SPATIAL AND TEMPORAL NUTRIENT LOADING DYNAMICS IN THE SPRAGUE RIVER BASIN, OREGON

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Executive Summary

This study evaluated the streamflow and nutrient dynamics of the Sprague River Basin over the period WY2002 – 2014 using biweekly flow and nutrient measurements collected by Klamath Tribes at eight sampling stations across the basin. Continuous daily timeseries of flows, loads, and concentrations were computed using methodologies similar to those used in a previous nutrient budget study of the entire Klamath Basin (Walker et al., 2012). These daily time-series were used as a basis to investigate the spatial and temporal dynamics of nutrient concentrations and loads, estimate relative amounts of background and anthropogenic loading, and evaluate long-term trends at each sampling station.

The results of this study led to the following conclusions and recommendations:

1. Over the study period WY2002 – 2014, annual precipitation was generally lower than the long-term mean in all but two years, WY2006 and WY2011, which were considerably wetter than normal. Two of the years in the study period, WY2013 and WY2014, had low precipitation and small winter snowpack that led to regulation of water withdrawals in accordance with water rights. These latter years also showed earlier snowmelt consistent with other regional climate and streamflow trends.
2. The majority of annual streamflow increase (based on gauges) from the headwaters to the river outlet occurred in the upper parts of the watershed including the upper reach of the Sprague River above Godowa, the headwater sub-basins in the North and South Forks, and the Sycan River. In the lower reaches of the Sprague River (below the confluence with the Sycan River near Godowa), the total flow actually decreased under high flow conditions during winter and spring between the two lower-most stations at Lone_Pine and Power. During summer, flows did show some increase between these stations, but not as much as would be expected based upon estimates of groundwater seepage from Gannett et al. (2007). These results were confirmed using separate data sources and suggest that during winter and spring, the floodplains, wetlands, and other depressions along the river corridor in the lower Sprague may be acting as temporary storage basins that trap portions of overbank flows, which are then infiltrated to groundwater or lost by evaporation. However, these patterns may also be the result of inaccurate flow rating curves at one or more of the stations, especially under high flow conditions.
3. Comparisons between mean summer flows and estimates of groundwater discharge by Gannett et al. (2007) showed close agreement for the headwater sub-basins of the upper North and South Forks, the Sycan River, and in the upper section of the Sprague River mainstem above Godowa. However, in the middle and lower sections of the Sprague River, groundwater discharge estimates were substantially higher than the net flow changes along these reaches. These differences suggest significant flow losses likely due to evaporation and irrigation withdrawals.
4. Mean annual FWM concentrations for TP ranged from 47 ppb in the upper South Fork to 72 ppb near the outlet of the Sprague River at Power over WY2010 – 2014. The majority of this increase occurred in the lower reaches of the South and North Forks primarily due to increases in particulate P. The increases in particulate P suggest that sediment input/transport is a major

concern in these reaches and are further reflected by a similar large increase in TSS. On a seasonal basis, the largest increases in both TP and PP occurred in winter and spring when flow conditions are high, further suggesting significant inputs of particulate phosphorus due to erosion of stream banks, upland slopes, streambed sediments, floodplains, and/or other areas. During summer, both TP and PO4 concentrations decreased from the confluence of the North and South Forks to the outlet likely due to biological uptake of dissolved PO4, which also decreased along the river whereas particulate P concentrations remained steady.

5. Consistent with high groundwater inflow (which includes adjacent springs), the largest increases in flows and TP load per unit area, but the smallest change in FWM TP concentration, occurred in the middle Sprague River basin between Godowa and the SF_Ivory + NF_Ivory confluence. In contrast, the largest increase in FWM TP concentration occurred in the lower South Fork between the SF_Ivory and SF stations. In addition, PP concentrations rose dramatically and consistently in the North and South Forks, while in most years PP concentrations remained relatively steady from Godowa to Power, declining slightly in some years, and increasing slightly in others.
6. Relative to total phosphorus, PP is the major anthropogenic contributor to loading.
7. Although misclassification appears to be an issue with the NLCD land use data, rendering analyses less useful than they might otherwise be, comparisons between nutrient concentrations and land use composition of the associated sub-basins for each station showed strong positive correlations between both TP and PP and land uses for Planted/Cultivated and Herbaceous. Both TP and PP concentrations were also negatively correlated with Forest cover. However, there were no significant correlations between dissolved PO4 and any land use type. This suggests that human activities primarily cause an increase in particulate P, with dissolved P being primarily controlled by natural factors, especially groundwater discharge which has high dissolved P content.
8. Significant positive correlations were also found between annual mean TP concentrations and the fraction of the lower valley associated with Place of Use (POU) areas for irrigation surface water rights, which were used to represent agricultural areas. On a seasonal basis, the mean TP concentrations in both winter and summer also had significant positive correlations with fraction POU area. Similarly, particulate P was positively correlated with fraction POU area not only annually, but in all seasons except fall. However, dissolved PO4 showed no significant correlations either annually or in any season, which again suggests that human activities have a larger impact on particulate phosphorus than on dissolved PO4.
9. The North and South Fork stations all showed positive linear relationships between fraction TP as particulate (% PP) and flow, while the remaining stations showed more non-linear relationships with the % PP higher under lowest flows, decreasing during intermediate flows, and then increasing with increasing flow before tending to level off and decline at highest flows. These non-linear relationships may be the result of bio-uptake of dissolved phosphorus (PO4) under low flows during summer and increased particulate phosphorus loading through irrigation or other agricultural practices such as cattle access to degraded riparian areas. Relatively high fraction particulate TP under low flows at SF_Ivory compared to the other stations also suggests that even under low flows there is a major source of particulate phosphorus loading to the

lower South Fork reach between SF and SF_Ivory. Both TP concentrations and the fraction particulate TP showed positive relationships with TSS further confirming that sediment input/transport is a major source of TP in the Sprague system.

10. Similar to FWM TP, the mean annual and seasonal FWM TN concentrations showed a large increases between the relatively un-impacted SF station and the SF_Ivory station (particularly in summer), but a similar trend was not seen for the NF stations. Despite higher TN concentrations for the Sycan during all seasons, TN only increased slightly for the Sprague stations downstream of the Sycan confluence. Spring and summer NH4 and NO23 concentrations were low across all stations likely reflecting uptake by aquatic macrophytes and algae. Unlike other reaches, NO23 increased sharply between SF_Ivory + NF_Ivory and the Godowa station during late-summer, fall and winter as flows increased. Sycan NO23 values were relatively high (compared to other stations) in the summer and fall and decreased in the winter and spring as organic N was exported from the Sycan Marsh upstream.
11. TN concentration was non-linearly related to flow at most stations, with relatively high values occurring during the summer low-flow period, declining values in the fall, and increasing values as flow increased in the winter and spring. As with the phosphorus parameters, TN values tended to be higher in the winter than the spring during higher flows, and similar to PP, TN values tended to level off or decline at the very highest flows.
12. Sycan NO23 was negatively related to flow, and the pattern at Godowa was unique in that NO23 values increased with flow in the summer through early winter and then leveled off and declined in late winter and spring as flows increased further, although the cause of these dynamics is not clear. TN and organic-N concentrations generally remained constant over a range of TSS concentrations during summer and fall low-flow periods before increasing linearly with TSS during winter and spring at most stations.
13. The relative contributions of background versus anthropogenic TP loads were estimated using a revised methodology compared to that used previously (Walker et al., 2012). Background loads were divided into two separate components, one for groundwater and one for runoff. A background TP concentration of 60 ppb was derived for the groundwater discharge component based on synoptic measurements collected by Klamath Tribes in springs and creeks throughout the basin. For the runoff component, a background TP concentration of 34 ppb was computed from the total observed concentrations in the relatively un-impacted headwater sub-basins in the upper North and South Forks after accounting for the loads due to groundwater discharge. These background concentrations were then applied to the groundwater and runoff flow components at each water quality station. After combining the groundwater and runoff background loads, the total background TP concentrations ranged from 40 ppb to 56 ppb. These concentrations are lower than the 65 ppb background concentration estimated by Walker et al. (2012), but better reflect the annual mean concentrations observed in the relatively un-impacted sub-basins of the Sprague River.
14. After estimating background TP loads and concentrations at each station, the anthropogenic loads and concentrations were computed and ranged from 14% to 29% of the total load over the period WY2010 – 2014 among the stations excluding the un-impacted NF and SF, both of which had no or minimal anthropogenic loading. The largest fraction of anthropogenic loads

was in the lower South Fork at SF_Ivory. Near the outlet of the Sprague River at Power, anthropogenic loads accounted for 23% of the total load due to an increase in TP concentration of 17 ppb above a background level of 55 ppb yielding a total observed mean annual FWM concentration of 72 ppb over WY2010 – 2014.

15. Long-term trend analyses over the entire study period (WY2002 – 2014) showed a significant increasing trend in flow in the upper North Fork and significant decreasing trends in flow at the Sycan River and the upper Sprague River mainstem at Godowa despite no significant trends in precipitation.
16. The trend results for TP loads show significant increases in the upper North and South Forks, and decreases at Sycan, Godowa, and Lone_Pine. However, there was no significant trend near the Sprague outlet at Power.
17. TP concentration also showed a significant increasing trend in the upper North and South Forks, despite minimal agricultural impacts in these sub-basins, although there are other human impacts such as forest roads and some grazing. The two lower Sprague River stations (Power and Lone_Pine) both showed significant decreasing trends in TP concentrations, as did the Sycan River. Trends in PO4 and particulate P showed that the decrease in TP in these lower stations was due to decreasing trends in dissolved PO4 with no trends in particulate P. Conversely, the increasing trends in TP in the upper South and North Forks were attributed to increases in particulate P with no trends in dissolved PO4.
18. All stations showed significant decreasing trends in TN with the magnitudes of these trends being higher in the downstream stations.

In addition to these key findings, the following recommendations are provided:

1. Review of the flow rating curves for the Power and Lone_Pine stations, especially for high flow conditions to determine whether the decreased discharge between these stations during high flow periods is real or simply an artifact of inaccurate flow measurements.
2. Continue monitoring for TSS (added in 2010), and continue sampling the more recently added NF_Ivory and SF_Ivory monitoring stations (added in 2009). These important areas showed the greatest increases in phosphorus concentration. Continued monitoring will be useful for future analyses of trends and loading.
3. Perform intensive sampling at select reaches to quantify all sources and sinks and construct a detailed nutrient budget to better understand the magnitudes of the various in-stream and external fluxes of nutrients along the river.
4. Evaluate the efficacy of techniques such as use of stable isotopes to trace pathways of nutrient movement and recycling.
5. Increase synoptic sampling of nutrient concentrations in springs, irrigation return flows, and the lower Sycan (for Sycan determine source of high summer NO23).
6. Update the previous analysis of background and anthropogenic nutrient sources for the entire UKL basin (Walker et al 2012) utilizing this refined methodology, which separates the groundwater and runoff components.
7. Add DOC and TOC to the routine monitoring program to delineate organic fractions of TSS and particulate P.

8. Install continuous water quality probes at existing sampling locations, particularly for the collection of hourly dissolved oxygen, pH, and turbidity data. Compute ecosystem metabolism (gross primary productivity and net ecosystem productivity) for use in understanding ecosystem processes affecting algal and macrophyte related nutrient dynamics.
9. Take action to restore extensive riparian areas and stream channel function in the lower South Fork and lower North Fork reaches where the data show the largest increases in TSS, TP and particulate P concentrations. Riparian plant community restoration is a ubiquitous need that will be the most effective means of reducing erosion-related increases in PP concentration above the NF/SF confluence, and will increase roughness of floodplain surfaces and increase deposition of PP.
10. Reconfigure channelized stream reaches. The lower reach of the South Fork is a good example of a straightened channel that is diked along much of its length. The resulting increased slope, confinement of flow, and minimal lateral connectivity with floodplain surfaces increase erosion, scouring, and transport of fine sediments and the associated PP. Reconstruction of such reaches with appropriate channel morphology to provide lateral connectivity with the floodplain is essential.
11. Consider measures to accelerate aggradation of incised stream reaches, which are prevalent in the NF Sprague and in Meryl Creek. Encouraging beaver activity may be a useful approach (e.g. http://beaver.joewheaton.org/)
12. Restore or increase lateral connectivity of the Sprague River with its floodplain by removing or breaching constraining dikes. Focusing such efforts upstream of Godowa would help reduce the PP concentration at Godowa, which is typically the inflection point in PP and TP load plots; slope of these plots decreases moving downstream from Godowa. Similar restoration efforts downstream of Godowa would reduce PP as well. If done at sufficient scales, this may reduce the magnitude of loading in wetter years like 2006 and 2011.
13. Eliminate direct irrigation returns, which likely have high nutrient content, to rivers and streams.

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1 INTRODUCTION

Ecological restoration of the Sprague River Basin is an essential element of the overall restoration and ecosystem health in the entire Klamath Basin. For example, the Sprague River is important as a major tributary to Upper Klamath Lake (UKL), as fisheries habitat for endemic fishes, and as a potential future spawning and rearing habit for anadromous salmonids[1]. Issues in the Sprague River Basin proposed for remediation under the Klamath Basin Restoration Agreement (KBRA) include degraded riparian habitat and stream channels, passage barriers, diversions resulting in fish entrainment, adverse water quality conditions, adverse hydraulic conditions, and fluctuating water levels (KBRA 2010).

Water quality in the Sprague River is of particular concern, both from an in-river perspective (ODEQ 2002)[2] and as a source of nutrient loading to UKL (Kann and Walker 1999; Walker et al. 2012; ODEQ 2002). Reduction of nutrient loading to UKL (particularly phosphorus, P) has been identified as an important means of improving water quality affecting native fishes in UKL[3], as well as reducing export of organic matter and nutrients to the Klamath River downstream of UKL[4]. Phosphorus is a key element promoting the initial summer *Aphanizomenon* bloom (Kann 2015a; Hoilman 2008), and Eldridge et al. (2013) indicate that *Aphanizomenon* and microcystin toxin[5] are ultimately dependent on phosphorus to regulate growth and decline.

The dependence of UKL bloom-formers (primarily *Aphanizomenon* and secondarily hepatotoxin producing *Microcystis*) and subsequent poor water quality on nutrients (primarily phosphorus) that are both externally derived and internally recycled (Walker et al. 2012) led to development of a TMDL calling

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[1] The Sprague River and its tributaries currently provide native fish habitat for redband trout, bull trout, and endangered shortnose and Lost River suckers (among others), and historically provided habitat for chinook salmon and steelhead (USDI/CADFG 2013). In the event fish passage is restored in the main-stem Klamath River, anadromous fish would regain access to historical habitat on the Sprague River as well as other tributaries (KHSA 2010; USDI/CADFG 2013).

[2] In addition to habitat modification, the Sprague River is listed as water quality impaired for temperature, pH, chlorophyll-a, and low dissolved oxygen (ODEQ 1998).

[3] Upper Klamath and Agency Lakes are hypereutrophic and are seasonally dominated by large blooms of the nitrogen-fixing cyanobacterium *Aphanizomenon flos-aquae* (Kann 1998; Kann and Smith 1999). Bloom-driven water quality degradation that includes extended periods of low dissolved oxygen, elevated pH, and toxic levels of un-ionized ammonia has been associated with the decline of native endangered fish populations, including the Federally Listed shortnose (*Chasmistes brevirostris*) and Lost River (*Deltistes luxatus*) suckers (Perkins et al. 2000). More specifically these conditions have been linked to large fish kills and redistribution of the endangered sucker species in UKL (Perkins et al. 2000; Kann and Welch, 2005; Wood et al. 2006; Banish et al. 2009).

[4] Water quality degradation in the Link and Klamath Rivers below UKL is associated with phytoplankton derived organic matter exported from UKL (e.g., Sullivan et al. 2013)

[5] N-fixation by *Aphanizomenon* during the early summer appears to supply nitrogen for growth of toxigenic *Microcystis aeruginosa* later in the summer, and these secondary *M. aeruginosa* occurrences are responsible for production of the hepatotoxin microcystin in UKL (Jacoby and Kann 2007, Eldridge et al. 2012).

for reduction of external anthropogenic P loads[6] (Walker 2001; ODEQ 2002). The TMDL model was expressed in terms of long-term-average P load and it was determined that achieving the loading target (109 metric tons/year of TP) would require a 40% reduction in external P load relative to the historical baseline.

Previous nutrient balances using data collected between 1992 and 1998 (Kann and Walker 1999) formed the basis for the original TMDL (ODEQ 2002) as well as a more recent update to the TMDL model (Wood et al. 2013). Wood et al. (2013) provided additional uncertainty analyses[7] for the 2002 TMDL model and showed that although predicted UKL P and algal biomass (chlorophyll) were somewhat higher than earlier predictions, a 40% reduction in external P load was predicted to decrease in-lake P and chlorophyll by ~40% (the average reduction based on various model runs).

Using water and nutrient balances for UKL updated through 2010 (Walker et al. 2012), Wherry et al. (2015) recalibrated the TMDL model and predicted that the TMDL target watershed phosphorus reduction of 40% would achieve steady-state concentrations for water column total P and chlorophyll of 74 ppb and 27 ppb, respectively, and would reduce the overall magnitude and frequency of algal (cyanobacterial) blooms[8].

Sources of phosphorus in the UKL watershed have been related to erosional inputs occurring during the past century, including timber harvest, drainage of wetlands, agricultural activities associated with livestock grazing and irrigated cropland, and hydrologic modifications such as water diversions and channelization (Snyder and Morace 1997; ODEQ 2002; Bradbury et al. 2004; Eilers et al. 2004)[9].

1.1 Role of the Sprague River in Nutrient Export

As noted by Connelly and Lyons (2007), the primary land cover types in the Sprague River Basin include forestlands (mostly on hillslopes and ridges), rangelands, irrigated pasture, grass, hay, and open water and wetlands, with much of the pre-settlement riverside woodlands, riparian zones, and wetlands modified by diking, draining, herbicide application, land-clearing, and grazing. A high correlation between flow and phosphorus load in the Sprague River indicates that sediment transport during high flow events is an important contributor to high phosphorus concentrations in Upper Sprague River sub-basin streams (ODEQ 2002). Sources of the sediment inputs within the Sprague River drainage include agriculture, livestock grazing, forestry activities, and road-related erosion (ODEQ 2002; Connelly and Lyons 2007; Rabe and Calonje 2009).

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[6] ODEQ determined that reducing P loads linked to watershed development would be the most effective means of improving water quality conditions in the lake.

[7] Model uncertainty was evaluated based upon alternate chlorophyll models, P recycle mechanisms, phosphorus and light limitation coefficients, and updated initial sediment P concentration.

[8] Modelling indicated that the time required to achieve steady state was 19 years. In addition, further steps were recommended to reduce model uncertainty (Wherry et al. 2015).

[9] Paleolimnological and coring studies in particular showed increases in various indicators (e.g. Ti, Al, tephra, and charcoal) of watershed erosional inputs to UKL in the 20th century (Bradbury et al. 2004; Eilers et al. 2004; Simon and Ingle 2011)

On an overall annual basis, the Sprague River contributed 31% of the tributary TP load and 44% of the tributary TN load to UKL (Table 1). Although watershed export (load per unit area) was relatively low compared to the Sevenmile Creek and Wood River systems (Table 1) [10], much of the Sprague River watershed disturbance occurs in a smaller watershed area encompassing the valley floor and riparian areas. These disturbed areas, which generally lack healthy riparian zones, are prone to enhanced transport of nutrients during agricultural activities and higher flow events.

TABLE 1: SUMMARY OF TP AND TN LOADS, CONCENTRATIONS, AND EXPORT FOR UKL TRIBUTARIES, 1992 – 2010

	Flow	Nutrient Loads		Percent of Tributary Inflow to Upper Klamath Lake			FWM Nutrient Concentration		Drainage Area	Runoff	P Export	N Export
System	hm^3/yr	TP mt/y	TN mt/y	Flow	TP	TN	TP ppb	TN ppb	km^2	m/yr	kg/km^2 /yr	kg/km^2 /yr
Wood River	317.7	35.6	55.7	25%	29%	14%	112	175	394	0.81	90	141
7-Mile Creek/Canal	103.4	14.8	49.2	8%	12%	12%	143	476	96	1.07	153	510
Sprague River	501.9	38.1	177.3	40%	31%	44%	76	353	4,171	0.12	9	43
Williamson River[1]	344.0	35.3	118.9	27%	29%	30%	103	346	3,641	0.09	10	33
Total Tributary Inflow	1,267.0	123.8	401.1	100%	100%	100%	98	317	8,302	0.15	15	48

[1]not including Sprague River inputs

source: Walker et al. 2012

For example, the Sprague River alone can contribute upwards of 50% of the total tributary TP load to UKL during high flow events in late-winter to spring (e.g., Walker et al. 2012; Appendix E), and during those periods the export (kg/km^2/yr) of TP increases sharply. Records et al. (2014) note that the majority of agriculture in the Sprague River valley is flood-irrigated pasture concentrated in valleys of the South Fork and mainstem of the Sprague River, and that higher TP loading per unit area occurred in valley bottoms.

In addition, Walker et al (2012) showed a sharp increase in flow-weighted-mean (FWM) TP and TN concentrations longitudinally[11] from relatively un-impacted headwater stations on the upper North and South Forks of the Sprague River to stations representing agricultural areas on the lower South/North Forks and Sprague River mainstem (Figure 1 and Figure 2). Such increases reflect the cumulative impacts of loads from anthropogenic sources and potential spatial variations in local inflows related to geology and other unknown factors (Walker et al. 2012). GMA (2007) found substantial increases in suspended sediment loads between stations at the upstream end of alluvial reaches and those near the confluence with the mainstem in both the North Fork and South Fork drainages. Previous Sprague River watershed assessments also note that channelization, wetland/riparian area conversions are linked to increased erosion and particulate phosphorus transport (Rabe and Calonje 2009).

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[10] Sprague River TP export was 9 kg/km^2/yr compared to 90 and 153 kg/km^2/yr for the Wood and Sevenmile systems, respectively.
[11] FWM TP increased ~2-fold and FWM TN ~3-fold

A comprehensive analysis of the geomorphology and flood-plain vegetation of the Sprague and lower Sycan Rivers showed that while most important physical processes still functioned on the Sprague River, systematic trends in channel and floodplain conditions indicate broadscale human influence such as declining sinuosity, increased channel slope, decreased migration rates, local channel incision, and diminished short woody near-channel vegetation (O'Connor et al. 2013)[12]. In addition, O'Connor et al. (2013) concluded that entrainment of sediment was high on the South Fork and mainstem of the Sprague River during high flow events primarily due to channel and bank erosion in these reaches and across flood-plain surfaces. Historically these channels were less constrained with lower gradients, and provided greater lateral floodplain connectivity, sediment storage, and riparian vegetation suggesting that restoration of these functions would lead to decreased erosion and sediment transport via greater deposition and sediment capture.

[12] The authors further note that channel confinement by levees and other built features is probably the single most important factor contributing to these changes, but the direct and indirect consequences of other manipulations, such as local flow diversion and concentration, grazing, vegetation removal, and beaver eradication, have also been important, particularly at the valley-segment scale.

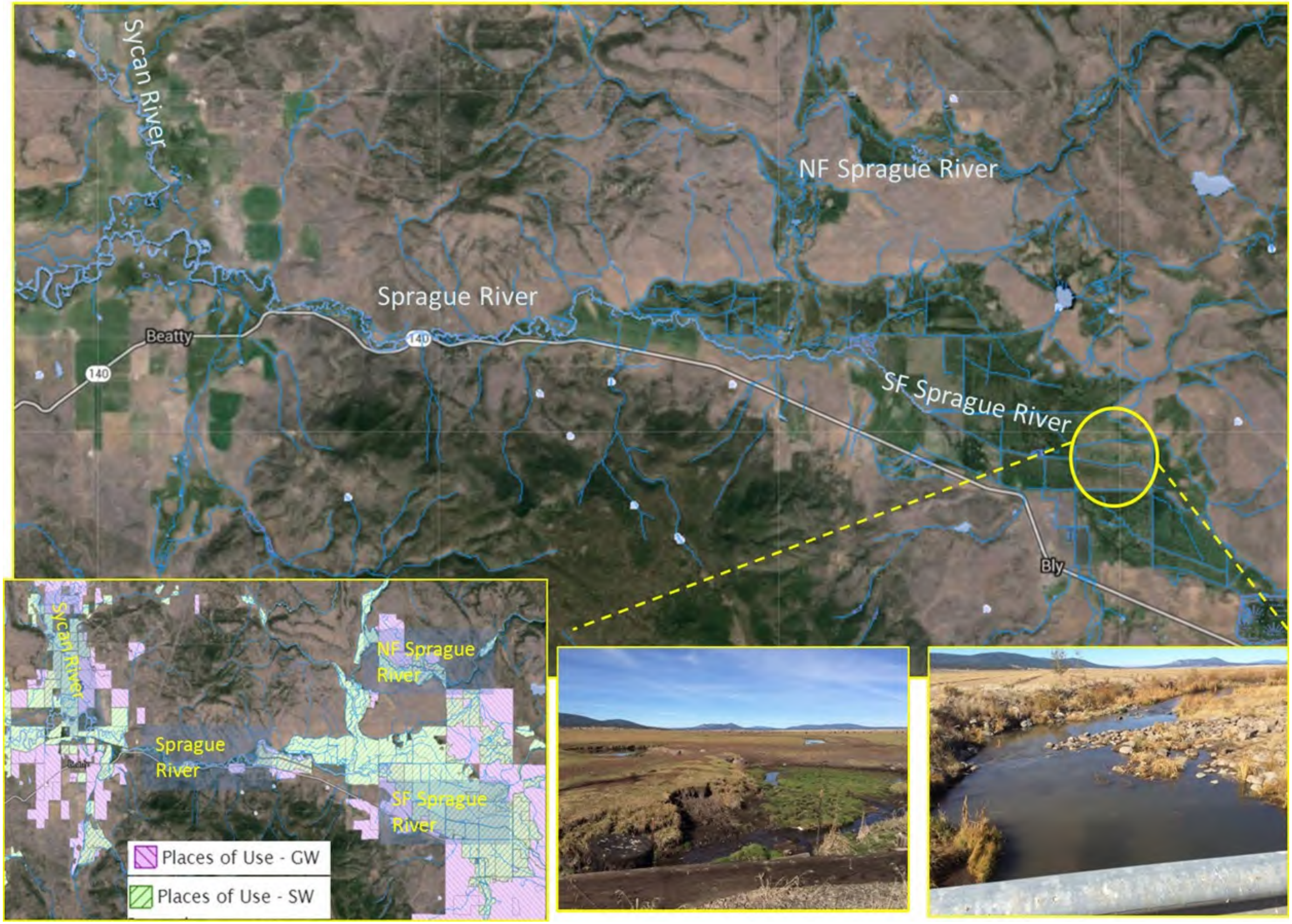

FIGURE 1: EXAMPLE OF AGRICULTURAL AREAS ON THE SF/NF SPRAGUE RIVER AND MAINSTEM.

Green areas (mainly in valley bottoms) show irrigated areas.
Inset map shows places of use for surface and groundwater diversions.
Inset photos show erosional areas in the SF Sprague.
Map Source: Oregon Water Resources Department (http://apps.wrd.state.or.us/apps/gis/wr/Default.aspx)

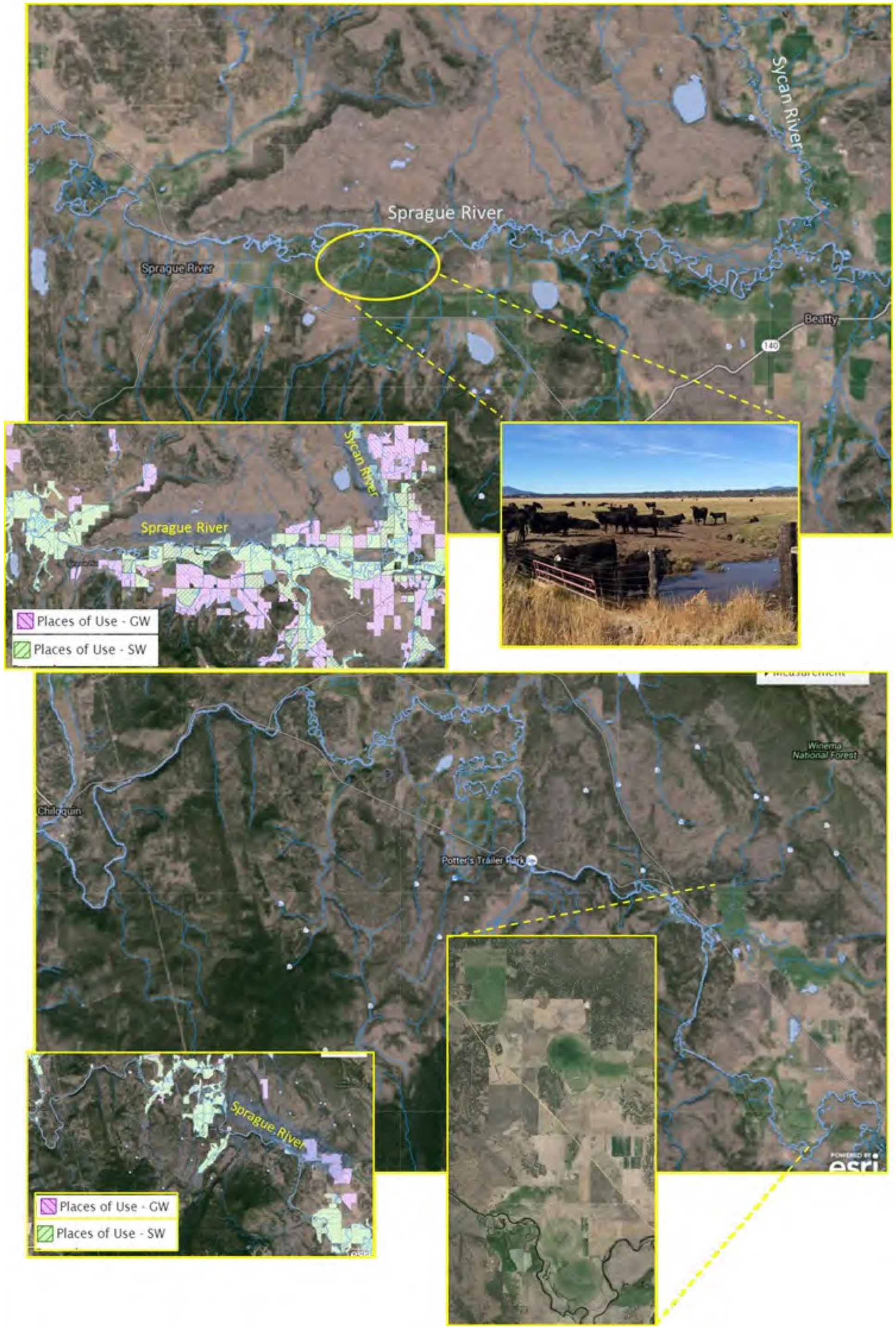

FIGURE 2: EXAMPLE OF AGRICULTURAL AREAS ON THE MIDDLE SPRAGUE RIVER MAINSTEM (TOP) AND LOWER SPRAGUE RIVER (BOTTOM).

Green areas (mainly in valley bottoms) show irrigated areas.
Inset maps show places of use for surface and groundwater diversions.
Map Source: Oregon Water Resources Department (http://apps.wrd.state.or.us/apps/gis/wr/Default.aspx)

1.2 Restoration Efforts

Numerous stream restoration projects have been implemented in the Sprague River Basin since the early-to-mid-1990s including fencing, wetland creation, floodplain reconnection, levee breaching, meander-bend cutoff plugging, riparian planting, channel realignment, fish screens, irrigation water management, spring reconnection, and wetland connection (USDA CEAP 2009; Newfields and Kondolf 2012; Stillwater Sciences et al. 2013). The types of restoration activities and their performance were evaluated by Newfields and Kondolf (2012), who developed a post-restoration project appraisal (PPA) framework to guide analysis and conceptual models to further understanding of the Sprague River Basin. In the subset of ten restoration projects they evaluated, performance for 70% of the projects satisfied some success criteria but not others and did not consider all critical processes, and 30% satisfied most or all success criteria.

Although many of these restoration projects have been beneficial, O'Connor et al. (2013) indicate that channel structure and function, and riparian vegetation were still compromised, and recommended restoration activities intended to promote a more natural channel and flood-plain geometry as well as channel aggradation to the extent that overbank flow becomes common[13]. Such geomorphological activities relate directly to sediment and nutrient transport dynamics. Other water quality-specific restoration recommendations included: (a) investigating the feasibility of constructing tailwater re-use systems and treatment wetland ponds for irrigation returns; (b) increasing shade and stream depth by restoring riparian corridors to their proper functioning; (c) implementing livestock grazing practices (e.g., rotation grazing and seasonal grazing) to limit stream access during critical growing seasons for riparian vegetation; and (d) managing for robust riparian communities (Connolly and Lyons 2007).

Based in part on pasture-level monitoring studies showing that first-flush irrigation and storm events have the potential to export large quantities of phosphorus from irrigated grazing land in the Upper Klamath Lake Basin (Cioti et al. 2010), a network of diffuse source treatment wetlands (DSTWs) were proposed to decrease external loading of phosphorus and nitrogen to Upper Klamath and Agency Lakes (Stillwater Sciences et al. 2013). Although just in the beginning stages of implementation, such DSTWs would consist of small (1 to 10s of acres) flow-through and terminal wetlands located along creeks and canals or in low-lying areas in fields within the Wood River and Sprague River valleys.

As noted below, one important objective of the current study is to perform trend analyses to advise whether existing restoration efforts may be associated with downward trends in Sprague River nutrient export.

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[13] These include restoration of natural channel migration processes, maintenance and enhancement of the frequency and extent of overbank flooding and lateral connectivity between channels and flood plains, and promotion of vegetation succession and disturbance processes conducive to reversing historical losses of short woody vegetation cover types.

1.3 WATER RESTRICTIONS

The Klamath Tribes senior in-stream water rights for the Sprague River and its tributaries were confirmed in 2013 by the Oregon Department of Water Resources (Final Order of Determination in the Klamath River Basin Adjudication[14]). These water rights specified minimum in-stream flows for each month. In a subsequent settlement called the Upper Klamath Basin Comprehensive Agreement, the Klamath Tribes agreed to regulatory thresholds (Specified In-stream Flow (SIF) thresholds) that change with the relative wetness or dryness of the near-term hydrologic conditions in exchange for permanent riparian restoration[15] and reductions in agricultural water use, among other things (UBCA 2014). Dry conditions in both 2013 and 2014 (2014 had particularly low rainfall/snowpack conditions, see Section 4.1 below) resulted in calls for regulating irrigation water in the Sprague River basin based on the SIF thresholds as well as on water rights associated with the Klamath Reclamation Project. Because regulation of water rights had never happened before throughout the Sprague River basin, hydrologic conditions in 2013 and 2014 were different from previous drought years during the irrigation season (e.g., Hess and Stonewall 2014).

1.4 CURRENT ANALYSIS EFFORT

The Klamath Tribes have maintained a long-term tributary and lake monitoring program (1990 – present) to understand nutrient and water quality dynamics and to inform management and restoration activities. These datasets were the basis for the initial computation of water and nutrient balances for UKL (Kann and Walker 1999) as well as the TMDL referenced above (ODEQ 2002). In a more recent effort to update the earlier UKL balances, Walker et al. (2012) provided water and nutrient balances for UKL for the water years 1991 – 2010. In addition, time-series trend analyses for total phosphorus (TP) and total nitrogen (TN) were computed for the major long-term stations analyzed in Walker et al. (2012). For the Sprague River, Walker et al. (2012) used the lower-most station located above the Williamson River confluence (Sprague at Kircher's which is just downstream from Sprague @ Power: Figure 4), and additional data summaries and trends for that station were also provided annually (e.g., Kann 2015b).

In response to the need for better understanding nutrient and sediment dynamics relative to land use practices and recommended restoration activities, the Klamath Tribes expanded their monitoring program in 2002, and again in 2009, to include a network of additional stations on the mainstem Sprague River and tributaries (Figure 4). As part of the detailed analysis of the lower-most Sprague River station, Walker et al. (2012) also provided a preliminary assessment of these expanded watershed stations. However, the preliminary analysis only included computation of flow-weighted-mean (FWM) concentrations using the biweekly samples for the overall 2002 to 2010 period, and did not include computation of daily nutrient concentrations and loads that would be necessary to determine seasonal

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[14] http://www.oregon.gov/owrd/pages/adj/index.aspx

[15] Implementation of Riparian Management Agreements with willing landowners that specify grazing management and nutrient reduction measures.

trends and refinement of specific watershed loading estimates. In addition, time-series trend analyses were not performed for these expanded stations.

Records et al. (2014) provided load computations and analysis of the expanded stations but only for 2001 to 2010, and did not include data for the North and South Forks above the confluence with the mainstem of the Sprague River (data collection for these stations, NF @ Ivory Pine Rd and SF @ Ivory Pine Rd, began in 2009). Thus, the primary goal of this study is to provide the first comprehensive analysis of the entire 2001 – 2014 Sprague River sampling program.

1.5 Study Area

The Sprague River Basin is located in the Upper Klamath River Basin of south-central Oregon and has a drainage area of approximately 4,124 km^2. There are three major tributaries to the Sprague River including the Sycan River and the North and South Forks of the Sprague River (Figure 4). Within the basin, elevation ranges from 1,268 at the Williamson River confluence to 2,549 m above sea level at Gearhart Mountain. The basin has a high semi-arid climate due to the rain-shadow casted east of the Cascade Mountain Range. As a result, mean annual precipitation ranges from less than 40 cm on the valley floors to 120 cm in high elevation margins (Figure 3; PRISM Climate Group 2014; O'Connor et al. 2013). The majority of precipitation falls between October and March with about 30-47% falling as snow in the lower valleys and 50-64% as snow in the uplands (Records et al. 2014; O'Connor et al 2013).

Despite significant groundwater and spring discharges (Gannett et al. 2007), Sprague River flows are still highly responsive to winter precipitation (Mayer and Naiman 2011). Mayer and Naiman (2011) also concluded that warmer winter temperatures and snowpack reductions have caused significantly earlier runoff peaks in both snowmelt and groundwater basins in the region, including the Sprague River.

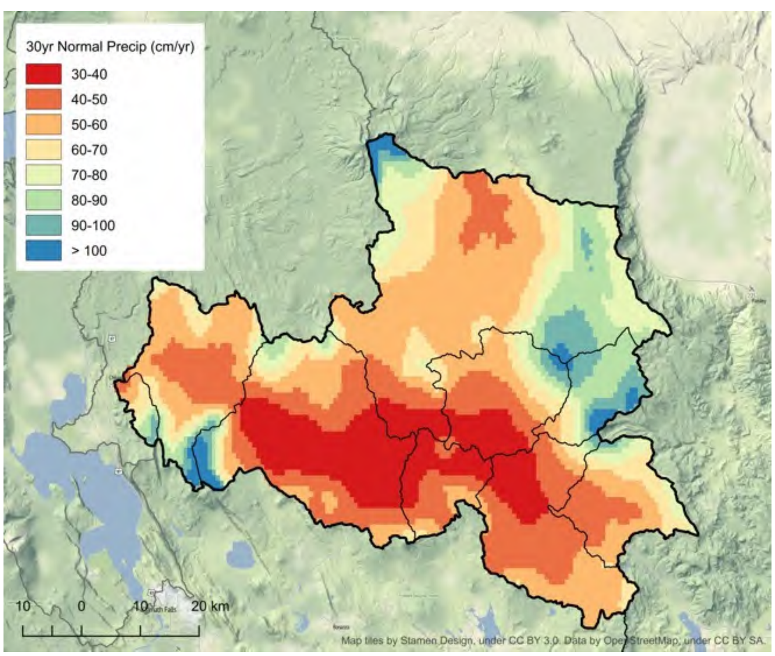

FIGURE 3: 30-YEAR NORMAL ANNUAL PRECIPITATION
Source: PRISM Climate Group (2004)

As noted by O'Connor et al. (2013) an upper reach of the Sycan River is designated as a Wild and Scenic River, and upper tributaries of the NF and SF Sprague include portions of the Gearhart Mountain Wilderness. Lower reaches of the tributaries as well as the mainstem of the Sprague River historically meandered through broad alluvial valleys[16] and currently support agriculture and livestock grazing. The Sprague River serves as the major tributary to the Williamson River (contributing about 59% of the total mean annual flow), which drains directly into Upper Klamath Lake, the outflow of which forms the Klamath River[17] that ultimately discharges to the Pacific Ocean in northern California.

Between 1991 and 2010, the Sprague River contributed on average 40% of the tributary flow and 31% and 44% of the TP and TN loads to UKL (Table 1). The three tributaries (Sycan River, North Fork, and South Fork) contribute 22%, 27%, and 19% of the mean annual flow to the Sprague River outlet, 15%, 24%, and 18% of the TP load, and 31%, 15%, and 20% of the TN Load, respectively, over water years 2010 – 2014 (Table 8 in Results and Discussion below).

[16] See O'Connor et al. (2013) for a detailed description of Sprague River basin geography and geology.
[17] The outflow from UKL is named the Link River which drains into Lake Ewuana before being renamed as the Klamath River.

FIGURE 4: MAP AND PHOTOS OF SPRAGUE RIVER BASIN AND WATER QUALITY SAMPLING STATIONS.

1.6 STUDY OBJECTIVES

The overall goal of this study was to use the Klamath Tribes' expanded sample collection effort to increase understanding of the Sprague River Basin's role in nutrient and hydrologic dynamics in the Klamath Basin. The specific study objectives are as follows:

1. Evaluate seasonal trends in concentration for major nutrient and sediment parameters including total phosphorus (TP), phosphate-phosphorus (PO_4-P), particulate phosphorus (PP), total nitrogen (TN), nitrate/nitrite nitrogen (NO_3+NO_2-N), ammonia-nitrogen (NH_4-N), and total suspended solids (TSS) [18] at Sprague River stations shown in Figure 4.

2. Evaluate seasonal trends in load for major nutrient and sediment parameters (TP, PO_4-P, PP, TN, NO_3+NO_2-N, NH_4-N, and TSS) at Sprague River stations shown in Figure 4.

3. Determine sub-watershed loading or unit area loading (e.g., kg/km^2/yr) to determine areas of concentrated loading in specific reaches occurring on both a seasonal and annual basis, and use these calculations to inform reach-specific restoration priorities.

4. Refine estimates of background loading from relatively un-impacted headwaters to inform estimates of loading attributed to land-use practices and include additional synoptic data from springs.

5. Determine upward or downward long-term trends in nutrient and sediment parameters for the study period of record (water years 2002 to 2014).

6. Interpret year-to-year variations and long-term trends relative to variations in climate.

[18] Abbreviated as TP, PO4, PP, TN, NO23, NH4, and TSS in the report.

2 DATASET COMPILATION

2.1 OVERVIEW OF DATA SOURCES

Table 2 summarizes the various datasets used in this study with further details provided in following sections.

TABLE 2: OVERVIEW OF DATA SOURCES

Dataset	Source	URL
Hydrology		
Precipitation	PRISM	http://www.prism.oregonstate.edu/
Snowpack	NRCS SNOTEL	http://www.wcc.nrcs.usda.gov/snow/
Streamflow	USGS	http://waterdata.usgs.gov/nwis
	OWRD	http://apps.wrd.state.or.us/apps/sw/hydro_report/
	Klamath Tribes	Provided as Excel Spreadsheet
Water Quality		
Nutrients/Sediment	Klamath Tribes	Provided as Excel Spreadsheet
GIS Data		
Hydrography	NHDPlus v2	http://www.horizon-systems.com/ NHDPlus/NHDPlusV2_home.php
Land Use	NLCD v2011	http://www.mrlc.gov/nlcd2011.php
Water Rights	OWRD WRIS	http://www.oregon.gov/owrd/pages/wr/wris.aspx
Geomorphology	USGS	http://or.water.usgs.gov/proj/Sprague/

2.2 HYDROLOGY

2.2.1 PRECIPITATION

Historical monthly precipitation data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2004). The PRISM dataset includes monthly precipitation and air temperatures for water years 1982 – 2014. The dataset is provided as a series of gridded raster layers (one layer per month) at 30 second spatial resolution (approximately 3.5 x 4.5 km grid cells). For each sub-basin and month, the mean precipitation was computed by intersecting the precipitation raster layer with the sub-basin boundaries (see Section 2.4.1), and then calculating the mean value across each sub-basin. The result is a monthly precipitation time-series for each sampling station sub-basin. Precipitation records were generated for each individual sub-basin in order to capture the spatial variability across the sub-basins (see Figure 3 above). Figures A1 and A2 in Appendix A show the monthly and annual precipitation, respectively, for each sub-basin over the study period, WY2002 – 2014.

2.2.2 SNOWPACK

Historical snowpack records were obtained from the Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) network (NRCS, 2015). Three SNOTEL stations were identified in the Sprague River basin that included snowpack records over the study period (WY2002 – 2014) (Figure 5; Table A2 in Appendix A). The amount of snowpack is represented by measurements of snow water equivalent (SWE), which is the depth of water contained in snowpack and reflects the amount of water available for conversion to runoff during spring snowmelt. Because snowmelt is a major source of streamflow in the

Sprague River, the snowpack records were used as context for interpreting year-to-year variations in the basin's hydrology.

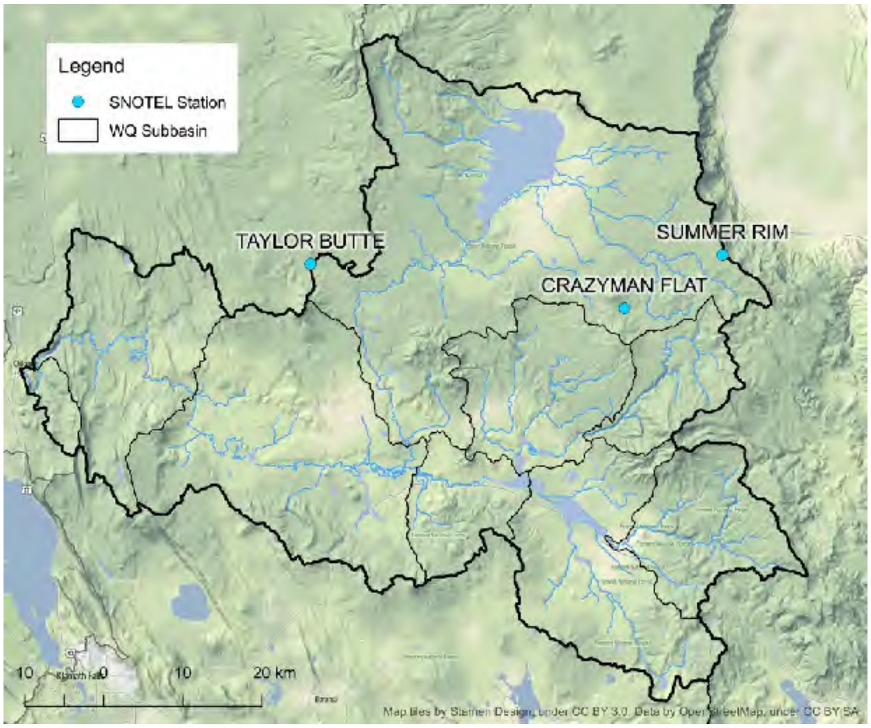

FIGURE 5: MAP OF SNOTEL MONITORING STATIONS

2.2.3 *STREAMFLOW*

Continuous daily streamflow data were obtained from the U.S. Geological Survey (USGS, 2001) and Oregon Department of Water Resources (OWRD, 2015). Figure 6 shows the locations of the continuous streamflow monitoring stations used in this study. Three of these stations were used to estimate daily streamflow at each water quality station; the remaining stations were used for comparison to the biweekly (measured every two weeks) flows measured by Klamath Tribes as part of the water quality sampling program (Section 3.1 below describes which streamflow station was used to estimate flows for each water quality station). Details about each streamflow station including the latitude/longitude and period of record are provided in Table A1 of Appendix A.

Instantaneous streamflow measurements[19] were also provided by Klamath Tribes at each water quality station. Flows were measured at each station during the time of nutrient sampling yielding paired flows and concentrations at approximately biweekly intervals. These biweekly flow measurements were related to the USGS and OWRD daily streamflow datasets to generate a continuous daily flow time-series for each station. Details of this process are described below in Section 3.1.

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[19] Specific discharge measurement methodology is contained in the Sprague River Water Quality Lab (SRWQL) SOP manual (Klamath Tribes, 2013a)

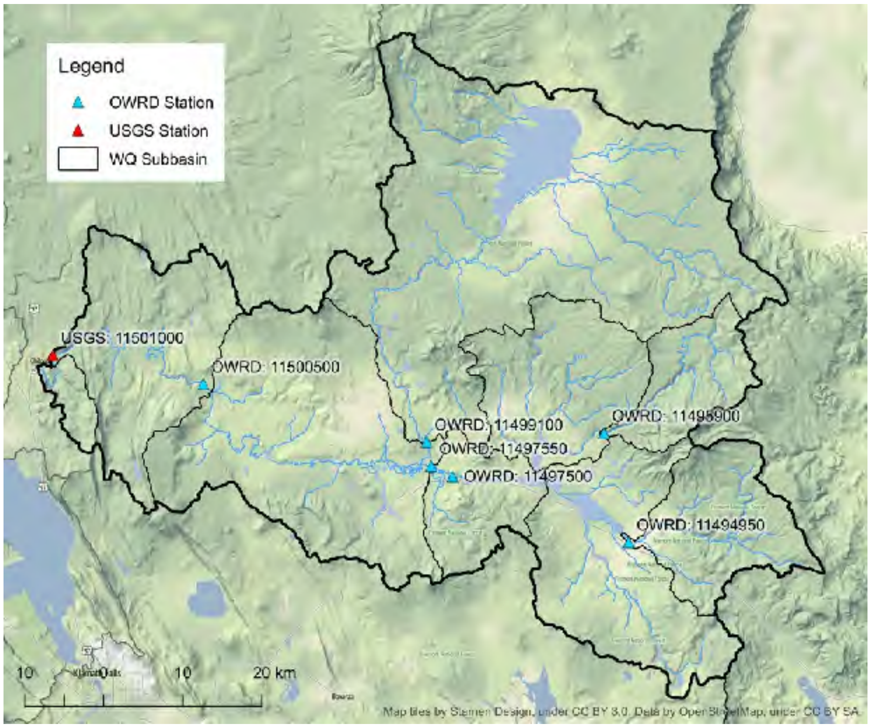

FIGURE 6: STREAMFLOW MONITORING STATIONS

2.3 WATER QUALITY DATA

Water quality samples of nutrient (nitrogen and phosphorus) concentrations were collected by the Klamath Tribes at six long-term monitoring stations (red symbols in Figure 4) within the Sprague River basin from WY2002 – 2014 at approximately biweekly intervals[20]. Two stations were added as routine sampling locations in August 2009 near the outlets of the the North and South Forks at Ivory Pine Rd (orange symbols in Figure 4). Although samples were also collected between 2005 – 2006 at the North Fork station at Ivory Pine Rd, these values were removed from the dataset due to a lack of flow measurements and a gap in sampling during 2007 – 2009. Total suspended solids (TSS) measurements were added to the sampling program as a routine parameter in September 2010 at all stations.

Table 3 lists the water quality stations including their locations, drainage areas, and periods of record. Figure 4 shows the locations and sub-basin drainage areas of these stations. The delineation of these sub-basins is described in Section 2.4.1 below. An exploratory data analysis of the water quality data including time-series of the sampled concentrations, comparisons between water quality parameters and flow at each station, and comparisons between the stations is provided in Appendix B.

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[20] Specific nutrient methodology and field collection protocol are contained in the Sprague River Water Quality Lab (SRWQL) SOP (Klamath Tribes 2013a) and QAPP (Klamath Tribes 2013b).

TABLE 3: WATER QUALITY STATIONS

ID	Name	Description	Latitude	Longitude	Drainage Area (km^2)	Period of Record
SR0090	Power	Sprague R @ Power Plant	42.5846	-121.8419	4,123	04/2001 – 09/2014
SR0080	Lone_Pine	Sprague R @ Lone Pine	42.5505	-121.6176	3,693	03/2001 – 09/2014
SR0060	Godowa	Sprague R @ Godowa Rd	42.4604	-121.2699	1,470	03/2001 – 09/2014
SR0070	Sycan	Sycan R @ Drews Rd	42.4855	-121.2785	1,441	03/2001 – 09/2014
SR0150	SF_Ivory	SF Sprague @ Ivory Pine	42.4394	-121.0954	753	08/2009 – 09/2014
SR0050	SF	SF Sprague @ Picnic Area	42.3761	-120.9694	280	03/2001 – 09/2014
SR0140	NF_Ivory	N. Fork Sprague R @ Ivory Pine	42.4560	-121.1094	535	08/2009 – 09/2014
SR0040	NF	NF Sprague @ 3411 Rd	42.4970	-121.0056	187	03/2001 – 09/2014

2.3.1 *DATA QUALITY REVIEW*

An extensive review of the water quality dataset was performed prior to the analyses in order to identify erroneous or abnormal data points. This review included:

1. Identifying samples that were abnormally low and thought to be the result of incorrectly labeled blank samples,
2. Removing negative concentrations (TSS only),
3. Removing concentrations of dissolved nutrient species that greatly exceeded total nutrient concentrations (i.e. if PO4 > TP, then the PO4 value was excluded from the dataset but the TP value was retained), and
4. Performing pairwise comparisons between related variables and stations to identify outliers that did not fit general trends or relationships in the dataset.

Table 4 lists the number of samples for each site and water quality parameter that were removed from the dataset after the data quality review. Further details of this review are provided in Appendix B.

TABLE 4: NUMBER OF SAMPLES REMOVED FROM WATER QUALITY DATASET BY STATION AND PARAMETER

Station	TP	PO4	TN	NH4	NO23	TSS
Power	2	0	1	0	0	0
Lone_Pine	1	0	1	0	0	2
Godowa	4	0	0	0	0	0
Sycan	1	1	1	2	1	1
SF_Ivory	0	0	0	0	0	0
SF	1	3	2	1	1	1
NF_Ivory	3	0	0	0	0	0
NF	0	4	0	0	0	0
Total Samples Removed	**12**	**8**	**5**	**3**	**2**	**4**
Total Samples Collected	**2,181**	**2,180**	**2,181**	**2,179**	**2,180**	**718**
% Samples Removed	**0.6%**	**0.4%**	**0.2%**	**0.1%**	**0.1%**	**0.6%**

2.3.2 *Changes in Detection Limits*

A review of the water quality dataset revealed changes in detection limits for the three nitrogen species (TN, NH4, NO23) that occurred in April 2008. Table 5 summarizes the detection limits of all parameters before and after these changes. Note that there were no changes to the detection limits of the phosphorus species, and TSS samples were only collected after 2008.

Table 5: Detection Limits of Water Quality Parameters

	Higher Limits (mg/L) 03/2001 – 03/2008	Lower Limits (mg/L) 04/2008 – 10/2014
TP	0.018	0.018
PO4	0.003	0.003
TN	0.1	0.03
NH4	0.01	0.006
NO23	0.01	0.008
TSS	N/A	1

In order to ensure that the dataset was consistent across the period of record, all concentrations were constrained to be no less than the higher detection limits used prior to April 2008. The effect of this constraint on the results of this study was evaluated by re-running the analyses for the nitrogen species using only the later years and constraining the concentrations to the lower detection limits. These results were then compared to the results using the higher detection limits and showed relatively small differences in the annual FWM concentration of each station and nitrogen species (Appendix D; Figure D2).

2.4 GIS Data

2.4.1 *Cumulative Sub-basin Delineation*

In this report, the term "cumulative sub-basin" refers to the total drainage area associated with each water quality station. These areas were delineated using the National Hydrograph Dataset (NHD) Plus v2 catchment delineation (McKay et al., 2012). Figure 4 above shows the delineations and Table 3 provides the drainage areas of these cumulative sub-basins. Note that the cumulative sub-basins are nested meaning upstream sub-basin areas are included within the downstream sub-basins since each sub-basin covers the entire drainage area for each station.

2.4.2 *Incremental Sub-basin Delineation*

The term "incremental sub-basin" refers to the drainage area between consecutive water quality stations along the river reach network. Table 6 lists the names, upstream and downstream stations, and drainage areas of the incremental sub-basins, which are shown in Figure 7. Note that the Upper Sprague + Lower SF/NF sub-basin (which excludes the SF_Ivory and NF_Ivory stations that were added in 2009), is only used when presenting results over the entire period of record (WY2002 – 2014).

TABLE 6: SUMMARY OF INCREMENTAL BASINS

Incremental Basin Name	Downstream Station	Upstream Station(s)	Drainage Area (km^2)
Lower Sprague	Power	Lone_Pine	430
Middle Sprague	Lone_Pine	Godowa + Sycan	782
Upper Sprague	Godowa	SF_Ivory + NF_Ivory	182
Upper Sprague + Lower SF/NF*	Godowa	SF + NF	1,004
Sycan	Sycan	--	1,441
Lower SF	SF_Ivory	SF	474
Upper SF	SF	--	280
Lower NF	NF_Ivory	NF	348
Upper NF	NF	--	187

* Only used when presenting results over the period of record (WY2002 – 2014) and is the combination of the Upper Sprague, Lower SF, and Lower NF sub-basins

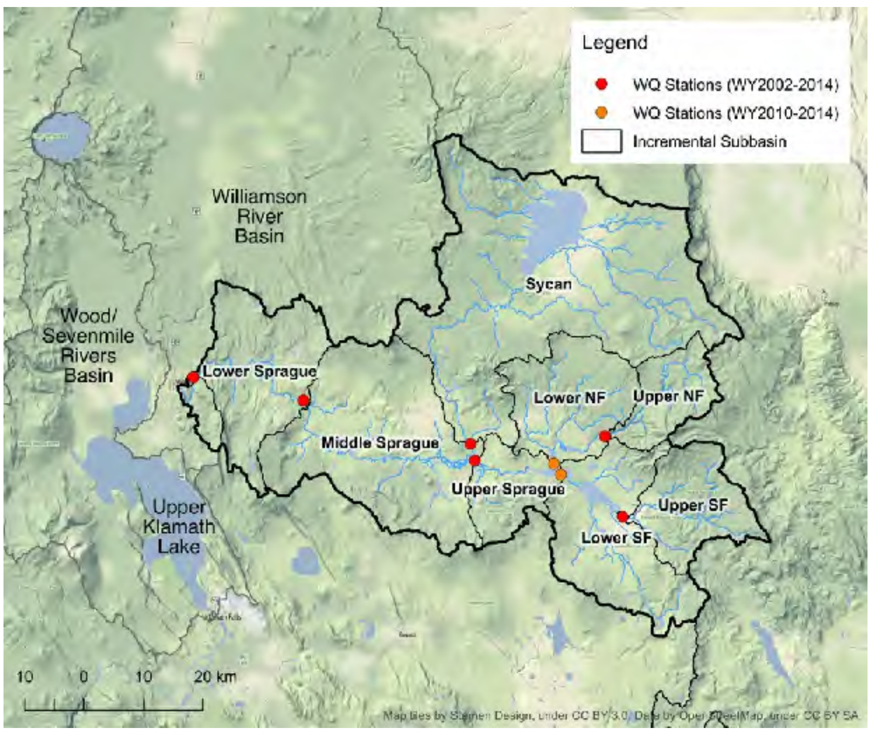

FIGURE 7: MAP OF INCREMENTAL SUBBASINS

2.4.3 *LOWER VALLEY DELINEATION*

A geomorphologic delineation of the lower valley of the Sprague River basin was used to characterize the land use composition of areas that have the greatest degree of human impact and thus expected to have the greatest effect on water quality[21]. The delineation of the lower valley was obtained from O'Conner et al. (2013) who performed this delineation using remote sensing data and field surveys. The lower valley region encompasses the floodplain and main alluvial valleys of the Sprague River and its major tributaries (Sycan River, North Fork, and South Fork). Figure 8 shows the extent of the lower valley.

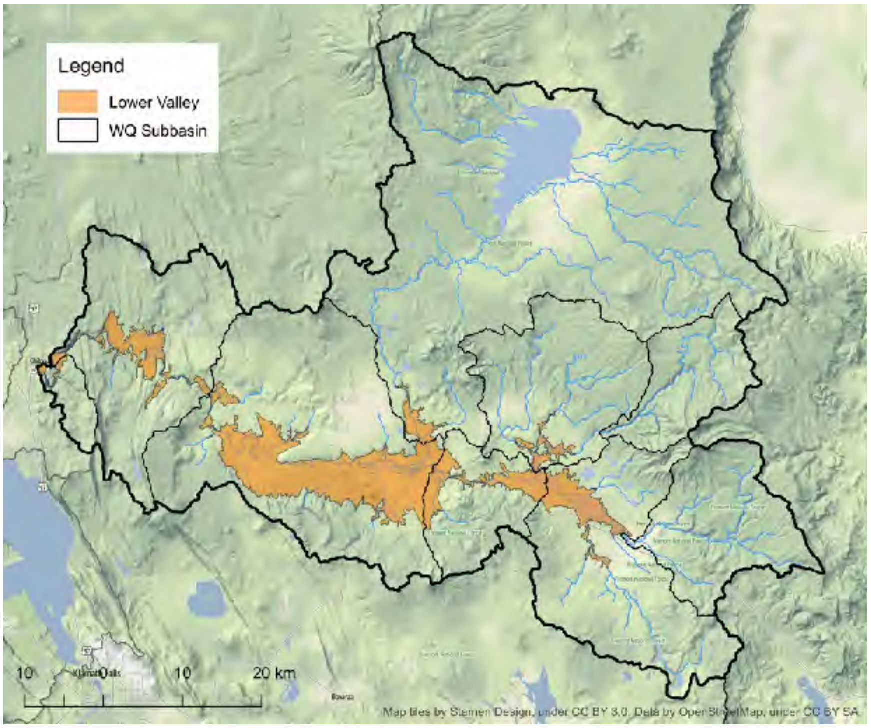

FIGURE 8: GEOMORPHOLOGICAL DELINEATION OF SPRAGUE RIVER VALLEY

2.4.4 *LAND USE*

Figure 9 presents the land use composition of the Sprague River basin based on the National Land Cover Dataset (NLCD) v2011 dataset (Homer et al., 2015).

The land use composition of each cumulative sub-basin (i.e., % area of each land use category) was determined by performing a spatial intersection between the land cover raster layer and the sub-basin polygons, and then tabulating the percent area of each sub-basin for each land use type using zonal statistics. The land use composition was similarly determined for the lower valley of each sub-basin by first clipping the land use raster to the lower valley delineation (see Figure 8).

The percent land-use composition of each sub-basin is shown in Figure 10 for both the lower valley and total area of each cumulative sub-basin. Note that the NLCD land use categories shown in Figure 10

[21] As discussed above, Records et al. (2014) note that the majority of agriculture in the Sprague River valley is flood-irrigated pastureland concentrated in the lower valleys.

were aggregated from the sub-categories shown in Figure 9 to higher level categories for the purpose of this study (e.g., Forest includes Deciduous Forest, Evergreen Forest, and Mixed Forest). Also note that because the lower valley delineation does not extend above the upper SF and NF water quality stations (see Figure 8; upper SF and NF watersheds), the lower valley land use composition is not shown for these sub-basins in Figure 10.

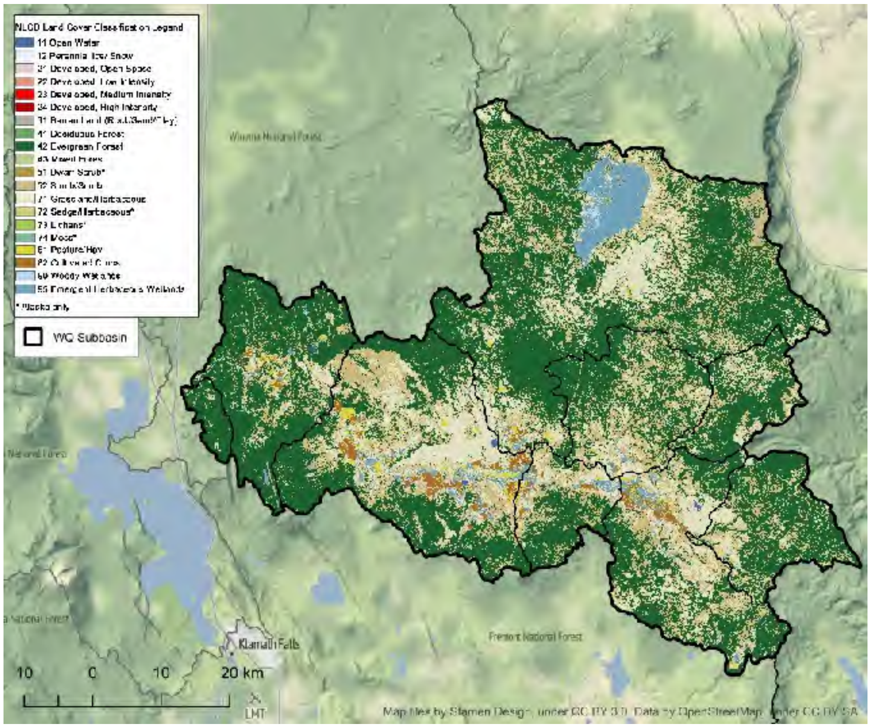

FIGURE 9: MAP OF NLCD LAND USE

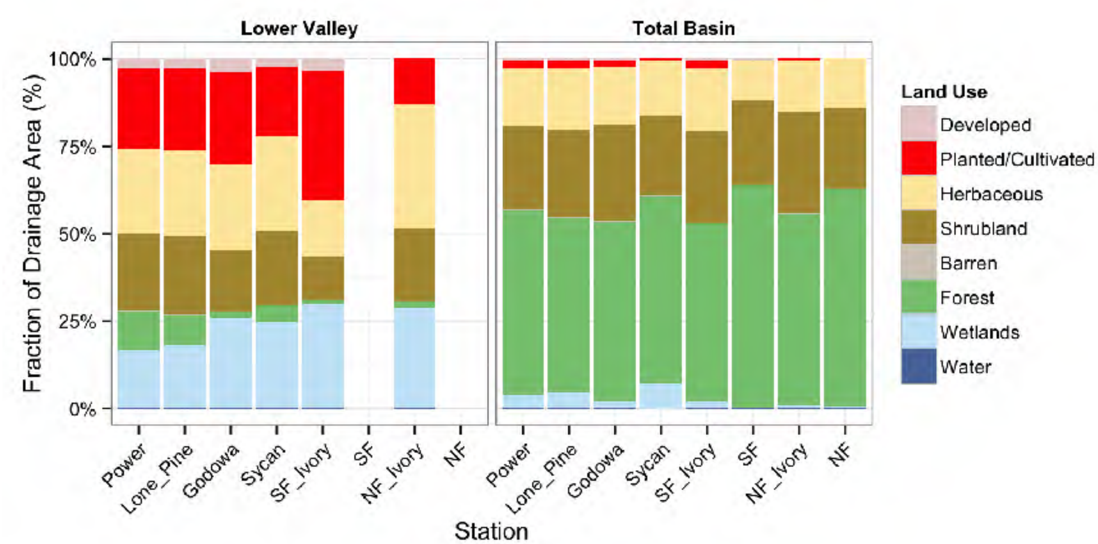

FIGURE 10: NLCD LAND USE COMPOSITION BY WATER QUALITY STATION IN LOWER VALLEY AND TOTAL SUB-BASIN

Comparison of the left and right panels in Figure 10 reveals differences in the land use composition within the lower valley relative to the total sub-basin areas. In general, the lower valley contains greater fractions of developed and planted/cultivated land use whereas the basin-wide areas are more than 50% forested. The fraction of wetlands is also much greater in the lower valley than across the entire sub-basin areas. However, this classification does not distinguish between natural and human-made wetlands caused by irrigation or other hydrologic modifications. A review of aerial imagery and ground photos revealed that many of the areas classified as wetlands are actually used for grazing and other agricultural uses. Similarly, some areas classified as herbaceous or shrubland are used for agricultural purposes. Therefore, there are limitations in using the NLCD dataset for differentiating between areas that are "natural" and those that are impacted by human activities.

2.4.5 Water Rights Place of Use (POU)

Because of the limitations in the NCLD dataset for differentiating between natural and anthropogenic land uses, an alternative representation of agricultural land use was derived from the Oregon Water Resources Department (OWRD) water rights database (OWRD, 2015a). This database classifies water rights by use types, which include not only consumptive uses (e.g. domestic water supply or irrigation) but also environmental uses such as minimum in-stream flows. For this study, the dataset was limited to surface water rights classified for irrigation use, which comprise the majority of water rights in the basin. For each registered water right, a delineation of the land parcel associated with that water right is also available in the database; these areas are referred to as Place of Use (POU). Although POUs may not always accurately delineate irrigated areas[22], they provide an alternative means of relating agricultural land use to spatial variations in water quality.

The POU areas associated with irrigation surface water rights were extracted from the database and used to represent land areas associated with agricultural land use. Figure 11 shows the POU irrigation areas and the associated water withdrawal locations referred to as points of diversion (POD). Figure 12 shows the percent of the cumulative drainage area as POU irrigation area for each water quality station within both the entire sub-basin drainage area and within only the lower valley. The percent POU areas in the lower valley are much greater than those for the total drainage areas indicating that most agricultural activities occur in the lower valley. The exception is the Sycan Marsh in the upper Sycan River basin, which is managed by The Nature Conservancy in cooperation with local ranchers for restoration and grazing (Connelly et al., 2007). The highest percent POU area in the lower valley occurs at SF_Ivory in the lower South Fork with over 80% of the lower valley upstream of this station being associated with POU irrigation areas. Above the Power station near the Sprague River outlet, POU areas account for 48% of the lower valley across the entire basin.

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[22] For example, only a portion of a POU may be irrigated in a given year and areas without POU's shown in Figure 11 may have also been irrigated.

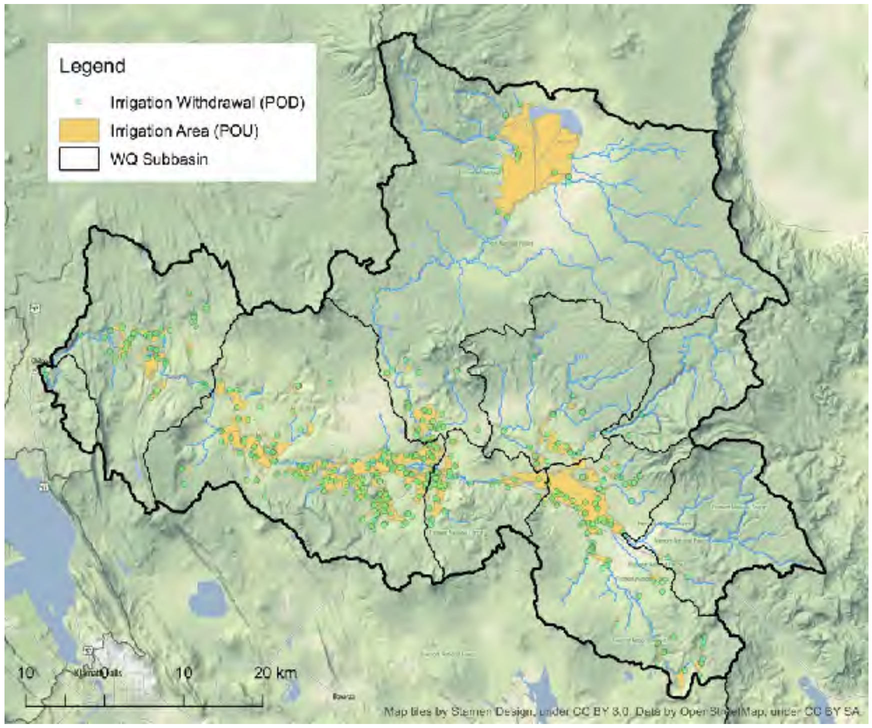

FIGURE 11: MAP OF PLACE OF USE (POU) AND POINTS OF DIVERSION (POD) FOR IRRIGATION WATER RIGHTS

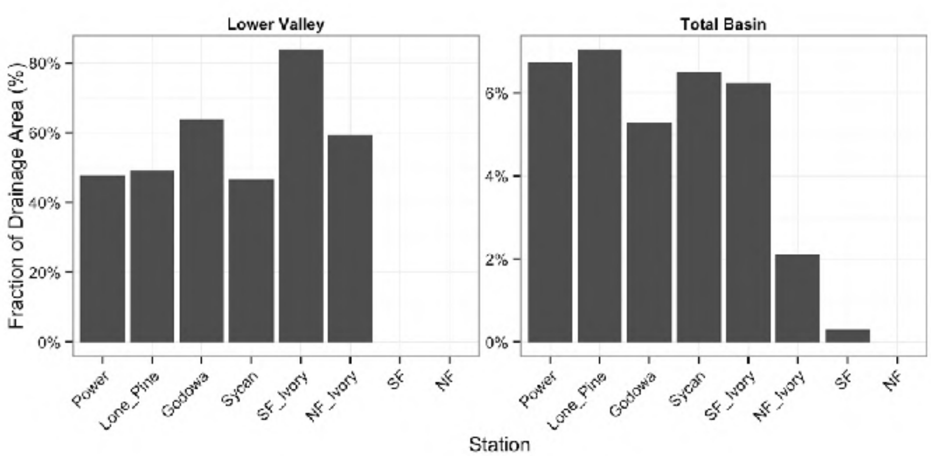

FIGURE 12: PERCENT DRAINAGE AREA AS POU IRRIGATION AREA IN LOWER VALLEY AND TOTAL BASIN FOR EACH WATER QUALITY STATION

3 METHODOLOGY

To meet the objectives of this study, daily time-series of flows, loads, and concentrations were generated for each water quality station and parameter using the methodology in Walker et al. (2012). Daily flows were generated from the biweekly flows measured by Klamath Tribes using daily streamflow records from three long-term, continuous streamflow gages in the basin. Similarly, daily concentrations were generated from the measured biweekly concentrations using predictions from a linear regression model that includes independent variables representing flow, time, and seasonality. Daily loads were computed by multiplying daily flows and concentrations. These daily time-series were aggregated to various monthly, seasonal, and annual timescales by computing the sum of flows and loads. Flow-weighted mean (FWM) concentrations were then computed by dividing the total load by corresponding total flow.

In this report, water years are used in place of calendar years to reflect the dynamics associated with the hydrologic cycle. Each water year begins on October 1 of the previous calendar year and ends the following September 30. For example, WY2002 refers to the period October 1, 2001 to September 30, 2002. This report also aggregates results to seasonal increments based on 3-month intervals: Fall (October-December), Winter (January-March), Spring (April-June), Summer (July-September).

Finally, many of the results presented in this report are based on mean annual values computed over multi-year periods for each station and sub-basin (e.g., mean annual flow, load, and FWM concentration). Because two of the stations (NF_Ivory, SF_Ivory) were added at the start of WY2010, the mean annual results were primarily computed over the last five years of the study period, WY2010 – 2014, in order to use consistent time periods across all stations. Mean annual results computed over the entire study period, WY2002 – 2014, are provided in the appendices and exclude the two stations in the North and South Forks at Ivory Pine Rd.

3.1 Streamflow Model

For each water quality station, a continuous time-series of daily flows was generated using the method described by Walker et al. (2012). Each water quality station was paired with a long-term continuous streamflow station maintained by USGS or OWRD, which are referred to as the reference[23] stations. Although there are other active streamflow gages in the basin (see Figure 6), only the three long-term stations with continuous data over the entire period of record (WY2002 – 2014) were used as reference stations. The other four continuous streamflow stations are located near the Klamath Tribes' water quality stations, but have shorter periods of record beginning in 2008 or 2009 and thus could not be used to compute daily flows over the entire study period. Daily flows measured at these other continuous stations were instead used for comparison purposes to evaluate amounts of bias and error in the computed daily flows at the coinciding water quality stations.

Figure 13 shows the pairing between the reference and water quality stations. The two stations in the lower basin (Power and Lone_Pine) were both paired with the USGS station 11501000, which is located near the water quality station on the Sprague River at Power. The Sycan station was paired with OWRD station 11499100, both of which are located at the outlet of the Sycan River. The remaining stations at Godowa and on the North and South Forks were paired with the OWRD 11497500 station, which is located a few river miles upstream of the Godowa station in Beatty, OR.

[23] Note that the term "reference" here does not imply that these stations represent background or un-impacted conditions as sometimes used in other studies, but rather that these stations are used as a reference for estimating the daily flows at nearby water quality stations.

FIGURE 13: REFERENCE FLOW STATIONS FOR ESTIMATING DAILY FLOWS

Using these paired reference stations, the continuous daily flow records for each water quality station were generated using the following algorithm:

1. For each month of the year, compute the mean flow over the period of record for the water quality station using the biweekly flows measured by Klamath Tribes, and for the corresponding reference station using only flows measured on water quality sampling dates (i.e., using the same dates as the biweekly flows).
2. For each month, divide the mean of the biweekly flows at the water quality station by the mean flow from the reference station to yield a mean flow ratio for that month.
3. Multiply the mean monthly flow ratios by the complete streamflow record from the reference station to generate an estimated daily flow record for each water quality station.
4. Compute log-transformed residual flows by dividing the estimated daily flow for each station by the biweekly flow measured by Klamath Tribes on each sampling date, and taking the logarithm of this ratio.
5. Perform a linear interpolation of the log-transformed residuals to generate a continuous time-series of daily log-residuals.
6. Multiply the interpolated daily log-residuals by the estimated daily flows generated in step 3.

By using the interpolated residuals of the estimated daily flows based on the monthly flow ratios, the end result is a continuous daily flow record for each water quality station that preserves the flows measured by Klamath Tribes on dates when water quality samples were collected. Between water quality sampling dates, the daily flows were computed using the log-residuals of the estimated daily flows computed from the monthly flow ratios. This process thus preserved the biweekly flows measured by Klamath Tribes and used the continuous reference streamflow datasets to fill in estimated daily flows between these biweekly flows via the algorithm described above.

3.2 Water Quality Concentration and Load Model

Continuous daily time-series of concentrations and loads for each water quality parameter and station were generated using the method in Walker et al (2012). This method uses a multiple linear regression model that relates the logarithm of concentration to various time and flow related terms.

3.2.1 Model Description

The linear regression model is defined by the following equation:

$$\ln(C_t) = \beta_0 + \beta_1 \ln(Q_t) + \beta_2[\ln(Q_t)]^2 + \beta_3[\ln(Q_t)]^3 + \beta_4 \ln\left(\frac{Q_t}{Q_{t-1}}\right) + \beta_5 t + \beta_6 t^2 + \beta_7 \cos\left(2\left(\frac{2\pi j}{365.25}\right)\right) + \beta_8 \sin\left(2\left(\frac{2\pi j}{365.25}\right)\right) + \beta_9 \cos\left(\frac{2\pi j}{365.25}\right) + \beta_{10} \sin\left(\frac{2\pi j}{365.25}\right)$$

where C_t is concentration on date t, Q_t is the flow on date t, t is the date (in decimal years), and j is the Julian day of the year (e.g. Jan 1 = 1). This equation includes 11 coefficients and incorporates the effects of flow, rate of change in flow, date, and time of the year (or seasonality) on daily concentrations.

For each water quality station and parameter, this equation was fitted to the sampled concentrations using ordinary least squares regression. Note that all terms in this model were retained for each station and water quality parameter regardless of the significance of each coefficient in order to maintain consistency across all stations and parameters. The regression models were then used to generate a continuous time-series of predicted daily concentrations, which were adjusted to correct for re-transformation bias from log space back to original concentrations units. Similar to the streamflow model described above, the log-residuals of the predicted daily concentrations were used to fill in estimated concentrations between sampling dates and thus generate continuous daily concentrations that preserve the measured values on dates when samples were collected. The resulting continuous daily concentration time-series were then multiplied by the corresponding daily flow time-series to generate daily loads for each station and parameter.

3.2.2 Uncertainty Estimates

Uncertainty estimates of loads and concentrations were computed using the coefficient of variation (CV_L) of daily predicted loads for each station. The coefficients of variation were computed from a series of intermediate statistics as follows:

$$RSS_L = \sum_{i=1}^{n}\left(\widehat{L_i} - L_i\right)^2$$

$$RMSE_L = \sqrt{\frac{RSS_L}{n-k}}$$

$$SE_L = \frac{RMSE_L}{\sqrt{n}}$$

$$RSE_L = \frac{SE_L}{\left(\frac{\sum_{i=1}^{n}\hat{L}}{n}\right)}$$

$$CV_L = \frac{RMSE_L}{\left(\frac{\sum_{i=1}^{n} \hat{L}}{n}\right)}$$

where RSS_L is the residual sum of squares based on the difference between the predicted ($\hat{L_i}$) and observed (L_i) daily load for all samples ($i = 1$ to n), $RMSE_L$ is the root mean squared error computed by dividing RSS_L by the number of degrees of freedom ($n - k$, where k is the number of model coefficients), SE_L is the standard error of the mean load, RSE_L is the relative standard error of the mean load computed by dividing SE_L by the mean predicted load, and CV_L is the coefficient of variation.

The CV_L is a dimensionless measure of uncertainty representing the ratio of the standard deviation to the mean load. Finally, the standard error of annual mean load and concentration ($SE_{L,y}$ and $SE_{C,y}$) was computed from the CV_L by:

$$SE_{L,y} = \frac{CV_L \cdot \overline{L_y}}{\sqrt{n}}$$

$$SE_{C,y} = \frac{CV_L \cdot \overline{C_y}}{\sqrt{n}}$$

where $\overline{L_y}$ and $\overline{C_y}$ are the annual mean load and concentration in year y computed over n days. Note that the mean concentration is computed as a flow-weighted mean (FWM) concentration by dividing the mean load by the mean flow.

3.2.3 *Particulate Phosphorus*

The daily concentration time-series for TP and PO4 were used to compute a daily concentration time-series of particulate phosphorus (PP) at each station by difference (PP = TP – PO4). Due to measurement uncertainty and other sources of error, this calculation yielded some negative PP concentrations where TP < PO4. In these cases, the PP concentration was set to 1 μg/L.

3.2.4 *Unit Area Runoff and Nutrient/Sediment Export by Cumulative Sub-basin*

Unit area flows and loads (i.e., runoff and export rates) were computed for each cumulative sub-basin by dividing the flows and loads by the corresponding drainage area. These quantities represent the total unit area flow and load across the entire drainage area for each water quality station. In addition, flow-weighted-mean (FWM) nutrient concentrations were calculated by dividing load by flow for various time periods and watershed areas.

3.2.5 *Net Changes in Flows, Loads and Concentrations by Incremental Sub-basin*

For each incremental sub-basin, the net changes in flows and loads were computed by subtracting the flows and loads at the downstream station from the sum of flows and loads at upstream stations. These differences in flows and loads represent the **net** changes between sampling stations and incorporate both sources (e.g., runoff, agricultural return flows, groundwater discharge) and sinks (e.g., biological uptake[24], settling, water withdrawals) along the corresponding river reach. The net change in FWM concentration was also computed by difference for each incremental sub-basin. The change in FWM concentration indicates whether the concentrations increased or decreased over each river reach and by how much. Note that the changes in concentrations are not direct estimates of the concentration associated with direct loading to the reaches because these changes incorporate both sources and sinks and are affected by in-stream water quality processes. The net changes in flows and loads per unit area were also computed by dividing the net flows and loads by the incremental sub-basin drainage areas.

Because the net changes in flows, loads, and concentrations were computed by difference, these terms can result in negative values if the sum of the upstream stations is greater than the value at the downstream station. These negative net changes thus indicate a decrease in flow, load, or concentration between the upstream and downstream stations.

3.3 Trend Analysis

Trend analyses were performed on the continuous time-series of flows, loads and concentrations at each long-term water quality station (excluding NF_Ivory and SF_Ivory) and water quality parameter (excluding TSS) as well as on precipitation to determine whether conditions have significantly changed over the entire study period due to either natural or anthropogenic activities. The daily time-series of each term was first aggregated to monthly time steps by computing the mean monthly flow and load, and then computing the monthly FWM concentration by dividing monthly load by flow.

Trends were evaluated using both non-parametric and parametric statistical tests. The primary trend test was based on the non-parametric Seasonal Kendall test, which is commonly used to evaluate trends in hydrologic time-series exhibiting seasonal patterns and is more robust than parametric methods that require assumptions regarding the distributions of the data (Helsel and Hirsch, 2002). The Seasonal Kendall test was applied to the entire time-series of each term, as well as monthly and seasonal subsets to determine whether trends occurred primarily during one or more seasons. In addition to the Seasonal Kendall test, trends in annual mean precipitation, flows, loads, and FWM concentrations were evaluated using the non-parametric Mann-Kendall test and a simple linear regression, which is a parametric test.

For all trend tests of flows, loads, and concentrations, the values were first transformed to a $\log_{10}$ scale (precipitation values were not transformed due to some months having zero precipitation). The significance of each trend test was evaluated by comparing the p-value to critical thresholds of α=0.05 ($p <= 0.05$ indicating high significance) and α=0.10 ($0.05 < p <= 0.10$ indicating moderate significance). The slope and intercept of each trend were estimated using the Sen slope estimator for the non-

[24] The Sprague River and tributaries are known for areas of extensive aquatic plant growth and attached algae (DEQ 2002). Although biological uptake occurs, it usually reflects a temporary sink as plant and algal material often detaches and is transported downstream. For example, dead plant material is often observed in the water column in the downstream most reaches of the Sprague and Williamson Rivers prior to entering UKL.

parametric methods (Helsel and Hirsch, 2002). The estimated slopes for flows, loads and concentrations were converted from log-transformed units (e.g. log(hm3/d), log(kg/d), log(ppb)) per year to percent per year by:

$$[\text{Slope in }\%/\text{yr}] = 10^{[\text{Slope in log(units)/yr}]} - 1$$

For precipitation, which was not based on a log-scale, the slope in percent per year was computed by dividing the slope in original units by the mean value over the study period.

4 Results and Discussion

The followings sections present and discuss key results with respect to:

4.1 Climate Conditions
4.2 Streamflow Model Results
4.3 Water Quality Model Results
4.4 Seasonal Patterns of Monthly Flows, Loads, and Concentrations
4.5 Spatial Patterns of Mean Flows, Loads, and Concentrations
4.6 Relationships between Concentrations and Land Use
4.7 Phosphorus, Sediment, and Nitrogen Dynamics with Respect to Flow and Season
4.8 Background vs Anthropogenic Loading
4.9 Trend Analyses

Additional results and diagnostic plots are provided in the following appendices:

C – Streamflow Model Results and Diagnostics
D – Water Quality Model Results and Diagnostics
E – Reach Network Plots of Flows, Loads, and Concentrations
F – Map Displays of Flows, Loads, and Concentrations
G – Trend Analysis Results and Diagnostics

4.1 Climate Conditions

Using the precipitation and snowpack datasets (see Sections 2.2.1 and 2.2.2), this section provides the hydrologic context for interpreting year-to-year and seasonal patterns in the streamflow and water quality results.

4.1.1 Precipitation

Figure 14 shows the annual precipitation by water year for the Sprague River Basin over the period WY1982 – 2014. During the study period (WY2002 – 2014), annual precipitation was less than the long-term (WY1982 – 2014) mean of 57 cm/yr in all but two years (WY2006, WY2011). One of the years in the study period (WY2014) ranked 4th lowest in the WY1982 – 2014 period of record with 40 cm/yr.

Figure 15 shows the total precipitation in the Sprague River basin for each 3-month season by water year over the study period (WY2002 – 2014). Precipitation is generally highest in fall and winter, followed by spring, and the lowest precipitation occurs in summer. The majority of precipitation in the fall and winter seasons occurs in the form of snowfall, although temperatures can vary widely during these seasons across elevations resulting in rain and rain-on-snow events.

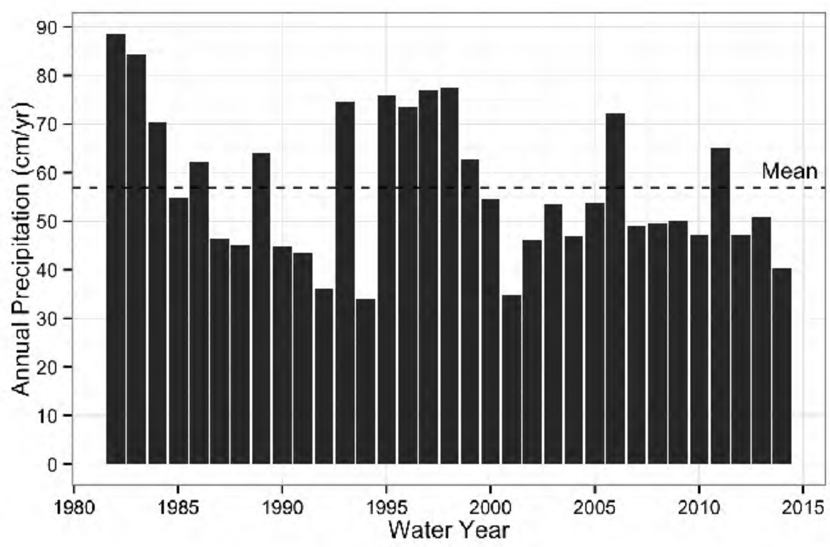

FIGURE 14: ANNUAL PRECIPITATION IN SPRAGUE RIVER BASIN BY WATER YEAR, WY1982 – 2014

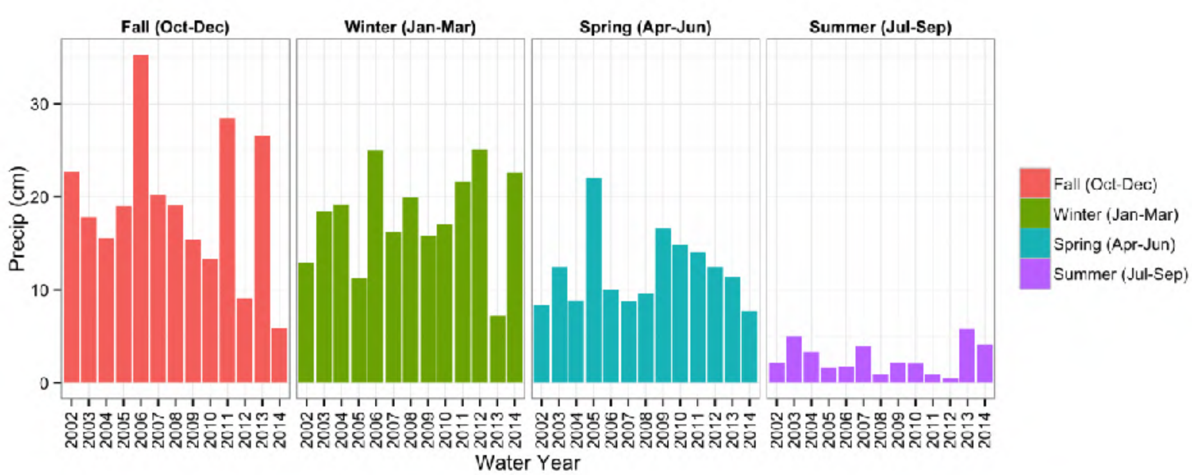

FIGURE 15: PRECIPITATION BY SEASON AND WATER YEAR, WY2002 – 2014

4.1.2 SNOWPACK

Figure 16 shows time-series of daily snow water equivalent (SWE) for each of the three SNOTEL stations (see location map in Figure 5). Based on these records, the largest snow packs occurred in WY2006 and WY2011 and the smallest snowpack occurred in WY2014, which is consistent with the annual precipitation records described in the previous section.

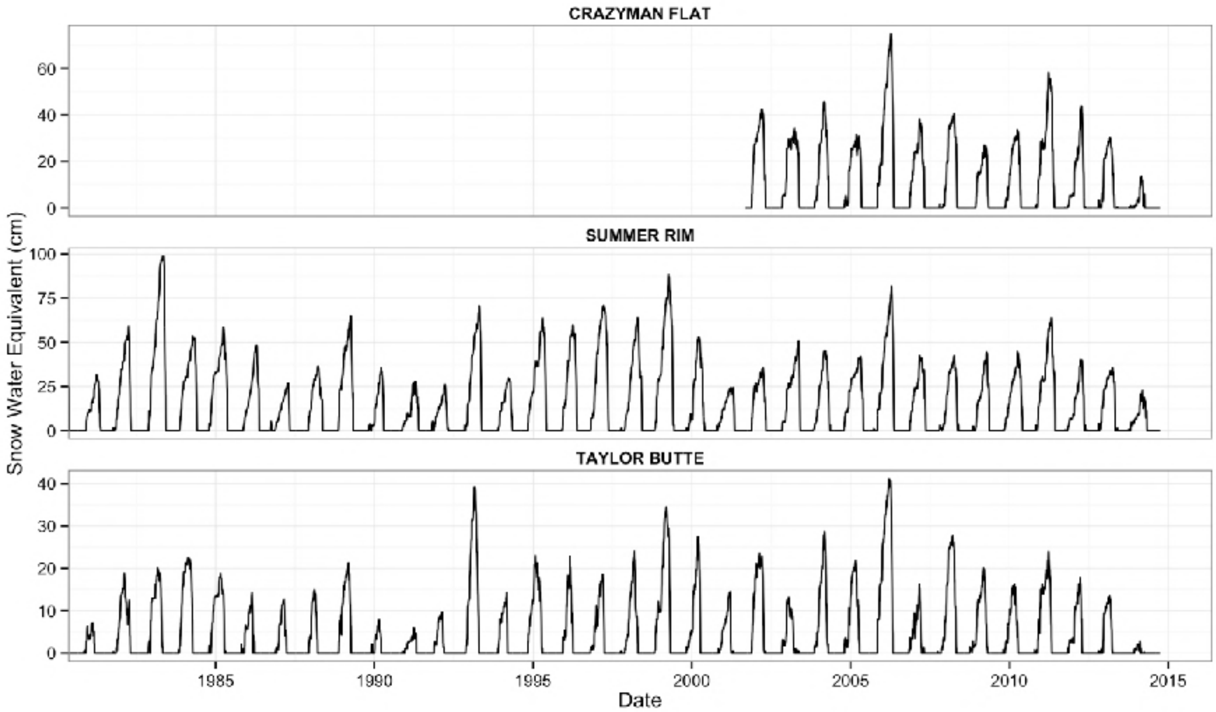

FIGURE 16: HISTORICAL DAILY SNOW WATER EQUIVALENT, 1979 – 2014

Figure 17 shows daily SWE by day of the year (starting at beginning of the water year on Oct 1) in order to compare the magnitude and timing of snowpack formation and melting across different years. Snowpack generally begins forming between mid-October and early-December, and melts in April or May depending on the location. The last two years of the study period, WY2013 and WY2014, are highlighted because low snowpack in these years led to activation of water withdrawal restrictions in the Sprague Basin (see Section 1.3). In WY2013, although the snowpack was slightly lower than normal, spring snowmelt occurred relatively early in the year, which, in combination with low precipitation during winter, resulted in low streamflows in spring and early summer. In WY2014, snowpack was both significantly lower than normal, and melted earlier than in other years at all three stations. The 2013 and 2014 trends in snowmelt timing are consistent with Mayer and Naman (2011) who concluded based on long-term streamflow analysis that warmer winter temperatures and snowpack reductions have caused significantly earlier runoff peaks in the Klamath Basin.

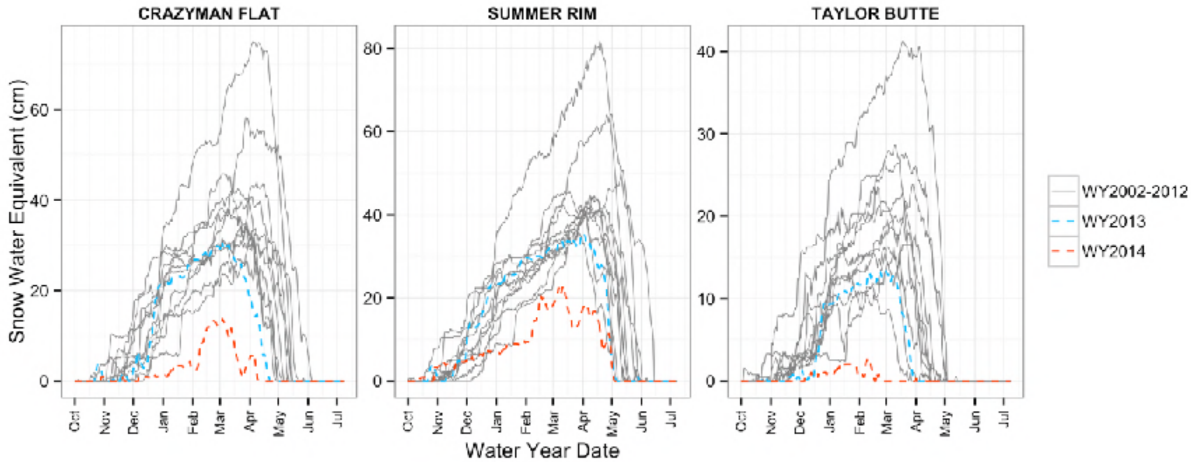

FIGURE 17: DAILY SNOW WATER EQUIVALENT BY DAY OF THE YEAR, WY2002 – 2014

4.2 STREAMFLOW MODEL RESULTS

4.2.1 RESULTS AND DIAGNOSTICS

For each water quality station, the daily streamflow model results are summarized by a diagnostic display containing the following charts:

- Time-series of the continuous daily flows at the reference station, biweekly flows measured by Klamath Tribes, and final computed daily flows for the water quality station.
- Scatterplot comparison between the biweekly measured flows and the corresponding continuous daily flows measured at the reference site.
- Distributions and mean values of the monthly flow ratios used to scale the daily reference flows.
- Time-series of the flow residuals.
- Scatterplot comparison of the flow residuals against the measured biweekly flows to show any potential bias under low or high flows.

Figure 18 provides an example of the streamflow model diagnostics for the Power water quality station on the Sprague River. The residuals time-series plot in this figure (bottom-center panel) shows greater variability in the first half of the period (before 2008) compared to the second half (after 2008). This change indicates greater differences between the biweekly flows measured by Klamath Tribes and the continuous measurements made by USGS at the nearby reference station. This pattern could be caused by changes in the rating curves at one or both of these stations, or a change in the river hydraulics caused by removal of the Chiloquin Dam in mid-2008, which was located a few miles downstream of these stations. Results and diagnostics for the other stations are provided in Appendix C (Figure C1), as well as comparisons between computed daily flows at the Lone_Pine, Godowa, SF, and NF stations and the corresponding continuous streamflow gages mentioned in Section 3.1 (Figures C2-C5).

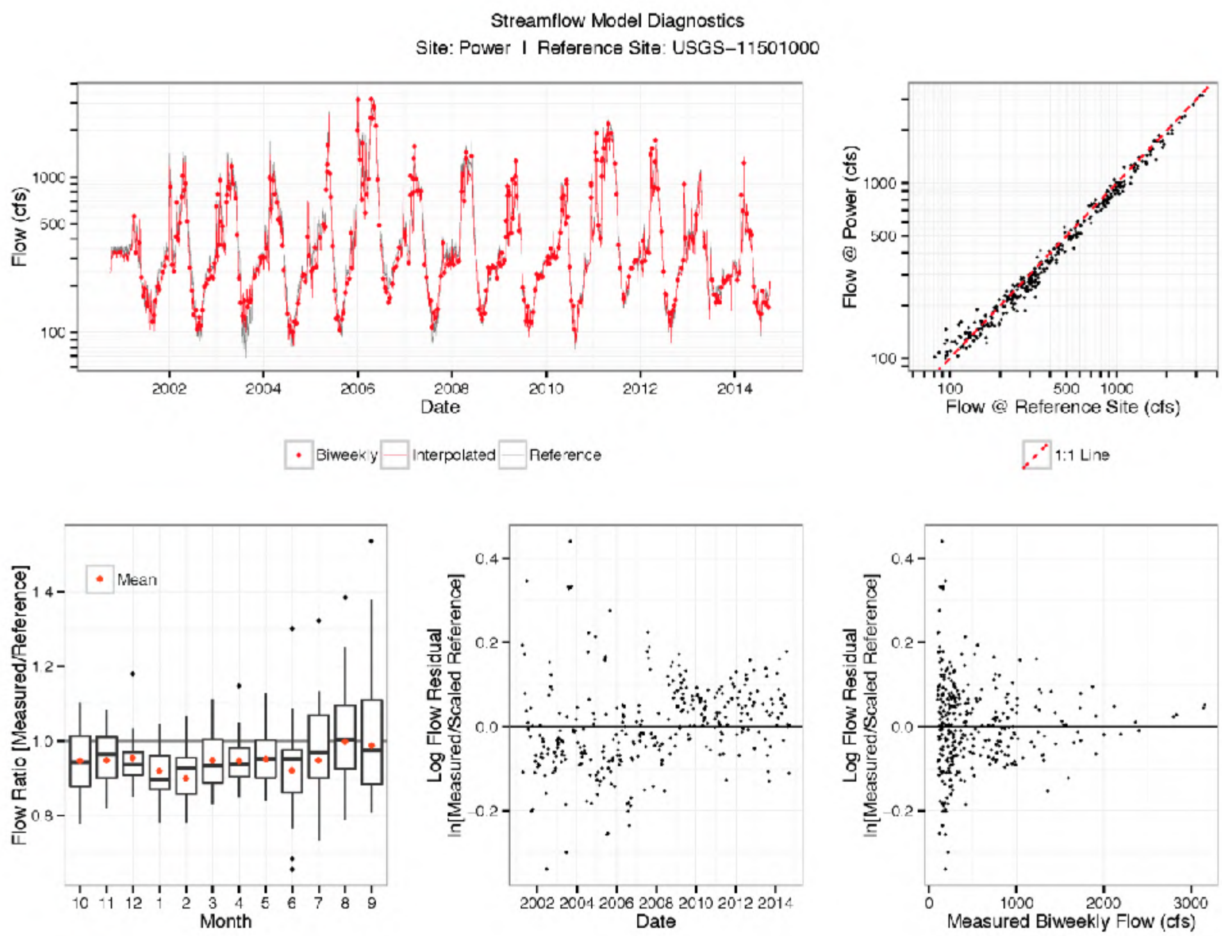

FIGURE 18: EXAMPLE OF STREAMFLOW MODEL DIAGNOSTICS DISPLAY FOR POWER WATER QUALITY STATION

4.2.2 ANNUAL AND SEASONAL STREAMFLOWS

Figure 19 shows the mean annual and seasonal flows at each water quality station over the last five years of the study period (WY2010 – 2014)[25]. This figure also includes the total flow for two pairs of combined stations: Godowa+Sycan representing the combined flow at the confluence of the Sprague and Sycan Rivers just downstream of the Godowa station, and SF_Ivory+NF_Ivory representing the combined flows from the South Fork and North Fork at the start of the upper Sprague River mainstem. As expected, the highest flows occur in spring due to snowmelt and the lowest flows occur in summer when there is little precipitation. Also in summer, there is relatively little change in flow along the lower Sprague River from Godowa to Power despite numerous springs and tributaries discharging between these stations (see Section 4.2.4 below).

[25] Only the last five years of the study period are shown in order to include the SF_Ivory and NF_Ivory stations

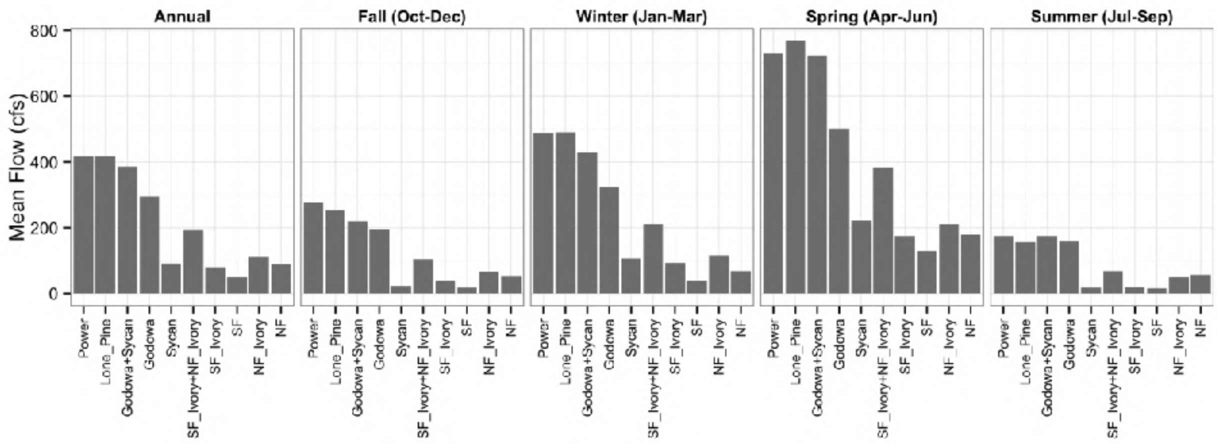

FIGURE 19: MEAN ANNUAL AND SEASONAL FLOWS, WY2010-2014

Figure 20 shows the net changes in mean annual and seasonal flow for each incremental sub-basin over WY2010 – 2014. The net change in mean annual flow showed no change in the lower Sprague River between Lone_Pine and Power despite an increase in drainage area of 420 km^2. Furthermore, there was a decrease of 40 cfs between these stations under high flow conditions during the spring. Section 4.2.3 discusses this loss in flow between Lone_Pine and Power in more detail.

Among the other sub-basins, flow also decreased by 7 cfs in the lower North Fork during summer, which was likely due in large part to the North Fork Ditch diversion (see photo in Figure 21) that transports water into agricultural areas in the lower South Fork basin[26]. Similarly, summer flows only increased by 2 cfs in the lower South Fork, which is heavily modified by canals and irrigation ditches. In the upper Sprague River, there was a fairly consistent increase in flow both annually and across all seasons ranging from 89 to 117 cfs. The relatively low variability across seasons suggests that flow gains in this reach were primarily from groundwater discharge, which is discussed further in Section 4.2.4 below.

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[26] The flow deficit occurs despite additional inflows below the diversion from Fivemile and Meryl Creeks.

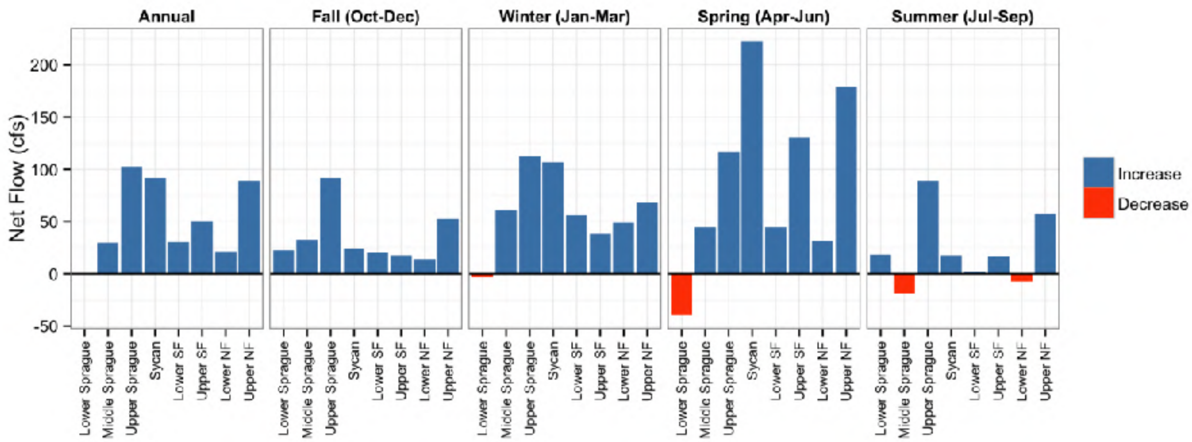


FIGURE 20: NET CHANGES IN MEAN ANNUAL AND SEASONAL FLOWS FOR EACH INCREMENTAL SUB-BASIN, WY2010-2014

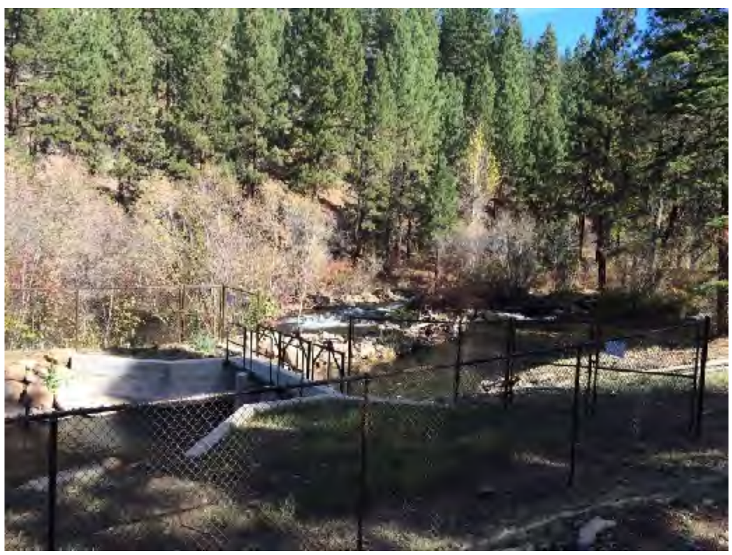


FIGURE 21: NORTH FORK SPRAGUE IRRIGATION DIVERSION DIRECTLY BELOW NF GAUGING STATION.

4.2.3 LOWER SPRAGUE RIVER FLOW DYNAMICS

As mentioned in the previous section, the streamflow results show flow decreased in the lower Sprague River sub-basin between Lone_Pine and Power, primarily in winter and spring during high flow conditions. Figure 22 compares the daily flows at Power against the flows at Lone_Pine using (a) the computed daily flows based on the biweekly flow measurements by Klamath Tribes and (b) continuous daily flow measurements at USGS and OWRD streamflow gages, both of which are at approximately the same locations as the water quality stations. Both sets of data (Klamath Tribes and USGS/OWRD) show that under high flow conditions, flows at Lone_Pine tended to be greater than those at Power, while under low flow conditions flows at Power tended to be greater than flows at Lone_Pine. Although the reduction in high flows could be due to flow attenuation whereby peak flows spread out over time as they travel downstream, similar relationships appear when comparing monthly flows as shown in Figure 23.

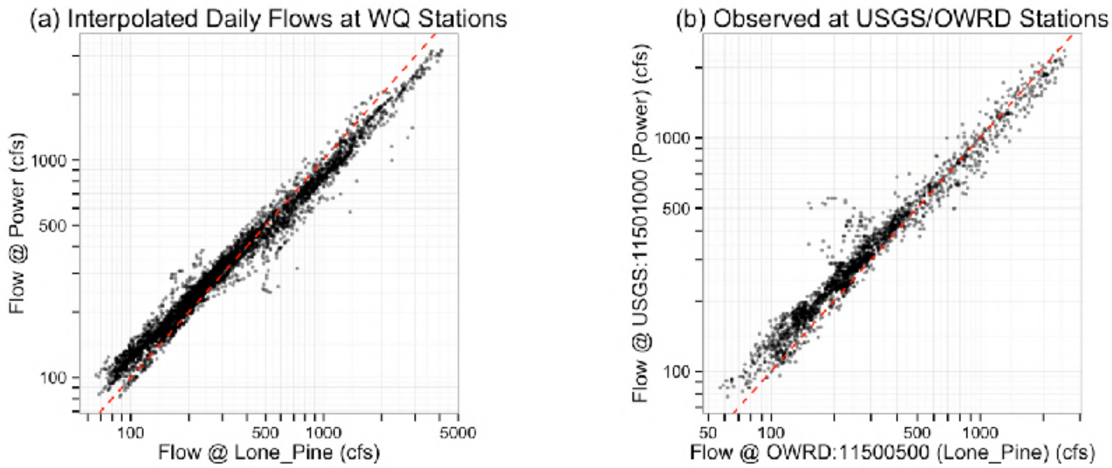


FIGURE 22: COMPARISON OF DAILY FLOWS AT POWER AND LONE_PINE, WY2002 – 2014

Red dashed line shows the 1:1 ratio

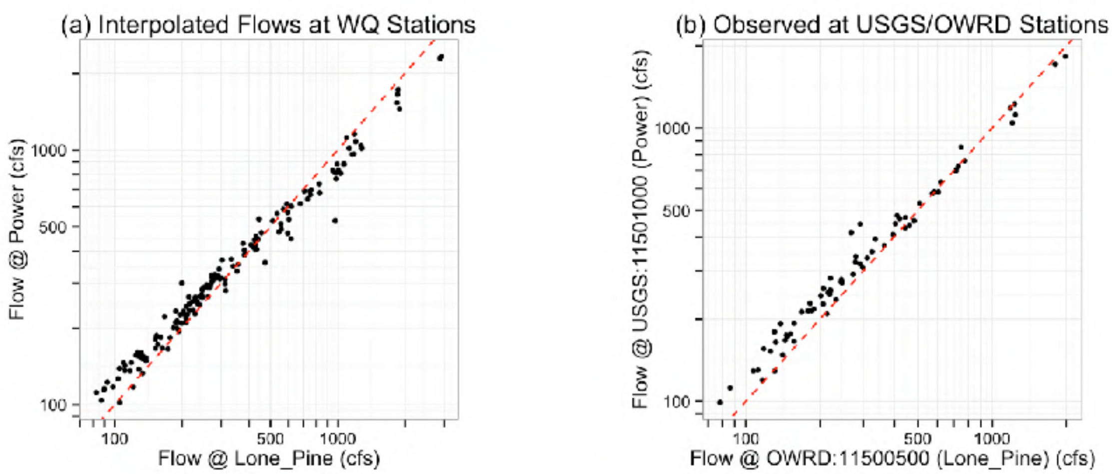


FIGURE 23: COMPARISON OF MEAN MONTHLY FLOWS AT POWER AND LONE_PINE, WY2002-2014

Red dashed line shows the 1:1 ratio

Unfortunately, there is insufficient information available to determine the cause of the decreasing high flows along the lower Sprague River from Lone_Pine to Power. One possibility is that as the water level rises and spreads out across the floodplain, the over-bank flow fills wetlands, oxbows, or other depressions that are normally disconnected from the main channel. These areas may provide temporary storage, trapping some of the high flow and preventing it from continuing downstream. As the flow and water levels then recede, some of the water remains in these depressions and ultimately infiltrates into the ground or evaporates. Another possible explanation could be inaccuracies in the rating curves at one or more of these stations under high flow conditions resulting in overestimated flows at Lone_Pine or underestimated flows at Power. However, given that both datasets (Klamath Tribes and USGS/OWRD) show similar patterns, the loss in high flows is more likely the result of complex flow routing over the floodplain.

To further illustrate the flow dynamics between Lone_Pine and Power, Figure 24 shows daily time-series of the computed daily flows at both stations during WY2010 – 2014. This figure also illustrates that flows at Lone_Pine were greater than or equal to flows at Power under high flow conditions during winter and spring, and, conversely, flows at Power were greater than those at Lone_Pine under low flow conditions during summer and fall.

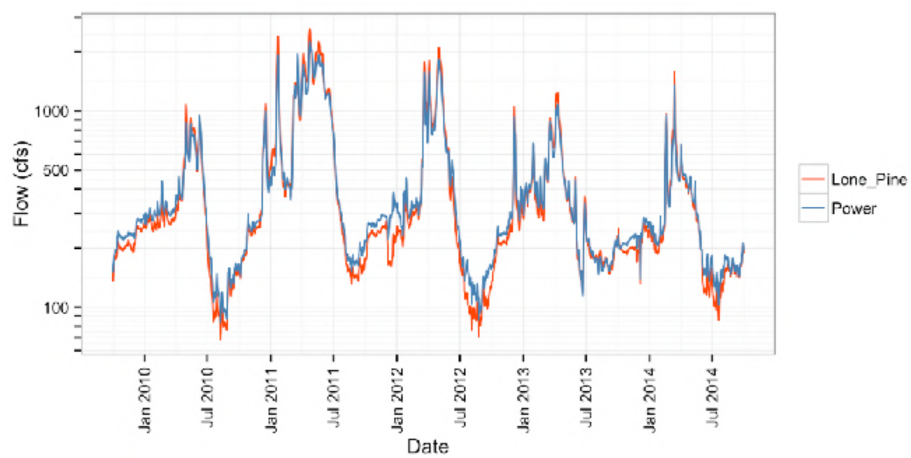


FIGURE 24: TIME SERIES OF DAILY FLOWS AT LONE_PINE AND POWER, WY2010 – 2014

A comparison of the combined flow at Godowa+Sycan with flows at Power indicates a similar trend with the upstream boundary (Godowa+Sycan) showing flows greater than or equal to flows at Power under high flow conditions during winter and spring, and flows at Power greater than those upstream under low flow conditions during summer and fall (Figure 25). During the low flow fall/early-winter period when irrigation should be minimal, the difference in flows at Power were closer to, but somewhat lower than the increase of 93 cfs expected due to groundwater inflow via springs (Table 7; Lower and Middle Sprague sub-basin). The negative difference between Power and Godowa+Sycan during July and August is likely due to irrigation withdrawals in that reach (Figure 25; bottom panel). While under-estimation of high flows at Power cannot be ruled out, the continuation of this trend in decreasing high flows when using Godowa+Sycan for the upstream boundary further indicates possible over-bank flows that are then lost from the system.

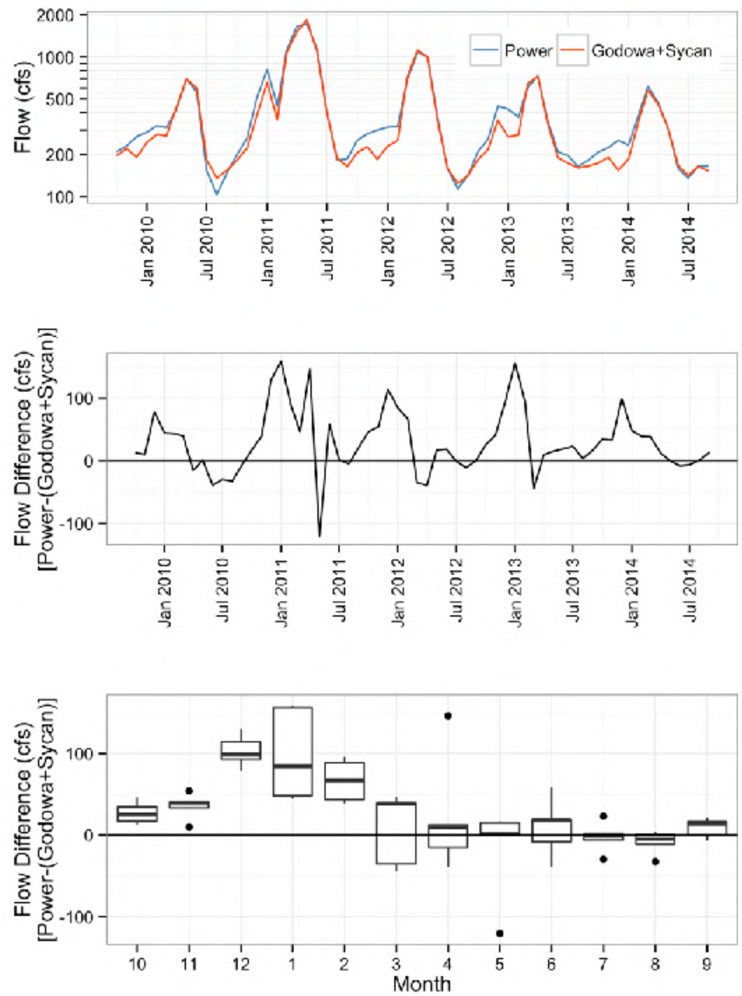


FIGURE 25: TIME SERIES OF MONTHLY FLOWS AND FLOW DIFFERENCE AT LONE_PINE AND GODOWA+SYCAN, WY2010 – 2014

4.2.4 GROUNDWATER DISCHARGE

In order to better understand the changes in flow along the Sprague River as well as the potential for nutrient loading from groundwater, the net changes in mean summer flow were compared to estimates of groundwater discharge reported by Gannett et al. (2007). Gannett et al. (2007) used synoptic flow measurements to estimate groundwater discharge rates from springs and seeps along discrete reaches of the Sprague River and its tributaries. In order to compare their estimates to the results of this study, the reaches defined by Gannett et al. (2007) (see Table 6 of their report) were aggregated to the reaches coinciding with incremental sub-basins based on the Klamath Tribes' water quality stations. Most of the reaches defined in Gannett et al. (2007) use start and end points that are located at or near the Klamath Tribes water quality stations, with one exception: Reach 10, which extends from the South Fork Sprague at Picnic Area (RM 10.2), where the SF station is located, to Sprague at Cinder Pit (RM 77.5), which is about 6 miles upstream of the Godowa station. Because about half of Reach 10 extends above the outlet of the South Fork at the SF_Ivory station, the total groundwater discharge from this reach was split evenly between the Upper Sprague and Lower South Fork sub-basins. Also, note that the total spring discharge for the Sycan River only includes the reaches below the Sycan Marsh, which Gannett et al. (2007) report as a net sink of groundwater at a rate between -10 to -20 cfs.

Table 7 lists the total groundwater discharge and the associated reaches from Gannett et al. (2007) for each incremental sub-basin, and compares these values to the net change in mean summer flow over the period WY2010 – 2014. The mean flows during summer were used due to the relatively little precipitation that occurs during this season, and thus most flow is expected to originate from groundwater seeps and springs. Figure 26 provides a comparison of the total groundwater discharges and the net change in summer flows.

TABLE 7: SPRING/SEEP DISCHARGE FROM GANNETT ET AL. (2007) AND MEAN NET SUMMER FLOWS BY INCREMENTAL SUB-BASIN, WY2010 – 2014

	Gannett et al. (2007)		WY2010 – 2014
Incremental Sub-basin	**Reaches***	**Total Flow (cfs)**	**Net Summer Flow (cfs)**
Lower Sprague	19-22	73	18
Middle Sprague	15-18	20	-19
Upper Sprague	10**-14	94	89
Sycan	27-31	21	17
Lower SF	10**	13	2
Upper SF	1-4	24	16
Lower NF	7-9	33	-7
Upper NF	5-6	59	58

* Reach numbers referenced from Table 6 of Gannett et al. (2007)

** Reach 10 split evenly between Upper Sprague and Lower SF

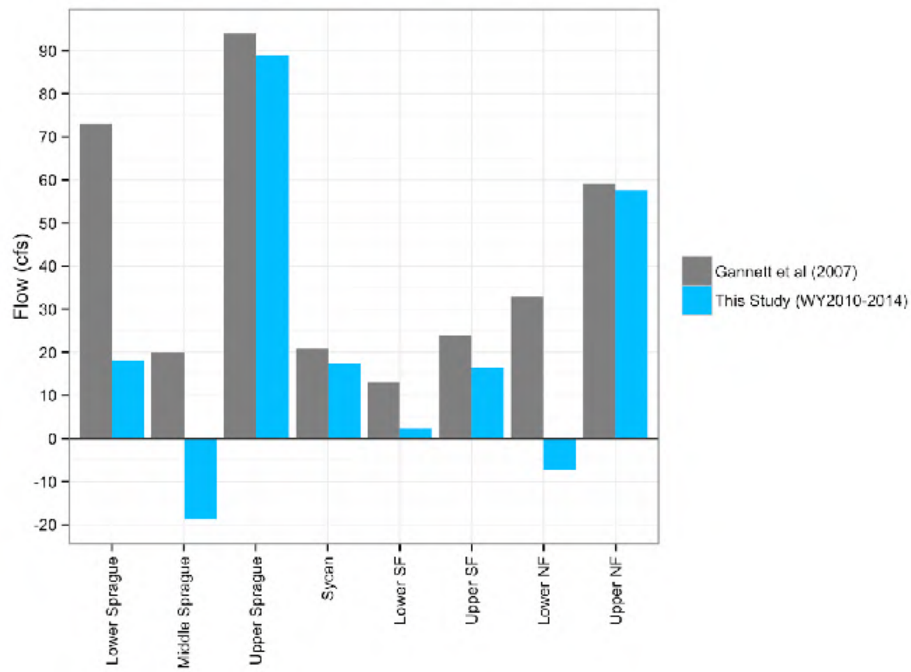


FIGURE 26: SPRING/SEEP DISCHARGE FROM GANNETT ET AL. (2007) AND MEAN NET SUMMER FLOWS BY INCREMENTAL SUB-BASIN, WY2010 – 2014

Table 7 and Figure 26 show close agreement between the total groundwater discharge from Gannett et al. (2007) and the net summer flow in some reaches, but not others. In the three headwater basins (upper North Fork, upper South Fork, and the Sycan River), net summer flows were slightly less than the total groundwater discharge, which is expected because the net flows incorporate losses due to, for example, evaporation and water withdrawals. Among the other incremental sub-basins, the large increase in net summer flow of 89 cfs in the upper Sprague River closely matched the total groundwater discharge of 94 cfs. As mentioned above in Section 4.2.2, the net increase in flow for this reach was fairly consistent across seasons. Therefore, this comparison provides further evidence that a large source of the flow gain in the upper Sprague River upstream of the Godowa station originates from groundwater discharge.

However, for the other incremental basins, there are greater differences between the net summer flow and total groundwater discharge. The largest difference was in the lower Sprague River between Lone_Pine and Power, which received an estimated 73 cfs of groundwater discharge, but had a net flow increase of only 18 cfs. In the middle section of the Sprague River between Lone_Pine and Godowa+Sycan, the total groundwater discharge was 20 cfs, but the net change in summer flow was -19 cfs. Because these differences were greater for areas with higher levels of human activity, this comparison suggests that human activity (e.g., irrigation withdrawal) has a significant impact on the flows in the river during summer. However, detailed quantification of the total sources (e.g., runoff, groundwater pumping, return flows) and sinks (e.g., evapotranspiration, consumption) in each reach is needed to determine the causes of these changes in flows and the differences relative to the total groundwater discharge estimates from Gannett et al. (2007).

4.3 Water Quality Model Results

4.3.1 *Diagnostic and Summary Data Displays*

Similar to the streamflow model results, the water quality model results are summarized by a series of data displays providing daily, annual, and monthly results as well as various diagnostic summary statistics and comparison charts. These summary and diagnostic displays are provided in Appendix D.

For each station and water quality parameter, a series of three data displays are generated. Figure 27-Figure 29 show examples for the results of TP at the Power water quality station located near the outlet of the Sprague River. The first set of charts (Figure 27) shows the daily and annual concentrations, flows, and loads as well as summary statistics of the model performance. The next set of charts (Figure 28) shows monthly time-series and distributions of mean values by month of the year to illustrate the seasonality in each term. Finally, the last set of charts (Figure 29) shows diagnostic plots of the model residuals and comparisons between the observed and predicted concentrations and loads. Similar sets of charts for the other stations and parameters are provided in Appendix D.

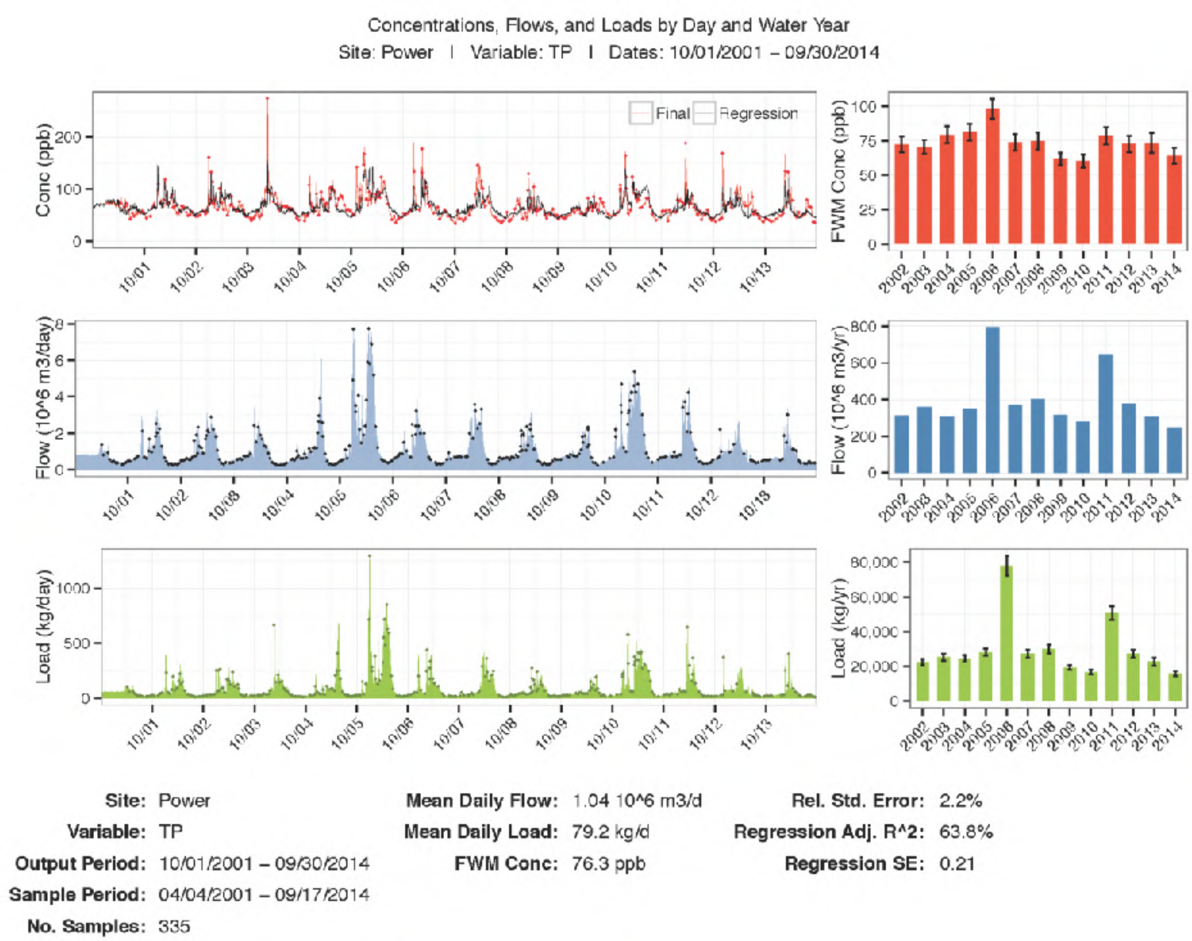


Figure 27: Example of Water Quality Model Diagnostics Display of Daily and Annual Results for TP at Power

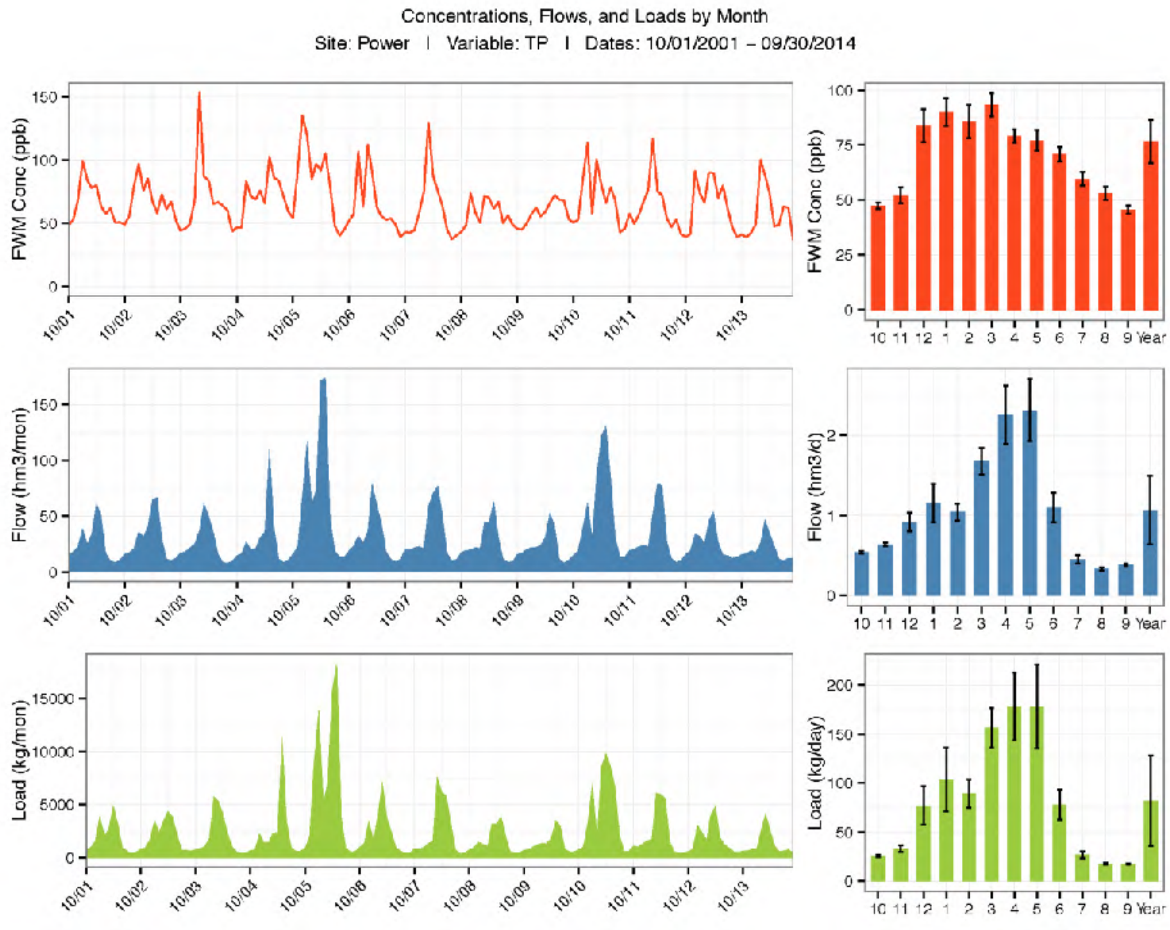


FIGURE 28: EXAMPLE OF WATER QUALITY MODEL DIAGNOSTICS DISPLAY OF MONTHLY RESULTS FOR TP AT POWER

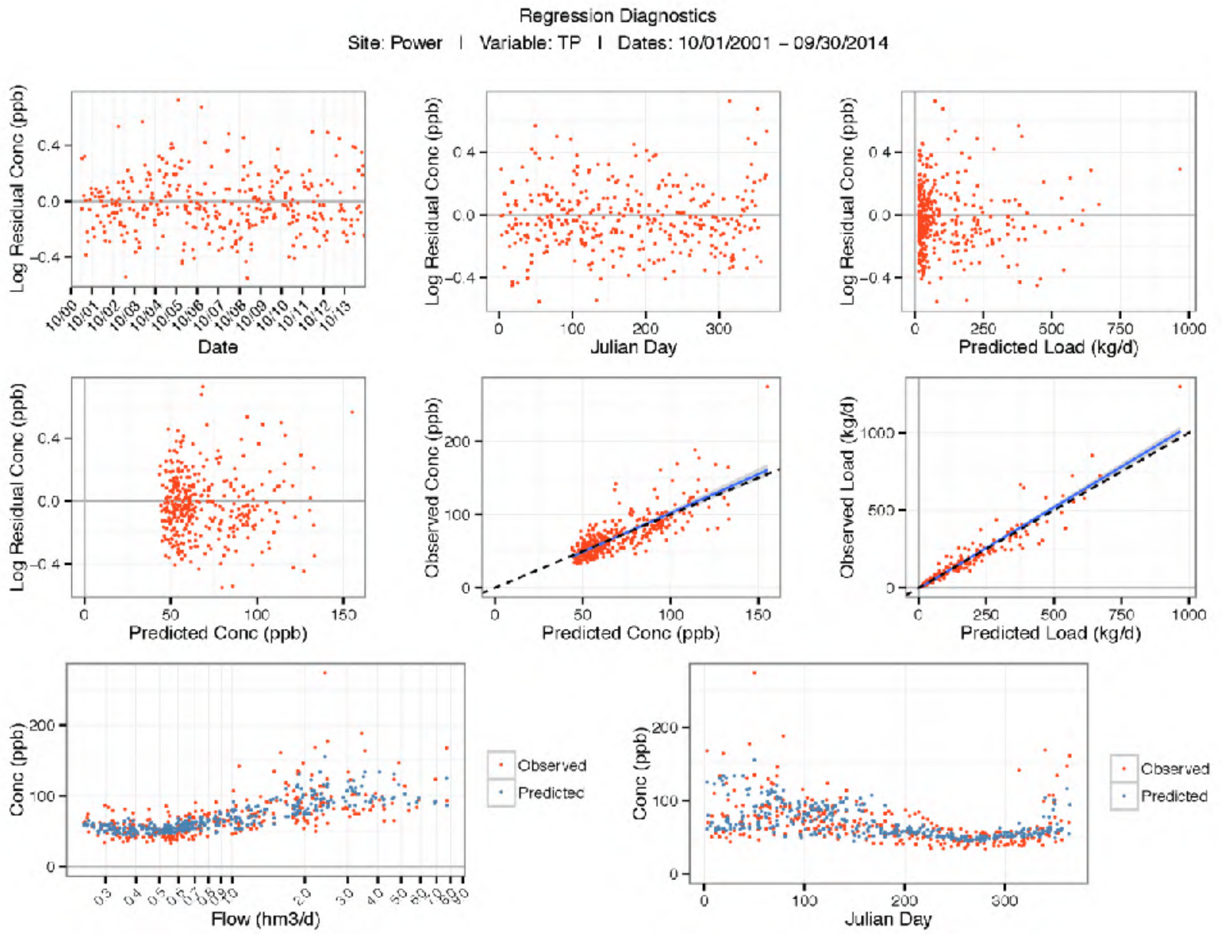


FIGURE 29: EXAMPLE OF WATER QUALITY MODEL DIAGNOSTICS DISPLAY OF RESIDUALS FOR TP AT POWER

4.3.2 MONTHLY FLOWS, LOADS AND CONCENTRATIONS

The daily time-series of flows, loads, and concentrations were aggregated to monthly time steps by computing the monthly mean flow and load at each station. The monthly flow-weighted mean (FWM) concentrations were then computed by dividing the monthly load by corresponding flow. Figure 30 shows the monthly flow, TP and TN load, and TP and TN FWM concentration for each station over the study period (WY2002 – 2014). Note that the results for SF_Ivory and NF_Ivory begin in October 2010 due to the limited sampling period at these stations. This figure illustrates the strong seasonality of flows and loads due to high snowmelt-driven flows in the winter and spring, and low summer flows originating primarily from groundwater. This figure also shows the higher flows and loads at Lone_Pine relative to Power during high flow seasons, as discussed above in Section 4.2.3. Both TP and TN concentrations also exhibit some seasonality with higher concentrations occurring in the winter and spring when flows are higher. Peak TP concentrations at high flow tended to occur at the lower and middle Sprague stations and SF_Ivory, while peak TN concentrations occurred at the Sycan station as well as these stations. Further interpretation of the seasonal and spatial patterns of these results are provided in Sections 4.4 and 4.5 below.

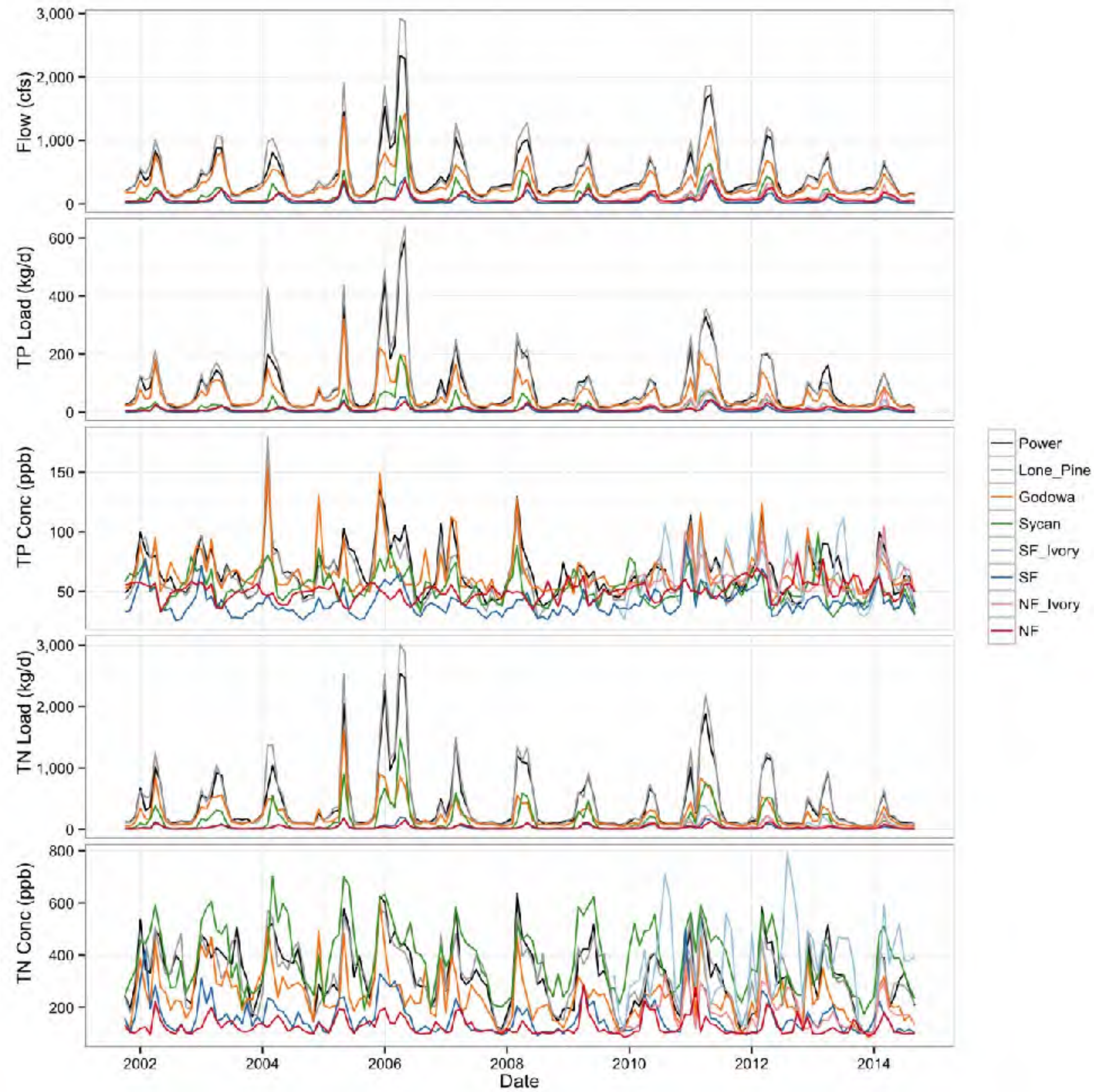


FIGURE 30: MONTHLY FLOW, TP AND TN LOAD, AND TP AND TN FWM CONCENTRATION, WY2002 – 2014

4.3.3 OVERALL MEAN AND ANNUAL FLOWS, LOADS AND CONCENTRATIONS

The overall mean annual flows, loads and FWM concentrations for TP, TN, and TSS over the period WY2010 – 2014 are summarized in Table 8. Only the last five years of the study period were used in order to maintain consistency across all the stations since the results for SF_Ivory and NF_Ivory begin in WY2010. The net flows, loads and changes in FWM concentrations for the incremental sub-basins over this same period are listed in Table 9. Note that the net change in FWM concentration for the headwater incremental sub-basins (Sycan, upper South Fork, upper North Fork) could not be computed because there are no upstream stations for these sub-basins, and negative net loads ocurred on a few occasions when downstream flows and/or concentrations were greater than upstream values (red colored values in Table 9). Interpretations of these mean annual summary results are discussed using reach network plots in Section 4.5 below.

Figure 31 shows the annual flow, runoff (flow per unit area), TP and TN load, TP and TN export (load per unit area), and TP and TN FWM concentration for each station by water year. The error bars for concentration and loads per unit area indicate +/- 1 standard error based on the water quality model residuals (see Section 3.2.2). Note that results are not shown for years before 2010 at SF_Ivory and NF_Ivory since these stations were added to the routine sampling program in 2009. Figure 32 shows the annual FWM concentration of each water quality parameter and station.

TABLE 8: MEAN ANNUAL FLOWS, LOADS AND FWM CONCENTRATIONS FOR TP, TN AND TSS BY STATION, WY2010 – 2014

				Load (mt/yr)			Load per Area ($kg/km^2/yr$)			FWM Conc		
Sampling Station	Drainage Area (km^2)	Flow (hm^3/yr)	Flow per Area (cm/yr)	TP	TN	TSS*	TP	TN	TSS*	TP (ppb)	TN (ppb)	TSS* (ppm)
Power	4,123	371.5	9.0	26.7	126.4	5,740	6.5	30.7	1,390	71.8	340	14.5
Lone_Pine	3,693	371.8	10.1	26.0	134.7	5,860	7.0	36.5	1,590	69.8	362	14.7
Godowa	1,470	262.9	17.9	17.5	64.3	3,520	11.9	43.7	2,400	66.7	245	12.9
Sycan	1,441	82.4	5.7	4.1	39.1	812	2.8	27.2	564	49.6	475	8.9
SF_Ivory	753	72.4	9.6	4.7	25.6	1,810	6.3	34.0	2,410	65.2	354	23.3
SF	280	45.1	16.1	2.1	8.4	445	7.5	30.0	1,590	46.6	186	9.4
NF_Ivory	535	98.9	18.4	6.4	19.1	1,930	12.0	35.7	3,600	65.1	193	18.2
NF	187	79.7	42.6	4.1	11.1	348	21.9	59.6	1,860	51.3	140	4.2

* TSS results based on WY2011 – 2014

TABLE 9: SUMMARY OF ANNUAL NET CHANGES IN FLOWS, LOADS AND FWM CONCENTRATION FOR TP, TN AND TSS BY INCREMENTAL SUB-BASIN, WY2010 – 2014

				Net Change in Load (mt/yr)			Net Change in Load per Area (kg/ km^2/yr)			Net Change in FWM Conc		
Incremental Sub-basin	Drainage Area (km^2)	Net Change in Flow (hm^3/yr)	Net Change in Flow per Area (cm/yr)	TP	TN	TSS*	TP	TN	TSS*	TP (ppb)	TN (ppb)	TSS* (ppm)
Lower Sprague	430	-0.2	-0.1	0.7	-8.3	-121	1.7	-19	-281	2.0	-22.1	-0.2
Middle Sprague	782	26.5	3.4	4.3	31.3	1,530	5.6	40	1,950	7.2	62.8	2.8
Upper Sprague	182	91.9	50.4	6.4	19.6	-214	35.0	108	-1,180	1.5	-16.5	-7.4
Sycan	1,441	82.4	5.7	4.1	39.1	812	2.8	27	564	--	--	--
Lower South Fork	474	27.3	5.8	2.6	17.3	1,370	5.5	36	2,890	18.7	168.4	13.9
Upper South Fork	280	45.1	16.1	2.1	8.4	445	7.5	30	1,590	--	--	--
Lower North Fork	348	19.2	5.5	2.4	8.0	1,580	6.7	23	4,530	13.8	53.4	14.0
Upper North Fork	187	79.7	42.6	4.1	11.1	348	21.9	60	1,860	--	--	--

* TSS results based on WY2011 – 2014

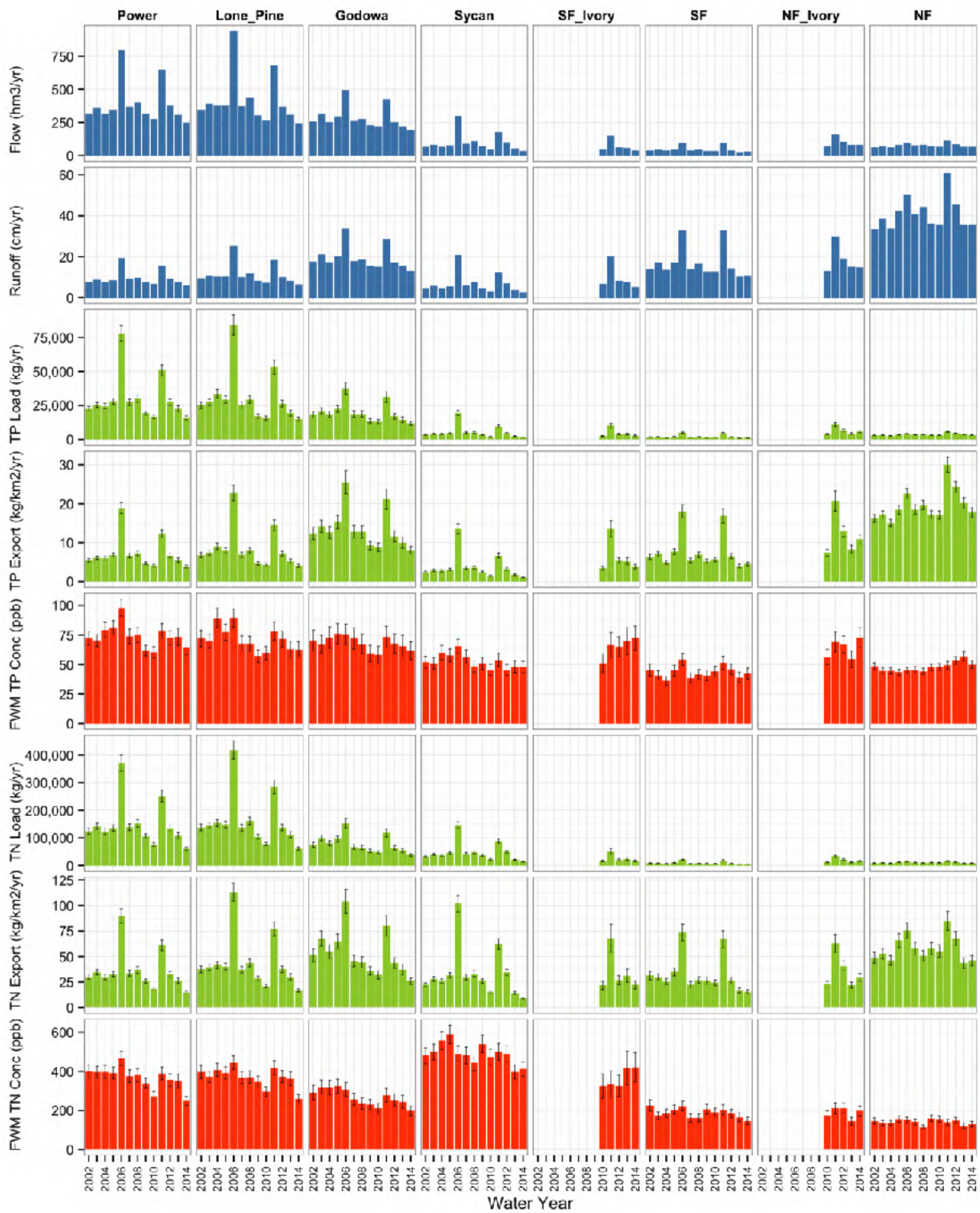


FIGURE 31: ANNUAL FLOW, RUNOFF, TP AND TN LOAD, TP AND TN EXPORT, AND FWM TP AND TN CONCENTRATION FOR EACH WATER QUALITY STATION

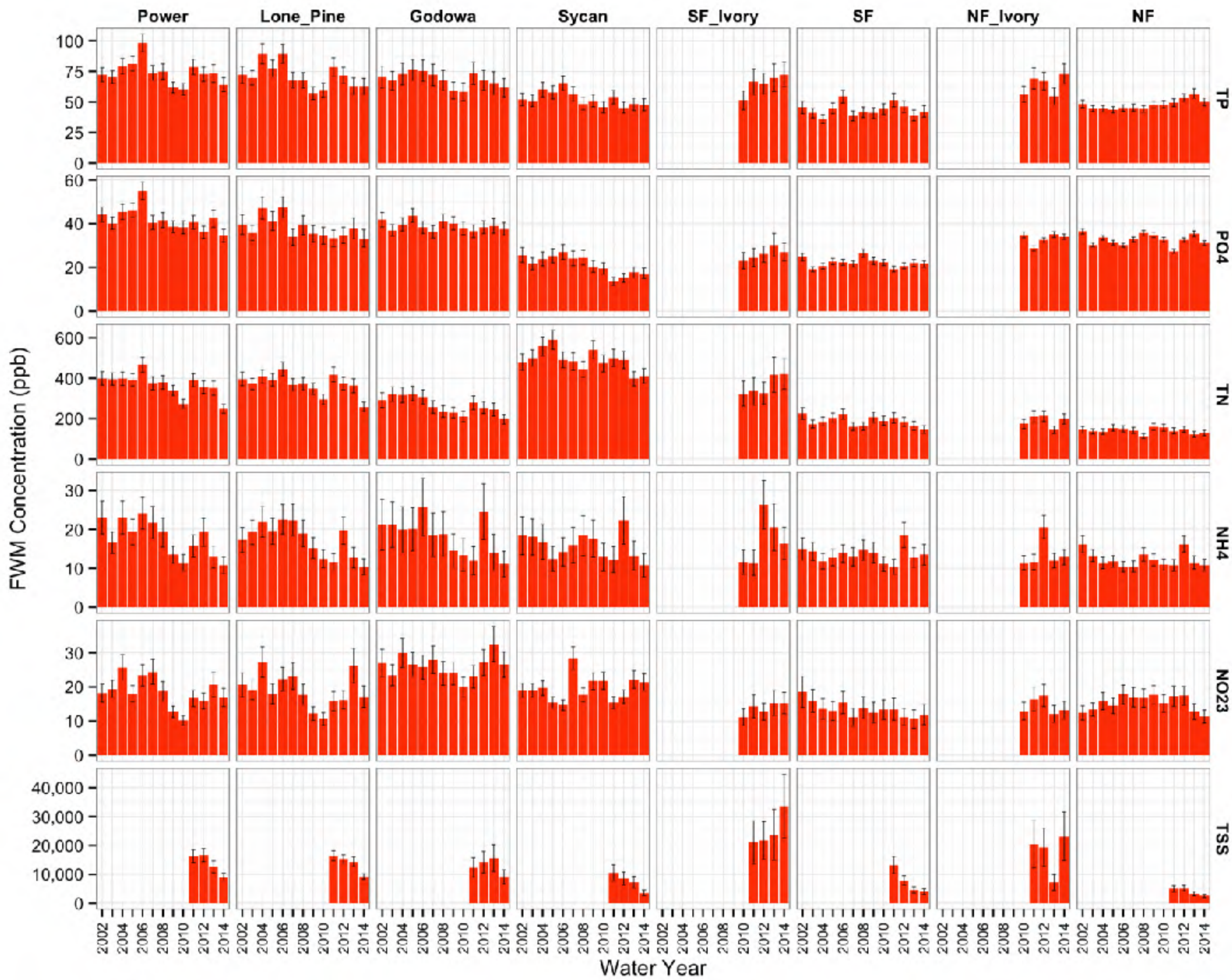


FIGURE 32: ANNUAL FWM CONCENTRATION FOR EACH WATER QUALITY STATION AND VARIABLE

On an inter-annual basis, TP and TN load and export were related to flow and water runoff at most stations, with highest values occurring in WY2006 and WY2011 (Figure 31). For the lower Sprague station at Power, both TP and TN concentrations were also highest in WY2006 and WY2011, but at other stations the concentration pattern appeared to be less tied to annual flow (Figure 32). For example, Lone_Pine showed higher TP concentration in WY2004 than in WY2011 (Figure 32). The Sycan showed higher TP concentration in WY2006, but TN was highest in WY2005 (Figure 32). Despite being low flow years, WY2013 and WY2014 showed relatively high concentrations of TSS, TP, PO4, TN, NH4, and NO23 at SF_Ivory, and values were high in WY2014 for TP and TSS at NF_Ivory. Annual means for TN concentration were consistently higher at Sycan than other stations, and NO23 mean annual values were consistently higher at Godowa. Other inter-annual trends include consistently higher NH4 values in WY2012[27] at all stations, and an apparent decline in TN over time at the Power, Lone_Pine, and Godowa stations (this and other time-series trends are discussed further in Section 4.9, below).

4.4 Seasonal Patterns of Monthly Flows, Loads, and Concentrations

The continuous daily time-series of flows, loads, and concentrations provide a basis for more detailed analyses and interpretations related to the seasonal and spatial patterns in the watershed. A series of data visualizations were used to present these results in different contexts in order to facilitate comparisons between stations, seasons, years, and water quality parameters.

Seasonal patterns in flows and concentrations are shown using heatmaps in Figure 33. A heatmap is a visualization technique used to show large quantities of data in a condensed format. This type of chart consists of a set of tiles, with the color of each tile representing an individual value (in this case, monthly flow or FWM concentration). Because the range of values varies between flows and water quality concentrations, the data are standardized in order to use a consistent color scale across all parameters. The values for each parameter were first transformed to a logarithmic scale and then normalized by subtracting the mean and dividing by the standard deviation of all values for that parameter across the stations. The result is a set of standardized monthly values for each flow and water quality parameter which have roughly the same overall distribution (standard normal) and can thus be represented by a single color scale.

[27] It is not clear whether the 2012 spike is a real event or possibly due to a data quality assurance issue.

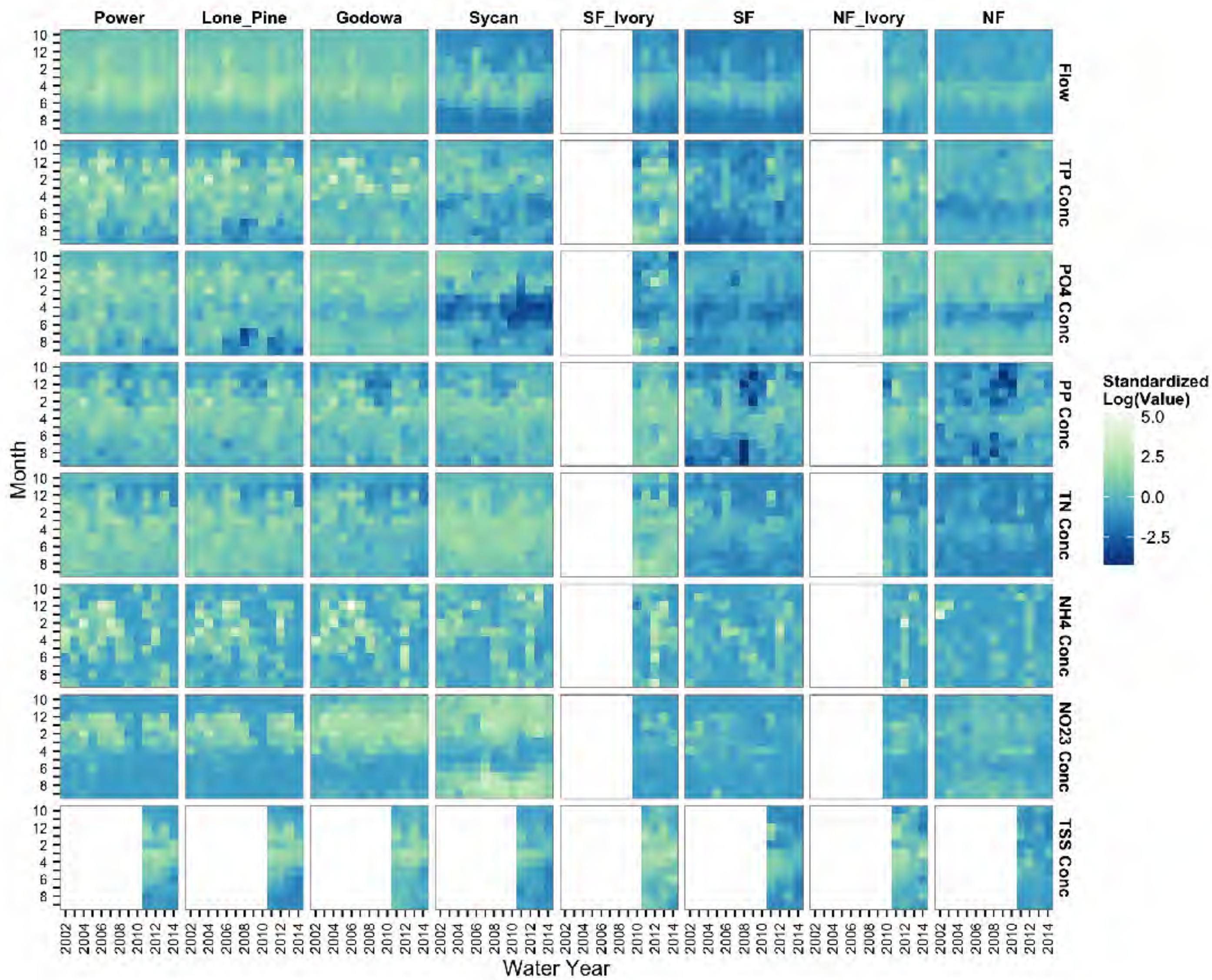


FIGURE 33: HEATMAPS OF MONTHLY FLOWS AND FWM CONCENTRATIONS

The top row of Figure 33 shows the monthly flows at each station. The highest values tended to occur between March and June as expected due to spring snow-melt. However, in some years (WY2006 and WY2011, which were wet years in the study period) high flows also occurred in the winter between December and February at most stations.

The second row in Figure 33 show the seasonal patterns of monthly FWM concentrations for TP. These panels show that among the three mainstem stations (Power, Lone_Pine, Godowa) as well as the Sycan River station, the highest concentrations tended to occur in the winter (December-March), and lowest concentrations occurred in fall (September-November). The upper SF station showed relatively little seasonality compared to the other stations, and SF_Ivory showed high TP concentrations in summer (July-September) unlike the other stations. The upper NF station exhibited a different seasonal pattern with relatively constant TP concentrations in all months except in May and June when flows were highest and concentrations were lowest. This pattern is likely due to dilution of groundwater sources by spring snowmelt, which has relatively low phosphorus content.

Although discussed in more detail relative to flow and season below, observations for the other water quality parameters include:

- For PO4, the Godowa, NF_Ivory and NF stations showed the highest concentrations across much of the year except during spring snowmelt between April and June. The SF station had the lowest concentrations year-round. Power and Lone_Pine both had higher concentrations during the winter (December-March) and lower concentrations in late summer and fall (August-November).
- For PP, concentrations tended to be highest during winter and spring likely due to high flows in these seasons. At SF_Ivory and NF_Ivory, concentrations also remained relatively high in summer between June-September. The upper SF and NF stations had the lowest overall concentrations and exhibited less seasonality than at the other stations.
- For TN, highest concentrations occurred at most stations between February-September and lowest concentrations occurred in the fall between October-December. One exception is SF_Ivory which had highest concentrations in August and September. TN concentrations were lowest in October and November at all stations before increasing substantially in December. The NF and SF stations showed relatively constant low concentrations with some increase during spring months of April-June. The Sycan station had the overall highest concentrations year-round.
- For NH4, concentrations exhibited less seasonality than for the other parameters across all stations. The mainstem stations at Power, Lone_Pine and Godowa showed elevated concentrations in winter (December-May) in some years, but not as often in later years (2009 – 2014). The Sycan showed higher fall NH4 concentrations, while NH4 was lowest in summer and fall at Power, Lone-Pine, and Godowa. Note that a significant number of NH4 measurements were reported below the detection limit and thus the lack of seasonality may simply reflect the inability to accurately measure these low concentrations.
- For NO23, Power and Lone_Pine generally showed high concentrations in winter (December-March) in most years except 2009 and 2010. Sycan showed a different pattern with concentrations highest in the summer and fall/early-winter, and with lowest concentrations occurring during spring (April-June). Godowa showed a longer period of high concentrations (November-April) relative to other stations and values increased beginning in the fall. SF and SF_Ivory both had relatively low and constant concentrations year-round. Concentrations at the upper NF station were also relatively constant but somewhat elevated, and higher than all other stations except Sycan in the summer.
- For TSS, most stations had high concentrations during the winter and spring likely due to erosion during high flows, except for NF which had relatively low concentrations year-round.

4.5 Spatial Patterns of Mean Flows, Loads, and Concentrations

4.5.1 *REACH NETWORK PLOTS*

Reach network plots are designed to show how flows and concentrations change longitudinally along the Sprague River and its tributaries from the headwaters to the outlet. In these plots, the flows, loads, and FWM concentrations are plotted against cumulative drainage area such that the upstream stations appear on the left-hand side and downstream stations on the right-hand side of each panel. The stations are connected by line segments to show the network of reaches between stations. The thicker lines represent the mainstem reaches of the Sprague River, and the thinner lines represent the tributary reaches. The slope of these line segments reflect the change in flow, load, and concentration per unit change in drainage area. Line segments with large positive slopes indicate a large increase per unit area, and large negative slopes indicate a large decrease. These plots also include two additional points representing the confluence of two pairs of stations (Godowa+Sycan and NF_Ivory+SF_Ivory). Note that the flows, loads and concentrations at these points are computed by mass balance, as opposed to from direct measurements as done for the individual stations. For flows and loads, the values at these confluences are simply the sum of the flows and loads for the corresponding pair of stations. The FWM concentration is computed by dividing the sum of the loads by the sum of the flows.

Figure 34 shows reach network plots of the annual and seasonal flow, TP and TN load and FWM TP and TN concentration over the period WY2010 – 2014. The seasonal mean values for each station and variable were computed by first calculating the mean value within each season and water year, and then computing the mean across all water years. This figure shows only mean values computed over the last 5 years in order to include the two stations added in WY2010 (SF_Ivory and NF_Ivory). Similar figures for the other water quality parameters and using only the long-term stations over the period of record (WY2002 – 2014) are provided in Appendix E.

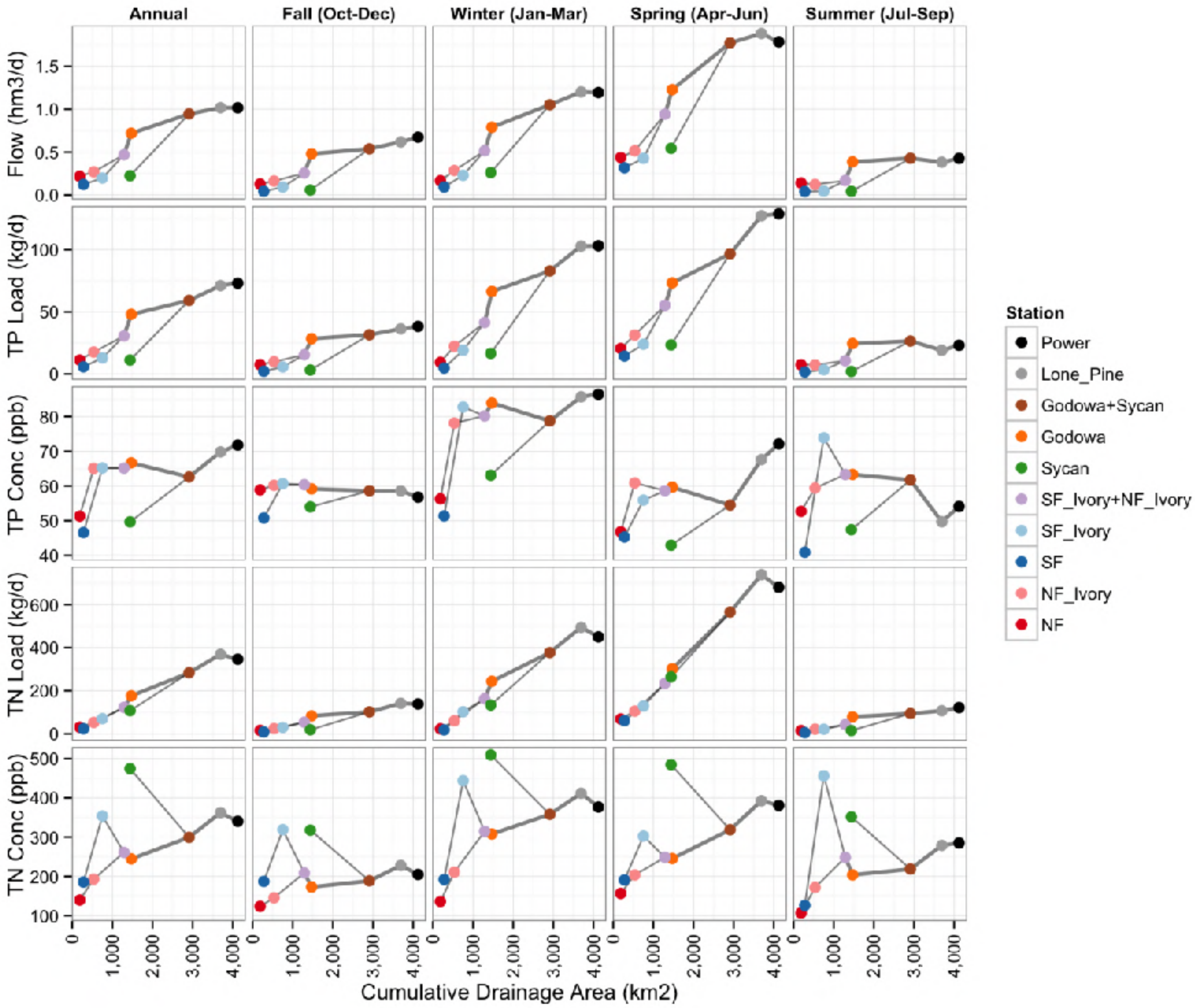


FIGURE 34: REACH NETWORK PLOTS OF MEAN ANNUAL AND SEASONAL FLOW, TP AND TN LOAD, AND FWM TP AND TN CONCENTRATION, WY2010 – 2014

Note: Values for Godowa+Sycan and SF_Ivory+NF_Ivory represent the confluence of two stations and are computed by mass balance

The reach network plots show how flows, loads, and FWM concentrations changed from the headwaters to the outlet of the Sprague River (Figure 34 and Figure 35). For example, annual flows (top left panel) showed a steep increase between the confluence of SF_Ivory+NF_Ivory and Godowa, and negligible change in the lower Sprague River between Lone_Pine and Power (Figure 34). The seasonal mean flows showed that the largest increase in flow occurred in spring, and to a lesser extent in winter. During summer, there was almost no change in flow along the mainstem from Godowa to Power, as was discussed in Section 4.2.3 above. As expected due to the greater variability of flow relative to concentration, mean annual and seasonal TP loads showed nearly identical patterns as those for flow. Longitudinal patterns in TN loads were also related to flow but to a lesser extent, and tended to show a more linear upstream to downstream pattern than did TP load (i.e., for TP load the slopes between stations were more variable compared to those for TN; Figure 34).

The mean annual FWM TP concentration of each station showed a large increase from 51 and 47 ppb at the relatively un-impacted NF and SF stations to 65 ppb at both the NF_Ivory and SF_Ivory stations near the confluence of the North and South Forks (Figure 35). From this confluence at the start of the upper Sprague River mainstem to the Godowa station the concentration increased only slightly to 67 ppb (Figure 35) despite the large increase in flow (Figure 34; top left panel). The Sycan river station also had a relatively low concentration of 50 ppb. The confluence of Godowa+Sycan had an estimated combined annual FWM concentration of 63 ppb, which then increased to 70 ppb at Lone_Pine. Finally, there was a small increase from 70 to 72 ppb at the Power station near the Sprague River outlet. In short, this figure indicates that a large fraction of the increase from background concentrations in the headwater basins occurred between the upper NF/SF and corresponding lower NF_Ivory/SF_Ivory stations, with some additional increase from the confluence of the Sycan and Sprague Rivers near Godowa down to Lone_Pine.

On a seasonal basis FWM TP concentrations showed large variations in these patterns. For example, in the fall there was relatively little change in the concentration along the entire river with a slight decrease from an estimated 60 ppb at the confluence of the South and North Forks (SF_Ivory+NF_Ivory) to 57 ppb at Power near the Sprague River outlet. During winter, the greatest increases in concentration occurred, primarily between SF/NF and SF_Ivory/NF_Ivory in the lower South and North Forks. In summer, there was a decrease in concentration of 9 ppb from 63 ppb at the confluence of the North and South Forks to 54 ppb at Power. This decrease, which primarily occurred between Godowa+Sycan and Lone_Pine, may reflect biological uptake by aquatic vegetation and algae. Eilers and Eilers (2006) noted that these Sprague River reaches can have high rates of primary production associated with macrophytes, attached algae, floating macrophytes and suspended algae. Others have noted the importance of periphyton as a temporary nutrient sink during summer growing seasons, with delayed downstream nutrient transport occurring during high energy flow events (Godwin et al. 2009).

Although there was only a small change in the annual FWM TP concentration between the SF_Ivory and NF_Ivory stations to Godowa, there was a large increase in PO4 and a large decrease in PP (Figure 35). This pattern indicates a change in the relative fraction of dissolved vs. particular phosphorus, which is likely due to large groundwater discharges and springs just upstream of the Godowa station that contain high dissolved phosphorus content. The mean PO4 and PP concentrations during the summer also showed that the majority of the decrease in TP between Godowa+Sycan and Lone_Pine was due to a decrease in PO4, with PP concentrations remaining relatively constant, again indicative of uptake by aquatic vegetation and algae.

Similar to FWM TP, the mean annual and seasonal FWM TN concentration showed a large increase between the relatively un-impacted SF station to the SF_Ivory station (particularly in summer), but a similar trend was not seen for the NF stations (Figure 35). Despite higher TN concentrations for the Sycan during all seasons, TN only increased slightly for the Sprague stations downstream of the Sycan confluence. Spatial and seasonal patterns were more apparent for NH4 and NO23, where NH4 increased sharply between SF and SF_Ivory during the fall and winter (but particularly in the fall) with relatively little longitudinal change observed for remaining stations, even though NH4 was substantially higher for the Sycan during the winter season[28]. Spring and summer NH4 and NO23 concentrations were low across all stations likely reflecting uptake (assimilation) by aquatic macrophytes and algae. NO23 increased sharply between SF_Ivory+NF_Ivory and the Godowa station on an annual basis and during the fall and winter, and NO23 at Sycan was relatively high in the summer and fall, although the high Sycan summer concentration did not have a large effect in terms of raising downstream concentrations. Although less likely than assimilation by primary producers, nitrification/denitrification dynamics may also play a role in certain seasons and reaches, but further analysis is outside the scope of this report. For further discussion of nitrogen seasonal dynamics see Section 4.7, below.

[28] The lack of longitudinal effect despite higher concentration inflows such as the Sycan reflects the relatively low overall concentrations and loads for these parameters (NH4<20 ppb and NO23<50 ppb)

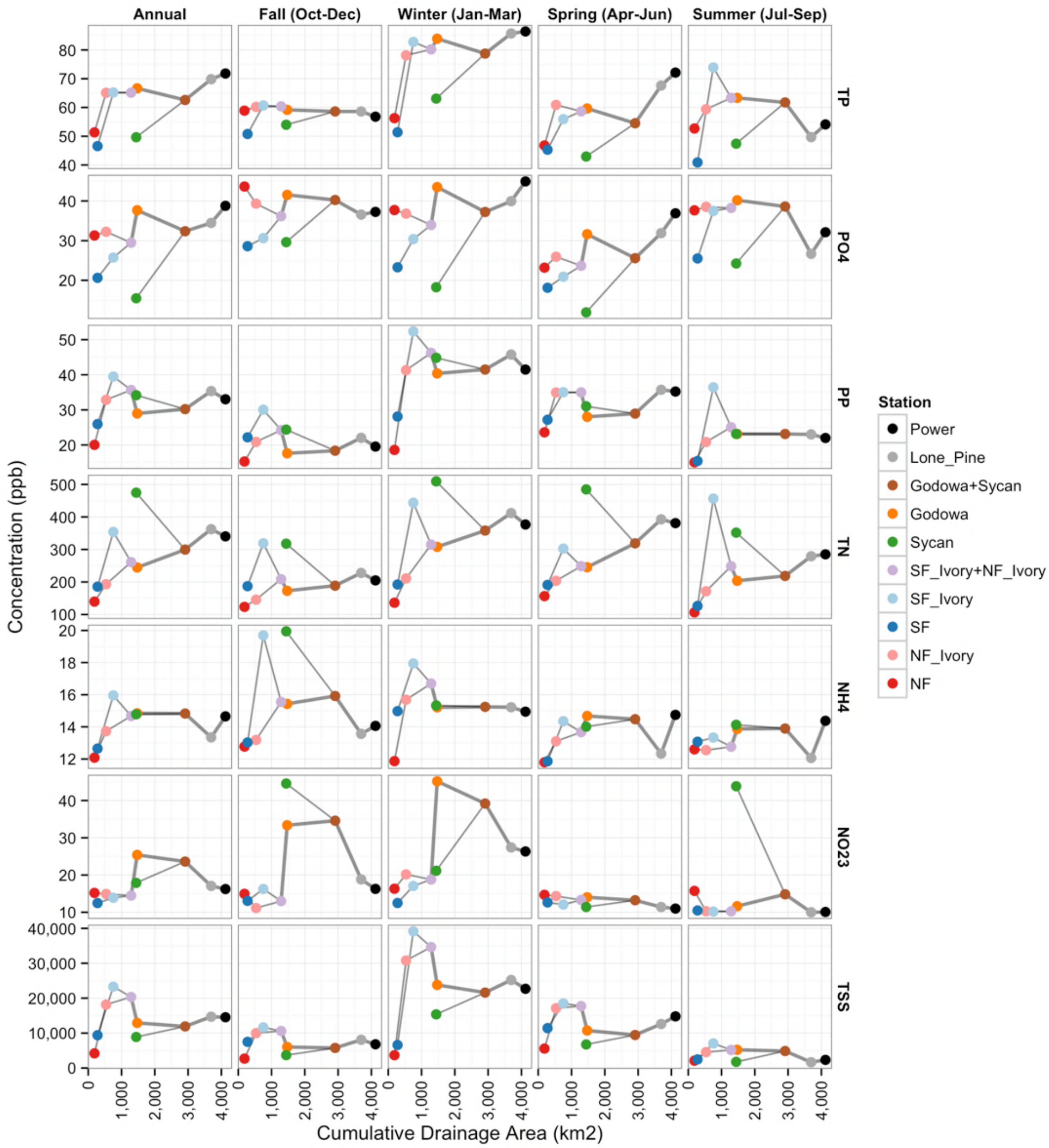


FIGURE 35: REACH NETWORK PLOTS OF MEAN ANNUAL AND SEASONAL FWM CONCENTRATIONS, WY2010 – 2014

Note: Values for Godowa+Sycan and SF_Ivory+NF_Ivory represent the confluence of two stations and are computed by mass balance

4.5.2 SUB-BASIN MAPS

In addition to the reach network plots, the streamflow and water quality results were also summarized by a series of map displays, which provide an alternative format for exploring the spatial patterns across the basin. Separate sets of maps were generated for both the cumulative and incremental sub-basins. The cumulative sub-basin maps show the mean annual flows, loads, and concentrations associated with the total drainage area of each station. The incremental sub-basin maps show the net changes in mean annual flows, loads, and concentrations for the drainage areas of each reach between consecutive stations. Both flows and loads are shown on a per unit area basis (i.e. runoff and export rates), in order to remove the effect of drainage area on the total flow volumes.

This section presents the map displays for flow per area, TP load per unit area, and TP FWM concentration over the period WY2010 – 2014, which was chosen in order to include the sub-basins associated with the lower South and North Fork sub-basins associated with the SF_Ivory and NF_Ivory stations.

Appendix F provides similar map displays for other parameters and for the mean annual results over the entire study period, WY2002 – 2014, in which the lower South and North Fork basins are combined with the upper Sprague River basin due to the limited period for the SF_Ivory and NF_Ivory stations.

4.5.2.1 Cumulative Sub-basin Maps

Figure 38-Figure 36 show map displays of mean annual flow per area, TP load per area, and TP FWM concentration for the cumulative sub-basins computed over the period WY2010 – 2014. Each display includes a map (top) and bar chart (lower left) both showing the mean annual values for each sub-basin, and a heatmap (lower right) showing the individual values for each water year. A separate map is shown for each cumulative sub-basin because the values are associated with the entire drainage area for each station. Appendix F provides similar sets of plots for all water quality parameters based on WY2010 – 2014 (Figure F1) and WY2002 – 2014 (Figure F2).

The figures below show that the highest flow and TP load per unit area occurred in the upper NF sub-basin, which is primarily spring and snow-melt driven. The highest concentrations, however, occurred in the downstream mainstem stations (Power, Lone_Pine). The relatively unimpacted sub-basins (Sycan, NF, SF) had lower concentrations ranging between 47 to 51 ppb. The heatmaps of annual values show that the highest flows and loads occurred in the wettest year (WY2011) at all stations. TP concentrations were also highest in that year at all stations except SF_Ivory, NF_Ivory, and NF.

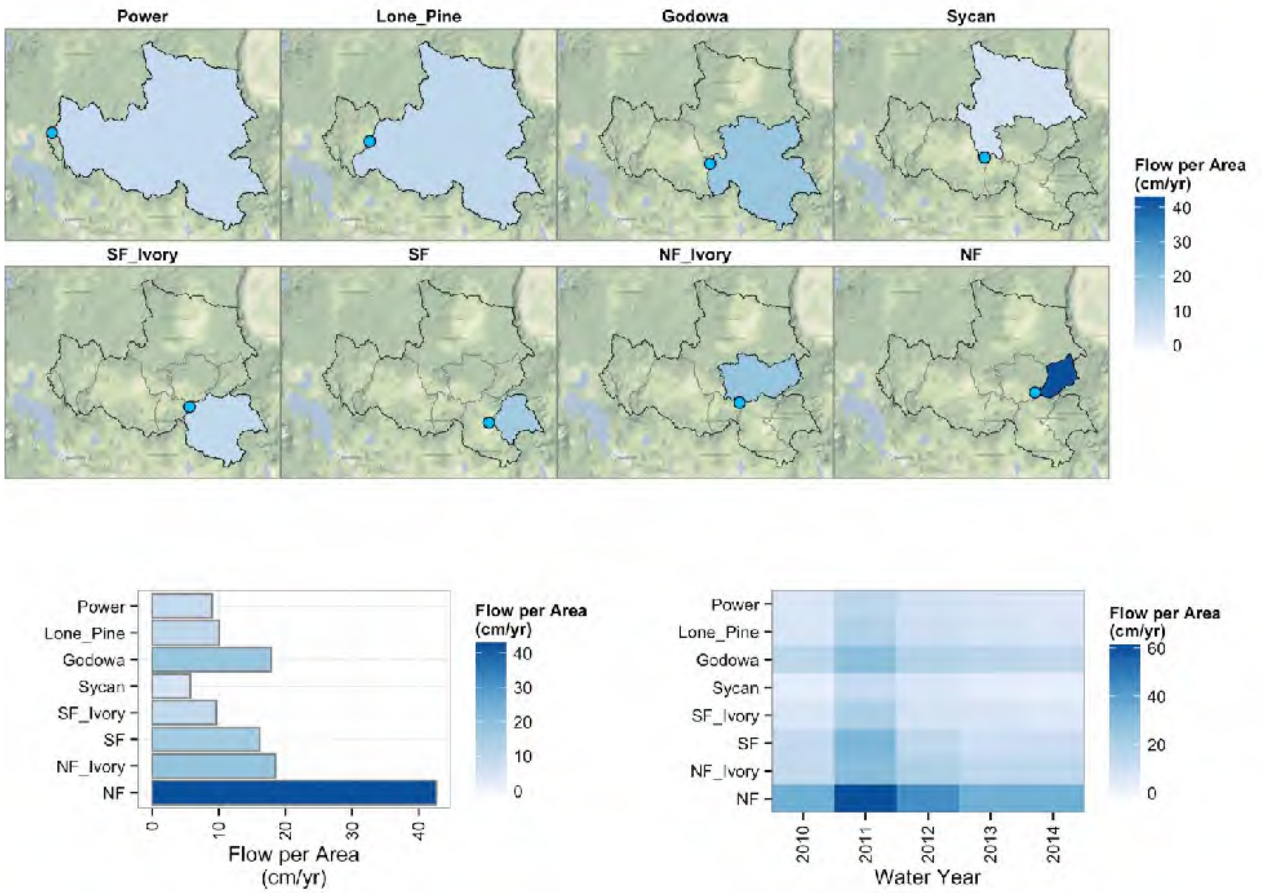


FIGURE 36: CUMULATIVE SUB-BASIN MAPS OF MEAN ANNUAL FLOW PER UNIT AREA, WY2010 – 2014

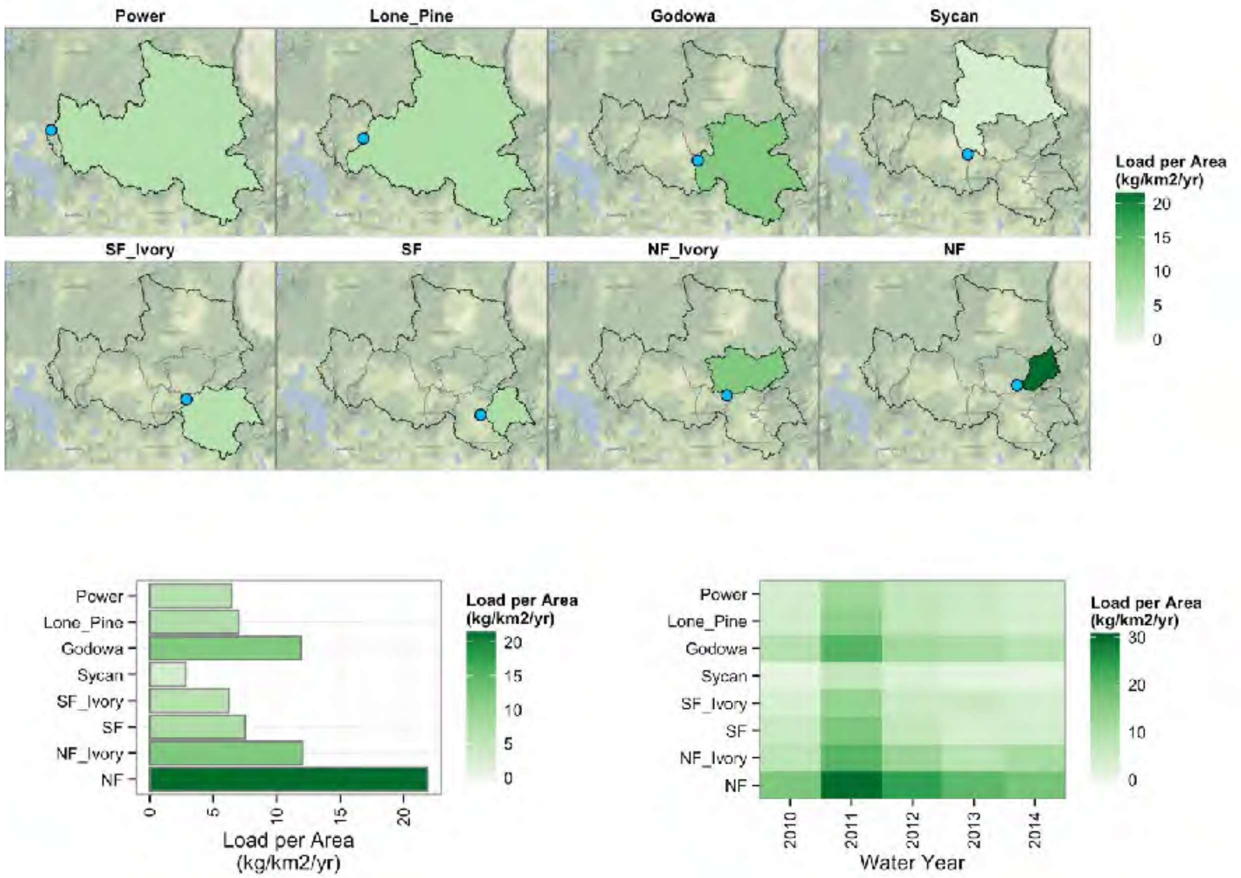
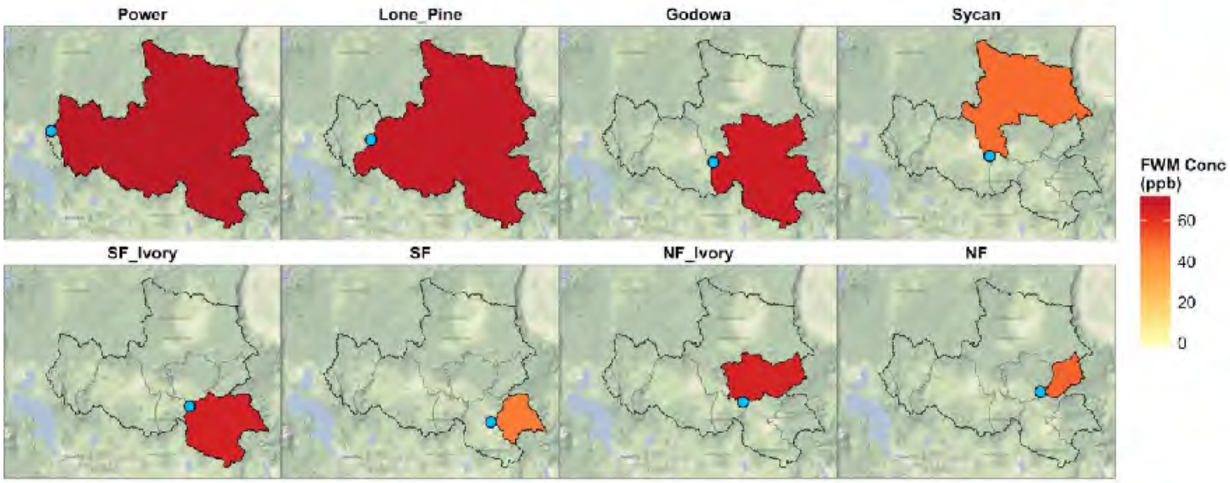
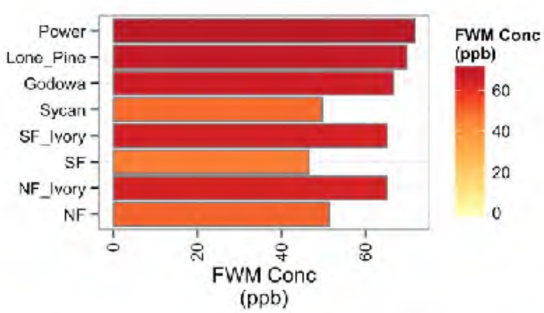


FIGURE 37: CUMULATIVE SUB-BASIN MAPS OF MEAN ANNUAL TP LOAD PER UNIT AREA, WY2010 – 2014





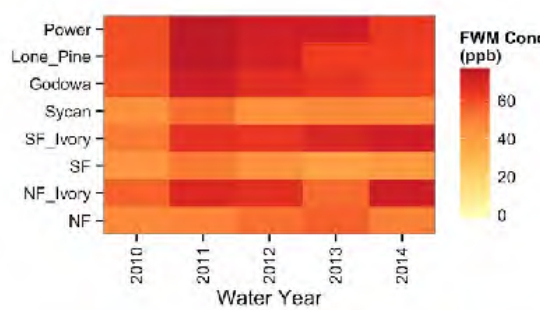


FIGURE 38: CUMULATIVE SUB-BASIN MAPS OF MEAN ANNUAL TP FWM CONCENTRATION, WY2010 – 2014

4.5.2.2 Incremental Sub-basin Maps

Figure 39 to Figure 41 show the net changes in mean annual flow per unit area, TP load per unit area, and TP FWM concentration for each incremental sub-basin over the period WY2010 – 2014. Each figure includes a map (top) and bar chart (lower left) that both show the net changes in mean annual values for each incremental sub-basin, and a heatmap (lower right) showing the net changes for each individual water year. The net changes in flow and load for each incremental sub-basin were computed by subtracting the sum of flows and loads at the upstream stations from those at the downstream station; the net change in FWM concentrations were computed by subtracting the combined FWM concentration of the upstream station(s) from the FWM concentration at the downstream station. Note that net changes in concentration cannot be computed for the three headwater sub-basins (Sycan, upper NF, upper SF) because there are no upstream stations, and thus no values are shown for these sub-basins in Figure 41. Appendix F provides similar sets of plots for all water quality parameters based on WY2010 – 2014 (Figure F3) and WY2002 – 2014 (Figure F4).

The figures below show that the largest increase in flows and TP load per unit area occurred in the upper Sprague River sub-basin between Godowa and the SF_Ivory+NF_Ivory confluence. However, this incremental sub-basin had the smallest change in FWM TP concentration. The largest increase in FWM concentration occurred in the lower South Fork sub-basin between the SF_Ivory and SF stations.

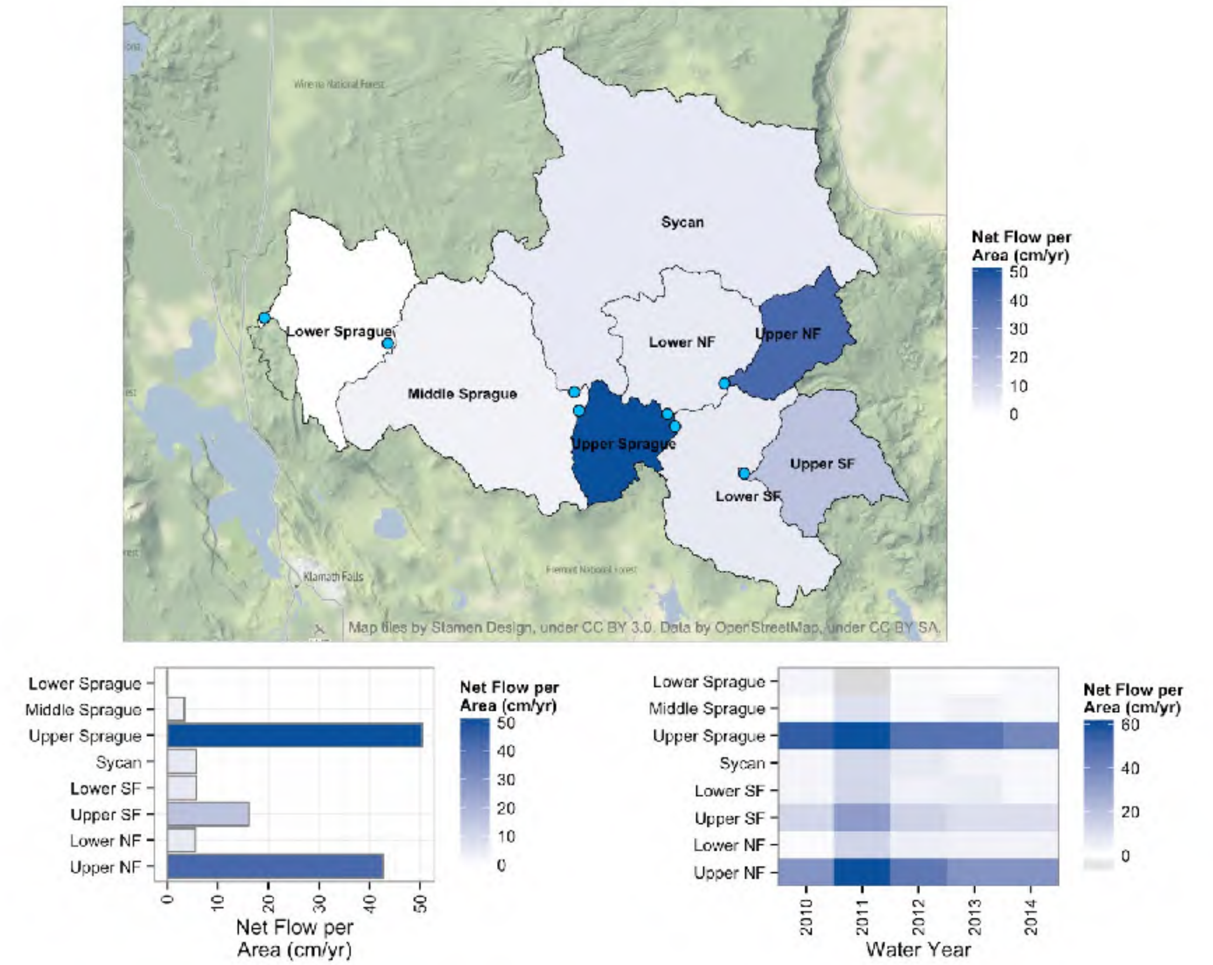


FIGURE 39: MAP OF NET CHANGE IN FLOW PER AREA BY INCREMENTAL SUB-BASIN, WY2010 – 2014

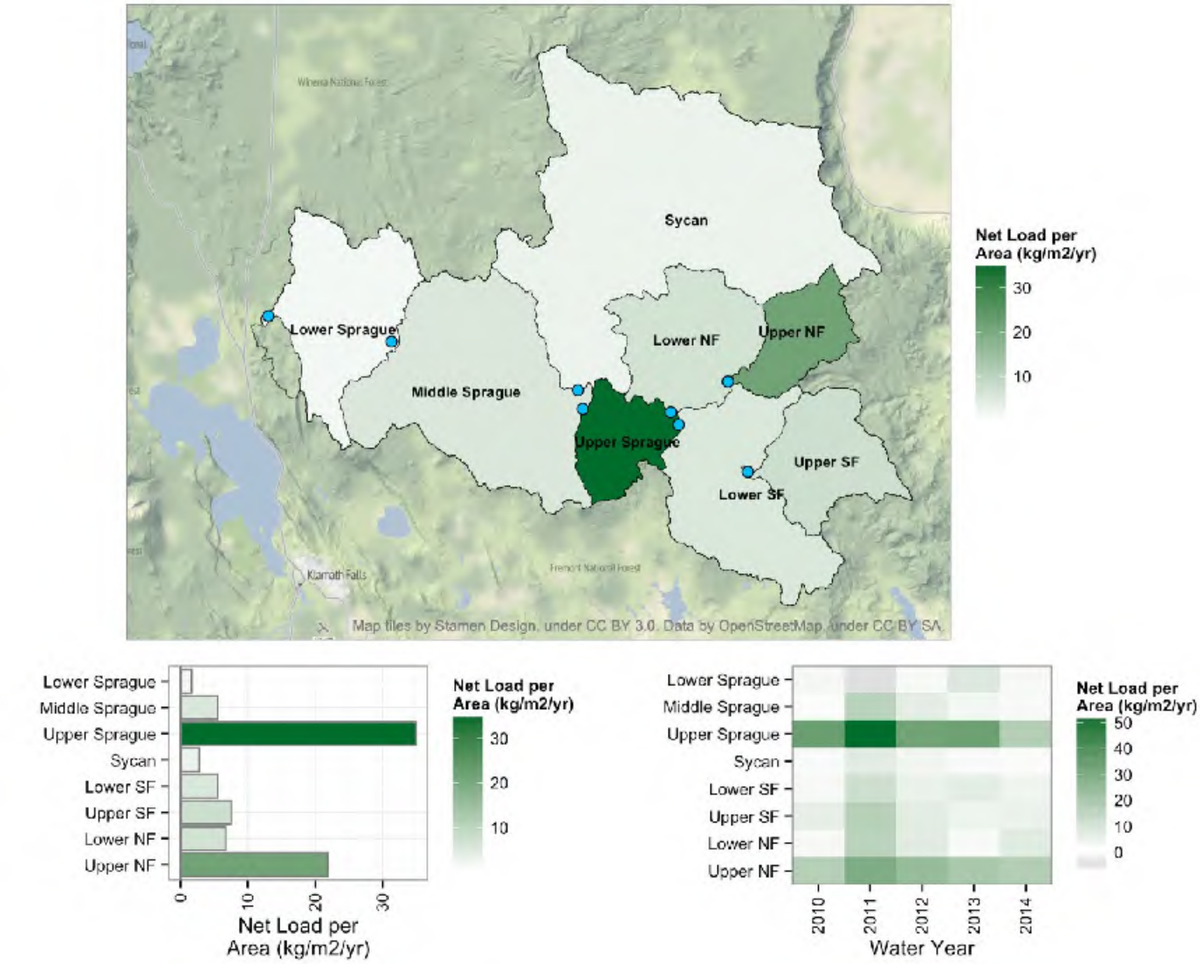


FIGURE 40: MAP OF NET CHANGE IN TP LOAD PER AREA BY INCREMENTAL SUB-BASIN, WY2010 – 2014

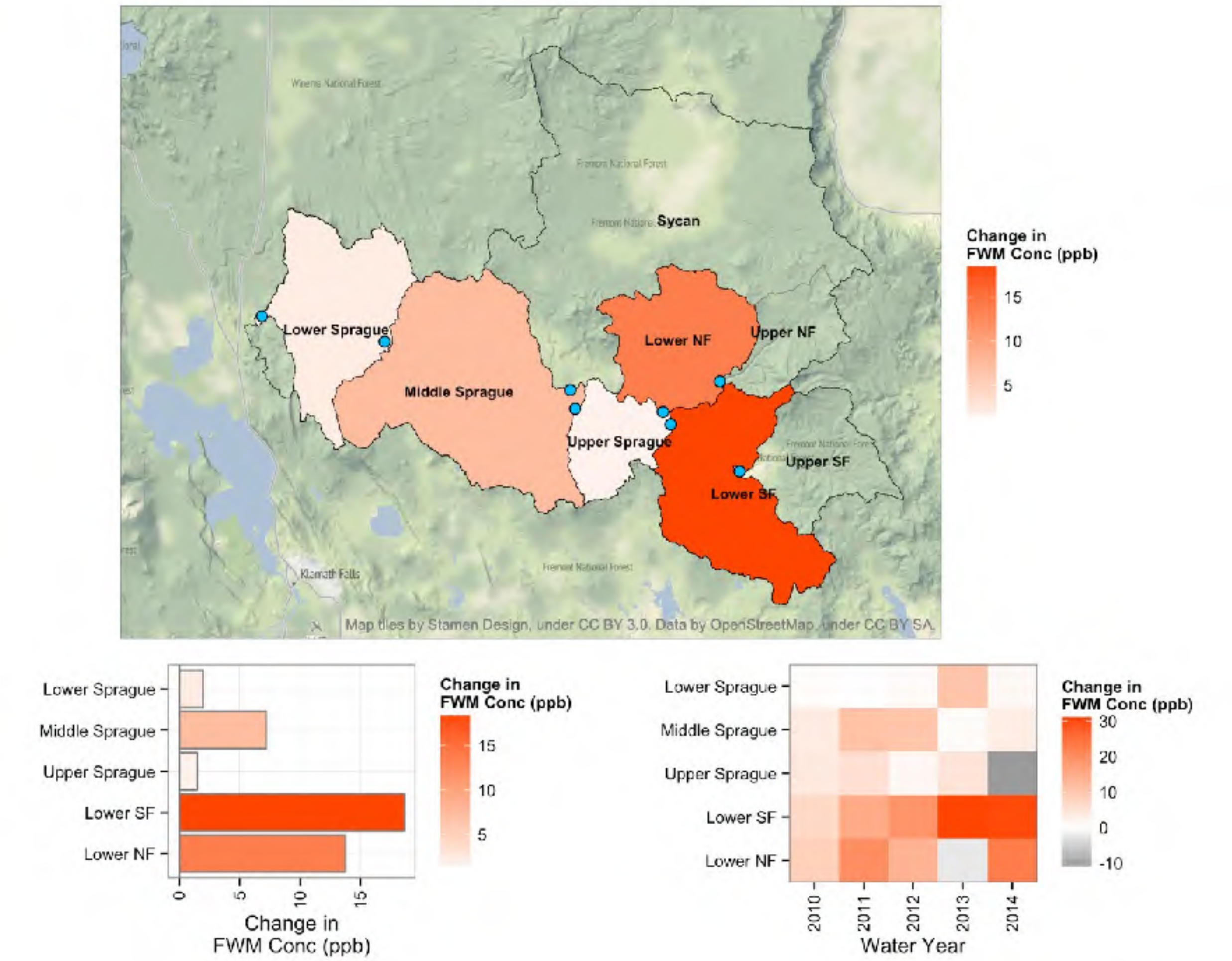


FIGURE 41: MAP OF NET CHANGE IN FWM TP CONCENTRATION BY INCREMENTAL SUB-BASIN, WY2010 – 2014

The incremental sub-basin map for the net change in TN load per unit area showed a somewhat similar pattern to the net change in TP unit area loading (Figure F4, Appendix F, p. 54) except for the Sycan which had proportionally larger unit area loading compared to TP, and the lower Sprague which showed a negative net change in TN unit area load. The change in FWM TN concentration was highest in Lower SF, followed by the Middle Sprague and Lower NF, and the low flow years of 2013 and 2014 showed highest change in FWM TN for the Lower SF (Figure F4, Appendix F. p. 55). Similar to FWM TN, the net change in FWM NH4 was also highest in the Lower SF, however, the next highest concentrations were found in the Lower NF and the Lower Sprague watershed areas (Figure F4, Appendix F, p. 57). As noted above in the discussion of the reach network plots, the net change in FWM NO23 was greatest in the Upper Sprague watershed area (Figure F4, Appendix F, p. 59)

4.6 RELATIONSHIPS BETWEEN CONCENTRATIONS AND LAND USE

Relationships between concentrations and land use composition were generated to investigate the effects of anthropogenic activities on water quality. It is important to note that these relationships are based on the in-stream water quality conditions, which reflect the cumulative effects of both sources (e.g., runoff, groundwater discharge, irrigation return flows) and sinks (e.g., settling, biological uptake) within each sub-basin. Although these relationships provide some indication of whether land use composition effects in-stream water quality, a more detailed nutrient budget that accounts for individual sources and sinks is recommended to accurately represent the effect of land use composition on loads to the river.

4.6.1 NLCD Land Use

Figure 42 shows the relationships between mean annual FWM concentration computed over WY2010 – 2014 and land use composition for each water quality parameter. Land use composition is represented by the fraction of total cumulative drainage area for each land use type (see Figure 10, above). The black lines in each panel show linear regression trend lines. Solid lines indicate a significant correlation using the Pearson correlation coefficient with $p \leq 0.10$; dashed lines indicate that the correlation is not significant with $p > 0.10$.

For the annual TP concentrations shown in the top row, there were significant positive correlations against both planted/cultivated and herbaceous, and a significant negative correlation against forest cover. PP concentrations had similar significant relationships, however, PO4 showed no significant relationships for any land use type. This suggests that land use has a greater effect on particulate phosphorus than on dissolved phosphorus likely due to channel modifications, destabilized riverbanks, and other anthropogenic changes along the river corridor. Among the different land use types, forest cover had significant negative correlations for all water quality parameters except PO4 and NO23. TN showed strong positive correlations with both barren and wetlands cover and NH4 showed positive relationships for planted/cultivated and herbaceous.

As mentioned above in Section 2.4.4, the NLCD dataset was found to have limitations in its classification of land use types and for differentiating between un-impacted vs human-impacted conditions. In particular, many areas known to be used for grazing were classified as wetlands, herbaceous or shrubland. Therefore, these results should be interpreted with caution and may not accurately reflect the effects of anthropogenic activities on in-stream water quality concentrations.

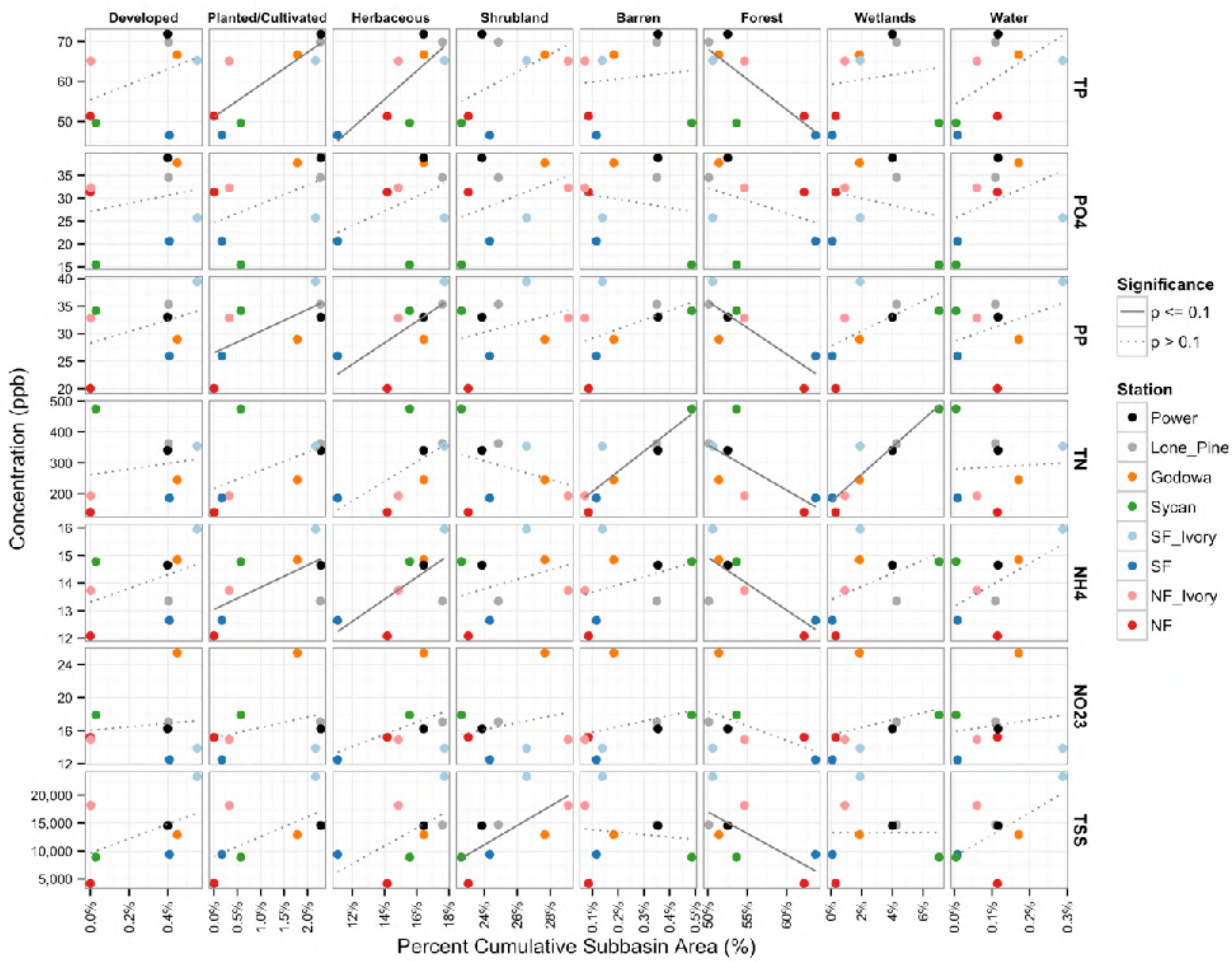


FIGURE 42: RELATIONSHIP BETWEEN ANNUAL FWM CONCENTRATION AND CUMULATIVE SUB-BASIN LAND USE COMPOSITION, WY2010 – 2014

4.6.2 IRRIGATION WATER RIGHTS PLACE OF USE (POU)

The OWRD water rights database was used as another data source for characterizing agricultural land use based on the Place of Use (POU) areas associated with irrigation surface water rights (see Section 2.4.5 above). Figure 43 shows the relationship between annual and seasonal FWM concentrations computed over WY2010 – 2014 versus the fraction of lower valley area used for irrigation (determined from POU area data; see Figure 12, above). The black lines in each panel show linear regression trend lines. Solid lines indicate a significant correlation using the Pearson correlation coefficient with $p <= 0.10$; dashed lines indicate that the correlation is not significant with $p > 0.10$.

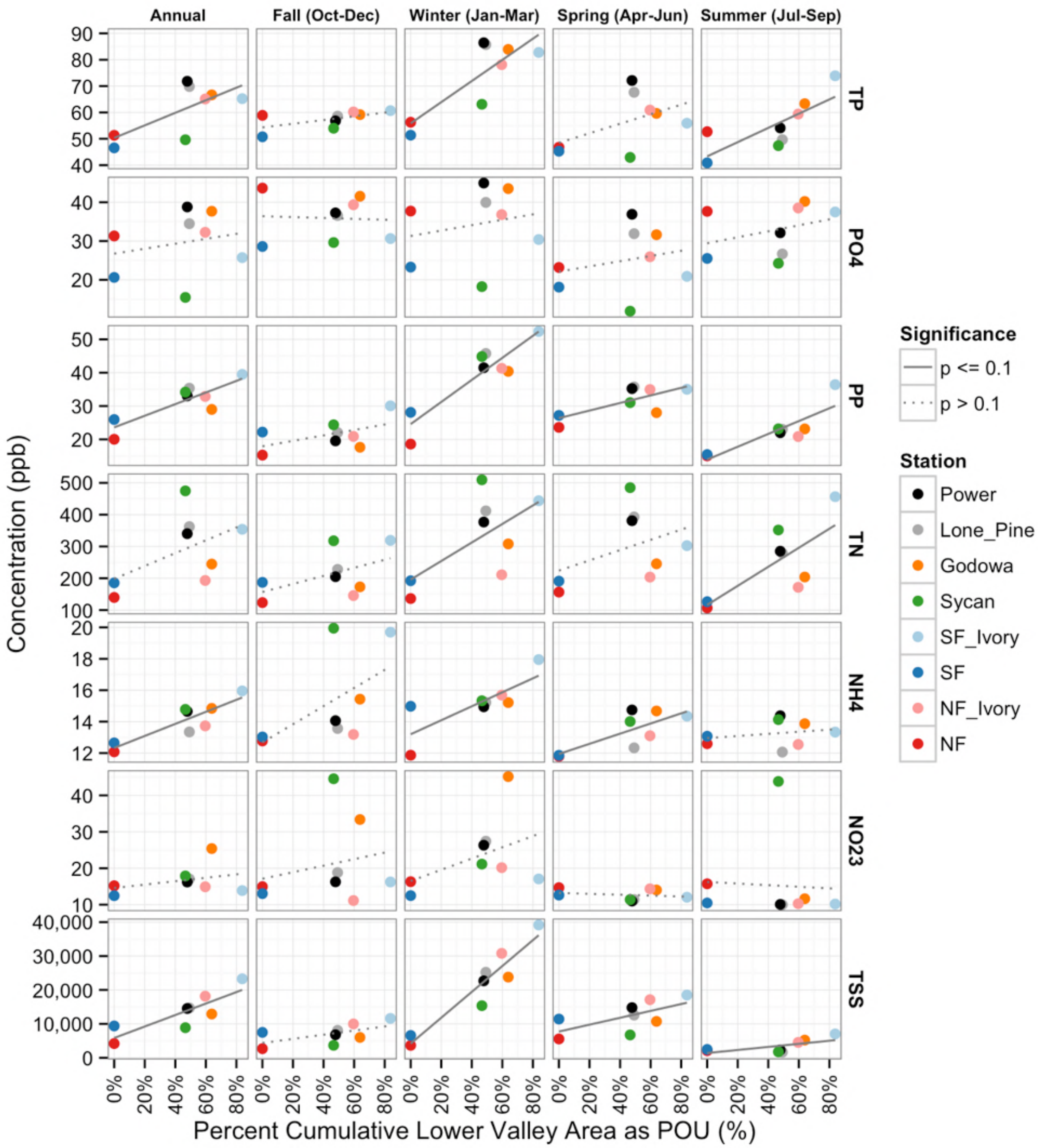


FIGURE 43: FWM CONCENTRATION VS PERCENT CUMULATIVE LOWER VALLEY AS POU IRRIGATION AREA, WY2010 – 2014

The panels in the top row of Figure 43 show significant positive relationships for annual, winter and summer mean TP concentration. In the fall season, there was little variability in TP concentrations among the stations resulting in no significant relationship against the fraction POU area. In the spring season, the relationship was not significant possibly due to a dilution effect from snowmelt, which comprises a larger portion of flows in the spring relative to other seasons.

For PO4, there were no significant relationships at the annual or any seasonal scale. This suggests that PO4 concentrations are driven by non-anthropogenic factors, most likely groundwater discharge which has a relatively high concentration of dissolved phosphorus (see Section 4.8.1 below).

Both PP and TSS concentrations showed strong positive correlations based on annual and seasonal means in all seasons except fall due to the low variability in concentrations across stations. These strong correlations suggest that increasing agricultural land use tends to increase the amount of erosion, which thus increases particulate and total phosphorus concentrations. Further discussion on erosion potential across the basin is provided in Section 4.7 below.

Among the nitrogen species, there were significant correlations for TN in winter and summer as well as annual and seasonal NH4 in winter and spring, but none for NO23.

4.7 Phosphorus, Sediment, and Nitrogen Dynamics with Respect to Flow and Season

4.7.1 Particulate Phosphorus and Sediment Dynamics

The river network plots of annual FWM concentrations in Figure 35 above showed large increases in both PP and TSS concentrations in the lower North and South Fork sub-basins between NF and NF_Ivory, and between SF and SF_Ivory in all seasons, but especially during winter and spring under high flow conditions. These increases suggest sediment transport from disturbed channel and floodplain areas may be a significant source of phosphorus in the lower reaches of the North and South Forks. To further explore whether sediment[29] input is a major contributor of phosphorus loads in the various sub-basins, the following section presents the relationships between flow, TSS, TP, and the percent of TP as particulate phosphorus (% particulate P). Note that the figures in this section are based on the sampled biweekly concentrations and not the computed daily concentrations.

Figure 44 shows the relationship between TSS concentration and flow at each station with each symbol colored by season. The black lines are locally weighted scatterplot smoothing (LOWESS) trends used to indicate the general shape of the relationships (Helsel and Hirsch, 2002). This figure shows positive relationships between TSS concentrations and flow at all stations, with lower TSS concentrations and lower flows during summer, and higher concentrations and flows in winter and spring. It also shows that SF_Ivory, NF_Ivory, and Godowa tended to have higher TSS concentrations under low flow conditions than at the other stations suggesting that stream banks may be more unstable and vulnerable to erosion than in other reaches, or that there are other sources of particulates in the lower North and South Forks and upper Sprague sub-basins possibly related to irrigation return flows during summer low flows[30]. There was also greater non-linearity in the relationships for the mainstem stations at Power, Lone_Pine, and Godowa with TSS concentrations decreasing at extreme high flows, which likely reflects floodplain deposition (e.g., settling of particulates as water distributes over the floodplain), possible dilution from snowmelt, or seasonal hysteresis whereby sediment transport occurs during early season flows but is then depleted during later season high flow events. TSS concentrations

[29] This does not include bedload sediment transport which was not measured as part of this study

[30] The increased TSS suggests a dominant fine-grained fraction since the flows are very low during these periods, inferring that the summer sediment sources are due to riparian grazing, channel straightening, and related incision (see Figure 1 for stream channel example in the lower South Fork).

in winter tended to be greater than those during spring under high flow conditions (the red symbols are generally above the smoother lines and the blue symbols are below) indicating that first-flush events in the winter transport proportionally greater suspended material. TSS at lower stations Power and Lone_Pine tended to show greater variability with flow in the winter, and increased scatter in the relationship at the Godowa site likely reflects the large groundwater influences there.

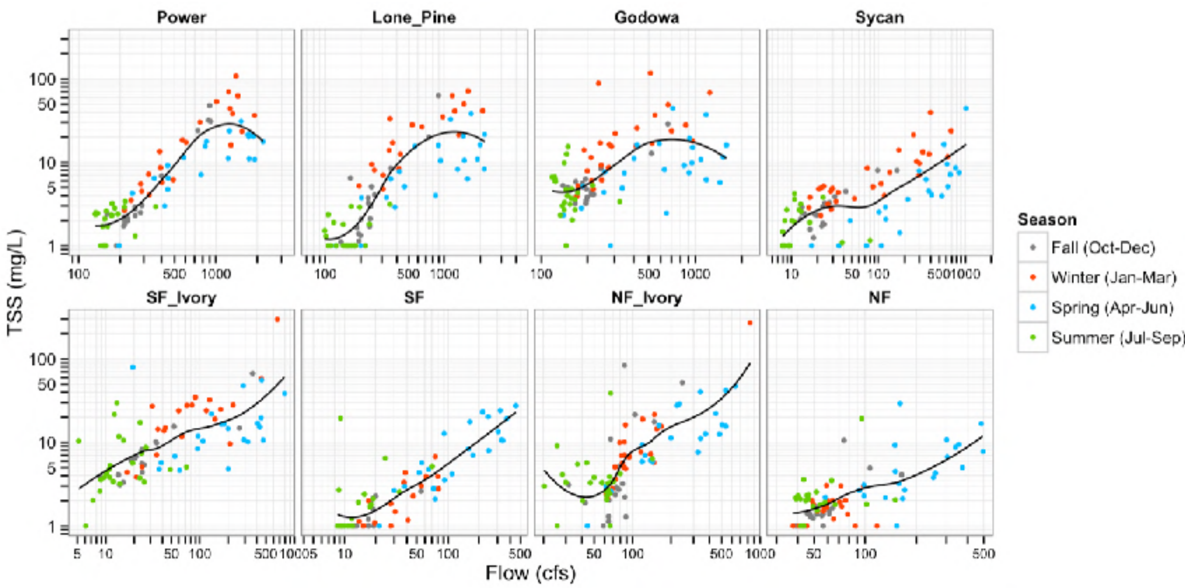


FIGURE 44: RELATIONSHIPS BETWEEN SAMPLED TSS CONCENTRATION AND FLOW

To explore the relationships between TSS and phosphorus, the percent particulate P (% PP) was computed by dividing the PP concentration (PP = TP - PO4) by the TP concentration. Figure 45 shows the distribution of % PP at each station. The highest % PP occurred at SF_Ivory with a median of 53%. The upper SF station, however, had a median of 31% indicating a significant increase in particulate phosphorus relative to dissolved phosphorus between these stations in the lower reach of the South Fork. Similarly, there was an increase in the median % PP in the lower North Fork reach from 20% at NF to 37% at NF_Ivory. The NF station had the lowest % PP indicating that dissolved phosphorus from groundwater is likely the primary source of phosphorus loading to the upper North Fork sub-basin.

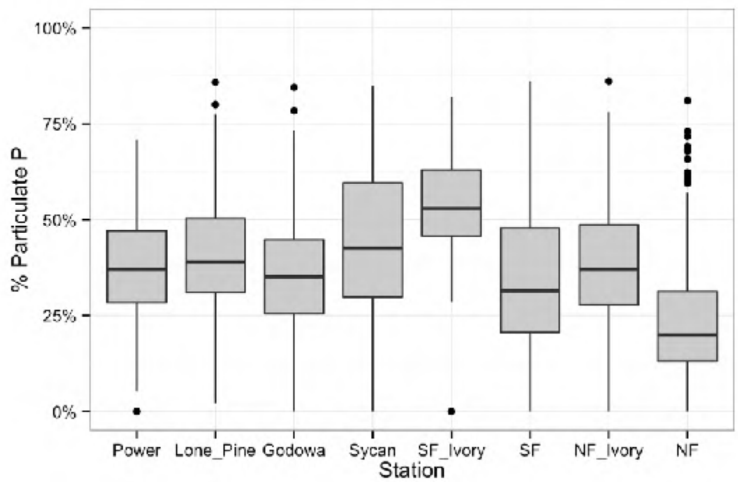


FIGURE 45: BOX PLOT DISTRIBUTIONS OF PERCENT PARTICULATE P BY STATION

Figure 46 shows the relationship between fraction particulate TP (% PP) and flow for each station with the symbols colored by season. The black lines again show LOWESS trends. The four stations in the North and South Forks (bottom row) all show relatively positive linear relationships between fraction particulate TP and flow. The other four stations (top row) show more non-linear relationships with the fraction particulate TP higher under lowest flows, decreasing under intermediate flows, and then increasing with flow before tending to level off and decline at highest flows. The relatively high % PP under low flows at these stations occurred primarily during summer and was likely caused by a combination of bio-uptake of dissolved phosphorus (PO4) during the summer growing season, sloughing of algal and macrophyte material, and increased particulate phosphorus loading through irrigation or other agricultural practices such as cattle access to degraded riparian areas (e.g., see inset photos in Figure 1). The relatively high fraction of particulate P under low flows at SF_Ivory compared to the other stations again suggests that even under low flows there is a major source of particulate phosphorus loading to the lower South Fork reach between SF and SF_Ivory. Declines in fraction particulate at intermediate flows (occurring in late-fall to early winter) indicate initial dilution prior to an increase in higher energy flows associated with increased particulate P occurring in the winter.

Periphyton/macrophyte mediated cycling among dissolved, particulate, organic and inorganic nutrient forms is a well documented phenomenon that influences temporal and longitudinal nutrient variation in river systems (e.g., Newbold et al. 1982; Mullholand et al. 1985; Anderson and Carpenter 1998).

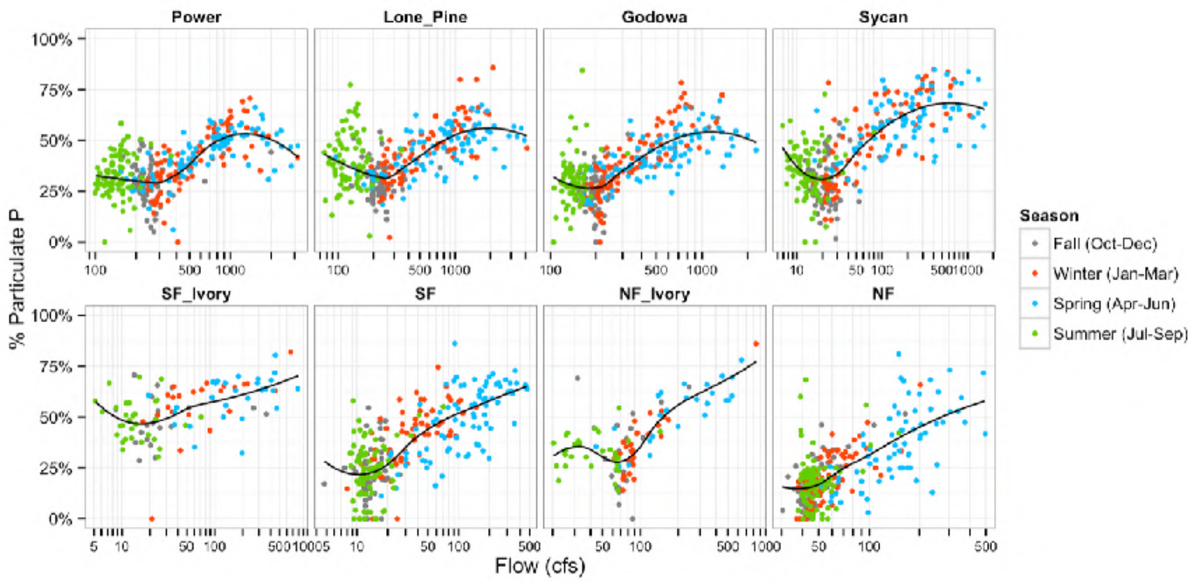


FIGURE 46: RELATIONSHIPS BETWEEN PERCENT PARTICULATE P AND FLOW

Figure 47 shows the relationships between TP and TSS concentrations, and Figure 48 shows the relationships between fraction particulate TP and TSS. Both TP concentrations and the fraction particulate TP (PP/TP) show positive relationships with TSS further confirming that erosion is a major source of TP in the Sprague system. These results are consistent with O'Connor et al (2013), who in a review of the GMA (2007) sediment transport study, observed that significant sediment entrainment in the South Fork valley segment likely resulted from channel and bank erosion, including additional sources of sediment from eroding bank crevasses or cuts which facilitate conveyance of sediment entrained from flood-plain surfaces and irrigation channels.

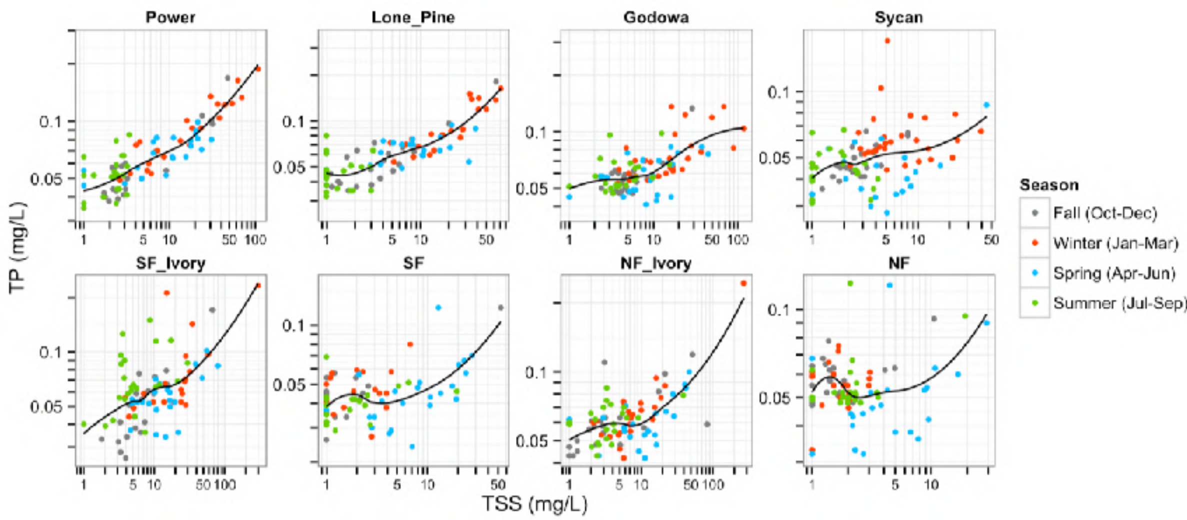


FIGURE 47: RELATIONSHIPS BETWEEN TP AND TSS CONCENTRATIONS

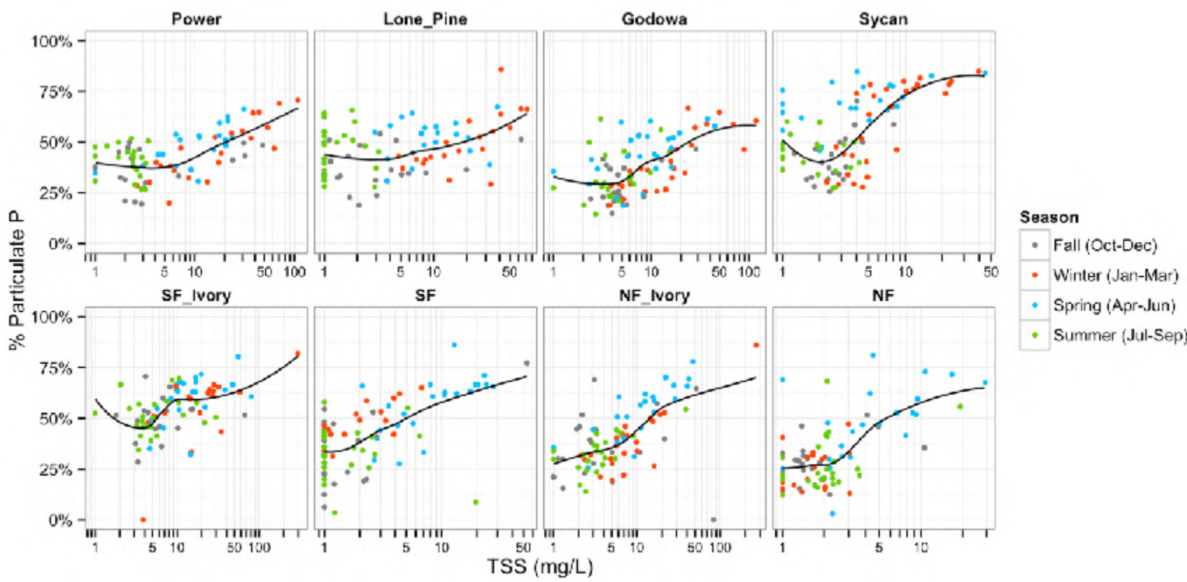


FIGURE 48: RELATIONSHIPS BETWEEN PERCENT PARTICULATE P AND TSS CONCENTRATIONS

Finally, Figure 49 shows the relationships between particulate P concentrations and TSS, and Figure 50 shows particulate P versus flow. Again, all stations show positive relationships between particulate P and both TSS and flow, as expected. Similar to the relationships between TSS and flow shown in Figure 44, Figure 50 shows that under high flows, particulate P concentrations tended to be higher in winter than in spring at most stations.

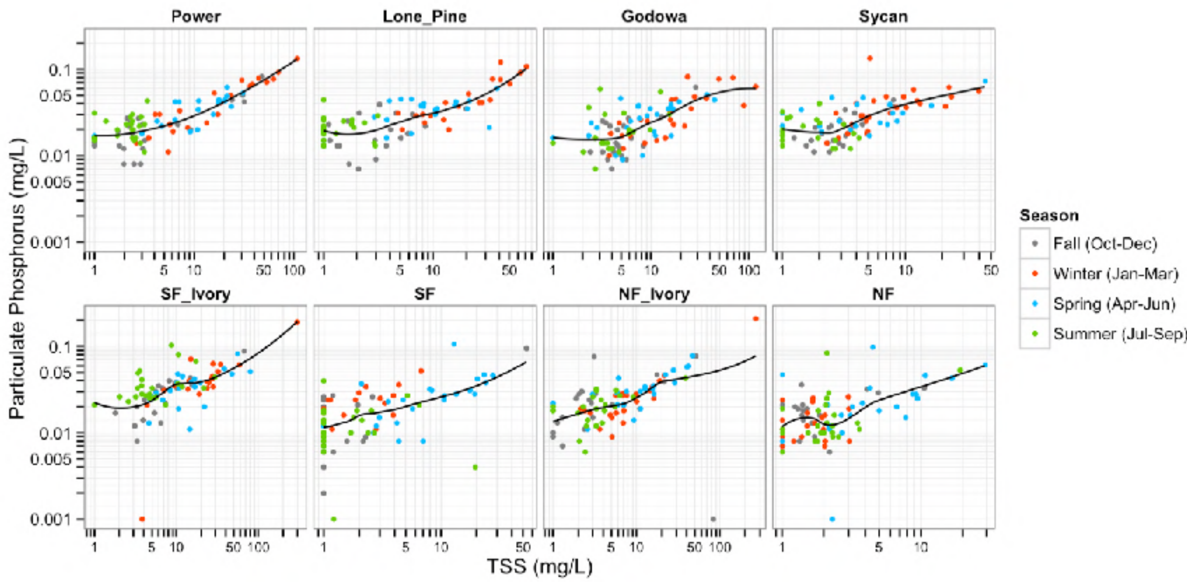


FIGURE 49: RELATIONSHIPS BETWEEN PARTICULATE PHOSPHORUS AND TSS CONCENTRATIONS

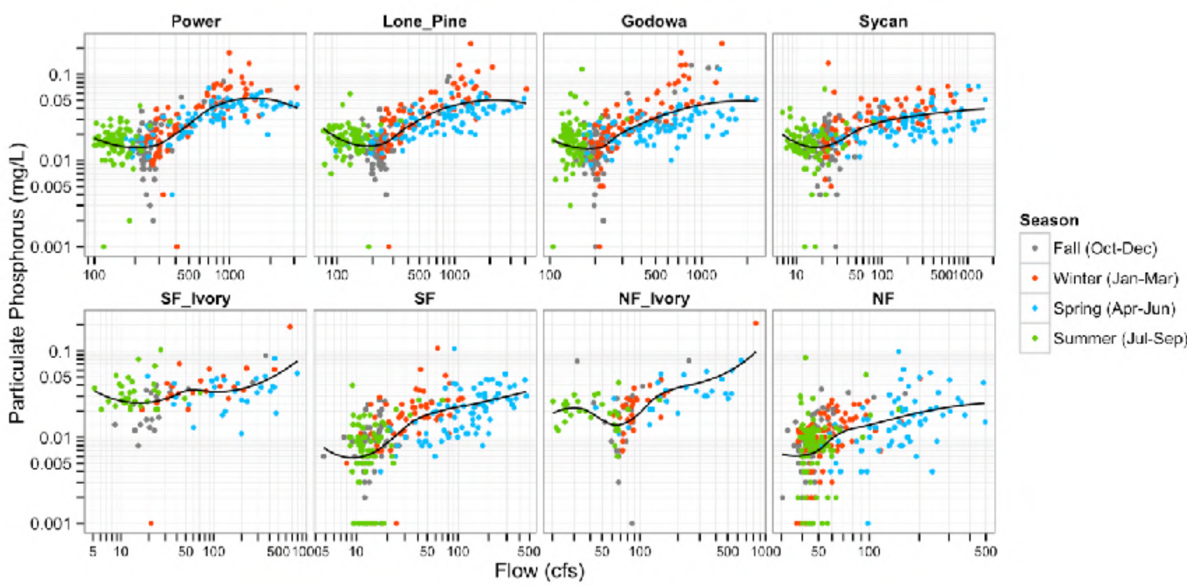


FIGURE 50: RELATIONSHIPS BETWEEN PARTICULATE PHOSPHORUS CONCENTRATION AND FLOW

4.7.2 NITROGEN DYNAMICS

Similar plots were created for comparing various nitrogen parameters to flow and TSS at each station (including symbols colored by season and a LOWESS trend line). TN concentration was non-linearly related to flow at most stations, with relatively high values occurring during the summer low flow period, declining values in the fall and increasing values as flow increased in the winter and spring (Figure 51). As with the phosphorus parameters, TN values tended to be higher in the winter than the spring during higher flows (Figure 51; blue symbols below the smoother, red symbols above), and similar to PP, TN values tended to level off or decline at the very highest flows. At several stations (Power, Lone_Pine, SF_Ivory and NF_Ivory) the low flow summer TN values were among the highest for any season and flow, and higher summer flows tended to be associated with lower TN concentration at Power, Lone_Pine, and NF_Ivory.

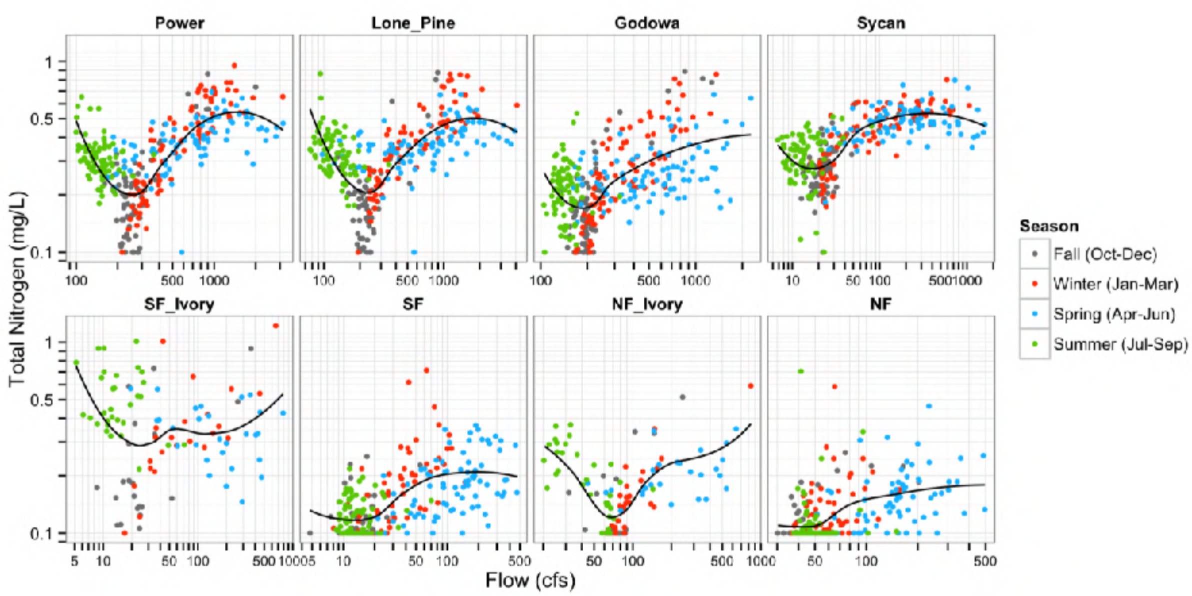


FIGURE 51: RELATIONSHIPS BETWEEN TOTAL NITROGEN CONCENTRATION AND FLOW

With the exception of the Sycan and Godowa stations for NO23, NH4 and NO23 showed only slight relationships with flow compared to those for TN (Figure 52 and Figure 53). In most cases, summer NH4 values were as high as other seasons and the LOWESS trend line was relatively flat with only a slight increase at the highest flows for the Sprague mainstem stations (Figure 52). In contrast, summer NO23 values tended to be lowest in summer for all stations except the Sycan and NF stations (Figure 53). The Sycan was unique in that NO23 showed a strong negative relationship with flow, with summer and fall values highest and winter-spring high flow values lowest. Aldous (2009) also noted that NO23 loads increased between the outlet of Sycan Marsh and the confluence with the Sprague River but was unsure of the NO23 source. Since flows from the Sycan marsh upstream abate between mid-June and the end of October, fall/winter concentrations and load are driven by outflow from the marsh, but summer values are driven by the watershed below the marsh outfall, including spring inflow (e.g., Torrent Springs), tributaries, and agricultural activities.

The NF NO23 values were high in summer, fall, and winter and generally leveled off or declined during the spring. The pattern at Godowa was also unique in that NO23 values increased with flow in the summer through early winter and then leveled off and declined in late winter and spring as flows increased further, although the cause of these dynamics is not clear. Low summer values at Power, Lone_Pine, SF_Ivory, NF_Ivory, and SF likely reflect uptake by attached algae and macrophytes, dilution from spring inflow, and possible denitrification.

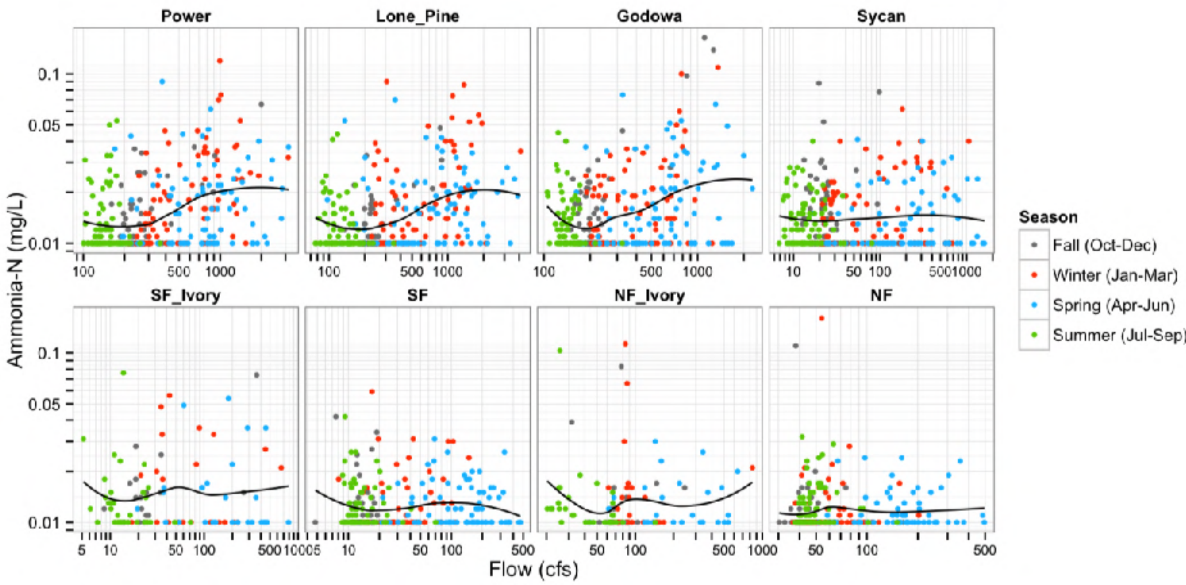


FIGURE 52: RELATIONSHIPS BETWEEN AMMONIA-N CONCENTRATION AND FLOW

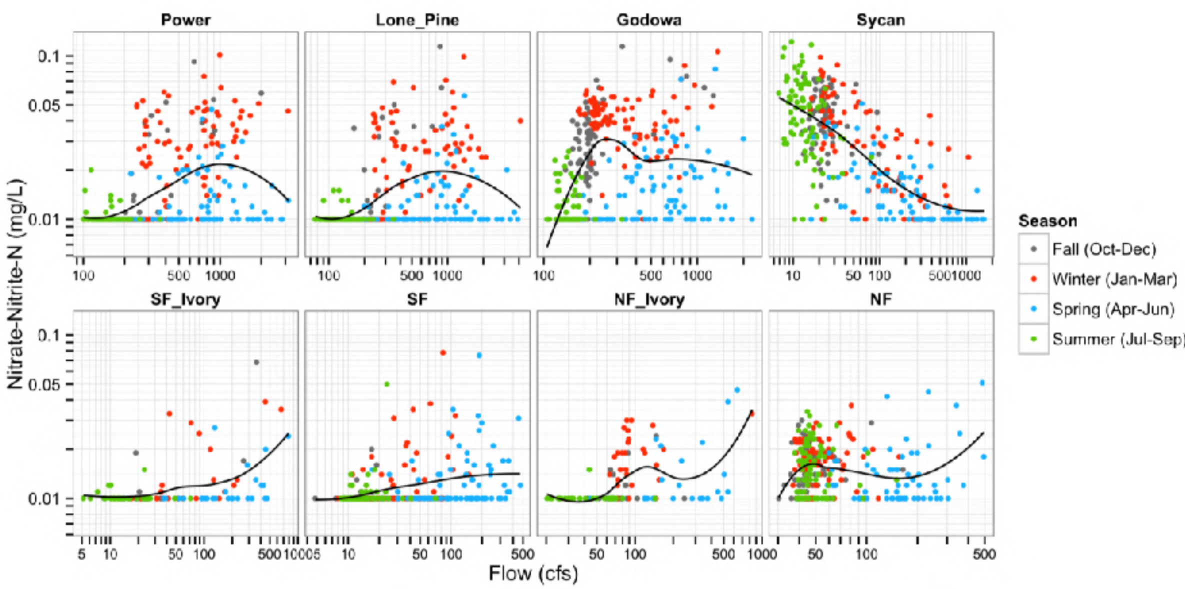


FIGURE 53: RELATIONSHIPS BETWEEN NITRATE-NITRITE-N CONCENTRATION AND FLOW

As expected given the generally low NH4 and NO23 concentrations, the pattern in organic-N (computed as TN minus the sum of NH4 and NO23) was similar to that for TN on a seasonal basis (Figure 54). The ratio of organic to inorganic-N generally followed the organic-N pattern (higher during summer low flow values, declining at intermediate flows in summer and fall, and increasing again in the winter and spring; Figure 55). One exception was for the Sycan which showed low summer-fall ratios due to the relatively high NO23 values occurring at that time, before increasing as flows from the Sycan marsh commence in the late fall (Figure 55). In addition, ratio values at Godowa tended to be lower than those for Power and Lone-Pine overall (Figure 55), and the percent organic-N declined sharply at Godowa (data not shown) during the fall/early-winter period that coincided with an NO23 increase.

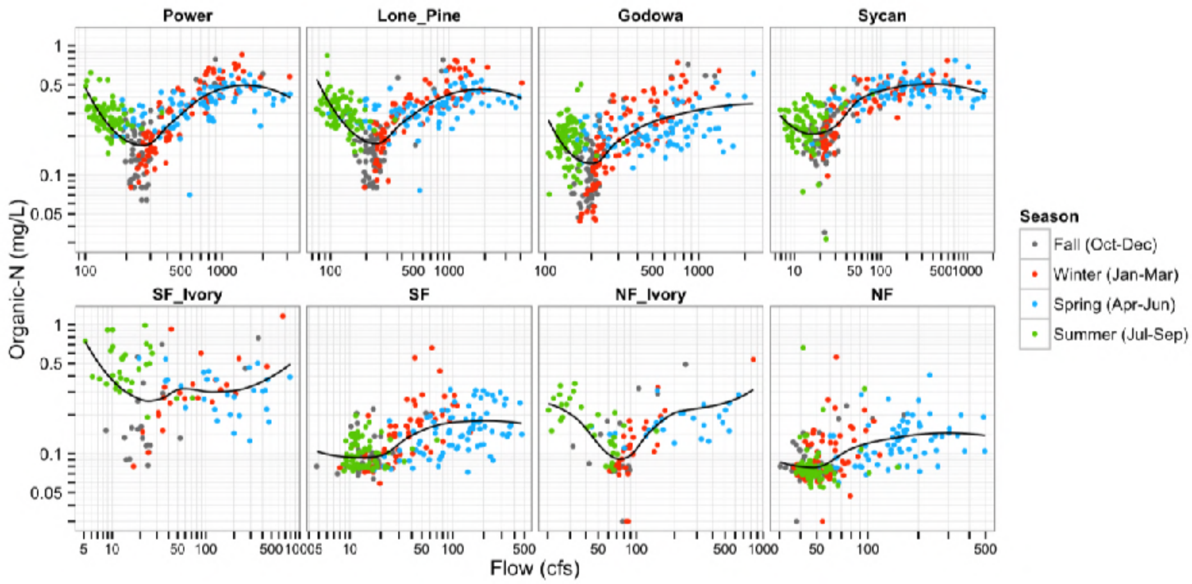


FIGURE 54: RELATIONSHIPS BETWEEN ORGANIC-N CONCENTRATION AND FLOW

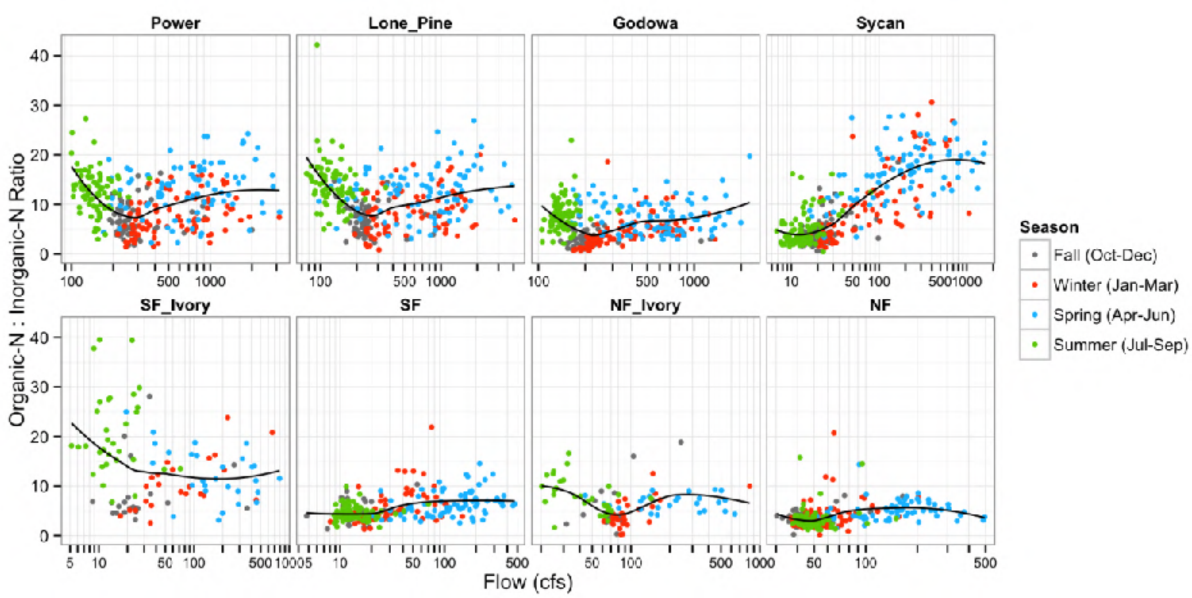


FIGURE 55: RELATIONSHIPS BETWEEN ORGANIC-N TO INORGANIC-N RATIO AND FLOW

TN and organic-N (not shown since patterns were identical to TN) concentrations generally remained constant over a range of TSS concentrations during summer and fall low flow periods before increasing during winter and spring increases in TSS at most stations (Figure 56). One exception was for the SF_Ivory station which showed higher TN and organic-N values during the summer season and summer values were higher than fall-winter even at similar TSS concentrations (Figure 56). Unlike % PP which increased with increasing TSS (Figure 48) percent organic-N remained relatively constant with increasing TSS in most cases indicating a decoupling between the fractionation of organic- vs. inorganic-N and TSS (Figure 57).

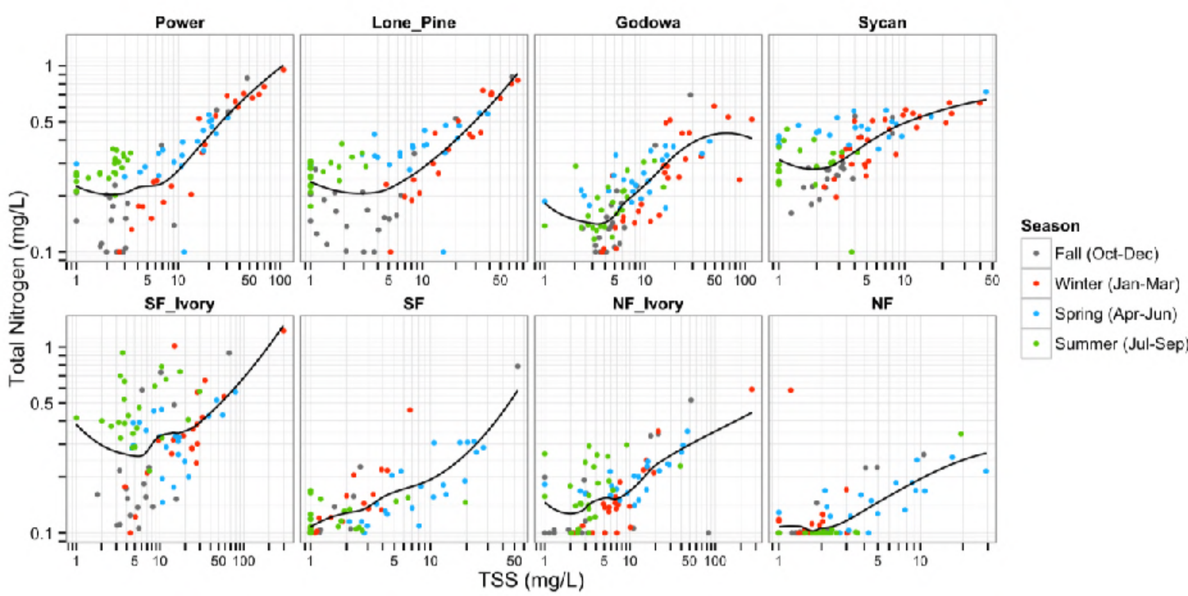


FIGURE 56: RELATIONSHIPS BETWEEN TOTAL NITROGEN AND TSS CONCENTRATIONS

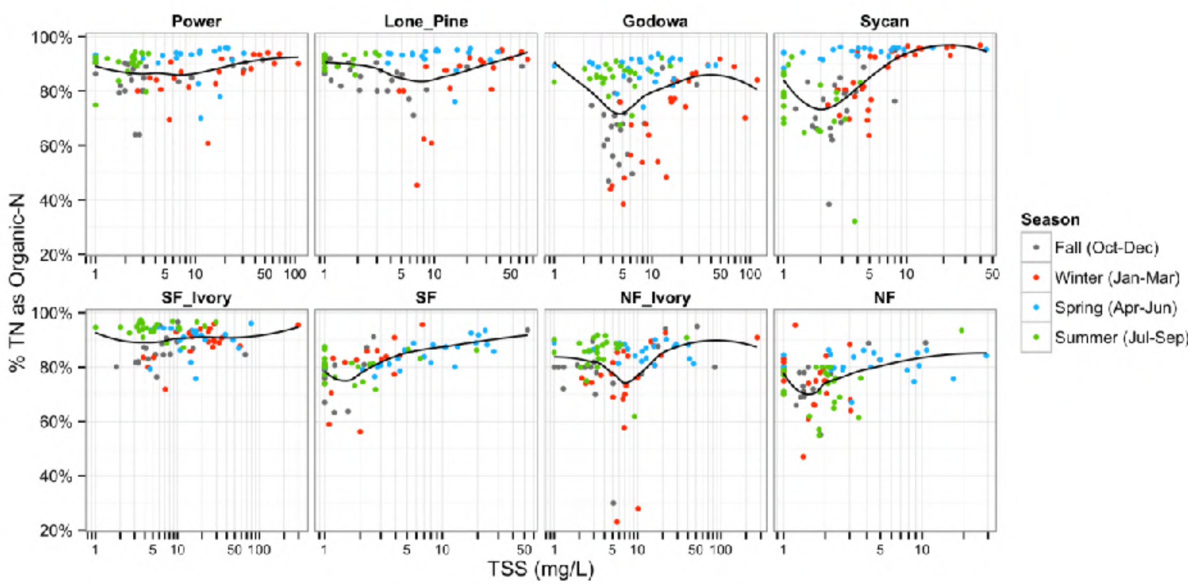


FIGURE 57: RELATIONSHIPS BETWEEN PERCENT ORGANIC-N AND TSS CONCENTRATION

4.8 Background vs Anthropogenic Loading

As one of the study objectives, the water quality results were used to refine estimates of background TP loading from areas with minimal anthropogenic impacts, and to estimate the relative contributions of anthropogenic activities to the total TP loading in the Sprague River system. Walker et al. (2012) performed a similar analysis of background and anthropogenic loading for the entire Upper Klamath Lake basin. In that study, we used a background TP concentration of 65 ppb and estimated that 31% of the total loads to UKL were associated with anthropogenic activities over the period WY2008 – 2010 (see Table 4 of that report). However, we also noted that within the Sprague River Basin, the two relatively un-impacted sub-basins in the upper South and North Forks had observed FWM concentrations lower than the basin-wide background concentration (46.6 and 51.3 ppb, respectively, over WY2010 – 2014 based on the results of this study, see Table 9). These lower concentrations suggested that background concentrations may be lower within the Sprague River system relative to other basins draining to Upper Klamath Lake. The methodology of Walker et al. (2012) was therefore modified to better reflect the lower concentrations observed in the relatively un-impacted upper South and North Forks.

For this study, background loading was divided into two components: 1) groundwater discharge from seeps and springs, and 2) runoff due to snowmelt, rainfall, and any other non-groundwater inputs. These two components will be referred to as "groundwater" and "runoff" in this report, although it is important to note that the latter includes all inputs not accounted for by the groundwater discharge estimates.

Using the estimates of groundwater discharge from Gannett et al. (2007) (see Section 4.2.4) the total flow at each station was partitioned into the separate groundwater and runoff components. The background concentration associated with groundwater discharge was estimated based on direct measurements collected from springs and creeks by the Klamath Tribes. The background concentration for runoff was then calculated from the total loads (L_{Total} as calculated and described above in Section 3.2.1) and FWM concentrations from the relatively un-impacted sub-basins (upper North Fork, upper South Fork). The difference between the total loads at each station and the total background loads, which includes both groundwater and runoff, were then computed to represent anthropogenic loads. These calculations are represented by the following equations:

$$L_{GW} = Q_{GW}C_{GW}$$
$$L_{Runoff} = (Q_{Total} - Q_{GW})C_{Runoff}$$
$$L_{Background} = L_{GW} + L_{Runoff}$$
$$L_{Anthropogenic} = L_{Total} - L_{Background}$$
$$C_{Anthropogenic} = \frac{L_{Anthropogenic}}{Q_{Total}}$$

Note that the concentration associated with anthropogenic loading represents the *increase* from background levels to the total observed concentration as opposed to the concentration associated with discharges originating from anthropogenic sources (e.g., irrigation return flows).

4.8.1 BACKGROUND CONCENTRATION FOR GROUNDWATER

The background concentration associated with groundwater discharge was estimated using water quality data collected by Klamath Tribes as part of a synoptic sampling program in the Sprague River Basin. The synoptic samples were collected on springs and creeks at locations that are not part of the routine biweekly sampling program. Because these samples were collected at different times of the year and with varying frequency, annual FWM concentrations could not be directly calculated as was done for the routine sampling locations. However, the synoptic data were primarily collected from groundwater-fed springs and thus expected to have relatively constant concentrations over time. The locations of the synoptic samples are shown in Figure 58. Figure 59 shows the sampled TP concentrations as well as the median of each location.

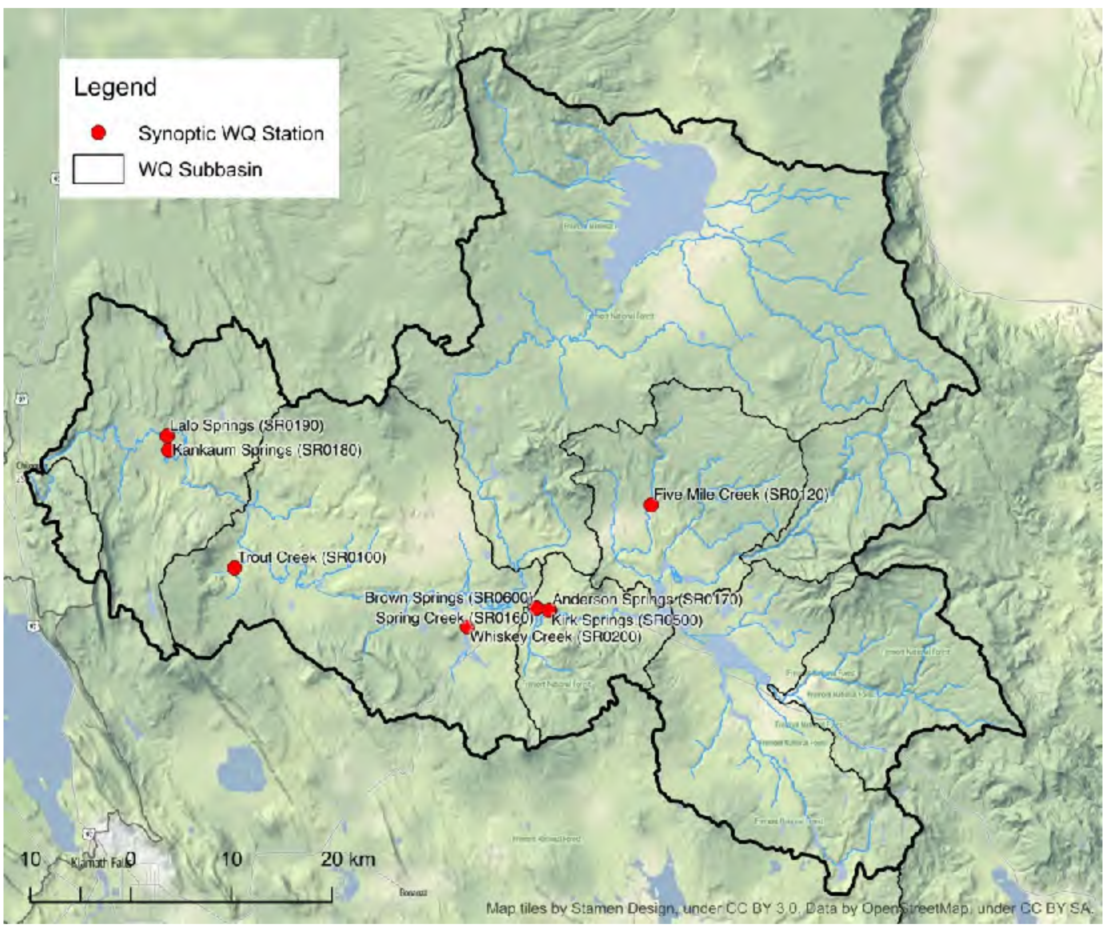


FIGURE 58: MAP OF SYNOPTIC WATER QUALITY STATIONS

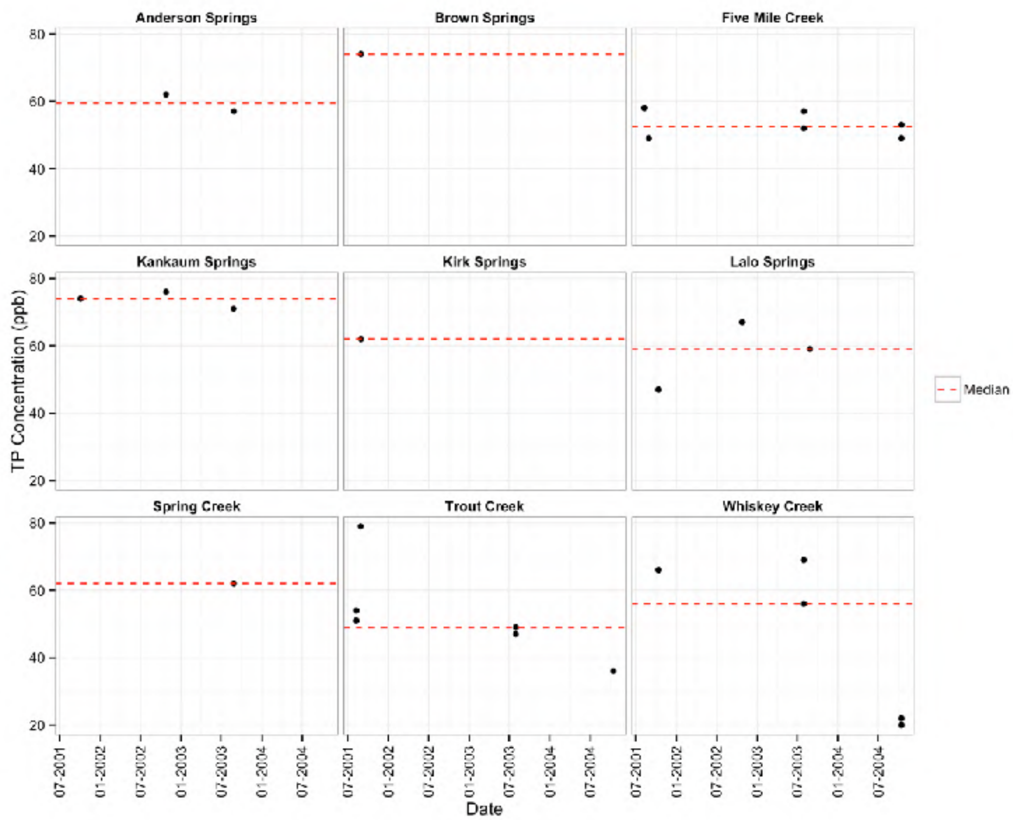


FIGURE 59: TP CONCENTRATIONS FROM SYNOPTIC DATASET OF SPRINGS AND CREEKS

The median TP concentration and number of samples for each station are listed in Table 10. At three of the stations, only one sample was collected, which was assumed to be representative of the median value for that location. Some sites, notably Trout Creek and Whiskey Creek, exhibit greater temporal variability relative to the other sites. The overall median TP concentration across the stations was 60 ppb, which is 5 ppb less than the background concentration of 65 ppb used in Walker et al. (2012). A concentration of 60 ppb was therefore used as the background concentration associated with groundwater discharge.

TABLE 10: MEDIAN TP CONCENTRATIONS OF SYNOPTIC SPRING AND CREEK SAMPLES

Station ID	Description	Median TP (ppb)	Number of Samples
SR0100	Trout Creek	49	7
SR0120	Five Mile Creek	53	6
SR0160	Spring Creek	62	1
SR0170	Anderson Springs	60	2
SR0180	Kankaum Springs	74	3
SR0190	Lalo Springs	59	3
SR0200	Whiskey Creek	56	5
SR0500	Kirk Springs	62	1
SR0600	Brown Springs	74	1
	Overall Median:	**60**	

Although NRCS (2009) reported considerably higher TP concentrations (>200 ppb) in shallow ground water based on direct measurements using shallow piezometers and direct sampling of seeps in the lower Sprague River, these extremely high concentrations are unlikely to accurately reflect background concentrations for groundwater discharge, but are likely to reflect the effect of agricultural activities, such as manure from cattle grazing and irrigation seepage. Furthermore, shallow groundwater is unlikely to be transported directly to receiving waters in large volumes. If water with sufficient volume and such high concentration were reaching the Sprague River, this would be reflected in large increases in TP concentrations and loads, which are not evident in the results of this study. The shallow ground water measurements referenced by NRCS (2009) were taken in the lower Sprague River reaches and these reaches showed almost no increase in concentration (e.g., see Figure 39). Therefore, high TP groundwater sources with sufficient flow reaching the river channel are not reflected by the data, and thus a background concentration associated with groundwater discharge of 60 ppb is assumed to be more accurate based on the direct measurements from relatively high volume springs as determined from the Klamath Tribes' synoptic sampling program.

4.8.2 BACKGROUND CONCENTRATION FOR RUNOFF

Using the background TP concentration of 60 ppb and the estimates of groundwater discharge from Gannett et al. (2007), the concentration associated with runoff and other non-groundwater sources that are unaffected by land use alterations or other human activities was estimated from the observed mean annual FWM concentrations for the relatively un-impacted NF and SF stations in the upper North and South Fork sub-basins. For each of these stations, the runoff concentration was computed by the equation:

$$C_{Runoff} = \frac{L_{Runoff}}{Q_{Runoff}} = \frac{L_{Total} - Q_{GW}C_{GW}}{Q_{Total} - Q_{GW}}$$

Table 11 lists each of these terms for the NF and SF sub-basins. The total flows and loads are based on the annual means computed over the 5-year period WY2010 – 2014, which were listed in Table 8 above.

TABLE 11: BACKGROUND TP CONCENTRATION ASSOCIATED WITH GROUNDWATER AND RUNOFF IN UN-IMPACTED SUB-BASINS

	Total			Groundwater			Runoff		
Station	Flow (hm3/yr)	Load (mt/yr)	Conc (ppb)	Flow (hm3/yr)	Load (mt/yr)	Conc (ppb)	Flow (hm3/yr)	Load (mt/yr)	Conc (ppb)
SF	45.1	2.10	46.6	21.5	1.29	60.0	23.7	0.81	**34.4**
NF	79.7	4.09	51.3	52.8	3.17	60.0	26.9	0.92	**34.3**

Note: calculations were performed prior to rounding and are thus slightly different from results computed using rounded values

The estimated TP concentrations associated with runoff for SF and NF were thus 34.4 and 34.3 ppb, respectively. Based on the flow-weighted mean of these two concentrations, the background concentration for runoff across the entire Sprague River Basin was set to 34.4 ppb.

4.8.3 ANTHROPOGENIC AND BACKGROUND TP LOADS AND CONCENTRATIONS

Using background TP concentrations of 60 and 34.4 ppb for groundwater and background runoff, respectively, the total background and remaining anthropogenic loads were computed for each station based on the total mean annual flows and loads over WY2010 – 2014. Table 12 lists the flow, load, and FWM concentration for each component and water quality station. In order to determine the portions of the total *loads* and *concentrations* associated with background and anthropogenic sources, the flows for the Total Background and Anthropogenic components were set to the Total flow at each station. As noted above, the concentration associated with anthropogenic loading represents the *increase* in concentration above the total background level due to anthropogenic activities. Table 13 lists the percent of the total TP load associated with each component. The TP loads associated with each component are shown in Figure 60 and the fractions of the total TP load associated with each component are shown in Figure 61 for each station.

TABLE 12: BACKGROUND AND ANTHROPOGENIC TP LOADS AND CONCENTRATIONS, WY2010 – 2014

	Total			Background as GW			Background as Runoff			Total Background			Anthropogenic		
Station	Q	L	C	Q	L	C	Q	L	C	Q	L	C	Q	L	C
Power	371.5	26.7	71.8	301.4	18.1	60.0	70.1	2.4	34.4	371.5	20.5	55.2	371.5	6.2	16.7
Lone_Pine	371.8	26.0	69.8	236.1	14.2	60.0	135.7	4.7	34.4	371.8	18.8	50.6	371.8	7.1	19.2
Godowa	262.9	17.5	66.7	199.4	12.0	60.0	63.5	2.2	34.4	262.9	14.1	53.8	262.9	3.4	12.8
Sycan	82.4	4.1	49.6	18.8	1.1	60.0	63.7	2.2	34.4	82.4	3.3	40.2	82.4	0.8	9.5
SF_Ivory	72.4	4.7	65.2	33.1	2.0	60.0	39.3	1.4	34.4	72.4	3.3	46.1	72.4	1.4	19.1
SF	45.1	2.1	46.6	21.5	1.3	60.0	23.7	0.8	34.4	45.1	2.1	46.6	45.1	0.0	0.0
NF_Ivory	98.9	6.4	65.1	82.3	4.9	60.0	16.6	0.6	34.4	98.9	5.5	55.7	98.9	0.9	9.4
NF	79.7	4.1	51.3	52.8	3.2	60.0	26.9	0.9	34.4	79.7	4.1	51.3	79.7	0.0	0.0

Q = Flow (hm3/yr), L = TP Load (mt/yr), C = FWM TP Concentration (ppb)
Note: calculations were performed prior to rounding and are thus slightly different from results computed using rounded values

TABLE 13: PERCENT OF TOTAL TP LOAD AS BACKGROUND AND ANTHROPOGENIC, WY2010 – 2014

Station	% Total TP Load as: Groundwater Background	Runoff Background	Total Background	Anthropogenic
Power	68%	9%	77%	23%
Lone_Pine	55%	18%	73%	27%
Godowa	68%	12%	81%	19%
Sycan	28%	53%	81%	19%
SF_Ivory	42%	29%	71%	29%
SF	61%	39%	100%	0%
NF_Ivory	77%	9%	86%	14%
NF	77%	23%	100%	0%

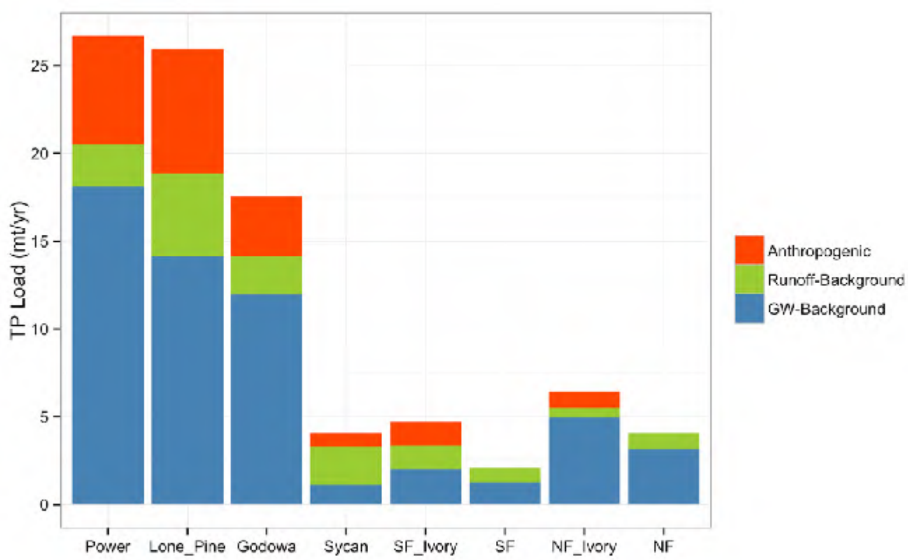


FIGURE 60: BACKGROUND AND ANTHROPOGENIC TP LOADS, WY2010 – 2014

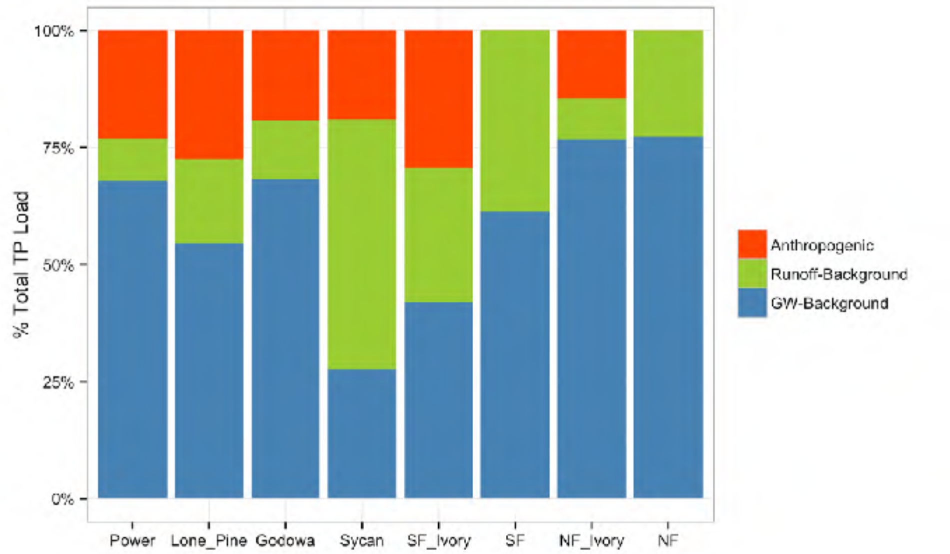


FIGURE 61: FRACTIONS OF TOTAL TP LOAD AS BACKGROUND AND ANTHROPOGENIC, WY2010 – 2014

As shown in Table 12, total background concentrations ranged from 40.2 ppb in the Sycan River to a maximum of 55.7 ppb at the NF_Ivory station in the lower North Fork. The differences in total background concentrations reflect the relative fractions of total flow associated with groundwater versus runoff. At stations where groundwater comprises a greater fraction of total flow, the total background concentrations are greater due to the higher background concentration in groundwater relative to runoff. The increase in TP concentration associated with anthropogenic activities among the impacted stations[31] ranged from 9.4 ppb at NF_Ivory to 19.2 ppb at Lone_Pine. At the Power station near the outlet of the Sprague River, the total background concentration was 55.2 ppb, which is increased by 16.7 ppb due to anthropogenic activity to yield an overall concentration of 71.8 ppb.

Table 13 and Figure 61 show that the fraction of the total TP load as anthropogenic ranges from a minimum of 14% at NF_Ivory to a maximum of 29% at SF_Ivory among the impacted stations[27]. At the Power station near the Sprague River outlet, anthropogenic loads account for 23% of the total TP load.

For comparison, Walker et al. (2012) previously reported that for the total TP loading from all basins and sources to UKL[32], anthropogenic loads accounted for 31% over the period WY2008 – 2010, and 37% over the entire period used in that study, WY1992 – 2010 (see Tables 4 and 3 of that report). Although basin-specific estimates of anthropogenic loading were not provided in that report, using the same methodology with a background TP concentration of 65 ppb and an overall observed concentration at

[31] Excluding the un-impacted upper SF and NF stations, which were used as the basis to estimate background concentrations and thus had no anthropogenic loading

[32] This estimate includes discharge from the Williamson River and Wood River Basins, other ungauged basins, as well as discharge pumped directly from agricultural areas along the edge of UKL

the Power station of 71.8 ppb (see Table 12), anthropogenic loading would account for only 9% of the total Sprague River discharge. Therefore, the revised methodology used in this study, which accounts for both groundwater and runoff background sources, resulted in lower total background concentrations (55.2 ppb at Power) and thus higher relative fractions of anthropogenic loading (23% at Power). The lower background concentrations used in this study are also more reflective of the observed FWM concentrations in the relatively un-impacted headwater sub-basins in the upper North and South Forks (51.3 and 46.6 ppb, respectively, see Table 12).

One limitation of this approach is that the observed loads at each station incorporate both sources and sinks of nutrients due to in-stream processes such as settling, biological uptake, and flood deposition as well as human activities such as irrigation withdrawals that remove flow (and thus load) from the river. Therefore, a portion of the direct loads to the river are likely not included in the measured loads since some nutrients are lost due to these in-stream processes as water moves downstream. This would result in an under-estimation of the total as well as the anthropogenic loads. In order to more accurately determine the total loads due to both natural sources and human activities, a detailed nutrient budget accounting for all sources and sinks within specific reaches is needed. Such an effort would require a study designed specifically for this purpose, which was beyond the scope of the current effort to provide an initial analysis of the Klamath Tribes long-term Sprague River water quality dataset.

4.9 Trend Analyses

Trend analyses were performed on the six long-term monitoring stations over the period of record (WY2002 – 2014). These analyses were performed on monthly flows, loads, and FWM concentrations computed from the continuous daily time-series generated for each station and parameter. The two stations added in 2009 (SF_Ivory and NF_Ivory) as well as results for TSS were excluded from the trend analysis due to an insufficient period of sampling. Additional figures and tabulated results of the trend analyses are provided in Appendix G.

4.9.1 Diagnostics Data Displays

Figure G3 in Appendix G provides diagnostic displays of the trend tests for each station and parameter. An example of these diagnostics are shown in Figure 62 for the FWM concentration of TP at the Power water quality station. These displays include the following elements:

- Time-series of monthly values, colored by 6-month seasons (Apr-Sep and Oct-Mar) as well as the trend slope lines computed from the Seasonal Kendall test.
- Time-series of annual values and trend lines using the Mann Kendall test and linear regression.
- Time-series of monthly values grouped by month of the year to show the trend in individual months.
- Bar chart showing the slope and significance of trends in each month, season, and overall annual trends based on the Seasonal Kendall, Mann Kendall and linear regression tests.
- Summary statistics of the primary trend results for all months using the Seasonal Kendall test.

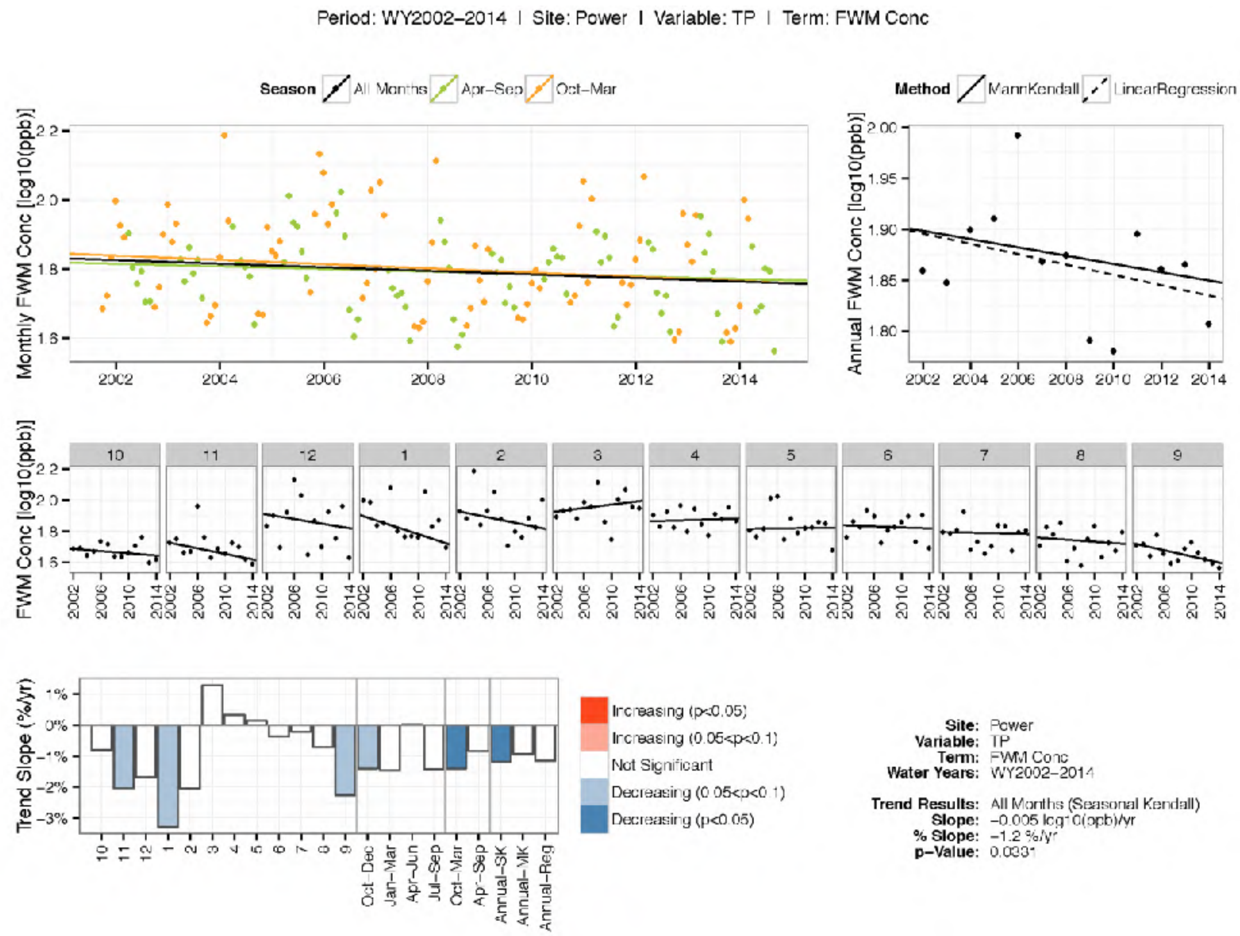


FIGURE 62: EXAMPLE OF TREND ANALYSIS DIAGNOSTIC DISPLAY FOR TP CONCENTRATION AT POWER

Colors in bottom left chart denote whether trend is increasing (red), decreasing (blue), or not significant (white)
Shading of colors denotes significance with darker colors for high significance (p < 0.05) and lighter colors for moderate significance (0.05 < p < 0.10)

4.9.2 TREND SLOPES AND SIGNIFICANCE

Figure 63 summarizes the trend analysis results for annual and seasonal precipitation, flow, TP and TN load, and FWM TP and TN concentration at each station. The shading and colors of the trend slopes indicate the significance level and direction (positive or negative) of each trend. The slopes are reported in terms of %/yr. Similar figures for the other water quality parameters are provided in Appendix G (Figures G1 and G2).

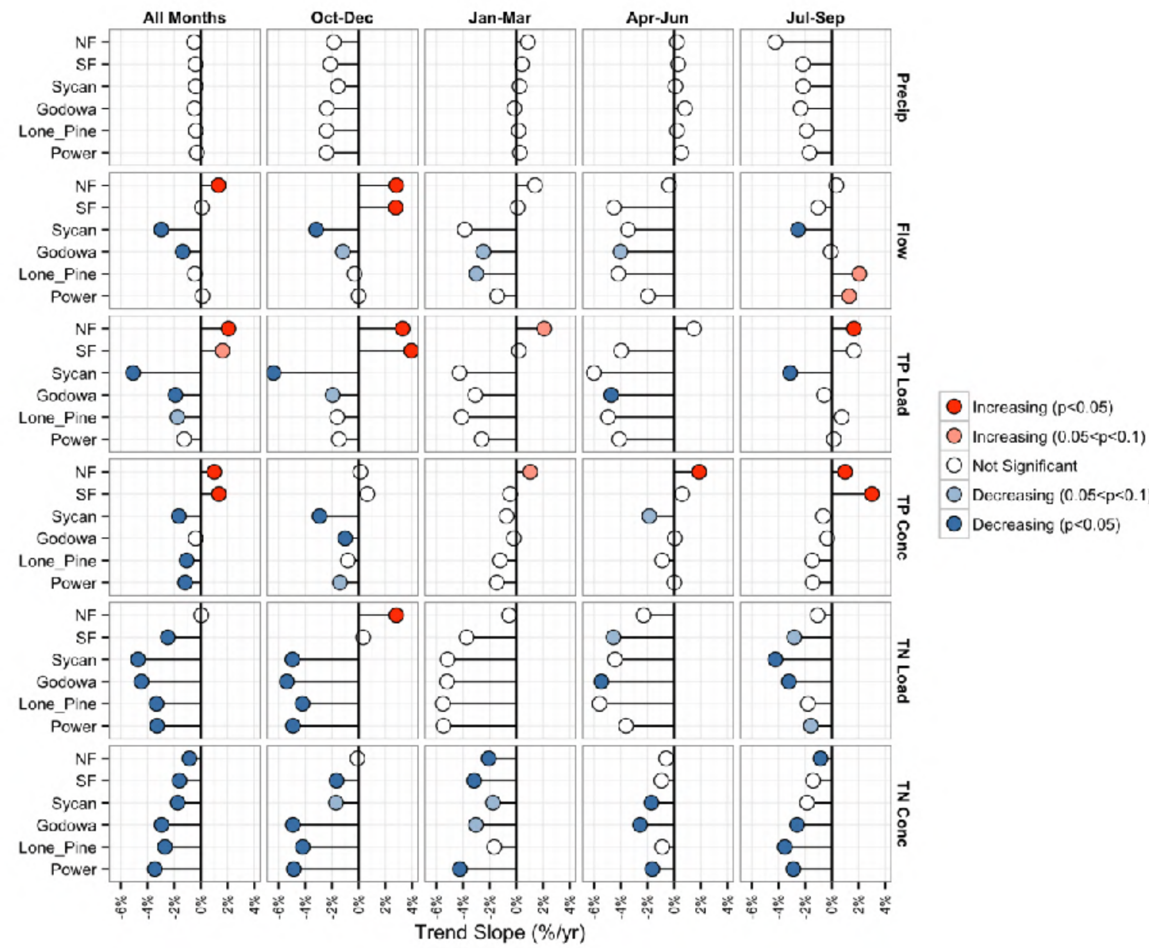


Figure 63: Annual and Seasonal Trend Results of Precipitation, Flow, TP and TN Load, and FWM TP and TN Concentration, WY2002 – 2014

Colors denote whether trend is increasing (red), decreasing (blue), or not significant (white)
Shading of colors denotes significance with darker colors for high significance ($p < 0.05$) and lighter colors for moderate significance ($0.05 < p < 0.10$)

Figure 63 shows that although there was a decrease in precipitation primarily in the fall (Oct-Dec) and summer (Jul-Sep) seasons, the trends were not significant ($p > 0.10$). Although Walker et al. (2012) reported a significant decreasing trend in precipitation, the precipitation records used in that study were based on a different data source and location (Klamath Falls International Airport) and also included a longer period of record (WY1992 – 2010). Mayer and Naman (2011) also report a decline in the net inflow to UKL between 1961 and 2007 indicating that precipitation has declined over a longer period than can be detected during the 2002 to 2014 water years evaluated in this study, which does not include the wetter period occurring during the 1990's.

Despite the lack of trends in precipitation, there were significant increasing trends in flow at the NF station across all months, and at both NF and SF during the fall. In contrast, significant decreasing trends in flow occurred across all months at Sycan and Godowa. There were also weakly significant ($0.05 < p < 0.10$) increasing trends at Lone_Pine and Power during the summer.

For TP concentrations, there were increasing trends of 1.0 and 1.3 %/yr in the upper headwaters at NF and SF, respectively, and decreasing trends between -1.1 to -1.7 %/yr among the lower Sprague River and Sycan River stations. Both TP loads and concentrations decreased at Sycan, primarily during the fall season. At Godowa, there was a significant decreasing trend in TP load of -1.9 %/yr but no trend in TP concentration across all months. However, TP concentrations did decrease at Godowa during the fall. TP concentrations significantly declined at Lone_Pine at a rate of -1.1 %/yr, but the decreasing trend in TP loads was less significant. Similarly, TP concentrations declined at Power at a rate of -1.2 %/yr, but TP loads showed no significant trend.

For TN loads and concentrations, there were decreasing trends for all stations except NF across all months (Figure 63). Decreasing trends in TN load occurred during the fall for the SF, Sycan, and mainstem stations, while the trend in TN load increased for the NF in the fall period. There were also decreasing trends in TN concentration for most stations during the fall and winter, as well as for several stations in the spring (Sycan, Godowa and Power) and summer (NF and mainstem stations)

Figure 64 summarizes the trend results of the FWM concentrations for all water quality parameters. This figure shows that the decreasing trends in TP concentration at Sycan, Lone_Pine and Power were primarily due to decreases in PO4, whereas the increasing trends in TP at NF and SF were due to increasing PP primarily during the summer. Among the nitrogen species, there were decreasing trends in NH4 at the three mainstem stations (Godowa, Lone_Pine, and Power) in all months as well as winter and spring. For NO23, there were decreasing trends at SF, Lone_Pine and Power across all months and in the spring (except SF), and an increasing trend at Sycan in all months as well as summer and fall.

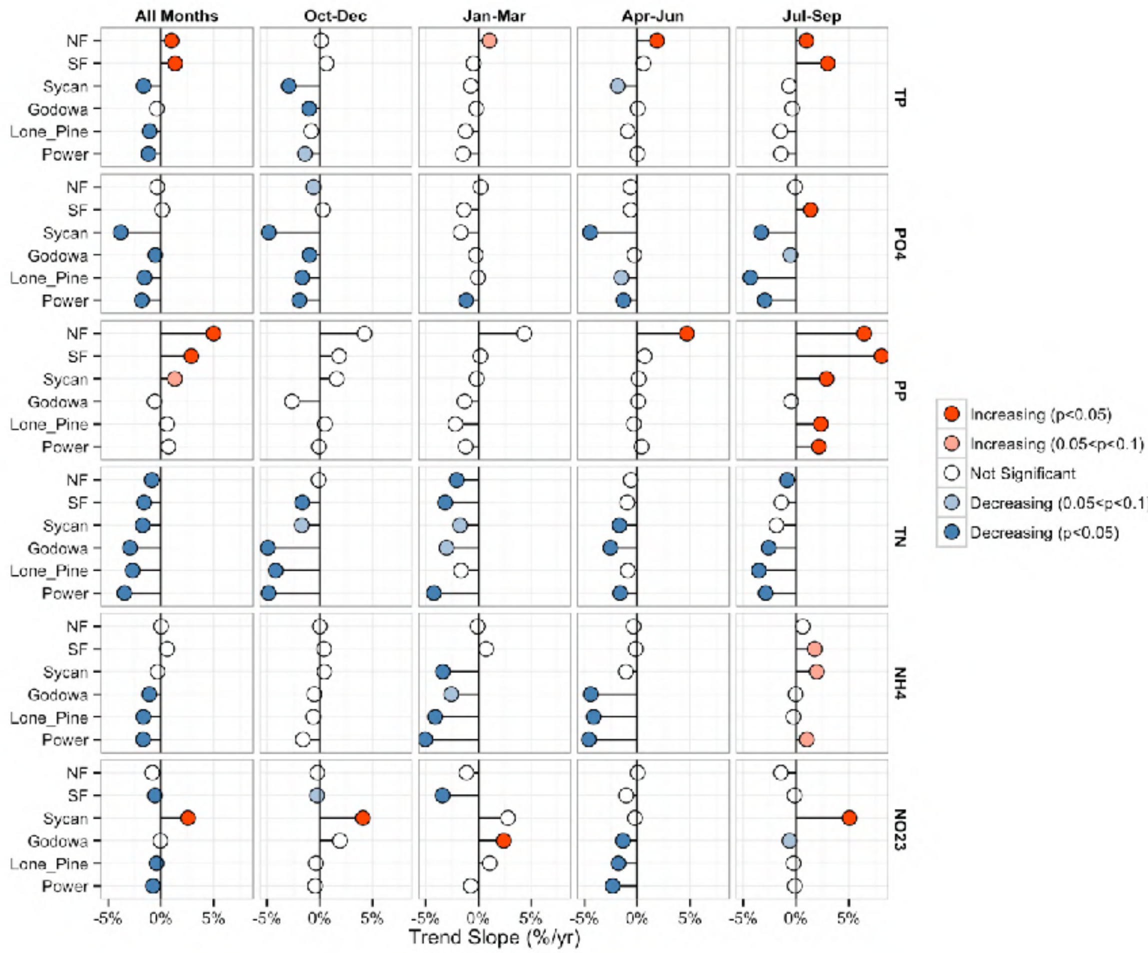


FIGURE 64: ANNUAL AND SEASONAL TREND RESULTS OF FWM CONCENTRATIONS FOR ALL WATER QUALITY VARIABLES, WY2002 – 2014

Colors denote whether trend is increasing (red), decreasing (blue), or not significant (white)
Shading of colors denotes significance with darker colors for high significance (p < 0.05) and lighter colors for moderate significance (0.05 < p < 0.10)

In summary, the trend results indicate increases in total phosphorus concentrations and load in the two headwater sub-basins in the North and South Forks, and decreasing trends in the lower Sprague River mainstem stations. The increases in the North and South Forks were primarily due to increases in particulate phosphorus mainly in summer, which is surprising as flows are usually low during this season and thus erosion would not be expected to be a major source of particulate loading[33].

[33] The lower SF and NF (SF_Ivory and NF_Ivory) do show increases in particulate loading in the summer but are not included in the trend analyses due to their shorter period of record.

The decreases in TP concentrations in the lower Sprague River stations were primarily due to decreases in dissolved phosphorus (PO4) in most seasons. These decreases may be caused by restoration activities that reduce the phosphorus content of irrigation return flows or other sources, but support for this would require an accounting of restoration activities in this reach. The decreases may also indicate a reduction in groundwater discharge, which has a high dissolved phosphorus content, as the latter few years in the study period were relatively dry with small snow packs, and thus groundwater levels may have been lower across the basin leading to less discharge.

Interestingly, there were significant decreasing trends in total nitrogen (TN) at all stations and in most seasons. This may reflect the effects of restoration activities targeting runoff or return flows from agricultural areas, which have higher nitrogen content than natural background sources (nitrogen is generally below detection in groundwater sources).

5 Conclusions and Recommendations

This study evaluated the streamflow and nutrient dynamics of the Sprague River Basin over the period WY2002 – 2014 using biweekly flow and nutrient measurements collected by Klamath Tribes at eight sampling stations across the basin. Continuous daily timeseries of flows, loads, and concentrations were computed using similar methodologies as the previous nutrient budget study for the entire Klamath Basin (Walker et al., 2012). These daily time-series were used as a basis to investigate the spatial and temporal dynamics of nutrient concentrations and loads, estimate relative amounts of background and anthropogenic loading, and evaluate long-term trends at each sampling station.

The results of this study led to the following conclusions and recommendations:

1. Over the study period WY2002 – 2014, annual precipitation was generally lower than the long-term mean in all but two years, WY2006 and WY2011, which were considerably wetter than normal. Two of the years in the study period, WY2013 and WY2014, had low precipitation and small winter snowpack that led to regulation of water withdrawals in accordance with water rights. These latter years also showed earlier snowmelt consistent with other regional climate and streamflow trends.
2. The majority of annual streamflow increase (based on gauges) from the headwaters to the river outlet occurred in the upper parts of the watershed including the upper reach of the Sprague River above Godowa, the headwater sub-basins in the North and South Forks, and the Sycan River. In the lower reaches of the Sprague River (below the confluence with the Sycan River near Godowa), the total flow actually decreased under high flow conditions during winter and spring between the two lower-most stations at Lone_Pine and Power. During summer, flows did show some increase between these stations, but not as much as would be expected based upon estimates of groundwater seepage from Gannett et al. (2007). These results were confirmed using separate data sources and suggest that during winter and spring, the floodplains, wetlands, and other depressions along the river corridor in the lower Sprague may be acting as temporary storage basins that trap portions of overbank flows, which are then infiltrated to groundwater or lost by evaporation. However, these patterns may also be the

result of inaccurate flow rating curves at one or more of the stations, especially under high flow conditions.

3. Comparisons between mean summer flows and estimates of groundwater discharge by Gannett et al. (2007) showed close agreement for the headwater sub-basins of the upper North and South Forks, the Sycan River, and in the upper section of the Sprague River mainstem above Godowa. However, in the middle and lower sections of the Sprague River, groundwater discharge estimates were substantially higher than the net flow changes along these reaches. These differences suggest significant flow losses likely due to evaporation and irrigation withdrawals.
4. Mean annual FWM concentrations for TP ranged from 47 ppb in the upper South Fork to 72 ppb near the outlet of the Sprague River at Power over WY2010 – 2014. The majority of this increase occurred in the lower reaches of the South and North Forks primarily due to increases in particulate P. The increases in particulate P suggest that sediment input/transport is a major concern in these reaches and are further reflected by a similar large increase in TSS. On a seasonal basis, the largest increases in both TP and PP occurred in winter and spring when flow conditions are high, further suggesting significant inputs of particulate phosphorus may be due to erosion of stream banks, upland slopes, streambed sediments, floodplains, and/or other areas. During summer, both TP and PO4 concentrations decreased from the confluence of the North and South Forks to the outlet likely due to biological uptake of dissolved PO4, which also decreased along the river whereas particulate P concentrations remained steady.
5. Consistent with high groundwater inflow (which includes adjacent springs), the largest increases in flows and TP load per unit area, but the smallest change in FWM TP concentration, occurred in the middle Sprague River basin between Godowa and the SF_Ivory + NF_Ivory confluence. In contrast, the largest increase in FWM TP concentration occurred in the lower South Fork between the SF_Ivory and SF stations. In addition, PP concentrations rose dramatically and consistently in the North and South Forks, while in most years PP concentrations remained relatively steady from Godowa to Power, declining slightly in some years, and increasing slightly in others.
6. Relative to total phosphorus, PP is the major anthropogenic contributor to loading.
7. Although misclassification appears to be an issue with the NLCD land use data, rendering analyses less useful than they might otherwise be, comparisons between nutrient concentrations and land use composition of the associated sub-basins for each station showed strong positive correlations between both TP and PP and land uses for Planted/Cultivated and Herbaceous. Both TP and PP concentrations were also negatively correlated with Forest cover. However, there were no significant correlations between dissolved PO4 and any land use type. This suggests that human activities primarily cause an increase in particulate P, with dissolved P being primarily controlled by natural factors, especially groundwater discharge which has high dissolved P content.
8. Significant positive correlations were also found between annual mean TP concentrations and the fraction of the lower valley associated with Place of Use (POU) areas for irrigation surface water rights, which were used to represent agricultural areas. On a seasonal basis, the mean TP concentrations in both winter and summer also had significant positive correlations with

fraction POU area. Similarly, particulate P was positively correlated with fraction POU area not only annually, but in all seasons except fall. However, dissolved PO4 showed no significant correlations either annually or in any season, which again suggests that human activities have a larger impact on particulate phosphorus than on dissolved PO4.

9. The North and South Fork stations all showed positive linear relationships between fraction TP as particulate (% PP) and flow, while the remaining stations showed more non-linear relationships with the % PP higher under lowest flows, decreasing during intermediate flows, and then increasing with increasing flow before tending to level off and decline at highest flows. These non-linear relationships may be the result of bio-uptake of dissolved phosphorus (PO4) under low flows during summer and increased particulate phosphorus loading through irrigation or other agricultural practices such as cattle access to degraded riparian areas. Relatively high fraction particulate TP under low flows at SF_Ivory compared to the other stations also suggests that even under low flows there is a major source of particulate phosphorus loading to the lower South Fork reach between SF and SF_Ivory. Both TP concentrations and the fraction particulate TP showed positive relationships with TSS further confirming that sediment input/transport is a major source of TP in the Sprague system.
10. Similar to FWM TP, the mean annual and seasonal FWM TN concentrations showed a large increases between the relatively un-impacted SF station and the SF_Ivory station (particularly in summer), but a similar trend was not seen for the NF stations. Despite higher TN concentrations for the Sycan during all seasons, TN only increased slightly for the Sprague stations downstream of the Sycan confluence. Spring and summer NH4 and NO23 concentrations were low across all stations likely reflecting uptake by aquatic macrophytes and algae. Unlike other reaches, NO23 increased sharply between SF_Ivory + NF_Ivory and the Godowa station during late-summer, fall and winter as flows increased. Sycan NO23 values were relatively high (compared to other stations) in the summer and fall and decreased in the winter and spring as organic N was exported from the Sycan Marsh upstream.
11. TN concentration was non-linearly related to flow at most stations, with relatively high values occurring during the summer low-flow period, declining values in the fall, and increasing values as flow increased in the winter and spring (Figure 51). As with the phosphorus parameters, TN values tended to be higher in the winter than the spring during higher flows, and similar to PP, TN values tended to level off or decline at the very highest flows.
12. Sycan NO23 was negatively related to flow, and the pattern at Godowa was unique in that NO23 values increased with flow in the summer through early winter and then leveled off and declined in late winter and spring as flows increased further, although the cause of these dynamics is not clear. TN and organic-N concentrations generally remained constant over a range of TSS concentrations during summer and fall low-flow periods before increasing linearly with TSS during winter and spring at most stations.
13. The relative contributions of background versus anthropogenic TP loads were estimated using a revised methodology compared to that used previously (Walker et al., 2012). Background loads were divided into two separate components, one for groundwater and one for runoff. A background TP concentration of 60 ppb was derived for the groundwater discharge component based on synoptic measurements collected by Klamath Tribes in springs and creeks throughout

the basin. For the runoff component, a background TP concentration of 34 ppb was computed from the total observed concentrations in the relatively un-impacted headwater sub-basins in the upper North and South Forks after accounting for the loads due to groundwater discharge. These background concentrations were then applied to the groundwater and runoff flow components at each water quality station. After combining the groundwater and runoff background loads, the total background TP concentrations ranged from 40 ppb to 56 ppb. These concentrations are lower than the 65 ppb background concentration estimated by Walker et al. (2012), but better reflect the annual mean concentrations observed in the relatively un-impacted sub-basins of the Sprague River.

14. After estimating background TP loads and concentrations at each station, the anthropogenic loads and concentrations were computed and ranged from 14% to 29% of the total load over the period WY2010 – 2014 among the stations excluding the un-impacted NF and SF, both of which had no or minimal anthropogenic loading. The largest fraction of anthropogenic loads was in the lower South Fork at SF_Ivory. Near the outlet of the Sprague River at Power, anthropogenic loads accounted for 23% of the total load due to an increase in TP concentration of 17 ppb above a background level of 55 ppb yielding a total observed mean annual FWM concentration of 72 ppb over WY2010 – 2014.
15. Long-term trend analyses over the entire study period (WY2002 – 2014) showed a significant increasing trend in flow in the upper North Fork and significant decreasing trends in flow at the Sycan River and the upper Sprague River mainstem at Godowa despite no significant trends in precipitation.
16. The trend results for TP loads show significant increases in the upper North and South Forks, and decreases at Sycan, Godowa, and Lone_Pine. However, there was no significant trend near the Sprague outlet at Power.
17. TP concentration also showed a significant increasing trend in the upper North and South Forks, despite minimal agricultural impacts in these sub-basins, although there are other human impacts such as forest roads and some grazing. The two lower Sprague River stations (Power and Lone_Pine) both showed significant decreasing trends in TP concentrations, as did the Sycan River. Trends in PO4 and particulate P showed that the decrease in TP in these lower stations was due to decreasing trends in dissolved PO4 with no trends in particulate P. Conversely, the increasing trends in TP in the upper South and North Forks were attributed to increases in particulate P with no trends in dissolved PO4.
18. All stations showed significant decreasing trends in TN with the magnitudes of these trends being higher in the downstream stations.

In addition to these key findings, the following recommendations are provided:

1. Review of the flow rating curves for the Power and Lone_Pine stations, especially for high flow conditions to determine whether the decreased discharge between these stations during high flow periods is real or simply an artifact of inaccurate flow measurements.
2. Continue monitoring for TSS (added in 2010), and continue sampling the more recently added NF_Ivory and SF_Ivory monitoring stations (added in 2009). These important areas showed the

greatest increases in phosphorus concentration. Continued monitoring will be useful for future analyses of trends and loading.

3. Perform intensive sampling at select reaches to quantify all sources and sinks and construct a detailed nutrient budget to better understand the magnitudes of the various in-stream and external fluxes of nutrients along the river.
4. Evaluate the efficacy of techniques such as use of stable isotopes to trace pathways of nutrient movement and recycling.
5. Increase synoptic sampling of nutrient concentrations in springs, irrigation return flows, and the lower Sycan (for Sycan determine source of high summer NO23).
6. Update the previous analysis of background and anthropogenic nutrient sources for the entire UKL basin (Walker et al 2012) utilizing this refined methodology, which separates the groundwater and runoff components.
7. Add DOC and TOC to the routine monitoring program to further delineate organic fractions of TSS and particulate P.
8. Install continuous water quality probes at existing sampling locations, particularly for the collection of hourly dissolved oxygen, pH, and turbidity data. Compute ecosystem metabolism (gross primary productivity and net ecosystem productivity) for use in understanding ecosystem processes affecting algal and macrophyte related nutrient dynamics.
9. Take action to restore extensive riparian areas and stream channel function in the lower South Fork and lower North Fork reaches where the data show the largest increases in TSS, TP and particulate P concentrations. Riparian plant community restoration is a ubiquitous need that will be the most effective means of reducing erosion-related increases in PP concentration above the NF/SF confluence, and will increase roughness of floodplain surfaces and increase deposition of PP.
10. Reconfigure channelized stream reaches. The lower reach of the South Fork is a good example of a straightened channel that is diked along much of its length. The resulting increased slope, confinement of flow, and minimal lateral connectivity with floodplain surfaces increase erosion, scouring, and transport of fine sediments and the associated PP. Reconstruction of such reaches with appropriate channel morphology to provide lateral connectivity with the floodplain is essential.
11. Consider measures to accelerate aggradation of incised stream reaches, which are prevalent in the NF Sprague and in Meryl Creek. Encouraging beaver activity may be a useful approach (e.g. http://beaver.joewheaton.org/)
12. Restore or increase lateral connectivity of the Sprague River with its floodplain by removing or breaching constraining dikes. Focusing such efforts upstream of Godowa would help reduce the PP concentration at Godowa, which is typically the inflection point in PP and TP load plots; slope of these plots decreases moving downstream from Godowa. Similar restoration efforts downstream of Godowa would reduce PP as well. If done at sufficient scales, this may reduce the magnitude of loading in wetter years like 2006 and 2011.
13. Eliminate direct irrigation returns, which likely have high nutrient content, to rivers and streams.

6 ACKNOWLEDGMENTS

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