UPPER ELK RIVER SEDIMENT TMDL: ASSESSMENT OF THE FIRST FIVE YEARS

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Acronyms

AHCP	Aquatic Habitat Conservation Plan
ATM	Aquatic Trends Monitoring
BLM	Bureau of Land Management
CDFW	California Department of Fish and Wildlife
CGS	California Geologic Survey
CWC	California Water Code
CSDS	Controllable Sediment Discharge Sources
DDW	Division of Drinking Water
DFA	Division of Financial Assistance
ECP	Erosion Control Plan
ERRA	Elk River Recovery Assessment
ERRP	Elk River Recovery Plan
FPR	Forest Practice Rules
GDRC	Green Diamond Resources Company
HRC	Humboldt Redwood Company
MATO	Master Agreement for Timber Operations
MRP	Monitoring and Reporting Requirements
NHE	Northern Hydrology and Engineering
NMFS	National Marine Fisheries Service
NTMP	Nonindustrial Timber Management Plans
NRCS	Natural Resource Conservation Service
NTO	Notice of Timber Operation
NWS	National Weather Service
OLS	Ordinary Least Squares
OPP	Office of Public Participation
PG	Professional Geologist
ROWD	Report of Waste Discharge
SAFER	Safe and Affordable Funding for Equity and Resilience (SAFER)
SEV	Severity of Ill Effects
SSC	Suspended Sediment Concentrations
THP	Timber Harvest Plan
TMDL	Total Maximum Daily Load
UER	Upper Elk River
USFWS	U.S. Fish and Wildlife Service
WAU	Watershed Analysis Unit
WDR	Waste Discharge Requirement
WY	Water Year

Section 1: Introduction

Located in Humboldt County, the Elk River Watershed is 58.3 square miles and drains directly into the Humboldt Bay, south of Eureka, CA. Due to excessive sedimentation the entire watershed was placed on the Section 303(d)-Impaired Waters List of the Clean Water Act in 1998. Designed to address and reduce the excessive sediment sources in the upper 44.2 square miles of the watershed, the North Coast Regional Water Quality Control Board (Regional Water Board) adopted a sediment total maximum daily load (TMDL) and an implementing TMDL Action Plan in 2016. The Upper Elk River Sediment TMDL Action Plan (TMDL Action Plan) establishes the sediment loading consistent with current conditions in the impacted reaches[1], identifies a process for assessing and implementing necessary and feasible remediation and restoration actions, and describes a program of implementation."

To achieve its goals, the TMDL Action plan identifies three main elements: the Watershed Stewardship Program, the Elk River Recovery Assessment (ERRA), and Waste Discharge Requirements (WDRs) and/or Waivers of WDRs. In combination, these components are designed to reduce sedimentation, reduce nuisance flooding, expand sediment assimilative capacity, and establish an overall pathway to beneficial use recovery and water quality attainment.

The Watershed Stewardship Program is a community-based program under which implementation of health and safety projects, remediation and restoration activities, and science and coordinated monitoring serves to support beneficial use enhancement and a trajectory of watershed recovery including abatement of nuisance flooding and an expansion of sediment loading capacity. The Watershed Stewardship Program is discussed in greater detail in Section 3 of this report.

The Elk River Recovery Assessment, completed by CalTrout in 2019, is a comprehensive sediment and hydrodynamic modeling tool with which to evaluate different restoration and recovery strategies. This modeling tool predicts the routing of water and sediment through the watershed from above the confluence of the north and South Forks to Humboldt Bay under varying precipitation events when 1) sediment loading is reduced (boundary condition) and 2) a variety of restoration actions are implemented in appropriate reaches as recommended by a Technical Advisory Committee. The ERRA provides the basis for development of the Elk River Watershed Stewardship Program: Sediment Remediation and Habitat Rehabilitation Recovery Plan (Recovery Plan), which translates restoration concepts into landowner-vetted reach-scale projects. The Recovery Plan is a separate document, produced as a public draft in July 2022, which is a companion to this TMDL Assessment Report.

[1] The impacted reach extends from the confluence of Brown's Gulch on the North Fork Elk and Tom Gulch on the South Fork Elk to the mainstream Elk River at Berta Road and is contained within the delineated boundaries of the Upper Elk Watershed

The TMDL Action Plan identifies WDRs as "the primary regulatory mechanism utilized by the Regional Water Board to control nonpoint source pollution from past and ongoing timber harvest activities." WDRs were adopted by the Regional Water Board for the two commercial timber harvest operations in the watershed, Humboldt Redwood Company, LLC (HRC) and Green Diamond Resource Company (GDRC). WDRs and their implementation are discussed in greater detail in Section 4 of this report.

Table 4 of the TMDL Action Plan requires:

"*By 2021, the Regional Water Board shall evaluate the available information to assess the degree to which 1) adopted WDRs and waivers have successfully controlled sediment delivery from the upper watershed to the impacted reaches and 2) the efforts of the Watershed Stewardship Program are making sufficient progress towards achievement of health and safety, coordinated monitoring, and sediment remediation improvements*."

Section VII (Monitoring and Adaptive Management) of the TMDL Action Plan also provides:

"Approximately five years after adoption, Regional Water Board staff will conduct a formal assessment of the effectiveness of the implementation plan, including an evaluation of the effectiveness of WDRs and waivers, and make any necessary revisions to this TMDL Action Plan. This includes a review of the sediment source analysis and water quality data for the Upper Elk River, sediment deposition in the impacted reach and Lower Elk River, and the need for a Lower Elk River sediment TMDL, using Recovery Assessment tools and other available data, as appropriate. During reassessment, the Regional Water Board will consider how effective the requirements of the TMDL program of implementation are at meeting the TMDL, achieving water quality objectives, restoring the beneficial uses of water, and abating nuisance flooding conditions in the Upper Elk River Watershed. The success of the TMDL will be assessed based on water quality trends in the Upper Elk River Watershed, particularly the attainment of water quality standards in the impacted reach. Ultimately success is achieved when nuisance conditions are abated, and beneficial uses are supported."

This report presents the results of staff's assessment of TMDL implementation in the Elk River watershed to date, with associated findings and recommendations. It begins with general background information (Section 2). The report then includes assessment of activities within the Watershed Stewardship Program and progress towards recovery planning (Section 3), activities under the Waste Discharge Requirements and Waivers (Section 4), and assessment of changes in water quality conditions. It does not include a reassessment of the TMDL source analysis or recommendations for changes to the TMDL Action Plan at this time since the available data provide no evidence of appreciable improvements in water quality conditions or expansion of assimilative capacity for sediment. Section 5 presents analyses of available data and the results.

Section 6 includes a summary of the findings and staff' recommendations. A key recommendation is to standup a Science and Coordinated Monitoring Workgroup under the Watershed Stewardship Program, so as to establish a coordinated monitoring program that ensures data are collected in a manner capable of addressing key watershed health questions. This coordination is particularly important with respect to adaptive management, including consideration of future revisions to either the WDRs or TMDL.

It is important to note that the Elk River Watershed is a working landscape supporting residential, ranching, farming, and timber activities, as well as public access to conservation lands. The purpose of the TMDL Action Plan is to correct nuisance flooding conditions, restore beneficial uses and attain water quality standards. It is not to return the watershed to a pre-disturbance condition. Rather the goal is to regain a level of hydrological and ecosystem function, which supports beneficial uses, controls nuisance flooding and thus allows for the free use and enjoyment of public and private property across all sectors.

Section 2: Background

Periods of intensive logging over geologically unstable terrain in a watershed already subject to natural landslides and tectonic events has had detrimental impacts to water quality. Excessive sedimentation has caused widespread and ongoing exceedance of water quality objectives and impairment of beneficial uses, as well as nuisance conditions[2]. The term "nuisance is defined in Water Code section13050(m) as:

"*…anything which meets all of the following requirements: (1) Is injurious to health, or is indecent or offensive to the senses, or an obstruction to the free use of property, so as to interfere with the comfortable enjoyment of life or property. (2) Affects at the same time an entire community or neighborhood, or any considerable number of persons, although the extent of the annoyance or damage inflicted upon individuals may be unequal. (3) Occurs during, or as a result of, the treatment or disposal of wastes*."

Of particular concern to the TMDL Action Plan is the period during the late 1980-1990s when the timber operations of Pacific Lumber Company/Maxam (Palco) radically altered the sediment transport and hydrologic conditions of the watershed with intensive logging that destabilized slopes, increased peak flows, and accelerated sediment delivery to watercourses. Sediment from that era initiated a nuisance flooding condition just above the confluence of the North and South Forks of the Elk River and continuing to Berta Road, which continues today with ongoing aggradation in that reach, loss of channel cross-sectional area, and multiple overbank flooding events per year. It simultaneously resulted in impacts to water supplies, recreational opportunities, and salmonid habitat.

It is in this context that a sediment Total Maximum Daily Load was adopted for the Upper Elk River Watershed. Please see the Upper Elk River Technical Analysis for Sediment (TetraTech, 2015) for further background.

[2] Listed under Section 303(d) of the Clean Water Act as impaired in 1998

Section 3: Watershed Stewardship and Recovery Planning

Under Water Code section 13000 as enacted in 1969, "*the Legislature finds and declares that the people of the state have a primary interest in the conservation, control, and utilization of the water resources of the state, and that the quality of all the waters of the state shall be protected for use and enjoyment by the people of the state. The Legislature further finds and declares that activities and factors which may affect the quality of the waters of the state shall be regulated to attain the highest water quality, which is reasonable, considering all demands being made and to be made on those waters and the total values involved, beneficial and detrimental, economic and social, tangible and intangible*."

Further, Water Code section 13243 authorizes the Regional Water Board to prohibit the discharge of waste in Waste Discharge Requirements (WDRs) or the Basin Plan under certain conditions or in certain areas. In addition, Water Code section 13304 authorizes the Regional Water Board to order a person who discharges waste or threatens to discharge waste into waters of the state that causes or threatens to cause a condition of pollution or nuisance to clean up the waste or abate the effects of the waste, or in the case of threatened pollution or nuisance take other necessary remedial action.

In conformance with the Water Code, the Regional Water Board adopted: 1) the TMDL Action Plan defining the current assimilative capacity of the Elk River watershed for sediment and sedimentation, and the actions necessary to expand the current assimilative capacity and reduce sediment sources in conformance with water quality standards and protection against nuisance conditions, 2) WDRs for two industrial timberland owners, Humboldt Redwood Company (HRC) and Green Diamond Resources Company (GDRC), providing the restrictions necessary to control all controllable sources of waste sediment associated with timber operations in the Upper Elk River Watershed. The Regional Water Board did not require cleanup of past waste sediment discharges under a Cleanup and Abatement Order, largely because the past owner (Palco) responsible for those discharges declared bankruptcy and no longer owns the property where HRC and GDRC conduct operations. Instead, the Regional Water Board approved a Watershed Stewardship Program as a key element of the TMDL Action Plan, combining regulatory and non-regulatory resources of the Regional Water Board as the appropriate approach for endeavoring watershed recovery.

The issues confronting the Elk River Watershed are not wholly unique. The Regional Water Board's Watershed Stewardship Program is a participatory program designed to coordinate activities, build watershed-based partnerships, and improve and enhance watershed conditions across the North Coast Region. The program seeks to foster collaboration between component programs, stakeholders and agency staff by establishing effective collaborative partnerships to improve water quality and ecological resiliency throughout the region and uses both regulatory and non-regulatory tools and resources.

Impacts to water bodies in the North Coast Region such as the Elk River are often the result of large-scale landscape disturbances, which have physically altered watershed processes that directly contribute to ongoing pollutant loading and reduce the affected water body's assimilative capacity (i.e., resilience). The stewardship approach to these legacy impacts applies a coordinated program of regulation, grant support, and watershed partnerships to address both the historic and contemporary water quality issues in a comprehensive and cohesive manner, which marshals the resources of multiple agencies and responsible parties.

3.1 Elk River Watershed Stewardship Program

The Elk River is a watershed where the water quality conditions are no longer supportive of beneficial uses nor adequate to prevent nuisance conditions. This is largely due to the altered state of the watershed, wherein sediment and water are no longer transported normally in the stream channel during smaller storms. Instead, the channel capacity for water and sediment has been decreased by excessive sedimentation that results in multiple out-of-bank flows on an annual basis. The Watershed Stewardship Approach (Stewardship Approach) with its adaptive management component provides a framework for coordinating sediment source control and remediation/restoration actions, while also partnering with other essential organizations well-suited to provide health and safety protections. The Regional Water Board has a dedicated Humboldt Bay Steward, whose job includes coordinating the Elk River Watershed Stewardship Program.

The Stewardship Approach is being utilized in the Elk River watershed because:

- The Regional Water Board did not choose to issue a Cleanup and Abatement Order to require cleanup of past waste sediment discharges;
- The nuisance flooding conditions affecting properties associated with the impacted reach of the Elk River (Figure1) and other downstream public and private properties will not be corrected by sediment source control measures alone;
- There are several active Regional Water Board programs and contracted projects contributing to recovery requiring coordination and integration of activities across all participants;
- The magnitude and diversity of recovery actions will require the combined mandate and resources of multiple agencies to undertake stream restoration, improvements in public infrastructure, and to restore a reliable source of drinking water to watershed residents;
- The recovery program requires close coordination with landowners to implement voluntary restoration activities on their property.

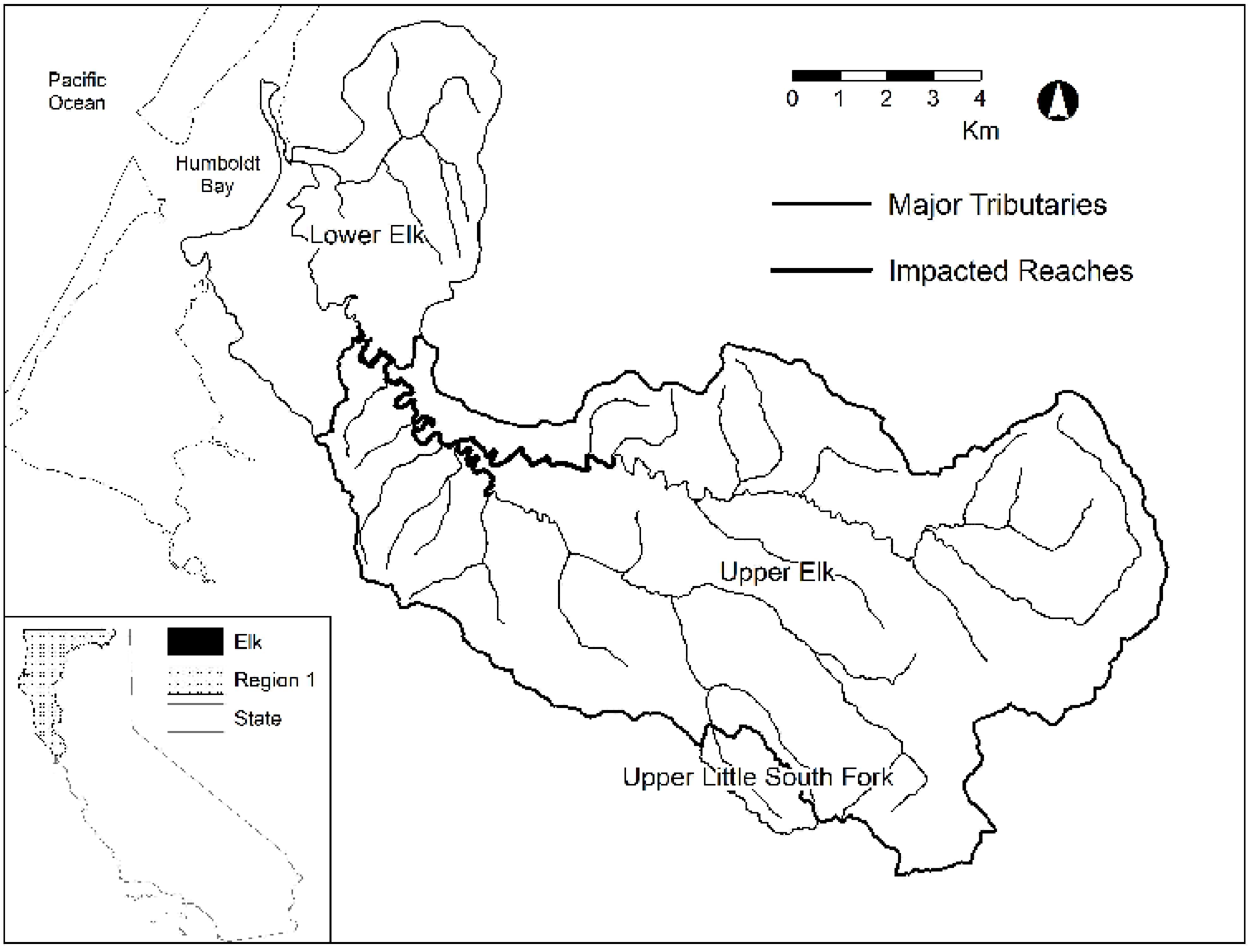


Figure 1. Elk River Watershed

The Elk River Stewardship Program is a community-based effort to restore the beneficial uses of water in Elk River and reduce nuisance flooding conditions. Following its initiation under the leadership of Humboldt County, the Elk River Stewardship Program has been implemented since 2019 by CalTrout and its subcontractors, Northern Hydrology Engineering and Stillwater Sciences under the guidance and support of the Regional Water Board, including grant and contract support. The purpose of the Stewardship Program is to couple its approach to reducing waste sediment discharge from the upper watershed (see Section 4) with its effort to engage Elk River stakeholders in a collaborative planning, design, and implementation process that seeks to:

Identify Strategies to:

- Improve the hydrologic and sediment processes, water quality conditions, and aquatic and riparian habitat functions in Elk River
- Reduce nuisance flooding and the consequent risks to residents and properties, and improve transportation routes during high water conditions

- Improve drinking water and agricultural water supplies for residents in Elk River

Ensure actions are prioritized and integrated to:

- Collectively yield the greatest benefit to residents and natural resources in the Elk River watershed
- Ensure actions are implemented in a cost-effective manner

Conduct a monitoring and adaptive management program to:

- Track responses and outcomes of implemented actions
- Quantify project benefits and temporary and permanent impacts

3.2 Elk River Recovery Assessment and Recovery Plan

Table 4 of the TMDL Action Plan requires that

"*By 2017, CalTrout will produce a final report detailing the results of full-scale sediment and hydrodynamic modeling, including feasible remediation and restoration activities sufficient to achieve water quality standards and return the watershed to a trajectory of recovery.*"

The State Water Resources Control Board (State Water Board) funded through the Cleanup and Abatement Account the development of a sediment transport and hydrodynamic model called the Elk River Recovery Assessment: Recovery Framework (ERRA). The ERRA was built as a predictive tool to assess watershed response to 1) reduction in sediment loading from the upper watershed and 2) implementation of various appropriate restoration approaches in reaches across the watershed from just above the confluence of the north and South Forks of the Elk River all the way to Humboldt Bay. The development of the ERRA and the modeling scenarios were guided by a Technical Advisory Committee comprised of technical experts, representatives from the timber companies, and residents. The final ERRA report was submitted by CalTrout in March 2019.

The ERRA established a restoration framework, which formed the basis for development of the Elk River Watershed Stewardship Program: Sediment Remediation and Habitat Rehabilitation Recovery Plan (Recovery Plan) also developed by CalTrout and its subcontractors under contract to the Regional Water Board. Completion of the Recovery Plan is contemporaneous with this staff assessment, so is not summarized here. It presents a landowner-vetted strategy for sediment remediation and habitat rehabilitation approaches across four planning areas from just above the confluence of the north and South Fork all the way to Humboldt Bay. This planning document provides the basis for funding, design, permitting, and implementation of on-the-ground restoration activities beginning immediately.

3.3 Evolution of Elk River Watershed Stewardship

Table 4 of the TMDL Action Plan describes the expected actions of the Watershed Stewardship Program as follows:

"By 2016, in coordination with a steering committee, Humboldt County will initiate a watershed stewardship program for the Elk River Watershed in conformance with the 319(h) grant contract, including establishment of: a Health and Safety workgroup responsible for developing recommendations appropriate for resolving water supply, flooding, and road access issues; a Science and Coordinated Monitoring workgroup responsible for developing recommendations appropriate for improving the effectiveness of water quality, sediment and flow monitoring efforts throughout the watershed; a Sediment Remediation workgroup responsible for developing recommendations appropriate for remediating instream stored sediment and improving floodwater conveyance, sediment transport, and ecosystem function. Final reports documenting the workgroup's recommendations, including plans and schedules are due in 2018."

In 2014, the Regional Water Board saw the need for a comprehensive coordination framework for the Elk River watershed and initiated a series of meetings to discuss the development of a watershed stewardship charter (later defined as an operating agreement) with local organizations. The operating agreement was intended to guide voluntary partnerships for a watershed stewardship approach for Elk River recovery. Several organizations were engaged in the process, with the following serving on the steering committee: USDA Natural Resource Conservation Service (NRCS), Regional Water Board, CalTrout, Humboldt County, and Humboldt County University of California Cooperative Extension Service. The first Stewardship Operating Agreement meetings were convened in the fall of 2014. Steady progress was made in crafting a charter and the group submitted a proposal to fund its work. The 319(h) grant was awarded to Humboldt County in March 2015.

The initial focus of the Steering Committee was to organize a series of public meetings to 1) communicate the findings of the ERRA, 2) gauge the public's interest in a large-scale watershed restoration effort and 3) solicit public input on restoration priorities. The public meetings were well attended and successful in communicating technical findings and soliciting input on stewardship priorities. In addition, two newsletters were developed, and an initial Elk River Watershed Stewardship Program website created.

It was a challenge to align and coordinate the ERRA contract activities of CalTrout and the 319(h) grant activities of the County, which together constituted the foundation for the Watershed Stewardship Program. Not only were they funded under separate agreements that started at different times, but they also had different lead contractors, deadlines, and areas of focus. CalTrout was the prime contractor for the technical based ERRA, and the Humboldt County was the lead contractor for the community-based Watershed Stewardship Program. Due in large part to these difficulties the Watershed Stewardship Program underwent a major transition in January 2017 when Humboldt County terminated its involvement in the Watershed Stewardship Program.

Regional Water Board staff worked with State Board staff to transfer the remaining funds to CalTrout who was selected because of their existing role on the Elk River Watershed Stewardship Steering Committee and their work on the ERRA. During this transition period the ERRA model scenarios developed in collaboration with the ERRA Technical Advisory Committee, were run, and provided a technical basis to begin designing a recovery program. Because the recovery program would require the voluntary participation of individual landowners, the project team shifted their stakeholder involvement from public meetings to individual meetings with potentially affected landowners. The program progressed from a general conceptual recovery strategy, the ERRA, to a more detailed Recovery Plan, released for public review in July 2022.

- Stewardship program pivoted from large-scale community meetings to meetings with individual landowners, especially those whose property would be involved in recovery activities
- With landowner approvals an *Elk River Watershed Stewardship Program: Sediment Remediation and Habitat Rehabilitation Recovery Plan* (Recovery Plan) has been completed
- Presentation to the community and Regional Water Board will be conducted at the special Regional Water Board meeting in Eureka scheduled for August 30, 2022

Table 1 includes a summary of the timeline and milestones for Watershed Stewardship Program. The table does not include many of the essential milestones completed by the ERRA and others (e.g., Salmon Forever, City of Eureka, California Department of Fish and Wildlife) also working in the watershed on shared recovery and restoration objectives but includes broad strokes.

Table 1. Elk River Watershed Stewardship Program Timeline and Milestones 2013-2022

Date(s)	Program Phase	Milestone Description
2013 – 2018	ERRA (preceded the establishment of the Stewardship Program)	• Elk River Summit public workshop • Elk River Hydrodynamic and Sediment Transport Modeling Pilot Project • Advisory team meetings to review and inform model development • Completion of Steel Bridge removal pilot project.
2014 - 2017	Operational Charter Development, Establishment of Stewardship Program Steering Committee, Initial Public Engagement	• Facilitated meetings among organizations committed to supporting long-term voluntary coordination framework for watershed restoration. Steering Committee consisted of Humboldt County, UC Berkeley Humboldt Extension Service, USDA Natural Resource Conservation Service, CalTrout, and the Regional Water Board. • Individual meetings with residents and local organizations (e.g., Humboldt County Farm Bureau) to inform charter development. • Elk River Watershed Stewardship Charter signed in June 2016. • Series of Steering Committee meetings to define objectives of the program and to coordinate with the ERRA • Public workshops to receive community input on scope and objectives • Outreach facilitated through newsletter distribution and the creation of a project website • Transition from Humboldt County to CalTrout as lead contractor
2016 – 2017	Initial Implementation of the Stewardship Program	• Initiate design plans for two pilot projects (Wrigley Orchard and Elk River Flood Curve). • Development of recovery strategy modeling scenarios to evaluate three implementation program approaches • Initiated pilot project permitting process and CEQA analysis. • South Fork conceptual planning process begun including baseline condition surveys and vegetation mapping. • Integration of the ERRA and Stewardship Program to ensure full consideration of the scientific conclusions drawn from the sediment and

Date(s)	Program Phase	Milestone Description
		hydrodynamic modeling of the ERRA into the planning and implementation efforts
2017 - 2020	Integration of ERRA with Stewardship Program and Development of Recovery Plan	• Meeting with individual landowners to share ERRA modeling scenario results and proposed restoration actions • Compiled landowner-supported actions into a Preferred Recovery Strategy • Information compiled into a single report: Elk River Assessment Recovery Framework providing reach by reach restoration prescriptions for several categories of restoration activities (i.e., vegetation management, sediment remediation, riparian restoration, channel realignment) • Conduct several resource management agency meetings to begin permitting discussions for the Recovery Plan
2019 - 2022	Translating HST Model Scenarios into Design Documents, Pilot Project Development, Environmental Reporting (CEQA), Permitting, Program Design Reports Elk River Recovery Plan	• Run additional HST modeling scenarios with additionally collected data, which supported development of an updated sediment remediation and habitat restoration action plan • Continue CEQA and permitting activities for Wrigley Orchard and Elk River Flood Curve Projects. • Design plans completed to 65% for Elk River Flood Curve and 100% for Wrigley Orchard. • Newsletter distributed • Produce a monitoring framework to guide watershed stewardship and adaptive management activities. • Conducted a pilot modeling exercise to investigate climate change impacts on rainfall – runoff impacts. Technical memorandum reporting on results indicating impacts for 100-year floodplain boundary • Initiate Health and Infrastructure Community Surveys to better understand impacts and solutions for drinking water, flooding, and impacts on septic systems • Project Design reports completed in this period include:

Date(s)	Program Phase	Milestone Description
		• ERRA: Recovery Framework • Elk River Sediment Remediation Pilot Implementation Projects: Basis of Revised 65% Draft Engineering Designs • South Fork Elk River 10% Design Report • Elk River Mainstem Reaches (MSR) 1-2 10% Design Report • Elk River Stewardship Program, Final Project Report: Landowner Outreach, Technical Advisory Committee Outreach, Stewardship Meetings, Newsletters • Elk River Sediment Remediation and Habitat Rehabilitation: Draft Project Description

3.4 Health and Safety

Staff have identified five topics critical to understanding health and safety issues in the Elk River watershed: 100-year flood levels, road flooding, impacts to structures, onsite waste treatment systems, and drinking water supply. It was initially identified that these topics would be addressed by the Stewardship Program with Humboldt County as the lead. With the loss of Humboldt County as lead of the Stewardship Program who was well suited to direct progress on the health and safety issues, the progress on those issues has been sparse in this first 5-year period of TMDL implementation; it clearly deserves more immediate attention. To that end, the Regional Water Board has hired a new Humboldt Bay Watershed Steward whose duties include leadership on the topics of health and safety, particularly identifying appropriate agencies and resources with the authority to address these infrastructure needs.

On the other hand, under the leadership to CalTrout, there has been tremendous progress in the realm of recovery planning, including the completion of the Recovery Plan from which to initiate funding, design, permitting, and implementation of sediment remediation and habitat rehabilitation projects. Completing the Recovery Plan is crucial to making progress correcting the fundamental causes of health and safety issues, but the timeline for completion of these projects is long.

While leading the Watershed Stewardship Program, Humboldt County established a Road Flooding Workgroup and committed to hold four public meetings. The meetings were designed to identify potential road improvement projects that would alleviate nuisance flooding on Elk River Road, Wrigley Road, Zanes Road, Berta Road, and Elk River Court. However, only one meeting was held prior to Humboldt County ending their leadership role in the Stewardship Program. Attendees of that 2016 meeting were asked to complete surveys to address their flooding experiences including magnitude, frequency, direct impacts from flooding, relative interest in roads projects designed to alleviate flooding, and perceived causes for severe road flooding in the Elk River watershed. Eight participants submitted hard copy responses and two completed the survey online. A majority of respondents identified the need to alleviate road flooding as either “very important” or “extremely important.” Road Flooding Workgroup survey results are included as Appendix A.

As part of the previously discussed ERRA, Northern Hydrology and Engineering (NHE) subcontracted by CalTrout later expanded the model to also include extreme flood events up to the 1% annual chance flood. The results are presented in the September 2020 technical memorandum 1% Annual Chance Flood Elevation Estimates for the Lower Elk River, Humboldt County (100-year Flood Memo), posted to the Regional Water Board’s Elk River TMDL web page. This analysis may be useful to FEMA, Humboldt County, and other entities with authorities associated with flood protection and mitigation.

The 100-year Flood Memo has been distributed to stakeholders, including Humboldt County. Re-engagement with county staff suggests that road flooding around Humboldt Bay is an issue not unique to the Elk River watershed. Further, the County may be under-resourced to address this issue itself. Staff have determined that further engagement with the County, the Office of Emergency Response, and the FEMA could be fruitful. This is an area of growth for the Watershed Stewardship Program.

3.5 Community Drinking Water Programs

Regional Water Board staff have begun discussions with the Division of Drinking Water, Division of Financial Assistance, and Office of Public Participation about programs available to provide Elk River residents with reliable drinking water. The Safe and Affordable Funding for Equity and Resilience (SAFER) program is run jointly by Division of Drinking Water, Division of Financial Assistance, and Office of Public Participation to address the continuing disproportionate environmental burdens in the state by creating a fund that will assist in providing safe drinking water in every California community. Through conversations with these State Water Board divisions, Regional Water Board staff have identified the need to engage Humboldt County, the Humboldt Bay Community Services District, and the Humboldt Bay Municipal Water District in discussions of potential SAFER program fund applications, as well as other water infrastructure and drought relief program funding options. This is an area of further growth for the Watershed Stewardship Program.

3.6 Health and Safety Interviews

Regional Water Board staff prepared a set of interview questions (Appendix B) designed to address each of the five critical health and safety topics identified above (i.e., 100-year flood levels, road flooding, impacts to structures, onsite waste treatment systems, and drinking water supply). Staff identified initial interview participants as those residents of properties at increased risk of flooding hazards based on the 100-Year Flood Memo. In March 2022, initial outreach and interview scheduling efforts began. In an effort to increase engagement, Regional Water Board staff offered in person, phone, or virtual interviews with the participant selecting the interview method. Thirteen property owners expressed interest in participating in the first phase of the health and safety interviews. Later phases of this effort will include a broader group of residents and additional stakeholders. Interviews began in May 2022 and are expected to continue through summer 2022. To date, nine interviews have been conducted, eight in-person and one via conference call.

Health and safety interviews are designed to serve two primary purposes: 1) record residents' recent experience of flooding and related hazards and 2) prepare a comprehensive list of the solutions participants favor for reducing the impact of those hazards. Participants are provided NHE's 100-year flood memo and given the opportunity to ask questions about its findings. They are also asked to describe the frequency, duration, and extent of flooding on their property and to identify any critical infrastructure that has been inundated including onsite wastewater treatment and drinking water system, access to roads, and impacts to agricultural function.

As of May 2022, nine groups of Elk River property owners have been interviewed. (Interviews with remaining impacted property owners still to be scheduled). Road flooding was the most frequently identified challenge, noted by five of the nine groups. Loss of drinking water supply was identified as a major challenge by four groups, while decreased property value was noted by three groups. Other challenges discussed by property owners include a loss of agricultural function of the property, risk to property and personal safety, loss of recreational and fishing beneficial uses, flooded structures, silt accumulation, loss of wash water supply, and impacts to septic systems.

Health and safety interviews are not designed to gauge property owners' positions on any specific land use activity and the topic of support for solutions to flooding challenges was presented as an open-ended, unprompted set of questions. When asked what solutions they support to address the challenges discussed, timber harvest restrictions and related source control were proposed by 1/3 of the property owners interviewed. Two groups noted that they support connection to a community water system and two groups identified raising structures on their property as a valuable solution. Other proposed solutions include, among others, constructing or replacing bridges, geomorphic projects to promote channel incision and sediment delivery to Humboldt Bay, sediment removal from the channel, construction of flood control channels and/or culverts, removing log jams, and riparian restoration projects.

Upon completion of the first phase of health and safety interviews, Regional Water Board staff will determine how best to expand the group of participants. Once all interested parties have had the opportunity to complete the interview process, Regional Water Board staff will review the responses and identify priority projects supported by the community. Many of the suggested solutions are outside of the authority and expertise of the Regional Water Board and will require engagement with other organizations and agencies (e.g., Humboldt County, Department of Water Resources, Office of Emergency Response).

Section 4: Waste Discharge Requirements

Timber harvesting is one of the primary land uses in the Elk River Watershed. Current data from Humboldt County indicates that approximately 84% of the watershed is zoned as Timber Production[3] Zone. The two largest owners are Humboldt Redwood Company, LLC (HRC) and Green Diamond Resource Company (GDRC). HRC owns and actively manages approximately 209,000 acres in the Upper Elk Watershed while GDRC owns and operates 22,000 acres. The Bureau of Land Management (BLM) is also a major landowner along the South Fork, but only minimal forest management activities occur on BLM land. In addition to the HRC and GDRC various smaller landowners throughout the watershed continue to conduct timber operations.

All timber operations, regardless of owner, must adhere to specific Forest Practice Rules (FPRs) and must be conducted under valid Timber Harvest Plans (THPs), Nonindustrial Timber Management Plans (NTMPs), or Notices of Emergency, or Exemptions and must also be permitted under Waste Discharge Requirements (WDRs) or Waivers of WDRs from the Regional Water Board.

THPs for HRC and GDRC are covered under WDRs that are specific to their Elk River timberlands (Orders No. R1-2019-0021 and R1-2020-0001, respectively). THPs on other ownerships may be covered under either General WDRs (Order No. R1-2004-0030) or the Categorical Waiver (Order No. R1-2014-0011). NTMPs must seek coverage under the NTMP General WDR, Order No. R1-2013-0005. Exemption and Emergency Notices are ministerial projects under the FPRs and are automatically covered under the Categorical Waiver.

Table 4 of the TMDL Action Plan requires for sediment source control:

“Humboldt Redwood Company shall implement its revised WDRs adopted by the Regional Water Board to implement phase 1 of the Upper Elk River Sediment TMDL and a zero load allocation”

“Green Diamond Resource Company shall implement its revised South Fork Elk River management plan approved by the Regional Water Board to implement phase 1 of the Upper Elk River Sediment TMDL and a zero sediment load allocation"

“Prior to any timberland management activities, non-industrial timberland owners shall enroll under the General NTMP WDR in Tier B (Order No. R1-2013-0005 General Waste Discharge Requirements for Discharges for Timber Operations on NTMPs) or a future Order that replaces Order No. R1-2013-0005"

[3] (g) “Timberland production zone” or “TPZ” means an area which has been zoned pursuant to Section 51112 or 51113 and is devoted to and used for growing and harvesting timber, or for growing and harvesting timber and compatible uses, as defined in subdivision (h).

With respect to the general plans of cities and counties, “timberland preserve zone” means “timberland production zone.”

“For other timber harvest plans, landowners shall enroll individual THPs under the General Timber WDRs (Order No. 2004-0030) or a future Order that replaces Order No. R1-2004-0030 and incorporate any additional conditions identified during the timber review process as necessary to be consistent with the TMDL Action Plan”

“The Bureau of Land Management shall request enrollment of any projects with potential sediment discharges under the U.S. Forest Service Waiver (Order No. R1-2015-0021) or a future Order that replaces Order No. R1-2015-0021"

4.1 Regulatory Requirements

All timber operations conducted under the plans described above must comply with additional requirements including all applicable FPRs, Habitat Conservation Plans, California Department of Fish and Wildlife (CDFW) Master Agreement for Timber Operations, and Regional Water Board WDRs or Waiver of WDRs. While Regional Water Board permits rely in large part on the FPRs, Habitat Conservation Plans and the CDFW Master Agreement for Timber Operations, the Regional Water Board may also establish additional requirements as deemed necessary for water quality protection. Therefore, in addition to establishing specific requirements, Regional Water Board permits establish a direct regulatory relationship with project proponents and explicitly make enforceable water quality protection requirements. Water quality protection requirements are designed to meet the following goals:

Control sediment- Identify and treat existing controllable sediment discharge sources. Implement management practices to prevent or minimize the potential for creating new sediment discharge sources. (e.g., special limitations in winter conditions)

Protect riparian zones- Establish minimum tree retention and limit ground disturbance. This serves to control and filter sediment discharge, protect vulnerable streambanks and hillsides, protect stream temperature, and promote large wood recruitment potential into streams.

Protect stream temperature- Adequate riparian zone protection ensures that trees that provide shade to watercourses with summertime flow are retained thereby keeping stream temperatures naturally cooler.

Prevent exacerbating cumulative impacts- Minimize project specific impacts, which exponentially increase when distributed throughout the watershed (e.g., established harvest rate thresholds for HRC and GDRC).

Establish monitoring requirements- Complete regular site inspections to ensure best management practices implementation and function. Monitoring requirements for HRC and GDRC include monitoring of water quality, aquatic habitat/stream conditions, and landslides.

Regional Water Board requirements may vary dependent upon the type of permit or plan and can either apply to the lifetime of the specific plan area, or to a larger area where the plan exceeds the life of an individual THP. For example, WDRs for HRC and GDRC include specific THP requirements as well as additional requirements independent of THP, which are primarily related to monitoring and sediment control from roads.

NTMPs are long term management plans that provide landowners with an approved plan to conduct timber operations by submitting a Notice of Timber Operations (NTO) to CAL FIRE. An NTO is effective for one year and requires landowners (or their consulting foresters) to conduct an evaluation of the NTMP to ensure conditions have not changed, and/or address any changed conditions as needed. The NTMP General WDR provides two options for compliance, Tier A and Tier B. Tier A permits landowners to enroll individual NTOs and requires the identification and implementation of corrective action of sites within the NTO that could adversely impact beneficial uses of water. Tier B requires landowners submit and maintain an Erosion Control Plan (ECP) consisting of an inventory and schedule for implementation of corrective action for controllable sediment discharge sources. Except under Exemptions and Emergencies, Regional Water Board permits establish requirements that landowners develop ECPs and conduct annual inspections of the project area.

4.2 Timber Harvesting and Associated Activities 2016-2021

Regional Water Board staff conduct rigorous oversight of all forest management projects in the Elk River Watershed, including office review of all proposed projects, field review of most projects during the approval process and subsequently during active operations and following completion of operations. The purpose of the field oversight is to ensure compliance with water quality requirements, evaluate implementation and effectiveness of management practices designed to protect water quality, and provide feedback and guidance to landowners on water quality protection. Since the TMDL Action Plan was adopted by the Regional Water Board in May 2016, staff from the Forest Activities Program have conducted 39 field inspections, including pre-consultations, preharvest, active and completion inspections. All inspections are documented by an inspection memo and/or database record.

Staff conducted 27 inspections of HRC operations, 4 inspections of GDRC operations, and 6 inspections of the operations of other timberland owners. In general, Regional Water Board staff find high levels of compliance with applicable water quality requirements associated with timber operations.

4.2.1 Humboldt Redwood Company

On November 30, 2016, the Regional Water Board adopted Order No. R1-2016-0004, which superseded the 2006 WDR for HRC management activities in the Elk River

Watershed. The Order established general and specific requirements for their timber harvesting and associated management activities to control sediment and temperature impacts. It also included best management practices intended to implement applicable water quality standards from the Water Quality Control Plan for the North Coast Region (Basin Plan), which includes the TMDL Action Plan. Below is a summary of the requirements contained in Order No. R1-2016-0004, which is not intended to replace or revise the actual conditions contained within the order.

Order No. R1-2016-0004 is based largely on the Report of Waste Discharge (ROWD) submitted to the Regional Water Board by HRC in 2015, with additional measures as warranted to meet applicable water quality protection requirements.

The ROWD includes HRC's proposed long term strategy, including measures designed to prevent or minimize water quality impacts from activities associated with its forest management, including:

- Timber harvesting
- Road use, construction, reconstruction, decommissioning, repair, and maintenance
- Measures to prevent or minimize controllable sediment discharge from roads, skid trails, landslides, and other sources related to timberland management
- Retention of riparian vegetation to preserve and/or restore shade, supply large wood, filter sediment from upslope sources, help maintain and restore channel form and in-stream habitat, and moderate peak flows
- Treatment of controllable sediment discharge sources
- In-stream and riparian zone habitat restoration by enhancement of in-stream large wood for habitat restoration
- Implementation and Effectiveness Monitoring
- Watershed trend monitoring

On June 6, 2019, in response to a directive from the State Water Board, the Regional Water Board adopted Order No. R1-2019-0021, which revised certain requirements of the 2016 Order. The primary revisions were increased Riparian Management Zones and additional limitations on wet weather log hauling. The existing requirements, discussed below, include:

- Riparian zone protection, which requires minimum 50% post-harvest overstory canopy cover within 300 feet of Class I and II watercourses and 150 of Class III watercourses
- Identification and treatment of controllable sediment discharge sources
- Review by Professional Geologist (PG) of all proposed activities, including harvesting and construction or reconstruction of roads and watercourse crossings

- Wet weather requirements that winter period hauling shall cease for a period of 48 hours following a precipitation event that results in 0.25 inches or more of rainfall within any 24-hour period
- Implementation of HRC's Elk River/Salmon Creek Watershed Analysis hillslope management prescriptions
- A requirement that HRC conduct a study to evaluate the feasibility of methods to control, trap, or meter out sediment from in-channel sources; and
- A robust hillslope and in-stream monitoring requirement.

4.2.1.1 Habitat Conservation Plan

All of HRC ownership in the Elk River watershed is covered by a multi-species state and federal Habitat Conservation Plan (HCP) approved in 1999. A critical element of the HCP is Watershed Analysis, in which HRC's approximate 209,000-acre ownership is divided into eight primary watersheds for focused inventory and investigation of conditions and processes related to mass wasting, surface erosion, riparian function, stream channel, and aquatic habitat. The first Watershed Analysis conducted for the Elk River/Salmon Creek Watershed Analysis Unit (WAU) involved several years of study culminating in a final report released in 2005. Forest management prescriptions pertaining to slope stability and riparian forest protection were developed and formally established in consultation with multiple state and federal agencies including National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service (USFWS), California Department of Fish and Wildlife (CDFW), and California Geological Survey (CGS), as a result of this process. Regional Water Board staff participated intermittently in the initial watershed analysis as well.

The 2014 *Elk River/Salmon Creek Watershed Analysis Report* analyzed the effectiveness of HRC's forestry prescriptions in Elk River, along with watershed trends affecting aquatic habitat conditions. A primary purpose of the report was to assess the effectiveness of the current Elk River/Salmon Creek forestry prescriptions in meeting the HCP Aquatic Conservation Plan goal 'to maintain or achieve, over time, a properly functioning aquatic habitat condition'. As such, the report was an important supporting document to the ROWD relevant to understanding the effects of contemporary forestry practices on beneficial uses of waters of the state. Many of the HCP prescriptions related to water quality protection, such as road management, geologic prescriptions, riparian protection, and in-stream monitoring have been incorporated into the WDR.

Another important element of the HCP is its Road Auditing and Inspection Program patterned after the U.S. Forest Service Best Management Practice Evaluation Program. This program evaluates the effectiveness of road treatment in minimizing sediment delivery to streams. The program has been in effect since 2006 and has been established as an element of monitoring and reporting requirements of the WDR.

4.2.1.2 Timber Harvesting

HRC utilizes uneven-aged single-tree and small group selection silviculture within its timberlands in the Upper Elk River watershed. Variable retention may be used in some instances to address certain stand conditions, such as high levels of whitewood or hardwood species, animal damage, or general poor form and vigor due to past logging history. Other silvicultural methods that may be applied infrequently include Rehabilitation of Understocked Areas, Seed Tree Removal, and Sanitation Salvage. Consistent with the ROWD, HRC does not utilize the clearcut harvest method.

4.2.1.3 Harvest Rate Limitations

Harvest rate limitations were first established in the Elk River Watershed by the Regional Water Board with adoption of WDRs in 2006. Those WDRs established harvest limits that applied separately to HRC's (originally PALCO) timberlands in the North and South Fork Elk River. HRC owns approximately 14,049 acres in the 14,336 acres North Fork and 6,560 acres of the 13,120 acres in the South Fork Elk River. Harvest rate limitations from the 2006 WDR were based on two empirical models, the Landslide Reduction Model in the North and South Forks, and the Peak Flow Reduction Model (Peak Flow Model) in the North Fork only. The Peak Flow Model, which was designed to limit harvest related increases in peak flow, established a limit of 264 Equivalent Clearcut Acres[4] per year in the North Fork. The Landslide Reduction Model was designed to limit harvest related landslides and applied to both the North and South Fork watersheds. Annual harvest limits from the Landslide Reduction Model for the North Fork Elk watershed was 266 acres in low hazard zones, 21 acres in high hazard zones, or any combination of acres between the high and low hazard zones that satisfies the following relationship:

Low Hazard Harvest Acres=-12.807(High Hazard Harvest Acreage)+266.01*

Annual harvest limits for the South Fork Elk River from the Landslide Reduction Model was 114 acres on the Discharger's lands in the South Fork Elk River watershed for all hazard zones combined.

The Elk River WDR included a "zero landslide-related discharge" requirement for harvest acreage in excess of the landslide reduction model limits. Regional Water Board staff developed a methodology for evaluating enrollment of harvest acreage in excess of the limits based on the landslide reduction model but not to exceed those established under the Peak Flow Model.

With adoption of the revised WDRs in 2016, harvest limits based on the two empirical models were replaced by a threshold of concern of 2% equivalent clearcut acres in any sub watershed over any 10-year period. With each enrollment application, HRC provides a table showing harvest acreage for the previous 10-year period and

[4] [4] Equivalent clearcut area (ECA) is a widely used methodology developed by the USFS to account for the relative impacts of different types of silvicultural treatment. It assigns a weighting factor of one to clearcutting and a value less than one for partial harvesting silvicultural treatments. The weighting factor for a silvicultural treatment is multiplied by total area treated under each silviculture to arrive at a normalized disturbance calculation. Therefore, 100 acres of selection harvest, which is typically assigned a ECA factor of 0.5, would be counted as 50 equivalent clearcut acres.

calculations demonstrating the average annual equivalent clearcut area for that period for each sub watershed in which the plan is located.

Regional Water Board and HRC staff evaluated the relative risk of sediment production and discharge in each sub watershed in the Upper Elk River. Based on suspended sediment data, landslide hazard, and observations by field staff of areas dominated by the Hookton Formation[5], areas within portions of six sub watersheds were identified as high risk to water quality for the purposes of the WDR. Those six subwatersheds are: Clapp Gulch, Railroad Gulch, Tom Gulch and Lower South Fork in the South Fork Elk River and Lower North Fork and South Branch North Fork in the North Fork Elk River. For the five-year period following adoption of the WDR, timber harvesting in the high risk areas is limited to units of THP 1-12-110 HUM, which was approved by CAL FIRE prior to the completion of the Upper Elk River TMDL. THP 1-12-110 HUM includes harvest in the high risk subwatersheds of Clapp Gulch, Railroad Gulch, Tom Gulch and Lower South Fork. No later than five years from the date of adoption of the WDR in June 2019, the Regional Water Board will consider the conditions limiting harvest activities in high-risk areas, and after public notice and comment will provide staff direction on potential changes to the harvest limitations. In the absence of changes to the WDR, harvesting in high-risk areas for the period beginning five years after the adoption of the WDR will be limited to the acreage identified in the ROWD.

On November 15, 2021, as required by the monitoring and reporting requirements established by Order No. R1-2019-0021, HRC submitted a 5-year synthesis report, which is discussed in more detail below. Since 2016, HRC has harvested approximately 3775 acres under 15 separate THPs. Harvesting was primarily under single tree or group selection with 38 acres harvested under the variable retention silviculture method. The Table below provides a breakdown of harvest acreage by sub watershed 2016-2021 and the percent of the subwatershed harvested, calculated as clearcut equivalent acres over the previous 10-years, as provided by the WDR.

Table 2. Humboldt Redwood Company Harvest Acreage by Sub Watershed

Subwatershed	**Acreage**	**% Harvest (10 year rolling average)**
Bridge Creek	200	1.15
Browns Gulch	3	1.78
Clapp Gulch	17	0.13
Dunlop Gulch	34	2.63*
Lake Creek	2	1.38

[5] From Tetra Tech (2015) “Geology: The argillite-dominated rock units of the Yager terrain are typically deeply weathered and sheared and subject to deep-seated flow failures on moderate slopes (Marshall and Mendes 2005). Deep-seated landslides and earthflows enclosing blocks of component sandstone are common in the Franciscan Complex Central Belt. These blocks commonly create steep slopes and weather to soils that have little strength and are susceptible to debris slides and debris flows (Marshall and Mendes 2005). Shallow landsliding and deep-seated bedding plane failures are common in Hookton terrain (Marshall and Mendes 2005).”

Subwatershed	Acreage	% Harvest (10 year rolling average)
Lower NF	211	0.77
Lower SF	361	1.27
Mainstem Elk	193	0.17
McCloud Creek	39	0.13
McWhinney Creek	121	1.51
North Branch NF	773	1.87
North Fork Elk	623	1.24
Railroad Gulch	103	0.73
South Branch NF	133	1.04
South Fork Elk	909	1.33
Tom Gulch	9	0.03
Upper NF	44	1.11
Total	**3,775**	**0.97**

**Exceedances of the 2% timber harvest rate limitation are only seen in Dunlop Gulch.*

4.2.1.4 Sediment Control-Roads

As required by the WDRs, as of October 15, 2021, HRC's entire road system has been storm proofed or decommissioned. Road inventories were conducted prior to decommissioning and any necessary sediment control work was implemented. Table 3 summarizes the current status/classifications of the road network.

Table 3. Humboldt Redwood Company Total Roads by Classification

Road Classification	Total Miles
Permanent (Rocked/paved)	97
Seasonal (Native Surface)	124
Decommissioned	36

According to the HRC 5-year synthesis report (Miles, 2021), HRC has treated 104 road-related sediment discharge sites since 2016 for an estimated control of approximately 15,600 cubic yards of sediment delivery. An additional 12 historic off-road skid trail sites, primarily old watercourse crossings, were treated for the removal and control of an estimated 220 cubic yards of sediment discharge. The report further states that over 350,000 cubic yards of sediment have been removed or prevented from entering the Elk River stream system as a result of storm proofing road activities conducted on its ownership over the last 20 years.

4.2.1.5 Feasibility Study

The WDR requires HRC to conduct a feasibility study for control of in-channel sediment sources on its timberlands. In response, HRC implemented a sediment trapping pilot project in the lower reach of Bridge Creek, a tributary to the North Fork Elk River, pursuant WDRs. The project involved the 2019 removal of approximately 100 cubic yards of stored sediment, trapped in-channel behind a log jam. The log jam was retained intact during and following sediment removal, for the purpose of both aquatic habitat value and future sediment trapping. Several years of cross-sectional channel measurements were taken prior to removal of the stored in-channel sediment to evaluate pre-excavation aggradation and sediment accumulation. Cross-sectional measurements continue to be taken annually, post sediment removal, to evaluate subsequent channel change including any measurable sediment entrapment. Results to date indicate two percent or less of the Bridge Creek's sub-basin measured sediment load are being captured at this location annually. While the study demonstrated that in-stream structures can be utilized to trap and remove sediment, the difficulty in finding suitable locations that can be accessed by equipment and the relatively insignificant total volume of sediment removed, staff conclude that sediment trapping may not have a significant role in watershed restoration efforts.

4.2.1.6 Restoration

Recently HRC and its non-profit partner Trout Unlimited were notified in November of 2020 that HRC's North Fork Elk River Salmonid Habitat Enhancement Project Designs proposal was selected for funding by CDFW through the agency's Fisheries Habitat Restoration program. The project is the engineering design step for restoration actions that reduce road related sediment delivery and restore and enhance 1.5 miles of instream, floodplain, and off-channel habitats along the North Fork Elk River. Input of large wood into the stream channel for the benefit of rearing and spawning habitat as well as sediment storage and sorting, is a significant component of the project. The project is intended to improve water quality and increase habitat complexity for all life stages of salmon and steelhead; and is consistent with and implements recommendations found in the ERRA.

4.2.1.7 HRC Compliance Summary

Regional Water Board staff closely track HRC’s compliance with applicable water quality requirements, including permit provisions, through frequent field inspections and monitoring and reporting requirements. In general, staff find HRC’s compliance with permit provisions to be very high.

Since adoption of the revised WDR in November 2016, the Regional Water Board has issued one Notice of Violation for sediment discharge resulting from two poorly constructed watercourse crossings on a new ridgetop road. HRC reconstructed the two crossings properly to control the discharge and the violations were considered adequately resolved.

During a November 9, 2017, preharvest inspection, staff encountered two reconstructed culverted watercourse crossings on a road within the logging area of the proposed THP 1-16-112 HUM. At both locations, fill slopes were failing and discharging earthen material to watercourses. On November 22, 2017, the Regional Water Board received discharge notifications from HRC for each site, as required under section II.M of the Order, describing site conditions and documenting corrective action taken on November 20, 2017, to control sediment discharge to receiving waters, including photographs showing work that has been implemented. Subsequent site visits confirm that corrective action remains effective, and no further discharge has occurred

4.2.2 Green Diamond Resource Company

Green Diamond owns 1,905 acres in the South Fork of Elk River, mostly in the McCloud Creek sub watershed. In June 2010, the Regional Water Board adopted an ownership-wide Road Management WDR (Order No. R1-2010-0044). In October 2012 the Regional Water Board also adopted the ownership-wide Forest Management WDRs (Order R1-2012-0087) for associated activities on GDRC property within the North Coast Region. The Road Management WDR covers systematic road upgrading and decommissioning, as well as maintenance and monitoring of the road system associated with the Road Management Plan from GDRC Aquatic Habitat Conservation Plan (AHCP). Conditions specific to the Elk River in the GDRC Roads Management and Forest Management WDRs largely rely upon the GDRC Operating Conservation Program, with specific prescriptions described in the South Fork Elk River Management Plan.

GDRC conducted a full road assessment within GDRC Elk River ownership in 2006, with additional sites identified during THP development since 2006. To date, 96.6% of the sites have been treated, representing an estimated total of over 38,000 cubic yards, or 98.7% of the road related sediment volume that could have potentially delivered to a watercourse.

GDRC maintains a master inventory of all sediment discharge sites deemed feasible to treat, including road-related sites both associated and not associated with THPs, non-road related sites associated with THPs (e.g., skid trail crossings), and non-road related sites not associated with THPs. All controllable sediment discharge sites at which corrective action was deemed feasible have been treated. Ongoing regular inspections to identify and treat new discharge sites are undertaken by GDRC.

The South Fork Elk River Management Plan addresses watershed specific operating procedures in the following five key categories:

- Riparian Prescriptions
- Geological Prescriptions
- Harvesting, Yarding and Hauling Prescriptions
- Road Management
- Seasonal Restrictions

On February 6, 2020, the Regional Water Board adopted Order No. R1-2020-0001, which was developed to be consistent with the hillslope indicators and numeric targets contained in the 2016 Total Maximum Daily Load Action Plan. This Order superseded portions of the GDRC Forest Management WDR that apply to certain activities conducted by GDRC on its timberlands in the Upper Elk River Watershed. The 2020 Order retains much of the provisions of the South Fork Elk River Management Plan. A summary of these requirements is for discussion purposes only; they are not intended to replace or revise the requirements as they are described in the adopted orders. The primary revision resulting from the new order are RMZ requirements that GDRC must retain a minimum of 50% post-harvest forest overstory canopy cover well distributed throughout the area and not utilize group openings larger than 0.25 acres within 300 feet from Class I and II watercourses and 150 feet from Class III watercourses.

The 2012 Order limited harvest rate in their South Fork Elk River timberlands to no more than 75 acres per year, calculated on a 3-year rolling average. The 2020 requirements established a reduced rate of harvest, limiting GDRC to 55 acres per year of net clearcut, calculated on a 3-year rolling average.

Since 2016, GDRC has had three active THPs. Table 4 shows the THPs and annual harvest acreage 2016-2021.

Table 4. Green Diamond Resource Company Harvest Acreage 2016-2021

Year	1-12-113 HUM (Acres)	1-14-119 HUM (Acres)	1-17-116 HUM (Acres)	Total Acres	Rolling 3 Year Average (Acres)
2016	0	28	0	28	34
2017	0	0	0	0	
2018	0	0	73	73	
2019	0	0	0	0	24
2020	0	33	63	96	56
2021	0	0	0	0	32

It should be noted that acreage reported above is total harvest acres, not net clearcut

4.2.3 Other Timber Harvest Plans

In addition to the two large industrial timberland owners, other landowners continue to conduct timber operations in the lower portions of the Elk River watershed under THPs, NTMPs, Exemptions and Emergencies, as summarized below:

4.2.3.1 Timber Harvest Plans:

Since 2016, there have been five new Timber Harvest Plans submitted in the Elk River watershed on properties other than HRC and GDRC, totaling 92.7 acres.

Table 5. Timber Harvest Plans in Elk Watershed Since 2016

THP Number	**Acreage**	**Subwatershed**	**Enrollment Status**	**Silviculture**
1-20-00029-HUM	40	Lower Elk	GWDR 6/2/20	Group Selection
1-21-00082-HUM	19	Lower N/S Elk	GWDR 6/2/22	Seed Tree Seed Step
1-20-00070 HUM	8	Lower Elk	GWDR 6/30/20	Group Selection

THP Number	Acreage	Subwatershed	Enrollment Status	Silviculture
1-21-00038-HUM	7	Lower Elk	GWDR 6/29/21	Group Selection
1-21-00051-HUM	19	Lower Elk	Not Enrolled	Selection

In staff's judgment, these THPs are either outside the Upper Elk River Watershed boundary affected by the load allocation of the TMDL or presented prescriptions consistent with the Action Plan.

4.2.3.2 Non-Industrial Timber Management Plans:

Non-industrial Timber Management Plan (NTMPs) are long term management plans, which provide landowners with an approved plan to conduct timber operations by submitting a Notice of Timber Operations (NTO) to CAL FIRE. NTMPs must utilize uneven age management (no clearcutting). NTOs are valid for one year and require landowners (or their consulting foresters) to conduct an evaluation of the NTMP to ensure conditions have not changed and/or address any changed conditions. The NTMP General WDR, Order No. R1-2013-0005, provides two options for compliance, Tier A and Tier B. In Tier A, landowners can enroll individual NTOs and requires identification and implementation of corrective action of sites within the NTO that could adversely impact beneficial uses of water. Tier B requires landowners submit and maintain an Erosion Control Plan (ECP) consisting of an inventory and schedule for implementation of corrective action for controllable sediment discharge sources.

There are three NTMPs in the Elk River watershed, two of which submitted one Notice of Timber Operations since 2016 and one which has submitted four NTOs since 2016.

Table 6. Non-industrial Timber Management Plans in the Elk Watershed Since 2016

NTMP Number	NTO Year	Acres*	Subwatershed	Enrollment Status
1-01NTMP-004 HUM	2017	Less than 10**	Clapp Gulch	Tier B
1-02NTMP-034 HUM	2021	35	Lower Elk	Tier A
1-03NTMP-013 HUM	2016	204	Lower Elk	Tier A
1-03NTMP-013 HUM	2019	138	Lower Elk	Tier A
1-03NTMP-013 HUM	2021	35	Lower Elk	Tier A
1-03NTMP-013 HUM	2022	35	Lower Elk	Tier A

*NTOs do not always complete harvesting on the entire acreage listed, and therefore, subsequent NTOs may cover either identical or overlapping area covered by previous NTOs. As such, the acres listed in multiple NTOs may not necessarily be cumulative.
**A small portion of the northeastern corner of 1-01NTMP-004 HUM is located in the headwaters of Clapp Gulch.

4.2.3.3 Notices of Exemption

The Forest Practice Rules (FPR) includes three types of timber harvesting projects that are exempt from the requirement that a landowner prepare and submit a THP; Exemptions, Emergencies and Conversion Exemptions.

FPR section 1038 exempts the timber operations listed below from THP preparation and submission requirements. Such exemptions include restrictions on use of heavy equipment on steep slopes, construction of roads and skid trails, timber operations on unstable areas and riparian areas, and winter period operations.

Since 2016, 31 Notices of Exemption have been filed on timberlands other than HRC and GDRC within the Elk River watershed on a total of 639 acres. In addition, both HRC and GDRC have submitted Exemptions, HRC for forest fire prevention on 69.9 acres and GDRC for removal of dead and dying trees on the bulk of its Elk River timberlands.

4.2.3.4 Bureau of Land Management – Headwaters Reserve

The Bureau of Land Management (BLM) manages the 7,472-acre Headwaters Forest Reserve, of which 4,424 acres are located in the South Fork Elk River (comprising 30 percent of the South Fork), in partnership with the California Department of Fish and Wildlife. The Headwaters Reserve was purchased from Pacific Lumber in 1999 by the Federal and State governments and is managed as an ecological refuge and for environmental education.

BLM conducted two forest thinning/fuels management projects, consisting of masticating and chipping small trees and understory vegetation on 81 acres in 2017 and 103 acres in 2018. It also conducted two fish habitat improvement projects on the South Fork Elk River, including modification of a debris jam to improve fish passage in 2019 and an accelerated wood recruitment project on 1.75 miles of stream in 2021.

4.3 Monitoring and Reporting Requirements

Monitoring and reporting requirements are an essential mechanism for Regional Water Board to review and comment on ongoing activities and track compliance with requirements and progress in sediment control and restoration and efficiently focus staff resources and prioritize inspection efforts.

As a condition of their continued operations both HRC and GDRC are required to monitor water quality and potential sediment sources (e.g., roads, landslides, logging activities), and report any changed conditions. Further, HRC is required to provide a five-year synthesis report (2016-2021).

4.3.1 Humboldt Redwood Company Monitoring Requirements

Section IV of Order No. R1-2019-0021, Waste Discharge Requirements, describes HRC's Monitoring and Reporting Requirements for their holdings in the Upper Elk River watershed. Monitoring requirements are divided as follows:

1. Inspections of roads and timber harvest areas
2. Landslide monitoring to identify new or reactivated mass wasting activity
3. Water quality monitoring, including aquatic trends monitoring (ATM) every 3 years and hydrology trends monitoring annually

HRC is required to submit an annual report by January 31 of each year, which summarizes the previous year's activities, including the results of monitoring. The annual report also includes a workplan of all planned management activities in the reporting year. Further, HRC is required to submit a Five-Year Synthesis Report (Synthesis Report) to evaluate the effectiveness of its management activity in preventing and minimizing discharge of sediment and protection of water temperature increases that may impact beneficial uses of water in the Upper Elk River.

The first Synthesis Report was submitted on November 15, 2021. It contains:

- Timber harvest summary
- HRC Road Status Summary
- Landslide summary
- Water quality and stream channel condition trends
- Restoration summary
- Effectiveness Monitoring Summary

In a letter dated March 18, 2022, the Executive Officer approved the Synthesis Report as complete, though noting disagreement with some conclusions and the lack of scientific support for other conclusions in the report. Section 4.2.1 includes a review of timber harvest, road status, and restoration. Section 5 includes staff's analysis of the suspended sediment data that were available at the time of the assessment (water quality assessment), the aquatic trend monitoring analyses presented by HRC (stream channel condition trends), and a paired watershed study conducted in Railroad Gulch and presented by HRC (effectiveness monitoring). The Landslide Summary was unverifiable and is not included here. A general summary of Regional Water Board comments on the approved Synthesis Report are included in Appendix D.

4.3.2 Green Diamond Resource Company (GRDC) Monitoring Requirements

Attachment C of Order R1-2020-0001, Waste Discharge Requirements, describes GDRC's monitoring and reporting requirements for their holdings in the Upper Elk River watershed. GDRC's holdings are limited to lands in the McCloud sub watershed, a tributary to the South Fork Elk River. Monitoring requirements are divided as follows:

1. Inspections of roads and non-road sediment sources
2. Inventory and treatment of road and non-road sediment sources
3. Landslide monitoring to identify new or reactivated mass wasting activity

Water quality monitoring, including stage, velocity, streamflow, turbidity, and suspended sediment. These data are to be collected for 30-consecutive days with no rain between October 1 and May 15. GDRC submitted annual reports on timber harvest, watershed stewardship, the Master Inventory, and water quality trend monitoring. GDRC must provide reports of landslide inventories by December 31 of the most recent photo flight year.

Section 5: Data Assessment and Trend Analysis

Table 4 of the TMDL Action Plan requires that:

"By 2021, the Regional Water Board shall evaluate the available information to assess the degree to which 1) adopted WDRs and waivers have successfully controlled sediment delivery from the upper watershed to the impacted reaches and 2) the efforts of the Watershed Stewardship Program are making sufficient progress towards achievement of health and safety, coordinated monitoring, and sediment remediation improvements."

Section VII. Monitoring and Adaptive Management of the TMDL Action Plan specifies that:

"*Approximately five years after adoption, Regional Water Board staff will conduct a formal assessment of the effectiveness of the implementation plan, including an evaluation of the effectiveness of WDRs and waivers, and make any necessary revisions to this TMDL Action Plan. This includes a review of the sediment source analysis and water quality data for the Upper Elk River, sediment deposition in the impacted reach and Lower Elk River, and the need for a Lower Elk River sediment TMDL, using Recovery Assessment tools and other available data, as appropriate. During reassessment, the Regional Water Board will consider how effective the requirements of the TMDL program of implementation are at meeting the TMDL, achieving water quality objectives, restoring the beneficial uses of water, and abating nuisance flooding conditions in the Upper Elk River Watershed. The success of the TMDL will be assessed based on water quality trends in the Upper Elk River Watershed, particularly the attainment of water quality standards in the impacted reach. Ultimately success is achieved when nuisance conditions are abated, and beneficial uses are supported."*

The data analyzed in this section come primarily from Humboldt Redwood Company (HRC) via the monitoring and reporting requirements (MRP) of the WDR and Aquatic Habitat Conservation Plan (AHCP) (USFWS, 2019). Other data sources include the Elk River Recovery Assessment (ERRA) the Watershed Stewardship Program; Green Diamond Resource Company (GDRC); and various collaborators from academic institutions such as Humboldt State University.

The initial and primary focus of the data assessment and trend analysis was to assess available data for evidence that sediment sources in the upper watershed are controlled and impairments to beneficial uses are alleviating, water quality conditions are improving, and nuisance flooding conditions are improving. The analyses contained in this section are largely focused on the period of 2016 to 2021, the first five years of implementation under the TMDL Action Plan. Where appropriate, however, longer trends are considered. Not all data useful for this phase of TMDL assessment were available to us in the timeframe necessary for the review. But sufficient data for a subset of monitoring locations in the upper watershed were available and are fundamental to the analyses described below.

During the course of staff's analysis for this report we determined that the data collected under existing monitoring programs in the Elk River watershed do not constitute all that is necessary to assess all of the questions highlighted above. As such, staff have concluded that the development of a Science and Coordinated Monitoring Workgroup as contemplated in the TMDL Action Plan would be useful and is overdue. Such a workgroup could identify key monitoring questions, design a coordinated monitoring program, inform revision to the existing monitoring and reporting requirements of permittees, establish hypotheses appropriate for special study, and design a framework for adaptive management over the long term.

5.1 Overview and Summary

Consistent with requirements of the TMDL Action Plan, the purpose of this data assessment is to determine the degree to which sediment sources from the upper watershed are controlled and whether impairments to beneficial uses are alleviating, water quality conditions are improving, and nuisance flooding conditions are improving. To evaluate these questions, staff presents analyses from three sources. First, staff conducted an independent analysis of water quality trends in suspended sediment concentration and aquatic habitat parameters, which informs progress towards controlling sediment discharges and restoring the salmonid-related Beneficial Uses. Second, staff summarizes the work and findings of HRC's Synthesis Report relative to its paired watershed study in Railroad Gulch and its Aquatic Trend Monitoring (ATM) Program. Third, staff summarizes the work and findings of CalTrout, Northern Hydrology Engineering, and Stillwater Sciences in its 2019 Elk River Recovery Assessment: Recovery Framework document as it relates to trends in channel cross sections in the impacted reach. The following are the main findings from these analyses:

- After controlling for the influence from precipitation, streamflow, and calendar day, suspended sediment concentrations ("residual" SSC) have not changed from beginning of the record in Water Year[6] (WY) 2003 to WY2020. The same result of no trend also occurs between WY2008 and WY2020, with the former being the year that HRC assumed ownership of Elk River timberlands. The monitoring locations for SSC analysis comprise the mainstem, the North Fork, and the South Fork, all geographically close to one another (≤ 2 miles).
- Limiting the trend analysis to the last five years (WY2016-WY2020), staff found statistically significant increasing trends in SSC at the lower North and South Fork Elk River above their confluence. Due to fewer number of years (smaller dataset) and other analysis methods reporting no statistically significant results, the increasing trend at these locations is weakly supported.
- The severity of ill effects (SEV) scores quantify behavioral and physiological response of salmonids to suspended sediment concentrations. Staff analyzed ten HRC water quality monitoring stations for SEV scores. Only three stations show statistically significant time trends: the mainstem directly below the North and

[6] The Water Year or Hydrologic Year is defined as October 1st through September 30th

South Fork confluence (increasing SEV); the lower South Fork (decreasing); and Bridge Creek in the North Fork subbasin (decreasing). Greater SEV scores mean more severe effects and decreasing SEV scores indicate improved conditions. This result is consistent with the TMDL's findings for the impacted reaches where large in-channel sediment deposition are resistant to scour.

- Aquatic Habitat Trends data provide useful information for tracking watershed conditions related to sediment distribution and movement. HRC collected ATM data from seven locations throughout the watershed and data was compared to Aquatic Properly Functioning Conditions. Sites in the upper watershed are either at, or nearing, desired conditions for sediment related Aquatic Properly Functioning Condition parameters. However, sites downstream, specifically in the impacted reach, are far from desired conditions for sediment related parameters. Over the past five years, sediment related parameters in the impacted reach have shown a slight trend toward desired conditions, however, continued monitoring over the coming years will provide useful information as to whether conditions are improving due to management related activities or if modifications to management practices are necessary.
- In-channel cross-section data up through 2016 as reported in the ERRA Framework indicates continued channel aggradation, ranging from minimal to severe.
- The results of the Railroad Gulch study are confounded by landslide activities in the reference watershed, which prevent clear conclusions relative to the effects of management activities on water quality conditions.

5.2 Staff Analysis of Water Quality Trends

Parameters or variables for water quality trend analysis are residual suspended sediment concentrations (SSC) and the severity of ill effects (SEV) scores. Residual SSC is the difference between the observed and model predicted SSC. Conceptually, this residual value is the SSC after accounting for covariates included in a regression model. SEV is a rating scale that quantifies the effects on aquatic life due to continuous exposure time duration at fixed SSC values. The scale was initially developed by Newcombe & Macdonald (1991). Models for SEV can vary for different salmonid life stages (Newcombe & Jensen, 1996).

5.2.1 Data

Data used for this assessment are turbidity, SSC, stage or water depth, stream discharge or flow, and precipitation. The first four datasets are generally paired such that one predicts the other using a rating curve. Specifically, turbidity and stage (water depth) are measured on a continuous basis with observations collected every fifteen (15) or thirty (30) minutes. Simultaneous SSC and discharge measurements are more difficult and costly to acquire, and so they are collected over the range of the monitoring location's turbidity and stage. The paired datasets have a statistical relationship such that continuous turbidity or stage measurements can estimate continuous SSC or discharge, respectively. For stage-discharge rating curves, discharge is manually measured (i.e., cross-sectional area times velocity) at stages that correspond to different wetted perimeters as well as at different points in time during one or more rainstorm event(s). These rating curves generally follow power law relationships and may be modeled piecewise, corrected for hysteresis, and other post-processing procedures.

Turbidity threshold sampling (TTS) is the method for collecting SSC samples. TTS utilizes a field-deployed and an automated turbidimeter, stage measurement device, data logger, and a pumping sampler. When turbidity and stage measurements reach certain thresholds, the pump sampler begins collecting water grab samples at the same temporary frequency as the turbidimeter until the other measurement readings fall below the thresholds. The pumped samples are then analyzed in a laboratory to manually measure SSC. While similar in concept to stage-discharge, the turbidity-SSC rating curves may follow different statistical models, which are often fitted per storm event and the inter-storm periods. SSC samples are also considerably more frequent than discharge measurements (Lewis & Eads, 2001).

HRC maintains a rainfall gauge network within the Elk River watershed, but those gauges only have daily totals and the earliest year in HRC's record is 2010. For hourly precipitation measurements, HRC, stakeholders, and other interested parties rely on the National Weather Service (NWS) station on Woodley Island located in Eureka, CA. However, the Woodley Island (aka EKA) weather station is more representative of the coastal plain than the upper watershed and relying entirely on EKA introduces bias and inaccuracy (NCRWQCB, 2016). Instead, this assessment uses radar-based precipitation estimates, collected hourly and in a spatial grid with cell edge length at approximately four (4) kilometers. These estimates are bias corrected using rain gauge measurements where available. The data source for this gridded precipitation dataset is the National Center for Atmospheric Research (NCAR et al., 2000). Table 2 shows the total precipitation by water year (WY) in the Upper Elk River watershed for the period of record.

The continuous data aggregate to the annual WY scale to produce various metrics such as annual water yield, suspended sediment load (SSL), and tenth percentile turbidity (NTU15). Please see Table 7 and Figure 3 for more details of the annual metrics and a map of the monitoring locations, respectively. Annual datasets are relatively coarse, and not all monitoring location or stations will share the same number of years as stations are decommissioned due to funding and/or different catchments are prioritized for monitoring. Nevertheless, the annual datasets altogether can cover a large spatial range within the watershed. Additionally, annual data are more likely to (a) follow a normal probability distribution and (b) be independent and identically distributed (i.i.d.). Production and trend analysis of various annual scale metrics are found in HRC Five-Year Synthesis Report and will not be repeated here (Miles, 2021).

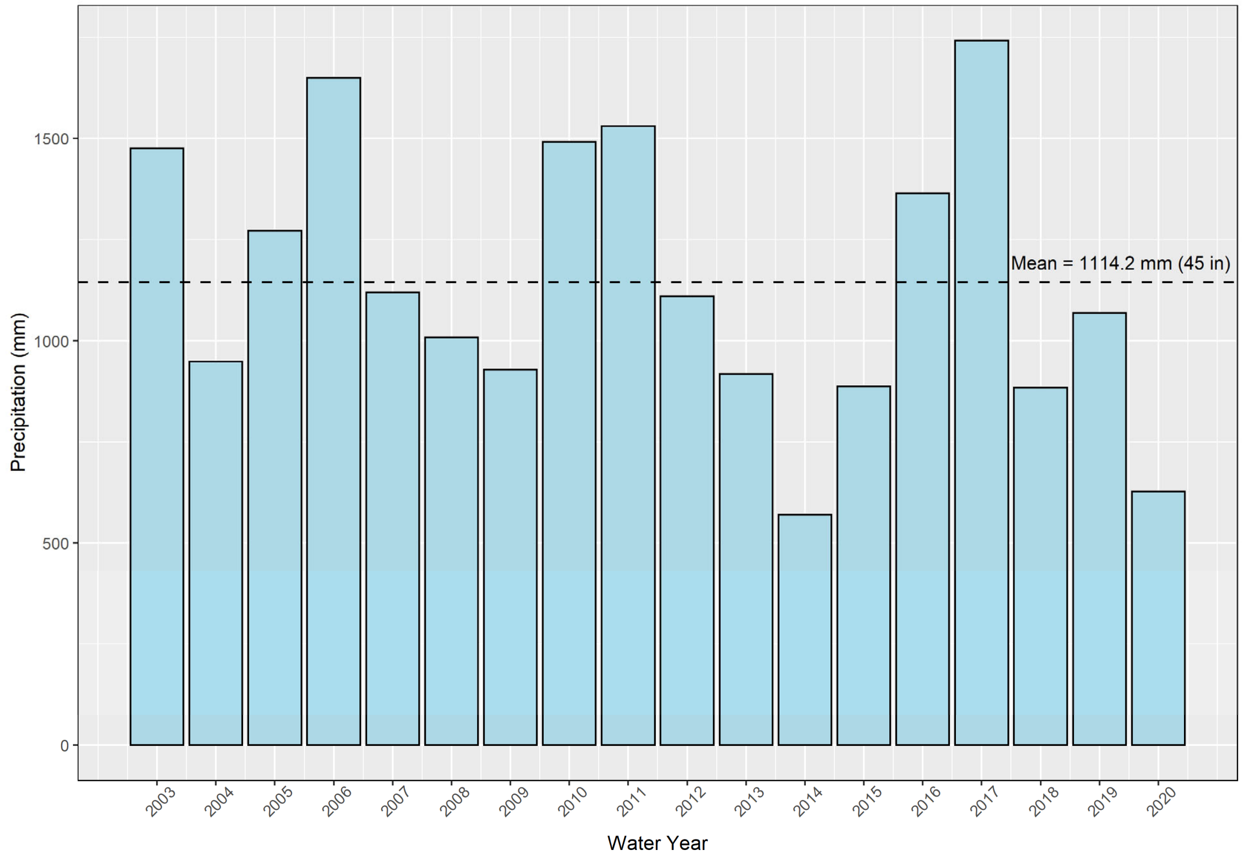


Figure 2. Annual precipitation for station HRC509 catchment

Table 7: Metrics and other quantities analyzed by Humboldt Redwood Company and Regional Water Board

Metric	Definition	Units	Analyzed By
10NTU	10% Exceedance Turbidity	NTU	HRC
RUN	Total Runoff (mm)	mm	HRC
PPT	Annual Precipitation at EKA	mm	HRC
NDG1	Days above one (1) inch rainfall	days	HRC
PQ	Peak flow	$m^3 \cdot s^{-1}$	HRC
MDP	Maximum daily precipitation	mm	HRC
SY	Sediment yield	$Mg \cdot km^{-2}$	HRC
FWMC	Flow-weighted mean concentration	$mg \cdot L^{-1}$	HRC
Residual SSC	Observed – model predicted SSC	log(mg·L^{-}	NCRWQCB
Mean SEV	Arithmetic mean SEV score for one WY	unitless	NCRWQCB
Median SEV	Median or 50th percentile SEV score for one	unitless	NCRWQCB
Max SEV	Maximum SEV score for one WY	unitless	NCRWQCB
90th SEV	90th percentile SEV score for one WY	unitless	NCRWQCB

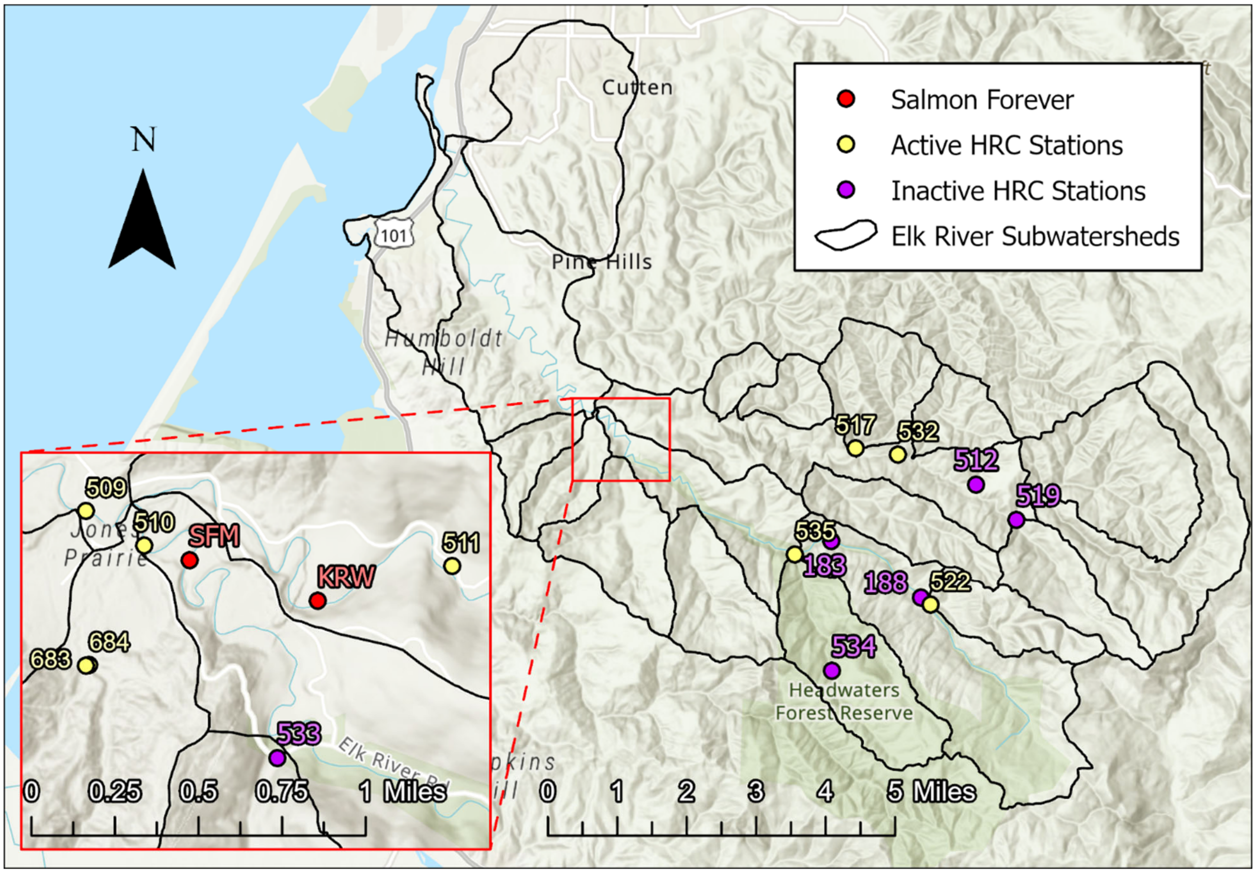


Figure 3. Map of Elk River hydrologic and water quality monitoring stations

5.2.2 Suspended Sediment Concentrations

5.2.2.1 Methods

The general methods for assessing time trends in residual SSC include: 1) graphical interpretation of data visualization such as time-series plot, correlograms, and model fits; 2) formal hypothesis testing using parametric and non-parametric methods; and 3) regression analysis. These methods are not mutually exclusive and complement each other where applicable (e.g., regression diagnostic plots). Exact statistical methods employed for hypothesis testing and regression modeling are largely determined by whether the estimate or metric are at the annual scale (see Table 7). Staff's analysis of suspended sediment concentrations uses each of these three approaches.

Annual metrics that are independent and normally distributed can be used with common statistical methods such as the *t*-tests, analysis of variance (ANOVA), Pearson's r correlation, and ordinary least squares (OLS) regression. However, normality is not assumed for any metric, and this assessment uses primarily non-parametric methods for detecting trends. The non-parametric are the Mann-Kendall (MK) test and the Theil-Sen estimator.

The MK test is based on the rank correlation statistic or Kendall's τ. The variable of interest is sorted by time and then their ranks are tested for monotonic trends, which are trends that strictly rise or fall. If τ is statistically significant, then the variable has an increasing (positive τ) or decreasing (negative τ) time trend. The Theil-Sen estimator takes the form of a simple, univariate linear equation—i.e., y = mx + b. The coefficients *m* and *b* are based on the data's medians with *m* being the Sen slope, which is the median slope of all slopes calculated from all possible pairs of data points. Similarly, *b* is the median intercept of all intercepts after solving for all slopes. The Sen slope provides an estimate of a trend's magnitude. Both methods are non-parametric and do not require knowing the data's probability distribution. As such, the Sen slope and the MK test are common methods for trend detection in environmental data (Mustapha, 2013).

The regression analysis uses a multiple log-linear model of SSC against the independent variables or covariates: discharge, antecedent precipitation, calendar day of year, and linear time. The full specifics of the regression model development can be found in Appendix B. The general form of the regression model[7] is:

$$\log(SSC) \sim \beta_0 + \beta_1 log(Q) + \beta_2\sqrt{API} + \beta_3 \sin(2\pi \cdot f_{doy}) + \beta_4 t$$

Where *Q* is stream discharge ($m^3 \cdot s^{-1}$); *API* is antecedent precipitation index (unitless); f_{doy} is calendar day of year fraction (unitless, e.g., January 1st would be 1/365 ≈ 0.003 during a non-leap year); and *t* is linear time (years). The various β terms are the model *coefficients*. In this model formulation, the coefficients can be exponentiated and then interpreted as a percent change in SSC per unit covariate. The most relevant covariate for this assessment is linear time. If the linear time coefficient is statistically significant, then a time trend exists[8]. The sign of the coefficient indicates the direction of the trend: positive indicates that SSC is increasing and negative means decreasing. The magnitude of the coefficient indicates the percent change rate of the trend. The probability of a trend not being different from zero is the coefficient's *p-value*, a number bounded by 0 to 1. Statistical significance is defined as a p-value less than 0.05 or α (alpha), the so-called "critical" threshold value.

As mentioned previously, SSC samples are more frequent and fully continuous during periods where turbidity thresholds are exceeded (i.e., during storm events). With a long record dating back to WY2003, the SSC datasets are large and statistically robust—that is, the presence of anomalous values are unlikely to change the overall result. That said, because the SSC samples are frequent in time, serial autocorrelation is likely present. Serial autocorrelation arises when the present value depends on or correlates with its previous values; how many values back is called the *lag* (i.e., lag 1 is previous value, lag 2 is the previous two, etc.).

Fitting an OLS regression model to a response variable with autocorrelation usually results in autocorrelated residuals, which violates one of the fundamental assumptions

[7] Unless otherwise specified, log refers to the natural logarithm with the base of *e*, the natural number.
[8] No statistical analysis can produce completely certain results. So "exist" really means that the trend has at least a 95 percent chance of existing—more precisely, the probability of the coefficient's true value being equal to zero is less than 0.05 or 5 percent.

of OLS that the residuals are independent and identically distributed. The consequences of autocorrelated residuals results in an “inefficient” estimate of the model’s coefficients. Statistical inefficient in means that the variance or “error” for coefficient estimates and fitted values are inaccurate and often biased downward (Granger & Newbold, 1974). To solve the autocorrelation issue, regression modeling uses the generalized least squares (GLS) method, which is a flexible model that can accommodate different error correlation structures. The importance of discussing OLS, GLS, and autocorrelation is that statistically inefficient estimates may *incorrectly* lead to a low p-value and, consequently, a finding of statistically significant results when in fact, they are not significant.

5.2.2.2 Results

For graphical interpretation, the regression model is fitted without a linear time term and then the model residuals or residual SSC are plotted with linear time on the horizontal axis and residual on the vertical. The MK test is conducted on the mean annual residual SSC for whole period of record (WY2003-WY2020). For the regression analysis, these regression models include linear time and then its coefficient’s p-value is assessed for significance. The p-value is assessed three times for three model fits, each corresponding with a timespan: a) the entire period; b) when HRC assumed timberland ownership (WY2008-WY2020); and c) the last five years (WY2016-WY2020). Outliers are also removed from the model fits. For complete details on results from this data assessment, please see Appendix C.

Due to lack of readily usable[9] data at the time that this assessment began, Regional Water Board staff only use SSC sample data for three monitoring stations: HRC509 on mainstem Elk River immediately downstream of the South and North fork confluence; HRC510 on lower South Fork; and HRC511 on the lower North Fork. As shown on, HRC510 and HRC511 locations are immediately above the South and North Fork confluence, respectively. These stations and their locations are very close to each other with all three being approximately one mile or less from each other. As such, comparisons between these three may not yield much information about upslope and other land disturbance processes’ impact on SSC. That is, their lower watershed locations and cumulative effects may “drown” out any signal produced in the upper watershed.

Where data are available, staff strongly recommend performing the residual SSC analysis to all upstream monitoring stations. By including the upper watershed, the overall results of this analysis may substantially change once staff are able to disentangle the SSC trends and signals between different catchments and their respective management history.

[9] Readily usable in this case is defined as tabular and machine-readable file data formats. Example of readily usable data formats: comma separated value text files (CSV) and Microsoft Excel spreadsheets. SSC sample data for all other stations are either in non-usable formats or not in Regional Water Board possession.

5.2.2.3 Visual Inspection

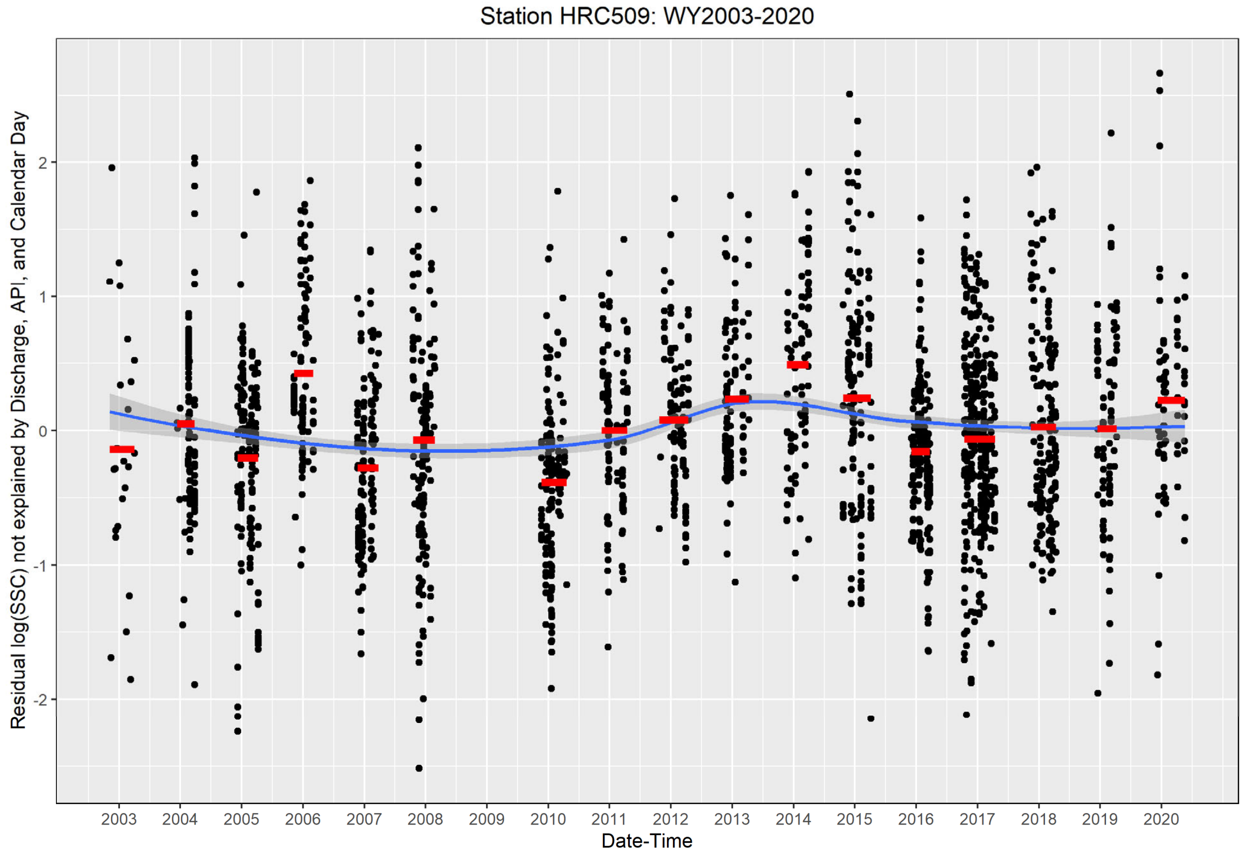


Figure 4. Mainstem station HRC509 residuals with outliers removed

Figure 4 shows station HRC509's residual SSC over the full period of record. Black dots are the individual residuals; the red bars are the annual mean residual; and the blue line is the locally estimated scatterplot smoothing (LOESS[10]) curve with the curve's confidence interval in gray. From WY2003 to WY2020, the linear trend appears relatively flat—that is, residual SSC at the beginning shows little difference with the end. That said, the curve has a noticeable dip or convex shape between WY2003 and WY2012 with observed SSC being lower than predicted after controlling for discharge, antecedent precipitation, and calendar day. The exception to this dip is WY2006 whose mean annual residual SSC is the second highest of all years, but WY2006 also has the second highest annual precipitation total. Immediately after the dip, a bump appears between WY2012 and WY2016, right in the middle of the historic 2011-2017 California drought (Luo et al., 2017).

[10] LOESS stands for locally estimated scatterplot smoothing. LOESS us an algorithm that produces "smooth" curves from a scatterplot, capturing general patterns in the data. [INSERT CITATION]

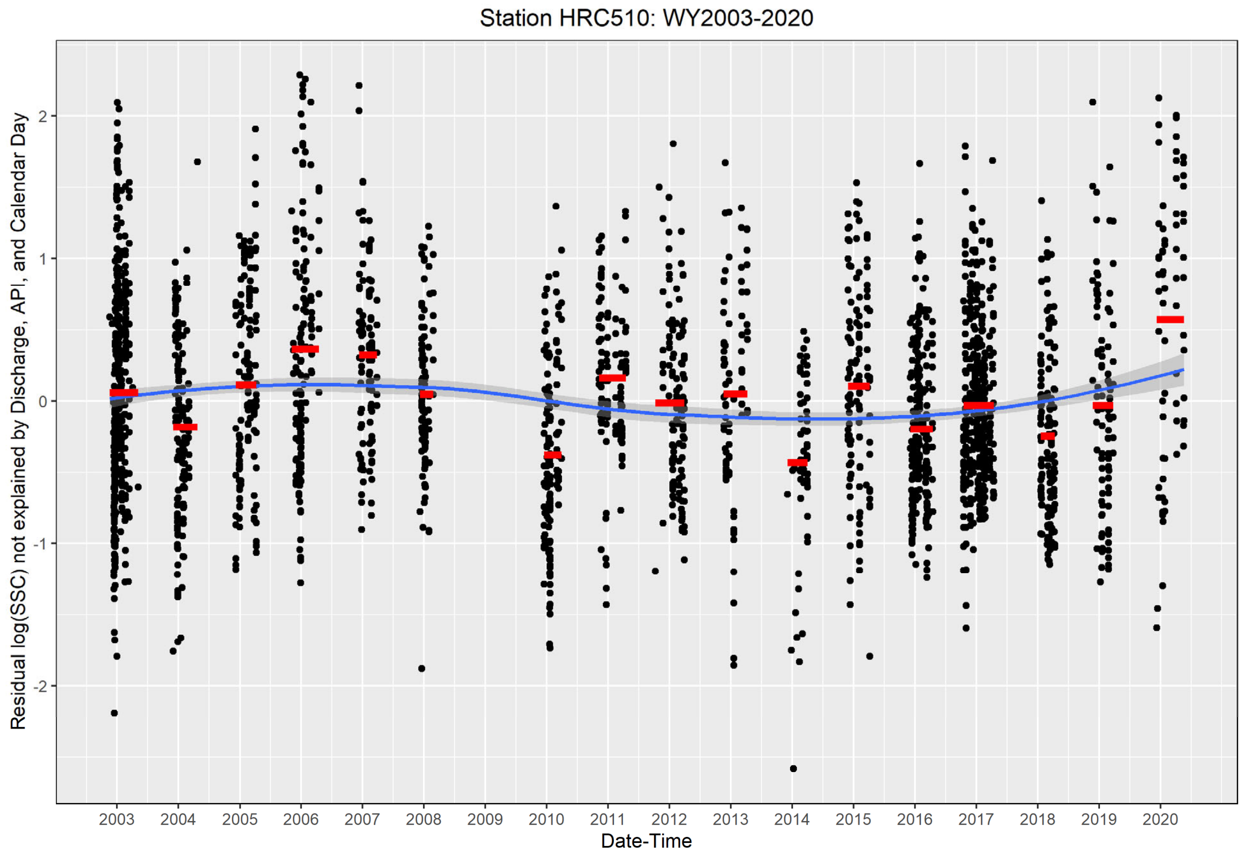


Figure 5. South Fork station HRC510 SSC residuals with outliers removed

Figure 5 shows SSC residuals over time at station HRC510 on the lower South Fork Elk River. In contrast with HRC509, the LOESS curve is somewhat inverted compared to HRC510 with an initial rise and then subsequent fall; however, the confidence bands for the curves are much closer to zero, indicating that the deviations from zero may not be statistically significant. Residual SSC spikes at the end in WY2020. One possible explanation for the spike is the presence of a sediment discharge source that is not affected by precipitation, streamflow, or calendar day. This source would continue discharging and with low flows and low water volume, any sediment input would result in higher SSC.

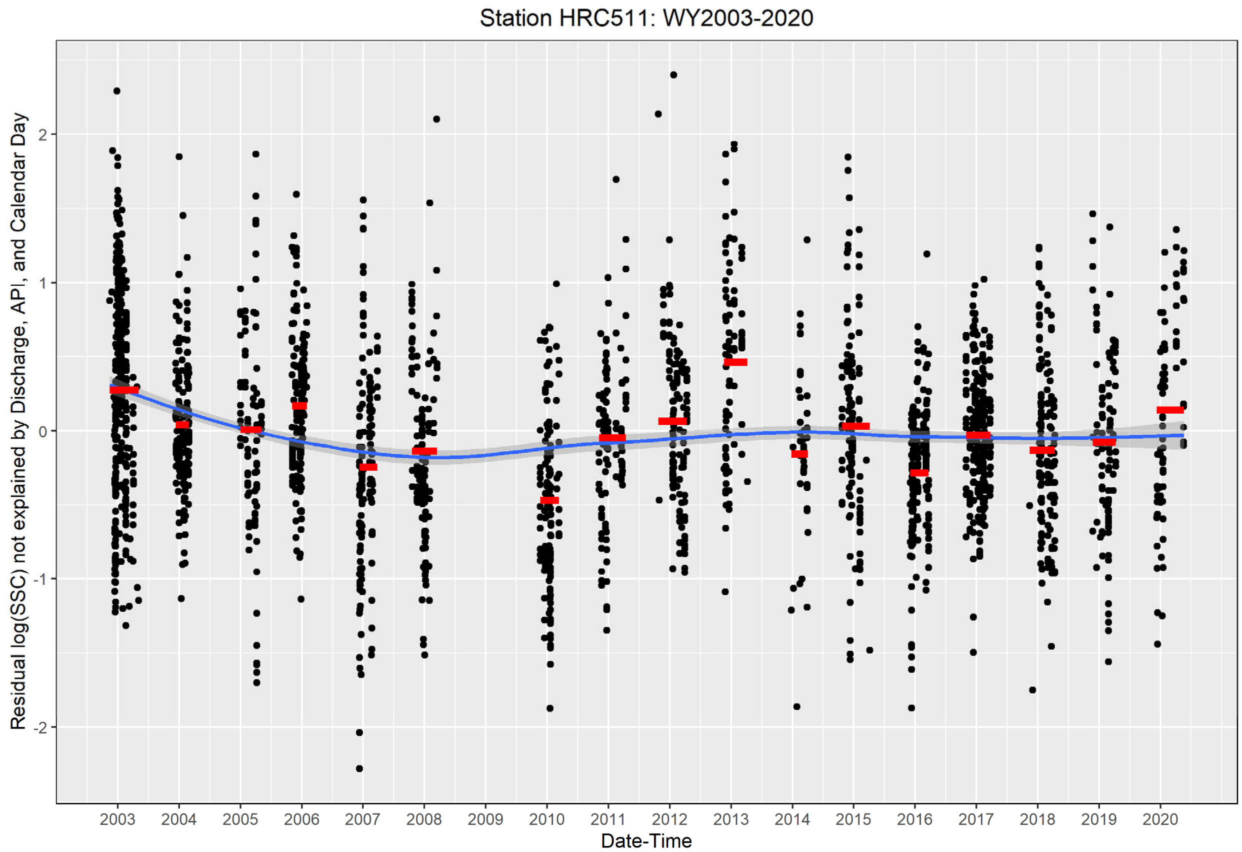


Figure 6. North Fork station HRC511 SSC residuals with outliers removed

Figure 6 shows the residual SSC for station HRC511 on lower North Fork Elk River with the outliers removed. The initial values from WY2003 to WY2010 indicate a steeper downtrend than the dip seen at HRC509. The annual mean SSC residuals then climb, peaking at WY2013, a year with below average precipitation and near the beginning of the 2011-2017 drought. After the climb, residual SSC falls and stays near zero through WY2020.

In general, the plots indicate stations HRC509 (mainstem) and HRC511 (North Fork) are more similar to each other than with HRC510 (South Fork). The mainstem and North Fork stations exhibit a dip during the earlier years, then subsequently rise in the middle before flattening out. While the LOESS curve shows a more pronounced rise in HRC509, the rise at HRC511 seems to be due to WY2013 being an anomalous year. HRC510 is the odd one out with a rise at the beginning, dip in the middle, and then a large uptick in WY2020.

Overall, these visual interpretations of these plots by themselves do not provide conclusive information about SSC trends since WY2003. The year-to-year individual differences may be random noise or the result of some unknown and unquantified variable. Without further testing of variables, visual conclusions are weak. Specifically, visual interpretation of plots is qualitative at best, but at worst can be misleading.

5.2.2.4 Non-Parametric Trend Testing

The mean annual residual SSC values are tested against time or water year for the entire period of record. Annual values are used because the TTS method collects pump samples in an episodic (i.e., storm-based) manner, complicating season definition needed for seasonal MK tests. Table 8 shows the results of the MK test and Sen slopes for the three stations. None of the annual mean residuals have statistically significant results, indicating no monotonic trends and static conditions since WY2003.

Table 8: Trends in mean annual log SSC residuals

Station	Location	Trend	MK p-val	Significant
509	Mainstem	Increasing	0.232	No
510	South Fork	Decreasing	0.343	No
511	North Fork	Decreasing	0.537	No

5.2.2.5 Regression Analysis and Findings

Table 9 shows the results of the regression analysis when including linear time (*t*) in the GLS model. The model is then refitted with the trimmed time periods corresponding to HRC's present ownership and the last five years.

Table 9: Statistically significant regression results for linear time

Station	Start WY	p-value	% per year	Low CL %	Up CL %
510	2016	0.001	+15.57	+6.053	+25.948
511	2016	0.041	+8.657	+0.336	+17.667

Only two station-time period model fits produce statistically significant coefficients: HRC510 on South Fork and HRC511 on the North Fork, both based on using the last five years. From WY2016 through WY2020, residual SSC at HRC510 on South Fork is increasing at approximately 15.6 percent per year with a confidence interval of 6.1 percent and 25.9 percent. Residual SSC at HRC511 on North Fork is increasing at 8.7 percent per year with a confidence interval of 0.34 percent and 17.7 percent. This means that after correcting for effects of discharge, antecedent precipitation, and calendar day, suspended sediment concentrations have increased at these two sites during the last five years.

The p-value for HRC510's time coefficient is highly significant as it is far below the 0.05 significance threshold. The same cannot be said for HRC511 as the p-value is very close to the threshold. Considering the potential implications for the TMDL program of implementation (e.g., role of timber harvest operations on increased suspended sediment discharges), these results warrant greater scrutiny.

To better assess these data, the other trend detection methods are re-applied to the constrained time period, followed by visual inspection of SSC residuals. Table 10 shows the MK tests and Sen slopes for HRC510 and HRC511 in the last five years. Note: both datasets have equal size (n = 5), and with a rank-based correlation, the calculated Kendall's τ being the same for both stations are not an unexpected result. While both Sen slopes are positive, the p-values for τ are not statistically significant. With such a small sample size, the MK test is unlikely to give significant results unless the change in log residual SSC over time is very large in absolute terms; that is, the estimated t coefficients are small relative to the other covariates.

Table 10: MK tests and Sen slopes for mean annual log SSC residual for WY2016-WY2020

Station	Location	Trend	MK p-value	Significant
510	South Fork	Increasing	0.221	No
511	North Fork	Increasing	0.221	No

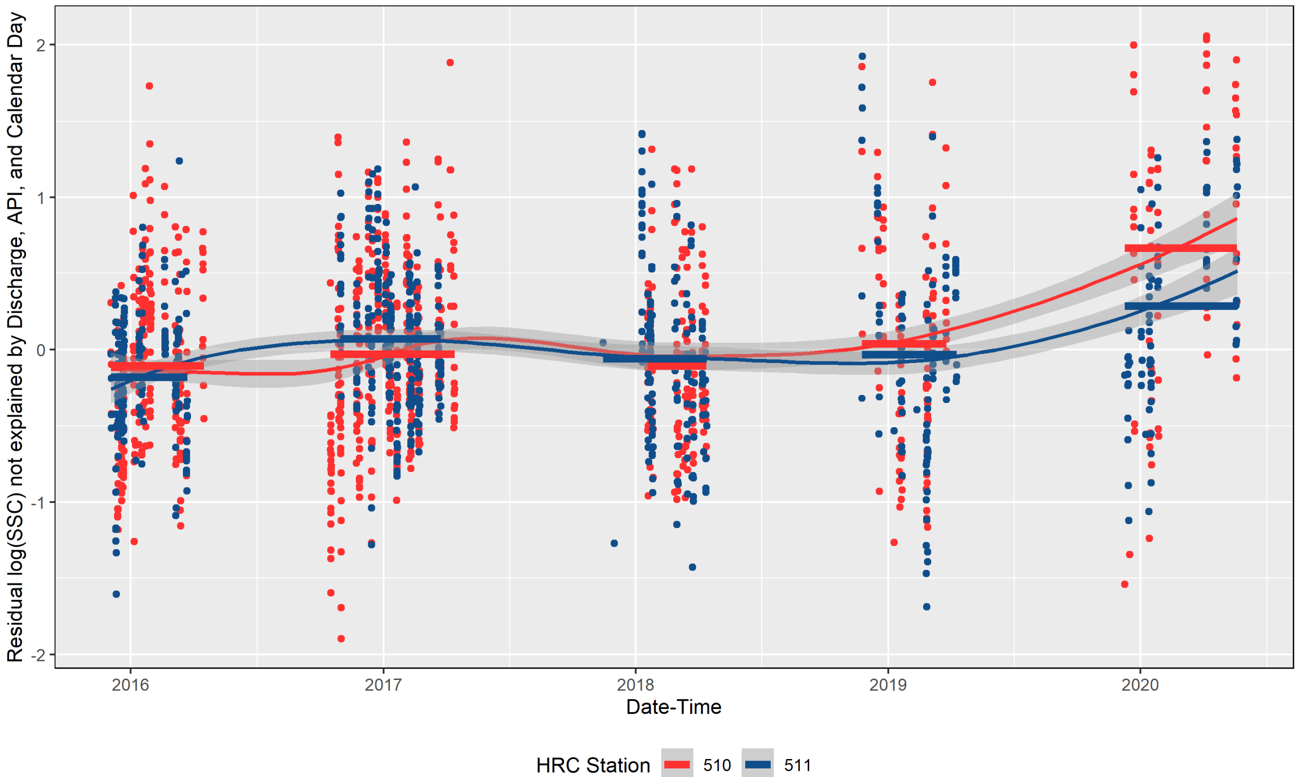


Figure 7. SSC residuals for stations HRC510 and 511 while using only the last five years for statistical modeling

Figure 7 shows the model residuals of the shortened time period when excluding linear time. WY2020 seems to be driving the uptrend as all the other years have their means hovering around zero. So, while the regression analysis results have statistically significant increasing trends in residual SSC since WY2016, the other methods either have disagreement (MK test) or indicate high leverage from WY2020 (visual inspection). Data points with high leverage tend to skew the results, similar to how extreme values affect the mean of a sample population. Over time as more data becomes available, redoing this regression analysis would likely provide more insight on whether the statistically significant trend in the North and South Forks is genuine or is a result of outliers.

5.2.3 Severity of Ill Effects

5.2.3.1 Methods

Based on a meta-review of studies investigating suspended sediment impact, the Severity of Ill Effects (SEV) model is a regression equation taking the form:

$$SEV = a + \mathrm{b} \cdot \log(SSC) + c \cdot \log(ED)$$

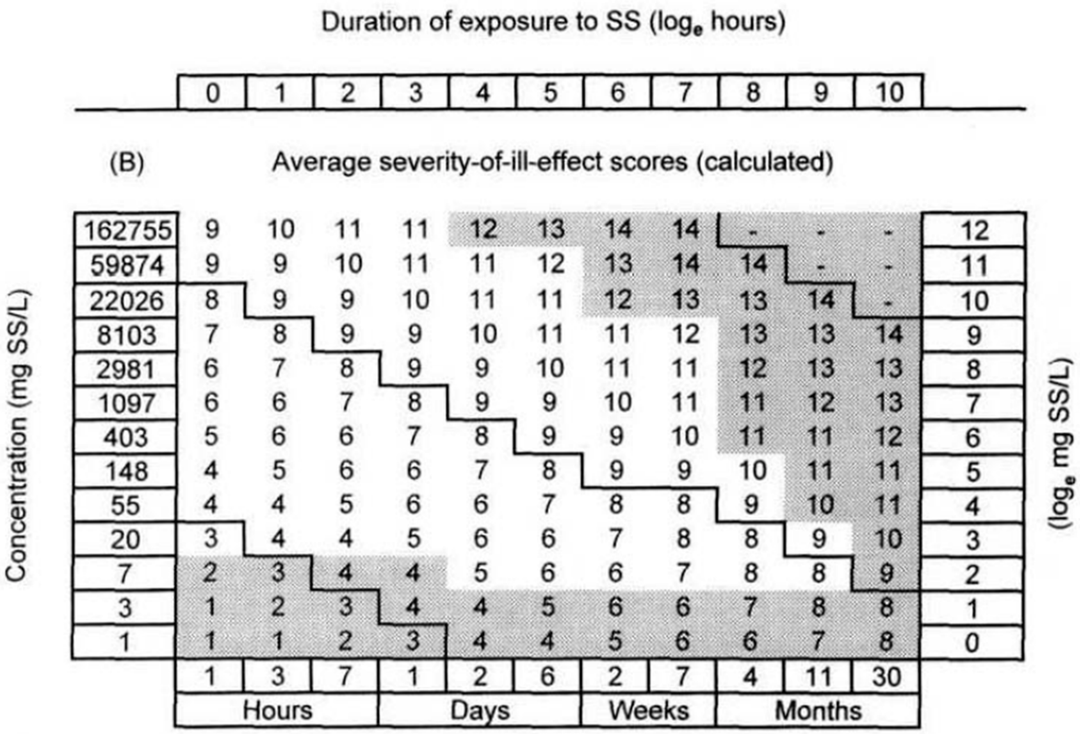
Where *ED* is the time continuous exposure duration in hours at a fixed SSC value specified in the formula with *a*, *b*, *c* as regression coefficients. Regression coefficient values vary with life stage, taxon, and publication. Consistent with the ERRA analyses, staff use the salmonid eggs/larvae and juvenile life stages from Newcome and Jensen (1996). Additionally, staff also use Coho salmon under yearling and juvenile life stages from Bray (2000), which were not used in the ERRA. While Newcombe and Jensen included observation data of Coho salmon, their model pooled many other non-salmonid species. Bray (2000) calibrated the SEV model to just Coho salmon; moreover, the Bray model parameters are more recent and may provide more accurate results. The SEV scale ranges from 0 to 14 with 0 being no effect and 14 being greater than 80 percent fish mortality. The scale has four general groups: no effect (SEV = 0); behavioral effects (1-3); sublethal effects (4-8); and lethal effects (9-14).

Table 11 contains descriptions of select SEV scores and the effects they describe, modified from Newcombe & Jensen (1996). For the ERRA, SEV scores' purpose is to contrast different sediment transport and hydraulic model scenarios. Using observed SSC data from WY2003 through WY2015 at monitoring locations HRC509 (mainstem downstream of South and North Forks' confluence), 510 (lower South Fork), and 511 (lower North Fork), the ERRA's SEV analysis yielded scores between 5.0 and 13.4 for the eggs/larvae life stage and between 5.7 and 8.6 for the juvenile life stages. Table 11 provides qualitative descriptions of aquatic life effects associated with SEV scores.

Given SSC and corresponding exposure durations, SEV can be visualized as a grid. Newcombe and Jensen (1996) constructed the grid by discretizing a range of SSC, as shown in Figure 8. The right vertical axis has increments of one natural log unit, and on the left is the corresponding SSC in mg/L after exponentiation (e.g., e0 = 1). ERRA used an SSC range of three (3) through eight (8) log units or 55 to 2981 mg/L. For this assessment, staff discretized the entire range in 0.1 log units, resulting in exactly 121 corresponding exposure durations and calculated SEV scores. Each monitoring station and each WY have 121 SEV scores. From the raw SEV scores, the following summary or descriptive statistics are calculated: mean, median, 90th percentile, and maximum SEV scores. These annual descriptive statistics are the basis of the SEV trend analysis, which differs from the approach in the ERRA.

Table 11: Select SEV scores and their associated effects on aquatic life

SEV Score	Effects Description
5	Minor physiological stress; increased respiration rate
6	Moderate physiological stress
7	Moderate habitat degradation
8	Indications of major physiological stress; long-term reduction in feeding
9	Reduced growth rate; delayed hatching
10	0-20% mortality; moderate to severe habitat degradation
13	>60-80% mortality



Concentration (mg SS/L)	0	1	2	3	4	5	6	7	8	9	10	($\log_e$ mg SS/L)
162755	9	10	11	11	12	13	14	14	-	-	-	12
59874	9	9	10	11	11	12	13	14	14	-	-	11
22026	8	9	9	10	11	11	12	13	13	14	-	10
8103	7	8	9	9	10	11	11	12	13	13	14	9
2981	6	7	8	9	9	10	11	11	12	13	13	8
1097	6	6	7	8	9	9	10	11	11	12	13	7
403	5	6	6	7	8	9	9	10	11	11	12	6
148	4	5	6	6	7	8	9	9	10	11	11	5
55	4	4	5	6	6	7	8	8	9	10	11	4
20	3	4	4	5	6	6	7	8	8	9	10	3
7	2	3	4	4	5	6	6	7	8	8	9	2
3	1	2	3	4	4	5	6	6	7	8	8	1
1	1	1	2	3	4	4	5	6	6	7	8	0
	1	3	7	1	2	6	2	7	4	11	30	
	Hours			Days			Weeks		Months			

Figure 8. Newcombe and Jenson (1996) figure showing SEV as a function of SSC and SSC time duration

The same non-parametric methods for residual SSC (MK test and Sen slope) are used again for assessing trends in descriptive SEV score statistics. The MK test requires a minimum of four (4) samples (i.e., four years). Trend tests are performed for every unique combination of life stage, SEV statistic, and monitoring station (e.g., maximum SEV for juveniles at station HRC509 on the mainstem). For trend testing, selected stations must meet two criteria: a) contains at least four years and b) either currently operating or ceased operation after WY2016. While somewhat arbitrary, the latter requirement reflects the five-year review time span (WY2016 – WY2020).

The MK test can also be applied to a geographic area, a variation also known as the regional MK test (Helsel & Frans, 2006). The regional MK test is based on the seasonal MK test, that latter of which is usually used for sub-annual data exhibiting cyclical patterns. Each season is a “block” or group, and the regional test replaces the season block with location. The regional MK test and its associated Sen slope can indicate whether the area of interest has an overall trend direction and magnitude. Because the Elk River watershed is relatively small at 58.3 mi^2, monitoring data may have inter-station correlation due to spatial autocorrelation of underlying processes. Particularly, if the catchment draining to the monitoring station’s location is a subset of another (e.g., nearly all monitoring stations’ catchments are contained within HRC509 or the mainstem’s catchment). The software package for conducting MK tests can modify results to account for inter-station correlation (Marchetto, 2021). Conceptually, correcting for inter-station correlation is similar to correcting the effects of serial autocorrelation on the SSC regression coefficients for the purpose of obtaining accurate p-values.

5.2.3.2 Results

Figure 9 contains violin plots showing the distributions of SEV scores across WYs, descriptive statistic, and salmonid life stages, aggregating scores across all monitoring stations. SEV scores below 4 describe behavioral effects and no physiological symptoms. Sublethal effects (SEV scores 4 – 8) include minor to major physiological stress. Lethal and paralethal effects (SEV 8 – 14) start at reduced growth rate and progressively increases mortality rate until the maximum score. The eggs/larvae life stage faces the most risk, because their SEV scores are higher than the other life stages. The annual median eggs/larvae SEV statistic has higher variability and the largest range, but most scores hover between 7 and 10 (sublethal to lethal effects). The maximum SEV statistic may be the most concerning with its mean being above 13 and going off the scale; the maximum is 14 and its associated effects include greater than 80 percent mortality.

With four (4) life stages or model parameters; four (4) descriptive statistics; and ten (10) stations, a total of 160 trend tests were conducted. Of those 160, only four are statistically significant. That is, at the majority of stations, statistical analysis is not able to determine if conditions are worsening or improving over time. Table 12 shows the results of trend tests on the descriptive SEV statistics where the trends’ p-value are less than 0.05; highlighted rows are statistically significant. Between WY2003 and WY2020, station HRC509 (mainstem) has seen an increase in the median SEV score for eggs/larvae and juvenile (Bray) life stages.

For eggs/larvae, the average median SEV statistic across all years at HRC509 is approximately 9.75, a score that describes effects of reduced growth rate, delayed hatching, and reduced fish density. Scores 10 and above describe increasing mortality rate, which is 0–20 percent of the population at SEV 10; 20–40 percent at 11; etc. until 14, the maximum score, the effects of which is 80–100 percent mortality. Using the average score as a starting point and assuming a constant trend, a median SEV score of 10 would be present in less than two years and an 11 score would be present in less than ten years. For juveniles and with Bray's model, the rate of increase is half of the eggs/larvae. The average median is 7.33, which describes moderate habitat degradation. If constant, the score would move to 8 within ten years; 8 describes major physiological stress and long-term reduction in feeding rate.

The other two trends are more optimistic—the maximum SEV statistic for station HRC510 (lower South Fork) and 90th percentile statistic for HRC517 (Bridge Creek, tributary to North Fork) are both decreasing, but at relatively lower rates. Assuming a constant trend, these SEV scores would decrease by one in ten to twenty years. Although their scores are high—SEV 12 describes 40 – 60 percent mortality—the SEV statistics (90th percentile and maximum) for HRC510 and HRC517 are less useful as they do not describe a central tendency and instead are extreme values. High SEV scores are to be expected at the extremes, and their slow rate of decrease is less informative of future conditions. Nevertheless, any decrease at all should be noted in this heavily impaired watershed.

Table 12: Statistically significant trends in descriptive SEV statistic. Mean SEV statistic is the arithmetic average across all years of data. Increasing SEV indicates worsening conditions.

Station	Life Stage	SEV Statistic	Trend	ΔSEV/year	Mean
509	Eggs/Larvae	Median	Increasing	+0.137	9.75
517	Eggs/Larvae	90th Percentile	Decreasing	-0.071	12.3
509	Juvenile (Bray)	Median	Increasing	+0.072	7.33
510	Juvenile (N&J)	Maximum	Decreasing	-0.044	11.1

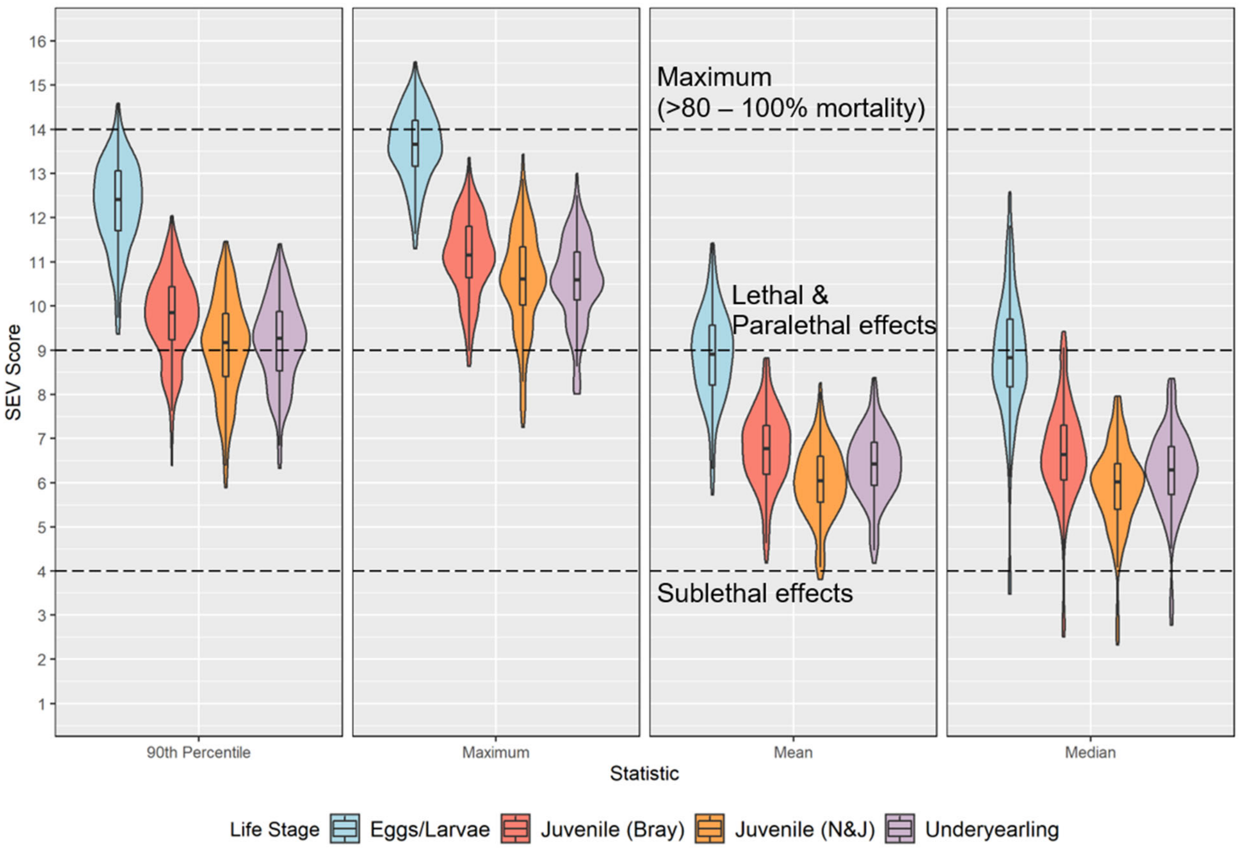


Figure 9. Distribution of descriptive SEV statistics by life stages across all stations and all years

5.2.4 Discussion

Overall, water quality trends for the Upper Elk River have mostly remained in stasis over the period of record. Weak evidence exists for worsening SSC conditions in the period of 2016-2021 at the lower South Fork (HRC510) and lower North Fork (HRC511) monitoring stations (see

Table *9* and

Figure 7. SSC residuals for stations HRC510 and 511 while using only the last five years for statistical modeling

Evidence also exists for worsening ill effects for salmonid eggs, larvae, and juveniles at the mainstem station (HRC509) just below the confluence (Table 12). However, there are two bright spots. The SEV analysis shows a decrease in the maximum ill effects for juveniles in the lower South Fork station and a decrease in the 90th percentile ill effects on eggs/larvae at the Bridge Creek station, a tributary to the North Fork Elk.

The Elk River's current state is heavily impaired, and the evidence referenced above suggests that conditions may be improving in the upper watershed and worsening in the confluence area. Specifically, ill effects for salmonids are decreasing in Bridge Creek and the lower South Fork. Ill effects for salmonids at station HRC509 are increasing; and sediment concentrations have increased since 2016 at stations HRC510 and HRC511. Assessment results for the confluence area are consistent with the TMDL's original findings, which brought focus to the immobile in-channel sediment deposition within the impacted reaches and sediment loading from the North and South Forks to the impacted reach. Yet, the analyses performed require some discussion before coming to firm conclusions about the TMDL's program of implementation, trends in water quality conditions, and conclusions about the efficacy of upper watershed controls on sediment discharge.

First, covariates in the SSC regression models are not directly related to causal mechanisms for sediment discharge. Streamflow could arguably be the hydrologic response to both rainfall and/or upslope management operations, but this analysis cannot disentangle natural and anthropogenic hydrologic responses. Therefore, further assessment is warranted to avoid fallacious inferences by omission. Examples of such inferences or conclusions can include: (a) no trend means current management practices have no effect on sediment concentrations or (b) legacy sources are so great or too entrenched to detect their depletion in the current data. These conclusions cannot be directly supported, and both are speculative at best.

The TMDL Action Plan requires the Regional Water Board to conduct an assessment over the last five years. This requirement was met by restricting the data record to WY2016-WY2020. The restriction produced statistically significant results for increasing sediment concentrations at the North and South Fork monitoring stations, but the results were not corroborated by the other trend analysis methods, which produce no statistically significant results. Thus, doubts remain as to whether the last five years' SSC increases are real or due to random chance or other factors not included in this assessment.

With respect to the whole data record (WY2003-WY2020), the most likely conclusion for water quality is fairly mundane: SSC has not substantively changed at the three monitoring stations after accounting for variability attributed to the covariates. Any non-zero residual SSC may be random errors/noise or attributed to an unknown variable or process, thus deserving further evaluation. Until a similar regression analysis incorporates covariates related to management practices and/or legacy sediment discharge sources, interpreting their effect on SSC warrants skepticism. Examples of such analyses include Klein et al. (2012) or Lewis (1998). Klein (2012) included variables related to roads (e.g., density and use type) and timber harvest in clearcut equivalent area[11] since 1990. Lewis (1998) took a paired watershed approach with the treatment watershed undergoing various disturbance actions such as road cuts, skid trails, and yarding. While neither study utilized the same regression model—particularly, the temporal resolution—both papers nevertheless provide example variables. Staff recommends that the next steps for the residual SSC trend analysis be to develop the

[11] Clearcut equivalent area (CCE) transforms different silvicultural practices into a standardized unit based on the impacts of clearcutting. The transformation is typically done as a fraction weighting factor, e.g., commercial thinning has a weighting factor of 0.50

same regression models for the monitoring locations in upstream catchments. The main downstream stations and trend signals are likely complicated by or entangled with cumulative effects of activities on the landscape and/or by the heavy sediment deposition in the impacted reaches.

SEV scores describe the state of salmonid health and habitat. SEV is function of SSC as well as SSC's time duration. While SSC by itself may not be any different from WY2003, changes in sediment fate and transport could explain the trends in SEV scores. That is, suspended sediment lingers at HRC509 (mainstem) longer than at HRC517 (Bridge Creek). SEV scores in general depend on the validity of the empirical models developed by Newcombe and Jensen (1996) and Bray (2000), especially the latter's models being directly related to Coho salmon, a species for which the Elk River watershed historically supported in large populations (NCRWQCB, 2014). While the SEV scale itself has seen scrutiny due to scoring subjectivity, the scale is still used widely as a semi-quantitative method for assessing SSC impacts on fisheries (Smedley et al., 2011). The Newcombe & Jensen (1996) model fits are not stellar with r^2 values for eggs/larvae and juvenile being approximately 0.60 and 0.55, respectively [12]. As a point of reference, the ordinary least squares (OLS) analysis performed for this assessment had r^2 greater than 0.70.

However, the bar for acceptable model goodness-of-fit in ecological studies is different due to inherent uncertainties in environmental data. Møller & Jennions (2002) reviewed forty-three (43) published papers and from those papers' results, the maximum r^2 found is 0.487 with more than 80 percent of values having r^2 lower than 0.10. Thus, in comparison, the Newcombe and Jensen (1996) models have excellent r^2 values and model fits. Still, alternatives or modifications to the original SEV model likely exist. Because the data assessment is a continuation of prior work—particularly, the ERRA—the investigation of alternative methods is outside the scope of this analysis but should nevertheless be considered in future assessment iterations as well as proposed activities for the coordinated science and monitoring components of the Watershed Stewardship Program.

Given everything presented in the water quality trends analysis, current data and methods employed all indicate persistent sediment impairments in Elk River. Without additional data related to anthropogenic activity, the question of whether this persistence is due to contemporary upper watershed timberland management, legacy sources, or a new equilibrium favoring greater "natural" sediment discharge cannot be answered. Nevertheless, hydrology and water quality data are valuable assets, and continued data collection efforts are critical in monitoring the effects of future recovery actions implemented through the Watershed Stewardship Program.

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[12] In simple linear regression, r^2 is also known as the coefficient of determination, which indicates the amount of variance that a model predicts compared to the response variable's variance. For more complex models, the coefficient of determination's mathematical definition may not be applicable, and r^2 takes on different forms and names. The one used here and in papers referenced is the squared Pearson correlation between the observed and model predictions.

5.3 Summary and Review of HRC Studies

In compliance with its MRP, HRC submitted a report in November 2021, which synthesized the data it collected and analyzed in the previous five years. The report included assessment of landslide activity, water quality trends, aquatic habitat trends, and the results of a paired watershed study (as well as summaries directly associated with timber operations and summarized in Section 4.2.1). In staff's review of the Landslide Monitoring, we found that there were insufficient data (including photographs) for us to independently corroborate the presented findings. This section remains silent on that topic, reserving discussion for a time when the Science and Coordinated Monitoring workgroup can address the topic collaboratively. As above, staff were able to independently analyze water quality data (e.g., suspended sediment data) to present findings, which are described in Section 5.2. In this section, staff summarizes HRC's findings relative to its Aquatic Trend Monitoring, which we were able to verify. Similarly, staff summarize the approach and findings of the Railroad Gulch Paired Watershed Study, with uncertainties identified.

5.3.1 Aquatic Trend Monitoring

Collecting data on in-stream physical habitat characteristics is essential for tracking watershed conditions and trends related to the distribution and movement of sediment throughout the watershed. The Class I Stream Aquatic Habitat Trends Monitoring Summary for the Elk River Watershed (Lackey, 2021) or Appendix C in HRC 5-year Synthesis Report highlights trends over the complete record of available monitoring data (2002 – 2020). Therefore, this section of this report provides an overview of those findings and the relevance of those findings in light of key beneficial uses SPAWN, COLD, and MIGR. HRC staff conducted aquatic trends monitoring (ATM) of Class I stream habitat at seven locations for channel substrate (pebble counts), pools, large wood, riparian canopy, water temperature, fish surveys, and channel cross sections. Water quality trend monitoring by HRC is a requirement of the Monitoring and Reporting Program (MRP) which is a primary component of Order No. R1-2019-0021. As described in Section 4.3, Section IV of R1-2019-0021 requires ATM every three years. Within the period of 2016 to 2021, ATM parameters were measured once in 2017 and a second time in 2020.

ATM data is compared to desired condition thresholds defined by the Aquatic Properly Functioning Conditions matrix. ATM parameters vary spatially throughout the watershed as well as temporally. Some ATM parameters are doing well compared to Aquatic Properly Functioning Conditions benchmarks and are either above or trending towards desired conditions. For example, canopy cover and stream temperature are within the Aquatic Properly Functioning Conditions desired conditions for all ATM sites and are not of concern at this time. However, temperature data was only collected once each year, so a greater resolution of data would provide useful information as to the effectiveness of canopy cover improving stream temperature conditions. The Regional Water Board's Temperature Policy highlights the importance of shade to stream temperature, but multiple additional influences on stream temperature can also be important. Other ATM parameters that are doing well compared to Aquatic Properly Functioning Conditions benchmarks include upstream substrate parameters, which are either achieving or close to achieving desired conditions.

However, downstream sites, specifically those within the impacted reaches (ATM175 and ATM166), are much further from desired conditions for these same parameters. ATM 175 is located along the South Fork Elk River above the confluence of the North Fork Elk River, and ATM 166 is located along the main stem below the confluence (Figure 10). For both stations, ATM parameters that are either achieving, or close to achieving desired conditions include all pool characteristics, stream temperature, and canopy cover, based on the two monitoring events reported in the 2016-2021 period. Median particle diameter (D_{50}) of the stream bed surface shows a slight coarsening trend, however, the 2020 D_{50}'s (ATM 175 = 6mm; ATM 166 = 7mm) are still far from the Aquatic Properly Functioning Condition target (65-95mm) (Figure 11). A positive trend suggests a slight coarsening of substrate particle size. A greater number of temporally spaced samples above and within the impacted reach would allow testing of statistical significance of trends for these parameters and whether data will reach desired conditions within the lifespan of the Habitat Conservation Plan (HCP).

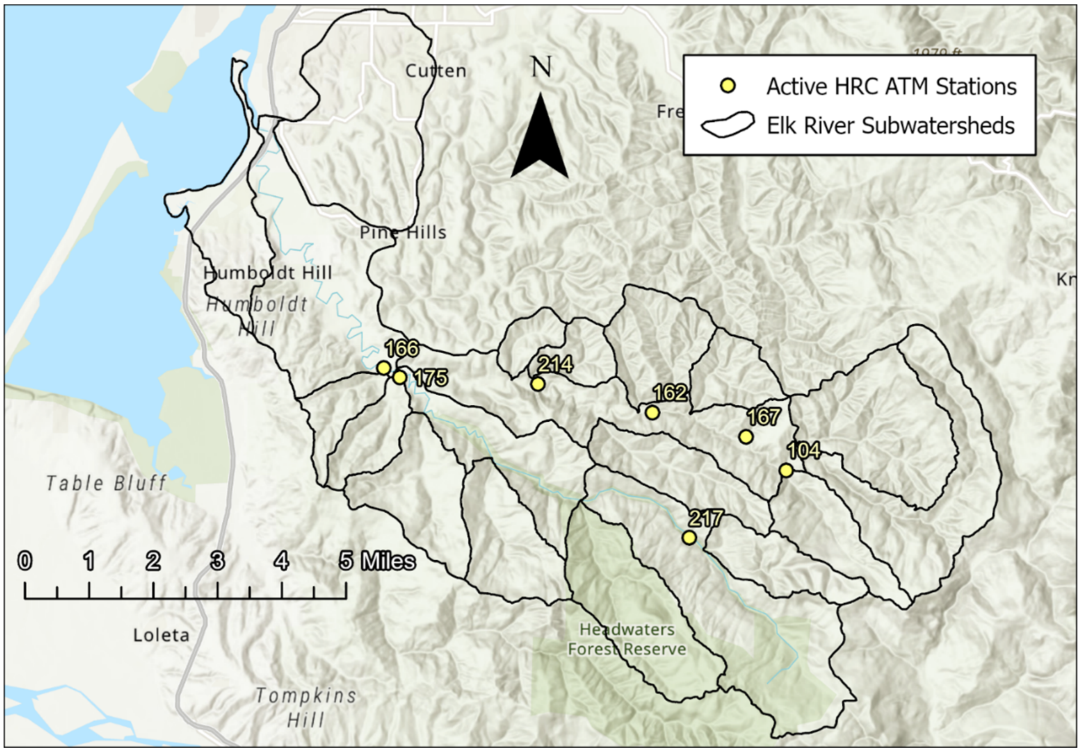
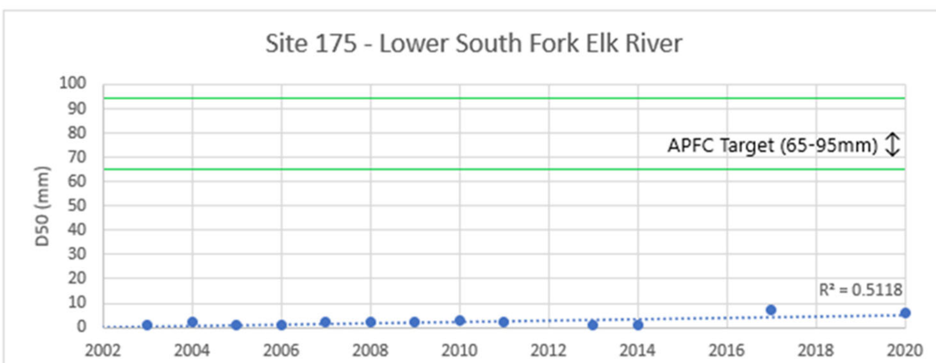


Figure 10. Map of ATM stations in Elk River



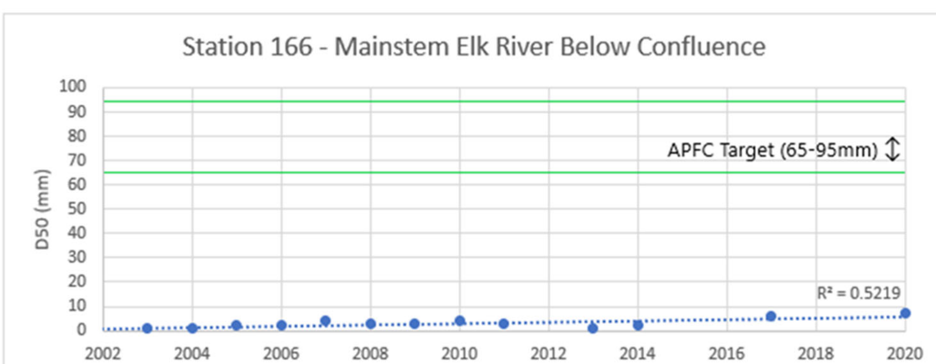


Figure 11: Temporal trends in median particle diameter (D50) from two ATM stations within the impacted reaches

HRC also presented cumulative frequency plots for mean surface particle sizes of three riffles measured within ATM 175 and ATM 166. Although raw data were not provided, these plots were visually analyzed and compared to desired conditions[13] of sediment-related indices for salmonid freshwater habitat (NCRWQCB, 2006). These parameters are directly tied to salmonid spawning habitat, and when streambeds are composed of too much fine sediment, redds can be covered, preventing the emergence of fry. Desired condition for percentage of particles less than 0.85mm (% Fines < 0.85) is less than or equal to 14%. Desired condition for percentage of particles less than 6.4mm (% Fines < 6.4) is less than or equal to 30%. Between 2005 and 2014, both conditions were not met at these sites. In 2017 and 2020, desired conditions for % Fines < 0.85 were met at both ATM 175 and ATM 166, however, desired conditions for % Fines < 6.4 have not been met to date for either site. Establishing appropriate thresholds of significance for substrate at these sites should be a high priority for a Science and Coordinated Monitoring Workgroup.

Summaries of change in cross sectional area were also provided in Appendix C of HRC's 5-year Synthesis Report. Both sites in the impacted reaches experienced an overall net sum of aggradation (ATM 175 = -0.15 m^2; ATM 166 = -12.98 m^2). When analyzing recent changes in cross sectional area (2017 and 2020), ATM 175 (lower South Fork) continued to experience aggradation with a net sum of -5.28 m^2 and ATM 166 (mainstem below the confluence) experienced scour with a net sum of 6.26 m^2. Raw data for further analysis was not provided and discussion of the relationship between watershed activity and change in cross sectional area was not included in Appendix C. Future reporting of data in a useable format will allow for comprehensive analysis of scour and aggradation trends in the watershed amongst all parties.

Based on the available data, it is difficult to determine the cause of recent coarsening of streambed substrate in the impacted reaches. Consistent with previous recommendations, development of specific monitoring questions (such as: what are the appropriate desired conditions for aquatic habitat in the impacted reach?) through a Science and Coordinated Monitoring Workgroup should inform monitoring strategies.

5.3.2 Railroad Gulch Paired Watershed Study

As part of the monitoring and reporting requirements outlined in Order R1-2019-0021, HRC submitted to the Regional Water Board *Evaluation of Best Management Practices in Railroad Gulch, Elk River Watershed: Final Report*, a summary report describing the results of their effectiveness monitoring programs for roads and timber harvest management practices in Railroad Gulch. The paired-watershed study was conducted by researchers from Humboldt State University, HRC, Colorado State University, Battelle Ecology, US Forest Service, and LRE Water Co. The objective of the study was to collect and evaluate specific sediment production, storage and delivery data to test the effectiveness of Habitat Conservation Plan (HCP) prescriptions in limiting sediment

[13] Desired conditions for % Fines are not included in Aquatic Properly Functioning Conditions, therefore desired conditions from an internal Regional Water Board Staff report, " Desired Salmonid Freshwater Habitat Conditions for Sediment-Related Indices," (NCRWQCB, 2006) are used for these parameters.

production and delivery from potential sources related to management practices. Railroad Gulch is a sub-basin of the Lower South Fork Elk River that consists of an East Branch and West Branch, each covering comparable areas. Nearly half of the East Branch is covered by the McCloud-Shaw Timber Harvest Plan (THP), while no timber activities have been conducted in the West Branch since 2003, allowing it to serve as the control watershed. The similar geology and terrain and isolation of timber harvesting to just one branch make Railroad Gulch a good location for a paired-watershed study.

A wide range of data were collected and analyzed for the Railroad Gulch study, including stage, continuous and storm turbidity measurements, road erosion, landslide characteristics, channel cross-sections, bed material size, and isotopic analysis of millennial scale erosion rates. The study finds elevated sediment loads in the East Branch (treatment) relative to the West Branch (control). Regional Water Board staff support both the study's paired watershed design and the study's objective of evaluating HCP prescriptions in limiting sediment production and delivery. The study addresses the effects of road construction and use on sediment production in particular detail and with an appropriate level of statistical rigor.

In spite of the good study design however, the Railroad Gulch study contained a number of confounding factors. Examples of these factors include the 2017 landslide in the control watershed; inherent differences in channel density and streambed grain size between East and West Branches; and large uncertainty in Be^{10} estimates between the control and treatment as well as compared to the rest of Elk River. The authors note that while it is likely that elevated sediment loads result in part from roads and harvest activities, they also suggest that non-harvest related differences between the two watersheds such as channel density and streambed grain size play a role as well. The authors ultimately conclude that road construction, road use, and timber harvesting have limited impacts on sediment loads in Railroad Gulch. Staff did not find these conclusions well-supported. In addition to the 2017 landslide and other confounding factors discussed above, the requirement in Order R1-2019-0021 to address the effects of management practices on sediment production in sensitive riparian zones is absent. Though a paired watershed study offers the potential to shed light on the relationship between management activities and water quality conditions, in the absence of raw data underlying the study, more detailed descriptions of how authors arrived at specific conclusions and because of the presence of several confounding factors, staff is unable to fully support the conclusions presented in the report.

5.4 Summary and Review of Elk River Recovery Assessment Cross-Section Analysis

The Elk River mainstem, North Fork and South Fork have shown a loss of channel cross-sectional area over time due to sedimentation. Cross-sectional area has been used to assess trends in sedimentation and loss of flow capacity, which results in an increase in overbank flooding. Both the listing of the Elk River watershed on the 303(d) list in 1998 and the adoption of the TMDL Action Plan in 2016 are actions reflective of this ongoing sedimentation.

CalTrout, Stillwater Sciences, and Northern Hydrology and Engineering prepared a technical memorandum dated March 2019 titled *Elk River Recovery Assessment: Recovery Framework* (Recovery Framework), following adoption of the TMDL Action Plan. Among other things, this memorandum assessed the record of cross-section data up through 2016, the last year of record. As reported in the Recovery Framework document:

"Transect surveys conducted at 23 sites in the North Fork Elk River, South Fork Elk River, and Mainstem Elk River by HRC over a period from 1997 to 2016 indicate consistent trends in reduced cross-sectional area since 1997. There were also typically net decreases in channel cross-sectional area observed at 27 sites surveyed in the North Fork Elk River, South Fork Elk River and Mainstem Elk River by the ERRA team and partners from 2002 to 2014."

Table 13: From CalTrout et al (2019), Changes in bed elevations and cross-sectional areas at bridge sites

Bridge site	Average bed elevation change		Percent reduction in cross-section area	
	Period	Change, ft	Period	% change
North Fork Bridge	1947–2002	4.2	1971–2016	44
Steel Bridge	1958–2015	6.2	1958–2016	24
Zanes Road	1969–2014	6.3	2006–2016	5
Berta Road	1969–2016	6.5	1969–2016	50

As described in the ERRA, these data indicate a continued loss of channel cross-sectional area, which is relevant to conditions of nuisance flooding. The Science and Coordinated Monitoring workgroup should consider continuing collection of these data and discuss appropriate adaptive management thresholds.

5.5 Evaluation of TMDL Effectiveness

Section VII (Monitoring and Adaptive Management) of the TMDL Action Plan says:

"Approximately five years after adoption, Regional Water Board staff will conduct a formal assessment of the effectiveness of the implementation plan, including an evaluation of the effectiveness of WDRs and waivers, and make any necessary revisions to this TMDL Action Plan. This includes a review of the sediment source analysis and water quality data for the Upper Elk River, sediment deposition in the

impacted reach and Lower Elk River, and the need for a Lower Elk River sediment TMDL, using Recovery Assessment tools and other available data, as appropriate. During reassessment, the Regional Water Board will consider how effective the requirements of the TMDL program of implementation are at meeting the TMDL, achieving water quality objectives, restoring the beneficial uses of water, and abating nuisance flooding conditions in the Upper Elk River Watershed. The success of the TMDL will be assessed based on water quality trends in the Upper Elk River Watershed, particularly the attainment of water quality standards in the impacted reach. Ultimately success is achieved when nuisance conditions are abated, and beneficial uses are supported."

The main goals of this assessment and data analyses were to evaluate the overall effectiveness of the TMDL Implementation Plan and to report the current conditions in the Upper Elk River watershed with respect to water quality and aquatic habitat parameters. Ideally, the quantitative element of this evaluation would allow staff to definitively tease apart sediment contribution and effects from land management versus the natural background, for example. However, significant data gaps were present when staff began its assessment. Beyond the gaps in SSC sample data in the upper watershed, and raw aquatic habitat monitoring data, staff were also originally hampered by a dearth of management-related data, such as annual harvest activity data. As such, staff were unable to develop an analytical approach to testing land management activities as covariates associated with SSCs. Instead, staff's analyses focused on the trends and effects of suspended sediment at a subset of monitoring stations for the period of 2016-2021 where data were more readily available.

Notably, the results of even this relatively focused work indicates that conditions are in stasis; with evidence of potential worsening at stations near the confluence and impacted reach during the period of 2016-2021 and cross-section data indicating continued aggradation in the impacted reach. As such, consideration of revisions to the TMDL source analysis, loading calculations, or assimilative capacity calculations are premature. Similarly premature are revisions of WDR requirements to either decrease or increase sediment control and discharge protections, including the protections afforded by timber harvest limitations.

With respect to the Lower Elk River, the Recovery Plan identifies recovery actions throughout the Elk River watershed from just above the confluence of the North and South Forks, all the way to the estuary. These recovery actions are derived from modeling results and vetted with individual affected landowners. Proposed recovery actions in the lower watershed include significant sediment remediation and habitat rehabilitation efforts, specifically endeavoring to improve flood pathways and direct sediment deposition. Further, the stormwater management requirements of the City of Eureka and permitted dairies in the lower watershed periodically will be updated to reflect ongoing sediment control needs in the lower watershed. Finally, the Regional Water Board has committed to developing a Grazing Management Program, which will among other things address sediment discharge. These actions are an alternative to an established TMDL to direct sediment source control from landowners downstream of

Berta Road (i.e., the boundary between the lower and upper watersheds). A TMDL alternative is allowed by U.S. EPA. Based on these factors, staff have determined that it is not necessary to develop a TMDL specific to the Lower Elk River, at this time.

Consistent with the TMDL Action Plan's monitoring and adaptive management approach, on-going assessment of watershed conditions and determination of potential revisions to the TMDL and program of implementation will be an adaptive process. This report serves as one milestone in that assessment process. Coordinated monitoring and assessment will inform future reviews. To support this on-going process, Regional Water Board staff have several findings and recommendations, outlined below.

At the time of this document's preparation and after several communications, staff did receive substantial water quality data from HRC for upper watershed monitoring stations, including harvest-related data. These data will be valuable to further explore questions of water quality trends; beneficial use improvement; changes to the rate of overbank flooding; sediment loading; assimilative capacity; and the relationship of roads, harvest, riparian protection, and other management factors to these issues. Coordination amongst parties and renewed watershed collaboration (e.g., development of a Science and Coordinated Monitoring Workgroup) will vastly improve the potential to design and implement an effective analytical framework. In any event, staff propose that the same trend analysis methods applied to the three monitoring stations near the confluence be extended to other monitoring stations in the upper watershed for which there is SSC sample data.

While staff greatly appreciate the final delivery of these datasets from HRC, limitations in the Monitoring and Reporting Program (MRP) language led to delays such that this review could not include these data in the overall assessment within the timeframe prescribed by the TMDL Action Plan. Additionally, the details for aquatic trends monitoring originating in the HCP remain largely unchanged as written in the WDR's MRP. Thus, another issue that needs addressing is updating the requirements of the MRP and improving clarity on expected deliverables, including delivery of data in useable format.

Language regarding submission of monitoring data in usable formats[14] is found only in a subsection of the MRP detailing annual summary report for water quality monitoring. Since the WDR's adoption, only water quality has been submitted in usable format. Only after formal letters citing Water Code section 13267 did staff receive the data requested. Data submitted in non-usable formats present a significant barrier to analysis. For example, for raw data in the form of tables embedded in PDF (portable document format) files to be used, it must be converted to tabular form, introducing transcription errors in the process, which must be quality controlled/quality assured before use in data analysis. This data format issue is particularly notable in data related to timberland management, e.g., the lack of geospatial data for harvested areas and road updates.

[14] Staff define usable data as electronic tabular or otherwise machine readable using non-proprietary computer software. Data of a spatial nature (e.g., landslide locations or aerial imagery) must also be georeferenced and readable in non-proprietary GIS (geographic information systems) computer software.

With respect to the aquatic habitat indicators, monitoring requirements and collection frequency are not linked to the relevant data analyses. The MRP states in general terms that monitoring data can "improve understanding of the spatial and temporal association between sediment loads and management activities." However true this statement, the parameters listed plus their collection frequencies (once every three years) are likely insufficient. For example, common trend detection methods (i.e., the Mann-Kendall) require a minimum number of four observations as well as minimal gaps to provide useful inferences.

Data collection and information generation should flow in a loop from permittee, to core regulatory staff, to planning/adaptive management staff, and back to permittee, along with dissemination to other stakeholders where relevant or requested. This process need not occur once every five years and can be done annually. Maintaining such a routine will ensure that data are consistently submitted in usable formats and that time-based regulatory requirements such as the Five-Year Review (plus others expected in 2026 and 2031) are completed in a timely manner.

The WDR highlighted the Watershed Stewardship Program as the main or proper forum for discussing methods and manner of assessing monitoring data, including examining potential research questions and their data requirements. Up until the Five-Year Synthesis Report's release and staff's active work on this data assessment, neither the Regional Water Board nor timberland owners have coordinated on the science and monitoring front. This lack of coordination is partially due to issues beyond either party's control (i.e., the Watershed Stewardship Program's initial stall, staffing changes, the Covid pandemic, etc.), but going forward, the parties should agree to a style and frequency of data sharing, and develop joint goals and protocols for communication and coordination, including, where appropriate, other stakeholders in the watershed. Watershed Stewardships' publication of the Elk River Recovery Plan includes coordinated monitoring and science recommendations. These recommendations should form the starting point for discussion between Regional Water Board and HRC/GDRC staff, as well as the broader engagement of a Science and Coordinated Monitoring Workgroup.

Finally, the ERRA is now a completed modeling tool that may continue to prove useful in assessment, adaptive management, and future revision of the TMDL. It offers the ability to predict water quality outcomes of multiple sediment loading and remediation/rehabilitation scenarios, even beyond those that were funded as part of the ERRA and Elk River Recovery Plan projects. It may be particularly useful in reassessing assimilative capacity in the impacted reach, once recovery actions have been designed.

Section 6: Summary of Findings and Recommendations

This section summarizes staff's findings and recommendations relative to the requirements described in Table 4 and Section VII of the TMDL Action Plan at this five year milestone.

Table 4 of the TMDL Action Plan requires:

Timberland owners will implement WDRs and waivers of WDRs "*to implement phase 1 of the Upper Elk Sediment TMDL and a zero load allocation.*"

"By 2016, in coordination with a steering committee, Humboldt County will initiate a watershed stewardship program for the Elk River Watershed in conformance with the 319(h) grant contract, including establishment of: a Health and Safety workgroup responsible for developing recommendations appropriate for resolving water supply, flooding, and road access issues; a Science and Coordinated Monitoring workgroup responsible for developing recommendations appropriate for improving the effectiveness of water quality, sediment and flow monitoring efforts throughout the watershed; a Sediment Remediation workgroup responsible for developing recommendations appropriate for remediating instream stored sediment and improving floodwater conveyance, sediment transport, and ecosystem function. Final reports documenting the workgroup's recommendations, including plans and schedules are due in 2018."

"By 2017, CalTrout will produce a final report detailing the results of full-scale sediment and hydrodynamic modeling, including feasible remediation and restoration activities sufficient to achieve water quality standards and return the watershed to a trajectory of recovery."

"By 2021, the Regional Water Board shall evaluate the available information to assess the degree to which 1) adopted WDRs and waivers have successfully controlled sediment delivery from the upper watershed to the impacted reaches and 2) the efforts of the Watershed Stewardship Program are making sufficient progress towards achievement of health and safety, coordinated monitoring, and sediment remediation improvements."

Section VII (Monitoring and Adaptive Management) of the TMDL Action Plan also provides:

"Approximately five years after adoption, Regional Water Board staff will conduct a formal assessment of the effectiveness of the implementation plan, including an evaluation of the effectiveness of WDRs and waivers, and make any necessary revisions to this TMDL Action Plan. This includes a review of the sediment source analysis and water quality data for the Upper Elk River, sediment deposition in the impacted reach and Lower Elk River, and the need for a Lower Elk River sediment

TMDL, using Recovery Assessment tools and other available data, as appropriate. During reassessment, the Regional Water Board will consider how effective the requirements of the TMDL program of implementation are at meeting the TMDL, achieving water quality objectives, restoring the beneficial uses of water, and abating nuisance flooding conditions in the Upper Elk River Watershed. The success of the TMDL will be assessed based on water quality trends in the Upper Elk River Watershed, particularly the attainment of water quality standards in the impacted reach. Ultimately success is achieved when nuisance conditions are abated, and beneficial uses are supported."

6.1 Summary of Findings

The Regional Water Board adopted the TMDL Action Plan for the Upper Elk River Watershed in 2016, which was subsequently approved by the State Water Resources Control Board, Office of Administrative Law, and U.S. Environmental Protection Agency. The whole of this report presents staff's assessment of TMDL implementation at this five-year milestone as required in Table 4 and Section VII of the TMDL Action Plan. This section summarizes staff's findings relative to these requirements, while Section 6.2 of this report presents staff's recommendations.

6.1.1 Watershed Stewardship

Table 4 of the TMDL Action Plan requires that a Watershed Stewardship Program be developed, including a Science and Coordinated Monitoring Workgroup, a Health and Safety Workgroup, and a Sediment Remediation Workgroup. Staff's findings are that the Watershed Stewardship Program has been robustly stood-up, with dramatic accomplishments specifically related to development of an actionable Recovery Plan ready for grant funding, design, permitting and implementation (See 6.1.2). However, early growing pains, including loss of Humboldt County as the grant funded lead entity, resulted in significant delays relative to development of workgroups as noted below.

1. The Science and Coordinated Monitoring Workgroup has not yet been established and has emerged as a high priority, with a first meeting soon to be scheduled.

2. The Health and Safety Workgroup has not yet been established. But recent efforts show promise, including a) efforts to coordinate directly with affected residents and b) identify agencies and programs with funding and authority to address flooding of public and private infrastructure and assess and supply public drinking water. It is a high priority of the Humboldt Bay Steward to continue and complete one-on-one interviews with residents; identify the proper agencies, programs and funding resources to address noted health and safety issues; and develop a strategic plan for implementing noted actions. Establishing a Health and Safety Workgroup may

continue to be an important element of the strategic plan, depending on community support.

3. The Sediment Remediation Workgroup was not established. But, the concept of Sediment Remediation Workgroup was altered when CalTrout became the new Watershed Stewardship Program lead. Rather than route sediment remediation and habitat restoration concepts through a workgroup, CalTrout worked directly with landowners on whose property remediation/restoration projects were considered. Through this one-on-one engagement, CalTrout has been able to complete a well vetted, thorough and thoughtful Recovery Plan, which provides the immediate basis for design, permitting, funding and implementation of restoration and rehabilitations projects, as prioritized across four Planning Areas.

6.1.2 Elk River Recovery Assessment

Table 4 of the TMDL Action Plan requires the completion of the Elk River Recovery Assessment: Recovery Framework (ERRA) to report the findings derived from a sediment transport and hydrodynamic model developed to test the predicted effect of sediment loading reduction and multiple restoration scenarios. The CalTrout team composed and engaged a Technical Advisory Committee made up of local experts, agency representatives, timber company representatives, and residents. The Recovery Framework was completed as required.

Further, the Recovery Framework formed the basis for development of the *Elk River Watershed Stewardship Program: Sediment Remediation and Habitat Rehabilitation Recovery Plan* (Recovery Plan), which was not required by the TMDL Action Plan, but the necessary next step towards grant funding, design, permitting, and implementation of reach-specific sediment remediation and habitat rehabilitation projects. The Recovery Plan was completed in July 2022 and is a companion to this staff report. It represents an enormous advancement in our ability to begin implementation of recovery actions.

1. Development of the Recovery Plan was not specified in the TMDL Action Plan but is the natural outgrowth of the Recovery Framework. The loss of Humboldt County as the lead entity for Watershed Stewardship has meant a delay in establishing workgroups, especially to address health and safety and science and coordinated monitoring (See 6.1.1). On the other hand, the significant benefit of CalTrout as the new lead for Watershed Stewardship, is the dramatic advances in sediment remediation and habitat rehabilitation planning. As a result of CalTrout's leadership, the Recovery Plan is now available as the critical starting point from which to generate project designs, receive permits, acquire funding, and ultimately implement the restoration and rehabilitation projects that will reduce overbank flooding and

otherwise improve the ability of the Elk River to transport sediment and water in a manner consistent with beneficial use protection.

2. The Recovery Plan includes a monitoring framework, which will advance the work of the Science and Coordinated Monitoring Workgroup when it is formed.

6.1.3 Waste Discharge Requirements

Table 4 of the TMDL Action Plan requires that waste discharge requirements (WDRs) and waivers of WDRs be implemented to implement phase 1[15] of the Upper Elk River Sediment TMDL and a zero load allocation. Key milestones and findings include:

1. HRC WDR was revised in 2016 and again in 2019.
2. GDRC WDR was revised in 2020.
3. Available data are insufficient to comprehensively assess the degree to which WDRs and Waivers have successfully controlled sediment delivery to the impacted reach.
4. Focused data assessment indicates conditions are generally in stasis, with evidence of worsening in and around the confluence of the north and South Forks and continued aggradation in the impacted reach.

6.1.4 Effectiveness of the Implementation Plan

Table 4 of the TMDL Action Plan requires assessment of the degree to which the revised WDRs have controlled sediment discharges and the Watershed Stewardship Program has made sufficient progress. Similarly, Section VII of the TMDL Action Plan requires that at about the five-year milestone staff assess the effectiveness of the implementation plan, with considerations for revisions to the TMDL Action Plan, particularly the sediment source analysis. It further requires consideration of changes in sedimentation trends in the impacted reach and the degree to which a Lower Elk River Sediment TMDL is necessary. The subsections above summarize staff's findings relative to implementation of the WDRs and progress in implementation of the Watershed Stewardship Program. This subsection focuses on staff's findings relative to a) revision to the TMDL Action Plan and sediment source analysis, b) sedimentation in the impacted reach, and c) the need for a Lower Elk River Sediment TMDL.

1. Staff found no evidence that suspended sediment concentrations at stations in the upper watershed are decreasing, though aquatic trend monitoring data indicates some locations where statistically significant trends show improvement. There is not, however, definitive evidence that implementation of the WDRs is successfully controlling all controllable sources of sediment. Nor is there clear evidence that changes to the WDRs is necessary at this time in order to increase

[15] Phase 1 of the Upper Elk River Sediment TMDL refers to the phase in which the assimilative capacity for additional sediment to the top of the impacted reach is calculated as zero. Future phases of the TMDL will be established following completion of recovery actions and expansion of the impacted reach and lower river for additional sediment. At that time, a new sediment load allocation will be calculated, which is consistent with the expanded assimilated capacity.

sediment controls. On the other hand, some revisions to HRC's MRP is necessary and appropriate.

2. Staff find that implementation of the HRC WDR since 2019 and the GDRC WDR since 2020 is too short a time to expect detectable signals of improved sediment source control and water quality conditions. Further, the currently available data is inadequate to detect such a signal, even with sufficient time.

3. In channel cross-sections show continued aggradation in the impacted reach, though the existing dataset available to staff only includes data up through 2016.

4. Implementation of the Recovery Plan is intended to begin with proposed recovery actions in the lower river and estuary where there is substantial opportunity to improve stream channel-floodplain interaction and beneficial sediment deposition.

5. Staff plan to begin development of a Grazing Program in the near future, which will help address any sediment discharge issues associated with lower river grazing activities.

6. The Regional Water Board already implements a Dairy Program and a Stormwater Program, which address sediment discharge issues. As needed, the requirements of these programs can be updated to improve sediment discharge control from dairies in the lower watershed and from the City of Eureka.

7. Staff finds that it is premature to consider any revisions to the TMDL, including the sediment source analysis, calculation of assimilative capacity, or implementation plan.

8. Staff conclude that a sediment TMDL to address sources of sediment in the lower watershed are not necessary at this time, as existing regulatory programs can directly address individual sources, as necessary. Further, staff find that the Recovery Plan adequately addresses the sediment remediation and habitat rehabilitation needs from the top of the impacted reach down through the estuary, thereby identifying recovery actions necessary in the lower watershed.

6.2 Recommendations

This section enumerates a series of recommendations, divided by category, that result from staff's assessment as described in the sections above. Recommendations are related to implementation of the Watershed Stewardship Program, the Recovery Plan, and WDRs, with a special attention to the issue of science and coordinated monitoring. Science and coordinated monitoring is an area of special focus because of the limitations to this five year assessment, which are the result of significant data gaps. Further, staff's ability to assess TMDL effectiveness in the future, will be improved by better collaboration and coordination around science and monitoring, as will adaptive management of WDRs and implementation of recovery actions.

6.2.1 Watershed Stewardship

1. Staff recommend the formation of the Science and Coordinated Monitoring Workgroup. A Science and Coordinated Monitoring Workgroup can develop a coordinated monitoring plan, beginning with the monitoring framework included in the Recovery Plan. A coordinated monitoring plan will help to ensure that data are collected in a manner capable of addressing key questions of watershed health and recovery, inform revision to the existing monitoring and reporting requirements of permittees, establish hypotheses appropriate for special study, and design a framework for adaptive management over the long term.

2. Staff recommend completion of the Health and Safety Interviews and completion of a final summary report.

3. To address issues related to drinking water, staff recommend the engagement of Humboldt County, the Humboldt Bay Community Services District, and the Humboldt Bay Municipal Water District in discussions of potential Safe and Affordable Funding for Equity and Resilience (SAFER) program fund applications, as well as other water infrastructure and drought relief program funding options.

4. To address issues related to flooding generally, staff recommends engagement with the Federal Emergency Management Agency (FEMA) through the California Office of Emergency Services and its contractor The Nature Conservancy. In coordination with the Coastal Conservancy, the Regional Water Board could be a State government applicant for FEMA funding designed to support installation of green infrastructure to abate flooding. Such funding would support recovery actions described in the Recovery Plan.

5. To address issues related to flooding on public roads, staff recommends continued engagement with Humboldt County to encourage the County to assess and prioritize county roads within Elk River watershed in need of flood retrofit.

6. To address issues related to flooding of private infrastructure, staff recommends engagement with a Health and Safety Workgroup to identify and engage with agencies with authority and resources to address these issues (e.g., including

private roads, private structures, onsite wastewater treatment systems, and others).

6.2.2 Recovery Plan

1. Staff recommend implementation of the Recovery Plan, with CalTrout as the lead. This will require Regional Water Board support on grant applications, as a grant applicant itself (e.g., see discussion of FEMA grant above), in 401 permitting, with monitoring and assessment resources, and with Stewardship resources.

2. Staff recommend the engagement of upper and lower watershed landowners in support of grant applications; other funding (as applicable); and recovery action design, implementation, and assessment.

6.2.3 WDRs

1. Staff recommend that the water quality protections of the current WDRs not be reduced until there is evidence that impairment conditions are improving.

2. Staff recommend that data collection required by the MRPs be expanded beyond once every three years to a more statistically significant number (i.e., the Mann-Kendall). Further, staff recommend MRPs require a minimum number of four observations as well as minimal gaps to provide useful inferences. Finally, the MRPs should be revised to provide greater clarity on issues such as data format, useability, and sharing.

3. Staff recommend the engagement of HRC and GDRC in the Science and Coordinated Monitoring Workgroup when it is formed. Their engagement will be critical to establish meaningful monitoring questions, identify additional data and analyses that may help inform adaptive management, and establish appropriate thresholds to support modification of MRPs, WDRs, and the TMDL, as warranted.

4. Regional Water Board staff and HRC and GDRC staff should be more active in coordinating science and monitoring. While the MRP is correct in saying that the Watershed Stewardship Program is the appropriate forum for such coordination and dialogue, the process need not wait for a more formal workgroup to emerge. That is, staff should build the foundation in anticipation of an active group existing. The Elk River Recovery Plan provides detailed guidance on recommended direction (i.e., monitoring framework); the MRP should incorporate these recommendations to the extent feasible.

5. Staff recommend that Suspended Sediment Concentration analyses, as described in Section 5, be applied to the whole upper watershed dataset, where there are sufficient data to do so. Staff further recommend that an approach to

assessing management-related covariates be considered. Staff should collaborate with HRC and GDRC on this work, at least until a Science and Coordinated Monitoring workgroup is established under the Watershed Stewardship Program.

6.2.4 Future Assessment

The TMDL Action Plan's reassessment milestones are summarized here:

- 2026: Evaluate the available information to assess the degree to which recommended health and safety, coordinated monitoring, and sediment remediation improvements have been achieved.
- 2031: Re-evaluate the sediment loading capacity and load allocation for the Upper Elk River Watershed and revise accordingly.

Staff intend that a Science and Coordinated Monitoring workgroup, once active, become the venue for discussing and addressing science and monitoring needs relative to implementation of the TMDL and the assessment of trends towards recovery. Implementation of new monitoring and assessment efforts should be distributed among: the timberland owners through their associated MRPs; the implementers of the Recovery Plan; the Regional Water Board including its Surface Water Ambient Monitoring Program (SWAMP); other agency partners (e.g., California Department of Fish and Wildlife bioassessment team); and other watershed stakeholders. Associated with this workgroup will be the need for agreement around data sharing and collaboration on assessment. With a long vacant Steward position now filled as a Humboldt Bay Steward, staff are eager to enter into this next phase of TMDL implementation with greater coordination, collaboration, and observable action on the ground.

Appendices

Appendix A: Humboldt County Road Flooding Workgroup Survey Responses, 2016

Elk Road Survey (19388)

User	Date	Name:	Address:	Email (preferred):	Phone number (if no email):
1013039	11/23/2016 7:57:36	[redacted]	[redacted]	[redacted]	[redacted]
1013222	11/23/2016 14:05:27	[redacted]	[redacted]	[redacted]	

How long have you lived in Elk River?	Which road receives flooding that directly impacts you? (if more than one road- please complete a survey for each road)	How would you describe the severity of the flooding impacts?
27 years	Elk River	Major disruption
18 years	Berta	Major disruption

If you selected "other" for the previous question- please briefly describe.	How important is it to try to alleviate road flooding?	Has road flooding prevented you from traveling to and from your home?
	Extremely important	Several times
	Extremely important	Several times

Please describe how road flooding impacts you; For example: How does road flooding affect your access to work- school- mail service- medical resources- or other services? How frequent are these impacts? Does road flooding affect access for emergency services to your neighborhood?
We moved out to Elk River in 1990. My son and I would walk over 300 yards along the bank of the north fork that runs along our property. We had a large paddle board that we could float and pole down our river. We watched salmon and otters swim upriver under the concrete bridge. Things began to change during the mid-90's. We were told when we moved to Elk River that on occasion the river does flood. Our first flood was three years later. After that, we started seeing the river flood once a year, then increasing to multiple times a year. We now see flooding 3-4 times a year with much less rainfall. When it flooded in the 2000's I would ferry the family back and forth to work and school with a rowboat. At one time we were needed to help our neighbor get to the doctor. I had to use an outboard motor because the current was swift. On occasion the motor would stop and panic would set in as we drifted towards the trees in the swift current. Luckily we never were injured. Now that we are older and retired, we avoid venturing out to cross the flooded river. Fortunately, in recent times there have been no emergencies so we have been able to wait for the flooded river to subside. The flooding prevents us from getting out of home for up to 12 to 48 hours. Many times in the past, we had to trudge a half mile through knee deep water and mud through fields and barbed wire just to get home after work to feed the animals. Our vehicles have had many repairs over the years related to the flooding such as bearing and hubs. The first and second floods of the year produce about an inch of silt covering the road at the bottom of our driveway. The car tracks silt into our garage and into the house. Mail and paper deliver is often delayed and household service calls have to be rescheduled. Cars have been found in the river after a flood. Some neighbors wade chest deep through the swollen river to reach their homes. It's a matter of time before we have a real disaster. The siltation of the river is our main problem. The maintenance on our water systems is a big issue. The valves fail regularly, the tanks collects silt, the river pumps get buried. In the summer, the river almost disappears under the silt. We need domestic water delivered during the dry season. We collect rain water in the wet season.
We cannot drive to Elk River Road. We have to cancel appointments, travel, etc.

Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road; For example: Where do the floodwaters come from? How long is road access impacted by flooding? How deep is the water? What are the key causes and factors that affect road flooding?	**How has road flooding changed over time?**
As we have mentioned, it started in the early 90's once every three years. It has progressed up to 4 times a year even through our drought years. Once the ground gets saturated it only takes 2 inches of rain to flood our cement bridge. In times past, it could rain for days and days before we got flooding; now it can happen during any heavy rain. The flooding that affects us directly is that from the North fork. The flooding can go over the guard rail on the concrete bridge, halfway up the blue Headwater sign. The flood waters have gotten into our mailbox three times. The residents in Elk River agree without question that the flooding is due to increasing siltation which constricts the river channel. The channel's banks are steeper and the channel itself is narrower causing the river to overflow its banks with much less water. Both the concrete bridge and the logging bridge on the mail stem act as partial dams restricting the flow or the river. The culprit is past logging practices, bad roads and continued disturbance through current harvest permits. We saw a short lived reprieve in the early 2000's when there was a logging moratorium, it is time for another.	Yes, more frequent, more silt.
We've seen it as high as 3 feet our car became stuck when it was @ 2 feet. Another car needed a new engine, carpets, etc. Very expensive.	It seems to be the same every year.

DEPARTMENT OF PUBLIC WORKS
COUNTY OF HUMBOLDT

Elk River Road Flooding Survey

Please return by December 15, 2016 to:

Humboldt County Public Works
1106 Second Street, Eureka, CA 95501
c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	
Phone or E-mail	
How long have you lived In Elk River?	53 years

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	Elk River Rd.
2. How would you describe the severity of the flooding impacts?	☐ Inconvenient ☐ Minor Disruption ☐ Major Disruption ☒ Other: Danger of my house flooding.
3. How important is it to try to alleviate road flooding?	☐ Not important ☐ Somewhat important ☐ Moderately important ☐ Very important ☒ Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐ Never ☐ Once or twice ☒ Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access for emergency services to your neighborhood?	We can't get to work, get mail and we can't get medical help in an emergency The frequency + severity of flooding depends on how much rain we get after the ground is saturated. Last year I had to stay in town at least 3 times.

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	The depth + duration depends on how much it rains in the mountains around us in our watershed and how fast it drains out of the valley. Our house is approximatly 100' from the rivers edge. we have a 6' flood marker on the Edge of the river. When the water is close to our house the post is almost covered 5½'. When the water is around our house the post is covered and it gets into our pump house that is 30' into our field. Its on stilts 6' high. Key causes of flooding are run off from the watershed and the river channel is Blocked with silt, trees and log jams.
7. How has road flooding changed over time?	It takes less rain to flood the road. In 1964 the water didn't get around the house. Now it gets in our garage and all the way around the house. It has come within an Inch of getting into our house.
	When the water gets into our garage. the rails on the bridge are under water complety.
8. What project concepts are worth further evaluation?	☐ Road and bridge improvements ☒ Drainage improvements ☐ Alternative access routes: emergency access only ☐ Alternative access routes: emergency and non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments: The river channel needs to be cleaned out first. If the road at Stockoff corner is raised before the river channel is improved. our house and others, will get water inside our homes.

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c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	[redacted]
Phone or E-mail	[redacted]
How long have you lived In Elk River?	73 yrs.

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	Clover Ln. & Berta Rd.
2. How would you describe the severity of the flooding impacts?	☒ Inconvenient ☐ Minor Disruption ☐ Major Disruption ☐ Other: ______
3. How important is it to try to alleviate road flooding?	☐ Not important ☒ Somewhat important ☐ Moderately important ☐ Very important ☐ Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐ Never ☒ Once or twice ☐ Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	To much RAIN
7. How has road flooding changed over time?	None
8. What project concepts are worth further evaluation?	☐ Road and bridge improvements ☐ Drainage improvements ☐ Alternative access routes: emergency access only ☒ Alternative access routes: emergency and non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments:

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c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	[redacted]
Phone or E-mail	[redacted]
How long have you lived In Elk River?	[redacted] 33 yrs

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	Elk River and Berta Rds
2. How would you describe the severity of the flooding impacts?	☐Inconvenient ☐Minor Disruption ☒Major Disruption ☐Other: ______
3. How important is it to try to alleviate road flooding?	☐Not important ☐Somewhat important ☐Moderately important ☐Very important ☒Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐Never ☐Once or twice ☒Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	Missed work school + special events many times. Emergency services completely cut off. Have had to relocate many times. Utilities unable to access

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	Over 1 inch of rain can cause Berta Rd to flood. Breeching banks up river & at Berta Rd Bridge causes flooding along multiple sections of Road. Some areas flowing swiftly across road. Up to 1'-3' Road access impacted 2-8 times per year extending 1-3 days per incident.
7. How has road flooding changed over time?	30 yrs ago the road (Berta) was only threatened after approx. 3 days of heavy rain. In the last 7-10 years it takes only 1"-2" of rain to cause flooding. Silt has built up along road to have the road act as a "causeway" attracting breeching waters.
8. What project concepts are worth further evaluation?	☒ Road and bridge improvements ☒ Drainage improvements ☒ Alternative access routes: emergency access only ☐ Alternative access routes: emergency and non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments:

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1106 Second Street, Eureka, CA 95501
c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	[redacted]
Phone or E-mail	[redacted] / [redacted]
How long have you lived In Elk River?	20 years

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	The road flooding does not directly impact me as I live above the flood plain, off Westgate (bluff above Elk River).
2. How would you describe the severity of the flooding impacts?	☐ Inconvenient ☐ Minor Disruption ☑ Major Disruption ☐ Other: ______
3. How important is it to try to alleviate road flooding?	☐ Not important ☐ Somewhat important ☐ Moderately important ☑ Very important ☐ Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☑ Never ☐ Once or twice ☐ Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	The road flooding does not affect me directly as mentioned above, however I am aware that for those residents who live right on or directly off Elk River Rd, the flooding disrupts all normal activities of life that require access to points outside of Elk River, ie, work, school, medical services etc; and that these disruptions occur regularly during

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	The floodwaters appear to come from higher up in the river, closer to the source (Headwaters). The road access is impacted for about 2 weeks I think, following a significant rain event. I do not have any clear idea of how many inches rainfall within a specific period of time, eg 24 hrs, produces flooding of a specific floodwater height. The water appears 3-4' high in places. Causes, I believe, are logging practices leading to excessive sedimentation (+ accumulation in the river bed.) Another cause may be natural flooding: what was the original width of the flood plain prior to development for agriculture + residency? And what was the cycle for flood events? Surely not annually? Or was it a regular thing?
7. How has road flooding changed over time?	It appears to have increased.
8. What project concepts are worth further evaluation?	☑ Road and bridge improvements ☑ Drainage improvements ☐ Alternative access routes: emergency access only ☐ Alternative access routes: emergency and non-emergency conditions maybe, if there is money for this. ☐ Roads should be left as-is, focus on the river only Comments: I would focus on improving river quality + conditions, in addition to considering road improvements, (if road improvements do in fact become feasible). I would like to get some specific information on exactly how much rainfall is producing what level of floodwater. I am primarily

DEPARTMENT OF PUBLIC WORKS
COUNTY OF HUMBOLDT

Elk River Road Flooding Survey

Please return by December 15, 2016 to:

Humboldt County Public Works
1106 Second Street, Eureka, CA 95501
c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	
Phone or E-mail	
How long have you lived In Elk River?	44 YEARS

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	ELK RIVER Rd + Wrigley Rd
2. How would you describe the severity of the flooding impacts?	☐ Inconvenient ☐ Minor Disruption ☒ Major Disruption ☐ Other:
3. How important is it to try to alleviate road flooding?	☐ Not important ☐ Somewhat important ☐ Moderately important ☐ Very important ☒ Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐ Never ☐ Once or twice ☒ Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	ALL 1 To 5 TIMES YES

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	1 To 3 dAYS 2" To 5'
7. How has road flooding changed over time?	
8. What project concepts are worth further evaluation?	☒ Road and bridge improvements ☒ Drainage improvements ☒ Alternative access routes: emergency access only ☐ Alternative access routes: emergency and non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments:

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(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	
Phone or E-mail	
How long have you lived In Elk River?	12 years

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	Berta Rd.
2. How would you describe the severity of the flooding impacts?	☐Inconvenient ☐Minor Disruption ☑Major Disruption ☐Other: ________
3. How important is it to try to alleviate road flooding?	☐Not important ☐Somewhat important ☐Moderately important ☑Very important ☐Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐Never ☐Once or twice ☑Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	Negatively impacts travel to work, School for my two children, & mail delivery, several times a year,

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	
7. How has road flooding changed over time?	
8. What project concepts are worth further evaluation?	☐ Road and bridge improvements ☐ Drainage improvements ☐ Alternative access routes: emergency access only ☐ Alternative access routes: emergency and non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments:

DEPARTMENT OF PUBLIC WORKS
COUNTY OF HUMBOLDT

Elk River Road Flooding Survey

Please return by December 15, 2016 to:

Humboldt County Public Works
1106 Second Street, Eureka, CA 95501
c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	
Phone or E-mail	
How long have you lived In Elk River?	17

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	Elk River Court
2. How would you describe the severity of the flooding impacts?	☐ Inconvenient ☐ Minor Disruption ☒ Major Disruption ☐ Other: ______
3. How important is it to try to alleviate road flooding?	☐ Not important ☐ Somewhat important ☐ Moderately important ☒ Very important ☐ Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐ Never ☐ Once or twice ☒ Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	Prevents me & my family from Leaving or getting home. Prevents emergency crews from assisting Happens every time there are heavy rains.

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - How deep is the water? - What are the key causes and factors that affect road flooding?	following heavy rains the road is not passable, w/ water levels reaching one plus feet flowing over the bridge itself. My opinion is that the flood waters affecting this Rd is influenced by the tide.
7. How has road flooding changed over time?	it seems to be happening more fregaently on a yearly basis with higher water levels
8. What project concepts are worth further evaluation?	☒ Road and bridge improvements ☐ Drainage improvements ☐ Alternative access routes: emergency access only ☐ Alternative access routes: emergency and non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments: Take Elk River Court on as a County Road!

DEC 1 5 2016

DEPARTMENT OF PUBLIC WORKS
COUNTY OF HUMBOLDT

Elk River Road Flooding Survey

Please return by December 15, 2016 to:

Humboldt County Public Works
1106 Second Street, Eureka, CA 95501
c/o Hank Seemann

(for an electronic version of this form, please e-mail hseemann@co.humboldt.ca.us)

Name	[redacted]
Address	[redacted]
Phone or E-mail	[redacted]
How long have you lived In Elk River?	9 years

1. Which road receives flooding that directly impacts you? (if more than one road, please complete a survey for each road)	Berta Rd.
2. How would you describe the severity of the flooding impacts?	☐Inconvenient ☐Minor Disruption ☒Major Disruption ☒Other: Also, after flooding, road greatly deteriorated
3. How important is it to try to alleviate road flooding?	☐Not important ☐Somewhat important ☐Moderately important ☐Very important ☒Extremely important
4. Has road flooding prevented you from traveling to and from your home?	☐Never ☐Once or twice ☒Several times
5. Please describe how road flooding impacts you. For example: - How does road flooding affect your access to work, school, mail service, medical resources, or other services? - How frequent are these impacts? - Does road flooding affect access	During our 9 years, it seems that Berta Rd floods every other year. When it floods, the flooding event can last 3 to 5 days. Only if you have a "lifted" truck can you possibly get out. We average 3 to 4 flooding events every other year. NO emergency services will come through the flooding event to reach our homes. Another serious affect:

6. Please share your observations on flooding patterns and the magnitude and frequency of flooding at this road. For example: - Where do the floodwaters come from? - How long is road access impacted by flooding? - ~~How deep is the water?~~ - What are the key causes and factors that affect road flooding?	The floodwaters come from 3 places: 1. From the east (from "Headwaters" area). 2. From our own immediate hillside. 3. Overspill from Elk River. Each flooding occurence last approximately 2 or 3 days at a minimum. Up to 5 days to drain completely. The water averages from 1 to 3 feet deep (depending on different locations). The key causes of flooding: no street drainage, no drainage systems for entire area of Elk River community, and natural drainage (tide) is very slow.
7. How has road flooding changed over time?	Over the 9 years, there appears to be little or No change.
8. What project concepts are worth further evaluation?	☒ Road and bridge improvements ☒ Drainage improvements ☒ Alternative access routes: emergency access only ☒ Alternative access routes: emergency <u>and</u> non-emergency conditions ☐ Roads should be left as-is, focus on the river only Comments:

Appendix B: 2022 Health and Safety Interview Questionnaire

Elk River Watershed Stewardship Program
Health and Safety Interview

Property Address:
APN(s):
Property Owner(s):
Phone Number:
Email Address:
Length of Residence/Ownership:

Flood Memo

Do you have any questions about the 100-year flood memo?

General

Have you observed any changes to the frequency and magnitude of flooding on your property over the last 5, 10, 20 years? If so, please describe.

What is the greatest challenge that flooding presents to your life?

Flood Insurance

Are you currently covered by a flood insurance policy?

Infrastructure

Structures

Have structures on your property flooded? Frequency, duration, levels?

Wastewater

Where on the property is your Onsite Wastewater Treatment System (OWTS) located? [*mark on image*]

Have you experienced any known OWTS failures due to flooding?

What solutions do you think will best address the impacts (if any) of flooding to wastewater on your property?

Drinking Water

What is the source of your drinking water: well, stream, other?

Do you have an existing water right? If so, please describe.

If groundwater well is used, do you know the depth-to-bottom and screened intervals?

If surface water intake:

Appendix C: Water Quality Trend Analysis

This appendix provides the full details for the water quality trend analysis of suspended sediment concentrations (SSC) and the severity of ill effects (SEV) from elevated SSC on salmonids. Readers and the target audience should have statistics or data analysis background and possess some familiarity with R computer programming. This appendix and their various attachments (i.e., raw data and additional code not documented here) should provide anyone with the appropriate skills and understanding to fully replicate the trend analysis.

The methods used and applied are a continuation of past work in the Elk River Recovery Assessment (ERRA) (California Trout et al, 2018). Broadly, this appendix has six sections that describe the steps needed: (1) code modernization; (2) updating precipitation data; (3) initial model selection; (4) final model selection; (5) trend analysis; and (6) SEV trend analysis. Sections (1) through (5) constitute a stepwise procedure for compiling and analysis of SSC samples and other data. Section (6) is a separate procedure altogether, because the SEV calculations are based on continuous SSC data—that is, data derived from turbidity-SSC rating curves as opposed to true lab samples.

1. Code modernization

As one of the tasks in the ERRA, Jack Lewis performed the suspended sediment concentration (SSC) trend analyses on Humboldt Redwood Company's (HRC) data for stations 509, 510, 511 or the mainstem, South Fork, and north fork of the Elk River, respectively. This analysis use methods developed in a Water Board funded grant to Salmon Forever, a non-profit organization that collected SSC, flow, and rainfall data from 2003 to 2013 in the Elk River as well as other watersheds draining into Humboldt Bay (California Trout et al., 2018; Lewis, 2013). Both Salmon Forever and the ERRA utilized R, an object-oriented programming (OOP) language for statistics and data science, along with third-party R "packages" that perform specific statistical methods, as well as custom code written by Lewis for his 2011 and 2017 analyses. Created in 1993, R as a tool for data science has progressed substantially over its lifetime (R Core Team, 2019). The most popular integrated development environment (IDE) software for managing R projects is RStudio (RStudio Team, 2022). The creators of RStudio have developed whole paradigms improving the legibility, reproducibility, and efficiency over "base" R. This paradigm is the `tidyverse`, which the creators call a "design philosophy" (Wickham et al., 2019) and includes a collection of R packages that replace base R functions as well as third party developers who follow the `tidy` paradigm. To ensure that future iterations or extensions of this TMDL data assessment proceeds smoothly and remains replicable, we first *tidy* Lewis's code.

Date and time objects in R

The largest difference between the 2013/2017 (henceforth "Lewis") code and the `tidy` version is the treatment of time. The Lewis code utilized the `chron` package, which supported basic datetime objects[16] with methods that generated various components of a date-time stamp (timestamp). For example `chron::hours()`[17] and `chron::minutes()` are functions that return the hour and minute of an input timestamp. The issue with `chron` timestamp objects is that they do not conform to Portable Operating System Interface (POSIX) standards for defining date and time in computational contexts. POSIX standards are specified by the Institute of Electrical and Electronics Engineers (IEEE) Computer Society (IEEE, 2001). One concrete example is that `chron` does not include information about time zones or daylight savings time, which are important details when handling time series data, particularly when combining datasets that are collected or recorded using different time zones. The first step, then, is to convert the Lewis timestamp data.

We first load the various R packages within `tidyverse` as well as `lubridate` and `chron`. `lubridate` is a package that provides `tidy`-style functions for handling timestamp data objects. To "pick up" where Lewis left off, we load in the `*.RData` binary file containing all objects created by Lewis for the 2017 analysis. For time conversion we use Coordinated Universal Time (UTC) minus 8 hours or UTC-8; this convention was formerly known as Greenwich Mean Time (GMT), centered at Greenwich in the United Kingdom. To simplify the dataset and avoid missing values, Daylight Savings Time (DST) changes are ignored. UTC-8 is equivalent to permanent Pacific Standard Time.

Automated data loggers usually do not adjust for DST. When processing timestamp data in R and POSIX, the time zone must be included. If no timezone is defined, R will assume a local time that may include DST, which results in dropped observations. For example, the timestamp 2016-03-13 02:00 does not officially exist for California local time, because that hour jumps to 03:00 to start Pacific Daylight Time (PDT). The timestamps for raw data do not skip to 03:00 and ignores DST. Thus, UTC-8 is the appropriate timezone for these data as it ignores DST and avoids having observations removed when data are imported into R. R uses various character strings to represent time zones, based on Eggert & Parenti (2022). `Etc/GMT+8` represents UTC-8 despite the signs (`+` instead of `-`) being the opposite.

```
library(tidyverse)
library(here)
library(glue)
library(fs)
library(lubridate)
library(chron)
tzone <- 'Etc/GMT+8'

Lewis_2017 <- here('studies/2017_Lewis_ERRA/Trend analyses')
load(path(Lewis_2017, '.RData'))
```

We start with the data objects contained within the `*.RData` file and extend them with comma separated value (CSV) text files containing the raw data. The ERRA revised the HRC hydrology and SSC datasets, but that work only covered Water Year (WY) 2003 through WY2015. The original discharge values produced better model fits than the revised version, so we use the original hydrology throughout the data assessment. The code block below generates and

[16] "Objects" in OOP are computational elements that contain data and code, which can be used by certain methods or functions that change or manipulate the object (Kindler & Krivy, 2011)

[17] The `::` syntax indicates package that provides the function.

applies a function that *tidy* Lewis code, objects, and their names. The block also checks for any differences between the two timestamp data objects–a value of zero mean they are equal.

```
generate_new_df <- function(stn, in_dir, out_dir, tzone, save = TRUE){
  hrc_2017 <- glue('hrc{stn}') %>% str2expression %>% eval
  raw_fname <- glue('HRC{stn} SSC w NHE discharge all years.csv')
  # dts = date time stamp
  hrc_new <- read_csv(file = path(in_dir, raw_fname),
                      show_col_types = F) %>%
    mutate(dts = parse_date_time(date.time, 'm/d/y H:M:S', tzone),
           .before = 1)
  names(hrc_new)[-1] <- c('Local', 'qOrig', 'qNHE', 'ssc')
  hrc_new <- hrc_new %>% select(dts, Local, qOrig, ssc)
  # Compare dates between chron package and POSIX format
  hrc_2017$chr <- hrc_2017$chr %>% as.character %>%
    parse_date_time('m/d/y H:M:S', tzone)
  idx_new <- which(hrc_new$dts %in% hrc_2017$chr)
  nmis <- sum( ! hrc_new$qOrig[idx_new]  == hrc_2017$q.orig, na.rm = T)
  # nmis should equal 0 if all goes to plan
  cat(glue('\n{nmis} values different between RData and CSV for {stn}\n\n'))
  # convert date times to characters when writing to file
  hrc_out <- hrc_new %>%
    mutate(UTC = strftime(dts, '%Y%m%d%H%M', tz = 'UTC'),
           Local = strftime(dts, '%Y-%m-%d %H:%M UTC-8', tz = tzone),
           .before = 1) %>% select(-dts)
  out_fpath <- here(out_dir, glue('HRC{stn}_2003-2015_Q_SSC.csv'))
  if (save) write_csv(hrc_out, out_fpath, na = '')
  return(hrc_new)
}
stns_dfs <- c(509:511) %>% map(
    ~generate_new_df(.x, in_dir = here('data/Lewis'),
                     out_dir = here('data/HRC'),
                     tzone = 'Etc/GMT+8'))

0 values different between RData and CSV for 509
0 values different between RData and CSV for 510
0 values different between RData and CSV for 511
```

Comparing Lewis and *tidyverse* functions

Now that the data are consistent with *tidy* convention, we do the same to the Lewis functions. We create a function that calculates and matches antecedent precipitation index (API) to an SSC sample's timestamp, rounded to the earliest hour (i.e., at the beginning of the hour for the observation datum). The Lewis and *tidy* functions are *get.hapi* and *hourly_api*, respectively. One complicating factor is that many R packages use the same names for different functions, and whichever package loads last will "mask" the previous package's function. To address this issue, we first unload *tidyverse*, use the Lewis function, then re-load *tidyverse*. The exception is the *api* function which does not depend on either *tidyverse* or Lewis; however, *filter* is called within *api* and is a very common function name. We rewrite *api* and make it explicit with *stats::filter*, which is the only change from the Lewis version.

```
api <- function (ppt, decay) {
  as.vector(stats::filter(ppt, decay, method = 'recursive'))
}
```

```r
detach(package:tidyverse, unload = T)
lewis17_hapi86hrc509 <- get.hapi(hrc509$chr, hppt, decay = 0.86)
lewis17_hapi95hrc510 <- get.hapi(hrc510$chr, hppt, decay = 0.95)

library(tidyverse)
hourly_api <- function(hppt, decay, prefix = '', api_only = F,
                       origin_dt = '2002-01-01 00:00') {
  hppt <- hppt %>% as.data.frame %>% 'names<-'(c('dts', 'ppt'))
  origin_dt_days <- origin_dt %>% parse_date_time('Y-m-d H:M') %>%
    as.numeric %>% '/'(60*60*24) # convert to days
  hppt$days <- hppt$dts %>% as.numeric %>% '/'(60*60*24) %>%
    '-'(origin_dt_days)
  colname <- sprintf('%.2f', decay) %>% str_replace('0\\.|\\.', '')
  hppt_out <- decay %>% 'names<-'(colname) %>%
    map_dfc(~api(hppt$ppt, .x)) %>%
    'names<-'(glue('{prefix}api{colname}')) %>%
    cbind(hppt, .)
  if (api_only) {
    return(hppt_out %>% select(contains('api')))
  } else {
    return(hppt_out)
  }
}

tidy_hppt <- data.frame(dts = names(hppt), ppt = as.numeric(hppt)) %>%
  mutate(dts = parse_date_time(dts, '(m/d/y H:M:S)', tzone))
tidy_hapi <- hourly_api(tidy_hppt, c(.86, .95))
dts_seq <- seq(tidy_hppt$dts[1], last(tidy_hppt$dts), by = 'hour')
hrc_dts <- list(
  `509` = parse_date_time(as.character(hrc509$chr), '(m/d/y H:M:S)', tzone),
  `510` = parse_date_time(as.character(hrc510$chr), '(m/d/y H:M:S)', tzone)
)

# No need for extra function to get hourly api for q/ssc observation timestamps
# We can just use lubridate::floor_date and match the rounded timestamp to the
# continuous timestamp vector
hapi_idx <- hrc_dts %>% map(~floor_date(.x, unit = 'hours')) %>%
  map(~match(.x, dts_seq))

# Tidy outputs
tidy_hapi86hrc509 <- tidy_hapi$api86[hapi_idx$`509`]
tidy_hapi95hrc510 <- tidy_hapi$api95[hapi_idx$`510`]
```

Now let’s see how the two examples compared by using the `all.equal` function, which will return `TRUE` if they are the same:

```r
all.equal(tidy_hapi86hrc509, as.vector(lewis17_hapi86hrc509))
[1] TRUE
all.equal(tidy_hapi95hrc510, as.vector(lewis17_hapi95hrc510))
[1] TRUE
```

All `TRUE` means we can proceed with the rest of the data processing and analysis using `tidyverse` style and conventions.

North Coast Regional Water Quality Control Board
August 2022

Update HRC datasets

HRC has had relatively high turnover with their hydrology staff. The turnover resulted in hydrology and sediment data being delivered to the Regional Water Board in different file formats. We start in WY2016, where Lewis left off. For WY2016, each station has several Microsoft Excel files containing files related to stream flow measurements; sediment samples and loads; and continuous data estimated from proxy variables (stage and turbidity for discharge and SSC, respectively). We change the names of columns and sheets for the Excel files so as to process the data more efficiently; no change to the actual data values were performed. For 2017 and later, the data follow a regular format with CSV files for continuous flow and SSC. Data compilation for these WYs were automated with the `get_Q_SSC_wy1720` function. In general data are unmodified from files submitted to the Regional Water Board with the exception of the following:

- Timestamps are in UTC-8 or permanent Pacific Standard Time to avoid losing observations
- SSC samples with missing or incorrectly entered (e.g. 1900-01-01 00:00) timestamps were dropped
- Some years have missing SSC sample data, but data were provided by HRC staff after personal communication
- Various edits to data files so that R does not encounter errors when reading into memory. Specifically:
  - Merged 2016 SSC samples spreadsheet (`Station_511_Samples_WY2017.xlsx`) with the main spreadsheet for WY2016 (`Station_511_Sediment_Yield_WY2016.xlsx`). The main WY2016 Excel did not have a sheet for SSC samples like other WYs formatted in Excel.
  - Removed `DateTime` for WY2017 and WY2019 data because columns `Date` and `Time` were already present.
  - Removed empty column 7 in WY2017, Station 509 continuous data file
  - Removed empty rows 96 - 113 in WY 2019, Stations 509 and 510

Because HRC data from 2017 to the present follow a regular format, we can create a function to automate importing HRC hydrology data into R.

```
get_Q_SSC_wy1720 <- function(data_path, stn, wy, tzone) {
  cat(glue('\n{wy}\n\n'))
  stn_path <- path(data_path, glue('WY_{wy}'), glue('Data/Elk_River/{stn}'))
  ssc_path <- path(data_path, glue('WY_{wy}/{stn}{substr(wy, 3, 4)}_SSC.csv'))
  q_path <- path(data_path, glue('WY_{wy}/{stn}_ContinuousData.csv'))

  ssc <- read_csv(ssc_path, col_types = 'cn', show_col_types = F) %>%
    'names<-'(c('dts', 'ssc')) %>%
    mutate(dts = parse_date_time(dts, 'm/d/Y H:M', tzone))
  q <- read_csv(q_path, col_types = 'cc', show_col_types = F)
  if ('DateTime' %in% names(q)){
    q <- q %>%
      mutate(dts = parse_date_time(DateTime, 'Y/m/d H:M:S', tzone))
  } else {
```

```
    q <- q %>%
      mutate(DateTime = paste(DATE, TIME)) %>%
      mutate(dts = parse_datetime(DateTime, locale = locale(tz = tzone)))
  }
  q_out <- q %>% rename(qOrig = FLOW, ssc = SSC) %>% select(dts, qOrig)
  q_ssc <- right_join(q_out, ssc, by = 'dts') %>%
    mutate(UTC = strftime(dts, '%Y%m%d%H%M', 'UTC'),
           Local = strftime(dts, '%Y-%m-%d %H:%M UTC-8', tzone), .after = dts)
  if (nrow(q_ssc) != nrow(ssc) ){
    missing_dts <- ssc$dts[ssc$dts %in% q$dts]
    cat(glue('\nWY{wy} Missing these dates:\n'))
    cat(as.character(missing_dts) %>% paste0(collapse = '\n'))
    cat('\n')
  }
  return(q_ssc)
}
```

The next code block combines, by station, data from 2003-2015 (extracted from Lewis `*.Rdata` and written as a CSV), the 2016 spreadsheet, and the regular CSV files from 2017 onward. We then export the combined dataset as CSV.

```
stns <- c(509, 510, 511)
tzone <- 'Etc/GMT+8'
for (stn in stns) {
  hrc_wy0315 <- read_csv(here('data', glue('HRC/HRC{stn}_2003-2015_Q_SSC.csv')),
                   show_col_types = F) %>%
    mutate(dts = parse_date_time(UTC, 'YmdHM', 'UTC'), .before = 1) %>%
    mutate(dts = with_tz(dts, tzone))

  ssc_path <- here('data/HRC/WY_2016',
                   glue('Station_{stn}_Sediment_Yield_WY2016.xlsx'))
  ssc_coltypes <- c('date', rep('numeric', 3))
  wy16ssc <- read_excel(ssc_path, sheet = "SSC_Samples") %>%
    select(DateTime, SSC) %>% rename(dts = DateTime, ssc = SSC) %>%
    mutate(dts = force_tz(dts, tzone))
  q_path <- here(glue('data/HRC/WY_2016/Station_{stn}_QAQC_WY2016.xlsx'))
  q_coltypes <- c('numeric', 'date', 'text', rep('numeric', 10), 'text')
  wy16q <- read_excel(q_path, sheet = 'All_Data', col_types = q_coltypes) %>%
    select("DateTime", "Discharge (cms)") %>%
    rename(dts = DateTime, qOrig = `Discharge (cms)`) %>%
    mutate(dts = force_tz(dts, tzone))
  wy16 <- inner_join(wy16ssc, wy16q, by = 'dts') %>%
    mutate(UTC = strftime(dts, '%Y%m%d%H%M', 'UTC'),
           Local = strftime(dts, '%Y-%m-%d %H:%M UTC-8', tzone), .before = 2) %>%
    relocate(ssc, .after = qOrig)
  hrc_with_wy16 <- rbind(hrc_wy0315, wy16)

  hrc <- 2017:2020 %>%
    map_dfr(~get_Q_SSC_wy1720(here('data/HRC'), stn, .x, tzone)) %>%
    rbind(hrc_with_wy16, .) %>% select(-dts)
  write_csv(hrc, here(glue('data/HRC{stn}C_QSSC_WY03-WY20.csv')), na = '')
}
```

While we recommend using the processed data for further analysis, readers may request the raw data and follow this process for replication and validation.

North Coast Regional Water Quality Control Board
August 2022

2. Update hourly precipitation

The Lewis 2013 analysis used two rain gauges: one located in Freshwater Creek watershed, managed by Salmon Forever, but no longer operating, and the other is operational and located on Woodley Island near Eureka ("EKA"), managed by the National Weather Service and affiliated entities[18] (NCEI, 2020). Precipitation and its influence on SSC are quantified with the antecedent precipitation index (API), which is a metric for soil moisture or wetness (Kohler & Linsley, 1951). API decays over time when no precipitation has occurred; that is, the influence of rainfall is greatest on the day it occurs, and the influence gradually reduces with subsequent days (or any other time step). Formally:

$$\text{API}_t = P_t + kP_{t-1} + k^2P_{t-2} + \cdots + k^mP_{h-m}$$

or

$$\text{API}_t = k\text{API}_{t-1} + P_t$$

Where:

- API_h is the antecedent precipitation index for time step *t*
- P_h is the rainfall for time step *t*
- *k* is a decay factor less than 1
- *m* is the number of observations before time step *t*

Calculating API requires a complete rainfall time series dataset (i.e., no gaps). Lewis 2013 imputed gaps with the EKA rain gauge. If no alternative gauges were available, then precipitation was assumed to be zero. Lewis 2017 utilized radar-based rainfall estimates produced by the National Center for Atmospheric Research (NCAR & DOC, 2000). NCAR mosaics radar estimates after bias correction with rain gauges into hourly time series for the continental United States (CONUS). Reliable NCAR data start in 2001 and continues to the present time. NCAR provides two precipitation datasets: "Stage II" (ST2) and "Stage IV" (ST4). The main difference between the two is that ST4 has manual QAQC steps. Unfortunately, our area of interest in Humboldt County did not seem to receive this manual QAQC as early ST4 data have significant accuracy issues, particularly between 2001 and 2010. Lewis 2016 used ST2 exclusively, but for this Data Reassessment, we combine ST4 and ST2 together and also include one additional dataset.

Managed by Iowa State University, the Iowa Environmental Mesonet (IEM) is a re-analysis of NCAR data (Department of Agronomy, 2020). IEM estimates are available as a web service[19] in which users provide geographic coordinates and a timestamp, and the IEM web service returns hourly or daily precipitation along with other meteorology estimates such as barometric pressure and air temperature. We use three precipitation datasets because the true value of hourly precipitation within the Upper Elk River watershed is unknown. Keeping options open allows greater flexibility and acknowledges that precipitation at EKA is not representative of the Upper Elk River watershed.

[18] https://www.ncdc.noaa.gov/cdo-web/
[19] http://mesonet.agron.iastate.edu/iemre/

Procedure

The general procedure for pre-processing precipitation data for use in statistical modeling has the following steps:

1. Acquire and compile any available hourly precipitation gauge data from EKA. While the gauge data will not be used by themselves for statistical modeling, they are useful for screening out any anomalous values in the other datasets.
2. Acquire and process ST2 and ST4 data, whose raw forms are georeferenced raster grids for the entire CONUS. Each hour has its own raster and that means over 150,000 individual raster files for the time period WY2003 through WY2020. Data extraction for the Elk River watershed geographic area done using GIS methods written in several R scripts. While Lewis 2017 already went through the processing steps for 2003-2015 ST2/ST4 datasets, code modernization requires redoing the entire period.
3. Query and acquire IEM estimates using ST2 NCAR grid centroids. Along with being a candidate precipitation dataset for statistical modeling, IEM is useful for imputation when neither gauge nor NCAR data are available. The IEM dataset is complete and has no gaps.
4. Compile the three datasets into comma-separated value (CSV) files, imputing where necessary. The output CSV files contain a complete precipitation time series with no gaps.

The remainder of this section contains descriptions of the R scripts and what they do. The scripts run sequentially, but manual inspection of inputs and outputs is still necessary.

Scripts

1. `compile_ppt_Gage.R`

`compile_ppt_Gage.R` gathers rain gauge data from EKA and produces a single CSV with six fields–three for timestamps and three for precipitation measurements. The timestamp fields are for three different time zones. *`UTC`* is formatted as YYYYMMDDHH; *`Local`* is YYYY-MM-DD HH:DD UTC-8 or permanent Pacific Standard Time (PDT); and *`DST`* is YYYY-MM-DD HH:DD PST or Pacific Daylight Time (PDT), depending on whether DST is in effect. *`UTC`* is necessary because NCAR timestamps are based on UTC and must be converted to local time. Two entities collect and store measurements from EKA with different time spans and frequencies; they are the Cooperative Observer Program (*`COOP`*), a citizen weather observer network managed by the National Weather Service and the US Army Corps of Engineers, whose *`WBAN`* network stands for Weather-Bureau-Army-Navy. WBAN data contain measurements described as “trace” amounts of rainfall and recorded as 0.0001 inches. *`EKA`* combines the *`COOP`* and *`WBAN`* datasets, including what was compiled for Lewis 2013. NWS-COOP hourly data collection ended on November 2016, but WBAN continues to provide hourly measurements to the present day. Aside from trace rainfall, the two datasets are nearly identical.

```
gage_ppt <- read_csv(here('data/ppt_out/Gage_PPT_WY03-WY20.csv'),
                     col_types = 'cccnnn')
r <- cor(gage_ppt$COOP, gage_ppt$WBAN, use = 'pairwise') %>%
  sprintf('%.3f', .)
ggplot(data = gage_ppt, aes(x = COOP, y = WBAN)) +
  geom_point() + theme_classic() +
```

```
  annotate(geom = 'text', x = 0.2, y = 0.6, size = 5,
           label = glue("Pearson's r = {r}"))
```

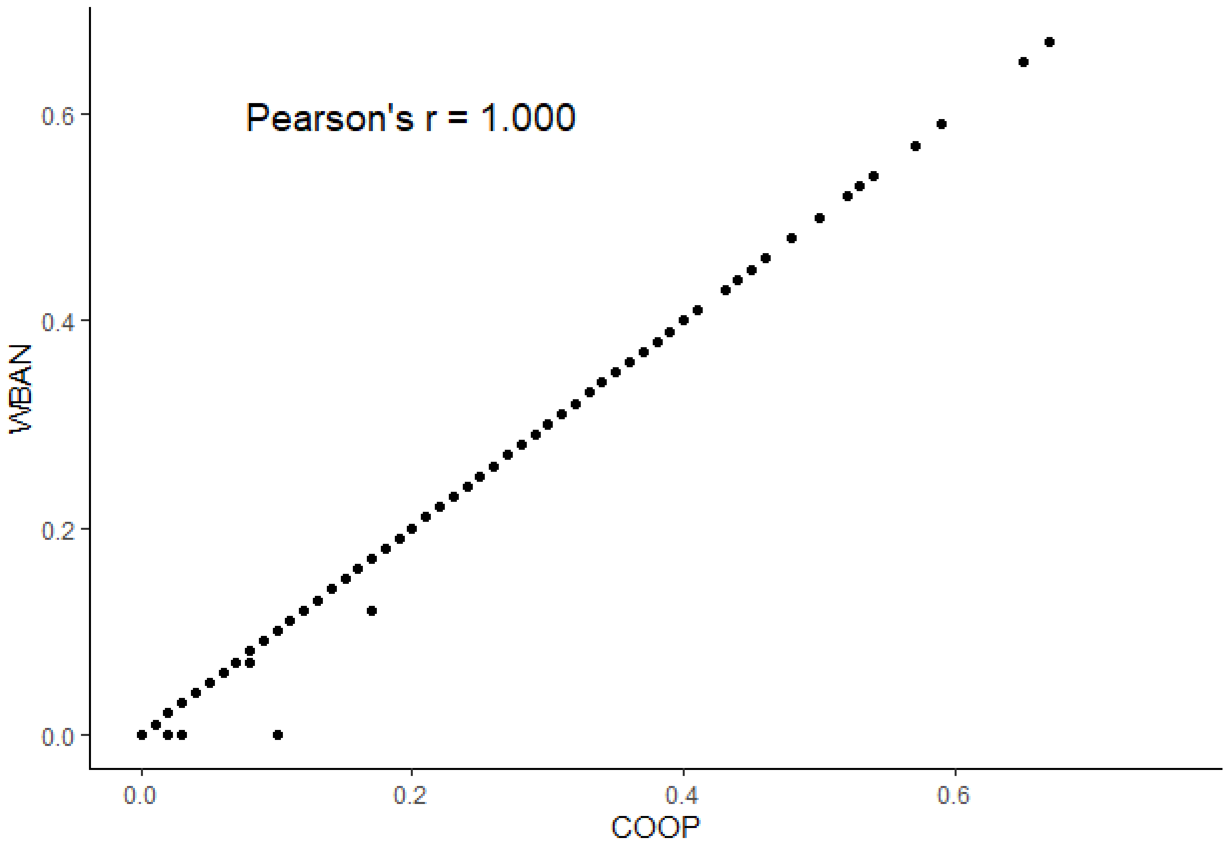


***Figure 1**: Correlation between WBAN and COOP hourly precipitation data*

2. `unzip_ncar.R`

`unzip_ncar.R` processes raw file from NCAR and outputs Gridded Binary (GRIB) files, which are georeferenced raster datasets designed for meteorological and climatic data. GRIBs are bundled into archival file formats (*.Z; *.zip), organized by month and year. Each GRIB is a time step, ranging between hourly to daily totals. This script calls the *7zip* (Pavlov, 2022) archival file manager program and extracts the relevant GRIBs to screen out non-hourly time steps. The script automates the unzipping process and assumes that all GRIBs have the same file name convention. However, filename conventions actually vary through the years and manual checking to adjust for changes in convention is necessary. This script runs on a command-line interface and *not* in an RStudio or another R IDE. Unless modified, the script can only process files from a directory that contains a sub-directory structure *`data/NCAR/{dataset}/{year}`*, where *`{dataset}`* is either ST2 or ST4 and *`{year}`* is the sub-folder that contains all zip archives. After navigating to the project directory, an example of the script execution would be:

```
Rscript code\unzip_ncar.R -y 2010 -e 'Grb' --dataset ST2 --threads 6
```

`Rscript` calls R and runs the script with the following parameters: year (*`-y 2010`*); file extension (*`-e Grb`*); dataset (*`-d ST2`*); and number of threads for multiprocessing (*`-t 6`*). The last parameter is optional, but greatly decreases processing time.

3. `extract_ncar_ppt.R`

`extract_ncar_ppt.R` takes in a shapefile and file path containing unzipped GRIB files. The outputs are hourly precipitation for each GRIB and arranged as rows in an CSV. The script produces two files containing: (a) the location or index of a raster cell that overlaps the shapefile and (b) the precipitation value for that raster cell. The index is based on the grid centroids (dots on Figure 2). This script assumes the GRIBs are consistently formatted and have the same dimensions and coordinate reference system (CRS).

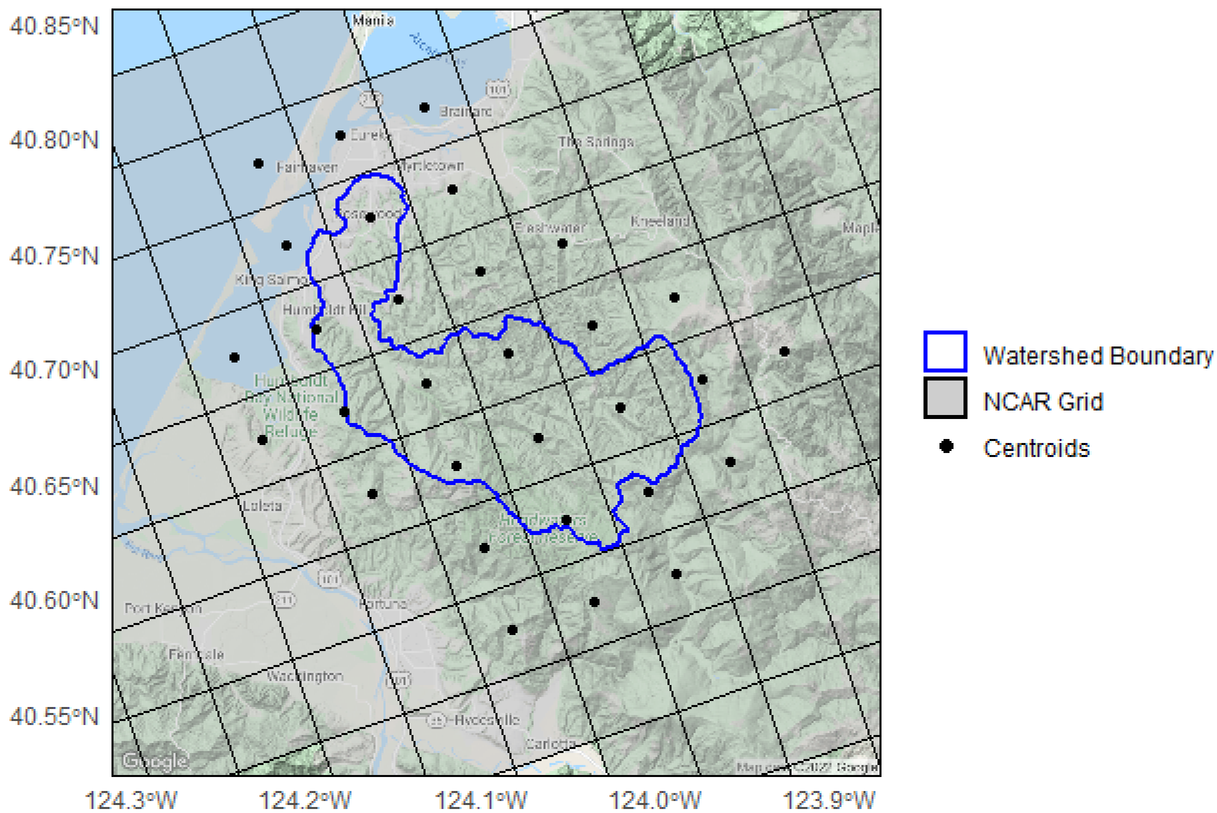


***Figure 2**: Map of NCAR grid cells and centroids in Upper Elk River*

This script must also run in a command-line or console interface after unzipping all GRIBs. Example:

```
Rscript code\extract_ncar_ppt.R -y 2010 -d ST2 -o data_outputs -p Elk.shp
```

The script has more parameters, but year (`-y`), dataset (`-d`), output directory (`-o`), and shapefile (`-p Elk.shp`) are required. The shapefile is the watershed boundary. Assuming a coordinate reference system (CRS) with horizontal unit of meters, a buffer of five (5) kilometers is added to the boundary to cover all possible grid cells; the buffer parameter can be changed (e.g., `-b`).

4. `ST4_grid_changes.R` *and* `clean_NCAR_ST4_2004_2020.R`

Calendar years 2004 and 2020 for the ST4 dataset have GRIBs that do *not* follow the same formats assumed in `extract_ncar_ppt.R`. These GRIBs have different raster extents; that is, the grid centroids have all geographically “shifted” (see Figure 3). Consequently, the indices for these GRIBs need adjusting in the outputs from `extract_ncar_ppt.R`. NCAR ST4 data from 2002 through 2020 have a total of three grids:

- `2002-01-01 00:00 UTC` through `2004-05-10 00:00 UTC`
- `2004-05-10 01:00 UTC` through `2020-07-19-23:00 UTC` (same as all ST2 data)
- `2020-07-20 00:00 UTC` and later

NCAR also switched to a new file type standard in the later years (*.grb to *.grb2) and this, among other issues, explains the geographic shift. These two scripts detect where and when the shift occurs and cleans the data to be consistent with the main GRIB extent.

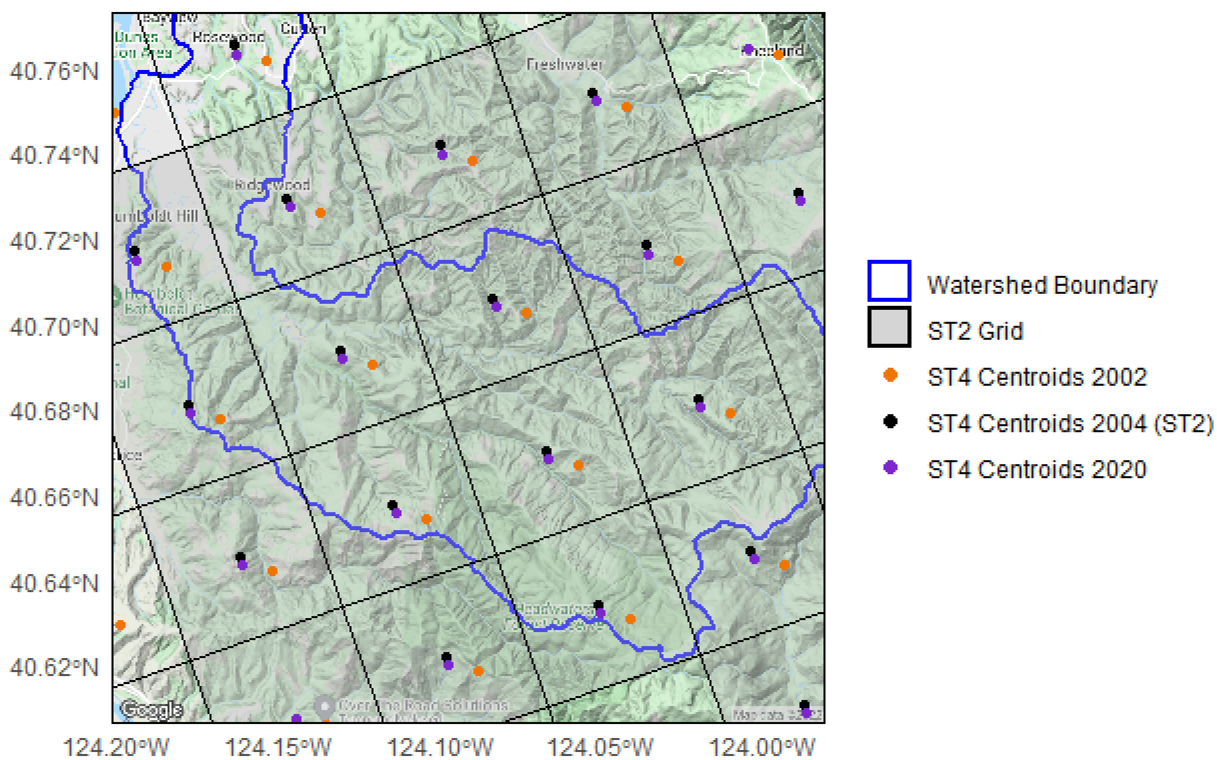


Figure 3*: Map of different grid points for different years in NCAR datasets*

5. `compile_ppt_NCAR_ST2.R` *and* `compile_ppt_NCAR_ST4.R`

Both of these scripts produce continuous precipitation time series from their respective datasets; however, the scripts are not identical. `compile_ppt_NCAR_ST2.R` merges the ST2 data compiled for the 2017 analysis with ST2 data extracted for years 2016 through 2020. `compile_ppt_NCAR_ST4.R` starts from 2003 and accounts for the GRIBs’ geographic shifts. Both scripts also generate additional statistics such as annual sums and extent of data gaps.

6. `grab_iemre.R` *and* `compile_ppt_IMERE.R`

These two scripts acquire and process the IME dataset. *`grab_iemre.R`* must run in a command-line interface. The user provides the geographic coordinates; start and end dates; and time resolution. The script queries the IEM web service with these parameters. A single query returns data for a specific timestamp. Given the start and end dates, this script runs queries for each time step. To speed this process up for long time periods (i.e., hourly data for calendar years 2003-2020), the user may turn on multiprocessing, allowing multiple, simultaneous queries. Example:

```
Rscript code/grab_iemre.R -y 40.693675 -x -124.130694 -s "2020-09-30" -e "2020-10-01"
-t "hourly" -o "m406948" -m TRUE -w 6
```

`-x` and *`-y`* are the longitude and latitude in decimal degrees, respectively; *`-s`* and *`-e`* are the start and end dates, respectively; *`-t`* is the time step; *`-o`* is output file name; and *`-m`* and *`-w`* control multiprocessing–*`-m`* accepts a boolean value and *`-w`* is an integer for number of threads.

`compile_ppt_IMERE.R` compiles the IEM query results and generates an output CSV consistent with the format of *`compile_ppt_Gage.R`*'s outputs.

7. `impute_NCAR.R`

This script imputes gaps in ST2 and ST4 datasets with gauge and IME datasets, with preference going to gauge. The script also replaces ST4 data with ST2 where there are substantial anomalies. These anomalies are centered in the Humboldt Bay area and the cause is not known nor documented in the NCAR metadata. Consequently, the ST4 dataset is a combination of ST2 and the original ST4. An example of the anomaly is shown below in Figure 4. Precipitation is zero everywhere except in the circle of grids. ST2 data for the same date do not show any precipitation in the same area.

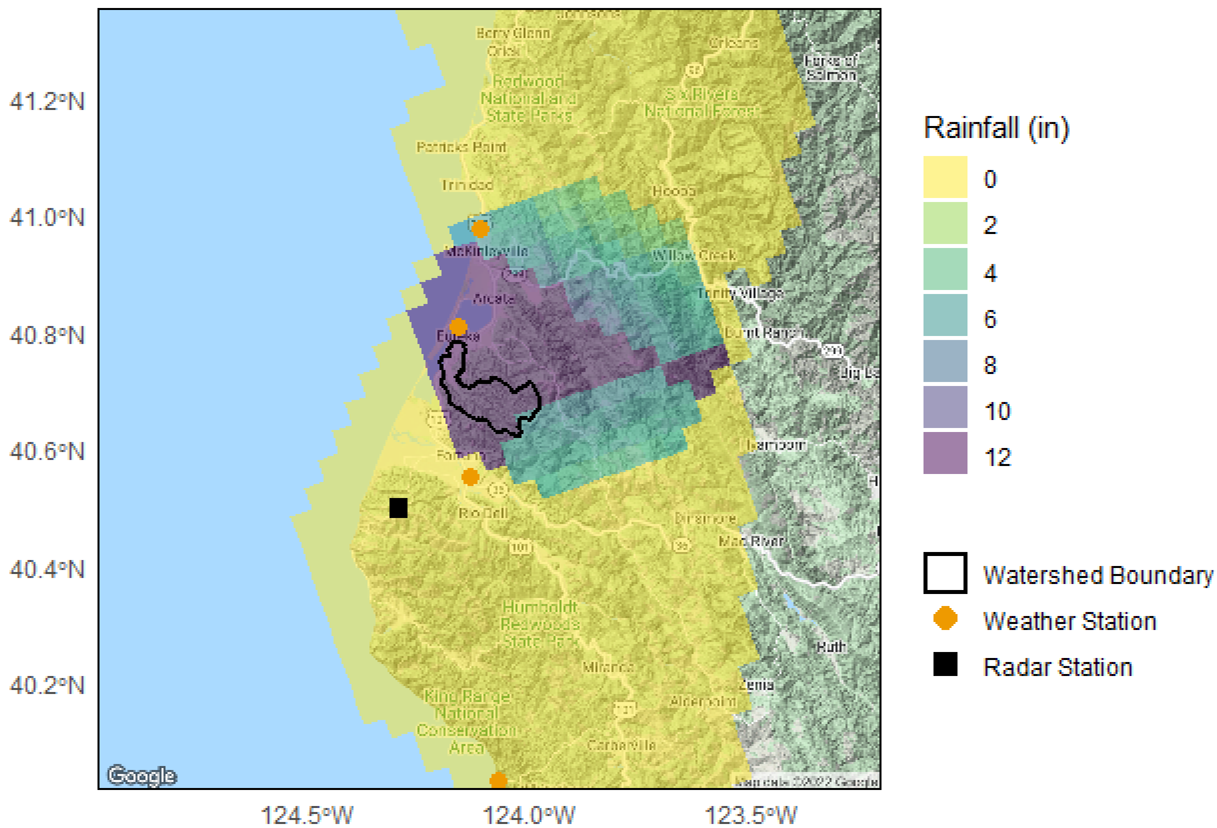


Figure 4: *Map of anomalous ST4 data*

8. `build_ppt_HRC.R`

This is the final script for producing precipitation data for use in statistical modeling. The statistical model only needs only one API covariate, but there are three datasets available. IEM only provides point estimates, so the simple average of all the points that lie within a monitoring station's catchment area constitute the IEM precipitation time series. ST2 and ST4 are gridded datasets and the catchments will have different fractions of the grid cells (see Figure 5 below). ST2 and ST4 each have two time series: one based on a simple average (`sm`) like IEM and another using a weighted average (`wm`) based on grid cell area fraction. In total this script produces five options for rainfall data.

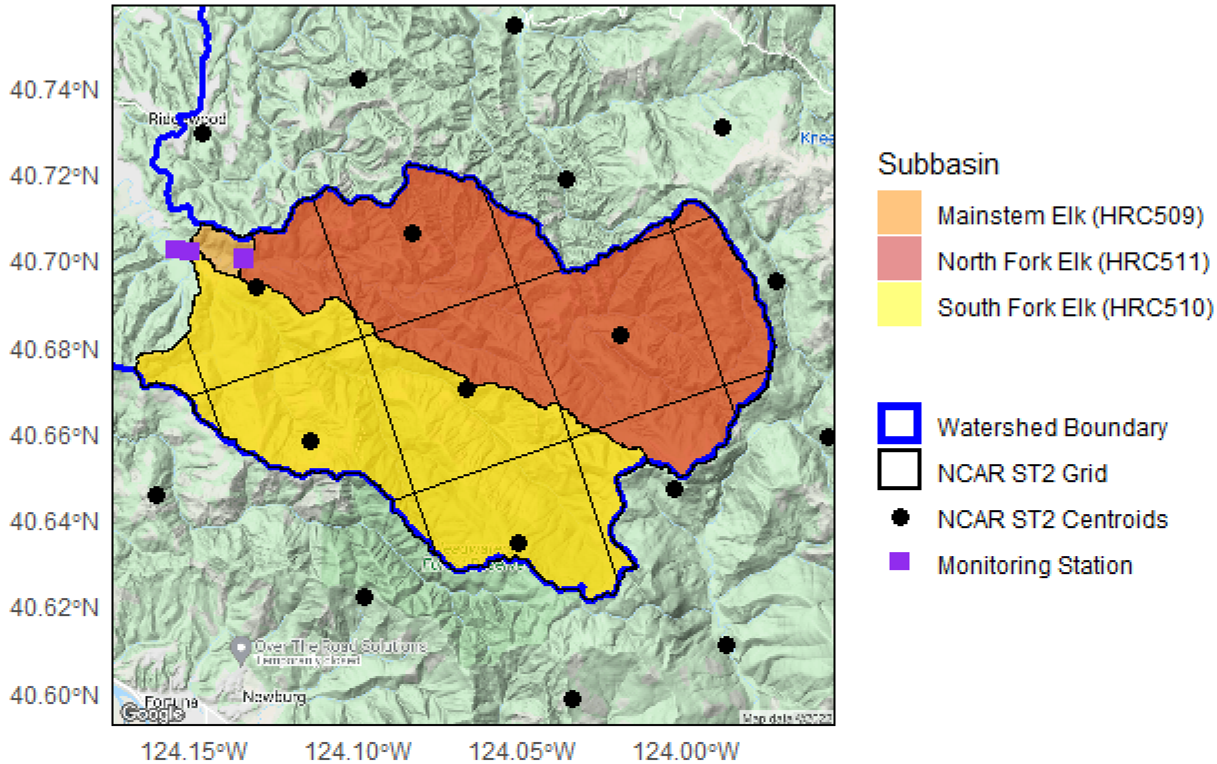


Figure 5: *Map showing area fraction of grid cells in monitoring station catchments*

The end result is the following CSVs and when read into R, they look like:

```
stn <- 509
# file names for updated hourly precipitation
hppt_fname <- glue('HRC{stn}_PPT_WY03-WY20.csv')
# Hourly precipitation and remove suffix indicating station
hppt_all <- read_csv(here('data', hppt_fname), col_types = 'ccc') %>%
  mutate(dts = parse_date_time(UTC, '%Y%m%d%H') %>%
           with_tz(tzone), .before = 1)
names(hppt_all) <- names(hppt_all) %>% str_replace_all(glue('{stn}'), '')

head(hppt_all) %>% select(-dts) %>% as.data.frame %>% flextable %>%
  set_caption('Precipitation data sample (inches)', style = 'Caption') %>% autofit
```

***Table 1**: Precipitation data sample (inches)*

WY	UTC	Local	ST2sm	ST2wm	ST4sm	ST4wm	IEMsm
2003	2002100108	2002-10-01 00:00 UTC-8	0	0	0	0	0
2003	2002100109	2002-10-01 01:00 UTC-8	0	0	0	0	0
2003	2002100110	2002-10-01 02:00 UTC-8	0	0	0	0	0
2003	2002100111	2002-10-01 03:00 UTC-8	0	0	0	0	0
2003	2002100112	2002-10-01 04:00 UTC-8	0	0	0	0	0
2003	2002100113	2002-10-01 05:00 UTC-8	0	0	0	0	0

3. Initial model selection

Lewis developed a multiple linear regression model with discharge, antecedent precipitation index (API), and linear time (days following the first observation) as covariates and suspended sediment concentration (SSC) as the response variable. The initial method for fitting the linear regression model was ordinary least squares (OLS). The model development process was progressive, adding one covariate in a stepwise fashion. Each step featured a regression model and diagnostic plots for the fitted model. Model development and covariate modifications continued until diagnostics showed that method's assumptions have been met. After finalizing the model "equation" or formula, Lewis addressed the issue of serial autocorrelation, the presence of which biases hypothesis testing and significance (i.e., artificially lower p-values). Autocorrelation was addressed using the generalized least squares (GLS) method. GLS adds additional model parameters to account for correlated errors. Estimating these parameters was an iterative process until the GLS model residuals no longer showed autocorrelation. After the GLS process, Lewis assessed the linear time coefficient and its p-value to determine statistical significant trends, along with plotting the regression residuals over time (with the linear time covariate removed).

Setting up R environment

Load in the required packages and set time zone UTC-8 or GMT-8. The `tidyverse` packages used extensively in this section are `ggplot2` for data visualization; `dplyr` for the data wrangling; and `purrr` for efficient iteration and improvements on the `apply` set of base R functions.

```
library(tidyverse)
library(lubridate)
library(here)
library(glue)
library(broom)
source(here('code/_functions.R')) # read in custom functions
tzone <- 'Etc/GMT+8'
NSE <- hydroGOF::NSE
```

Model selection criteria

For comparing models, we will use four goodness-of-fit (GOF) statistics or metrics: adjusted coefficient of determination (R^2); Nash-Sutcliffe model efficiency coefficient (NSE); Akaike information criterion (AIC); and Bayesian information criterion (BIC).

Adjusted R^2 accounts for the fact that R^2 naturally increases as covariates are added, and so adjusted R^2 penalizes a model if it has too many covariates (Leach & Henson, 2007). NSE is similar to R^2 and is commonly encountered in hydrologic modeling, but it has a range of $(-\infty, 1]$ while $R^2 \in (0,1)$ (Nash & Sutcliffe, 1970). For ordinary least squares (OLS) linear regression, NSE and R^2 are equivalent, so NSE is more applicable to cases where OLS does not apply; e.g. for time-series modeling using generalized least squares (GLS) regression, NSE can serve a similar purpose to R^2 for OLS.

AIC and BIC are both based on maximum likelihood and information theory, but BIC differs in giving greater penalties for additional terms (Stoica & Selen, 2004). Formally, AIC $= 2k - 2\ln\hat{L}$ and BIC $= k\ln(n) - 2\ln\hat{L}$, where $\hat{L}$ is the maximized likelihood function for the model; *n* is the sample size; and *k* is the number of model parameters.

Station HRC509

Hydrologic monitoring station 509 (HRC509) is located on mainstem Elk River just downstream of the North and South Fork confluence, but above the confluence with Railroad Gulch. The total catchment area is approximately 41.9 mi^2 (108.5 km^2) or 26,813 acres. HRC509 is located on the upper end of the impacted reaches' mainstem segments (Tetra Tech, 2015). In order of increasing proportion, the major geologic formations in catchment HRC509 are the Hookton Formation; Franciscan Complex Central Belt; Yager Formation; and Wildcat Group. All of these formations are prone to instability and are either composed of or can weather into fine sediment. HRC509 catchment contains the majority of HRC-owned timberlands within the Elk River watershed. The Hookton Formation makes up a majority of the lower Elk River, and this geologic unit is derived from shallow marine and fluvial deposits. The Wildcat Group is the dominant geologic setting and composed of poorly to moderately consolidated siltstone and fine-grained silty sandstone.

Because code is reused in the same manner for each of the stations, their initial instances will only be shown once.

Read in data and pre-process for model fitting

First, pick a station and read in data. We will use the original discharge values as provided by HRC hydrology staff. The code below prepares all the data needed to fit a regression model.

```
stn <- 509
# file names for updated hourly precipitation, flow, and SSC data tables
hppt_fname <- glue('HRC{stn}_PPT_WY03-WY20.csv')
qssc_fname <- glue('HRC{stn}_QSSC_WY03-WY20.csv')
# Hourly precipitation and remove suffix indicating station
hppt_all <- read_csv(here('data', hppt_fname), col_types = 'ccc') %>%
  mutate(dts = parse_date_time(UTC, '%Y%m%d%H') %>%
           with_tz(tzone), .before = 1)
names(hppt_all) <- names(hppt_all) %>% str_replace_all(glue('{stn}'), '')
# Flow and SSC, adding Water Year and date-time (POSIX)
```

```
qssc <- read_csv(here('data', qssc_fname), col_types = 'ccnnnn',
                 show_col_types = F) %>%
  mutate(dts = parse_date_time(UTC, 'YmdHM') %>% with_tz(tzone),
         .before = qOrig) %>%
  mutate(WY = get_WY(dts, tzone), .before = UTC)
# Entire hourly timestamps with no gaps for WY2003 trough WY2020
dts_all <- hppt_all$dts
decay_rates <- seq(.80, .90, .01) # decay rates for API calculation
decay_names <- sprintf('%.2f', decay_rates) %>% str_replace('0\\.|\\.', '')
ppt_all <- hppt_all %>% select(contains('sm'), contains('wm'))
ppt_names <- names(ppt_all)
# Calculate APIs for each ppt dataset with decay rates ranging from 0.80 to
# 0.90 at 0.01 intervals
hapis_all <- map2_dfc(ppt_all, ppt_names, ~hourly_api(
  data.frame(dts = dts_all, ppt = .x), decay_rates, .y, api_only = T))
# Add to discharge, SSC data frame by hour before SSC sample taken
hapi_idx <- qssc$dts %>% floor_date(unit = 'hours') %>%
  match(dts_all)
# Combine and remove all non-zero to avoid invalid log transforms
hrc_all <- hapis_all[hapi_idx, ] %>% cbind(qssc, .) %>%
  subset(qOrig > 0 & ssc > 0) %>% merge_dups_multi('dts', 1:4) %>%
  mutate(t = as.numeric(dts)/(60*60*24), .before = ssc) %>%
  mutate(t_decyr = decimal_date(dts), sindoy = sin_doy(dts), .before = ssc) %>%
  arrange(dts) %>% 'row.names<-'(NULL)
```

Choose precipitation dataset and decay rate

Start OLS regression with stream discharge as the only covariate.

```
fit0 <- lm(log(ssc) ~ log(qOrig), data = hrc_all)
summary(fit0)


Call:
lm(formula = log(ssc) ~ log(qOrig), data = hrc_all)

Residuals:
    Min      1Q  Median      3Q     Max
-6.3093 -0.6022 -0.1232  0.5751  5.0782

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.77991    0.03395  111.33   <2e-16 ***
log(qOrig)   0.76414    0.01378   55.47   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.9409 on 2295 degrees of freedom
Multiple R-squared:  0.5728,    Adjusted R-squared:  0.5726
F-statistic:  3077 on 1 and 2295 DF,  p-value: < 2.2e-16
```

From the work performed in the updating precipitation section, we have five (5) options for antecedent precipitation index (API):

- `ST2sm`: simple average of NCAR ST2 grid cells intersecting a catchment

- *ST2wm*: weighted average of NCAR ST2 grid cells' value by cell area proportion
- *ST4sm*: simple average of grid cell values from modified NCAR ST4 dataset
- *ST4wm*: weighted average of NCAR ST4 grid cells' value by cell area proportion
- *IEMsm*: simple average of Iowa Environmental Mesonet dataset, estimated at ST2 grid cell centroids

API also requires a decay parameter *k* that must be less than one. To maximize our options for the API covariate, we use a range of decay coefficients from 0.80 to 0.90. Five datasets and eleven (11) decay rates yield fifty-five (55) possible API covariates. We add API one at a time to *fit0* and select the API that has the lowest AIC value.

```
ppt_api_formula <- paste0(glue('{rep(ppt_names, each = length(decay_rates))}'),
                          glue('api{rep(decay_names, length(ppt_names))}'),
                          sep = '') %>%
  paste0(collapse = ' + ') %>% glue('~', '. +', .) %>% formula
pptapi_fit_compare <- add1(fit0, ppt_api_formula)
pptapi_fit_compare %>% arrange(AIC) %>% head
Single term additions

Model:
log(ssc) ~ log(qOrig)
           Df Sum of Sq    RSS     AIC
ST2smapi86  1    615.61 1416.3 -1104.8
ST2wmapi86  1    614.61 1417.3 -1103.2
ST2smapi85  1    614.55 1417.3 -1103.1
ST2smapi87  1    614.11 1417.8 -1102.3
ST4wmapi86  1    613.86 1418.0 -1102.0
ST2wmapi85  1    613.58 1418.3 -1101.5
ppt_api <- which(pptapi_fit_compare$AIC == min(pptapi_fit_compare$AIC)) %>%
  row.names(pptapi_fit_compare)[.]
```

ST2 simple average with decay rate of 0.86 has lowest AIC. With that chosen, we pare down *hrc_all* and create a new data frame *hrc* that includes just the API we chose. Following Lewis, we linearize *api* by taking its square root.

```
hrc <- hrc_all %>%
  select(WY, dts, t, qOrig, glue('{ppt_api}'), sindoy, t_decyr, ssc) %>%
  rename(api := glue('{ppt_api}')) %>%
  mutate(sindoy = sin_doy(dts), t_decyr = decimal_date(dts), .before = t) %>%
  'row.names<-'(NULL)
```

Other covariates

The covariates Lewis defined linear time as the number days (plus their sub-daily fractions) after an origin date of 2002-01-01, but here we use decimal year (*t_decyr*). Decimal year scales linear time to the Gregorian calendar year plus the year fraction. For example:

t = January 30th, 2002 10:30AM = *2002-06-30 10:00*

If t_{start} = *2002-01-01 00:00* and t_{end} = *2003-01-01 00:00*, then:

$$
\begin{aligned}
t_{decyr} &= 2002 + \frac{t_{start} + t}{t_{end} - t_{start}} \\
&= 2002 + \frac{4{,}330 \text{ hrs}}{8{,}760 \text{ hrs}} \\
&\approx 2002.494
\end{aligned}
$$

The rationale for using decimal year instead of days is that the regression coefficient will have units of $\log(SSC) \cdot year^{-1}$ instead of $\log(SSC) \cdot day^{-1}$. These units are more convenient for expressing SSC change on an annual basis.

Another covariate is the calendar day of year (DoY). This covariate is not found in any of Lewis work but is another parameter that can control for SSC's seasonality, and thus produce a better fit. DoY covariate is intended to describe a cyclical process and should not be treated "as is" (i.e., values of 1, 2, …, 366). Instead, using a Fourier-like approach, calendar day is transformed with a sine function and defined as:

$$sindoy = \sin\left(2\pi \cdot \frac{d}{D}\right)$$

D is the total number of days in a year, which is 365 or 366 depending on the leap year status. *d* is the calendar day, e.g., *d* = 1 = January 1st. Usually, a Fourier transform includes a cosine component and Fourier analysis itself produces the frequency and phase shift parameters for the sine and cosine functions. However, to keep things simple and the fact that including the cosine component resulted in a poorer fit, we just use the sine component.

The rationale for adding `sindoy` is to include any other seasonal processes beyond precipitation (API) and the watershed response to precipitation (stream discharge). One conceptual drawback for including `sindoy` as a covariate is that calendar day is not explicitly linked to any natural process. Calendar day may instead capture anthropogenic processes such as timber harvest or residential activities (e.g., driving in flooded streets during storms).

We summarize the response and covariates dataset, including their log transforms, but drop `t` (linear time in days), `WY` (water year), and `dts` (timestamp), as they will not be used for model fitting. While `t_decyr` is used in model fitting, a summary of that variable will just be the summary of data record's decimal years (i.e. min = 2003, max = 2020, etc.). After, fit the initial set of models that add covariates in a step-wise fashion as done in Lewis.

```
hrc %>% select(-c(WY, dts, t, t_decyr)) %>% summary
```

```
     qOrig              api              sindoy             ssc
 Min.   :  0.001   Min.   :0.00000   Min.   :-0.9735   Min.   :   0.50
 1st Qu.:  3.620   1st Qu.:0.09025   1st Qu.:-0.2068   1st Qu.:  93.22
 Median :  9.484   Median :0.23628   Median : 0.3140   Median : 254.32
 Mean   : 14.388   Mean   :0.29916   Mean   : 0.2474   Mean   : 420.01
 3rd Qu.: 20.260   3rd Qu.:0.44966   3rd Qu.: 0.8395   3rd Qu.: 553.70
 Max.   :110.200   Max.   :1.34561   Max.   : 1.0000   Max.   :3779.00
```

```r
fit1 <- lm(log(ssc) ~ log(qOrig) + api, data = hrc)
fit2 <- lm(log(ssc) ~ log(qOrig) + I(api^0.5), data = hrc)
fit3 <- lm(log(ssc) ~ log(qOrig) + I(api^0.5) + sindoy, data = hrc)
fit4 <- lm(log(ssc) ~ log(qOrig) + I(api^0.5) + sindoy + t_decyr, data = hrc)
```

Summarizing the model fits:

```r
coeff <- rbind(coef(summary(fit1)), coef(summary(fit2)), coef(summary(fit3)),
               coef(summary(fit4)))
coeff <- coeff %>% as.data.frame %>%
  mutate(fit = c(rep(1, 3), rep(2, 3), rep(3, 4), rep(4, 5)),
         Coefficient = row.names(coeff), .before = 1) %>%
  'row.names<-'(NULL)
coeff[, 3] <- sprintf('%.4f', coeff[, 3])
coeff[, 4] <- sprintf('%.4f', coeff[, 4])
coeff[, 5] <- sprintf('%.2f', coeff[, 5])
coeff[, 6] <- coeff[, 6] %>%
  map_chr(~(if (.x > 2e-16) sprintf('%.2e', .x) else '< 2e-16'))
coeff
```

```
   fit Coefficient Estimate Std. Error t value Pr(>|t|)
1    1 (Intercept)   3.4118     0.0307  111.30  < 2e-16
2    1  log(qOrig)   0.6374     0.0122   52.31  < 2e-16
3    1         api   2.0827     0.0660   31.58  < 2e-16
4    2 (Intercept)   2.9921     0.0344   87.00  < 2e-16
5    2  log(qOrig)   0.5886     0.0119   49.38  < 2e-16
6    2  I(api^0.5)   2.3785     0.0646   36.81  < 2e-16
7    3 (Intercept)   2.9677     0.0332   89.29  < 2e-16
8    3  log(qOrig)   0.5328     0.0123   43.43  < 2e-16
9    3  I(api^0.5)   2.4837     0.0629   39.52  < 2e-16
10   3      sindoy   0.3484     0.0266   13.09  < 2e-16
11   4 (Intercept) -19.3879     6.1920   -3.13 1.76e-03
12   4  log(qOrig)   0.5293     0.0123   43.13  < 2e-16
13   4  I(api^0.5)   2.4561     0.0632   38.89  < 2e-16
14   4      sindoy   0.3486     0.0265   13.13  < 2e-16
15   4     t_decyr   0.0111     0.0031    3.61 3.12e-04
```

```r
f <- function(fit) {
  data.frame(df = summary(fit)$df[1],
             Adj_R2 = summary(fit)$adj.r.squared,
             NSE = NSE(fitted(fit), fit$model$`log(ssc)`),
             AIC = AIC(fit), BIC = BIC(fit))
}

fitstats <- list(fit1, fit2, fit3, fit4) %>% map_dfr(~f(.x)) %>%
  mutate(fit = 1:4, .before = 1)
fitstats
```

```
  fit df    Adj_R2       NSE      AIC      BIC
1   1  3 0.7019430 0.7022026 5415.820 5438.777
2   2  3 0.7311832 0.7314173 5178.644 5201.601
3   3  4 0.7497644 0.7500914 5015.114 5043.811
4   4  5 0.7510710 0.7515046 5004.088 5038.524
```

Looks like including all covariates improves fit and GOF metrics. Next, we assess `fit4` for multicollinearity. Multicollinearity occurs when the explanatory variables strongly correlate with each other, resulting in regression coefficients whose confidence intervals (and p-values) are not reliable (Willis & Perlack, 1978). One measure of multicollinearity is the Variable Inflation Factor (VIF), a value computed based on the R^2 of multiple regression between covariates (e.g. `log(qOrig) ~ I(api^0.5) + sindoy + t_decyr`). Other measures include tolerance (inverse of VIF), corrected VIF, Leamer's method, and others. For simplicity, we use only VIF; albeit old, VIF is still one of the most commonly used multicollinearity metrics (Shrestha, 2020).

```
require(mctest)
mctest(fit4, type = 'i', method = 'VIF', corr = T)

Call:
imcdiag(mod = mod, method = method, corr = TRUE, vif = vif, tol = tol,
    conf = conf, cvif = cvif, ind1 = ind1, ind2 = ind2, leamer = leamer,
    all = all)


 VIF Multicollinearity Diagnostics

              VIF detection
log(qOrig) 1.3628         0
I(api^0.5) 1.2283         0
sindoy     1.1380         0
t_decyr    1.0363         0

NOTE:  VIF Method Failed to detect multicollinearity


0 --> COLLINEARITY is not detected by the test

===================================

Correlation Matrix
           log(qOrig) I(api^0.5)     sindoy    t_decyr
log(qOrig)  1.0000000 0.40001647 0.32654805 0.14273483
I(api^0.5)  0.4000165 1.00000000 0.01981128 0.16796473
sindoy      0.3265481 0.01981128 1.00000000 0.03024435
t_decyr     0.1427348 0.16796473 0.03024435 1.00000000

====================NOTE===================
```

Thresholds of concern for VIF is typically >5 (Sheather, 2009) or >10 (Kutner et al., 2005). None of the VIFs exceed either threshold. Next, we look at the covariates' partial residual plots and check if they are sufficiently linear, which is a necessary condition for using OLS:

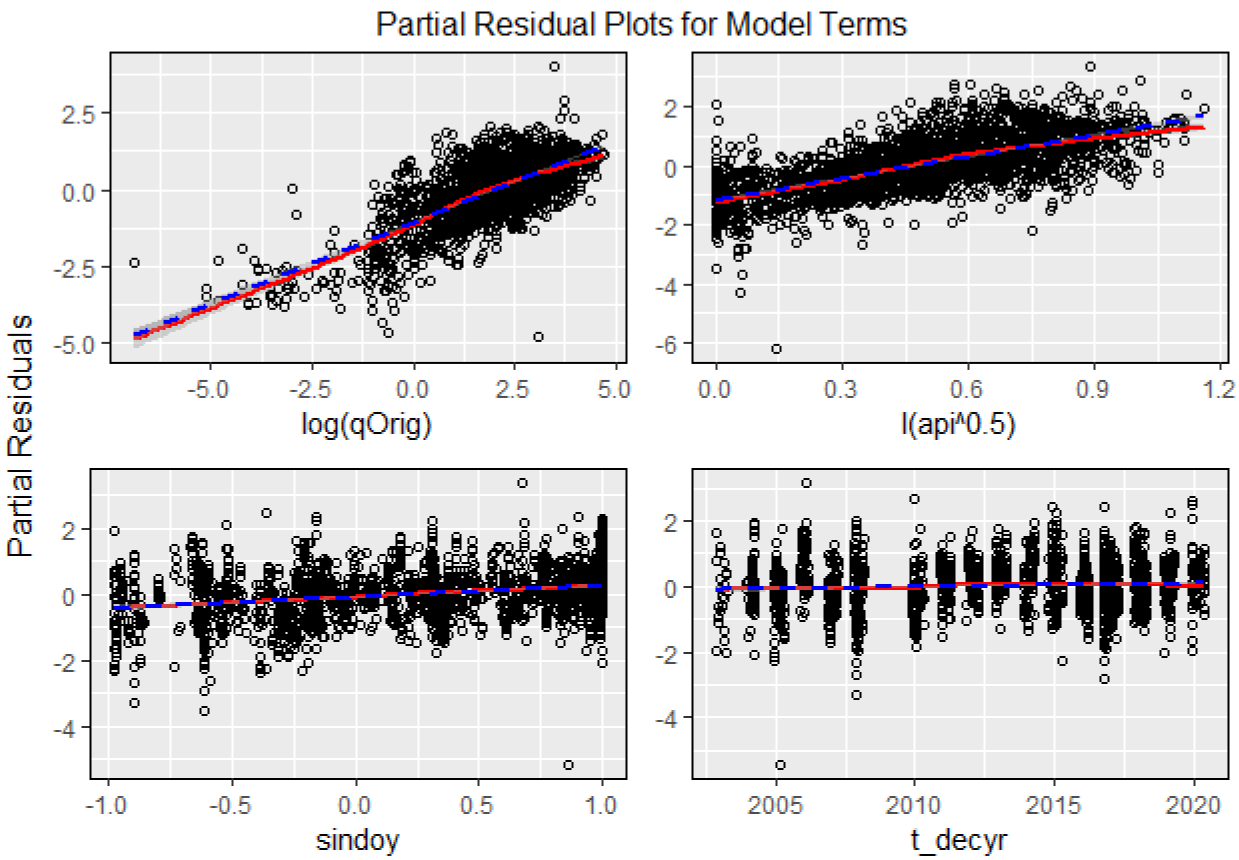


***Figure 6**: Partial residuals of HRC509 OLS model fit*

Most of the partial residuals look linear with some minor deviations from the confidence band for `Log(qOrig)` and `I(api^0.5)` at the extremities (low and high flows or high API).

Qualitatively (graphics) and based on the multicollinearity measure; model fit performance; and partial residual plots, all four covariates appear like they are suitable for inclusion. The lingering issue remains for the calendar day, and it may have to be addressed with covariates that better represent individual anthropogenic and/or other natural processes relevant to sediment production in the Elk River watershed.

Model diagnostics and identifying outliers

With `fit4` chosen as the initial model, we perform the standard diagnostics for OLS regression. Specifically, we check whether OLS assumptions have been met. We also identify potential outliers. Defining and removing outliers are perennially contentious practices among data analysts with no single standard metric or process for identification and treatment. Nevertheless, removing outliers can lead to better fits and greater satisfaction of method assumptions. OLS assumptions require that the residuals be identical and independently distributed (i.i.d.); normally distributed, uncorrelated; and homoscedastic. We know serially autocorrelation in the residuals exist, but address that later. We set the diagnostic plots to flag up to five outliers for each plot; there is no established rule or justification for using five, but that number seems appropriate given that `fit4` requires five degrees of freedom. The total number of outliers removed may include all the flagged observations.

```r
require(ggfortify)
autoplot(fit4, which = c(1:2, 4:5), shape = 1, label.colour = 'red',
         label.vjust = -1, label.fontface = 'bold',
         label.n = 5, label.size = 2.25) +
  theme(plot.title = element_text(hjust = 0.5, size = 12),
        axis.title.y = element_text(size = 12),
        axis.title.x = element_text(size = 12),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

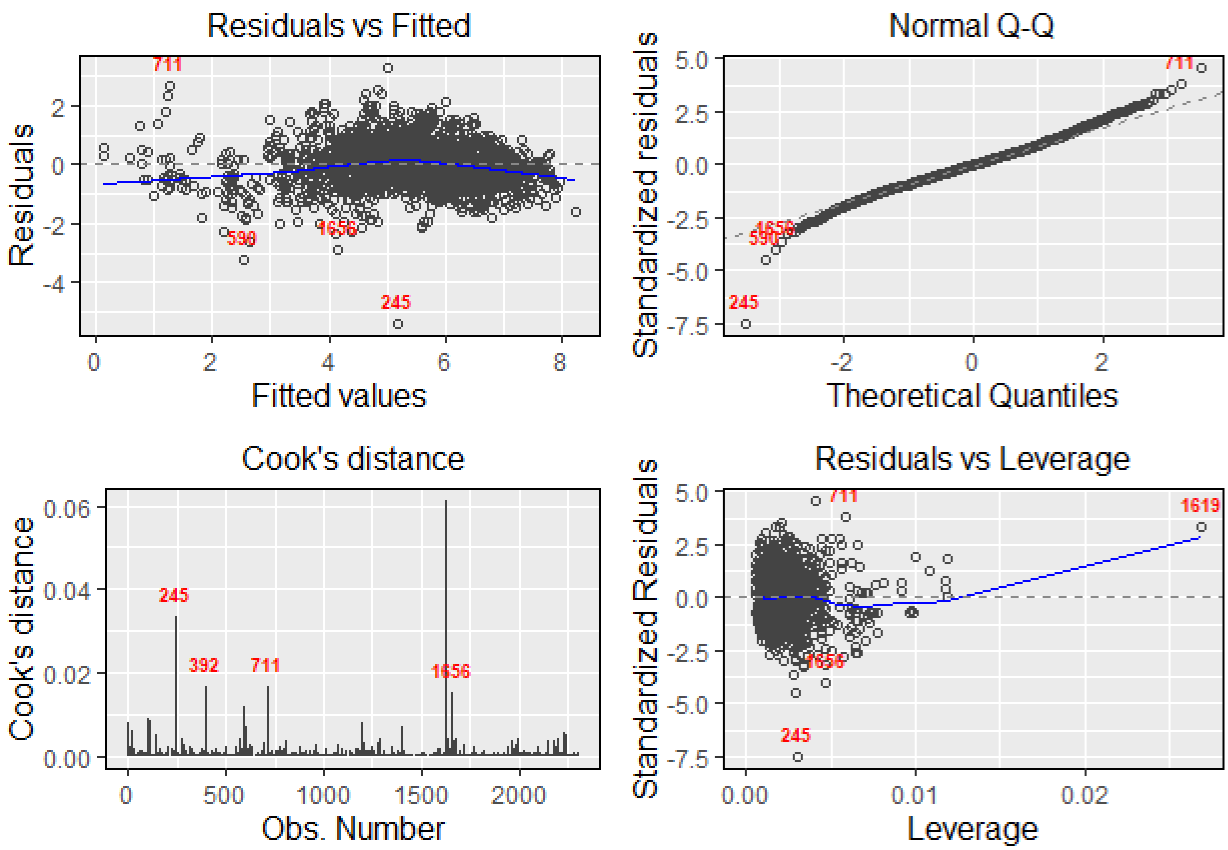


***Figure 7**: Diagnostic plot of HRC509 OLS model fit with outliers flagged*

The flagged values are observations 245, 392, 590, 711, 1619, and 1656. Inspecting them:

```
       WY                 dts  qOrig        api   sindoy  t_decyr      ssc
245  2005 2005-03-01 00:48:00 21.800 2.103e-02  0.85906 2005.162     0.84
392  2006 2006-02-12 04:32:00 32.620 1.107e-13  0.67684 2006.116  3779.00
590  2008 2007-11-22 15:15:00  0.534 3.537e-03 -0.61345 2007.892     0.50
711  2010 2009-12-09 10:55:00  0.050 2.214e-05 -0.36244 2009.938    52.10
1619 2017 2016-10-13 22:30:00  0.001 7.907e-01 -0.97351 2016.784    35.86
1656 2017 2016-10-27 05:00:00  0.461 5.629e-01 -0.89671 2016.820     3.67
```

These observations have one or more of the following characteristics: low flows (<1), low SSC (<1), and high SSC (>1000). As noted in Lewis, low flows have high leverage and are influential in the regression fit (defined by Cook's distance). The numeric value of 1 being the threshold is due to the log transformations, i.e., $\log(x) \leq 0$ if $x \in (0,1]$) and the lower abundance of SSC and flow observations below 1 mg/l and 1 cms, respectively. While HRC staff provided all the SSC pumped sample data, they did remove anomalously high SSC values when using the TTS Adjuster program to estimate continuous SSC from continuous turbidity. The table below shows the differences in GOF metrics between the full dataset's model (`fit4`) and fits with one outlier removed as well as removing the full list. Positive changes in R^2 and NSE indicate better fits. Comparisons using AIC and BIC require that all models have the same response data, so these metrics cannot be used to identify whether removing the outliers improves fit. We rely on R^2 and NSE as well as look at the diagnostic plots of the fit with all outliers removed.

```
outliers <- c(245, 392, 590, 711, 1619, 1656)
fits_sans_outlier <- as.list(outliers) %>% append(list(outliers)) %>%
  map(~update(fit4, data = hrc[-.x, ])) %>% 'names<-'((c(outliers, 'all')))
compare_outlier_fits(fits_sans_outlier, fitstats[4, ], names(fits_sans_outlier))
```

```
      Adj_R2     NSE
245  0.00454 0.00453
392  0.00178 0.00177
590  0.00032 0.00032
711  0.00144 0.00144
1619 0.00104 0.00104
1656 0.00088 0.00088
all  0.01011 0.01009
```

Removing any of the outliers improves the fit and the whole set being removed has the greatest effect. Let's look at the diagnostic plots again with all outliers removed.

```
autoplot(fits_sans_outlier[[7]], which = c(1:2, 4:5), shape = 1, label.n = 0) +
  theme(plot.title = element_text(hjust = 0.5, size = 12),
        axis.title.y = element_text(size = 12),
        axis.title.x = element_text(size = 12),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

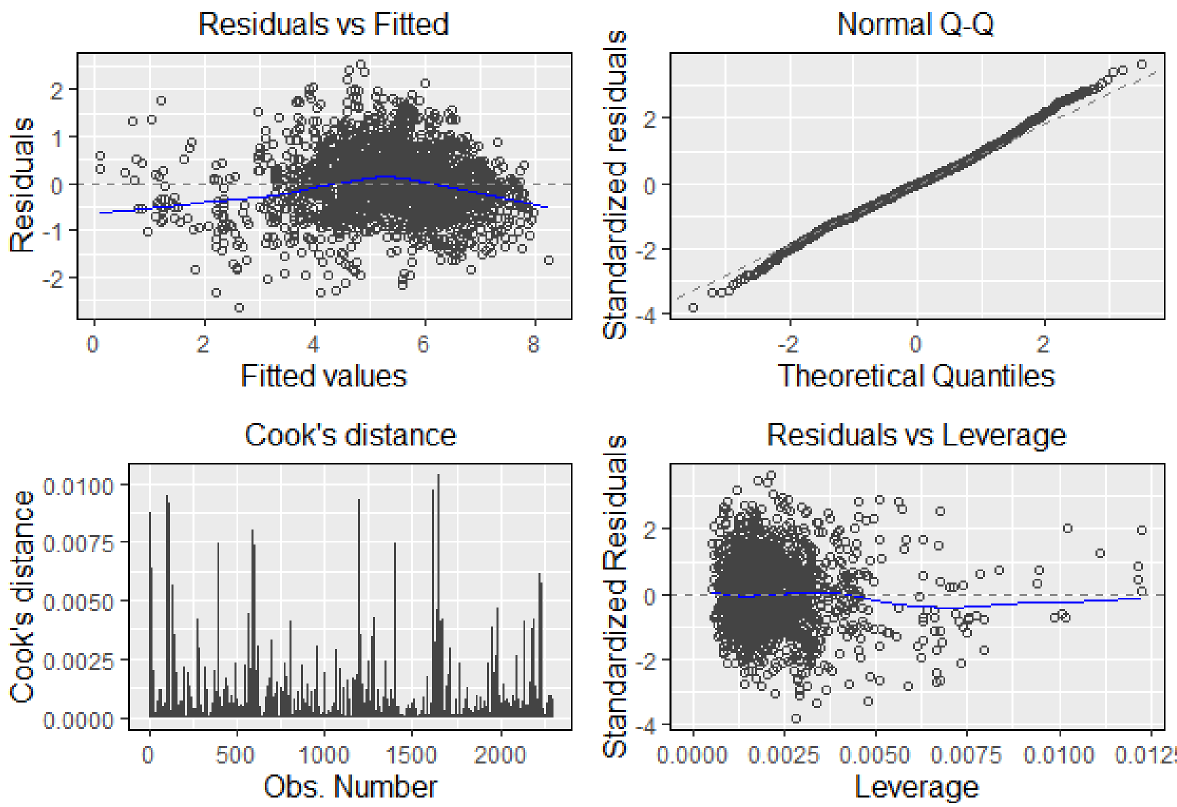


***Figure 8**: Diagnostic plot of HRC509 OLS model fit with outliers flagged*

The residuals look more normally distributed with the outliers removed. Cook's distance does not have as many extreme peaks as before. The smooth line in the residuals vs leverage plot is now flatter. The only plot that doesn't show improvement is residuals vs. fitted values, which appears more heteroskedastic than before; however, we address this issue when addressing serial autocorrelation.

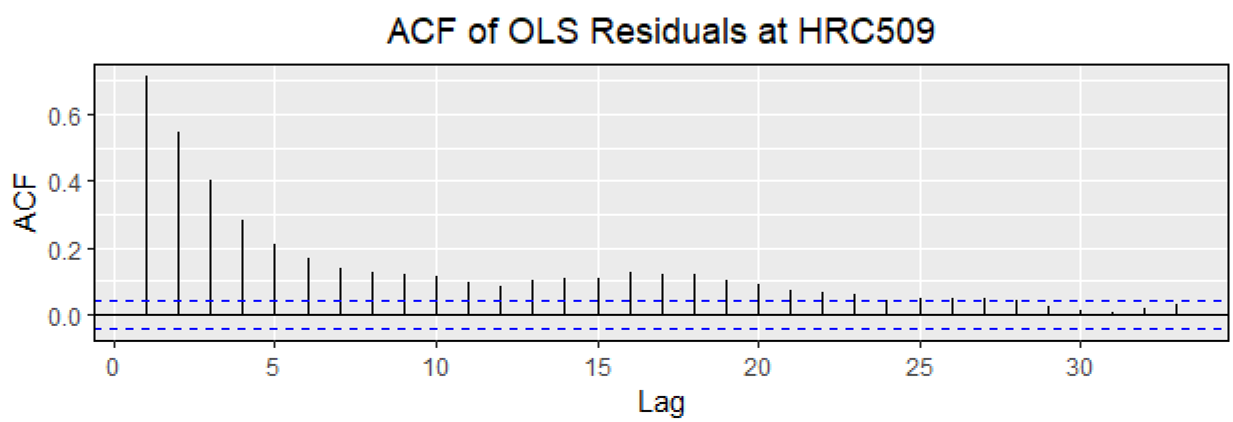
Given the large dataset, we are probably safe in removing these observations and can still expect similar results w.r.t. coefficient estimates and their p-values. Nevertheless, the data reassessment will apply the time-series trend analysis to both the full and modified datasets for comparison. If outliers are not due to measurement error or equipment malfunction, the outliers themselves may be important case studies for investigating specific sediment processes in the watershed. For example, SSC increasing in the absence of rainfall or high flows indicate sediment sources or processes that do not depend on hydrology.

Autocorrelated residuals

Because the data are time series (though not a complete one as the intervals are not equal), we should expect there to be serial autocorrelation among the model errors or residuals. In the presence of autocorrelated residuals, the OLS coefficient estimates are still unbiased and consistent, but their variances are unreliable, resulting in artificially lower p-values (Granger & Newbold, 1974) and potential false positives for the model coefficients' statistical significance. Autocorrelated errors can be dealt with using GLS regression with additional parameters that account for the error process. These terms include past residuals or a transform of the past values at some lag. The number of lags is the error structure's "order;" e.g., a second order structure would include two values in the past.

The details of GLS fitting and model selection are addressed in the next section of the Appendix. To finish the initial model selection, we use autocorrelation (ACF) and partial ACF (PACF) plots to confirm that autocorrelation exists. PACF plots can provide starting points in specifying the error correlation structure. That is, the lags with PACF exceeding the confidence band ($\alpha = 0.05$) can inform the order of the error correlation structure (i.e., the number of lags to include). For station HRC509 we will likely need at least a second order correlation structure as the PACF at lag 2 is above the PACF confidence band.

```
require(forecast)
acf_plt <- ggAcf(residuals(fit4)) +
  labs(title = glue('ACF of OLS Residuals at HRC{stn}')) +
  theme(plot.title = element_text(hjust = 0.5),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
pacf_plt <- ggPacf(residuals(fit4)) +
  labs(title = glue('PACF of OLS Residuals at HRC{stn}')) +
  theme(plot.title = element_text(hjust = 0.5),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
ggarrange(acf_plt, pacf_plt, nrow = 2, ncol = 1) +
  theme(axis.title.y = element_text(size = 12),
        axis.title.x = element_text(size = 12))
```



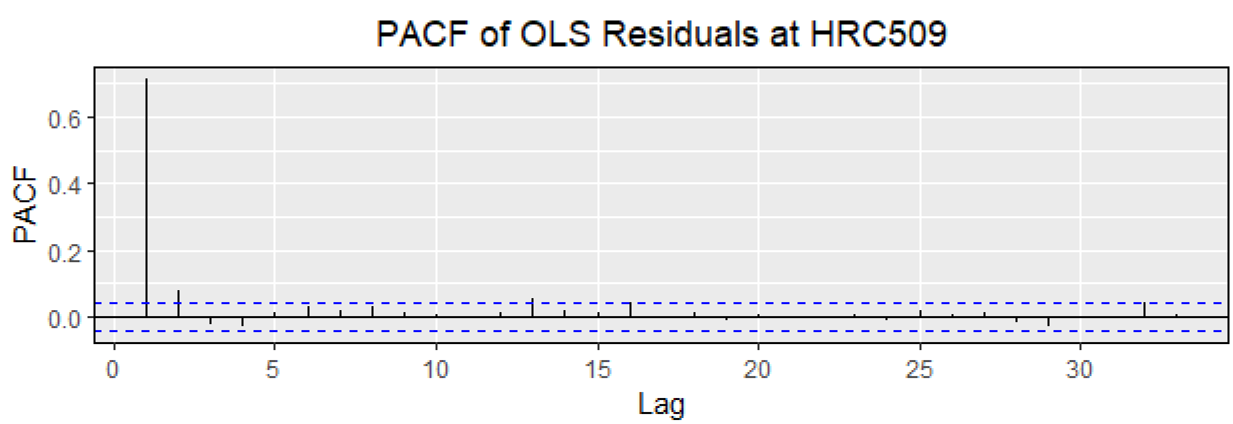


Figure 9*: ACF and PACF plot for HRC509 OLS residuals*

Writing and saving data to file

Finally, we save the results of the initial model selection and their data to an `*.RData` file, which can reload all the objects, picking up where we left off here. RData files are useful for providing continuity between sessions. RDS files are R objects themselves and not an environment. When loading an RDS file, one must specify the new object; for example, `obj <- read('data.rds)`, whereas with RData one would use `load('data.RData')`. RDS files are useful to compare between stations that follow the same initial model selection process, which is the case for stations HRC510 and HRC511.

```
hrc$outlier <- FALSE
hrc$outlier[outliers] <- TRUE
obj_ls <- ls()
obj_ls_out <- obj_ls %>%
  map(~eval(str2expression(glue('class({.x})')))) %>%
  map(~any(!'function' %in% .x)) %>% unlist %>% obj_ls[.]
# save as image
rda_fname <- here(glue('analysis/initial/init_model_HRC{stn}.Rdata'))
save(file = rda_fname, list = obj_ls_out)
```

Station HRC510

Station HRC510's catchment is approximately 19.4 mi^2 (50.3 km^2) or 12,419 acres. HRC510 is located on the South Fork Elk River (SF Elk) and contains Tom's Gulch, McCloud Creek, Corrigan Creek tributaries. This catchment also contains the Upper Little SF Elk River used as reference watershed in early TMDL development. SF Elk is the most diverse in terms of landownership: HRC, Bureau of Land Management (federal); Green Diamond Resource Company (GDRCo); Save the Redwoods League (non-profit); and the remainder being residential and small agricultural properties. Because the majority of the code used for HRC509 simply repeats with the other stations, their codes are not included for brevity. That said, if new code is utilized, they will be included here.

Choose precipitation dataset and decay rate

Repeat OLS regression with stream discharge and evaluate all precipitation and API decay rate options.

```
  adj.r.squared     sigma statistic p.value df      AIC     BIC nobs
1     0.6452047 0.8044595  4798.272       0  1 6344.745 6362.38 2639

         term  estimate  std.error statistic p.value
1 (Intercept) 3.9180647 0.02789794 140.44279       0
2  log(qOrig) 0.9997449 0.01443267  69.26956       0

Single term additions

Model:
log(ssc) ~ log(qOrig)
           Df Sum of Sq    RSS     AIC
ST4smapi83  1    348.11 1358.4 -1746.5
ST4smapi82  1    347.91 1358.6 -1746.1
ST2wmapi83  1    346.93 1359.6 -1744.2
ST4wmapi83  1    346.91 1359.6 -1744.1
```

```
ST4smapi84  1    346.86 1359.7 -1744.0
ST4wmapi82  1    346.66 1359.9 -1743.6
```

ST4 simple average with decay rate of 0.83 has lowest AIC.

Other covariates

Check the spread of dataset used for fitting:

```
     qOrig              api               sindoy             ssc        
 Min.   : 0.016   Min.   :0.00000   Min.   :-0.9856   Min.   :    0.05  
 1st Qu.: 2.530   1st Qu.:0.06442   1st Qu.:-0.1415   1st Qu.:  108.61  
 Median : 5.450   Median :0.20197   Median : 0.3158   Median :  287.70  
 Mean   : 8.083   Mean   :0.26098   Mean   : 0.2927   Mean   :  514.31  
 3rd Qu.:10.780   3rd Qu.:0.39476   3rd Qu.: 0.7895   3rd Qu.:  639.24  
 Max.   :59.686   Max.   :1.37877   Max.   : 1.0000   Max.   :14852.00  
```

Compared to both HRC509 and HRC511, the spread of SSCs is much wider with a minimum of 0.05 mg/L and max of 14,852 mg/L. Of the three stations, SF Elk River sustains the highest SSC, both on average as well as well as on the right tail given the larger SSC 3rd quartile.

```
   fit Coefficient Estimate Std. Error t value Pr(>|t|)
1    1 (Intercept)   3.6833     0.0265  139.08  < 2e-16
2    1  log(qOrig)   0.8809     0.0137   64.46  < 2e-16
3    1         api   1.6281     0.0626   25.99  < 2e-16
4    2 (Intercept)   3.4218     0.0305  112.36  < 2e-16
5    2  log(qOrig)   0.8509     0.0138   61.60  < 2e-16
6    2  I(api^0.5)   1.6498     0.0598   27.60  < 2e-16
7    3 (Intercept)   3.3704     0.0305  110.40  < 2e-16
8    3  log(qOrig)   0.8319     0.0138   60.44  < 2e-16
9    3  I(api^0.5)   1.6772     0.0590   28.44  < 2e-16
10   3      sindoy   0.2375     0.0262    9.06  < 2e-16
11   4 (Intercept)  22.3087     4.8516    4.60 4.46e-06
12   4  log(qOrig)   0.8361     0.0138   60.73  < 2e-16
13   4  I(api^0.5)   1.7102     0.0594   28.79  < 2e-16
14   4      sindoy   0.2488     0.0263    9.46  < 2e-16
15   4     t_decyr  -0.0094     0.0024   -3.90 9.72e-05
  fit df     Adj_R2       NSE      AIC      BIC
1   1  3 0.7174695 0.7176837 5744.700 5768.212
2   2  3 0.7246220 0.7248308 5677.031 5700.544
3   3  4 0.7328409 0.7331447 5598.067 5627.458
4   4  5 0.7342767 0.7346796 5584.845 5620.113
```

Including all covariates improves fit and GOF metrics. Now check for multicollinearity.

```

Call:
imcdiag(mod = mod, method = method, corr = TRUE, vif = vif, tol = tol, 
    conf = conf, cvif = cvif, ind1 = ind1, ind2 = ind2, leamer = leamer, 
    all = all)


 VIF Multicollinearity Diagnostics

                 VIF detection
```

```
log(qOrig) 1.2150         0
I(api^0.5) 1.2076         0
sindoy     1.0363         0
t_decyr    1.0577         0

NOTE:  VIF Method Failed to detect multicollinearity


0 --> COLLINEARITY is not detected by the test

===================================

Correlation Matrix
           log(qOrig)  I(api^0.5)      sindoy   t_decyr
log(qOrig)  1.0000000 0.390594435 0.143270635 0.1575960
I(api^0.5)  0.3905944 1.000000000 0.009268413 0.1852010
sindoy      0.1432706 0.009268413 1.000000000 0.1225314
t_decyr     0.1575960 0.185201044 0.122531351 1.0000000

====================NOTE===================
```

With no VIF values of concern, move on to partial residual plots.

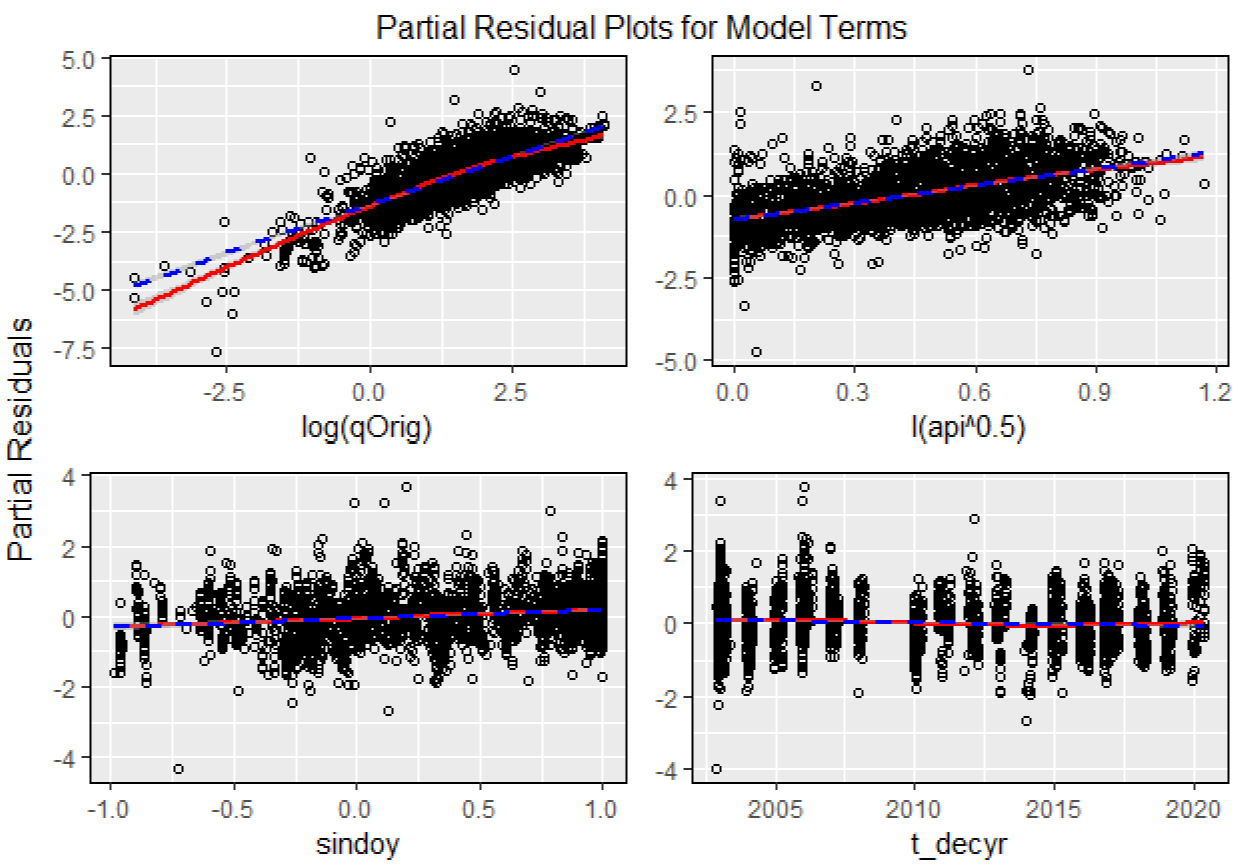


Figure 10*: Partial residuals of HRC510 OLS model fit*

Most of the partial residuals look linear except for `Log(qOrig)` which deviates at the low end, likely due to fewer observations on left tail of the distribution. That said, most of `Log(qOrig)` values are above -1.25 (≈ 0.287 cms) and the partial residuals are linear above that threshold. See whether truncating the data at that flow threshold improves the partial residuals and overall fit.

```
fit4_trunc <- update(fit4, subset = qOrig > exp(-1.25))
```

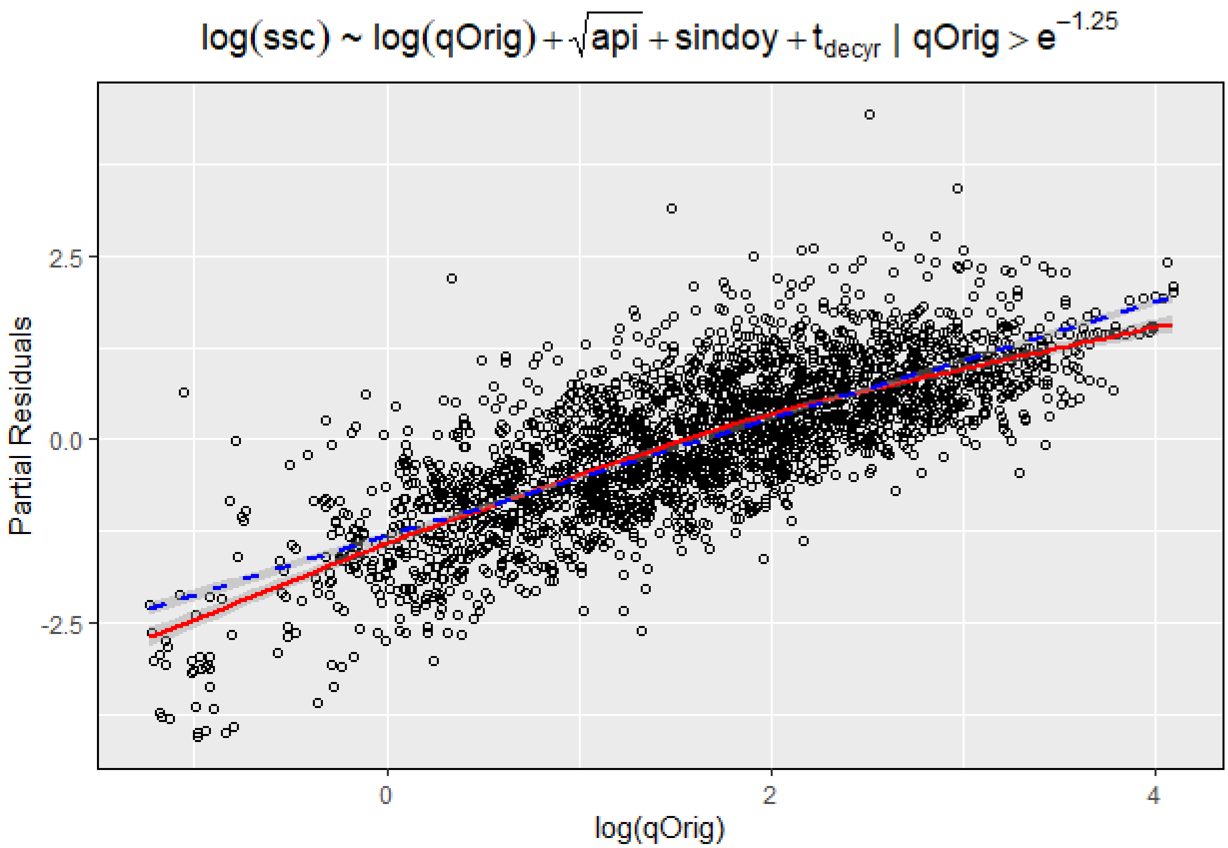


Figure 11*: Partial residuals of log(qOrig) of OLS fit with truncated dataset*

```
Call:
lm(formula = log(ssc) ~ log(qOrig) + I(api^0.5) + sindoy + t_decyr,
    data = hrc, subset = qOrig > exp(1.25))

# A tibble: 1 x 6
  r.squared adj.r.squared p.value    df df.residual  nobs
      <dbl>         <dbl>   <dbl> <dbl>       <int> <dbl>
1     0.702         0.702       0     4        2597  2602
```

`Log(qOrig)` is somewhat more linear now, but R^2 has decreased moderately from 0.7343 to 0.7016. Given that lower R^2, we keep the low SSC values and continue.

Model diagnostics and identifying outliers

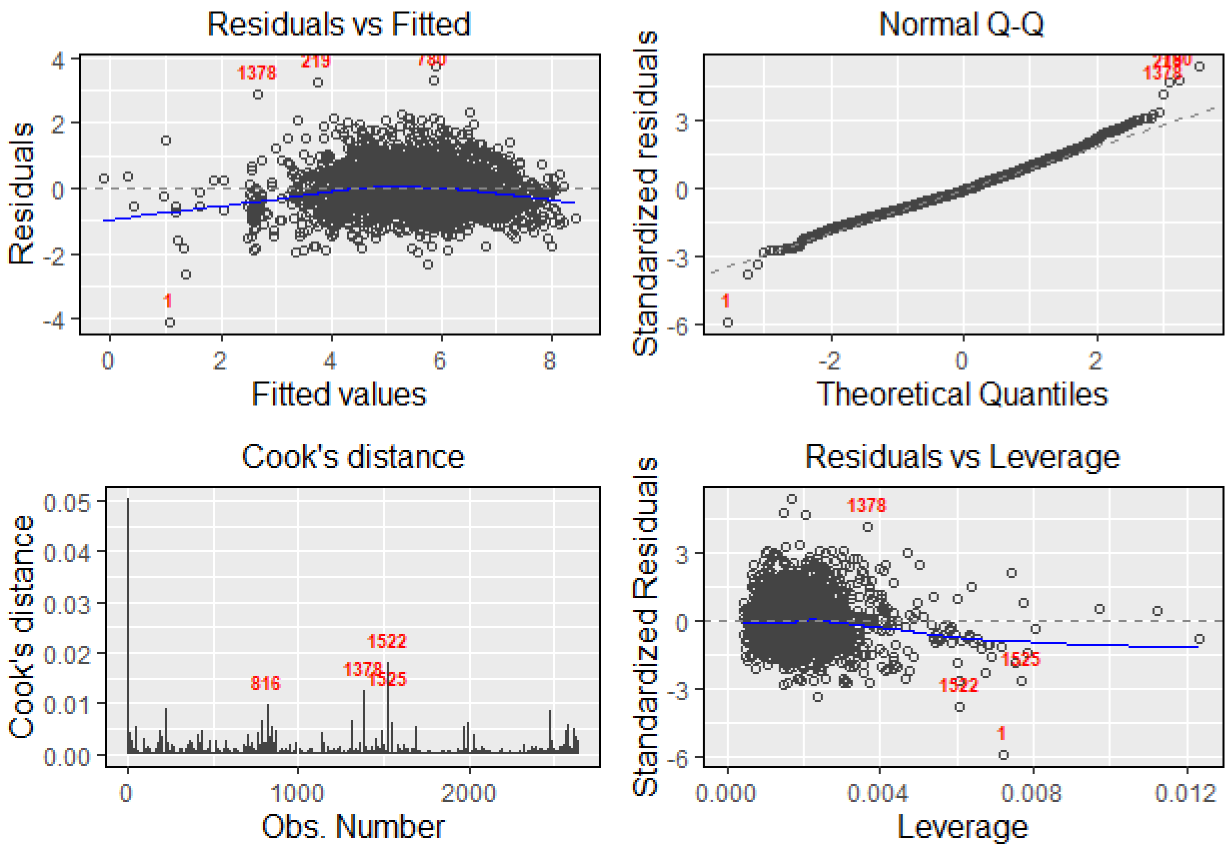


Figure 12*: Diagnostic plot of HRC510 OLS model fit with outliers flagged*

The flagged values are observations 1, 219, 780, 816, 1378, 1522, 1525:

```
       WY                 dts    qOrig        api   sindoy  t_decyr      ssc
1    2003 2002-11-13 09:45:00  0.06720 0.0030390 -0.73066 2002.867     0.05
219  2003 2003-01-06 10:08:00  1.40670 0.0001386  0.11033 2003.015  1120.60
780  2006 2005-12-30 11:26:00  4.40000 0.5334000 -0.00901 2005.996  9652.00
816  2006 2006-01-11 13:27:00 12.38000 0.0410300  0.19769 2006.029 14852.00
1378 2012 2012-02-21 13:30:00  0.34700 0.0001951  0.78479 2012.141   260.18
1522 2014 2014-01-07 10:45:00  0.09037 0.0005972  0.12786 2014.018     0.28
1525 2014 2014-01-28 12:30:00  0.05663 0.0263800  0.47148 2014.075     0.61
```

Again, these observations have one or more of the following characteristics: low flows (<1), low SSC (<1), and high SSC (>1000). Update the fit by removing one outlier at a time and then the entire set.

```
       Adj_R2      NSE
1    -0.00053 -0.00053
219   0.00210  0.00210
780   0.00153  0.00153
816   0.00196  0.00196
1378  0.00175  0.00174
1522 -0.00108 -0.00108
```

```
1525 -0.00132 -0.00132
all   0.00460  0.00460
```

Removing observations 1, 1522, and 1525 individually lowers the GOF metrics. Let's remove just 219, 780, 816, and 1378 (`subset0`), but flag three observations to see if 1, 1522, 1525 are still where they are.

```
fits_sans_outlier$subset1 <- update(fit4, data = hrc[-c(219, 780, 816, 1378), ])
compare_outlier_fits(fits_sans_outlier, fitstats[4, ],
                     names(fits_sans_outlier)) %>% tail(2)

         Adj_R2     NSE
all     0.00460 0.00460
subset1 0.00738 0.00737

autoplot(last(fits_sans_outlier), which = c(1:2, 4:5), shape = 1,
         label.colour = 'red', label.vjust = -1, label.fontface = 'bold',
         label.n = 3, label.size = 2.25) +
  theme(plot.title = element_text(hjust = 0.5, size = 12),
        axis.title.y = element_text(size = 12),
        axis.title.x = element_text(size = 12),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

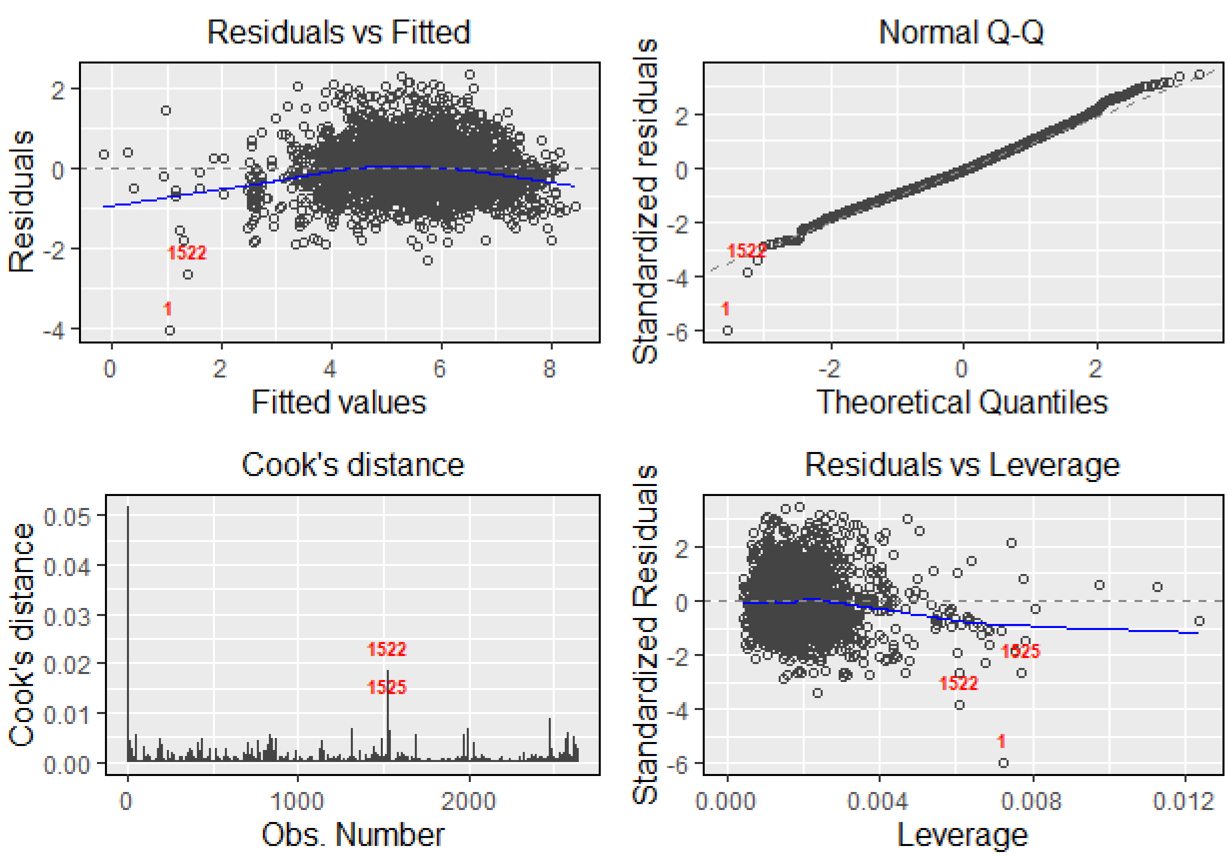


***Figure 13**: Diagnostic plot of HRC509 OLS model fit with three outliers flagged*

Observation 1 is still there as the greatest outlier with respect to high influence, leverage, and residual error. Let's re-include observation 1 (`subset2`) and flag two observations to make sure that no other outliers appear.

```
         Adj_R2     NSE
all     0.00460 0.00460
subset1 0.00738 0.00737
subset2 0.00693 0.00692
```

GOF metrics decrease when adding observation 1, but not by much (ΔNSE, $R^2 \approx 4.5 \times 10^{-4}$). Again, the diagnostic plots:

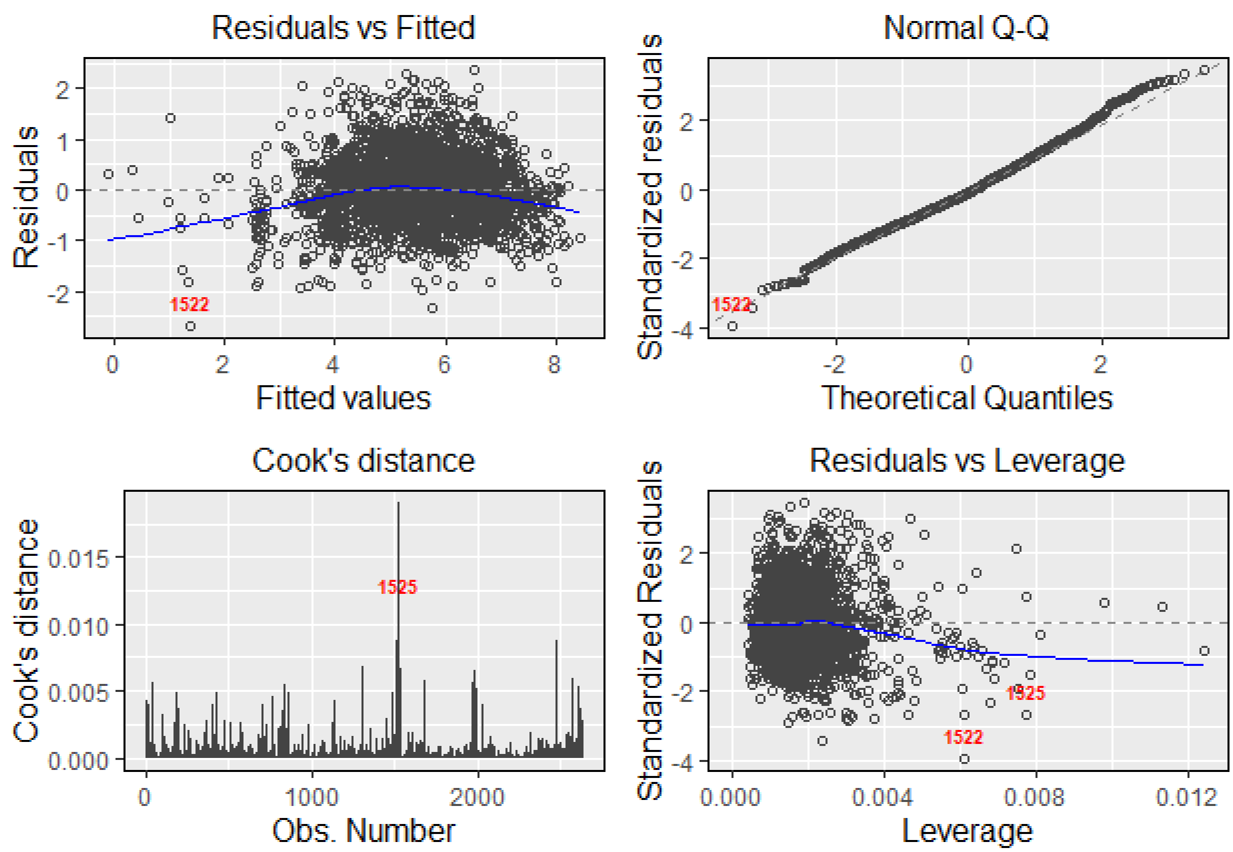


***Figure 14**: Diagnostic plot of HRC510 OLS model fit with two outliers flagged*

Observation 1522 and 1525 still have high influence relative to the other observations, but the magnitudes are much lower compared to observation 1. Let's see the spread of the coefficients' estimates with the various fits that exclude one, all, or a subset ($n_{fits} = 7$). Coefficient of variation (CV) for small sample sizes (Abdi, 2010) and quartile coefficient of dispersion (QCD) (Bonett, 2006) are measures of dispersion and expressed as percentages. Low values of either mean that there is little difference between the values in the dataset. In this case, the dataset are coefficients for different model fits.

```
fits_sans_outlier %>% map_dfr(~tidy(.x)) %>% group_by(term) %>%
  summarize(
    across(estimate, list(min, median, mean, max, ~QCD(.x),
                          ~100*(1+.25/10)*sd(.x)/abs(mean(.x))))) %>%
  'names<-'(c('term', 'min', 'median', 'mean', 'max', 'QCD (%)',
              'CV (%)')) %>%
  mutate('QCD (%)' = 100*`QCD (%)`) %>% as.data.frame
```

```
         term          min      median         mean          max   QCD (%)
1 (Intercept) 20.926244959 21.88083477 21.851014862 22.687800288 0.8429580
2  I(api^0.5)  1.702570278  1.71554299  1.714565707  1.721457851 0.2818788
3  log(qOrig)  0.825742739  0.83360874  0.833789270  0.838478273 0.2569789
4      sindoy  0.244357849  0.24862303  0.247667404  0.249926098 0.7386211
5     t_decyr -0.009612328 -0.00921452 -0.009201321 -0.008736446 0.9821934
     CV (%)
1 2.4922676
2 0.3799758
3 0.4662527
4 0.8972462
5 2.9382484
```

`api`, `qOrig`, and `sindoy` coefficients show very little variation across the different outlier fits (<1% QCD and CV). The intercept and `t_decyr` terms vary more, but not by much. Using the same rationale as HRC509 (large dataset), we exclude observations 1, 219, 780, 816, and 1378 to better satisfy the normally distributed errors assumption, but still use the full dataset for the trend analysis.

Autocorrelated errors

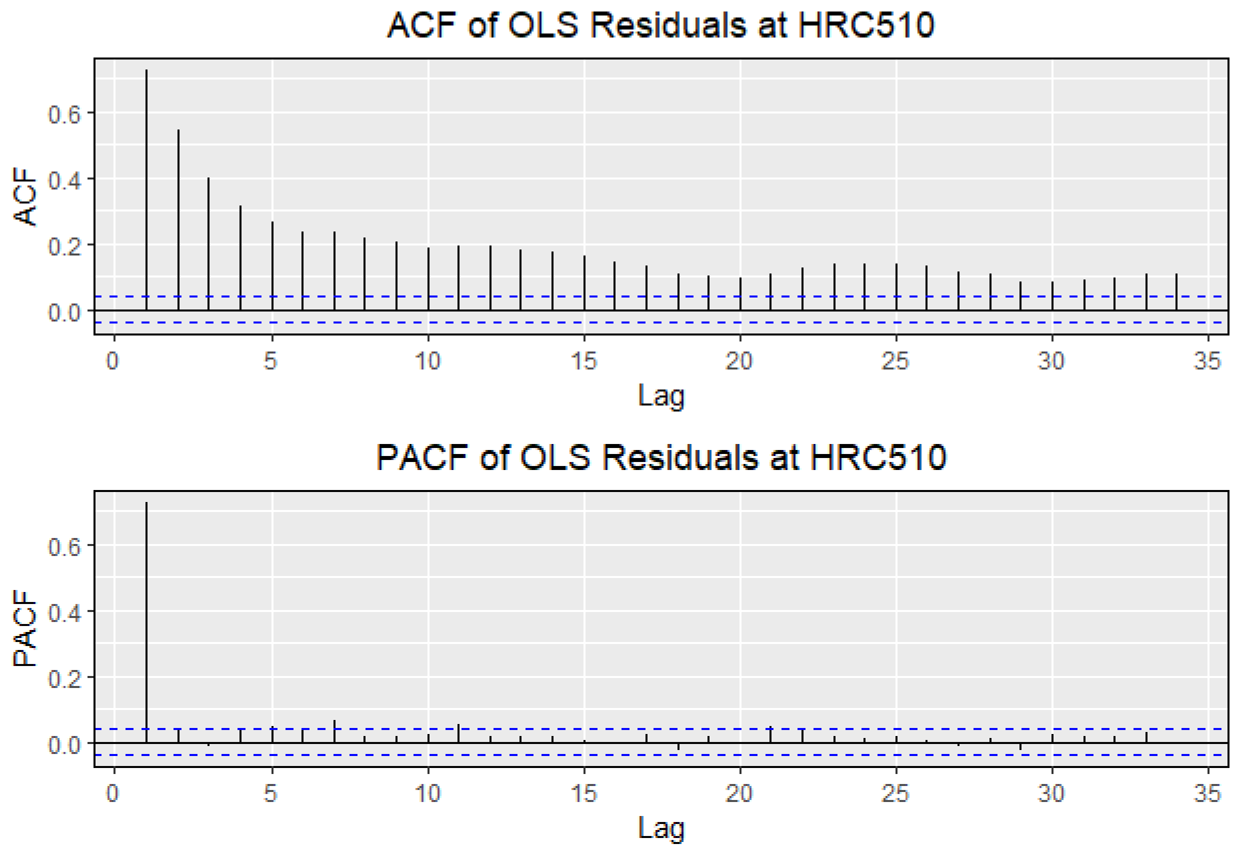


***Figure 15**: ACF and PACF plot for HRC510 OLS residuals*

For station HRC510 we may need a correlation structure at least to lag 2 and maybe higher as the PACF values are also statistically significant at lags 4, 5, and 6.

Station HRC511

Station HRC511's catchment is approximately 21.9 mi^2 (56.8 km^2) or 14,036 acres. HRC511 is located on the North Fork Elk River (NF Elk) and the catchment area itself is almost entirely owned by HRC and whatever remains is zoned for timber production. Relative to Upper Elk as a whole, residential properties are concentrated in the area between HRC511 and NF Elk's confluence with SF Elk. Given that HRC is practically the sole landowner in HRC511's catchment, any trends here (significant or not) will be particularly important w.r.t. assessing the effects of HRC's timberland management and harvest practices on SSC. Like HRC510 before, most of the code is identical with only the station number changed.

Choose precipitation dataset and decay rate

```
Call:
lm(formula = log(ssc) ~ log(qOrig), data = hrc_all)

Residuals:
    Min      1Q  Median      3Q     Max 
-2.8837 -0.4885 -0.0428  0.4253  3.2331
```

```
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.36225    0.02716   123.8   <2e-16 ***
log(qOrig)   1.00670    0.01302    77.3   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.7193 on 2401 degrees of freedom
Multiple R-squared:  0.7133,    Adjusted R-squared:  0.7132
F-statistic:  5975 on 1 and 2401 DF,  p-value: < 2.2e-16
```

Compare decay rates and choose precipitation dataset.

```
Single term additions

Model:
log(ssc) ~ log(qOrig)
           Df Sum of Sq    RSS     AIC
ST4smapi85  1    311.76 930.39 -2274.1
ST4smapi86  1    311.57 930.57 -2273.7
ST4wmapi85  1    311.17 930.98 -2272.6
ST4wmapi86  1    310.97 931.17 -2272.1
ST4smapi84  1    310.93 931.22 -2272.0
ST4wmapi84  1    310.35 931.80 -2270.5
```

ST4 simple average with decay rate of 0.85 has lowest AIC. With that chosen, move on to examining covariate additions.

Other covariates

Check the spread of dataset used for fitting:

```
     qOrig             api               sindoy              ssc
 Min.   : 0.016   Min.   :0.00000   Min.   :-0.9477   Min.   :   0.3
 1st Qu.: 3.034   1st Qu.:0.06529   1st Qu.:-0.1836   1st Qu.:  64.2
 Median : 6.360   Median :0.19103   Median : 0.2392   Median : 187.8
 Mean   : 9.563   Mean   :0.25860   Mean   : 0.2375   Mean   : 347.1
 3rd Qu.:13.260   3rd Qu.:0.38959   3rd Qu.: 0.7550   3rd Qu.: 478.9
 Max.   :66.002   Max.   :1.41527   Max.   : 1.0000   Max.   :2842.3
```

Of the three stations, HRC511 sees the lowest SSC with a range from 0.3 mg/L to 2,842.3 mg/L. Next, sequentially add `api`, `sindoy`, and `t_decyr` covariates and check whether they improve fits.

```
Coefficients

   fit Coefficient Estimate Std. Error t value Pr(>|t|)
1    1 (Intercept)   3.2151     0.0241  133.53  < 2e-16
2    1  log(qOrig)   0.8466     0.0126   67.14  < 2e-16
3    1         api   1.6556     0.0584   28.36  < 2e-16
4    2 (Intercept)   2.9471     0.0269  109.46  < 2e-16
5    2  log(qOrig)   0.8004     0.0130   61.41  < 2e-16
6    2  I(api^0.5)   1.7587     0.0583   30.15  < 2e-16
7    3 (Intercept)   2.9310     0.0269  108.87  < 2e-16
```

```
8    3  log(qOrig)   0.7866     0.0132   59.60  < 2e-16
9    3  I(api^0.5)   1.7796     0.0581   30.62  < 2e-16
10   3      sindoy   0.1312     0.0238    5.50 4.11e-08
11   4 (Intercept)  18.5601     4.6239    4.01 6.15e-05
12   4  log(qOrig)   0.7978     0.0136   58.74  < 2e-16
13   4  I(api^0.5)   1.7799     0.0580   30.70  < 2e-16
14   4      sindoy   0.1369     0.0238    5.74 1.07e-08
15   4     t_decyr  -0.0078     0.0023   -3.38 7.36e-04


GOF statistics
  fit df    Adj_R2       NSE      AIC      BIC
1   1  3 0.7851030 0.7852820 4547.276 4570.414
2   2  3 0.7918916 0.7920649 4470.141 4493.279
3   3  4 0.7944011 0.7946579 4441.986 4470.909
4   4  5 0.7952907 0.7956316 4432.564 4467.271
```

Including all covariates improves fit and GOF metrics. Now check for multicollinearity.

```
Call:
imcdiag(mod = mod, method = method, corr = TRUE, vif = vif, tol = tol,
    conf = conf, cvif = cvif, ind1 = ind1, ind2 = ind2, leamer = leamer,
    all = all)


 VIF Multicollinearity Diagnostics

              VIF detection
log(qOrig) 1.5235         0
I(api^0.5) 1.3863         0
sindoy     1.0447         0
t_decyr    1.1047         0

NOTE:  VIF Method Failed to detect multicollinearity


0 --> COLLINEARITY is not detected by the test

===================================

Correlation Matrix
           log(qOrig) I(api^0.5)     sindoy   t_decyr
log(qOrig)  1.0000000 0.52492194 0.18417976 0.3005405
I(api^0.5)  0.5249219 1.00000000 0.04188721 0.1552937
sindoy      0.1841798 0.04188721 1.00000000 0.1210546
t_decyr     0.3005405 0.15529367 0.12105462 1.0000000

===================NOTE===================
```

With no VIF values of concern, move on to partial residual plots.

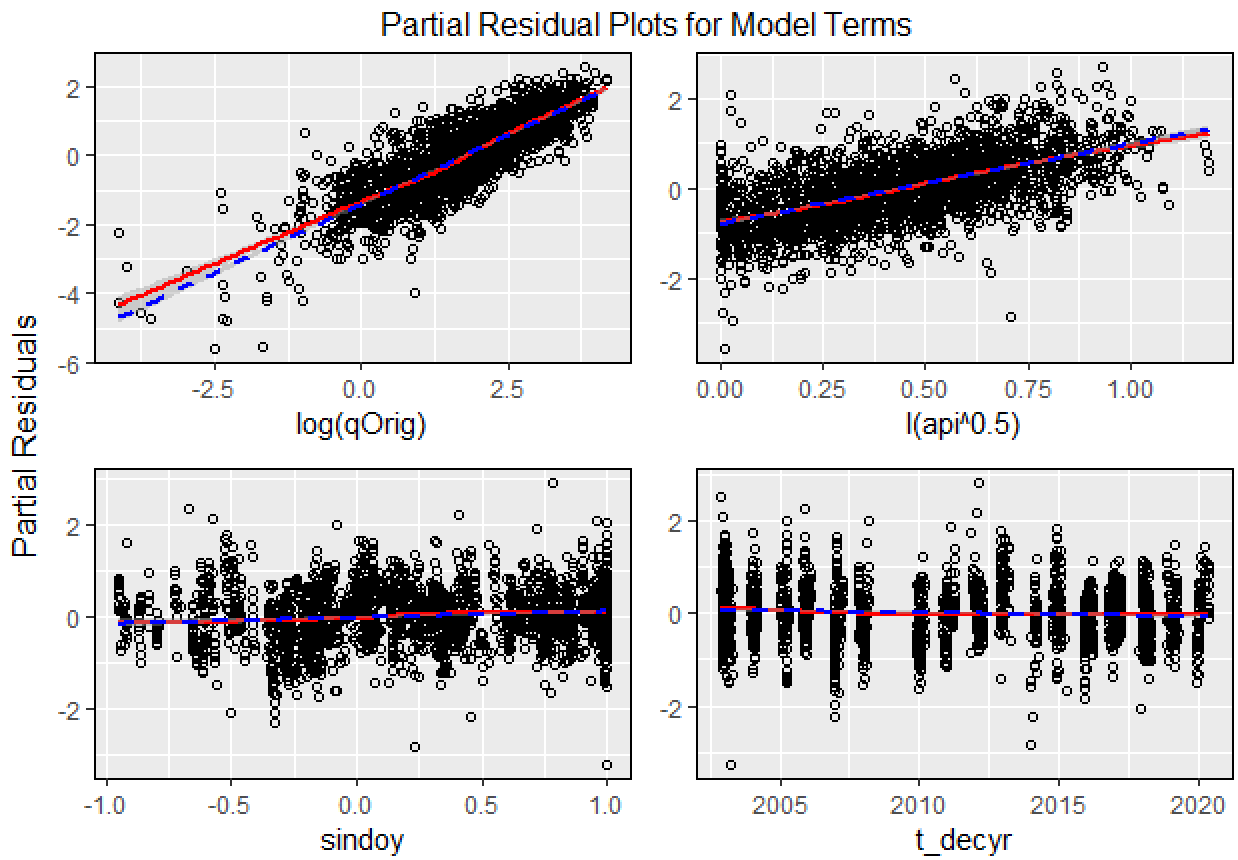


Figure 16: *Partial residuals of HRC511 OLS model fit*

All of the partial residuals look good. Next are diagnostics.

Model diagnostics and identifying outliers

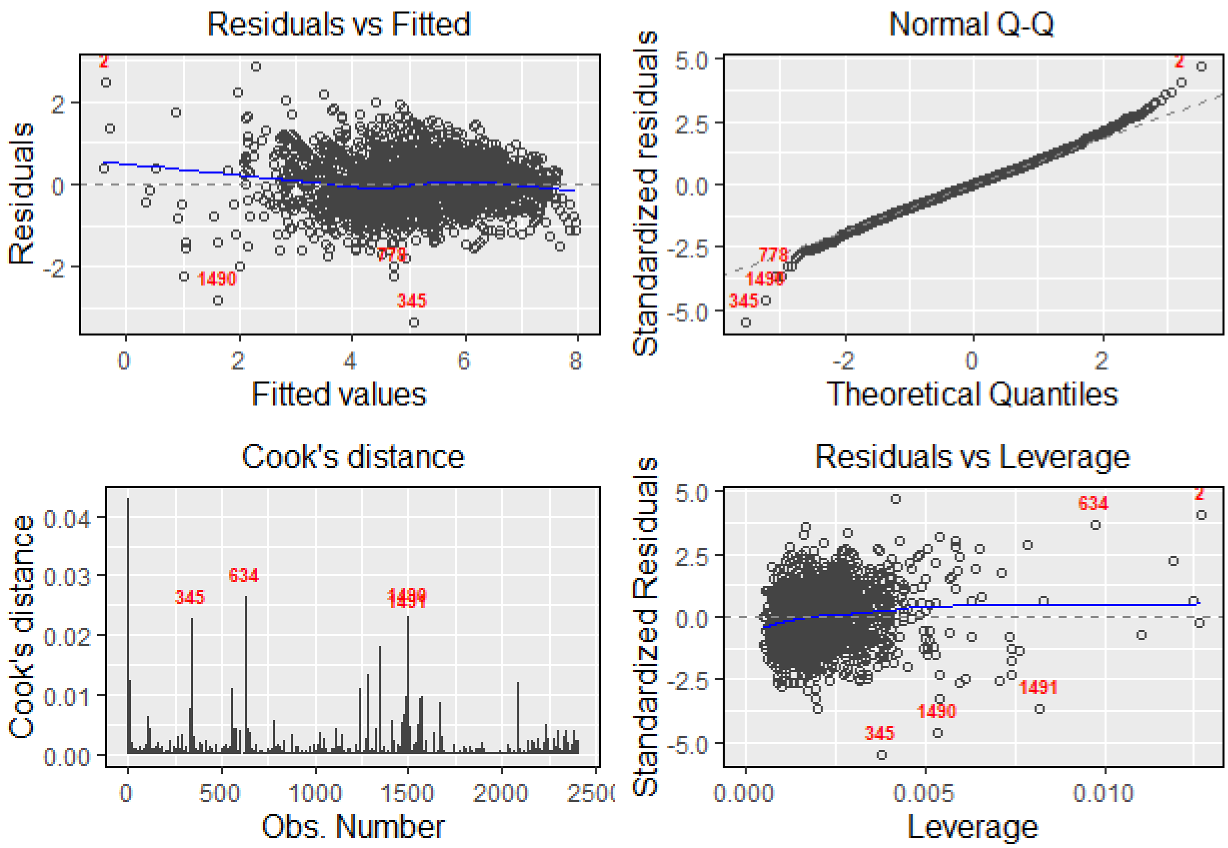


Figure 17: *Diagnostic plots for HRC511 OLS fit with outliers flagged*

The flagged values are observations 2, 345, 634, 778, 1349, 1490, and 1491.

```
       WY                 dts qOrig       api   sindoy  t_decyr    ssc
2    2003 2002-11-18 14:00:00 0.016 0.0007223 -0.66700 2002.881   8.10
345  2003 2003-04-04 00:59:00 2.460 0.5008000  0.99885 2003.255   5.80
634  2006 2005-11-25 06:29:00 0.090 0.3238000 -0.57701 2005.899  64.80
778  2007 2006-12-11 16:48:00 2.320 0.4330000 -0.32616 2006.944  12.00
1349 2012 2012-02-21 11:30:00 0.384 0.0005754  0.78390 2012.141 166.26
1490 2014 2014-01-13 12:00:00 0.188 0.0001226  0.23031 2014.034   0.30
1491 2014 2014-01-27 14:00:00 0.082 0.0008982  0.45718 2014.073   0.30
```

Unlike HRC510 and HRC509, not all outliers have the low flow, low SSC, and/or high SSC. Specifically, observations 345 and 778. 345 shows up in all four diagnostic lots, whereas 778 is only present in the residuals vs. fitted and normal Q-Q. Let’s look at the effect of removing outliers.

```
outliers <- c(2, 345, 634, 778, 1349, 1490, 1491)
fits_sans_outlier <- as.list(outliers) %>% append(list(outliers)) %>%
  map(~update(fit4, data = hrc[-.x, ])) %>% 'names<-'((c(outliers, 'all')))
compare_outlier_fits(fits_sans_outlier, fitstats[4, ], names(fits_sans_outlier))

       Adj_R2     NSE
2     0.00099 0.00098
345   0.00203 0.00203
```

```
634   0.00110  0.00110
778   0.00085  0.00085
1349  0.00186  0.00185
1490 -0.00007 -0.00007
1491 -0.00077 -0.00076
all   0.00607  0.00607
```

Removing observations 1490, 1491 individually lowers the GOF metrics. Removing 778 improves the fit but has the lowest effect compared to the other outliers. Let's remove just 2, 345, 634, 1349 (*subset1*) and flag three observations:

```
         Adj_R2     NSE
all     0.00607 0.00607
subset1 0.00602 0.00601
```

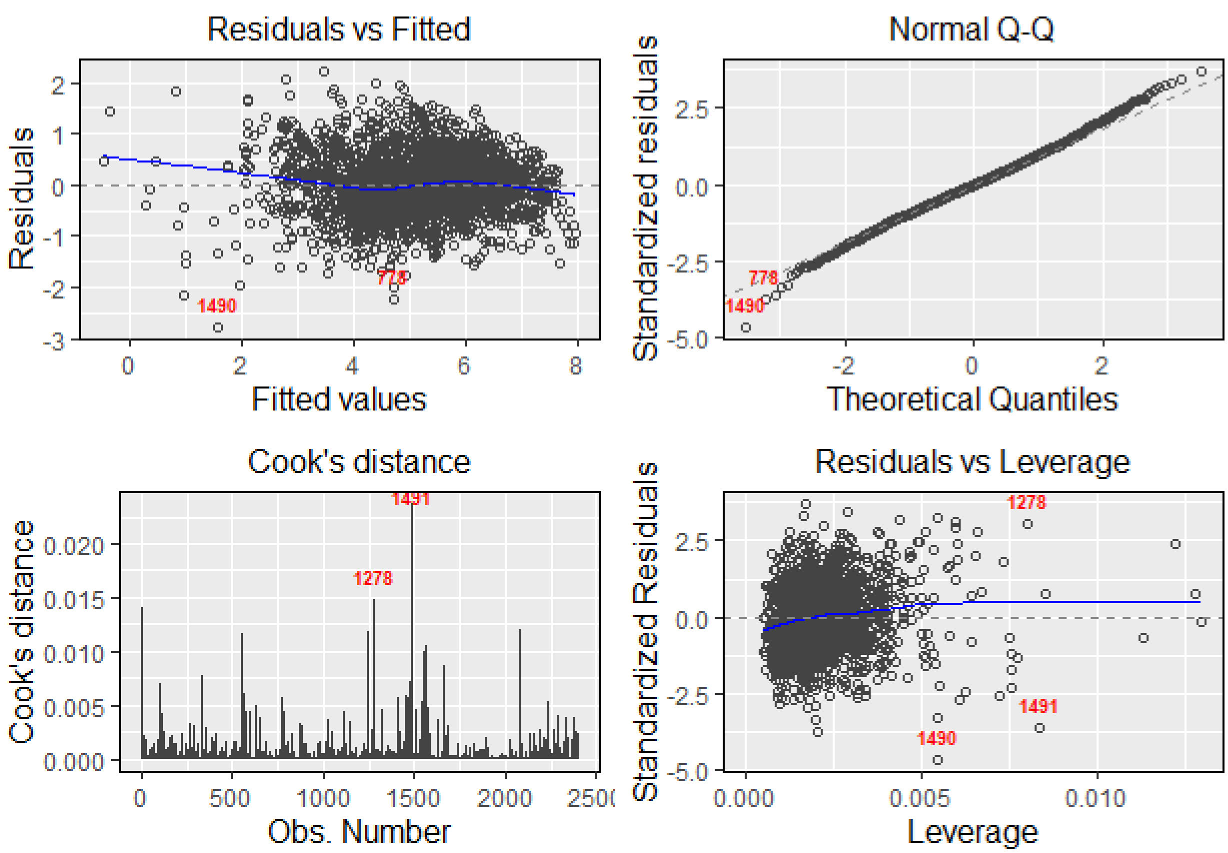


***Figure 18**: Diagnostic plots of HRC511 model fit with three outliers flagged*

Observations 1490 and 1491 still have high influence and leverage. 1490 appears in all four plots. Let's re-include observation 1491 (*subset2*) and flag two observations.

```
         Adj_R2     NSE
all     0.00607 0.00607
subset1 0.00602 0.00601
subset2 0.00596 0.00595
```

GOF metrics decrease when adding back 1490 compared to *all* and *subset2*, but not by much (*Δ*NSE, $R^2 \approx 6.0 \times 10^{-3}$). Again, the diagnostic plots:

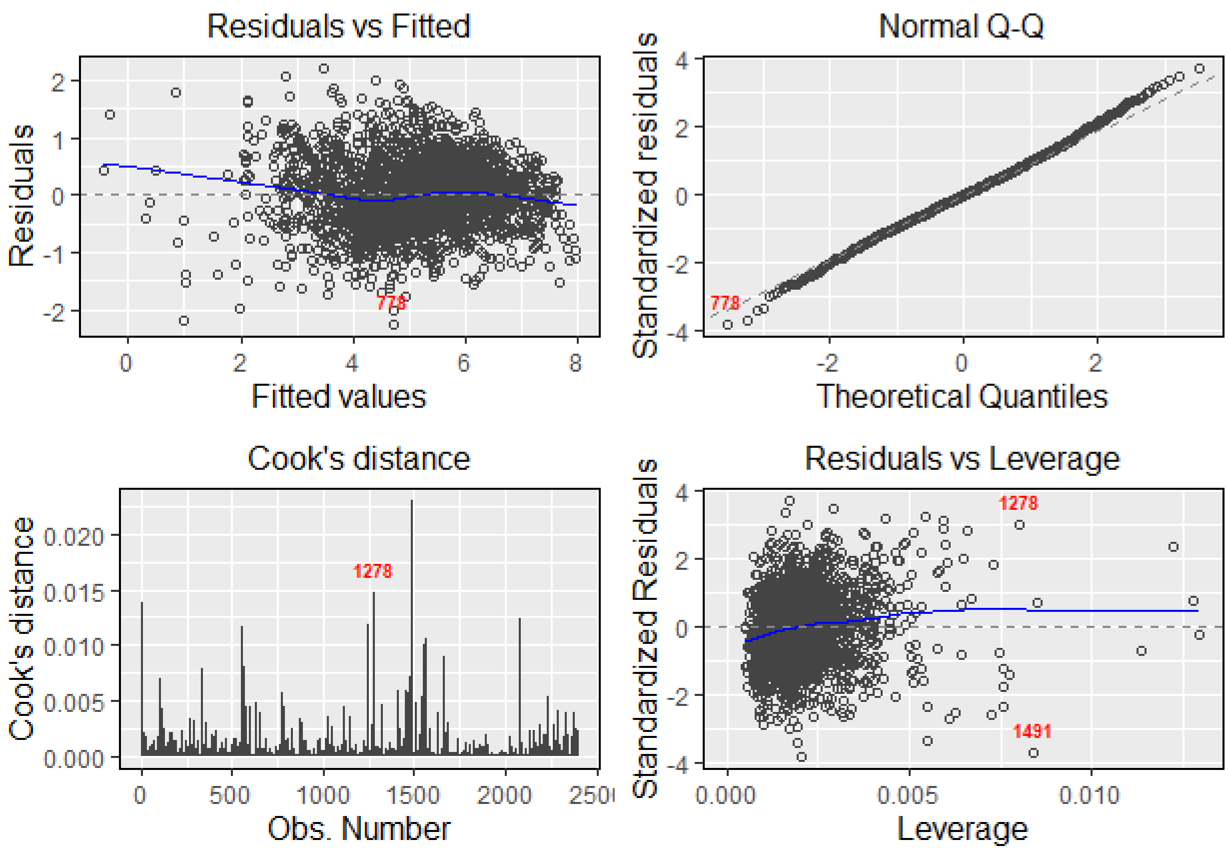


Figure 19*: Diagnostic plots of HRC511 model fit with two outliers flagged*

Observation 1491 has high influence relative other data points, but overall, these plots look better, so we'll treat observations 2, 345, 634, 1349, and 1490 as outliers. Let's see the spread of the coefficients' estimates with the various fits that exclude one, all, or a subset (n_{fits} = 10).

```
         term          min       median         mean          max   QCD (%)
1 (Intercept) 17.902660557 18.701966256 18.770253872 19.798208329 1.1994842
2  I(api^0.5)  1.767678556  1.780680057  1.779660626  1.791758329 0.2292382
3  log(qOrig)  0.793845684  0.800090361  0.799910778  0.808492948 0.4500310
4      sindoy  0.133679933  0.138475467  0.138937603  0.142467345 1.2910046
5     t_decyr -0.008408377 -0.007854525 -0.007889489 -0.007452204 1.4277634
     CV (%)
1 3.0806800
2 0.4005592
3 0.6262473
4 2.1565331
5 3.6911119
```

`api`, and `qOrig`, show very little variation across the different outlier fits (<1% QCD and CV), with `sindoy` in third (or fourth if using QCD). Once again, the intercept and `t_decyr` terms vary more, but not by a large amount.

Autocorrelated errors

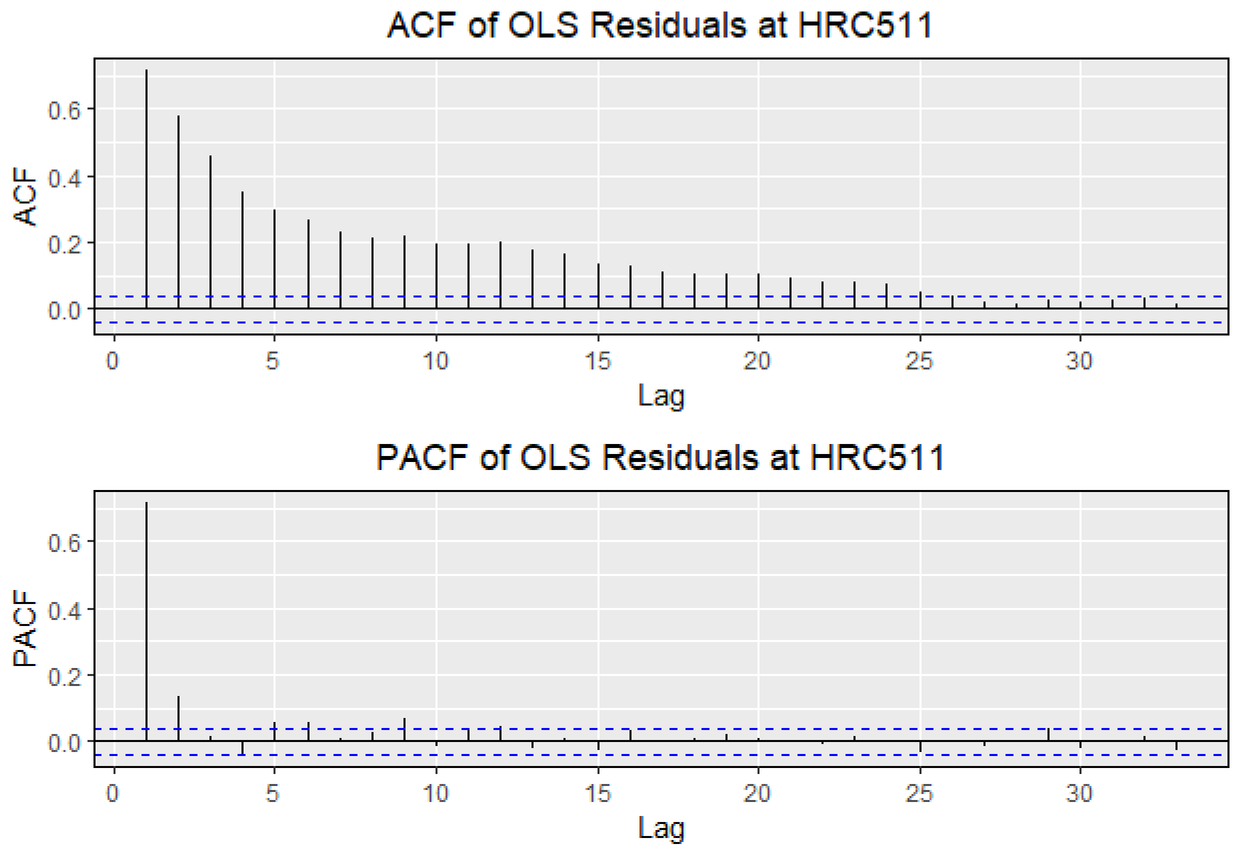


Figure 20*: ACF and PACF plot for HRC511 OLS residuals*

For station HRC511 we will need a correlation structure at least to lag 2 and maybe higher as the PACF values are also statistically significant at lags 4, 5, and 6.

Generalized least squares regression

Limitations of OLS

Serial autocorrelation is common in time series data, violating a major OLS assumption of uncorrelated residuals. While OLS provides unbiased *mean* estimates for the model terms (intercept, coefficients, error), the presence of correlated errors results in the estimates having biased variance, and the model is considered “inefficient.” Efficiency is a measure of a model’s statistical quality, sometimes expressed using the variances. If a model is inefficient, it will not provide the best variances for the model terms and, consequently, the p-values and confidence intervals would be invalid.

As an example, at station HRC509, the estimated linear time (`t_decyr`) coefficient for `fit4` is approximately $0.011118 \pm 6.039 \times 10^{-3}$. With all other covariates being equal, `Log(ssc)` increases by 0.011118 per year from the date of the first observation. An equivalent statement is that SSC has increased by approximately 1.118% per year. However, this estimate may not be statistically significant because the coefficient’s variance is biased and not correctly estimated.

GLS theoretical background

To estimate the best or least unbiased variance, we turn to generalized least squares (GLS), which is a technique for developing a regression model whose residuals or errors correlate with themselves, with the other covariates, or if the errors show heteroskedasticity (residuals have unequal variances over range of observations). GLS applies iterative numeric methods to estimate the covariance matrix that best fits the data. Letting *Y*, *X* be log(SSC) and its covariates, respectively; β the coefficients of the covariates; *k* the chronological order of the observations; and η_k the error term at the *k*th observation, the regression equation for log(SSC) is:

$$y_k = \beta_0 + \mathrm{X}^{\mathrm{T}} \cdot \boldsymbol{\beta} + \eta_k$$

Where:

$$\eta_k \quad = \sum_{i=1}^{p} \theta_i \, \eta_{i-1} + \sum_{i=1}^{q} \psi_i \, \varepsilon_{i-1} + \varepsilon_k$$

$$\eta_k \quad = \mathrm{AR}(p) + \mathrm{MA}(q)$$

The error term is a linear function containing two components: autoregression to lag *p* (AR) and moving average (MA) to lag *q*, respectively. θ, ψ are constants and ε is random and i.i.d. with mean zero. For reference, in OLS, $\eta = \varepsilon$ and the residual term has a mean of zero and constant variance. MA terms are easier to understand: the error of the k^{th} prediction is the previous error multiplied with a constant ψ_k. The AR terms[20] are less intuitively defined here because η_k is not an observed quantity, but a random variable whose covariance structure addresses correlated and heteroskedastic errors to lag *p*. In any case, *p* and *q* denote the number of additional coefficients or parameters that would be added to the regression model to correct for autocorrelation. If *q* is zero, then the error term is an AR(*p*) process and likewise if *p* is zero, then the error term is an MA(*q*) process. Additional details on GLS and time series modeling are plentiful (Aitken, 1936; Fox, 2002; Strutz, 2011).

Procedure

Normally, the next step from here is to try fitting models using the `nlme` package's `gls` function. Using the PACF and ACF plots as guides, one would iteratively specify integer values for *p* and *q* until the resulting fit eliminates autocorrelated errors. Example code for station 510, fitting an ARMA(1,1) model:

```
require(nlme)
fitARMAp1q1 <- gls(
  model = log(ssc) ~ log(qOrig) + I(api^0.5) + sindoy + t_decyr,
  data = hrc, correlation = corARMA(p = 1, q = 1), method = 'ML')
summary(fitARMAp1q1)
```

```
Generalized least squares fit by maximum likelihood
  Model: log(ssc) ~ log(qOrig) + I(api^0.5) + sindoy + t_decyr
  Data: hrc_qaqc
```

[20] In other contexts, purely autoregressive models are based on past response values, i.e., an AR(p) model is $y_k = \beta + \theta_1 \cdot y_{k-1} + \cdots + \theta_p \cdot y_{k-p} + \varepsilon$ – note the lack of covariates

```
      AIC      BIC    logLik
  3232.65 3279.657 -1608.325

Correlation Structure: ARMA(1,1)
 Formula: ~1
 Parameter estimate(s):
      Phi1     Theta1
0.74132358 0.03588333

Coefficients:
                Value Std.Error  t-value p-value
(Intercept) 19.523626 12.192863  1.60123  0.1094
log(qOrig)   0.882333  0.018224 48.41624  0.0000
I(api^0.5)   1.510990  0.062606 24.13509  0.0000
sindoy       0.212813  0.052037  4.08965  0.0000
t_decyr     -0.008033  0.006065 -1.32449  0.1855

 Correlation:
           (Intr) lg(qO) I(^0.5 sindoy
log(qOrig)  0.051
I(api^0.5)  0.077 -0.115
sindoy      0.065 -0.193  0.008
t_decyr    -1.000 -0.053 -0.079 -0.065

Standardized residuals:
        Min          Q1         Med          Q3         Max
-3.75552739 -0.70280649 -0.09856051  0.64646560  3.31374705

Residual standard error: 0.6818319
Degrees of freedom: 2633 total; 2628 residual
```

Then plotting the fitted model's residuals' ACF:

```
fit_acf <- ACF(fitARMAp1q1, resType = 'normalized')
fit_res <- residuals(fitARMAp1q1)
ggAcf(fit_res) + theme(plot.title = element_text(hjust = 0.5),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

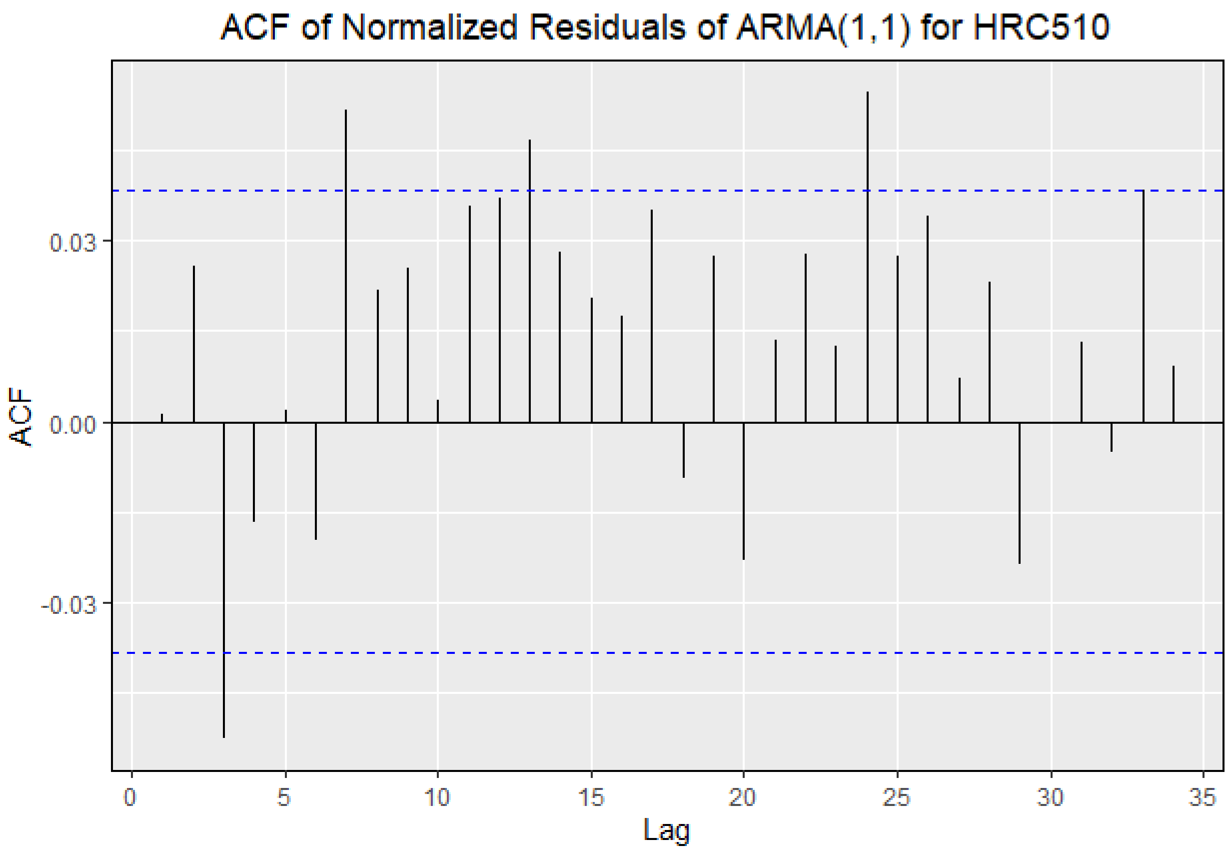


Figure 21*: Normalized residuals for HRC510 GLS fit with correlation structure ARMA(p=1,q=1)*

The blue dashed line is the 95% confidence interval below which autocorrelation is not statistically significant. The plot shows that autocorrelation still exists and that we need to use higher values of *p* or *q*.

Due to the size of the datasets and the number of covariates–each station has >2000 observations–the computation time is lengthy using the available numeric methods built into `nlme`; computation time can be upwards to 12 hours in some cases for high-order ARMA models. Fortunately, computation is cheap nowadays and automating this procedure is fairly straightforward with the right equipment.

Utilizing the Regional Water Board's dedicated modeling computer, we fit up to 40 models simultaneously as the CPU has 20 cores with two processing threads each. For each station, the automated procedure fits AR, MA, and ARMA models up to lag 4, with all combinations of MA and AR components. E.g. AR(1), MA(1), ARMA(1,1), MA(1,1), etc. with the final fit being ARMA(4,4). This procedure all took about 72 hours for all three stations, with and without outliers removed. Please see the script named `fitARMA.R` for the full details on the automated procedure. After the automated script completes, the next section of this appendix compares models to each other to choose the best fit for performing trends analysis.

4. Final model selection

This section steps through the diagnostics process for the selecting a fitted GLS model for trend analysis. The automated model fitting script (`fitARMA.R`) creates the `bestFit` model object for each station, with and without outliers removed. However, that model is not necessarily the best of the group, because the automated script defines "best" solely on Akaike's Information Criterion (AIC). The automated script produces an RData file that contains all GLS fits. The final model selection process utilizes other metrics as well as graphics to determine the best autocorrelation error structure. In general, the best fit should meet most or all of the following criteria:

- High goodness-of-fit statistics ($R^2 > 0.60$ and/or NSE > 0.60).
  - In general, all GLS models with autoregressive moving average (ARMA) correlation structures yield R2 and NSE very close to that of the OLS model. As such, R2 and NSE values are displayed only once per station-outlier combination.
- Autocorrelation (ACF) function accounts up to the first five lags for which the OLS model has statistically significant partial autocorrelation (PACF). We can inspect using ACF/PACF plots of the normalized residuals as well as checking the 95 percent confidence interval's (95CI) values against the ACF/PACF values. The ACF for a lag is significant if it exceeds the 95CI. The 95CI varies with the dataset size as the 95CI depends on the number of observations in the fitting dataset. Exceptions and caveats:
  - If the fifth significant lag is relatively short (≤5), then longer lags are considered
  - Conversely, if the fifth significant lag is very long (≥20), then a shorter lag is considered.
  - The choice of five lags is arbitrary and only serves as a guidepost on judging relative performance between models. Similar to the initial model selection process, the rationale for five is based tenuously on the five degrees of freedom used for the OLS fits.
- Formulas are relatively simple without sacrificing goodness-of-fit or likelihood (i.e., fewer parameter terms but comparable AIC/BIC)
- Statistically "unique" when compared to simpler models
  - That is, likelihood ratio test statistic's p-value is statistically significant at $\alpha = 0.05$ with an asymptotic χ^2 distribution
- Minimal AIC and/or BIC when compared to other model formulas

As noted above, diagnostics and final model selection process cover models with and without outliers removed. As with previous sections, code is shown once if reused later in the document.

Model fits using full dataset

Station 509

First, load in data:

```
load(here('analysis/full_dataset/SSC_fits_HRC509.RData'))
```

The top five models by AIC and their corresponding BIC are:

```
fit_compare %>% select(-p, -q, -BIC, -meanRank) %>%
  select(model, df, R2, NSE, contains('AIC'), rnkBIC) %>%
  head(5)
```

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   AIC rnkAIC rnkBIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp2q0     8 0.75  0.75  3363.      1      1
2 fitARMAp1q1     8 0.75  0.75  3364.      2      2
3 fitARMAp1q2     9 0.751 0.751 3364.      3      4
4 fitARMAp1q3    10 0.751 0.751 3365.      4      7
5 fitARMAp3q0     9 0.751 0.751 3365.      5      5
```

ARMA(2,0) [or simply AR(2) with no MA terms] performs the best out of the five. Let's average the AIC and BIC ranks to select models for ACF and PACF plotting.

```
fit_compare %>% select(-p, -q, -AIC, -BIC) %>% arrange(meanRank) %>%
  head(5)
```

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE rnkAIC rnkBIC meanRank
  <chr>       <dbl> <dbl> <dbl>  <dbl>  <dbl>    <dbl>
1 fitARMAp2q0     8 0.75  0.75       1      1      1
2 fitARMAp1q1     8 0.75  0.75       2      2      2
3 fitARMAp1q2     9 0.751 0.751      3      4      3.5
4 fitARMAp3q0     9 0.751 0.751      5      5      5
5 fitARMAp1q3    10 0.751 0.751      4      7      5.5
```

Going by the mean ranks, let's look at the ACF of the top three along with the PACF of OLS. While ACF and PACF are not the same thing, the PACF's vertical axis scales are more visually helpful in determining whether the PACF or ACF is significant. ACF/PACF values at lags 0 and 1 are not included for this reason.

```
colnms <- c('lag', 'ARMA(1,1)', 'AR(2)', 'AR(3)', 'OLS')
fits_acf <-
  list(fitARMAp2q0, fitARMAp1q1, fitARMAp3q0) %>%
  map_dfc(~ACF(.x, resType = 'normalized', maxLag = 25)$ACF) %>%
  cbind(lag = 0:25, .,
        OLS = c(0, pacf(residuals(fit_LM), plot = F, lag.max = 25)$acf)) %>%
    'names<-'(colnms) %>%
  pivot_longer(!lag, names_to = 'Model', values_to = 'ACF') %>%
  mutate(lag = as.factor(lag), Model = factor(Model, levels = colnms[-1]))
alpha = 0.95
conf_acf <- c(qnorm((1-alpha)/2)/sqrt(nrow(hrc)),
              qnorm((1+alpha)/2)/sqrt(nrow(hrc)))

ggplot(data = subset(fits_acf, !lag %in% c('0', '1')),
       aes(lag, y = ACF, fill = Model)) +
  geom_col(position = "dodge") +
  geom_hline(aes(yintercept = conf_acf[1], size = '95% CI'),
             linetype = 'dashed') +
  geom_hline(yintercept = conf_acf[2], linetype = 'dashed') +
```

```
  geom_hline(yintercept = 0) +
  scale_size_manual(values = c(0.3, 0.3), name = '') +
  scale_fill_grey(start = 0.8, end = 0.2) + theme_classic() +
  labs(title = 'Autocorrelation of Normalized Residuals (HRC509)',
       y = 'ACF or PACF', x = 'Lag') +
  geom_vline(xintercept = 1:length(unique(fits_acf$lag)) + 0.5,
             linetype = 'dotted', colour = 'gray65') +
  theme(plot.title = element_text(hjust = 0.5), legend.position = "bottom",
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

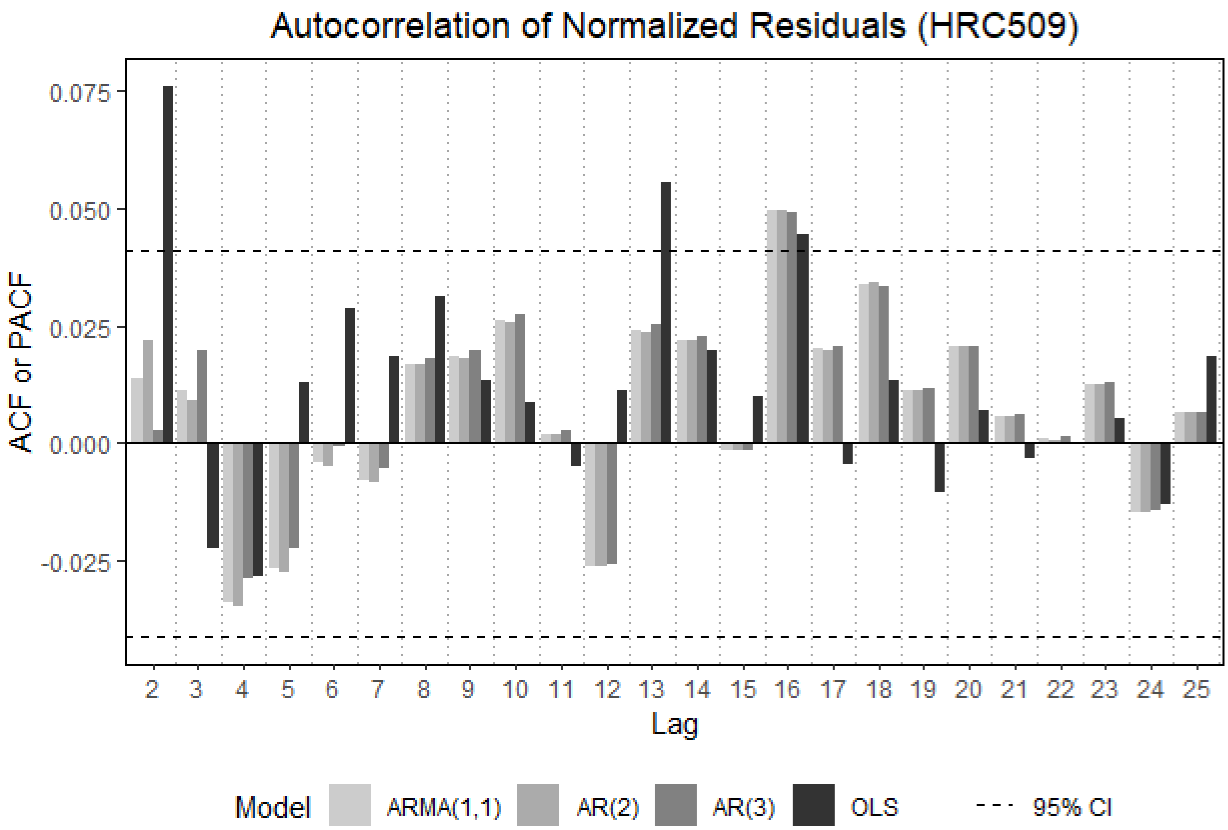


Figure 22: *ACF and PACF plots of the OLS and "top" GLS model fits for HRC509, respectively*

All three GLS models explain up to lag 16. Let's also get the exact ACF values, compare them to the critical/significant value, and look at the highest lag that the GLS models account for.

```
sig_acf <- fits_acf %>%
  pivot_wider(id_cols = everything(), names_from = Model, values_from = ACF) %>%
  select(-lag) %>% abs %>% '>'(conf_acf[2]) %>%
  apply(2, which) %>% map(~.x - 1)
```

Significant (α=0.05) ACF value is $\pm$ 0.041. Note that `conf_acf` increases as the square root term decreases. That is, at lag 1 and *N* total number of observations, we calculate the correlation between residuals 1 through *N*-1 and 2 through *N*, dropping one residual value for every lag (thus the square root term should really be *N*-1). For large *N*, the significant ACF decreases slowly, so for remainder of this document, “significant ACF” (or PACF) will use *N* for all lags to be conservative and avoid unnecessary plotting.

```
nlags <- sig_acf$`OLS` %>% length
if (nlags > 5) {
  nlags <- 5
  cat(glue("OLS residuals' fifth significant PACF is lag {sig_acf$`OLS`[nlags]}\n"))
} else {
  cat(glue("OLS residuals' highest significant PACF is lag {sig_acf$`OLS`[nlags]}\n")
)
}
```

```
OLS residuals' highest significant PACF is lag 16
```

```
cat("\nTop models' lowest significant ACF at lag:\n")
```

```

Top models' lowest significant ACF at lag:
```

```
map(sig_acf[-length(sig_acf)], ~.x[2]) %>% unlist
```

```
ARMA(1,1)     AR(2)     AR(3)
       16        16        16
```

They all account up to lag 16. The two simpler models do not have MA components and are thus less complex. AR(2) is also nested within AR(3), but the former has a lower AIC, BIC, and fewer terms. We go with AR(2) for station HRC509. We save the chosen model fit along with other data for the next step, explained in the Summary subsection at the end.

```
bestFit <- fitARMAp2q0
obj_save <- c('hrc_all', 'hrc', 'hrc_qaqc', 'qssc', 'ppt_api', 'hppt_all',
              'hapis_all', 'pptapi_fit_compare', 'decay_rates', 'fit_compare',
              'fits_acf', glue("fit{c(0:4, 'GLS', '_GLSnot', '_LM', '_LMnot')}"),
              'bestFit', 'stn', 'outly', 'sig_acf')
save(list = obj_save,
     file = here('analysis/full_dataset/SSC_bestFit_HRC509.RData'))
```

Station 510

The top five models by AIC are:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   AIC rnkAIC rnkBIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp4q4    14 0.732 0.732 3554.      1      8
2 fitARMAp4q1    11 0.732 0.732 3555.      2      1
3 fitARMAp3q4    13 0.732 0.732 3558.      3      3
4 fitARMAp4q3    13 0.732 0.732 3559.      4      5
5 fitARMAp2q4    12 0.733 0.733 3567.      5      9
```

The top five models by BIC are:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   BIC rnkBIC rnkAIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp4q1    11 0.732 0.732 3620.      1      2
2 fitARMAp1q0     7 0.734 0.734 3628.      2     10
```

```
3 fitARMAp3q4    13 0.732 0.732 3635.      3      3
4 fitARMAp1q4    11 0.734 0.734 3635.      4      6
5 fitARMAp4q3    13 0.732 0.732 3635.      5      4
```

Using both metrics, ARMA(4,1) is the best compared to the alternatives, but let's average the ranks.

```
# A tibble: 5 x 7
# Rowwise:
  model           df    R2   NSE rnkAIC rnkBIC meanRank
  <chr>        <dbl> <dbl> <dbl>  <dbl>  <dbl>    <dbl>
1 fitARMAp4q1    11 0.732 0.732      2      1      1.5
2 fitARMAp3q4    13 0.732 0.732      3      3      3
3 fitARMAp4q4    14 0.732 0.732      1      8      4.5
4 fitARMAp4q3    13 0.732 0.732      4      5      4.5
5 fitARMAp1q4    11 0.734 0.734      6      4      5
```

The average ranks favor more complex ARMA error structures. For plotting purposes, we use the top two and AR(1), which had a lower BIC, and get a better spread of degrees of freedom among the model fits.

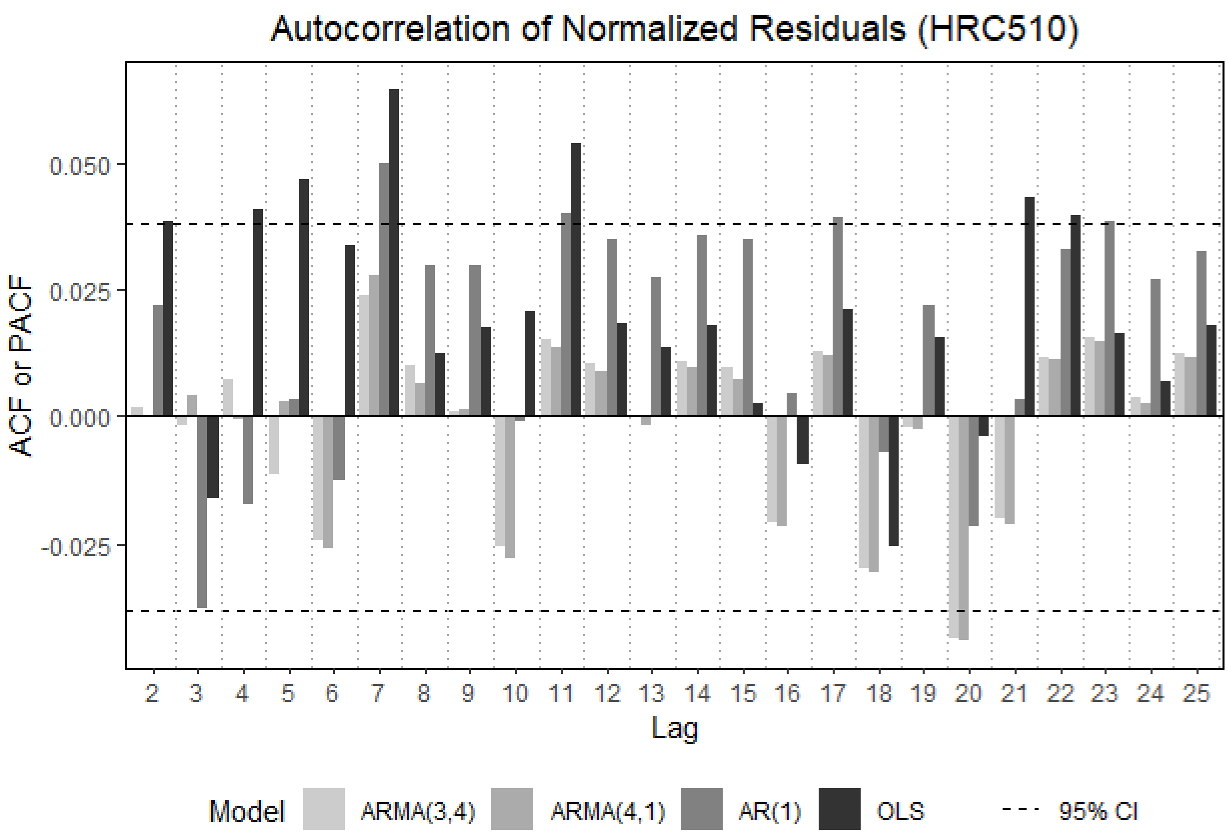


***Figure 23**: ACF and PACF plots of the OLS and "top" GLS model fits for HRC510, respectively*

For station HRC510, the significant PACF is approximately $\pm$ 0.038.

```
OLS residuals' fifth significant PACF is lag 7
```

```
Top models' lowest significant ACF at lag:
ARMA(3,4) ARMA(4,1)     AR(1)
       20        20         7
```

OLS residual's highest significant PACF is at lag 16. ARMA(4,1) accounts up to that lag and is less complex than ARMA(3,4). We select ARMA(4,1) as the residual correlation structure for station HRC510 fitted with the full dataset.

Station 511

The top five models by AIC are:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   AIC rnkAIC rnkBIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp4q3    13 0.794 0.788 2594.      1      7
2 fitARMAp4q4    14 0.794 0.788 2596.      2     16
3 fitARMAp1q4    11 0.794 0.788 2598.      3      3
4 fitARMAp3q3    12 0.794 0.788 2604.      4     11
5 fitARMAp4q2    12 0.794 0.788 2604.      5     13
```

By BIC:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   BIC rnkBIC rnkAIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp1q1     8 0.794 0.788 2659.      1     10
2 fitARMAp2q0     8 0.794 0.788 2659.      2     11
3 fitARMAp1q4    11 0.794 0.788 2662.      3      3
4 fitARMAp3q0     9 0.794 0.788 2666.      4     12
5 fitARMAp1q2     9 0.794 0.788 2666.      5     13
```

The only agreement between AIC and BIC is ARMA(1,4) and all the other models are on opposite ends. By mean rank:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE rnkAIC rnkBIC meanRank
  <chr>       <dbl> <dbl> <dbl>  <dbl>  <dbl>    <dbl>
1 fitARMAp1q4    11 0.794 0.788      3      3      3
2 fitARMAp4q3    13 0.794 0.788      1      7      4
3 fitARMAp1q1     8 0.794 0.788     10      1      5.5
4 fitARMAp2q0     8 0.794 0.788     11      2      6.5
5 fitARMAp3q2    11 0.794 0.788      6      8      7
```

For plotting, let's choose ARMA(1,4), ARMA(4,3), ARMA(4,4), ARMA(1,1), and AR(2).

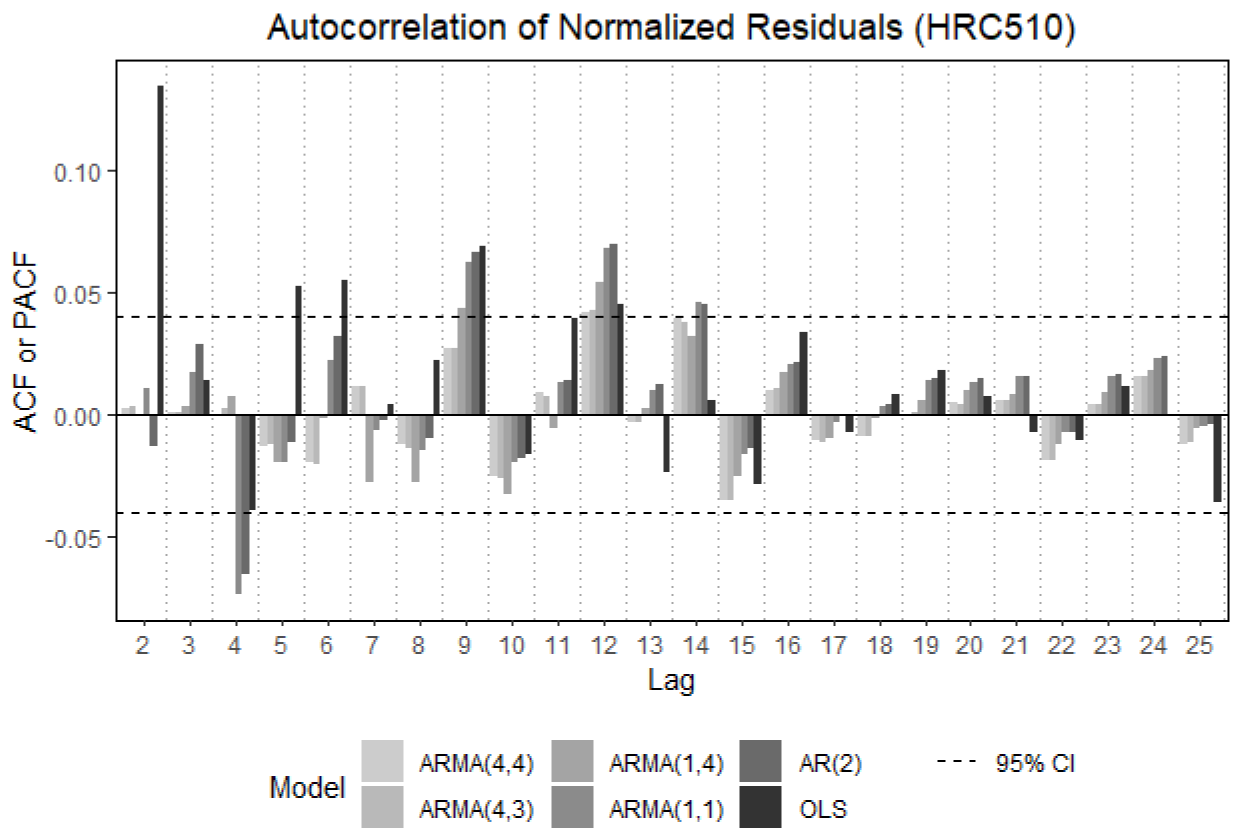


***Figure 24**: ACF and PACF plots of the OLS and "top" GLS model fits for HRC511, respectively*

```
OLS residuals' fifth significant PACF is lag 9


Top models' lowest significant ACF at lag:
ARMA(4,4) ARMA(4,3) ARMA(1,4) ARMA(1,1)     AR(2)
       12        12         9         4         4
```

While ARMA(4,3) is on the more complex side, that model accounts for autocorrelation greater than OLS's fifth significant PACF (the highest OLS significant lag is 12). We select ARMA(4,3) as the model for HRC511.

Models fits with outliers removed

Station 509

The top five models by AIC and their corresponding BIC are:

```
# A tibble: 5 x 7
# Rowwise:
  model            df    R2   NSE   AIC rnkAIC rnkBIC
  <chr>         <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp1q0      7 0.761 0.758 2985.      1      1
2 fitARMAp2q0      8 0.761 0.758 2986.      2      2
3 fitARMAp1q4     11 0.761 0.758 2986.      3     11
4 fitARMAp1q1      8 0.761 0.758 2986.      4      3
5 fitARMAp1q3     10 0.761 0.758 2986.      5      7
```

ARMA(1,0) performs the best out of the five for both metrics. Averaging AIC and BIC ranks to select models for ACF and PACF plotting:

```
# A tibble: 5 x 7
# Rowwise:
  model           df    R2   NSE rnkAIC rnkBIC meanRank
  <chr>        <dbl> <dbl> <dbl>  <dbl>  <dbl>    <dbl>
1 fitARMAp1q0      7 0.761 0.758      1      1      1
2 fitARMAp2q0      8 0.761 0.758      2      2      2
3 fitARMAp1q1      8 0.761 0.758      4      3      3.5
4 fitARMAp1q3     10 0.761 0.758      5      7      6
5 fitARMAp1q2      9 0.761 0.758      8      4      6
```

Going by the mean ranks, we look at AR(1), AR(2), and ARMA(1,1) of the top three along with the PACF of the OLS fit, outliers excluded.

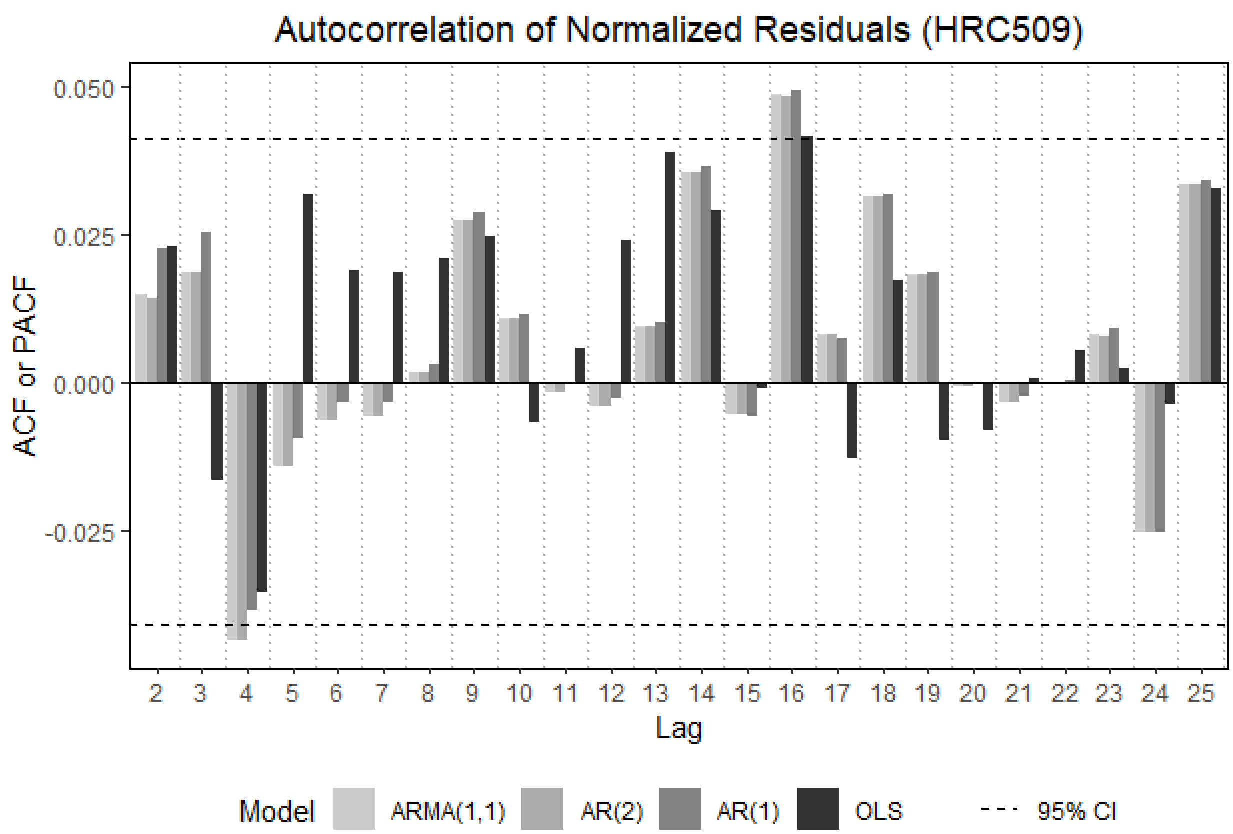


Figure 25*: ACF and PACF plots of the OLS and "top" GLS model fits for HRC509, respectively; outliers removed*

```
OLS residuals' highest significant PACF is lag 16


Top models' lowest significant ACF at lag:
ARMA(1,1)     AR(2)     AR(1)
        4         4        16
```

AR(1) is the simplest and also accounts for up to lag 16, which is the highest significant PACF for OLS and so we choose AR(1) for HRC509 fitted without outliers removed. Recall that for the full dataset model fit, HRC509's best performer is AR(1).

Station 510

The top five models by AIC are:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   AIC rnkAIC rnkBIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp4q1    11 0.739 0.739 3201.      1      1
2 fitARMAp4q4    14 0.739 0.739 3204.      2     12
3 fitARMAp2q4    12 0.739 0.739 3211.      3      6
4 fitARMAp2q3    11 0.74  0.74  3216.      4      5
5 fitARMAp1q4    11 0.74  0.74  3218.      5      7
```

The top five models by BIC:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE   BIC rnkBIC rnkAIC
  <chr>       <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp4q1    11 0.739 0.739 3266.      1      1
2 fitARMAp1q0     7 0.74  0.74  3274.      2     16
3 fitARMAp2q0     8 0.74  0.74  3279.      3     15
4 fitARMAp1q1     8 0.74  0.74  3280.      4     18
5 fitARMAp2q3    11 0.74  0.74  3281.      5      4
```

Averaging the ranks:

```
# A tibble: 5 x 7
# Rowwise:
  model          df    R2   NSE rnkAIC rnkBIC meanRank
  <chr>       <dbl> <dbl> <dbl>  <dbl>  <dbl>    <dbl>
1 fitARMAp4q1    11 0.739 0.739      1      1      1
2 fitARMAp2q4    12 0.739 0.739      3      6      4.5
3 fitARMAp2q3    11 0.74  0.74       4      5      4.5
4 fitARMAp1q4    11 0.74  0.74       5      7      6
5 fitARMAp4q4    14 0.739 0.739      2     12      7
```

The results are similar to the full dataset as the average ranks favor more complex models. We plot the ACF of ARMA(4,1), ARMA(2,4), ARMA(4,4), AR(1), and AR(2). While numerous, this selection also provides a good spread of degrees of freedom among the model fits.

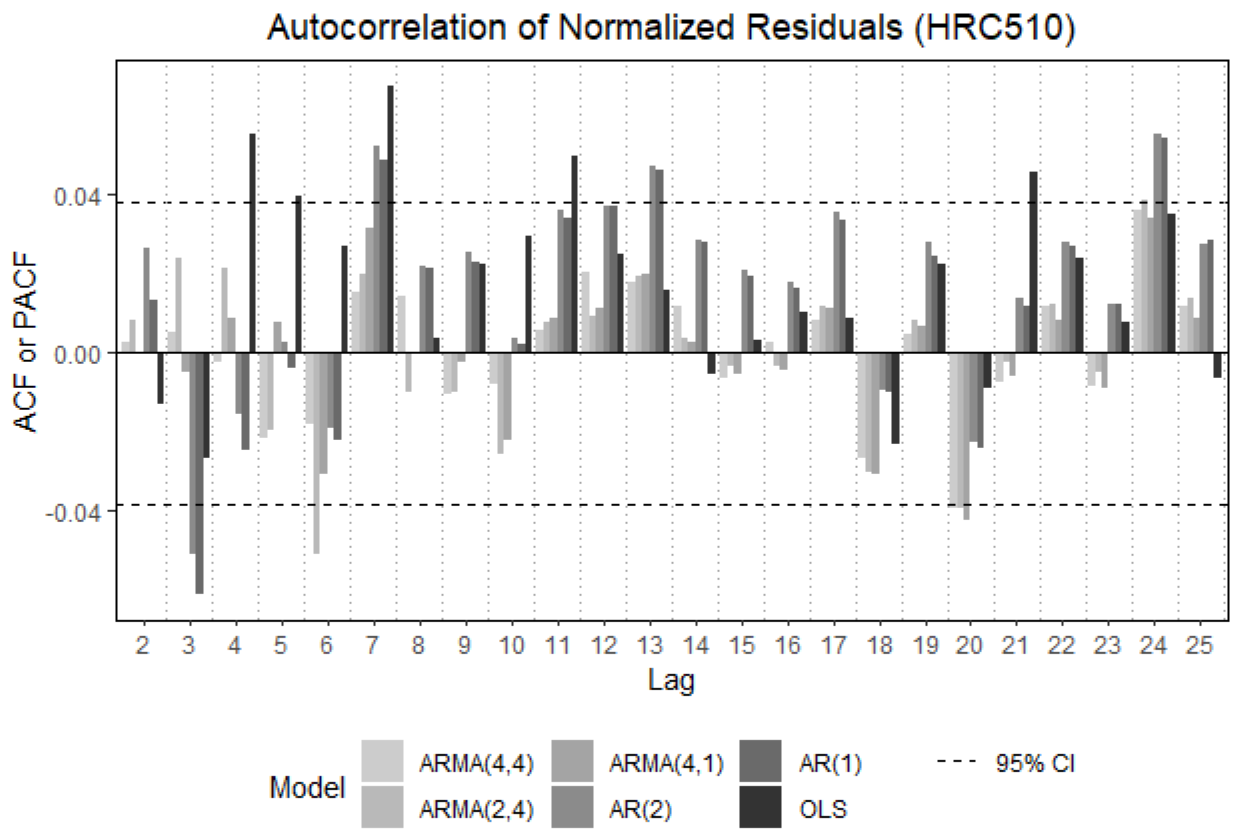


Figure 26: *ACF and PACF plots of the OLS and selected GLS model fits for HRC510, respectively; outliers removed*

```
OLS residuals' fifth significant PACF is lag 11


Top models' lowest significant lag at:
ARMA(4,4) ARMA(2,4) ARMA(4,1)     AR(2)     AR(1)
       20         6        20         3         3
```

OLS residual's fifth significant PACF is at lag 11 (highest PACF at lag 21). ARMA(4,1) accounts up to lag 20 and has the best performance for AIC/BIC. We go with ARMA(4,1) for the fits where outliers are removed. Note: ARMA(4,1) is the same error structure chosen for the full dataset.

Station 511

The top five models by AIC are:

```
# A tibble: 5 x 7
# Rowwise:
  model           df    R2   NSE   AIC rnkAIC rnkBIC
  <chr>        <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp4q3     13   0.8 0.791 2381.      1      7
2 fitARMAp1q4     11   0.8 0.791 2383.      2      1
3 fitARMAp4q4     14   0.8 0.791 2383.      3     16
4 fitARMAp3q3     12   0.8 0.791 2391.      4     11
5 fitARMAp4q2     12   0.8 0.791 2392.      5     13
```

By BIC:

```
# A tibble: 5 x 7
# Rowwise:
  model           df    R2   NSE   BIC rnkBIC rnkAIC
  <chr>        <dbl> <dbl> <dbl> <dbl>  <dbl>  <dbl>
1 fitARMAp1q4     11   0.8 0.791 2447.      1      2
2 fitARMAp1q1      8   0.8 0.791 2447.      2     10
3 fitARMAp2q0      8   0.8 0.791 2447.      3     11
4 fitARMAp3q0      9   0.8 0.791 2454.      4     12
5 fitARMAp1q2      9   0.8 0.791 2454.      5     13
```

Mean rank:

```
# A tibble: 5 x 7
# Rowwise:
  model           df    R2   NSE rnkAIC rnkBIC meanRank
  <chr>        <dbl> <dbl> <dbl>  <dbl>  <dbl>    <dbl>
1 fitARMAp1q4     11   0.8 0.791      2      1      1.5
2 fitARMAp4q3     13   0.8 0.791      1      7      4
3 fitARMAp1q1      8   0.8 0.791     10      2      6
4 fitARMAp2q0      8   0.8 0.791     11      3      7
5 fitARMAp3q3     12   0.8 0.791      4     11      7.5
```

Aside from ARMA(1,4), the ranks by AIC and BIC have large differences. Let’s plot the ACF and compare ARMA(4,3), ARMA(1,4), ARMA(1,1), and AR(2).

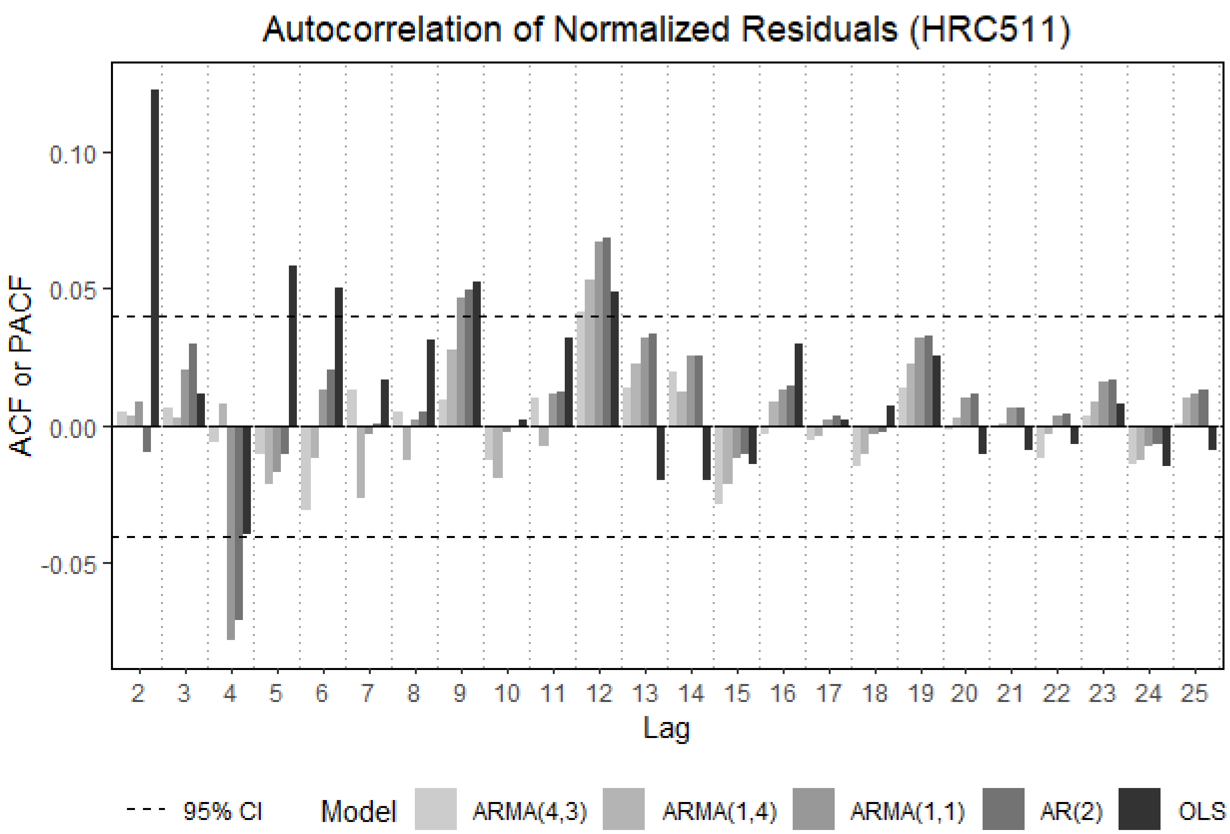


***Figure 27**: ACF and PACF plots of the OLS and "top" GLS model fits for HRC511, respectively; outliers removed*

```
OLS residuals' fifth significant PACF is lag 9


Top models' lowest significant lag at:

ARMA(4,3) ARMA(1,4) ARMA(1,1)     AR(2)
       12        12         4         4
```

OLS residual's fifth significant PACF is at lag 9 (highest PACF at lag 12). ARMA(1,4) accounts up to lag 12 and has the best performance by mean ranks of AIC and BIC. We will go with ARMA(1,4) for the dataset with outliers removed. Note: the chosen error structure for the full dataset is more complex at ARMA(4,3).

Summary

The table below summarizes the chosen error structures for each stations' datasets, with and without outliers.

```
summry <- tibble(
  'Station' = rep(paste('HRC', 509:511, sep = ''), each = 2),
  'Outliers Removed' = rep(c('No','Yes'), 3),
  'Error Structure' = c('AR(2)', 'AR(1)', 'ARMA(4,1)', 'ARMA(4,1)', 'ARMA(3,4)',
                        'ARMA(1,4)')) %>% as.data.frame
summry %>% flextable %>% autofit
```

Station	Outliers Removed	Error Structure
HRC509	No	AR(2)
HRC509	Yes	AR(1)
HRC510	No	ARMA(4,1)
HRC510	Yes	ARMA(4,1)
HRC511	No	ARMA(3,4)
HRC511	Yes	ARMA(1,4)

After final model selection, the next step is fitting the same error structure for models that cover various conditions. Specifically, these conditions are: (a) without linear time (`t_decyr`); (b) only including data for the time period that HRC has ownership (WY2008 - WY2020)[21], with and without linear time covariate; (c) only including data for the past five years (WY2016 - WY2020), with and without linear time covariate. This process is automated with the script `completeFit.R`. This script must be run in a command line interface. Once the script has finished for all station-outlier combinations, we will have all the pieces needed to perform the trend analysis.

[21] Note: while 2021 data is available with HRC's recent 2021 annual hydrology report, this analysis was completed before that date. Adding an additional water year is not trivial given that certain elements of the process would need to be repeated (e.g. hourly precipitation), including the computationally intensive automated model fitting.

5. Trend analysis

With the data processing and model fitting procedures completed, we can finally analyze trends over time using graphics as well as formal statistical inference. The specific variable we are looking at are the residual SSC after accounting for covariates: stream discharge, antecedent precipitation, and calendar day of year. The residual SSC is the observed SSC minus the model prediction. Positive residuals mean that observed SSC is greater than modeled and negative means they are lower. The logic is that if a statistically significant time trend exists, then that trend is less attributable to the covariates—that is, some unknown factor or variable not included in the model could explain the trend. If not statistically significant, then changes in SSC have not occurred between the start and end of the analysis time period.

The methods for trend analysis comprise:

- Graphical interpretation of residual SSC over time plot, derived from a model without a linear time covariate (i.e. `t_decyr` excluded). Where relevant, individual years that deviate from predictions will be examined more closely and this examination may include other statistical tests or comparisons to other covariate data.

- Mann-Kendall (MK) trend test and Theil-Sen slope estimator (Sen slope) of mean annual residuals versus water year (WY) (Mustapha, 2013). MK is a non-parametric statistical test commonly used in the environmental science fields for detecting monotonic trends and their direction. Sen slope is another non-parametric statistic to detect trends over time. Sen is based on a simple linear equation whose parameters are the covariate and response variable medians. Sen and MK are related via Kendall's τ, a non-parametric correlation statistic based on the data ranks or order.

  - For these statistical tests, we use residuals from models that exclude `t_decyr`, and we consider only the whole time period (WY2003-WY2020) and their annual means. Shorter time periods' sample size would be too small and, consequently, lack statistical power. Using annual means avoids SSC's seasonality as MK and Sen slope are only applicable to monotonic trends. While versions of MK tests exist to account for seasonality, not all WYs are recorded in the same manner. That is, the SSC data are not a complete time series with regular intervals throughout; the regular interval sample collection are based on the turbidity threshold sampling (TTS)–the sampling method employed by HRC and public agencies (Lewis & Eads, 2009).

- Where linear time is included, evaluate its coefficient's the p-value for statistical significance ($\alpha = 0.05$). If significant, evaluate the coefficient's sign (direction); magnitude; and confidence interval. The linear time coefficient is relative to the time period of analysis, of which there are three: entire record (WY2003+); HRC timberland ownership (WY2008+), and the last five years (WY2016-WY2020).

We use the following R package and a custom function to produce residual-over-time plots (`plot_resid_ts`). As like other Appendix sections, code is shown only once if repeated again in this section.

```
library(tidyverse)
library(here)
library(glue)
library(fs)
```

```r
library(lubridate)
library(rkt)

plot_resid_ts <- function(fit, fit_means, stn, tzone, start_yr = 2003,
                          end_yr = 2020, pref = 'HRC') {
  breaks <- paste(start_yr:end_yr, '-01-01 00:00:00', sep = '') %>%
    as_datetime(tz = tzone)
  cov_names <- 'logQ, API, and DoY'
  resid_plot <- ggplot(fit, aes(x = dts, y = res)) + geom_point() +
    geom_smooth(method = 'loess', formula = y~x) +
    geom_segment(data = fit_means, size = 2, colour = 'red',
                 aes(y = res, yend = res, x = start_dt, xend = end_dt)) +
    labs(title = glue('Station {pref}{stn}: WY{start_yr}-{end_yr}'),
         x = 'Date-Time',
         y = glue('Residual log(SSC) not explained by {cov_names}')) +
    theme(plot.title = element_text(hjust = 0.5),
          panel.border = element_rect(colour = 'black', fill = NA, size = .5)) +
    scale_x_continuous(breaks = breaks, labels = start_yr:end_yr)
  return(resid_plot)
}
```

Station 509 - Mainstem Elk River

Full dataset

First, load in the RData file generated after running `completeFit.R`.

```r
load(here('analysis/full_dataset/SSC_trends_HRC509.RData'))
```

SSC residuals over time plot

For each station, we start with residual SSC over time plots using the model fit without the linear time covariate `t_decyr`.

```r
plot_resid_ts(fit = mutate(hrc_fit, res = resGLSnotRaw), tzone = tzone,
              fit_means = mutate(hrc_fit_means, res = resGLSnotRaw), stn = stn)
```

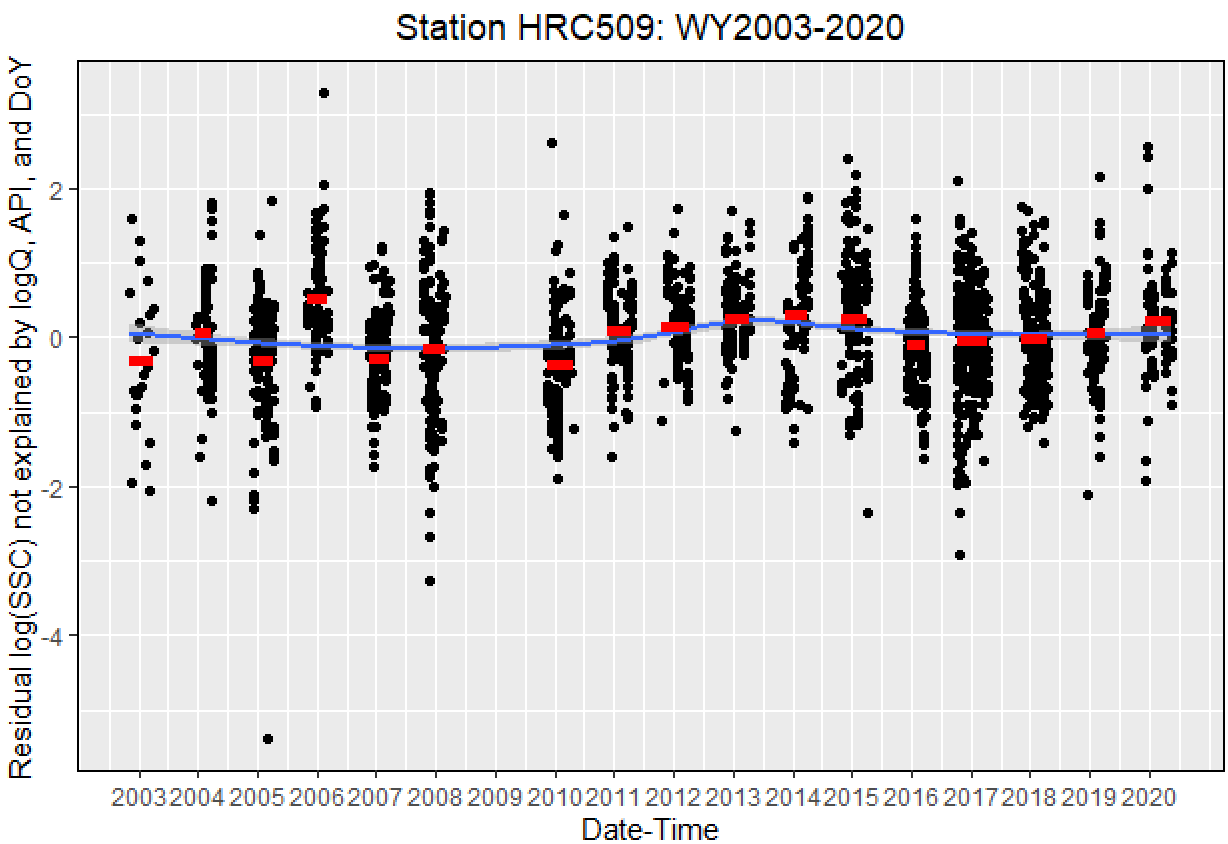


***Figure 28**: Mainstem station HRC509 SSC residuals with full dataset*

The overall trend looks flat. There's a slight dip in residual SSC from 2003 through 2011, but the axis scales and outliers may be obscuring the dip's magnitude. Later, we will remove outliers and get a better look at that dip.

Nonparametric trend testing

Next up is quantifying presence of detecting trends with the MK test and Sen slope. Note: the data record is missing WY2009, so an `NA` value will be assigned to that year's mean SSC residual. `NA` typically indicates missing data.

```
yrs <- 2003:2020
ssc <- c(hrc_fit_means$resGLSnotRaw[1:6], NA, hrc_fit_means$resGLSnotRaw[7:17])
rkt(yrs, ssc)


Standard model
Tau = 0.2794118
Score =  38
var(Score) =  589.3333
2-sided p-value =  0.1274769
Theil-Sen's (MK) or seasonal/regional Kendall (SKT/RKT) slope=  0.0207527
```

While the Sen slope and Kendall's τ indicate increasing residual SSC, they are not statistically significantly different from zero (p-value ≈ 0.127 > α).

GLS model fits with linear time

Second method to quantify trends is to look at the results of the model with linear time covariate included. The most important result is the coefficient's p-value. If the p-value less than the critical threshold of 0.05, then the coefficient is statistically significant.

```
summary(bestFit)
```

```
Generalized least squares fit by maximum likelihood
  Model: log(ssc) ~ log(qOrig) + I(api^0.5) + sindoy + t_decyr
  Data: hrc_qaqc
       AIC      BIC    logLik
  3363.382 3409.297 -1673.691

Correlation Structure: ARMA(2,0)
 Formula: ~1
 Parameter estimate(s):
      Phi1       Phi2
0.65882476 0.07775703

Coefficients:
                 Value Std.Error  t-value p-value
(Intercept) -20.276570 16.158205 -1.25488  0.2097
log(qOrig)    0.497291  0.017242 28.84255  0.0000
I(api^0.5)    2.619240  0.073824 35.47936  0.0000
sindoy        0.379757  0.053773  7.06222  0.0000
t_decyr       0.011550  0.008031  1.43814  0.1505

 Correlation:
           (Intr) lg(qO) I(^0.5 sindoy
log(qOrig)  0.064
I(api^0.5)  0.069 -0.161
sindoy     -0.016 -0.293 -0.007
t_decyr    -1.000 -0.066 -0.071  0.016

Standardized residuals:
        Min          Q1         Med          Q3         Max
-7.37008754 -0.63672097  0.01232402  0.59315566  4.66556557

Residual standard error: 0.7186271
Degrees of freedom: 2297 total; 2292 residual
```

The coefficient indicates increasing SSC over time, but the estimate is not statistically significant with a p-value = 0.1505. Curiously, the intercept term is also not statistically significant, indicating an initial SSC not being significantly different from zero; however, the intercept is not relevant here as we are looking only for trends within specific time periods[22].

Let's see what `t_decyr` looks like if we constrain the time periods to HRC's ownership and the last five years:

```
wy08 <- summary(bestFit_WY08_WY20)$tTable
wy16 <- summary(bestFit_WY16_WY20)$tTable
```

[22] Note: The `summary()` function prints a lot of information about the fitted model. For the remaining subsections, we look at just the coefficients' summary.

```
trimTab <- cbind(wy08[,c(1,4)], wy16[,c(1,4)]) %>% as.data.frame
trimTab_colnames <- c('Estimate (WY08)', 'p-value (WY08)', 'Estimate (WY16)',
                      'p-value (WY16)')
names(trimTab) <- trimTab_colnames
cat('\nTime Period of HRC Ownership (WY2008 - WY2020)\n')
summary(bestFit_WY08_WY20)$tTable
cat('\nLast Five Years (WY2016 - WY2020)\n')
summary(bestFit_WY16_WY20)$tTable
```

```
Time Period of HRC Ownership (WY2008 - WY2020)
                   Value   Std.Error   t-value       p-value
(Intercept) -28.96783052 25.35587367 -1.142450  2.534235e-01
log(qOrig)    0.45805374  0.01946912 23.527197 1.551520e-106
I(api^0.5)    2.64887825  0.08117852 32.630287 9.935403e-183
sindoy        0.44463495  0.06169026  7.207539  8.445543e-13
t_decyr       0.01588658  0.01258794  1.262047  2.071005e-01

Last Five Years (WY2016 - WY2020)
                    Value   Std.Error   t-value      p-value
(Intercept) -107.83968981 87.15821900 -1.237287 2.163112e-01
log(qOrig)     0.36994426  0.03048687 12.134543 1.933765e-31
I(api^0.5)     2.76764269  0.11431163 24.211383 1.260661e-99
sindoy         0.37549078  0.08333220  4.505951 7.500069e-06
t_decyr        0.05502372  0.04319492  1.273847 2.030544e-01
```

Similar to the full dataset, the coefficients are both positive but not statistically significant. At least for this station and location, SSC has not changed in any of the three time periods we selected.

Excluding outliers

Now, we will repeat the same process above for the model with the outliers removed.

SSC residuals over time plot

```
load(here('analysis/without_outliers/SSC_trends_HRC509.RData'))
```

Plotting entire period of record with residuals from the model without *`t_decyr`*:

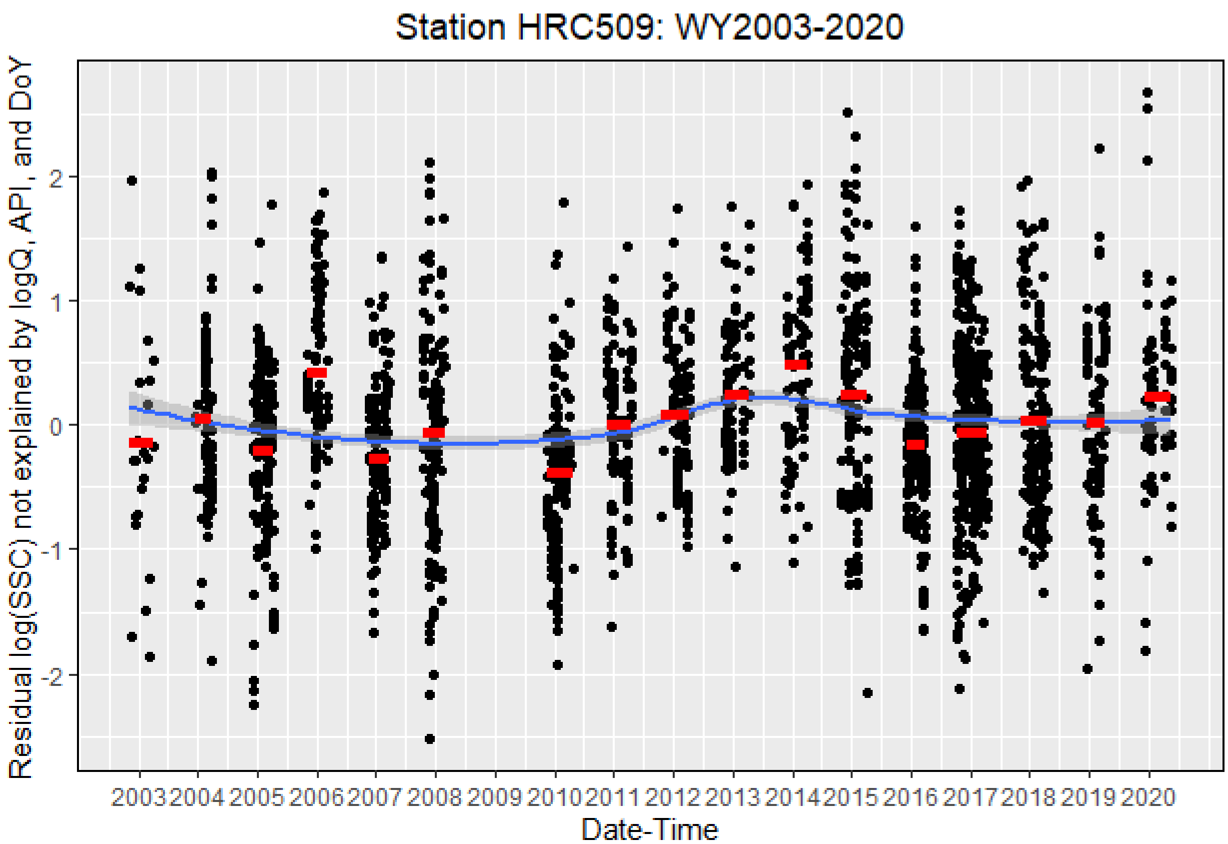


***Figure 29**: Mainstem station HRC509 SSC residuals with outliers removed*

Without the outliers, the dip from WY2003 through WY2011 is more noticeable as well as the bump from WY2013-WY2015. WY2010 has the lowest mean annual SSC residual and WY2014 has the highest. Let's look at the rainfall for those years.

```
# 2010 total across different datasets
ppt_wys <- hppt_all %>% group_by(WY) %>%
  summarize(across(starts_with('S') | starts_with('I'), sum)) %>%
  subset(WY %in% c(2010, 2014))
# Average for all 2003-2020
ppt_avg <- hppt_all %>% group_by(WY) %>%
  summarize(across(starts_with('S') | starts_with('I'), sum)) %>%
  summarize(across(!WY, mean)) %>% cbind(data.frame('WY' = 'Mean'), .)
print(rbind(ppt_wys, ppt_avg))
```

```
# A tibble: 3 x 6
  WY    ST2sm ST2wm ST4sm ST4wm IEMsm
  <chr> <dbl> <dbl> <dbl> <dbl> <dbl>
1 2010   58.5  59.1  58.5  59.0  48.1
2 2014   22.3  22.5  22.3  22.5  23.2
3 Mean   44.6  45.1  44.9  45.2  44.2
```

Relative to the time period of record (WY2013-WY2020) and among these rainfall datasets, WY2010 is an above average year and WY2014 is below average–in fact, WY2014 was the lowest in the record. Observed SSC for 2014 were greater than the modeled despite hydrologic conditions favoring the opposite. To support this finding, we check whether residuals are significantly different from zero. We use the *t* and Wilcoxon tests that evaluates whether the residual means and medians are, respectively, statistically significantly less (WY2010) or greater (WY2014) than zero (one sided α=0.05). To account for autocorrelation in the raw residuals, tests are performed with the normalized residuals[23].

```
alt <- c('less', 'greater')
res_type <- 'resGLSnotNorm'
res_wys <- hrc_fit %>% select(WY, !!res_type) %>%
  subset(WY %in% c(2010, 2014)) %>% split(., f = .$WY) %>%
  map(~.[, res_type])
wc <- res_wys %>% map2(.y = alt, ~wilcox.test(.x, alternative = .y)) %>%
  map(~.$p.value) %>% unlist
tt <- res_wys %>% map2(.y = alt, ~t.test(.x, alternative = .y)) %>%
  map(~.$p.value) %>% unlist
rbind(wc, tt) %>% cbind(data.frame(Test = c('t', 'Wilcoxon')),.) %>%
  'row.names<-'(NULL)
```

Test	2010	2014
t	2.008258e-09	0.01735892
Wilcoxon	3.269138e-03	0.01529176

The difference from zero are statistically significant. Graphically, the confidence interval band for the LOESS curve provides similar evidence. Next are MK test and Sen slope.

Nonparametric trend testing

```
Standard model
Tau = 0.2205882
Score =  30
var(Score) =  589.3333
2-sided p-value =  0.2322487
Theil-Sen's (MK) or seasonal/regional Kendall (SKT/RKT) slope=  0.01385855
```

Similar results as the full dataset: no significant trend. Next, model fits with linear time:

GLS model fits with linear time

```
HRC509 Fitted Model without Outliers and Error Correlation AR(1)
                     Value    Std.Error    t-value       p-value
(Intercept) -13.718861552 15.834679969 -0.8663807  3.863723e-01
log(qOrig)    0.588339981  0.017218943 34.1681829 4.530261e-207
I(api^0.5)    2.502871626  0.069492984 36.0161771 2.186855e-225
sindoy        0.345905126  0.051451110  6.7229867  2.241242e-11
t_decyr       0.008233442  0.007870419  1.0461251  2.956139e-01
```

Again, similar to full dataset, `t_decyr` is positive but not significant.

[23] Normalized residuals are the “raw” residuals divided by their standard error pre-multiplied by the inverse square root of the estimated error correlation matrix. See (Box et al., 2015) for additional details.

For the other time periods:

```
wy08 <- summary(bestFit_WY08_WY20)$tTable
wy16 <- summary(bestFit_WY16_WY20)$tTable
trimTab <- cbind(wy08[,c(1,4)], wy16[,c(1,4)]) %>% as.data.frame
names(trimTab) <- trimTab_colnames
trimTab %>% mutate(Term = row.names(.), .before = 1)
```

Term	Estimate (WY08)	p-value (WY08)	Estimate (WY16)	p-value (WY16)
(Intercept)	-20.55216425	4.406272e-01	-140.18624432	1.611947e-01
log(qOrig)	0.54281905	3.187593e-130	0.51112639	6.615586e-38
I(api^0.5)	2.60694050	3.384486e-190	2.78707569	1.389528e-104
sindoy	0.42895043	4.778912e-12	0.38673155	1.436683e-05
t_decyr	0.01163479	3.792209e-01	0.07089102	1.528363e-01

The coefficients for the duration of HRC ownership and the last five years are greater than the entire record, but neither are statistically significant.

Station 510 - South Fork Elk River

Full dataset

Load in data for HRC511:

```
load(here('analysis/full_dataset/SSC_trends_HRC510.RData'))
```

SSC residuals over time plot

Residual SSC plot over time for model without `t_decyr`:

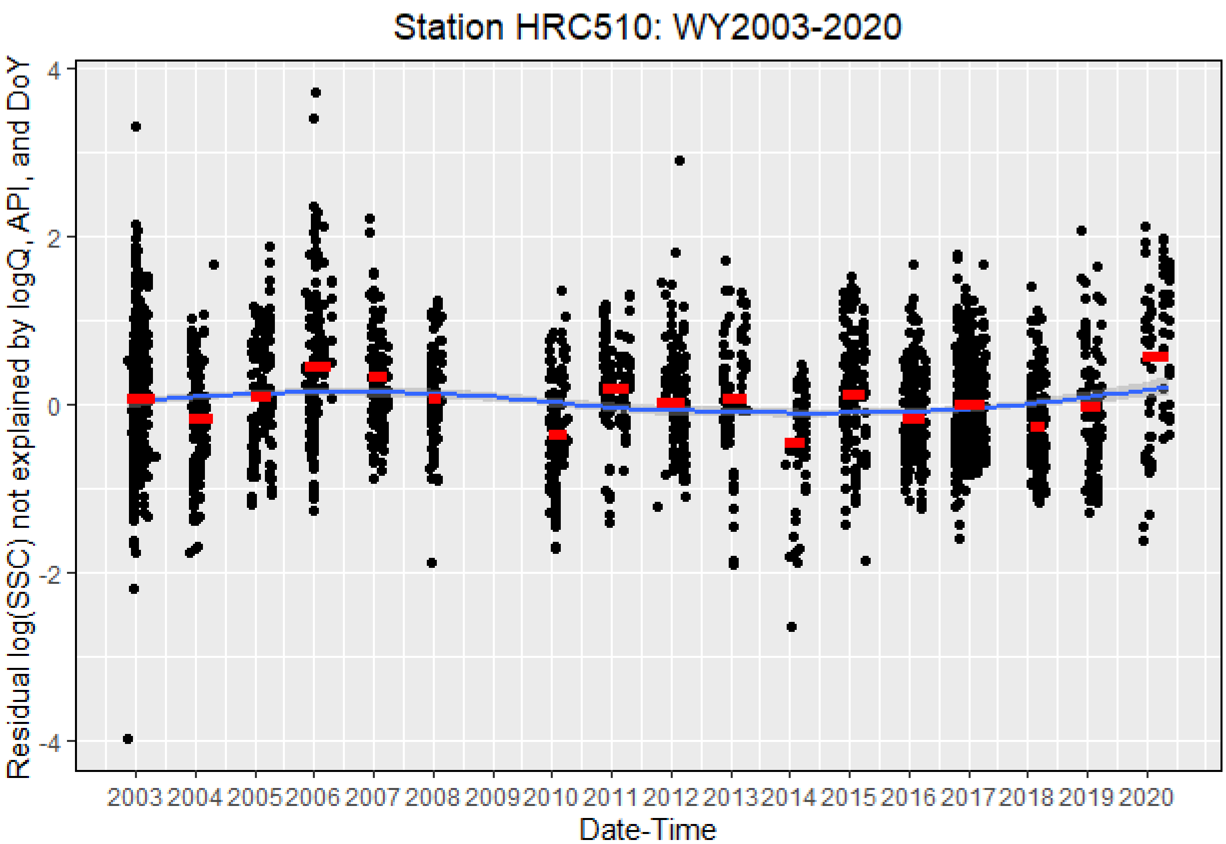


***Figure 30**: South Fork station HRC510 SSC residuals with full dataset*

Instead of a dip for WY2003-WY2010, there's a bump, but like HRC509's full dataset results, the bump is not too noticeable due to axis scales and outliers. That bump is in contrast to the 2013 analysis at Salmon Forever station SFM on the South Fork[24]. Instead of a bump, we see a dip:

[24] Note that the 2013 analysis did not include a calendar day covariate and its linear time term is in units of days after a origin date.

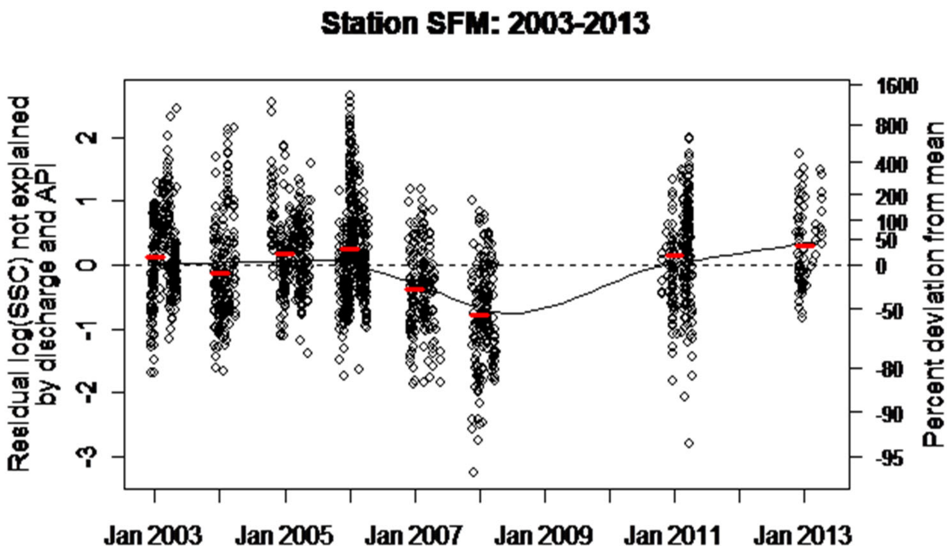


Figure 31: *Salmon Forever South Fork station SFM SSC residuals for WY2003-WY2013*

HRC510 WY2014's mean residual is lower than zero whereas HRC509 where mean residual is above zero. The bump that appeared later in HRC509 is also not present at HRC510. We will inspect WY2014 again after excluding outliers.

Nonparametric trend testing

```
Standard model
Tau = -0.1470588
Score =  -20
var(Score) =  589.3333
2-sided p-value =  0.4338268
Theil-Sen's (MK) or seasonal/regional Kendall (SKT/RKT) slope=  -0.007141237
```

The Sen slope and Kendall's τ are negative (decreasing SSC), but the trends are not statistically significant.

GLS model fits with linear time

Next, coefficients for the model with linear time included:

```
HRC510 Fitted Model with Error Correlation ARMA(4,1)
                     Value   Std.Error     t-value       p-value
(Intercept)  4.080781652 23.79339772  0.17150899  8.638367e-01
log(qOrig)   0.862358668  0.01895125 45.50404898  0.000000e+00
I(api^0.5)   1.517867606  0.06600177 22.99737773 8.342249e-107
sindoy       0.228306414  0.05719363  3.99181549  6.736090e-05
t_decyr     -0.000345456  0.01183200 -0.02919676  9.767099e-01
```

With the p-value = 0.9767, any linear trend is practically non-existent from WY2013-WY2020. What about the other time periods?

Term	Estimate (WY08)	p-value (WY08)	Estimate (WY16)	p-value (WY16)
(Intercept)	-26.51553185	3.651586e-01	-288.79860434	1.139918e-03
log(qOrig)	0.82299727	5.392607e-243	0.87450389	1.517134e-111
I(api^0.5)	1.62706176	3.632904e-98	1.97925119	1.874798e-79
sindoy	0.11920795	4.010052e-02	-0.03116853	6.944156e-01
t_decyr	0.01484122	3.071114e-01	0.14473310	1.004076e-03

The linear time coefficient for WY16-20 is statistically significant at p-value ≈ 0.001, which is much lower than any other station. Let's plot the residuals of this time period with time term excluded:

```
fit_1620 <- hrc_qaqc %>% subset(WY > 2015) %>%
  mutate(res = residuals(bestFit_not_WY16_WY20))
fit_1620_mn <- fit_1620 %>% group_by(WY) %>%
  summarize(start_dt = min(dts), end_dt = max(dts), res = mean(res))
plot_resid_ts(fit_1620, fit_1620_mn, stn, tzone, 2016, 2020)
```

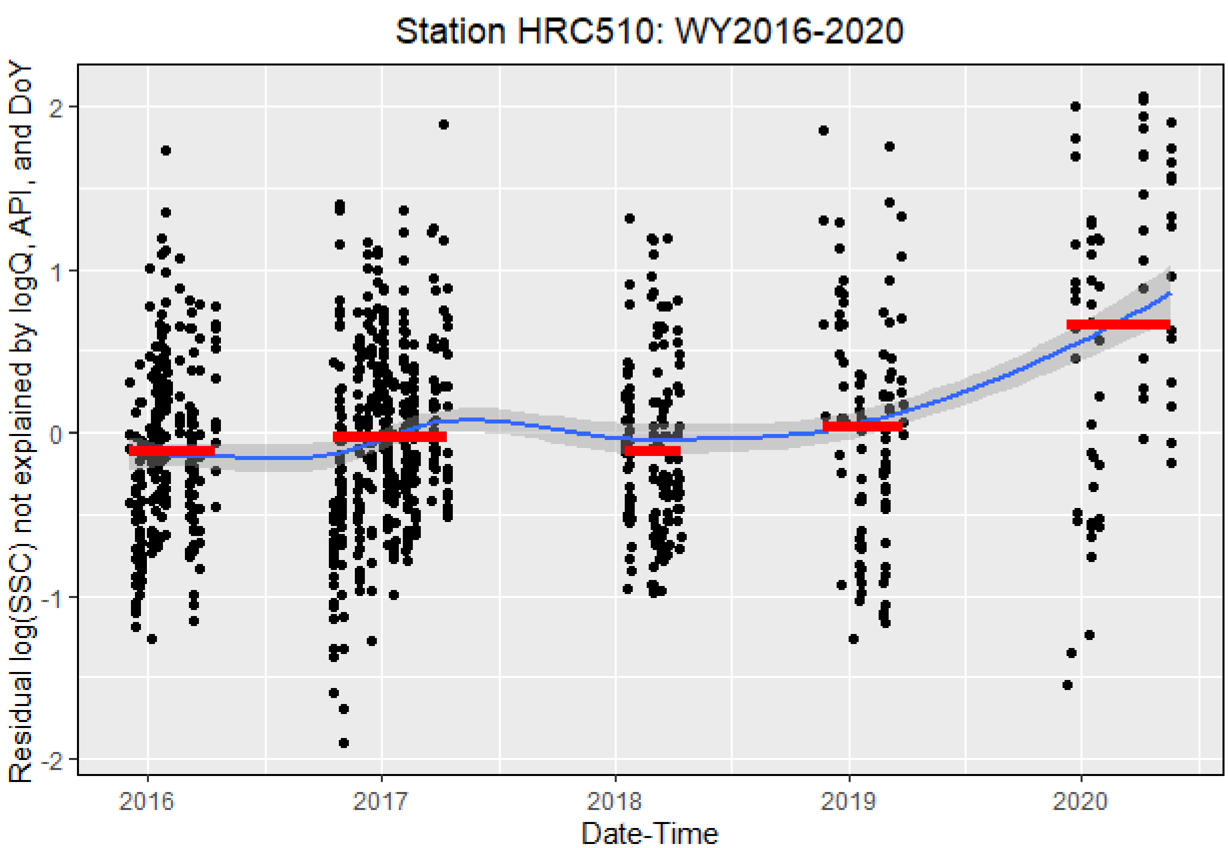


***Figure 32**: South Fork station HRC510 SSC residuals with full dataset and WY2016-WY2020*

Mean SSC residuals for WY2016-2019 are similar, but the large uptick in WY2020 might explain the uptrend. WY2020 also had historically low rainfall:

```
ppt_wys <- hppt_all %>% group_by(WY) %>%
  summarize(across(starts_with('S') | starts_with('I'), sum)) %>%
  subset(WY == 2020)
ppt_avg <- hppt_all %>% group_by(WY) %>%
  summarize(across(starts_with('S') | starts_with('I'), sum)) %>%
  summarize(across(!WY, mean)) %>% cbind(data.frame('WY' = 'Mean'), .)
print(rbind(ppt_wys, ppt_avg))
```

```
# A tibble: 2 x 6
  WY    ST2sm ST2wm ST4sm ST4wm IEMsm
  <chr> <dbl> <dbl> <dbl> <dbl> <dbl>
1 2020   25.1  25.1  25.9  25.8  32.3
2 Mean   45.4  45.6  45.9  45.7  42.8
```

Low rainfall corresponds with low flows, so small amounts of sediment discharge can rapidly raise concentrations. Whatever the sources of sediment for the WY2020 increase, they do not appear to be heavily influenced by hydrology.

Because the linear time coefficient for WY2016-WY2020 is statistically significant, we can go ahead and evaluate this number. However, as Lewis cautioned in 2017, “this is letting the data determine the hypothesis.” A smaller time period means fewer samples, thus statistical power is lower and the results of the trend analysis less convincing. Additionally, inter-annual variation and related phenomenon (e.g., El Nino/La Nina) could have influences not quantified in the model. That said, WY16-WY20 includes a below average (WY2020) and the highest (WY2017) rainfalls since 2003.

To interpret the results of a regression where the response variable is log-transformed and the explanatory variables are not, the coefficient is better understood as ratio of two observations per unit increase in the covariate. Starting with the linear equation:

$$\log SSC = \beta_0 + \sum_{i=1}^{n} \beta_i x_i$$

$$\log SSC_t - \log SSC_{t_0} = \left(\beta_0 + \sum_{i=1}^{n} \beta_i x_t\right) - \left(\beta_0 + \sum_{i=1}^{n} \beta_i x_{t_0}\right)$$

If all other covariates except linear time (β_t) are held constant:

$$\log SSC_t - \log SSC_{t_0} = \beta_t t - \beta_t t_0$$

$$\log \frac{SSC_t}{SSC_{t_0}} = \beta_t \Delta t$$

Where the linear time coefficient $\beta_t \approx 0.1447$; `Δt_decyr`$= \Delta t$; and the ratio of two years’ SSC is f_{SSC}, if Δt = 1 year, then after exponentiation to both sides:

$$
\begin{aligned}
\exp(\log f_{\mathrm{SSC}}) &= \exp(\beta_t \Delta t) \\
f_{\mathrm{SSC}} &= \exp(0.1447 \cdot 1) \\
f_{\mathrm{SSC}} &= 1.1557 \\
\Delta \mathrm{SSC}_{\%} &= (f_{\mathrm{SSC}} - 1) \times 100 \\
\Delta \mathrm{SSC}_{\%} &= 15.6\%
\end{aligned}
$$

To get the confidence interval of this increase:

```
confint(bestFit_WY16_WY20)
```

```
                   2.5 %       97.5 %
(Intercept) -462.23807718 -115.3591315
log(qOrig)     0.80815593    0.9408518
I(api^0.5)     1.79296817    2.1655342
sindoy        -0.18661541    0.1242783
t_decyr        0.05876641    0.2306998
```

$$
\begin{aligned}
95\%\ \mathrm{CI} \in \left[f_{\mathrm{SSC}_{0.250}}, f_{\mathrm{SSC}_{0.975}}\right] &= \left[\exp(\beta_{t,0.250}), \exp(\beta_{t,0.975})\right] \\
&\approx [1.0605,\ 1.2595]
\end{aligned}
$$

With the caveats for constraining the time period in mind, on a year-to-year basis and assuming all other variables constant, the mean ratio increase in SSC is approximately 15.6% per year with a confidence interval between 6.05% and 25.9%.

Excluding outliers

```
load(here('analysis/without_outliers/SSC_trends_HRC510.RData'))
```

SSC residuals over time plot

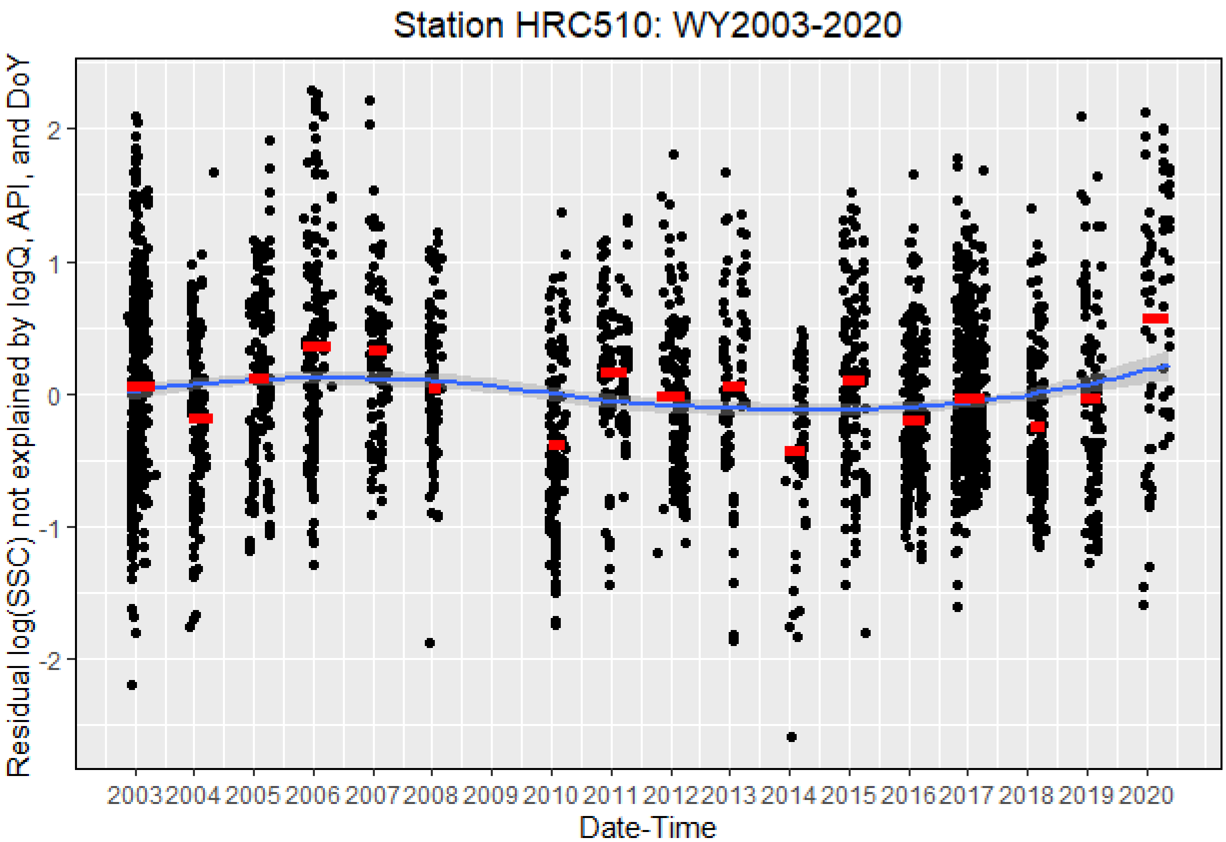


***Figure 33**: South Fork station HRC510 SSC residuals with outliers removed*

With outliers removed, the bump from WY2003-WY2008 is slightly more noticeable, but the LOESS curve's confidence band looks like it includes zero. WY2014 residuals bring down the curve such that there is a dip between WY2011-WY2016. So what's going on here? First, let's check whether WY2014 mean residual is actually significantly lower; we'll throw in WY2020 and WY2010 as well since these are also anomalous years. The hypotheses for mean and median residuals in WY2010, 2014, and 2020 are less, less, and greater than zero, respectively, at $\alpha = 0.05$. As before, we will use the normalized residuals.

Test	2010	2014	2020
t	0.0003160291	0.02522731	0.5534185
Wilcoxon	0.0465181613	0.11598641	0.1205190

Both tests indicate WY2010 is less than zero and thus below average SSC. For WY2014 the tests disagree. The t-test assumes that the residuals (or variable being tested) follows the normal distribution, which is a fair assumption given that we went through the effort of correcting for autocorrelation. Therefore, WY2014 is likely a below average residual SSC year, in spite of hydrology and other covariates favoring the opposite. That all said, what we really want to know is if WY2020 residual SSC are significantly greater than zero (i.e., greater despite hydrology favoring lower). Both tests show that the answer is no and WY2020 may just be a fluke after all.

Note that WY2020 has half the samples of WY2010 ($N_{WY10} = 138$, $N_{WY14} = 62$, $N_{WY20} = 67$). WY2020 has lower rainfall and fewer storms from which to sample, but the consequence is that statistical power is lower, and the chance of a false negative is greater (Type II error rate = β). If we assume the residuals are normally distributed, we can calculate statistical power ($1 - \beta$) post-hoc since we know α, the number of samples, and the effect size d:

```
pwr::pwr.t.test(n = length(res_wys$`2020`), alternative = 'greater',
                d = mean(res_wys$`2020`)/sd(res_wys$`2020`),
                sig.level = 0.5534185   , type = 'one.sample', )


     One-sample t test power calculation

              n = 67
              d = 0.1445312
      sig.level = 0.5534185
          power = 0.9061243
    alternative = greater
```

Statistical power in this case is very high, because $\beta = 0.20$ (or power = 0.80) is usually the cutoff used to determine minimum number of samples prior to data collection. The power analysis further supports the finding that residual SSC for WY2020 is not statistically significantly greater than zero. If the trend is entirely due to WY2020, then the SSC uptrend has little support. Goes to show that these plots can be quite misleading, and we always need additional evidence to support conclusions. In this case, the finding is whether a specific year is actually anomalous and not random noise.

Non-parametric trend testing

Going back to trends over the period of record:

```
Standard model
Tau = -0.1764706
Score =  -24
var(Score) =  589.3333
2-sided p-value =  0.3434195
Theil-Sen's (MK) or seasonal/regional Kendall (SKT/RKT) slope=  -0.008025858
```

The overall trend from WY2003 to WY2020 is negative, but not statistically significant.

GLS model fits with linear time

```
HRC510 Fitted Model without Outliers and Error Correlation ARMA(4,1)
                   Value   Std.Error    t-value       p-value
(Intercept) 11.681592601 20.62868360  0.5662791  5.712524e-01
log(qOrig)   0.885918997  0.01810835 48.9232295  0.000000e+00
I(api^0.5)   1.495377160  0.06222832 24.0304924 1.608679e-115
```

```
sindoy       0.198374071  0.05524825  3.5905943  3.359651e-04
t_decyr     -0.004130645  0.01025849 -0.4026561  6.872340e-01
```

Results with outliers removed are similar with the full dataset: negative but not significant. Next, other time periods:

Term	Estimate (WY08)	p-value (WY08)	Estimate (WY16)	p-value (WY16)
(Intercept)	-28.97598328	3.048303e-01	-288.79860434	1.139918e-03
log(qOrig)	0.84701136	6.260822e-255	0.87450389	1.517134e-111
I(api^0.5)	1.66364809	9.771886e-105	1.97925119	1.874798e-79
sindoy	0.09532717	1.004755e-01	-0.03116853	6.944156e-01
t_decyr	0.01603532	2.525437e-01	0.14473310	1.004076e-03

The results for WY2008-WY2020 are similar to the full dataset. Because no outliers are from WY2016-WY2020 and the error correlation structures are the same, WY2016-WY2020 coefficients and p-values are identical to the full dataset, so we do not need to re-evaluate the coefficient estimate.

Station 511 - North Fork Elk River

Full dataset

```
load(here('analysis/full_dataset/SSC_trends_HRC511.RData'))
```

SSC residuals over time plot

```
plot_resid_ts(fit = mutate(hrc_fit, res = resGLSnotRaw), tzone = tzone,
              fit_means = mutate(hrc_fit_means, res = resGLSnotRaw), stn = stn)
```

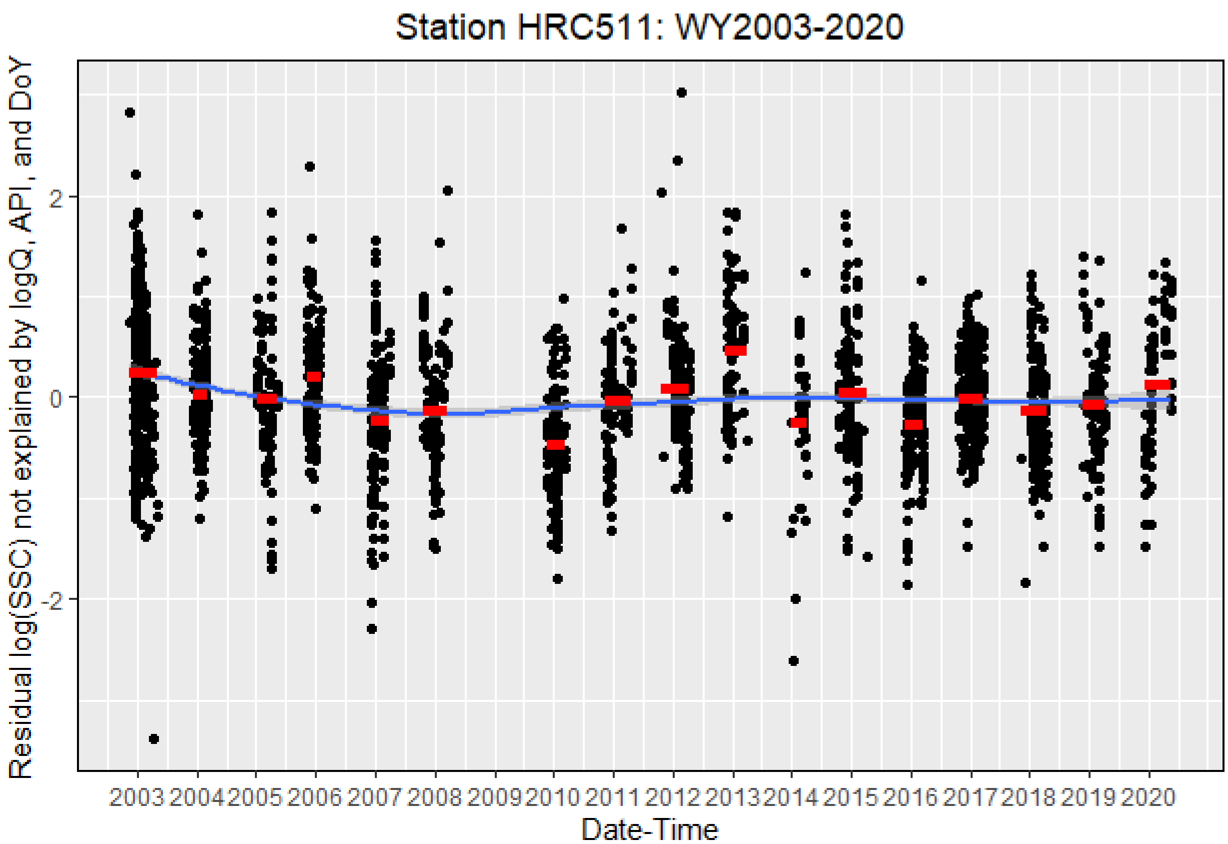


Figure 34*: North Fork station HRC509 SSC residuals with full dataset*

The trend is very flat from WY2011 onward, but a dip appears at the beginning, which is similar to HRC509. In contrast to HRC511/SFM, this dip is also consistent with Lewis 2013 for Salmon Forever station KRW on the North Fork, but less dramatic:

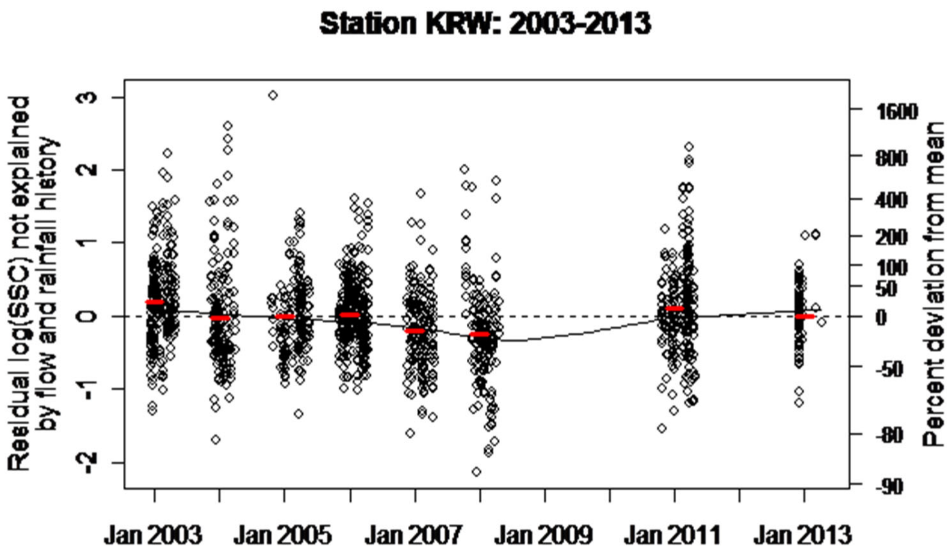


Figure 35: *Salmon Forever North Fork station KRW SSC residuals for WY2003-WY2013*

Non-parametric trend testing

```
Standard model
Tau = -0.1176471
Score =  -16
var(Score) =  589.3333
2-sided p-value =  0.5366482
Theil-Sen's (MK) or seasonal/regional Kendall (SKT/RKT) slope=  -0.005921323
```

While the Sen slope and Kendall's τ indicate decreasing residual SSC, they are not significant.

GLS model fits with linear time

```
HRC510 Fitted Model with Error Correlation ARMA(4,3)
                   Value    Std.Error   t-value       p-value
(Intercept) 22.633684735 17.384622125  1.301937  1.930629e-01
log(qOrig)   0.817763794  0.017269521 47.353010  0.000000e+00
I(api^0.5)   2.182389212  0.063500956 34.367817 8.125856e-211
sindoy       0.160155672  0.051695401  3.098064  1.970464e-03
t_decyr     -0.009914379  0.008647091 -1.146557  2.516793e-01
```

While the coefficient is negative, it is not statistically significant. For the other time periods:

Term	Estimate (WY08)	p-value (WY08)	Estimate (WY16)	p-value (WY16)
(Intercept)	-19.57237612	4.232629e-01	-171.29432217	3.459724e-02
log(qOrig)	0.79008215	8.650800e-205	0.92635007	2.712727e-119

Term	Estimate (WY08)	p-value (WY08)	Estimate (WY16)	p-value (WY16)
I(api^0.5)	2.32104406	1.997432e-157	2.25005565	2.968963e-109
sindoy	0.22654383	7.105376e-05	0.27326790	3.267790e-04
t_decyr	0.01100883	3.642507e-01	0.08604031	3.222787e-02

The coefficients for `t_decyr` in the two time periods are both positive (increasing SSC), but only the last five years are statistically significant (p-value ≈ 0.0322).

Calculating the percent change over the last five years:

```
Mean for t_decyr is 0.08604 and 95CI [0.0074458, 0.16463]
Percent change: mean 8.99 and 95CI [0.747, 17.9]
```

This change is smaller than HRC510, but nevertheless in the increasing direction.

Excluding outliers

```
load(here('analysis/without_outliers/SSC_trends_HRC511.RData'))
```

SSC residuals over time plot

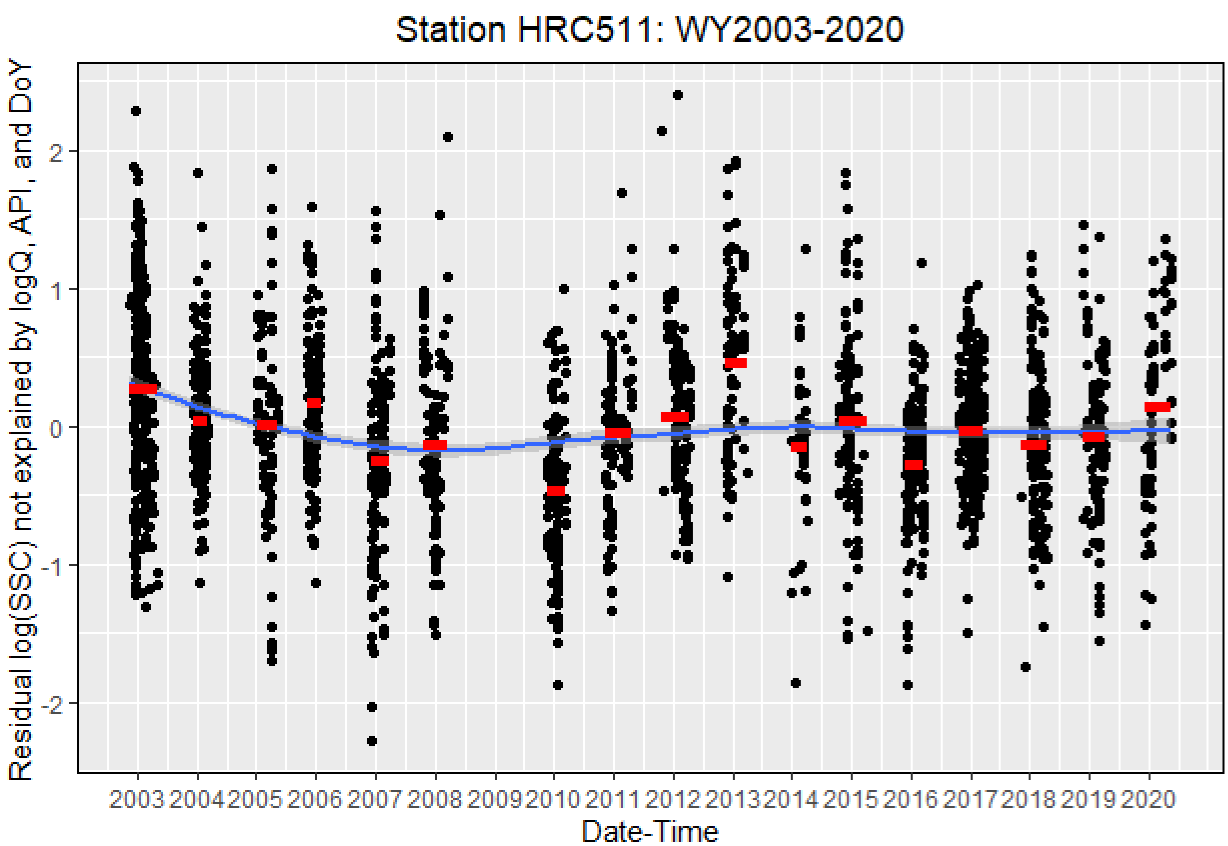


__Figure 36__: North Fork station HRC509 SSC residuals with outliers removed

With axes re-scaled and outliers removed, the dip is more noticeable. WY2013 is the outlier with the highest mean residual for the entire period. WY2010 has lowest mean residual, which is consistent with all the other stations. Let's compare these years:

```
ppt_wys <- hppt_all %>% group_by(WY) %>%
  summarize(across(starts_with('S') | starts_with('I'), sum)) %>%
  subset(WY %in% c(2010, 2013))
ppt_avg <- hppt_all %>% group_by(WY) %>%
  summarize(across(starts_with('S') | starts_with('I'), sum)) %>%
  summarize(across(!WY, mean)) %>% cbind(data.frame('WY' = 'Mean'), .)
print(rbind(ppt_wys, ppt_avg))
```

```
# A tibble: 3 x 6
  WY    ST2sm ST2wm ST4sm ST4wm IEMsm
  <chr> <dbl> <dbl> <dbl> <dbl> <dbl>
1 2010   58.7  58.8  58.1  58.7  52.3
2 2013   36.3  36.1  35.8  36.0  43.1
3 Mean   44.9  44.7  44.6  44.7  46.8
```

WY2013 had below average rainfall, but observed SSC is greater than what we expect if only hydrology was a factor. Opposite story with WY2010 with observed SSC less than what we expect. Let's check whether these means are significant:

Test	2010	2013
t	7.160126e-06	0.11114631
Wilcoxon	5.918001e-03	0.09344878

WY2010 residuals are statistically significantly below zero whereas WY2013 residuals are not significantly above, based on both tests. Once again, we should be careful not to over-interpret plots. Even non-substantive changes such as the plot's aspect ratio or axes scales could lead to faulty conclusions.

Non-parametric trend testing

```
Standard model
Tau = -0.1176471
Score =  -16
var(Score) =  589.3333
2-sided p-value =  0.5366482
Theil-Sen's (MK) or seasonal/regional Kendall (SKT/RKT) slope=  -0.007096966
```

With outliers removed, the magnitude of the downtrend is slightly higher, but neither statistics are significant.

GLS model fits with linear time

```
HRC511 Fitted Model without Outliers and Error Correlation ARMA(1,4)
```

```
                  Value   Std.Error   t-value       p-value
(Intercept) 25.85376366 16.39167230  1.577250  1.148702e-01
log(qOrig)   0.84565934  0.01691846 49.984423  0.000000e+00
I(api^0.5)   2.22459523  0.06118698 36.357330 8.052052e-231
sindoy       0.14266617  0.05066693  2.815765  4.905985e-03
t_decyr     -0.01154818  0.00815334 -1.416374  1.567961e-01
```

Similar to the full dataset, linear time trend is not statistically significant. Next, the other time periods:

Term	Estimate (WY08)	p-value (WY08)	Estimate (WY16)	p-value (WY16)
(Intercept)	-21.47730644	4.287159e-01	-165.20361858	4.435868e-02
log(qOrig)	0.82245901	1.692266e-219	0.91703751	7.151818e-112
I(api^0.5)	2.34336670	1.878053e-166	2.27633226	1.404606e-107
sindoy	0.20506927	3.892469e-04	0.29265239	1.936835e-04
t_decyr	0.01192078	3.762402e-01	0.08302221	4.146520e-02

Unlike HRC510, the error correlation structures are different between the full dataset and with outliers removed–ARMA(4,3) and ARMA(1,4), respectively. WY2008-WY2020 has similar results to the entire time period with a positive, non-significant coefficient. WY2016-WY2020's coefficient shows very little difference from the full dataset. The p-value is higher and almost at the critical threshold. Still, the p-value makes the cut, and we can calculate the year-to-year change in SSC.

```
Mean for t_decyr is 0.083022 and 95CI [0.003352, 0.16269]
Percent change: mean 8.66 and 95CI [0.336, 17.7]
```

The percent change when outliers are removed almost contains the entire confidence interval of the full dataset's ([0.747, 17.9]), so removing the outliers did very little aside from changing the error correlation structure.

Summary and Conclusion

Table 1 shows results for MK test and Table 2 summarizes model fits. Based on the Mann-Kendall test, no statistically significant trends are present at any of the stations for entire period of record starting in WY2003.

***Table 2**: Mann-Kendall test and Theil-Sen slope*

Station	Location	Error Corr.	Outliers	Kendall's τ	Sen slope	MK p-val
509	Mainstem	AR(2)	Kept	0.279	0.021	0.127
509	Mainstem	AR(1)	Removed	0.221	0.014	0.232
510	South Fork	ARMA(4,1)	Kept	-0.147	-0.007	0.434
510	South Fork	ARMA(4,1)	Removed	-0.176	-0.008	0.343
511	North Fork	ARMA(4,3)	Kept	-0.118	-0.006	0.537
511	North Fork	ARMA(1,4)	Removed	-0.118	-0.007	0.537

Results are mixed for the GLS regressions. All terms except for linear time were statistically significant. Statistically significant trends are found only in the time period WY2016 through WY2020 and only at stations HRC510 and HRC511. Both stations show an increasing trend of SSC at a rate of approximately 15.6 and 8.99 percent per year, respectively. All other time period and station combinations did not have statistically significant time trends. The removal of outliers as defined in had little effect on the overall results, changing the coefficients' magnitude and p-values in both directions with no discernible pattern.

***Table 3**: GLS Model Fits*

Station	Start WY	Outliers	*t*	*t* p-val	% Change	Low CL %	Up CL %
509	2003	Kept	0.012	0.151	1.162	-0.418	2.767
509	2008	Kept	0.016	0.207	1.601	-0.875	4.139
509	2016	Kept	0.055	0.203	5.657	-2.920	14.991
509	2003	Removed	0.008	0.296	0.827	-0.717	2.394
509	2008	Removed	0.012	0.379	1.170	-1.419	3.828
509	2016	Removed	0.071	0.153	7.346	-2.588	18.293
510	2003	Kept	0.00035	0.977	-0.035	-2.326	2.311
510	2008	Kept	0.015	0.307	1.495	-1.354	4.427
510	2016	Kept	0.145	0.001	15.573	6.053	25.948
510	2003	Removed	-0.004	0.687	-0.412	-2.395	1.610
510	2008	Removed	0.016	0.253	1.616	-1.136	4.445
510	2016	Removed	0.145	0.001	15.573	6.053	25.948
511	2003	Kept	-0.010	0.252	-0.987	-2.650	0.706
511	2008	Kept	0.011	0.364	1.107	-1.268	3.540
511	2016	Kept	0.086	0.032	8.985	0.747	17.896
511	2003	Removed	-0.012	0.157	-1.148	-2.715	0.444
511	2008	Removed	0.012	0.376	1.199	-1.437	3.906
511	2016	Removed	0.083	0.041	8.657	0.336	17.667

*Statistically significant results are highlighted rows. *t* is the coefficient for linear time in units of $\log \text{SSC} \cdot \text{year}^{-1}$.

6. SEV Analysis

The Severity of Ill Effects score (SEV) is a rating scale relating suspended sediment concentration (SSC) and continuous exposure duration to stress on aquatic organisms. Newcombe & Macdonald (1991) introduces the scale and generates models based on a metareview of and database compilation from publications detailing SSC and duration effects on various aquatic organisms. Newcombe & Jensen (1996) further develops these models to address different groups of salmonid life stages. The SEV scale and their values have four general groups: no effect (SEV = 0); behavioral effects (1-3); sublethal effects (4-8); and lethal effects (9-14). The Elk River Recovery Assessment (ERRA) uses model runs and observation data to calculate changes in SEV due to changes in sediment load or channel modification model scenarios (California Trout et al., 2018). ERRA results include only two salmonid life stages: eggs/larvae and juvenile. Observed SSC from WY2003 to WY2015 yields SEV scores between 5.0 and 13.4 for the eggs/larvae life stage and between 5.7 and 8.6 for the juvenile life stages. Table **4** is a description of select SEV scores and the effects they describe, modified from Newcombe & Jensen (1996):

***Table 4**: Slect SEV scores and their associated effects on aquatic life*

SEV Score	Effects Description
5	Minor physiological stress; increased respiration rate
6	Moderate physiological stress
7	Moderate habitat degradation
8	Indications of major physiological stress; long-term reduction in feeding rate
9	Reduced growth rate; delayed hatching
10	0-20% mortality; moderate to severe habitat degradation
13	>60-80% mortality

Calculating SEV scores requires continuous suspended sediment concentration (SSC) time-series data. Humboldt Redwood Company hydrology staff employ the turbidity threshold sampling (TTS) method to produce continuous SSC records (Lewis & Eads, 2009). TTS entails collecting water grab samples at certain turbidity and stream stage thresholds, usually corresponding to a storm event, but inter-storm periods are also sampled. The outcome is a dataset for developing SSC-turbidity rating curves. With continuous field turbidity measurements (validated with lab measurements from pumped samples), the curves produce equal-interval, time-continuous SSC record for each Water Year[25] (WY) at each monitoring station. From these records, maximum annual durations of continuous exposure at different levels of SSC are extracted. The continuous data are available for all stations, but many of those stations no longer operate. Figure **37** shows monitoring stations in the Upper Elk River; the stations shown are not an exhaustive list as new monitoring stations have yet to develop a data record fit for trend analysis.

[25] Most WY time series records start on October 1, the first day of any given WY. However, most if not all records *do not* extend to the end of the WY (September 30 of the following year). Most records end between April and May as flows are no longer observable.

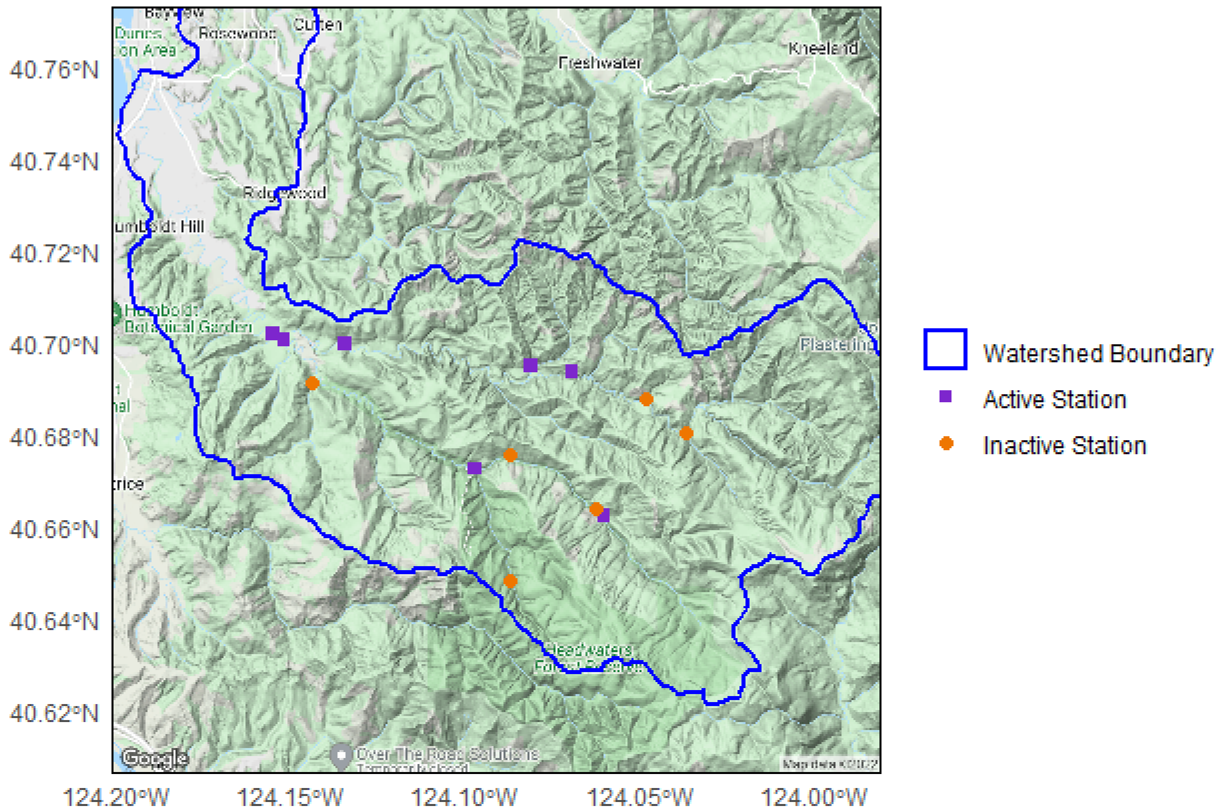


Figure 37*: Map of hydrology monitoring stations operated by HRC*

From HRC annual hydrology report data, the time-series for all available stations are aggregated into data frame objects stored in an RData file. Raw data (e.g., Excel, CSVs, etc.) used to generate the data frames are available upon request.

```
hrc <- readRDS(here('data/HRC/HRC_Continuous.rds'))
sev_models <- read_csv(here('data/SEV_models.csv'), col_types = 'icddddcicccc')
```

SEV model

The models from Newcombe & Jensen (1996) are all multiple linear regressions, and the life stages are represented as different regression coefficient values. The general model for SEV is:

$$\text{SEV} = a + b \cdot \log(\text{ED}) + c \cdot \log(\text{SSC})$$

Where *a*, *b*, and *c* are the coefficients; ED is the exposure duration in hours; and SSC is in units of mg/L. Unless otherwise specified, log means the natural log (i.e., $\ln$ or $\log_e$).

__Table 5__: SEV model coefficients for eggs/larvae and juvenile life stages

Source	Life Stage	*a*	*b*	*c*
Newcombe and Jensen (1996)	juvenile; adult	1.0642	0.6068	0.7384
Newcombe and Jensen (1996)	adult	1.6814	0.4769	0.7565
Newcombe and Jensen (1996)	juvenile	0.7262	0.7034	0.7144
Newcombe and Jensen (1996)	eggs/larvae	3.7466	1.0946	0.3117
Newcombe and Jensen (1996)	adult	3.4969	1.9647	0.2669
Newcombe and Jensen (1996)	adult	4.0815	0.7126	0.2829
Bray (2000)	juvenile	1.8700	0.8700	0.4600
Bray (2000)	underyearling	1.6000	0.7200	0.5700

Newcombe & Jensen (1996) presented results of these models by fixing the SSC and ED on equal intervals based on a log scale. That is:

$$\begin{aligned} \log(\mathrm{SSC}) &= \{1,2,3,\dots,10,11,12\} \\ \log(\mathrm{ED}) &= \{0,\dots,5,\dots,7,\dots,10\} \end{aligned}$$

Exponentiation and rounding to the nearest whole number returns:

$$\begin{aligned} SSC &= \{1,\ 3,\ 7,\dots,\ 22026,\ 59874,\ 162755\}\ \mathrm{mg}\cdot\mathrm{L}^{-1} \\ \mathrm{ED} &= \{1\ \text{hour},\dots,\ 6\ \text{days},\dots,\ 7\ \text{weeks},\dots,\ 30\ \text{months}\} \end{aligned}$$

These two data series can generate a grid wherein SEV scores are tabulated and compared to empirical data (Figure **38**).

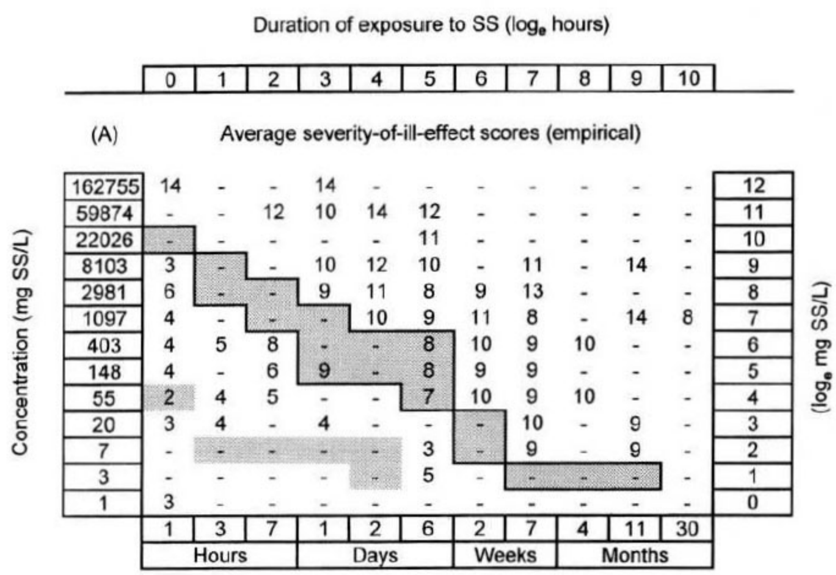


Figure 38*: Figure 1 of Newcombe and Jensen (1996); SEV scores for juvenile life stage*

For the Elk River at stations HRC509 (mainstem), HRC510 (South Fork) and HRC511 (North Fork), ERRA uses log SSC thresholds = {3, …, 8} and their calculated exposure durations to determine SEV scores. Because parallel computing is relatively easy to implement nowadays, here we use a more continuous series of SSC thresholds, increasing by 0.01 log units, i.e. $\log(SSC) = \{0.0,\ 0.1, \ldots,\ 11.9,\ 12.0\}$ for a total 121 SSC thresholds.

Calculating exposure duration

For calculating exposure durations, we create two custom functions. Given a monitoring location's SSC time series and an SSC threshold, `get_duration` returns the longest continuous amount of time that SSC measurements are at or above a given fixed threshold. Because we have many monitoring stations; multiple thresholds; and the need to summarize by Water Year for trend analysis, we create `get_duration_batch`, which runs `get_duration` in batches for all WY/threshold combinations.

```
# Arguments/inputs:
# ssc = vector of SSC with constant time interval (no gaps)
# dts = vector of date-time object
# thresh = threshold SSC
# unit = unit of time duration; default to hours, but other options include:
#        "mins", "secs", "days", "weeks"
# disp_warn = T to display warning, F to not
# excl.na = T to return NULL if duration is 0
#
# Outputs data frame with columns:
# StartDTS = start timestamp of highest duration at a given SSC
# EndDTS = end timestamp
# duration, units, ssc = self-explanatory, see inputs
get_duration <- function(ssc, dts, thresh, unit = 'hours',
                         disp_warn = F, excl.na = F){
  non_na <- !is.na(ssc)
  ssc_ <- ssc[non_na]
  dts_ <- dts[non_na]
  idx <- ssc_ >= thresh
  if (sum(idx) == 0) {
    if (excl.na) {
      return(NULL)
    } else {
      return(data.frame(StartDTS = NA, EndDTS = NA, duration = 0,
                        units = unit, ssc = thresh))
    }
  }
  deltaT <- diff(dts_) %>% unique
  if (length(deltaT) > 1 & disp_warn){
    cat('\nWarning: time-steps in continuous data are not constant with: \n')
    cat(glue('{paste0(deltaT, collapse = ", ")} minutes\n\n\n'))
  }
  runs <- with(rle(idx), {
    ends <- cumsum(lengths)
    starts <- ends - lengths + 1
```

```
    cbind(starts, ends)[values, ]
  }) %>% as.matrix
  if ('matrix' %in% class(runs)) runs <- runs %>% t %>% as.matrix
  runs_len <- runs[,2] - runs[,1]
  runidx <- runs[runs_len == max(runs_len), ]
  t <- diff(dts_[(runidx[1]-1):runidx[2]]) %>% sum
  units(t) <- unit
  out <- data.frame(StartDTS = dts_[runidx[1]], EndDTS = dts_[runidx[2]],
                    duration = as.numeric(t), units = unit, ssc = thresh)
  return(out)
}
# Run get_duration() on multiple thresholds and segregated by water year (or
# some other variable)
get_duration_batch <- function(df, threshs, by = 'WY'){
  if (!by %in% names(df)) {
    df <- df %>% mutate(WY = get_WY(df$DateTime, tzone), .before = 1)
  }
  map2_dfr(.x = rep(split(df, df[, by]), length(threshs)),
           .y = rep(threshs, each = length(unique(df$WY))),
           ~get_duration(.x$SSC, .x$DateTime, .y), .id = 'WY')
}
```

With our thresholds and custom functions defined above, we leverage parallel computing to rapidly calculate durations for all WYs and stations.

```
library(future)
library(furrr)
plan(multisession, workers = 6, gc = TRUE)
threshs <- seq(0, 12, .1) %>% exp
hrc_hrs <- hrc %>%
  future_map_dfr(~get_duration_batch(df = .x, threshs = threshs),
                 .id = 'Station')
hrc_hrs %>% na.omit %>% head
```

***Table 6**: Example output whe using the duration functions*

Station	WY	StartDTS	EndDTS	duration	units	ssc
183	2003	2002-12-02 12:00:00	2002-12-02 12:00:00	0.25	hours	1
183	2004	2003-11-29 13:30:00	2003-11-29 16:45:00	3.50	hours	1
183	2005	2004-10-17 10:15:00	2004-10-17 13:00:00	3.00	hours	1
183	2006	2005-11-02 13:30:00	2005-11-22 09:00:00	475.75	hours	1
183	2007	2006-10-15 20:30:00	2006-10-15 20:30:00	0.25	hours	1
183	2008	2007-10-15 15:15:00	2007-10-15 16:45:00	1.75	hours	1

Calculating SEV

We create another custom function, `calc_sev`, to calculate the SEV given SSC and exposure duration. This function is vectorized so that it accepts multiple pairs of SSC and durations. That is, we can use the `hrc_hrs` data frame columns as our inputs.

```r
# Function to calculate SEV for any arbitrary ssc and duration (hrs), but
# model must contain three values: a (intercept); b (coeff for log(duration));
# and c (coeff for log(ssc)). Model coefficients must be provided in that order
calc_sev <- function(hrs, ssc, model) {
  sev <- vector(mode = 'numeric', length = length(hrs))
  hrs_na <- !is.na(hrs)
  hrs_val <- hrs[hrs_na]
  sev[hrs_na][hrs_val <= 0] <- NA
  sev[hrs_na][hrs_val > 0] <- model[1] + model[2]*log(hrs_val[hrs_val > 0]) +
    model[3]*log(ssc[hrs_na][hrs_val > 0])
  sev[hrs_na][sev[hrs_na] < 0] <- 0
  return(as.numeric(sev))
}
```

Continuing from `hrc_hrs`, we calculate the SEV scores for eggs/larvae and juvenile salmonid life stages. Additionally, we summarize the SEV scores for each station/WY/life stage combination. That is, each combination contains 121 SEV scores. The summary output contains the mean, median, maximum, and 90th percentile of these 121 SEV scores. These descriptive SEV statistics are used for the trend analysis. The corresponding duration and SSC values for the maximum SEVs are also tabulated.

```r
hrc_sevs <- hrc_hrs %>%
  mutate(WY = as.integer(WY),
         SEV_eggNJ = calc_sev(duration, ssc, as.numeric(sev_models[4, cof])),
         SEV_juvNJ = calc_sev(duration, ssc, as.numeric(sev_models[3, cof])),
         SEV_undBr = calc_sev(duration, ssc, as.numeric(sev_models[8, cof])),
         SEV_juvBr = calc_sev(duration, ssc, as.numeric(sev_models[7, cof])))
calc_sev_stat <- function(df, sevcol){
  df %>% subset(!is.na(df[, sevcol])) %>% group_by(Station, WY) %>%
    summarize(maxSEV = max(!!!syms(sevcol)), meanSEV = mean(!!!syms(sevcol)),
              medSEV = median(!!!syms(sevcol)),
              q90SEV = quantile(!!!syms(sevcol), .90),
              durSEVmax = duration[which.max(!!!syms(sevcol))],
              sscSEVmax = ssc[which.max(!!!syms(sevcol))],
              .groups = 'drop_last')
}
lf_stg_abbrv <- hrc_sevs %>% select(contains('SEV')) %>% names
reval_lf <- c('Eggs/Larvae', 'Juvenile (N&J)', 'Underyearling',
              'Juvenile (Bray)') %>% 'names<-'(lf_stg_abbrv)
names(lf_stg_abbrv) <- reval_lf
sev_all <- lf_stg_abbrv  %>%
  map_dfr(~calc_sev_stat(hrc_sevs, .x), .id = 'Life Stage') %>%
  mutate('LFabbrev' = plyr::revalue(`Life Stage`, lf_stg_abbrv),
         .before = 'Station')

sev_all %>% select(-LFabbrev) %>% .[sample(nrow(.), 5), ]
```

```
# A tibble: 5 × 9
# Groups:   Station [4]
  `Life Stage`    Station    WY maxSEV meanSEV medSEV q90SEV durSEVmax sscSEVmax
  <chr>           <chr>   <int>  <dbl>   <dbl>  <dbl>  <dbl>     <dbl>     <dbl>
1 Juvenile (N&J)  510      2016   10.5    7.08   7.19   9.17      282.     3294.
2 Juvenile (N&J)  511      2015   10.9    5.96   5.48   9.21     1831       992.
3 Juvenile (Bray) 517      2020   11.0    5.67   5.64   8.37     1928.      270.
```

```
4 Underyearling    522       2005    11.1     6.15    5.42  10.7       2432.      992.
5 Underyearling    517       2015    10.5     6.60    6.60   8.97      1430.      665.
```

Now check the distribution of descriptive SEV statistics across all stations, WYs, and SSC concentrations:

```
stat_abbrv <- c('medSEV', 'meanSEV', 'q90SEV', 'maxSEV')
reval_stat <- c('Median', 'Mean', '90th Percentile', 'Maximum') %>%
  'names<-'(stat_abbrv)
sev_long <- sev_all %>%
  pivot_longer(contains('SEV') & !contains('dur') & !contains('ssc'),
               names_to = 'Statistic', values_to = 'SEV')
sev_long <- sev_long %>%
  mutate(statAbbrev = Statistic,
         Statistic = plyr::revalue(Statistic, reval_stat), .before = "SEV")
ggplot(data = sev_long, aes(x = Statistic, y = SEV, fill = `Life Stage`)) +
  geom_violin() +
  geom_boxplot(width=0.1, outlier.shape = NA, position = position_dodge(.90)) +
  facet_grid(. ~ Statistic, scales = "free", space = "free", switch = 'x') +
  labs(x = 'Statistic', y = 'SEV Score', title = NULL) +
  scale_x_discrete(labels = reval_stat) +
  scale_y_continuous(breaks = seq(0, 16, by = 1), limits = c(1,16)) +
  scale_fill_manual(values = c('lightblue', 'salmon', 'tan1', 'thistle3')) +
  theme(strip.text.x = element_blank(),
        plot.title = element_text(hjust = 0.5), legend.position = 'bottom',
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

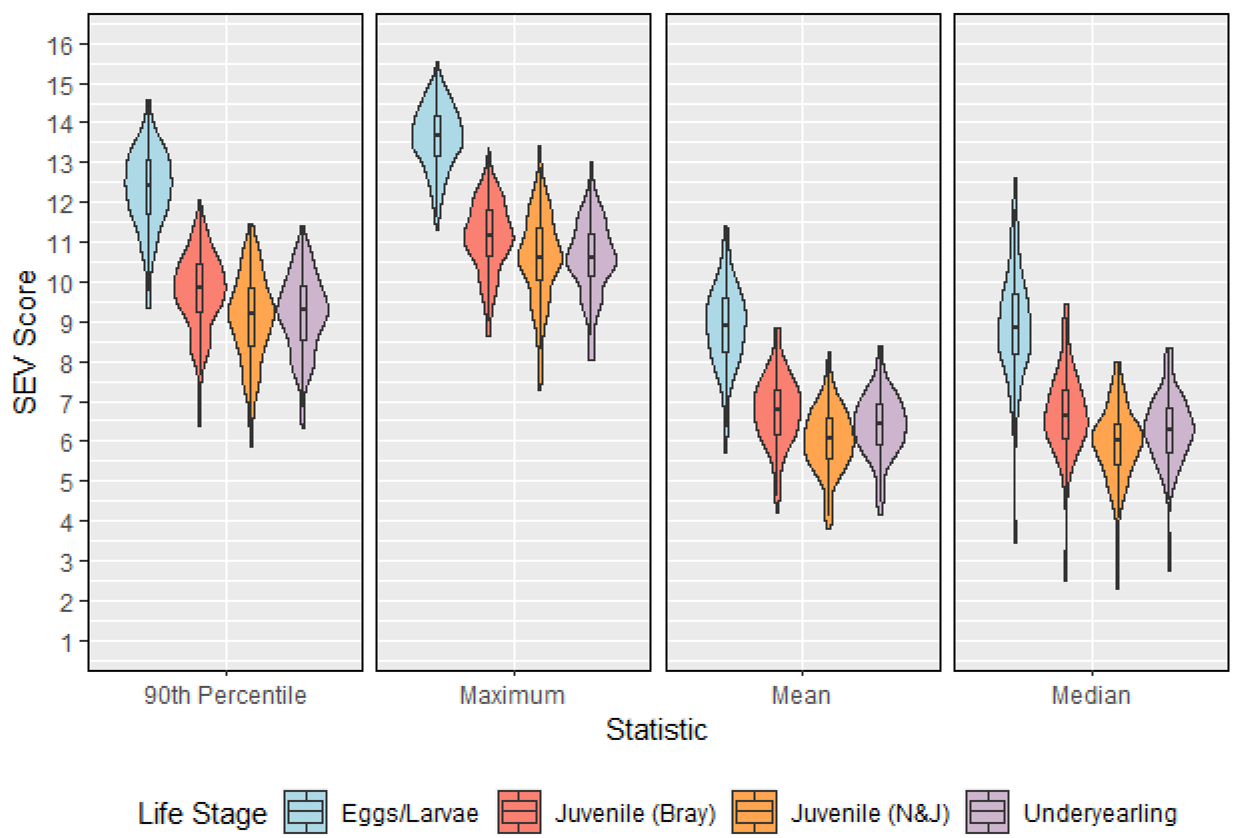


Figure 39: *Distribution of descriptive SEV statistics by life stages*

Figure **39** plot tells us that the eggs and larvae are more vulnerable than juveniles, as the SEV scores for the former are systematically greater for all statistics.

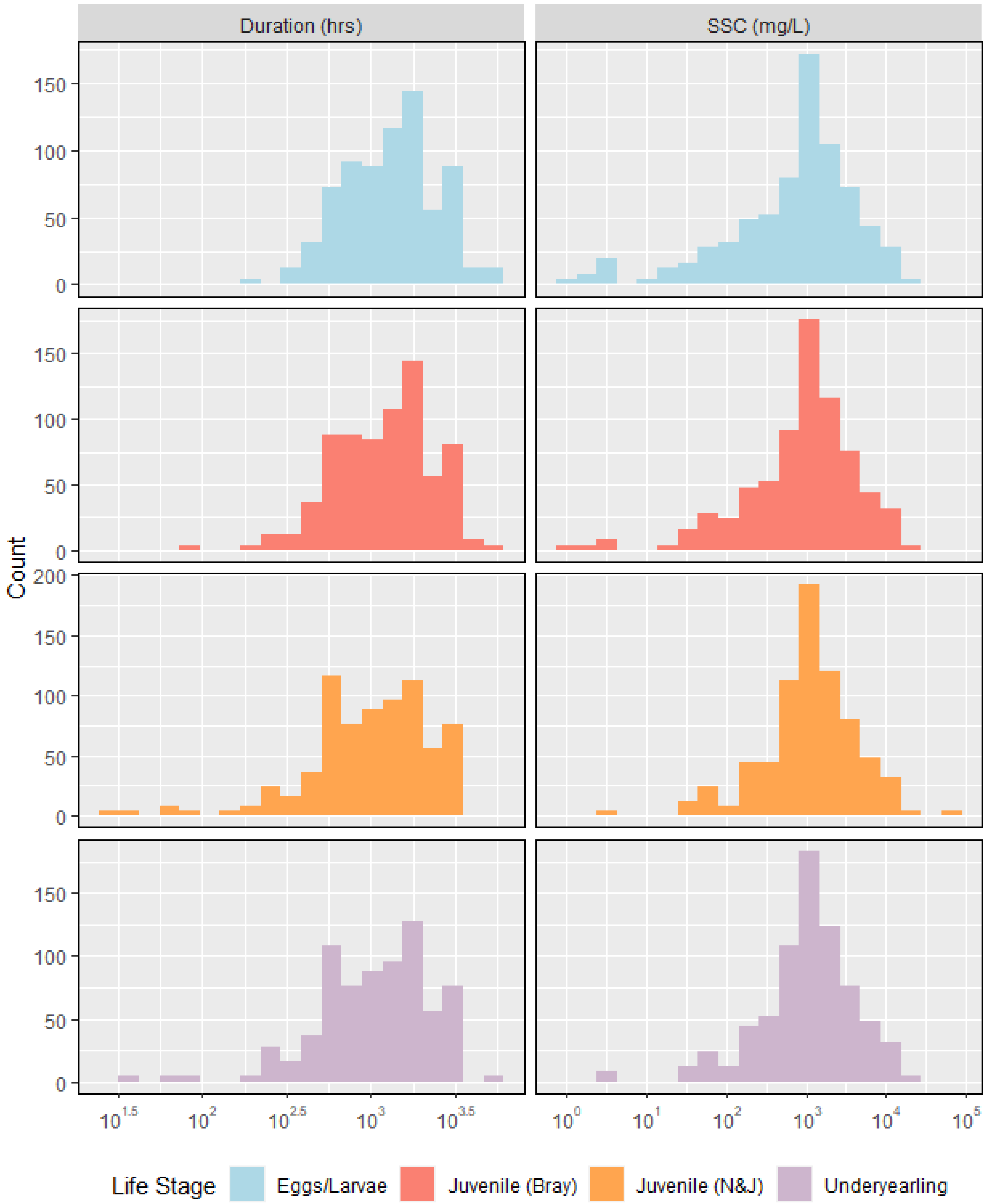
Picking just the maximum[26] SEV for each station/WY combination, we can check the distributions of the corresponding SSC and exposure duration values. That is, we want the distribution to be close to normal (or log-normal, in this case); if they are not, a given max SEV may over-depend on long durations or high SSC, but not both. Recall that the SEV model is the linear sums of the two variables: log SSC and log duration. We want to know or at least get a sense of these variables' relative contributions to high SEV scores.

```
require(ggpubr)
require(ggpmisc)
require(scales)

sev_max <- sev_long %>%
  pivot_longer(ends_with('max'), names_to = 'Covariate', values_to = 'CovValues') %>%
  mutate(Covariate = recode(Covariate, 'durSEVmax' = 'Duration (hrs)',
                            'sscSEVmax' = 'SSC (mg/L)'))

ggplot(data = sev_max, aes(x = CovValues, fill = `Life Stage`)) +
  geom_histogram(bins = 20) +
  facet_grid(`Life Stage` ~ Covariate, scales = "free") +
  scale_fill_manual(values = c('lightblue', 'salmon', 'tan1', 'thistle3')) +
  scale_x_log10(breaks = trans_breaks("log10", function(x) 10^x),
                labels = trans_format("log10", math_format(10^.x))) +
  labs(x = NULL, y = 'Count') +
  theme(legend.position = 'bottom', strip.text.y = element_blank(),
        plot.title = element_text(hjust = 0.5),
        panel.border = element_rect(colour = 'black', fill = NA, size = .5))
```

[26] Medians can have a specific observation if the dataset has an odd number of observations. If an even number, the median is average of the middle two values, thus no direct association.



Duration (hrs)
SSC (mg/L)
Count
150
100
50
0
200
$10^{1.5}$
10^{2}
$10^{2.5}$
10^{3}
$10^{3.5}$
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Life Stage
Eggs/Larvae
Juvenile (Bray)
Juvenile (N&J)
Underyearling

Figure 40: Histograms for SSC and exposure duration corresponding to maximum SEV scores

We see the max SEV scores' corresponding SSC values are fairly spread out in a log normal distribution for both life stages. For juveniles, the exposure duration has a longer left tail, indicating that those high SEV scores are primarily due to high SSC.

Trend analysis

Moving along, we look at the change in descriptive SEV statistics over time using the Mann-Kendall trend test and Sen slope (MK), the same methods used for assessing residual SSC in the previous sections. The MK test tests whether the rank correlation coefficient (Kendall's τ or tau) is statistically significantly different from zero. If τ is negative, then SEV is decreasing over time and increasing if positive. Related to Kendall's τ, the Sen slope estimates the magnitude of change, which in our case is in units of SEV score per year. We also use the regional MK test to test whether the upper watershed as a whole has any trends.

Station selection

MK tests on individual monitoring stations require a minimum of four years. All stations with less than four years are excluded. We also exclude stations that ceased operations before 2016, with the exception of HRC534. HRC534 was located within the Headwaters Forest Reserve (Reserve) in the Upper Little South Fork Elk River. This catchment was used as a reference watershed during TMDL development; reference catchments represent conditions that are closest to "natural" or minimally undisturbed by sediment discharge sources. HRC decommissioned HRC534 in 2015 and replace it with HRC535 in 2018. HRC535 is farther downstream and closer to the edge of the Reserve boundary, covering a greater catchment area and proportion of the Reserve.

HRC683 and HRC684 are located in Railroad Gulch but are no longer operating as of WY2021. With data records starting in WY2014, these stations seem to exist solely to support the Railroad Gulch study (Stubblefield et al., 2021). Railroad Gulch underwent a paired watershed study with East and the West Branches being the treatment and control catchments, respectively. West Branch also experienced a landslide in WY2016, which complicated findings from the study and likely this trend analysis as well. Nevertheless, they both have enough years (n=7) for the MK test. With all caveats and details in mind, the stations undergoing trend analysis are listed in Table **7**.

__Table 7__: Monitoring stations for SEV trend analysis

Station ID	Location	Start WY	End WY	n	gaps
509	Mainstem	2003	2021	17	2
510	South Fork	2003	2021	17	2
511	North Fork	2003	2021	17	2
517	Bridge Creek	2003	2021	17	2
522	Corrigan Creek	2003	2021	15	4
532	Upper North Fork	2005	2021	15	2
534	Upper Little South Fork	2004	2015	10	2
535	Lower Little South Fork	2018	2021	4	0
683	West Branch Railroad Gulch	2014	2020	7	0
684	East Branch Railroad Gulch	2014	2020	7	0

We also inspect the distribution of SEV scores by station. These SEV scores are not the descriptive statistics, but the raw scores from the SSC sequence (recall: $\log SSC = \{0.1, 0.2, \ldots, 11.9, 12\}$) and their maximum duration values. Raw SEV scores for all WYs are pooled together by station and life stage, as shown in in Figure **41**.

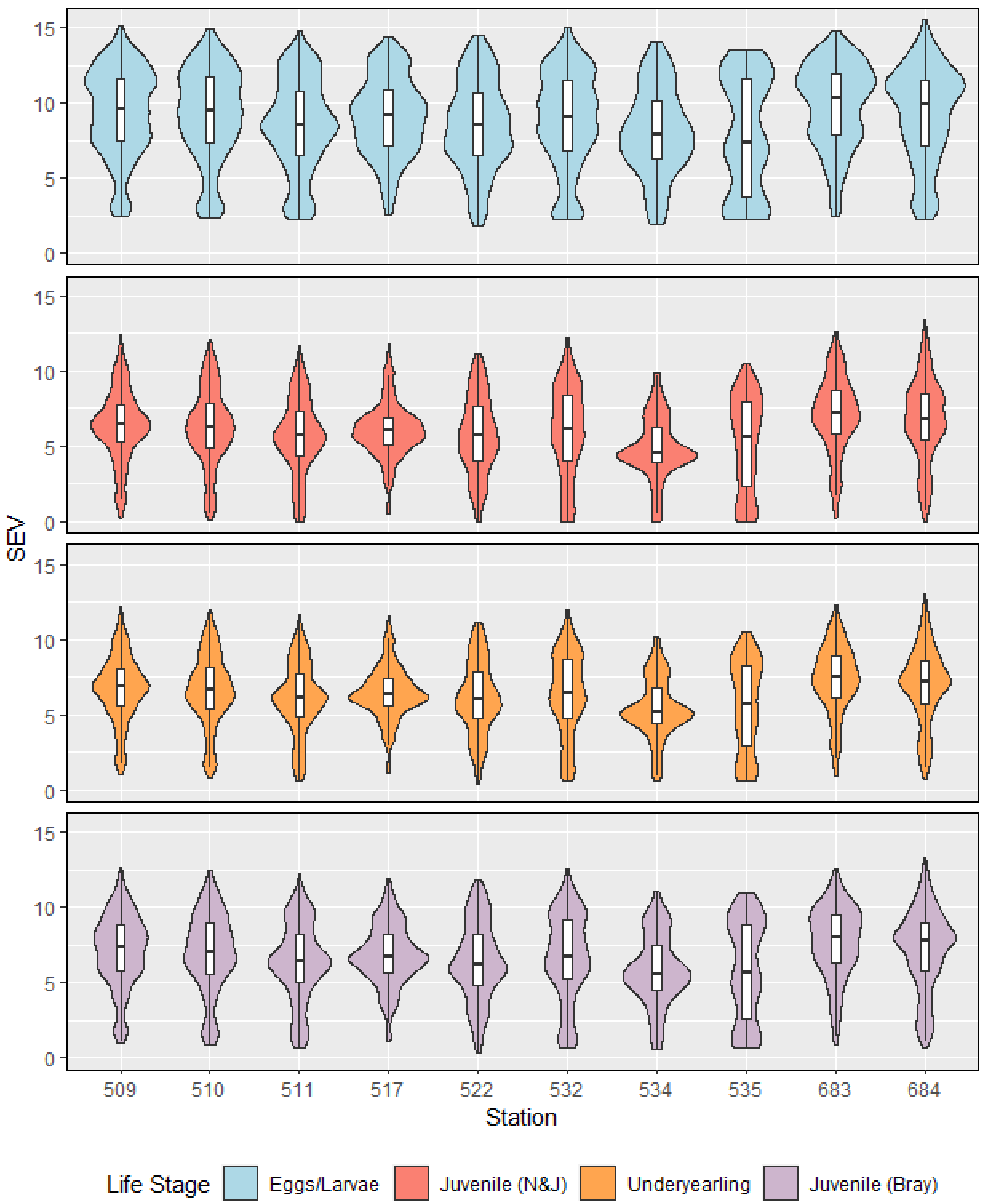


Figure 41*: Violin and boxplots of all SEV scores by monitoring station and life stage*

We can already see that HRC534 has the lowest medians and lowest maximums for both life stages, supporting the Upper Little South Fork use as a reference catchment;

however, the SEV scores themselves are still high, particularly for the eggs/larvae life stage. Recall that a score of 8 indicates major physiological stress. For impacts to eggs/larvae stage, HRC535 replacing HRC534 as the control or reference catchment seems justified; however, for the juvenile life stage, the SEV scores and their distribution do not look very different from the other non-reference stations.

Trend tests

Given four (4) descriptive statistics, nine (9) stations, and two (2) life stages, we create custom functions to help automate seventy-two (72) MK test runs. Additionally, there are 4 regional MK tests, one per statistic. `rkt_stn` computes the MK test and returns a data frame with Kendall's τ; the Sen slope; the MK test's p-value; and the mean of the SEV statistic across the station's years. `rkt_region` performs the regional test and returns results by SEV statistic; the mean SEV statistic for all WYs and stations; and two p-values, one for the regular test and the other corrected for inter-station correlation.

```
rkt_stn2 <- function(t, val){
  if (length(val) < 4) return(rep(NA, 4))
  df <- data.frame(t, val) %>% arrange(t)
  tstep <- diff(t) %>% unique
  if (length(tstep) > 1) {
    df_pad <- data.frame(t = seq(min(t), max(t), min(tstep)))
    df <- full_join(df_pad, df, by = 't')
  }
  mksen <- rkt::rkt(df[, 't'], df[, 'val'])
  df_out <- data.frame(tau = mksen$tau, sen = mksen$B, pval = mksen$sl,
            mean = mean(val))
  return(df_out)
}

rkt_region2 <- function(val, t, block){

  block_excl <- table(block) %>% as.data.frame() %>%
    subset(Freq < 4) %>% .$block
  t_all <- min(t):max(t)
  blocks_incl <- table(block) %>% as.data.frame() %>%
    subset(Freq >= 4) %>% .$block %>% unique
  df_in <- data.frame(t = rep(t_all, length(blocks_incl)),
                      block = rep(blocks_incl, each = length(t_all)))
  df0 <- data.frame(t, val, block) %>%
    subset(!block %in% block_excl)
  df_all <- full_join(df_in, df0, by = c('t', 'block'))

  mksen <- rkt::rkt(df_all$t, df_all$val, as.integer(df_all$block),
                    correct = T)

  df_out <- data.frame(mean = mean(val, na.rm = T),
                       tau = mksen$tau, sen = mksen$B, pval = mksen$sl,
                       corrected = mksen$sl.corrected)
  return(df_out)
}
```

Now apply both functions to the SEV data:

```r
sev_trend_stn <- sev_long %>% subset(Station %in% stns_df$`Station ID`) %>%
  group_by(Station, `Life Stage`, Statistic) %>%
  summarize(rkt = rkt_stn2(WY, SEV), .groups = 'keep') %>%
  unpack(cols = rkt)

# Regional tests
sev_trend_reg <- sev_long %>%
  group_by(`Life Stage`, Statistic) %>%
  summarize(rkt = rkt_region2(SEV, WY, Station), .groups = 'keep') %>%
  unpack(cols = rkt)
```

Table 8: *Mann-Kendall tests with statistically significant results*

Station	Life Stage	SEV Statistic	Kendall's τ	Sen slope	p-value	Mean[a]
509	Eggs/Larvae	Mean	0.324	0.080	0.077	9.35
509	Eggs/Larvae	Median	0.441	0.137	0.015	9.75
517	Eggs/Larvae	90th Percentile	-0.368	-0.071	0.044	12.3
535	Eggs/Larvae	Mean	-1.000	-0.338	0.089	7.76
509	Juvenile (Bray)	Median	0.397	0.072	0.029	7.33
510	Juvenile (N&J)	Maximum	-0.368	-0.044	0.044	11.1
532	Juvenile (N&J)	90th Percentile	-0.333	-0.059	0.092	9.71
532	Underyearling	90th Percentile	-0.333	-0.047	0.092	9.77

[a] This value is the mean of the SEV statistic and not the mean of all SEV scores for a station/life stage

For individual stations, only four station/SEV statistic combination yield statistically significant results. All other stations do not have statistically significant trends and are largely static over the stations' period of record. Figure **42** shows significant trends and their robust fit lines.

From WY2003 to WY2021, HRC509 on the mainstem has seen an increasing eggs/larvae SEV score at an approximate rate of 0.137 per year. The mean of those years' median SEV scores is approximately 9.75. A score of 9 on the scale is "reduced growth rate; delayed hatching; and reduced fish density." A score of 10 indicates 0-20% mortality plus moderate to severe habitat degradation.

HRC517 at Bridge Creek (tributary to North Fork) and HRC510 on the lower South Fork have decreasing trends for the eggs/larvae and juvenile life stage at -0.071 and -0.044 per year, respectively. These rates are fairly slow, and they would take 15-25 years to decrease by one SEV unit, assuming the trend is linear and non-stationary. This decrease only applies to the high SEV values; specifically, the 90th percentile for HRC517 and maximum for HRC510. SEV scores above 10 have increasing mortality percentage, so while an improvement, existing conditions are still dire.

***Figure 42**: Statistically significant robust trends by station, life stage, and SEV statistic*

Table **9** shows the results of the regional trend test, which uses all stations that have four or more years of data, irrespective of operational status and time of decommissioning. Only one regional test yielded a statistically significant trend: the annual maximum SEV score for the juvenile life stage. This trend is negative, indicating improving habitat conditions albeit from an already severely degraded state. The trend is significant only if we assume that max SEV scores for each station are independent. One indication of independence is the date-times of when the max SEV score occurs. If a group of stations have their annual max SEV score occur on dates far from each other, then one could argue that max SEV is independent between stations. Let's pick some stations with significant trends and a couple WYs to compare when their max SEV occurs, summarized in Table **10**.

```
fig_cap <- 'Time frame sample for maximum SEV occurrence for the juvenile life stage'
hrc_sevs %>% subset(Station %in% c(509, 510, 511, 517, 534)) %>%
  subset(WY %in% c(2010, 2015)) %>%
  mutate(WY = as.character(WY)) %>%
  group_by(Station, WY) %>%
  summarize(SEV = max(SEV_juvNJ, na.rm = T) %>% sprintf(fmt = '%.1f', .),
            'SSC (mg/L)' = ssc[which.max(SEV_juvNJ)] %>% sprintf(fmt = '%.1f', .),
            'Duration (hrs)' = sprintf(fmt = '%.1f', duration[which.max(SEV_juvNJ)]),
            'Start Date-Time' = strftime(StartDTS[which.max(SEV_juvNJ)], '%F %H:%M'),
            'End Date-Time' = strftime(EndDTS[which.max(SEV_juvNJ)], '%F %H:%M'),
            .groups = 'drop') %>%
```

```
arrange(WY) %>% as.data.frame %>% flextable %>%
set_caption(fig_cap, style = 'Caption',
            autonum = run_autonum(seq_id = "tab", bkm = "tfSample")) %>%
autofit
```

***Table 9**: Regional Mann-Kendall test results*

Life Stage	SEV Statistic	Mean[a]	Kendall's τ	Sen slope	p-value	p-value$_C$[b]
Eggs/Larvae	90th Percentile	12.3	0.052	0.018	0.407	0.631
Eggs/Larvae	Maximum	13.6	-0.082	-0.018	0.188	0.483
Eggs/Larvae	Mean	8.87	0.089	0.022	0.157	0.415
Eggs/Larvae	Median	8.85	0.091	0.035	0.148	0.351
Juvenile (Bray)	90th Percentile	9.77	0.026	0.008	0.684	0.830
Juvenile (Bray)	Maximum	11.1	-0.062	-0.014	0.321	0.589
Juvenile (Bray)	Mean	6.77	0.054	0.017	0.389	0.635
Juvenile (Bray)	Median	6.65	0.091	0.024	0.148	0.340
Juvenile (N&J)	90th Percentile	9.08	0.034	0.010	0.592	0.778
Juvenile (N&J)	Maximum	10.6	-0.139	-0.030	0.026	0.247
Juvenile (N&J)	Mean	6.02	0.014	0.006	0.833	0.911
Juvenile (N&J)	Median	5.91	0.000	0.000	1.000	n/a
Underyearling	90th Percentile	9.2	0.042	0.011	0.505	0.729
Underyearling	Maximum	10.6	-0.087	-0.021	0.167	0.466
Underyearling	Mean	6.39	0.042	0.010	0.505	0.719
Underyearling	Median	6.26	0.018	0.005	0.782	0.863

[a]This value is the mean of the SEV statistic and not the mean of all SEV scores for a station/life stage

Table 10*: Time frame sample for maximum SEV occurrence for the juvenile life stage*

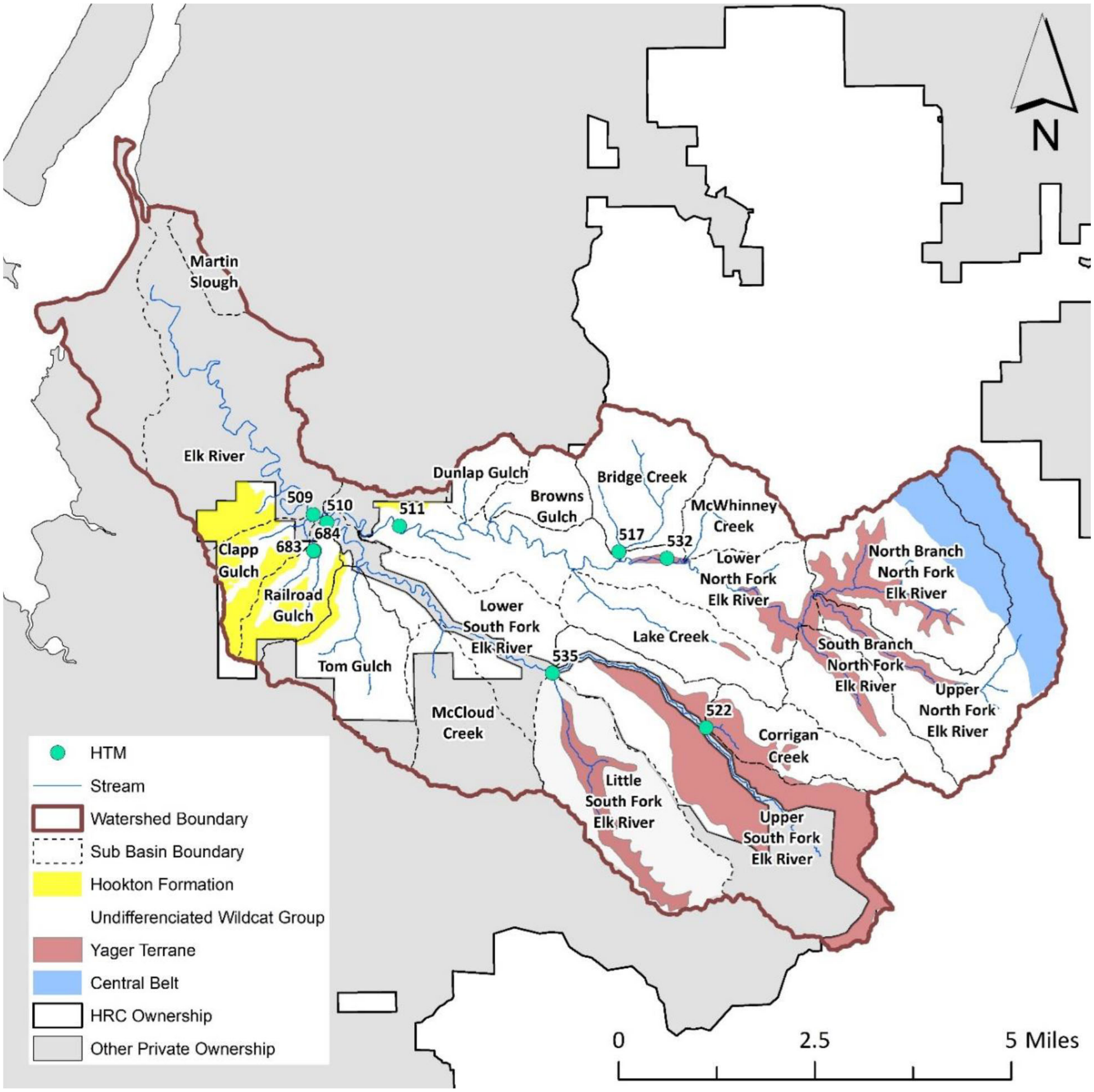
Station	WY	SEV	SSC (mg/L)	Duration (hrs)	Start Date-Time	End Date-Time
509	2010	10.7	1480.3	909.2	2010-01-19 11:30	2010-02-26 08:30
510	2010	11.0	1998.2	914.2	2010-01-19 08:30	2010-02-26 10:30
511	2010	10.5	992.3	923.5	2010-01-19 08:00	2010-02-26 19:15
517	2010	11.2	1808.0	1436.8	2009-11-20 11:15	2010-01-19 07:45
534	2010	7.8	54.6	428.2	2010-01-01 12:45	2010-01-19 08:45
509	2015	10.4	1808.0	467.0	2015-01-18 03:15	2015-02-06 14:00
510	2015	11.6	2981.0	1428.8	2015-02-06 11:15	2015-04-07 00:45
511	2015	10.9	992.3	1831.0	2014-11-22 09:00	2015-02-06 15:45
517	2015	10.5	665.1	1430.2	2015-02-06 09:30	2015-04-07 00:30
534	2015	9.8	200.3	1832.2	2014-11-22 02:45	2015-02-06 10:45

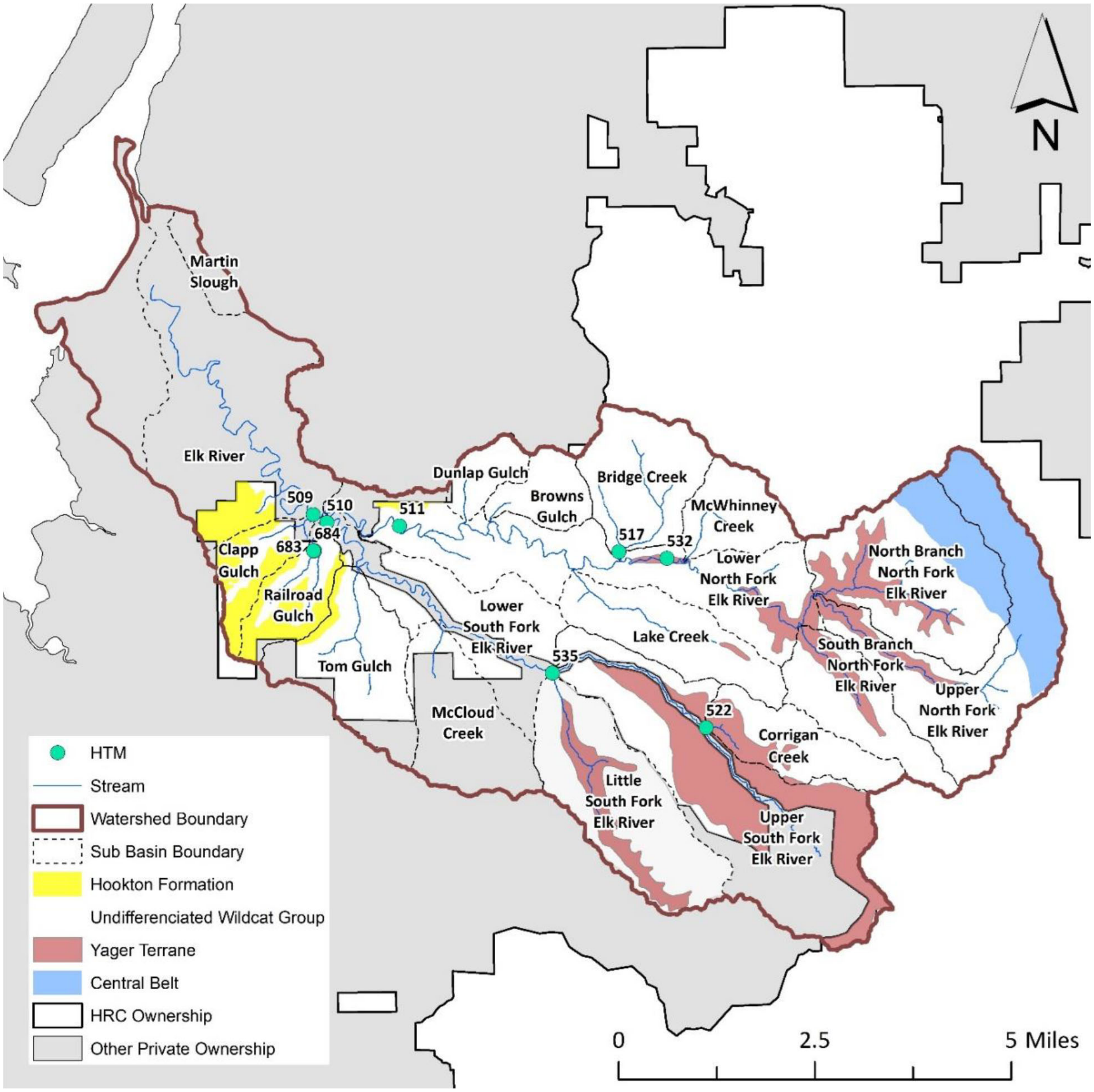
For WY2010 and downstream stations HRC509, 510, 511: the max SEV occurs within the same time frame (January 19 - February 26). HRC517 (Bridge Creek) and HRC534 (Upper Little South Fork) are located in different catchments, but their time frames also overlap with each other, but *not* with the downstream stations. WY2015 shows staggered time frames, i.e., HRC510 and HRC517 time frames (January 18 - February 6) start shortly after HRC509, HRC534 and HRC511 (February 6 - April 7).

This exercise tells us that the max SEV scores between stations are probably not independent, and this inter-station correlation has less to do with catchment locations (e.g., HRC510 and HRC511 are both within HRC509’s catchment) than it does with the timing of storm events and rainfall. Spatial autocorrelation in rainfall patterns very likely exists at this scale as the Elk River watershed is fairly small at 58.3 square miles. Thus, p-value adjusted for inter-station correlation is probably more reliable than the non-adjusted p-value. The adjusted p-value indicates a low probability of statistically significant regional trends.

#

North Coast Regional Water Quality Control Board
August 2022


N
Martin Slough
Elk River
Dunlap Gulch
Browns Gulch
Bridge Creek
McWhinney Creek
509
510
684
511
683
517
532
Clapp Gulch
Railroad Gulch
Lower North Fork Elk River
North Branch North Fork Elk River
Lower South Fork Elk River
Lake Creek
South Branch North Fork Elk River
Tom Gulch
535
McCloud Creek
522
Corrigan Creek
Upper North Fork Elk River
Little South Fork Elk River
Upper South Fork Elk River
HTM
Stream
Watershed Boundary
Sub Basin Boundary
Hookton Formation
Undifferenciated Wildcat Group
Yager Terrane
Central Belt
HRC Ownership
Other Private Ownership
0
2.5
5 Miles


Martin Slough
Elk River
Dunlap Gulch
Browns Gulch
Bridge Creek
McWhinney Creek
509
510
511
684
683
517
532
Clapp Gulch
Railroad Gulch
Lower North Fork Elk River
North Branch North Fork Elk River
Lower South Fork Elk River
Lake Creek
South Branch North Fork Elk River
Tom Gulch
535
Upper North Fork Elk River
McCloud Creek
522
Corrigan Creek
Little South Fork Elk River
Upper South Fork Elk River
HTM
Stream
Watershed Boundary
Sub Basin Boundary
Hookton Formation
Undifferenciated Wildcat Group
Yager Terrane
Central Belt
HRC Ownership
Other Private Ownership
0
2.5
5 Miles
N

Appendix D: Summary RWB Comments on Humboldt Redwood Company (HRC) 5-Year Synthesis Reporting Requirements

- Harvest summary over the previous five-year period by:
    - Acres harvested by sub-watershed
    - Silviculture method
    - THP name and number

- Roadwork update throughout their ownership in the Upper Elk River including:
    - Total length of active roads, including total amount of seasonal and permanent roads
    - Total length of road that meets the storm-proofed standard (this shall confirm that HRC's entire road network has been storm-proofed)
    - Total length of road decommissioned over the previous five-year period
    - Current road network map

- Landslide summary including landslide inventory and evaluation of the effectiveness of management measures intended to reduce the potential for management-related landslides. The updated inventory shall be prepared by a PG and shall include a description of all landslide activity identified during the previous five years based on field observations, interpretation of updated aerial photographs, and other available data sources, including:
    - An updated landslide inventory, describing all landslide activity observed within the past five years and whether observed landslides are new or reactivation of existing landslides
    - Estimated volume of sediment discharged by landslides over the previous five-year period by sub watershed
    - A map showing locations of landslide activity that has occurred during the previous five years
    - A description of data sources (aerial photograph, road inspection, THP layout, etc.)
    - Copies of aerial photographs of the Upper Elk River from the previous five-year period (may be scanned)
    - A discussion of overall landslide activity during the previous five years and any conclusions that can be made with respect to an association between management and landslide activity. This section shall include a discussion of potential modifications to management practices necessary to further minimize management-related sediment discharge

- Water quality trends report providing a summary of water quality monitoring results for the previous five years. This should, to the extent possible, be developed in coordination with the Watershed Stewardship program and should provide:
    - Discussion of any observable water quality trends detected during the previous five years and any conclusions with regard to sediment loads,

  - anadromous salmonid habitat and any possible association between management activities and in-stream conditions
  - Include discussion of potential modifications to management practices necessary to further minimize management related sediment discharge

- Restoration: Summary of all restoration projects HRC has conducted, participated in, or contributed to, within the Elk River watershed. Restoration activities are those projects designed to control in-stream sediment production and transport, improve beneficial uses of water, and abate nuisance conditions, and may include, but are not necessarily limited to:
  - Stabilizing banks through provision of root cohesion on banks and floodplains
  - Filtering sediment, chemicals, and nutrients from upslope sources
  - Supplying large wood to the channel, which maintains channel form and improves in-stream habitat complexity
  - Maintaining channel form, in-stream habitat, and an appropriate sediment regime through the restriction of sediment inputs or metering of sediment through the system
  - Moderating downstream flood peaks through temporary upstream off-channel storage of water
  - Maintaining cool water temperatures through provision of shade and creation of a cool and humid microclimate over the stream
  - Providing both plant and animal food resources for the aquatic ecosystem in the form of, for example, leaves, branches, and terrestrial insects

- Effectiveness Monitoring: Summary describing the results of HRC effectiveness monitoring programs for roads throughout the Upper Elk River and timber harvest related management practices in Railroad Gulch. Reports shall include:
  - Monitoring methods
  - Location of sites evaluated
  - Monitoring results
  - Discussion and any conclusion regarding the effects of their management practices with respect to sediment production from roads, watercourse crossings, harvest units, landslides, in-channel sources, and sensitive riparian zones.

Attachments

Attachments are made available via the North Coast Regional Water Board website, FTP, cloud service, or other electronic means. If the request is delivery by physical media, the requestor must provide flash memory storage device ("USB drives"). Requestors will pay any and all postage or other transport fees if request is by mail. Regional Water Board staff will not transmit data for any other physical media (e.g., optical discs, hard disk drives) unless requestor physically presents the device at the Regional Water Board office.

Due to file and data storage limits, all attachments after A-1 are available only by request. Similarly, raw, unprocessed data are also only available by request, with the exception of NCAR precipitation datasets, which are available at from NCAR/UCAR[27] for Stage IV and EOL[28] for Stage II. The free, open source *7z*[29] software or other compatible archival file manager are needed to open these archival files. Please contact Lance.Le@waterboards.ca.gov or NorthCoast@waterboards.ca.gov for these requests. If using the latter email address, please add *Attn: Basin Planning Unit* in the body or title of email.

A-1 *Data_Reassessment.7z*

Electronic archival file containing the RStudio project for the water quality trends analysis. Archive contains code (*.R); pre-processed data (*.csv); raw markdown (*.rmd); draft documentation (*.docx); figures (*.png); select binary data (*.Rdata or *.rds); and other files needed to replicate this analysis.

A-2 *full_dataset.zip*

Archive file for binary data (*.RData) related to generalized least squares model fitting outputs using full dataset.

A-3 *without_outliers.zip*

Archive file for binary data (*.RData) related to generalized least squares model fitting outputs using dataset with outliers removed.

[27] https://rda.ucar.edu/datasets/ds507.5/
[28] https://data.eol.ucar.edu/dataset/21.089
[29] https://www.7-zip.org

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