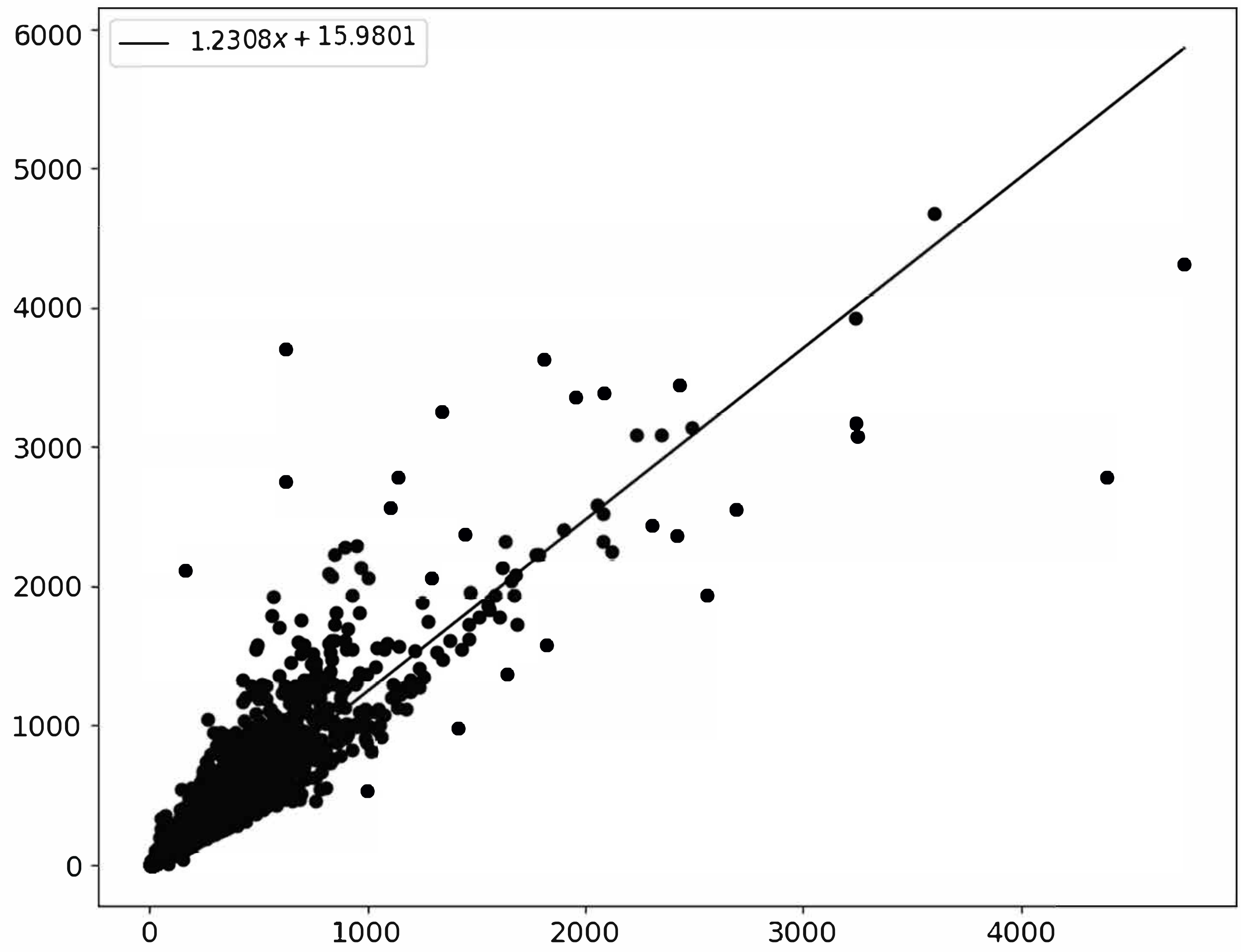
Optimization 2: Wet Season - Impaired gage Redwood C at Orick - October to April mean monthly cfs (1985-2022)

ME=-42.428
MAE=62.674
NSE=0.987
r2=0.994
d=0.997
NRMSE (Mean)=0.107
RMSE=92.548



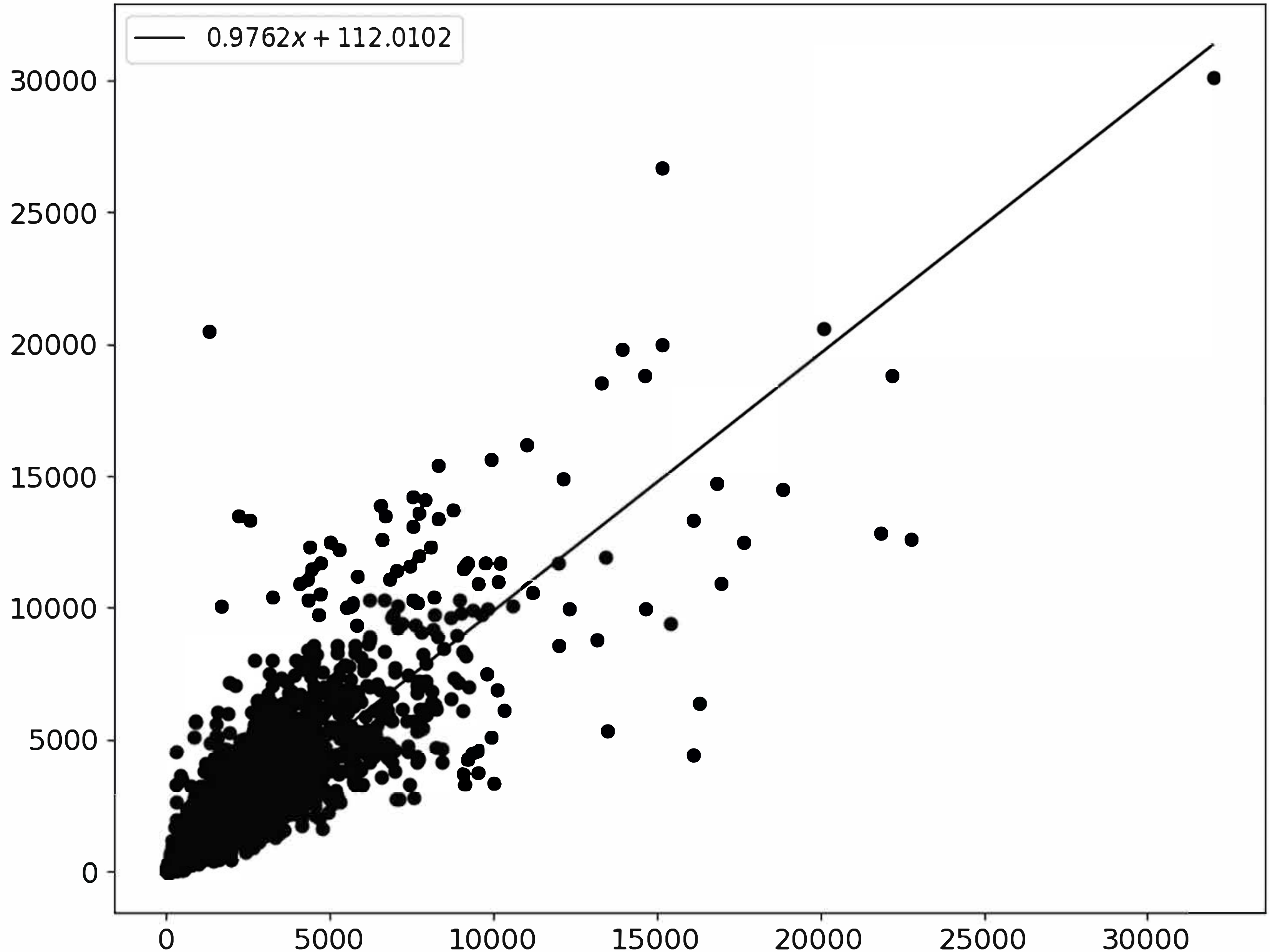
Optimization 1: Dry Season - Impaired gage Redwood C at Orick - May to September seasonal flows R squared (1985-2022)

r2=0.857

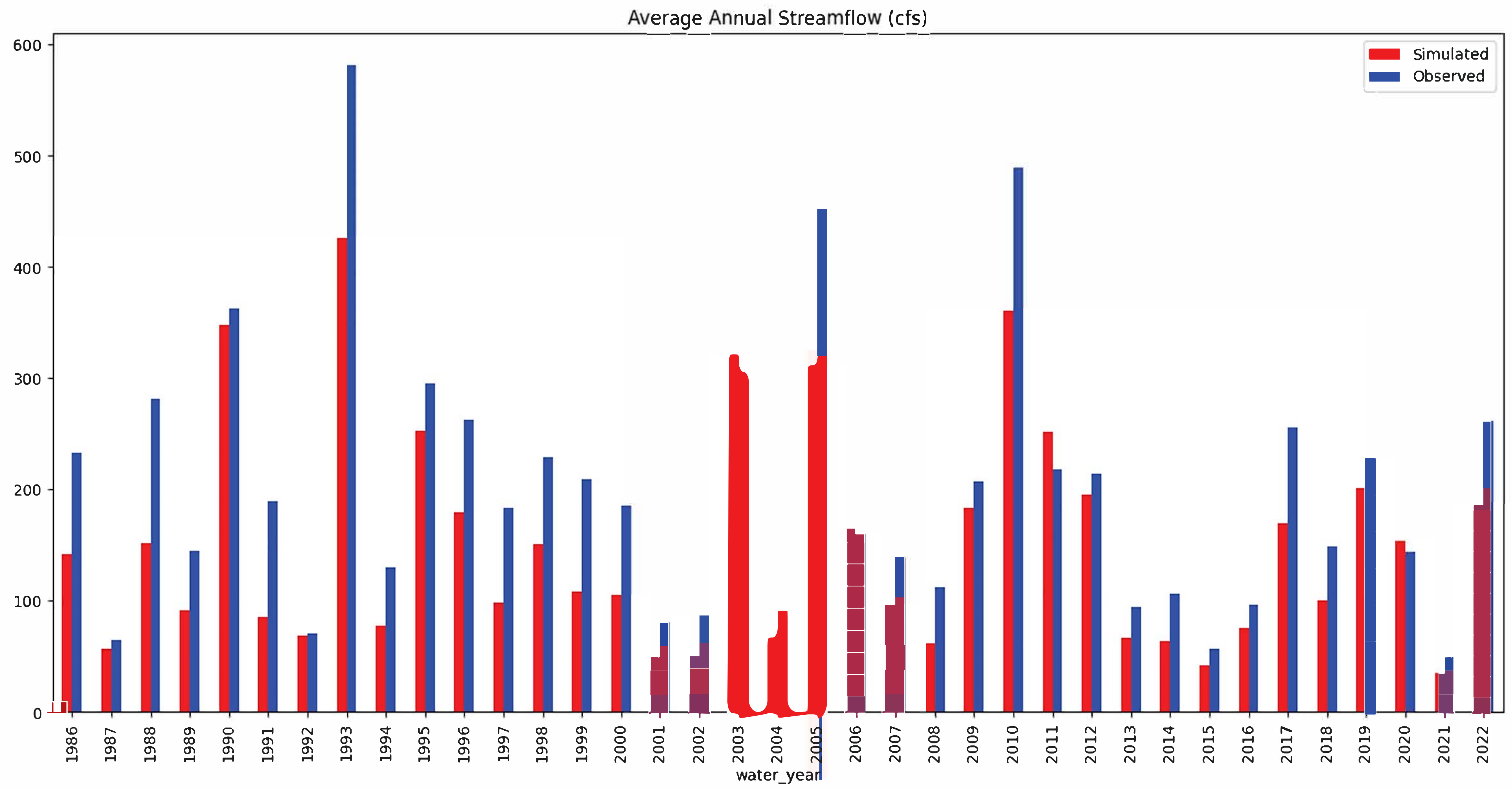


Optimization 2: Wet Season - Impaired gage Redwood C at Orick - October to April R seasonal flows R squared (1985-2022)

r2=0.771



Optimization 1: Dry Season - Impaired gage Redwood C at Orick - May to September seasonal water year average cfs



Optimization 2: Wet Season - Impaired gage Redwood C at Orick - October to April seasonal water year average cfs