# Truckee River Water Quality: Current Conditions and Trends Relevant to TMDLs and WLAs

Prepared for:
Truckee Meadows Water Reclamation Facility
City of Reno and City of Sparks, Nev.

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# Summary

The Truckee River's natural flow pattern has been severely modified, with negative repercussions for native fish and plant communities in the floodplain. Water quality problems were exacerbated in the 1980s as high nutrient loading and low flow during an extended drought resulted in the proliferation of aquatic macrophytes and benthic algae. In response, the Nevada Division of Environmental Protection (NDEP) developed the Truckee River Strategy. Total Maximum Daily Loads (TMDLs) for total nitrogen (TN) total phosphorus (TP) and total dissolved solids (TDS), and Waste Load Allocations (WLAs) for the Truckee Meadows Water Reclamation Facility (TMWRF), were adopted in 1994. The National Pollutant Discharge Elimination System (NPDES) permit for TMWRF was reissued in 2003. The permit allows potential TMDL and WLA adjustments if supported by appropriate scientific evidence. This report is an analysis of historical monitoring data for both the Truckee River and TMWRF effluent in order to help determine what adjustments, if any, can be made in the discharge levels of the facility.

The report is based mainly on the TMWRF river monitoring and treatment plant databases combined with U.S. Geological Survey (USGS) gage data. The water quality monitoring record started in 1985. The most important period considered here, though, is 1998–2006 because major modification of treatment plant processes and/or operating strategies continued through 1997.

The 30-day average (May–October) TN WLA was exceeded only 5 out of a possible 48 months since 1998, while the annual TN WLA was exceeded 3 of the 8 years since then. The portion of the TN load due to dissolved organic N (DON) is of interest because the DON pool as a whole is less bioavailable than inorganic forms of N. DON accounted for an annual median 65% of TMWRF wastewater TN. Published research suggests that about 40% of wastewater DON may be functionally recalcitrant. If so, there has been only a single "functional" exceedance of the 30-day TN WLA and none of the annual TN WLA. There were no trends in loading of any N fraction since the WLAs were adopted despite the increase in service area population, no doubt because of advances in treatment plant technology and operations with respect to N.

TP load exceeded its WLA an average of nine days per year since 1998. Few of these exceedances, however—only eight total since 1998—occurred during summer when periphyton metabolism is high and oxygen problems most likely. There is an increasing trend,

however, in TP and especially dissolved reactive P (DRP) loading since WLA adoption, reflecting at least in part an increase in the service area population.

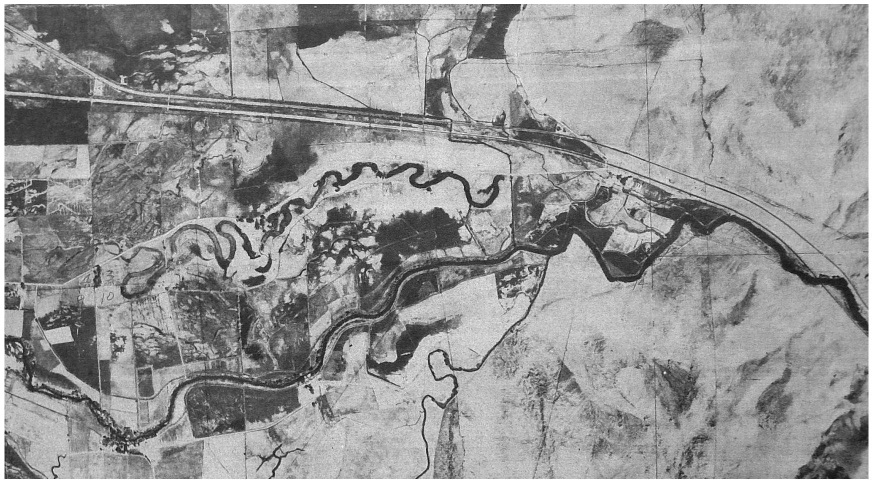
TDS loading always remained below its annual WLA, and there is no trend in loading since 1994.

Because Lockwood Bridge is the control point for the TMDLs, the river's water quality there is of special interest. During 1998–2006, TN exceeded the Nevada Administrative Code (NAC) standard 9% of the time. The mean annual TP exceeded the NAC standard in every year by a median of 52%. TDS was always well below the NAC standard. TN was very close to the EPA Ambient Water Quality Criteria Recommendations for this subecoregion while TP was about twice as high. TP, in contrast to TN, is therefore moderately elevated with respect to either criterion, and TDS does not appear to be a pressing issue.

For technical reasons related to nutrient concentrations below the analytical detection limit, trends were determined in river total Kjeldahl N (TKN) and nitrate rather than in TN. TKN concentration trends since TMDL adoption in 1994 were not significant in the river itself, although both Steamboat Creek (upstream of the TMWRF effluent) and the North Truckee Drain showed increasing trends. Nitrate concentration trends were negative in the river below the treatment plant and not significant upstream, probably reflecting resolution of a snail infestation problem at the plant during 1994–1997. In contrast, both TP and DRP concentration trends were positive in the river upstream of the treatment plant and DRP concentration trends were also positive downstream. These trends in TKN and P concentrations upstream of the plant, similar to the trends in effluent P loading, may simply reflect a population increase.

There are two important measures of loading in this system. The first is integrated loading over a year or longer period, which is most relevant for determining impacts on Pyramid Lake. During 1998–2006, TMWRF contributed 17% of TN, 22% of TP and 14% of the TDS load above Lockwood Bridge. Steamboat Creek upstream of the treatment plant contributed a little more than TMWRF, and North Truckee Drain much less. But the Truckee River contributed the most, 48-59% depending on the constituent.

Lockwood Bridge was chosen as the TMDL compliance point for assessing loads because most controllable sources were thought to be upstream. To whatever extent this is true, there are still important sources of nutrients downstream of *lockwood*. The transition from *lockwood* to *clark* is especially notable. TN and TP, and to a lesser extent TDS, increase between these two stations. The TN increase is actually larger than the TMWRF effluent load. Although the difference is not statistically significant, the increment between *lockwood* and *clark* appears to be almost entirely dissolved inorganic N (DIN) and therefore bioavailable. Accordingly, its TN contribution could be ecologically more important than TMWRF's despite the similar magnitudes. What are the N sources in this watershed increment? The identification of N sources in this watershed increment is obviously of great importance to the Pyramid Lake N balance: Controlling them may offer an opportunity for mitigation of TMWRF loads.



Old aerial view (1940) showing a tortuous branch of the original Truckee River and the modern channelized river.

The loading estimates at *nixon* are also notable because TN and TP loads exceed the loads at *clark*. The TN and TP loading increments between *wadsworth* and *nixon* are larger than the respective contributions by TMWRF effluent, as well as by the watershed increment between *lockwood* and *clark*. Concentration through evaporation cannot account for the change. Most of the TN change is attributable to a nitrate increase. Although some portion of the loading probably originated in the river upstream, the area between *wadsworth* and *nixon* may offer another opportunity for efficient reduction of N and P loading to Pyramid Lake.

The second important measure of loading is median daily loading during summer, which characterizes the nutrient supply at a time when periphyton metabolism is highest and oxygen problems most likely. The TMWRF contribution above Lockwood is somewhat higher by this measure, 22-29% depending on the constituent. But the river contribution is still the largest, especially for TN and TDS. Unlike the integrated loads, the summer medians are not substantially affected by contributions downstream of Lockwood.

The inorganic N:P ratios in summer are suggestive of strong N limitation for plant growth or biomass in the study area and especially downstream. But because nitrogen-fixing periphytic organisms can utilize atmospheric N, a more certain way to limit periphyton and other plant metabolism downstream is to limit the P supply.

For N or P control in the lower river, the analysis has therefore shown that the Truckee River upstream of East McCarran is providing the highest load in summer, followed by TMWRF and Steamboat Creek upstream of the treatment plant. For N or P supply to Pyramid Lake, additional areas downstream of Lockwood need to be considered as well.

# Contents

# Preface

This report represents one part of a project undertaken by Ecological Research Associates of Davis, California for the cities of Reno and Sparks, Nevada. It summarizes an analysis of water quality data collected over the past twenty years. The intent is to determine trends and identify opportunities and challenges related to the quantity of nutrients and salts that the Truckee Meadows Water Reclamation Facility can discharge. The analysis should help to determine what adjustments, if any, can be made in the discharge levels of the facility, which were established more than ten years ago. One major aspect of the study is to determine how much the clean discharge from the facility contributes to the nutrient and salt loads of the river and to Pyramid Lake.

There are many completed and ongoing field and laboratory studies of the mechanisms governing water quality in the Truckee River, some of which are referred to in this report. Here, the focus is more on an empirical description of the historical monitoring data. The summaries in this report do address some of the pressing questions directly, but we hope that they will also provide background for and support future field and laboratory investigations, as well as the monitoring program.

We thank Mike Brisbin and Helene Decker for help with accessing and using the databases analyzed here. Special thanks are due to Mahmood Azad for guidance and review throughout the analysis process, facilitating data access and providing photographs.[1]

[1] This report was originally issued on July 26, 2007. This revised version contains some minor changes.

# 1

# Background

The Truckee River originates in Lake Tahoe and flows northeast for about 200 km before discharging into Pyramid Lake. Streamflow, highest in the spring and lowest in the autumn, is primarily due to snowmelt from mountainous headwater areas. Surface water is the principal source of water supplies in the river basin and overall demand sometimes exceeds supply. Flow is highly regulated, including multiple diversions, returns and groundwater exchange. When irrigation is needed for the Newlands Project area, most streamflow during non-runoff periods is withdrawn at Derby Dam and conveyed via the Truckee Canal to Fallon and Fernley. A key aspect of the system is therefore severe modification of the natural hydrograph, except perhaps during periods of high flow. The altered hydrograph has had negative repercussions for native fish and plant communities in the floodplain.

In the upper stretches, highway cuts, ski slopes cause erosion and increase mineral suspensoid content of the river, clouding the waters and occasionally interfering with drinking water use. Un-vegetated burn areas are a further source of erosion and fine sediment. Further downstream, septic tank leachate and urban runoff enter the river, carrying nutrients and promoting growth of undesirable algae. Treated sewage effluent can be a substantial part of flow downstream from the Reno-Sparks urban area during low-flow conditions. Still further downstream, water withdrawals for agriculture return to the river as both surface drainage and groundwater, carrying increased levels of dissolved solids because of evaporation and natural mineral solubilization.

Truckee River water quality deteriorated in the 1980s as high nutrient loading and low flow during an extended drought resulted in the proliferation of aquatic macrophytes and benthic algae. Plant respiration and decaying plant material led, in turn, to incidents of low dissolved oxygen (DO), impairing habitat for Lahontan cutthroat trout, a threatened species, and cui-ui, an endangered species. In response, the Nevada Division of Environmental Protection (NDEP) developed the Truckee River Strategy. The strategy included timetables for numerous nonpoint source control projects such as stormwater permitting, wetlands treatment systems, pasture improvements, riparian restoration, and landowner education, as well as Total Maximum Daily Loads (TMDL) and Waste Load Allocations (WLA). The

Truckee River near Virginia Street Bridge in Reno.

Final Truckee River TMDLs and WLAs were adopted by the state and approved by EPA Region IX in 1994 [27]. These included TMDLs for total nitrogen (TN) total phosphorus (TP) and total dissolved solids (TDS), and WLAs for the major point source discharger in the basin, the Truckee Meadows Water Reclamation Facility (TMWRF). The TMDL was calculated below Derby Dam and the compliance point was set at Lockwood Bridge because most controllable sources are upstream of that location.

A National Pollutant Discharge Elimination System (NPDES) permit was first issued to TMWRF in 1981. The permit was reissued in 2003 for a five-year period, including approval to expand treatment capacity to 51.2 MGD. The permit requires effluent and stream monitoring at nine stations between East McCarran Bridge and Nixon, as well as streamflow data from five gaging stations between Farad and Nixon. These measurements are the main source of data used in this study. The permit allows water quality trading offsets such as flow augmentation that could increase the allowable discharge for a specific pollutant. It also includes other potential TMDL adjustments, namely, a seasonal WLA and exclusion of some of the dissolved organic nitrogen (DON) from the TN WLA if it can be shown to be biologically unavailable [14].

The main goals of this study are to provide a description of the conditions and trends for TMDL water quality constituents and to estimate loads of these constituents at key points in the river. Most of the effort is on analysis of the extensive TMWRF monitoring database for both the river and treatment plant effluent. A major motivation is to determine what adjustments, if any, might be warranted in the permitted discharge levels of the facility, which were established more than 10 years ago. Of related interest is the relative impact of TMWRF effluent compared to other sources of nutrients and salts for the river and Pyramid Lake. A secondary goal is to note opportunities for improving the monitoring database in terms of quality assurance and access, based on practical issues encountered during this analysis.

# 2

# Analysis methods

## 2.1 Data sources

This report is based mostly on data collected by the TMWRF monitoring program (Figure 2.1). Data spanning the period 1985–2006 were acquired from the monitoring database [24]. Of particular interest are nine sites from the East McCarran Bridge to Nixon (Table 2.1). These sites have more than 100 sampling events since 1994 and eight of them (all but *painted*) are near USGS gage stations with long streamflow records, allowing calculation of flow-adjusted constituent concentrations and trends, as well as loads. What we refer to as *clark* station data in this study is actually a composite of data from *clark* and *tracy* stations. Monitoring was switched from *tracy* to nearby *clark* in 1993, and so data from both sites were combined to create a longer record. Hourly sonde data for certain water quality characteristics (temperature, pH, conductivity, DO, turbidity) are also available for these sites and were used in certain analyses.

TMWRF also supplied water quality and discharge data for wastewater effluent. Discharge

Table 2.1: Key TMWRF monitoring stations, identification codes, coordinates, and distances in km from the source in Lake Tahoe.

| Name | Station code | Latitude | Longitude | Distance |
|---|---|---|---|---|
| Truckee at McCarran Br. | mccarran | 39.5175 | -119.7408 | 96.8 |
| N. Truckee Drain | ntd | 39.5250 | -119.7050 | 100.7 |
| Steamboat Ck. at Cleanwater Way | steamboat | 39.5131 | -119.7114 | 101.0 |
| Truckee at Lockwood | lockwood | 39.5100 | -119.6478 | 106.6 |
| Truckee at Clark Stn. | clark | 39.5653 | -119.4839 | 125.0 |
| Truckee at Derby Dam | derby | 39.5856 | -119.4483 | 131.0 |
| Truckee at Painted Rock Br. | painted | 39.5911 | -119.3664 | 138.9 |
| Truckee at Wadsworth Br. | wadsworth | 39.6397 | -119.2817 | 149.9 |
| Truckee at Nixon | nixon | 39.8292 | -119.3600 | 181.9 |

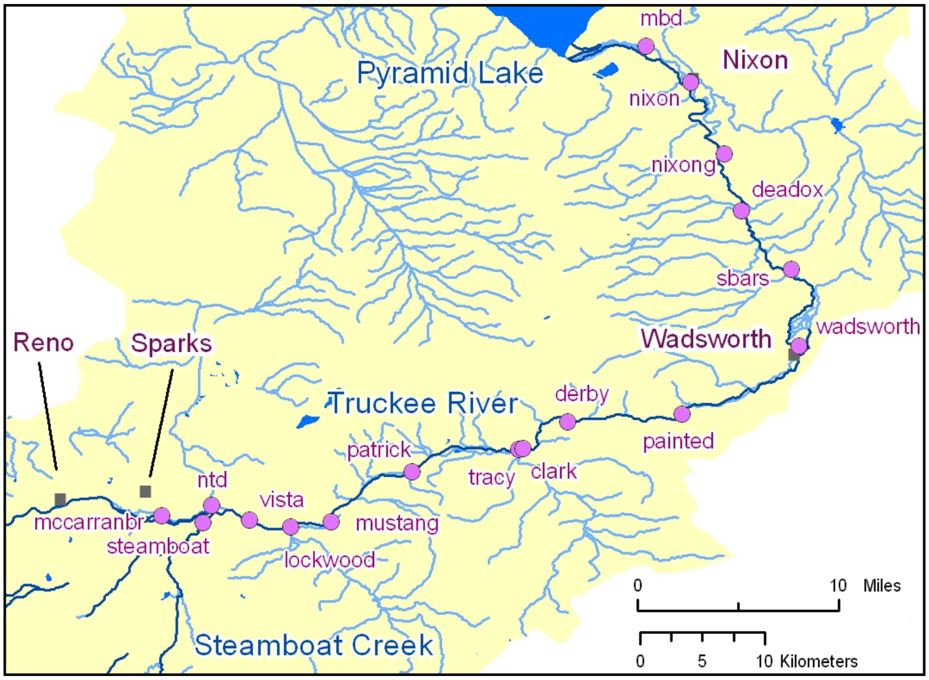



Figure 2.1: TMWRF monitoring stations.

is available on a daily basis and water quality constituents on a daily to weekly basis, depending on the constituent.

The NDEP monitoring database includes data for 75 measured variables from 100 stations, beginning as early as 1966 (Figure 2.3). This large storehouse is valuable for many purposes. In this report, however, we have a narrower need for data records that cover a long time span for certain constituents of interest. We first screened for stations that had at least 100 observations, yielding a total of 13 stations. The patterns of missing data for major constituents of interest at the 11 stations from Farad downstream is illustrated in Figure 2.2. One of the stations, RS1 on the Truckee just above the confluence with Steamboat, is missing most observations for these constituents. Of the remainder, only T1, T7, T2 and T4A have records that include data since 2000 (Table 2.2). These stations will be used to examine conditions upstream; the main emphasis, though, is on the TMWRF monitoring database.

Daily average streamflow data were acquired directly from the U.S. Geological Survey's

Table 2.2: NDEP monitoring stations used in this report.

| Name | Station code | Latitude | Longitude |
|---|---|---|---|
| Farad | T1 | 39.4213 | -120.0327 |
| Circle C Ranch | T7 | 39.5073 | -119.9034 |
| Idlewild Park | T2 | 39.5213 | -119.8299 |
| Vista Gage | T4A | 39.5142 | -119.6794 |

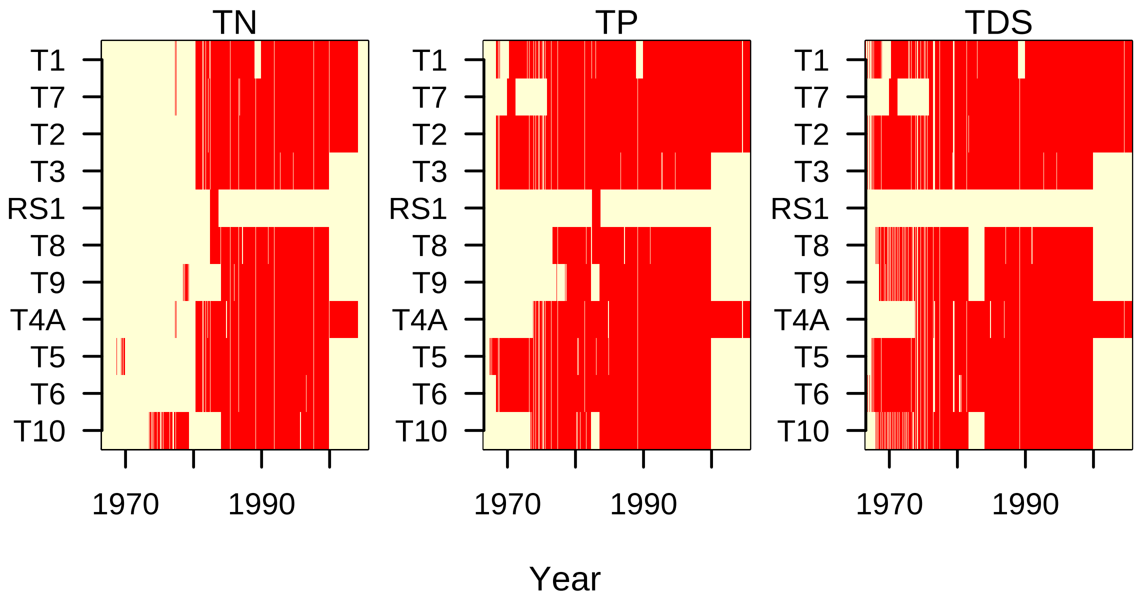



Figure 2.2: Missing data patterns for key constituents at Nevada NDEP stations with at least 100 total observations. Stations are arranged from upstream (Farad) to downstream (Nixon). *Red line,* data are available for that station and month.

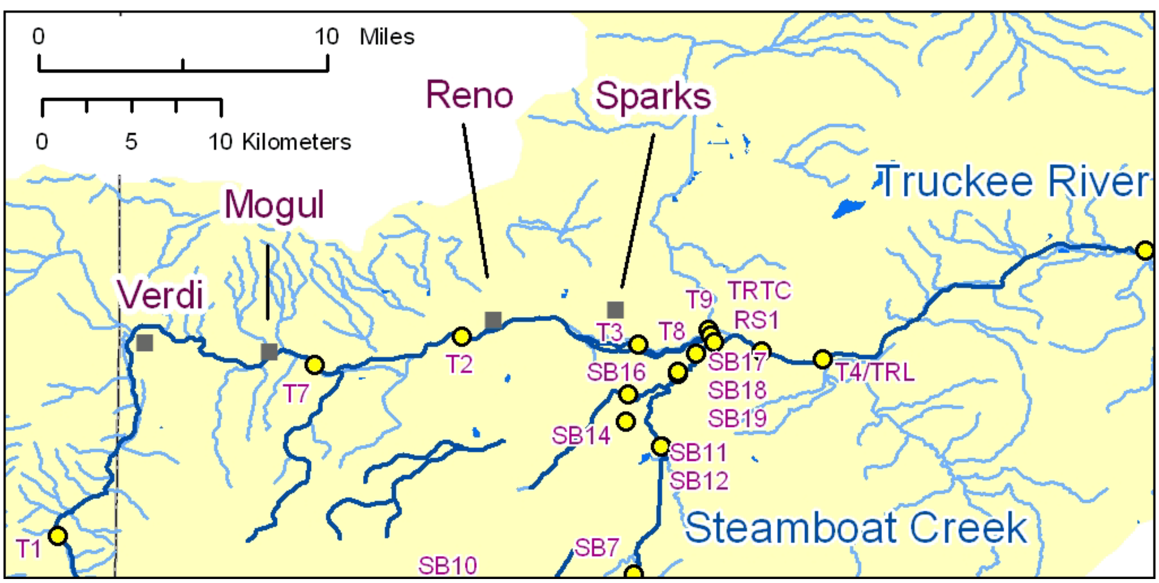



Figure 2.3: NDEP monitoring stations in the study area.

(USGS) National Water Information System (NWIS; Figure 2.4) [29]. Table 2.3 lists the gage sites of particular interest in this study and their monitoring station correspondences. These data were used preferentially for all calculations. In some cases, flow data for a particular station and sampling day were available in the TMWRF database but not in the NWIS database, especially for gaging stations 10348300 (*ntd*), 10349980 (*steamboat*) and 10351650 (*wadsworth*). When necessary, these data were used to supplement the NWIS data. The gaging station by Tracy was switched from 10350400 to 10350340 in 1997. Data from these two stations were combined under the latter's site number to give a continuous record. A value of 1 cfs was added to all streamflow values in order to avoid taking logarithms of zero values. Figure 2.5 is a schematic diagram of the flow system and gaging stations considered in this study.

## 2.2 Data analysis

Loads were estimated using a linear model in which the log of instantaneous load is related to streamflow:

$$\ln L = a_0 + a_1 \ln Q + a_2 \sin(2\pi T) + a_3 \cos(2\pi T) + a_4 T \tag{2.1}$$

where $L$ is instantaneous load; $Q$ is streamflow; $T$ is the decimal year; and the $a_i$ are constants. The first explanatory term accounts for dependence on streamflow, the second two form a first-order Fourier series to account for seasonal variability, and the last accounts for a potential time trend. This type of model specification has been found suitable for describing nutrient loads in larger watersheds [3].

Adjusted maximum likelihood estimation (AMLE) was used to handle censored data. A bias correction factor was used in transforming $\ln L$ back to $L$. AMLE suitability was assessed by examining residuals for normality with the probability plot correlation coefficient. The USGS software package LOADEST (version MOD36) was used for the entire

Table 2.3: USGS gage sites used in this study, gage site numbers, drainage areas (km$^2$) and corresponding monitoring stations for calculation purposes. Drainage area for 10350400, the predecessor of 10350340, is 4118 km$^2$.

| Name | Number | Area | Stations |
|---|---|---|---|
| TRUCKEE R NR SPARKS, NV | 10348200 | 2771 | mccarran |
| N TRUCKEE DRAIN AT KLEPPE LN NR SPARKS | 10348300 | - | ntd |
| STEAMBOAT C AT CLEANWATER WAY NR RENO | 10349980 | - | steamboat |
| TRUCKEE R AT VISTA, NV | 10350000 | 3706 | lockwood |
| TRUCKEE RIVER NR TRACY, NV | 10350340 | 4092 | clark |
| TRUCKEE R BL DERBY DAM NR WADSWORTH | 10351600 | 4341 | derby |
| TRUCKEE R AT WADSWORTH, NV | 10351650 | 4475 | wadsworth |
| TRUCKEE R NR NIXON, NV | 10351700 | 4732 | nixon |

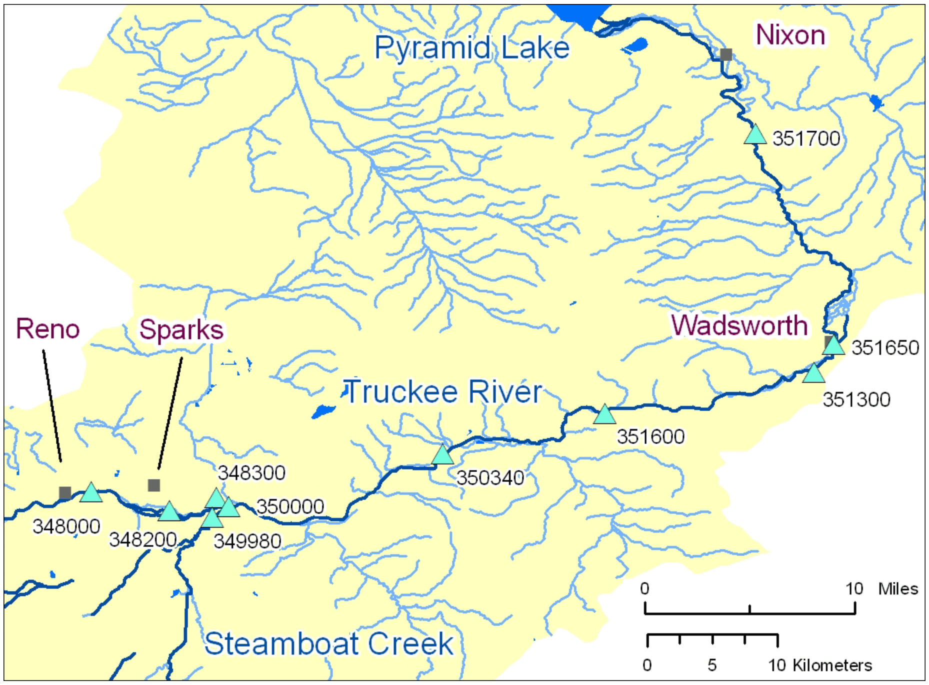



Figure 2.4: USGS gage sites in the study area (site numbers do not include 2-digit prefix of "10": see Table 2.3).

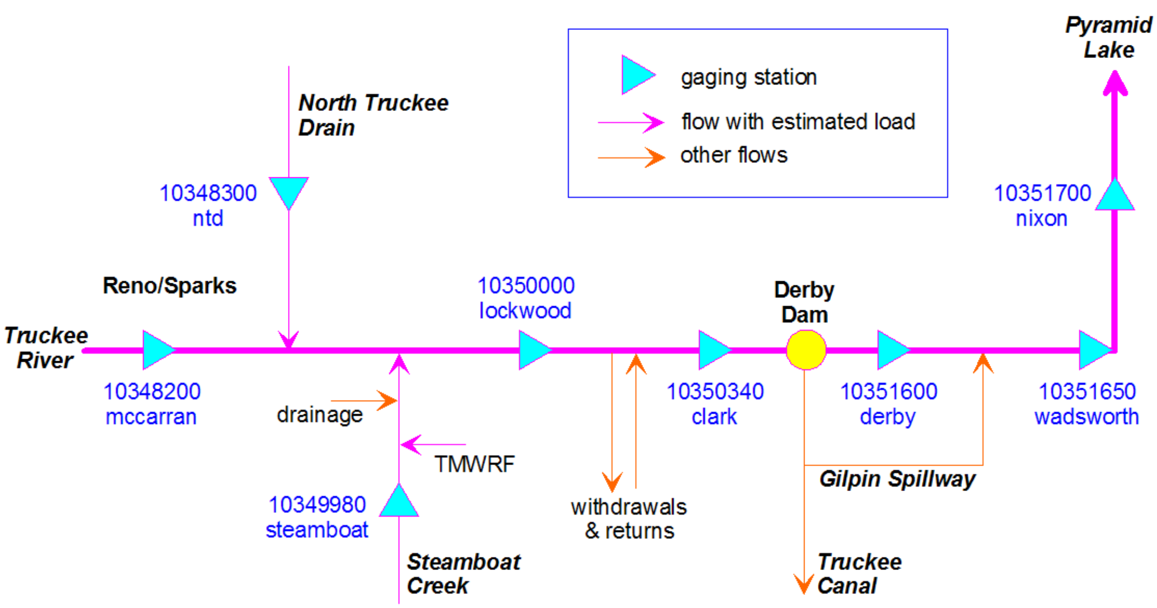



Figure 2.5: Schematic diagram of flow system and gaging stations used in this study. Below the gaging station code is the name of the TMWRF monitoring station associated with it for calculation purposes. Multiple withdrawals and return flows, including groundwater recharge, occur along the river, represented by only a single pair of arrows in the diagram.

process. Theory, methods and software are described in detail by Runkel and others [20] and the references therein.

The model was calibrated for each station and water quality variable using all available concentrations measured at that station and streamflow data for the same days from the most appropriate gage station. The entire streamflow record was then used with the calibrated model for a more complete record of loading estimates.

Treatment plant effluent measurements of interest for this study include daily flow volume, ammonium, nitrite, nitrate, DKN (dissolved Kjeldahl N), TKN (total Kjeldahl N), TP, and TDS. The data were examined for problem values (negative or otherwise unlikely flows) and duplicates, which were removed. TN was estimated by the sum of TKN, nitrate-N and nitrite-N. TON was estimated by TKN minus ammonium-N. Similarly, DON was estimated by DKN minus ammonium-N. Monthly average loads were estimated by

$$L = \overline{Q}\frac{\sum_{i=1}^{k} Q_i C_i}{\sum_{i=1}^{k} Q_i} \tag{2.2}$$

where $\overline{Q}$ is the monthly average of the daily flow volume, $k$ is the number of days when constituent concentrations were measured, and $Q_i$ is the daily flow volume and $C_i$ the measured constituent concentration for day $i$ of those days.

Trend significance was determined by the nonparametric Seasonal Kendall test with serial correlation correction [8]. The overall trend slope is computed as the median of all slopes between data pairs within the same season (no cross-season slopes contribute to the overall slope estimate). This is sometimes referred to as the Theil-Sen slope. Two criteria were used to insure that data records for different variables and locations represented the same period so that trend results were comparable: Tests were conducted for a particular water quality variable and station only if at least 50% of the total possible number of monthly values in the beginning and ending fifths of the record were present in the record; in addition, more than 50% of the maximum possible number of comparisons had to be present for at least 9 of the months. The Seasonal Kendall test is sometimes applied to longer monthly series (greater than 10 years) after first removing influences of variables other than time, especially flow rates, in order to increase the power of the test. Here, long-term trends were estimated after adjusting for total river inflow using locally weighted regression with a span of 0.5 and a locally linear fit.

Flow-adjustment cannot be done in the same way with highly-censored water quality data (> 5% of the data), nor are the Seasonal Kendall estimates reliable under these conditions. Instead, trends in these constituents were tested with a censored regression technique known as *Tobit* [2]. The data were modeled as described in Equation 2.1.

All calculations and tests, unless otherwise specified, were carried out in the R software environment [18]. The U.S. Geological Survey's S-PLUS library [23] and in some cases its stand-alone program Kendall.exe [7] were used for the Seasonal Kendall and Tobit tests. Modeling and analysis included extensive use of the Hmisc and Design [5] and nlme [17] libraries for R.

Steamboat Creek upstream of the treatment plant.

Box plots shown in this report are classic box-and-whiskers plots: Solid circle is the median; box is the interquartile range; whiskers extend to all points with 1.5 times the interquartile range; and empty circles are outlying points.

# 3

# Data summary

## 3.1 Streamflow

The NWIS gage data are plotted in Figure 3.1. This record covers the extended drought that persisted from 1987 through 1994, with some relief beginning in 1993. A less dramatic period of low flow occurred in 2000–2004. The records appear similar superficially, but there are important differences having water quality consequences, especially at low flows.

## 3.2 Water quality summary

The TMWRF monitoring record begins in 1985. The data set used here contains observations through October 2006. There are 24 measured variables in the database at up to 40 sites (although some of these are the same site with different names, as discussed above). Nine sites (counting *clark*/*tracy* as one site) have more than 100 records since 1994, i.e., the "post-TMDL" period, and these are the primary sites of interest. Their missing data patterns are shown in Figure 3.2. Monthly coverage is excellent for many important variables, especially since 1994. This is especially true of TP, TDS and the components used to calculate TN (= TKN + $NO_2$ + $NO_3$).

The variables sampled most completely are summarized in Table A.1 (in Appendix A). *Lockwood* is particulary well represented with more than 500 observations for some variables, while *painted* has distinctly fewer samples than the others. Ammonium is heavily censored at all stations with 39-80% of observations below the detection limit. Similarly, nitrite has 19-97% of observations below the detection limit. Nitrate is barely or moderately censored from *steamboat* through *derby*, but 20-46% censored upstream and downstream. This level of censoring must be taken into account in trend and loading analysis. The remainder of the table provides an overall summary useful for detecting outlying and pos-

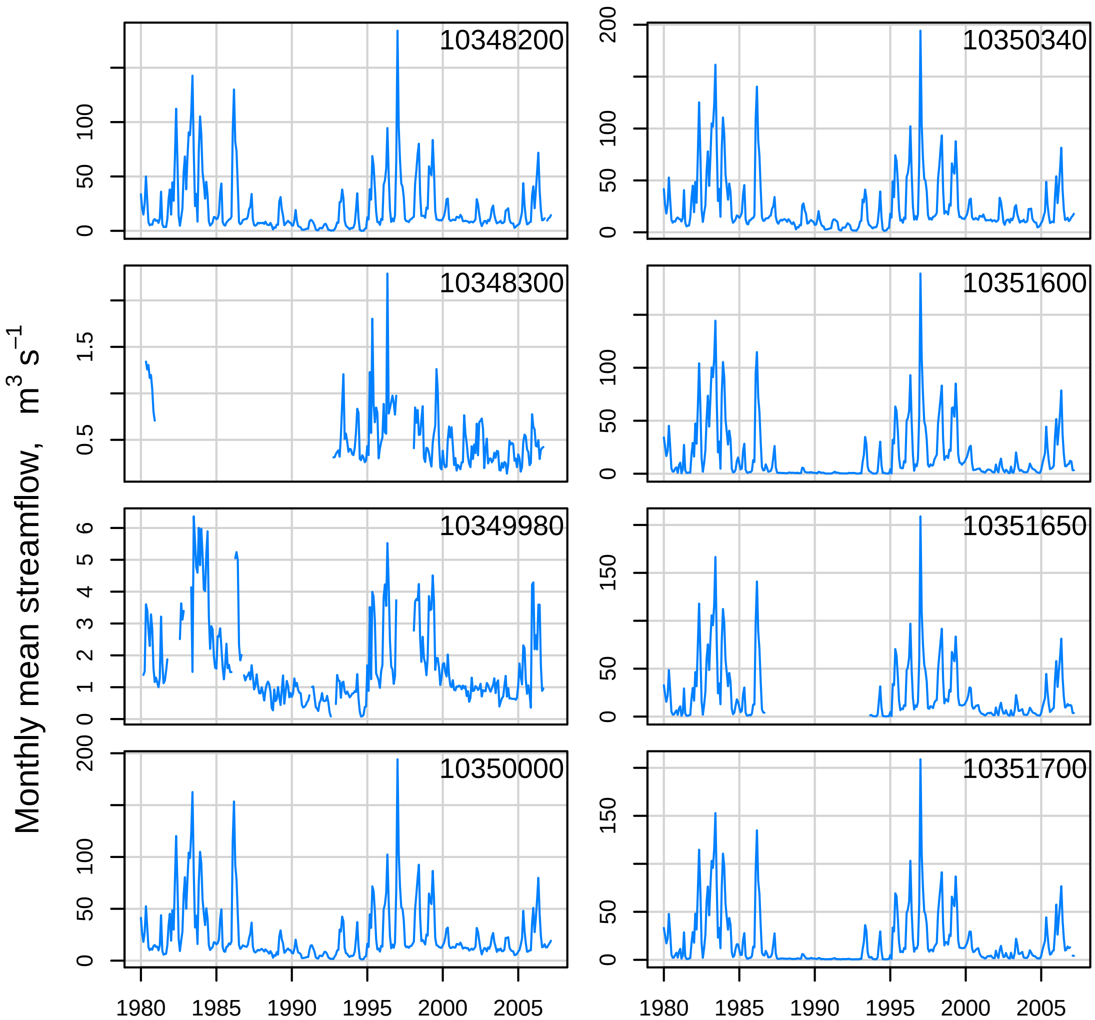



Figure 3.1: Time series of *monthly averages* of daily streamflow at eight gage sites on the Truckee R. and tributaries.

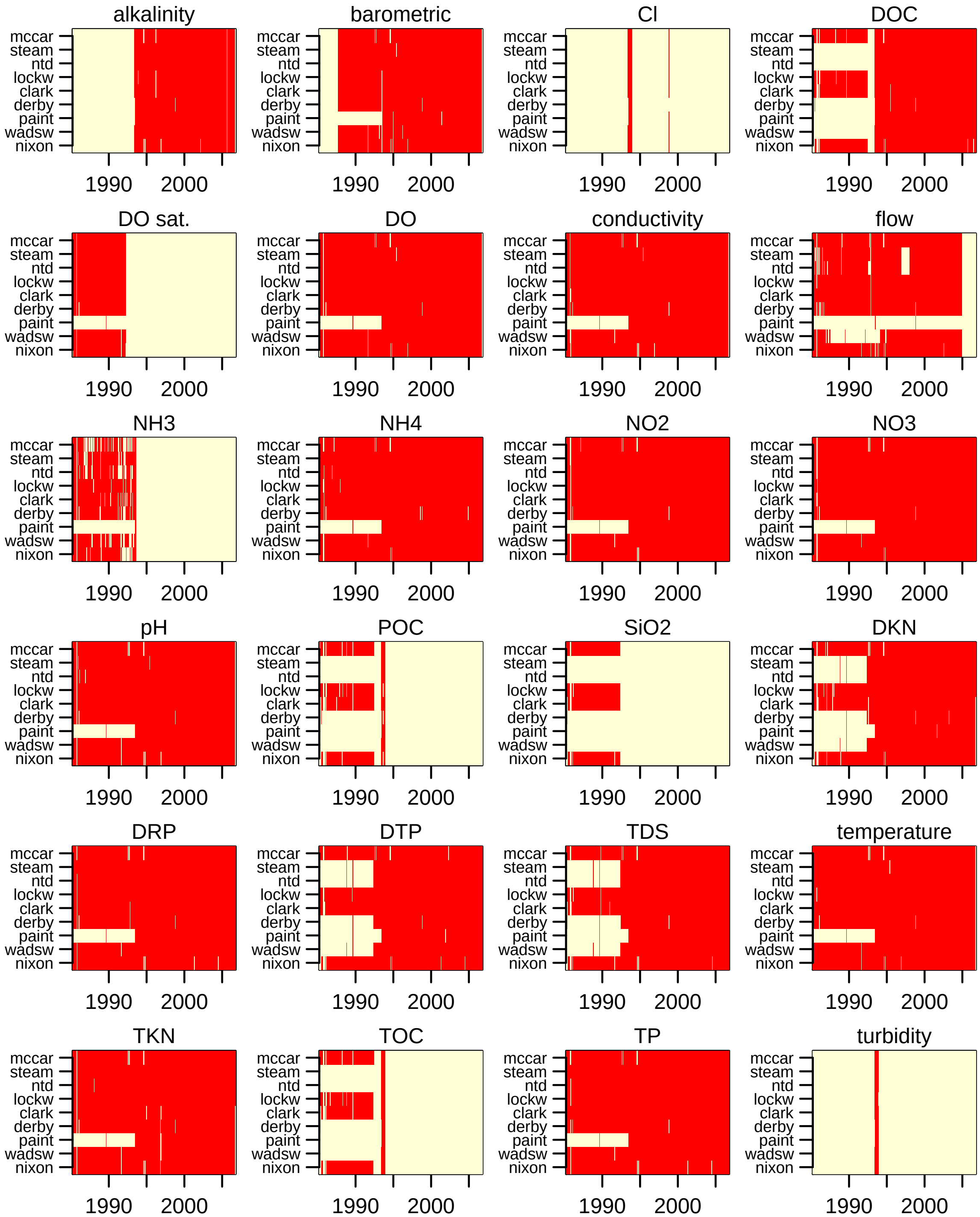



Figure 3.2: Missing data patterns for key constituents at TMWRF stations with at least 100 observations since 1994. Stations are arranged from upstream to downstream. *Red line,* data are available for that station and month.

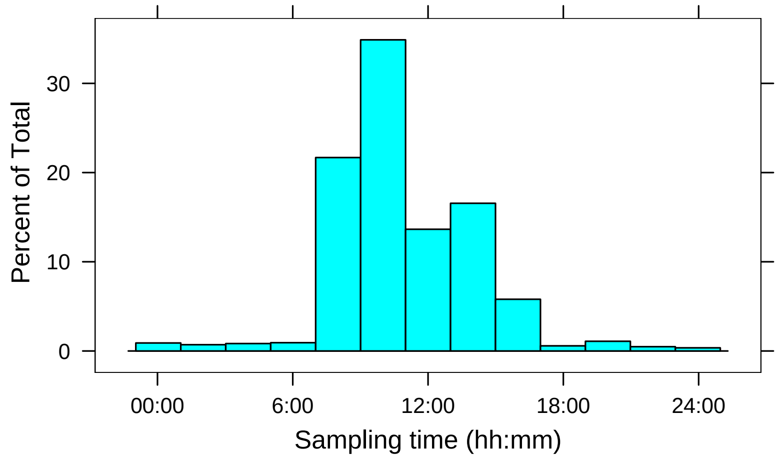



Figure 3.3: Distribution of sampling times during 1985–2006 for the same stations as in Figure 3.2.

sibly suspect observations. It also helps to formulate data range restrictions to be imposed on data entry into the TMWRF database.

Water quality observations can be affected by the sampling time of day. Sampling times should be in a narrow range for unbiased comparisons among observations. Figure 3.3 shows the distribution of sampling times for the most important stations considered here. The median sampling time was 10:18 and the interquartile range was from 09:00 to 13:00. This range is typical and reflects constraints imposed by logistical issues.

Because *lockwood* is the control point for the TMDL, its water quality is of special interest. Table 3.1 summarizes TMDL-related water quality constituents at *lockwood* for the period 1998–2006. As we have seen for the data as a whole, censored data are an issue only in the case of nitrite and ammonium. Nevada Administrative Code (NAC) water quality standards for the Truckee River at Lockwood Bridge [15] are shown where applicable, along with the fraction of exceedances since 1998, after establishment of the TMDLs and WLAs and after TMWRF N-treatment strategy was implemented. These standards give the highest single value for the most restrictive beneficial use. The acute cold-water fisheries criterion was used for ammonium but it is also subject to other criteria (chronic, as well as for un-ionized ammonia). The NAC standard for TP is actually set as an annual average so the exceedance fraction given is not strictly applicable; the annual TP average actually exceeded 0.05 mg $L^{-1}$ in every year. The median value of the annual average was 0.076 and it ranged from 0.065 to 0.11. That is, it typically exceeded the standard by 52% and was sometimes twice as high. TN exceeded the NAC standard 9% of the time. Of the 10 individual exceedances (out of a total of 107 observations), only 2 occurred in summer, the season of most concern with respect to hypoxia in the river (see Section 5.2).

These data can also be compared with the EPA Ambient Water Quality Criteria Recommendations [28]. The relevant regional category is Aggregate Ecoregion III (Xeric West), subecoregion 13. The criteria used are the 0.25 quantiles ($25^{th}$ percentiles) recorded for water quality constituents for rivers and streams in the same subecoregion. For the Truckee River, the relevant values are 0.42 mg $L^{-1}$ for TN compared to 0.41 actually observed; 0.23 mg $L^{-1}$ for TKN compared to 0.34 actually observed; 0.038 mg $L^{-1}$ for nitrate-N plus nitrite-N compared to 0.039 actualy observed; and 0.029 mg $L^{-1}$ for TP compared to 0.060 actually observed. N levels in the Truckee at *lockwood* are thus quite close to ambient conditions for this region whereas TP is moderately elevated.

## 3.3 Spatial distributions

Data for important water quality constituents are available for four NDEP and nine TMWRF stations since the TMDLs and WLAs were instituted in 1994, and so the period 1995–2006 was chosen for displaying spatial changes in constituent distributions. We focus on the constituents of TMDL concern: TN, TP and TDS. We first examined monthly mean concentrations at the NDEP stations relative to the most upstream station T1 (Farad), i.e., the monthly mean at each station was divided by the monthly mean at Farad. Distributions by water quality constituent and season are illustrated in Figure 3.4. The largest change by far for all three constituents occurs between Idlewild Park and Vista Gage. In particular, this is true of the summer, a particularly significant season because of periphyton accumulation and low DO conditions. The increase in summer is about twofold for TN and TDS, and more than fourfold for TP.

Similar summaries for TMWRF monitoring stations are illustrated in Figure 3.5. These

Table 3.1: TMDL-related water quality constituents in the Truckee R. at Lockwood Bridge during 1998–2006. *DL*, detection limit, mg $L^{-1}$; *Censor*, fraction of values below DL; 0.25 and 0.75, respective quantiles; *NAC*, Nevada Administrative Code standards, mg $L^{-1}$; *Exceeds*, fraction of values exceeding NAC.

| | DL | Censor | Min. | 0.25 | Med. | 0.75 | Max. | NAC | Exceeds |
|---|---|---|---|---|---|---|---|---|---|
| TN | | | 0.204 | 0.407 | 0.521 | 0.728 | 3.42 | 1.2 | 0.09 |
| TKN | 0.1 | 0 | 0.11 | 0.345 | 0.47 | 0.615 | 3.33 | | |
| DKN | 0.1 | 0.09 | 0.001 | 0.195 | 0.3 | 0.415 | 3.01 | | |
| $NO_3$-N | 0.005 | 0.05 | 0.001 | 0.038 | 0.066 | 0.117 | 0.77 | 2 | 0 |
| $NO_2$-N | 0.005 | 0.81 | 0.001 | 0.001 | 0.001 | 0.001 | 0.107 | 0.04 | 0.01 |
| $NH_4$-N | 0.02 | 0.87 | 0.001 | 0.001 | 0.001 | 0.001 | 2.68 | [a] | 0 |
| TP | 0.002 | 0 | 0.022 | 0.06 | 0.074 | 0.096 | 0.266 | 0.05 [b] | 0.89 |
| DTP | 0.002 | 0 | 0.007 | 0.034 | 0.047 | 0.064 | 0.122 | | |
| DRP | 0.002 | 0 | 0.013 | 0.028 | 0.04 | 0.052 | 0.127 | | |
| TDS | 2 | 0 | 63 | 122 | 141 | 164 | 372 | 500 | 0 |
| DOC | 0.05 | 0 | 1.15 | 2.08 | 2.42 | 2.9 | 15.4 | | |

[a] compared to acute cold-water fisheries criterion (pH-dependent)

[b] NAC standard is actually for annual average, not individual values

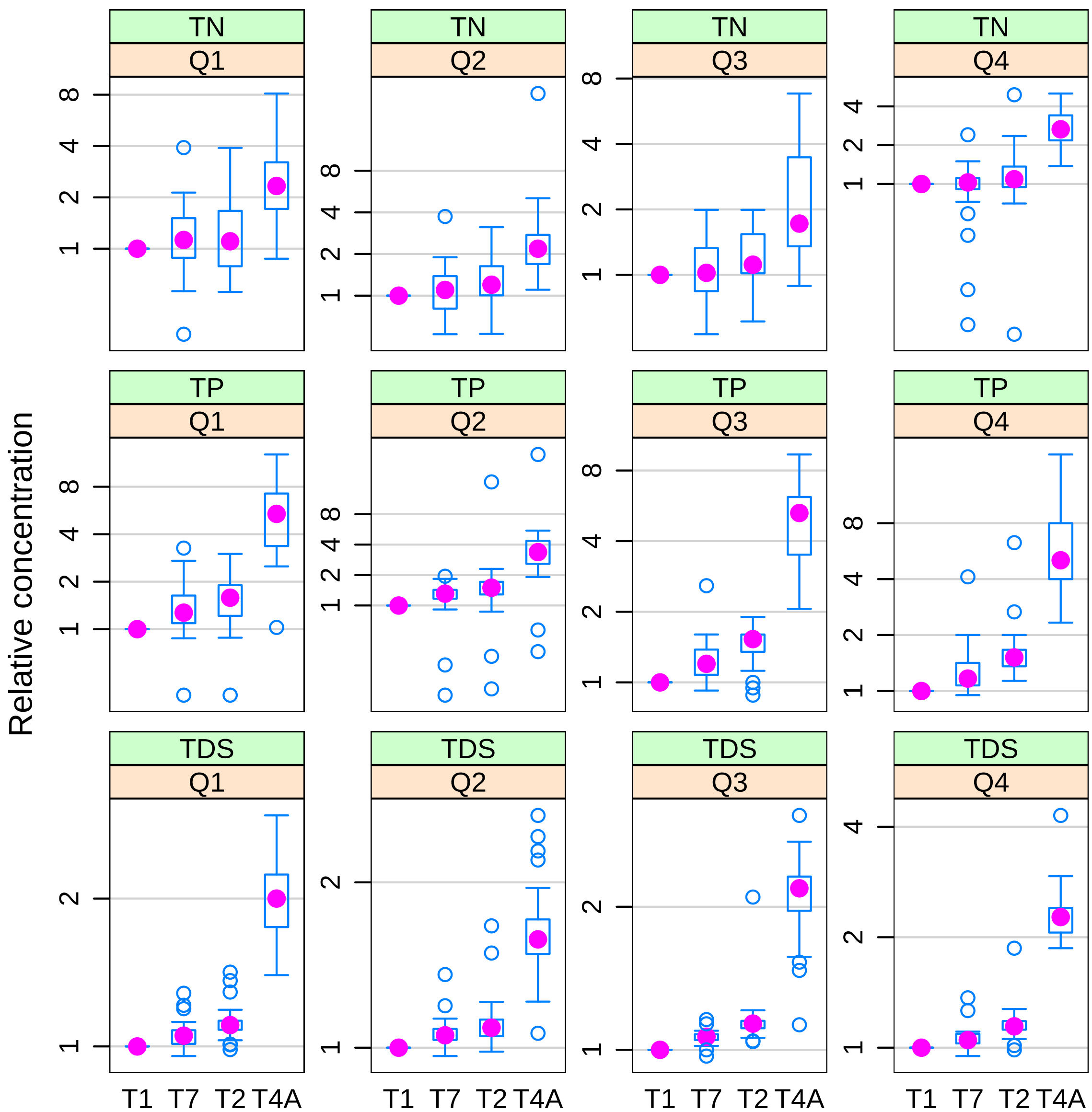



Figure 3.4: Distributions of monthly mean concentrations at NDEP stations relative to the monthly mean at T1, 1995-2005.

data were plotted separately from the NDEP data in case of sampling and analytical differences that could introduce artifacts into the spatial patterns. *Steamboat* and *ntd* carry the highest concentrations for all constituents and all seasons. During summer, the jump between *mccarran* and *lockwood* is again about twofold for TN and TDS, and nearly fourfold for TP. This is similar to the difference between T2 and T4A, as would be expected unless there were large sources between T2 and *mccarran*.

Ratios of N to P are important because they may be able to shed light on nutrient limitation for algal growth, but there are difficulties of interpretation. The Redfield ratio, N:P = 16, is an average atomic ratio for algal communities first observed in ocean waters. The ratio is now thought to vary widely for individual species according to the kind of environment they specialize in [11]. The concentrations of N and P individually also bear on whether either is limiting, and several empirical schemes have been developed that incorporate ratios *and* concentrations in an attempt to predict nutrient limitation [13]. In addition, the measured forms of N and P may not reflect the bioavailable amounts, although DRP is thought to be most useful for describing P bioavailability [19].

Figure 3.7 shows the distributions during each season of 1995–2006 for both TN:TP and DIN:DRP. The overall median TN:TP ratio was 23 at *mccarran* but decreased downstream and was close to 16 (15–17) below the treatment plant. There was relatively little change from season to season in the ratios and their longitudinal distribution. The overall median DIN:DRP ratio, on the other hand, was less than 16 everywhere except *ntd* in autumn. The seasonal cycle is strong because of uptake by algae, especially in summer when the drop downstream from *lockwood* is dramatic and the median ratio only 1 or less at *derby* and downstream. Because of censoring for DIN but not DRP data, some DIN:DRP ratios may be even lower. Before the treatment plant upgrades that reduced effluent nitrogen, the nitrogen-fixing periphytic cyanobacterium ("blue-green") *Calothrix atricha* was abundant upstream, although not downstream, of the treatment plant [21]. Given that downstream ratios in summer are now even lower than *mccarran* ratios, one would expect nitrogen-fixing cyanobacteria to be common in the downstream community.

Figure 3.6 shows summer inorganic N:P ratios versus DRP concentrations since treatment plant operations stabilized after 1997. It also indicates a dividing line between likely N and likely P limitation based on empirical evidence from many rivers [13]. The values observed in the Truckee River itself are therefore indicative of N limitation, except in a very few instances.

The reason DIN:DRP changes so much compared to TN:TP in summer is that DIN is a relatively small component of TN. It goes from 11% of TN at *lockwood* to only 2% at *nixon*, causing a large change in DIN but a small one in TN (Table 3.2). DRP goes from 54% of TP at *lockwood* to 49% at *nixon*, causing only a small change in both TP and DRP.

The effect on the lake is more complicated because the organic N and P fractions have more time in the lake to decompose and become bioavailable. More importantly, nutrient availability in the lake reflects the integrated loads of years. It is the ratio in these integrated loads over an appropriate time span that is relevant for the lake (see Section 5.2).

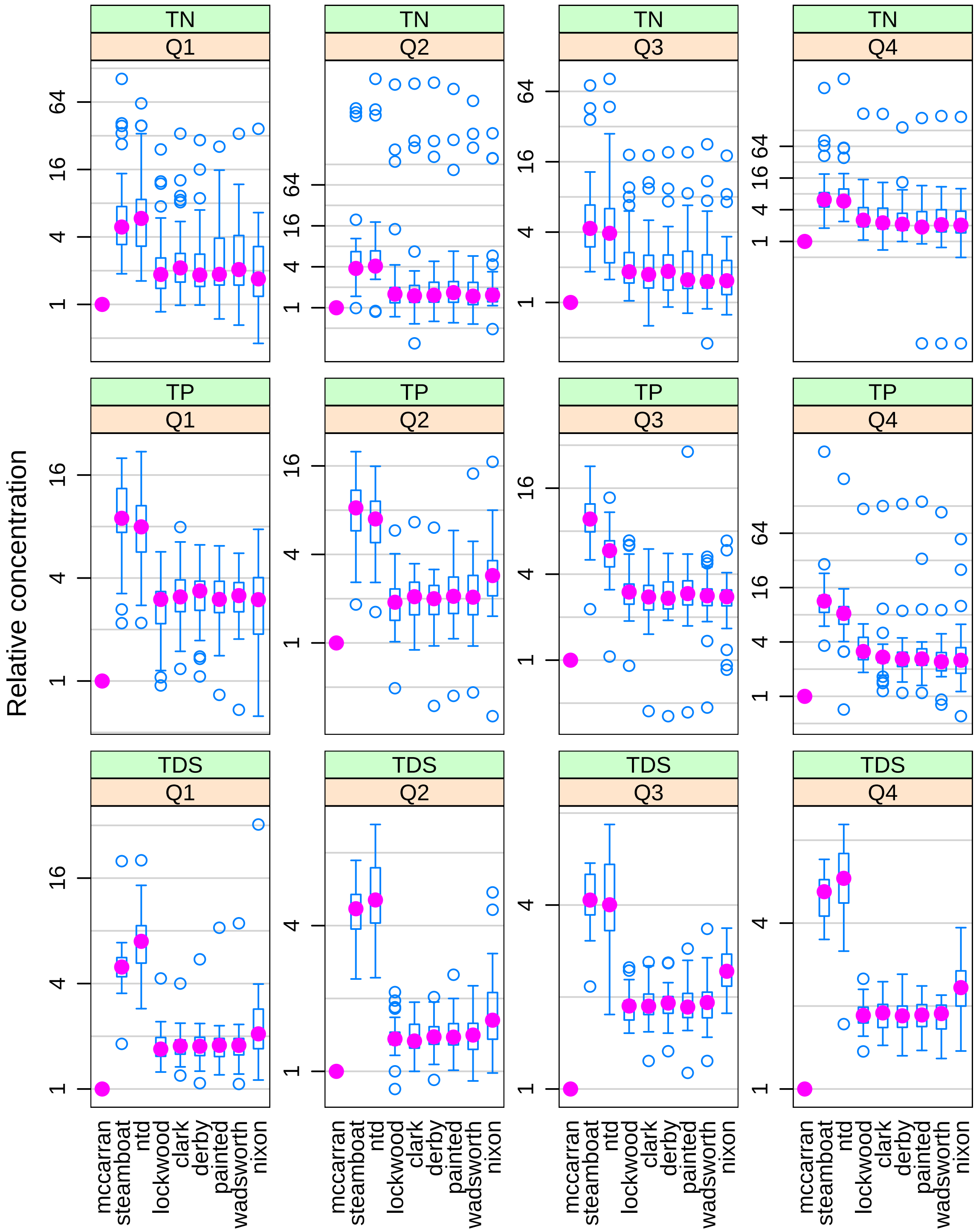



Figure 3.5: Distributions of monthly mean concentrations at TMWRF stations relative to the monthly mean at *mccarran*, 1995-2006.

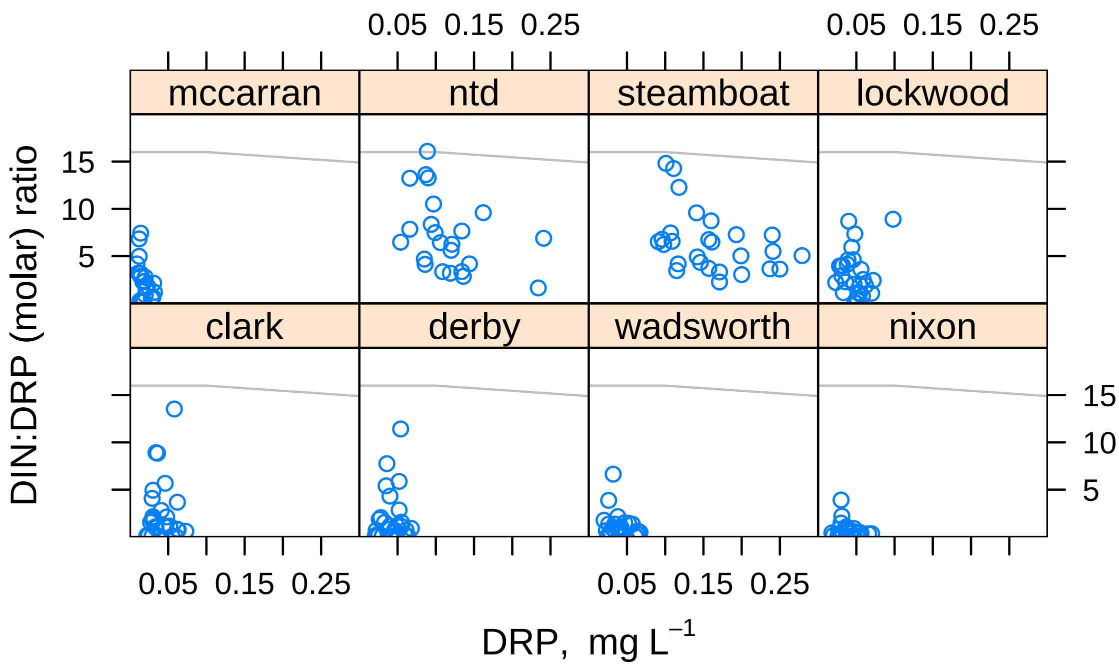



Figure 3.6: DIN:DRP molar ratios versus DRP at TMWRF stations during summers of 1998–2006. *Grey line,* dividing line between likely N and likely P limitation.

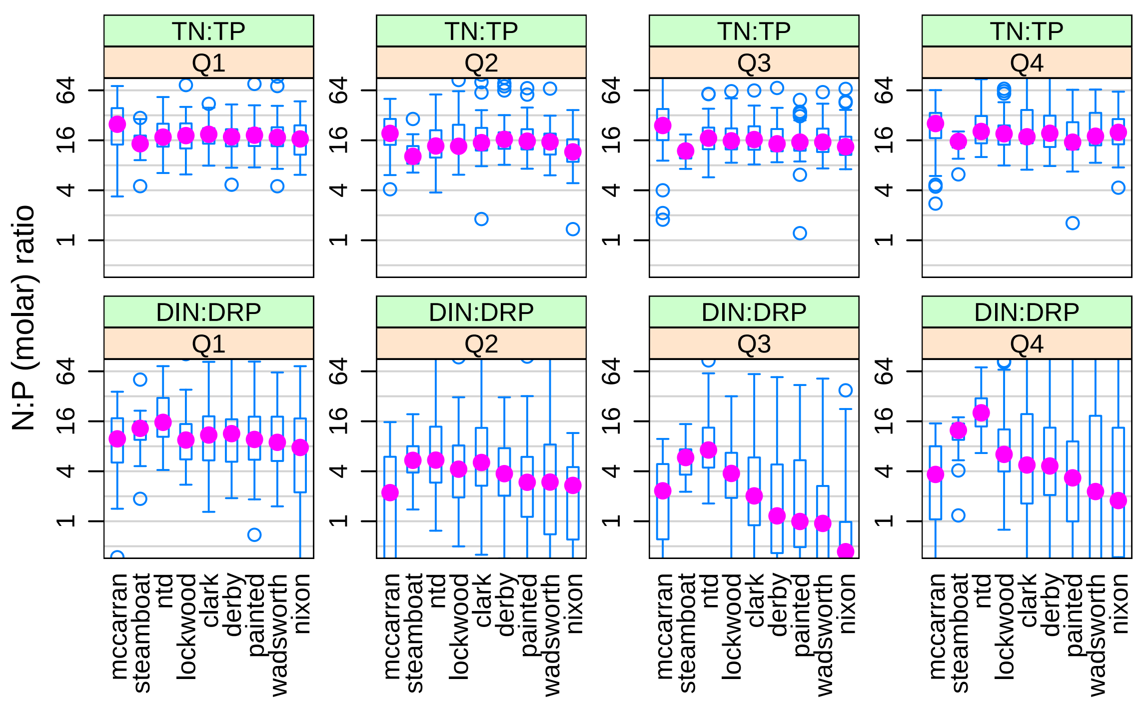



Figure 3.7: Seasonal distributions of total and inorganic N:P ratios at TMWRF stations during 1995–2006.

Table 3.2: Median fractions of TN and TP contributed by inorganic forms DIN and DRP, respectively, during 1995–2006.

| | Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|
| *DIN:TN* | | | | |
| mccarran | 0.22 | 0.08 | 0.04 | 0.07 |
| steamboat | 0.43 | 0.31 | 0.29 | 0.51 |
| ntd | 0.53 | 0.29 | 0.30 | 0.56 |
| lockwood | 0.26 | 0.12 | 0.11 | 0.21 |
| clark | 0.24 | 0.15 | 0.08 | 0.14 |
| derby | 0.26 | 0.12 | 0.04 | 0.13 |
| painted | 0.27 | 0.10 | 0.04 | 0.10 |
| wadsworth | 0.23 | 0.09 | 0.03 | 0.06 |
| nixon | 0.19 | 0.07 | 0.02 | 0.03 |
| *DRP:TP* | | | | |
| mccarran | 0.66 | 0.44 | 0.60 | 0.60 |
| steamboat | 0.58 | 0.62 | 0.62 | 0.60 |
| ntd | 0.63 | 0.63 | 0.67 | 0.61 |
| lockwood | 0.45 | 0.46 | 0.54 | 0.50 |
| clark | 0.44 | 0.45 | 0.54 | 0.51 |
| derby | 0.44 | 0.47 | 0.50 | 0.51 |
| painted | 0.45 | 0.45 | 0.52 | 0.50 |
| wadsworth | 0.41 | 0.41 | 0.46 | 0.49 |
| nixon | 0.37 | 0.32 | 0.49 | 0.40 |

Truckee River Water Reclamation Facility.

# 4

# TMWRF effluent trends and loads

## 4.1 Loading and WLAs

Monthly averages of daily loading were calculated for key water quality constituents related to WLAs for the Truckee River (Figure 4.1). These time series show a variety of patterns related, at least in part, to changes in plant operations and effluent flow rates. The latter is most obvious in the case of TDS, which simply reflects discharge rates. The former is most obvious in the case of TN: Beginning in 1994, the nitrification towers became contaminated with aquarium snails that grazed the nitrifying bacteria to very low levels, resulting in an increase of DIN and TN. The problem was brought under control in 1997. In 2001, an upgrade to the plant required a temporary reduction in N treatment efficiency, resulting in higher TN loading.

How did these effluent loads fare with respect to their Waste Load Allocations? Figure 4.2 illustrates some of these same data, but in relationship to the WLAs. The 30-day average (May–October) TN WLA was exceeded only 5 out of a possible 48 months since 1998, while the annual TN WLA was exceeded 3 of the 8 years since then. TDS always remained below its annual WLA of 120,168 lb $d^{-1}$. TP load exceeded its WLA an average of 9 days per year since 1998. Few of these exceedances, however—only 8 out of 70 days since 1998—occurred during summer when periphyte metabolism is high and DO problems most likely.

## 4.2 Effluent trends

Have there been any trends in effluent concentrations or loads since the TMDLs were instituted in 1994? Trends (Theil-Sen trends) were calculated for each of the constituents in Figure 4.1 and their statistical significance determined with the Seasonal Kendall test corrected for serial correlation (Figure 4.3). All N fractions other than DON exhibited negative

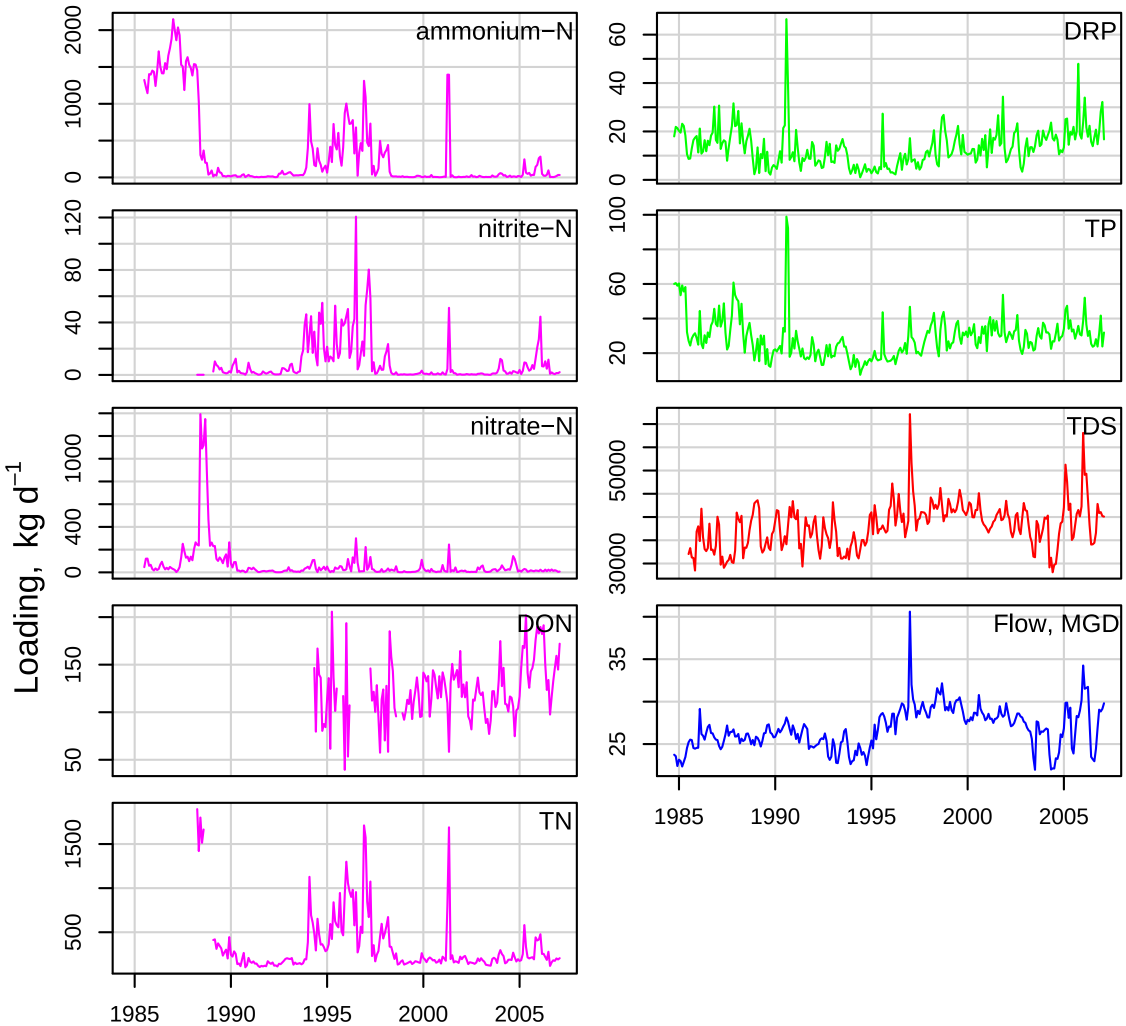



Figure 4.1: Monthly averages of daily constituent loads in TMWRF wastewater effluent.

trends in both concentration and loading. None of these were statistically significant, however, because of high year-to-year variability during this period. DON trends, in contrast, were positive, and the concentration trend in particular was statistically significant. Trends in TDS concentration and loads were both close to zero. DRP and TP, on the other hand, both showed statistically significant positive changes in concentration and loading, with the trends in DRP being much larger. For all of these constituents, it is the negligible trend in effluent flow during this period that causes the loading trends to reflect the concentration trends so closely.

County population increased at an almost perfectly exponential growth rate since the TMDL implementation, with a doubling time of 27 yr (1994–2004; Figure 4.4). The combined populations of Reno and Sparks exhibited an identical doubling time over the same period. Since 1995, the TP load has had a doubling time of 20 yr, slightly less than but consistent with the population increase. DRP, though, has had a much faster doubling time of only

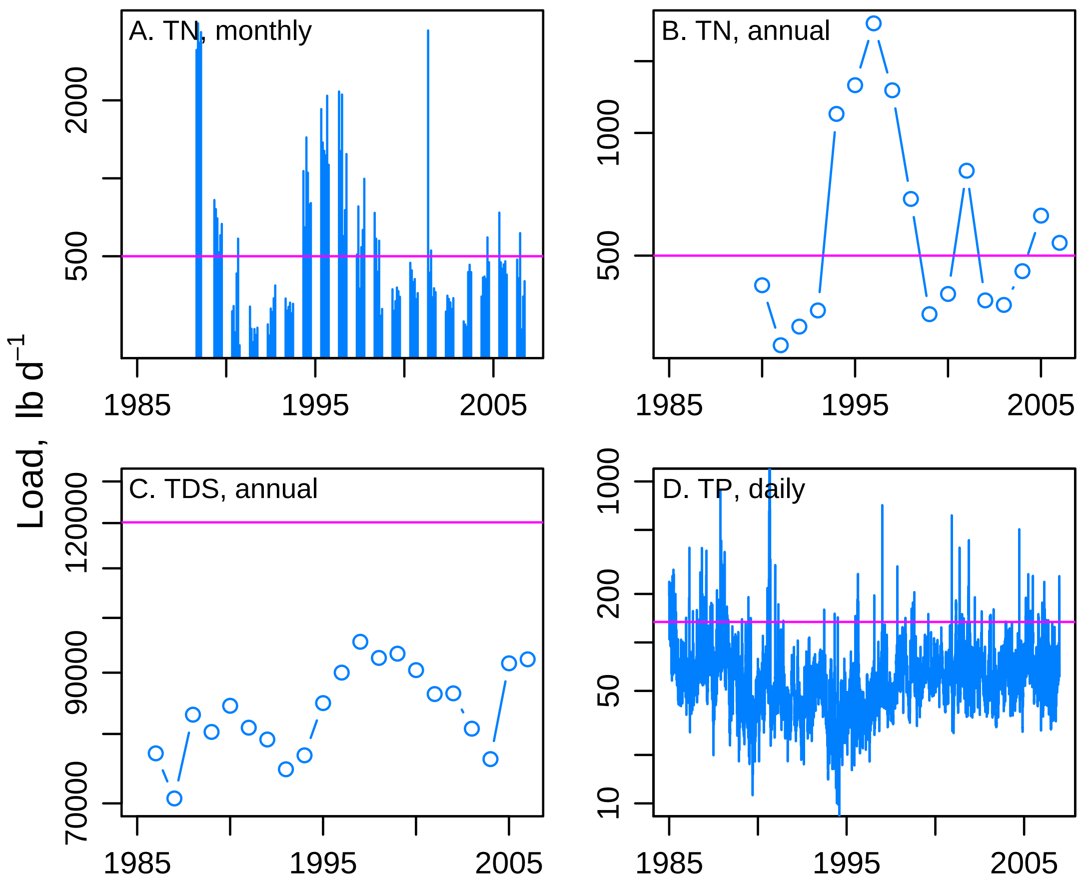



Figure 4.2: (A) Monthly average TN loads during May–October. *Horizontal line,* TN WLA 30-day average (May–October) (B) Annual average TN loads. *Horizontal line,* TN WLA annual average. (C) Annual average TDS loads. *Horizontal line,* TDS WLA annual average. (D) Daily TP loads. *Horizontal line,* TP WLA. All units are in lb $d^{-1}$ rather than metric to allow easy comparison with the original WLA specifications.

7 yr. Effluent trends do not necessarily mirror the population increase in Washoe County due to changes in product formulations (e.g., detergents), treatment processes, and possible discrepancies between the cities' and service area's populations. Moreover, the Truckee Meadows Water Authority has a water conservation effort that is more strongly implemented during drought years. The effect on annual influent/effluent flow as well as on the longer-term trend can be pronounced and there is little relation with population change. Nonetheless, the larger DRP trend may signify new sources over and above the population increase, which should be investigated with other data and tools.

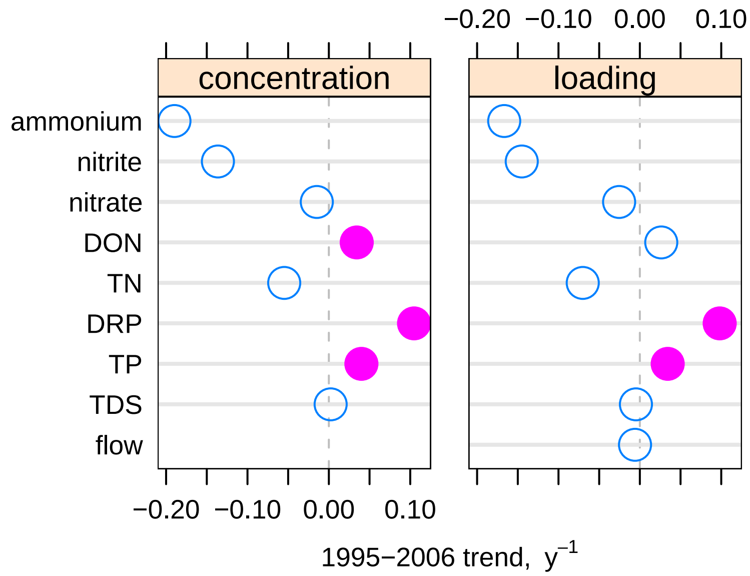



Figure 4.3: Trends in effluent concentrations and loads during 1995–2006. Trends are expressed as a fraction of the median data value during the period. Trends represented by solid circles are statistically significant ($p < 0.05$) whereas trends represented by empty circles are not.

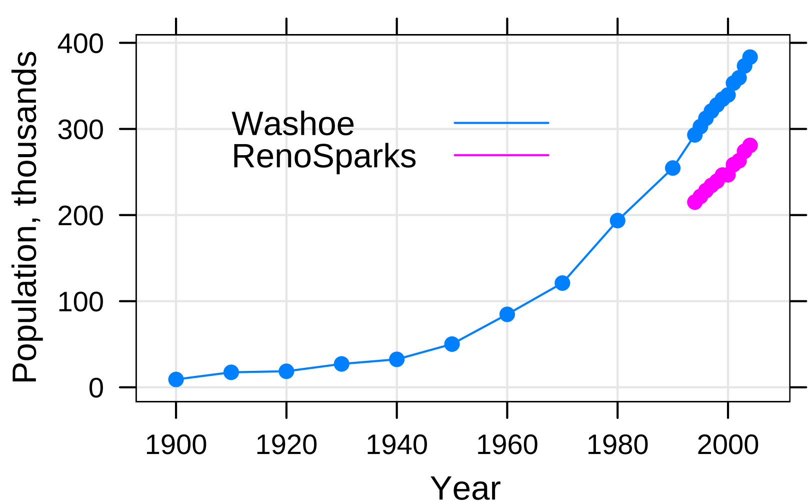



Figure 4.4: Population of Washoe County [25] and of Reno and Sparks combined [1].

## 4.3 DON in effluent

The portion of the TN load due to DON is of interest because the DON pool as a whole is less reactive than inorganic forms of N and may contribute less to eutrophication than otherwise suggested by its N content. DON is a complex mixture of compounds, from simple amino acids that are readily taken up by many plants to complex organic compounds that may be too large to cross cell membranes and too complex for decomposition by single extracellular enzymes. The DON percentage in effluent rose before 2000 because of treatment plant improvements that decreased the load of inorganic N. In the last five years, the monthly DON percentage ranged from 29 to 83%, with a median of 65. The annual DON percentage is much more stable, ranging from only 57 to 67%, with a median of 64. As a percentage of soluble N, these medians were 76 and 72%, respectively. The reactivity of DON therefore has a large impact on the eutrophication potential of the effluent TN loads.

It is interesting to compare the amount that actual TN loads exceeded WLAs with the loads due to DON. In the case of the monthly TN WLA, the "excess" amounted to 39-53% of the DON load (Figure 4.1). In other words, 39-53% of the DON load would have to be completely recalcitrant in order for TN loading to satisfy the "spirit," if not the "letter," of the WLAs. Similarly, 11-37% of the annual DON load would have to be recalcitrant.

The division into labile or bioavailable and recalcitrant fractions is highly dependent on the specific method chosen. Of special importance is the time allowed for whatever reaction is being used to assess bioavailability. Some DON may be recalcitrant with respect to the time required for transport between the treatment plant and Pyramid Lake, which is characteristically a week or two. But it will contribute to the DON pool in the lake and, over a longer time period, will increase the regeneration rate of DIN from DON in the lake. Because Pyramid Lake is a terminal lake, much more DON could eventually become available, aside from DON that exits during overflow years. The concept of "recalcitrance" can have a useful working definition with respect to the river, but may be too vague and require too many assumptions for application to the lake.

According to the available literature, then, what percent of the DON in effluent might be "recalcitrant" and unavailable, at least for plant growth, in the river downstream of the plant? Estimates of bioavailable N in runoff TN range from ca. 0 to 70%, depending

Table 4.1: For the period 2002–2006, individual months during May–Oct and whole years when average TN exceeded 500 mg $L^{-1}$. *Excess,* Amount over 500 as a fraction of DON.

| Year | Month | TN | DON | Excess |
|---|---|---|---|---|
| 2004 | Sep | 592 | 234 | 0.39 |
| 2005 | May | 737 | 446 | 0.53 |
| 2006 | Jul | 614 | 295 | 0.39 |
| | | | | |
| 2005 | annual | 627 | 345 | 0.37 |
| 2006 | annual | 538 | 332 | 0.11 |


Truckee River "Reach Y" near TMWRF.

to a large extent on whether the source is forest, agriculture or urban [22]. Estimates for wastewater are harder to come by but a recent study implies that the potential bioavailability of wastewater DON for algae may be as high as 60% [16]. Assuming that recalcitrant DON may be as low as 40%, only in May 2005 would there have been a "functional" exceedance of the WLA (Table 4.1) as far as the river is concerned.

With respect to the lake, the extent of DON bioavailability from the plant is probably not that important. During 1998–2006, the DON load from treatment plant effluent was only 13% of the river TN load above *lockwood*. In other words, the exact percent of the DON load that is recalcitrant, however this is defined, does not have important implications for Pyramid Lake because it is a minor part of the total N loading to the lake.

# 5

# River trends and loads

## 5.1 Trends

Time series for different N fractions at *lockwood* are plotted in Figure 5.1. These plots illustrate large decreases in the early 1990s, largely paralleling nitrification-denitrification improvements to the treatment plant and its reduced loading (Figure 4.1). The snail infestation that disrupted N treatment at the plant during 1994-1997 also has a clear signature in the river time series. Since then, N concentrations have remained at historically low levels, except for a brief period in spring 2001 when nitrification towers and denitrification fluidized beds were shut down for a treatment plant upgrade. Note that TN concentrations have increased more recently, but this reflects at least in part prolonged changes in streamflow (see below). Time series of P, TDS and DOC at *lockwood* are plotted in Figure 5.2. Declines have also taken place in these constituents since the early 1990s, although again somewhat reversed in recent years. An unusual spike in DOC occurred in 2005, but this was due to a single measurement.

Trends in key water quality constituents from the TMWRF database were estimated for the period since the TMDLs were adopted, namely, 1995–2006. The observations are highly affected by streamflow, especially for certain constituents like TDS. The time series were adjusted for flow and corrected for serial correlation as described in Section 2.2. Among the variables of most interest—TN, TP, and TDS—only TN was affected by censoring, most of it due to nitrate and especially nitrite measurements. TKN constitutes a median of 85.2% of TN, and TKN + nitrate-N a median of 99.7%, so it is preferable and almost as informative to examine trends in TKN and nitrate separately instead of in TN. Because only 2.6% of the TKN data were censored, nitrate was the only constituent that required use of Tobit regression. The Seasonal Kendall test was used for other constituents.

Although all Truckee River TKN trends were slightly positive, none of them were statistically significant (Figure 5.3). Only *ntd* and *steamboat* (upstream of the treatment plant) exhibited significant positive trends in TKN. Nitrate levels fell during this period at *lock-*

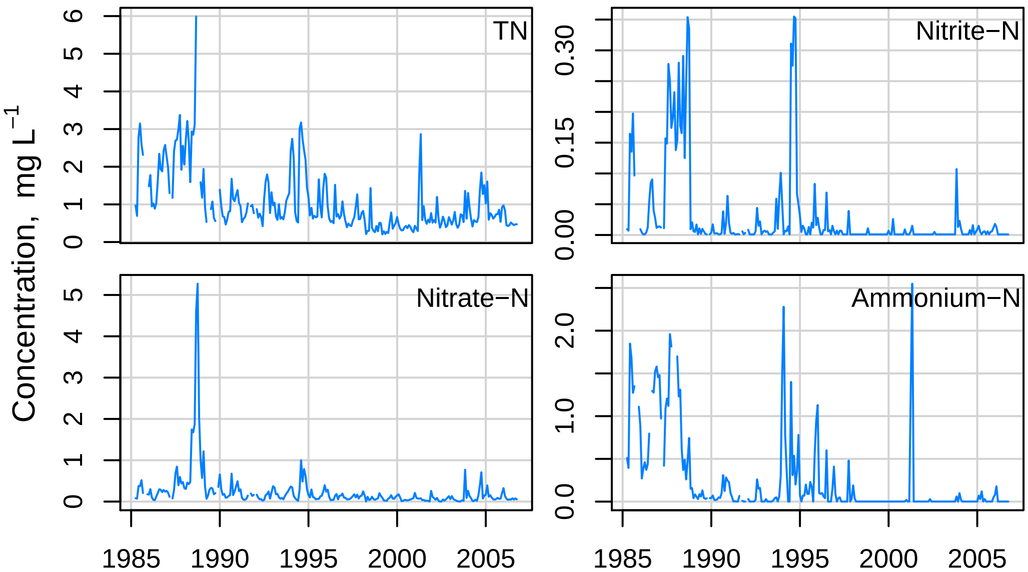



Figure 5.1: Time series of monthly average N fractions at *lockwood*.

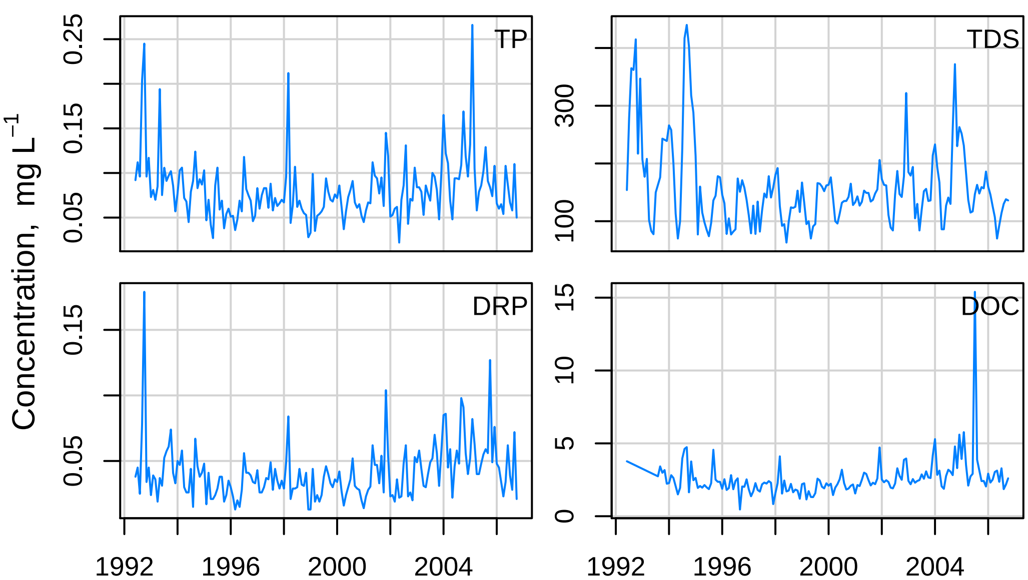



Figure 5.2: Time series of monthly average P fractions, TDS and DOC at *lockwood*. Missing months have been interpolated.

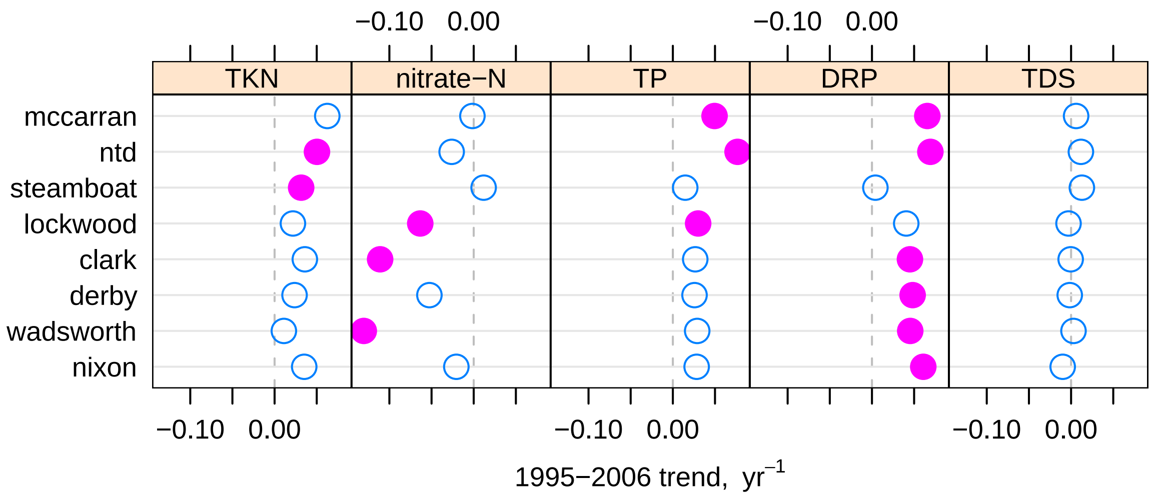



Figure 5.3: Trends in water quality constituents during 1995–2006, expressed as a fraction of median concentration. Trends are adjusted for flow and corrected for serial correlation. Trends represented by solid circles are statistically significant ($p < 0.05$) whereas trends represented by empty circles are not.

*wood*, *clark* and *wadsworth*. Nitrate trends at other stations were either close to neutral or negative, albeit not statistically significant. In contrast, TP trends were positive everywhere, and trends at *mccarran*, *ntd* and *lockwood* in particular were statistically significant. DRP trends were also positive everywhere and statistically significant at all stations except *steamboat* and *lockwood*. These P trends are consistent with TMWRF effluent loading trends described in Section 4.2. TDS exhibited no trends at all during this period.

## 5.2 Long-term average loads

How much does TMWRF effluent contribute to the river load? The most appropriate time scale and summary statistic for examining relative contributions to river loads depends on the exact form of this question. In Pyramid Lake, for example, the residence time of DIN is about four years [12]. N availability at any time therefore depends on the integrated contribution of many sources over several years rather than river loading during the current day or even month. One should therefore compare mean or cumulative daily contributions over at least several years. Here we look at mean contributions during the period 1998–2006 because it avoids earlier treatment plant anomalies (Section 4.1) and yet includes years of widely varying precipitation (Figure 2.4).

In the river itself, on the other hand, seasonal periphyton accumulations and resulting oxygen problems are most problematic in summer, which is therefore the appropriate season for assessing nutrient contributions. Moreover, the median load during summer is a more appropriate statistic than the mean load. The mean can be heavily influenced by isolated flow events that have only transient effects on the periphyton environment; the median will reflect more characteristic conditions that are ultimately more relevant for persistent periphyton problems. We therefore also examine median contributions during summer 1998–2006.

Mean loading estimates for 1998–2006 and their 95% confidence intervals are contained in Table B.1 (in Appendix B). The number of days in this period is 3287 and most stations have estimates for every constituent for every day. *Steamboat* and *ntd* are missing almost four months of estimates and may be somewhat biased. There are many uncertainties in the process of estimating loading from model-based rating curves such as Equation 2.1. Daily rating curves typically show much scatter, which implies that estimates of daily load based on discharge are usually highly uncertain. However, when averaging these estimates over long periods, such as several years, the errors cancel somewhat and the estimates of these long-term averages can be reliable enough to draw interesting conclusions. The confidence intervals in these tables bear this out in that, while large, they do point to clear differences among stations.

Table 5.1 is based on Table B.1. It contains the means for some of the same constituents, but also includes derived estimates for DON and TN, as well as effluent data for TMWRF. As a check, we first compare the load at *lockwood* with the sum of the following loads: TMWRF, *mccarran*, *steamboat* (upstream of TMWRF), and *ntd* (Figure 2.5). TN and TP are the relevant N and P constituents because they are more conserved during transport than individual components such as ammonium. Unless there are systematic losses or gains in these loads before *lockwood*, the long-term means should correspond approximately. For TN, the ratio of the sum of upstream loads to *lockwood* loads is 1.20. For TP and TDS, the ratios are 1.02 and 1.10, respectively. Because estimates of TMWRF loads are developed independently of river loads, the close correspondence for at least TP and TDS is gratifying: It suggests that the methods used to estimate river loads are not unduly biased. The TN correspondence is not as convincing but, given that TDS and especially TP are so close to 1, the discrepancy may represent real net TN losses from the sources in transit to *lockwood*.

The contribution of TMWRF effluent can be determined from the same table using the ratio of TMWRF load to the sum of all four loads upstream of *lockwood*, namely, *mccarran*,

Table 5.1: Mean daily loads (kg $d^{-1}$) of water quality constituents during 1998–2006.

| | $NH_4$-N | $NO_2$-N | $NO_3$-N | DON | TN | DRP | TP | TDS |
|---|---|---|---|---|---|---|---|---|
| tmwrf | 62.0 | 3.90 | 22 | 130 | 230 | 16.0 | 32.0 | 40000 |
| mccarran | 3.8 | 3.20 | 99 | 410 | 750 | 33.0 | 68.0 | 170000 |
| steamboat | 6.7 | 2.20 | 140 | 69 | 280 | 21.0 | 35.0 | 56000 |
| ntd | 1.4 | 0.96 | 21 | 25 | 59 | 4.7 | 7.8 | 21000 |
| lockwood | 35.0 | 8.30 | 140 | 620 | 1100 | 70.0 | 140.0 | 260000 |
| clark | 120.0 | 15.00 | 400 | 570 | 1400 | 67.0 | 160.0 | 270000 |
| derby | 91.0 | 9.20 | 330 | 350 | 1100 | 45.0 | 100.0 | 160000 |
| wadsworth | 65.0 | 13.00 | 280 | 460 | 1100 | 53.0 | 130.0 | 180000 |
| nixon | 25.0 | 14.00 | 650 | 480 | 1600 | 60.0 | 180.0 | 200000 |

*steamboat*, *ntd* and TMWRF itself. During this period, TMWRF contributed the following part of the river load upstream of *lockwood*: 17% of TN, 22% of TP and 14% of TDS. The largest contributions of all three constituents came from *mccarran*, which provided 57, 48 and 59%, respectively. TMWRF and *steamboat* upstream of the plant provided similar amounts and *ntd* substantially less.

Lockwood Bridge was chosen as the TMDL compliance point for assessing loads because most controllable sources are upstream. To whatever extent this is true, there are still important sources of nutrients downstream of *lockwood*. The transition from *lockwood* to *clark* is especially notable (Table 5.1). TN, TP and TDS increase between these two stations, 27, 14 and 4%, respectively. The TN increase is due primarily to nitrate but also ammonium. This increase of 300 kg $d^{-1}$ is actually larger than (although not significantly different from) the TMWRF effluent load. Moreover, given that the increment between *lockwood* and *clark* appears to be almost entirely DIN and therefore bioavailable, its TN contribution could be ecologically more important than TMWRF's despite the similar magnitudes. What are the N sources in this watershed increment? Their identification is obviously of great importance to the Pyramid Lake N balance: They contribute 27% of the TN load and 66% of the DIN load at *clark*. Controlling them may offer an opportunity for mitigation of TMWRF loads.

The watershed drainage area for *mccarran* is 2771 $km^2$ (Table 2.3), implying an annual mean TN yield of $365 \times 750 \div 2771 = 99$ kg $km^2$ $yr^{-1}$. The marginal yield between *mccarran* and *lockwood*, i.e., the increase in load per increase in drainage area, is 137 kg $km^2$ $yr^{-1}$, reflecting the more urbanized character of this watershed increment. But the marginal yield between *lockwood* and *clark* is 284 kg $km^2$ $yr^{-1}$, an unexpectedly large amount and again pointing to some unexpected source in this area. In the case of TP, the yield at *mccarran* is 9.0, the marginal yield at *lockwood* is 28, and the marginal yield at *clark* is 19 kg $km^2$ $yr^{-1}$. For TDS, the yield at *mccarran* is 22, the marginal yield at *lockwood* is 35, and the marginal yield at *clark* is only 9.5 t $km^2$ $yr^{-1}$. The urbanized watershed area therefore provides the highest yield for both TP and TDS but not for TN.

The interpretation becomes more complex downstream of *clark*. Loads at derby reflect not only increases due to inputs from the additional watershed area but also diversion into the Truckee Canal. Loads of all water quality constituents are lower here compared to *clark* (Table 5.1). Further downstream, flows are a result of irrigation withdrawals through additional diversions, return flows from the canal via the Gilpin Spillway plus leakage, and other surface and subsurface irrigation return flows. Runoff is relatively unimportant [10].

The loading estimates at *nixon* are notable because TN and TP loads exceed the loads at *clark*. Concentration through evaporation cannot account for the change because TDS increases by only 11% whereas TN increases by 45%. Most of the TN change is attributable to a nitrate increase. The TN and TP loading increments between *wadsworth* and *nixon* are larger than the respective contributions by TMWRF effluent, as well as by the watershed increment between *lockwood* and *clark*. The area between *wadsworth* and *nixon* may therefore offer an opportunity for efficient reduction of N and P loading to Pyramid Lake.

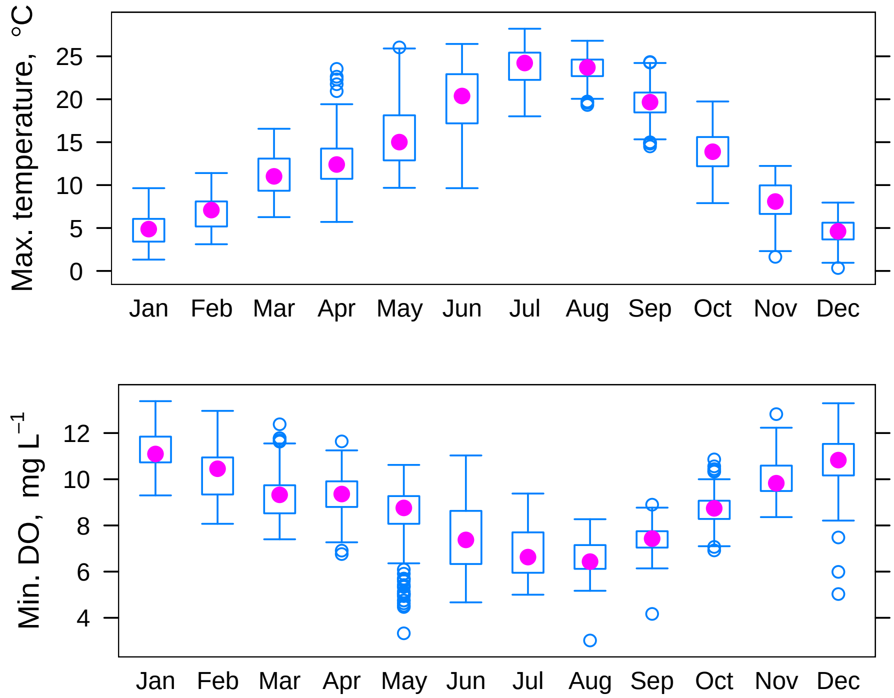



Figure 5.4: Distributions of daily maximum temperature and minimum DO at Wadsworth during 1998–2006. These boxplots are based on hourly sonde data because most sampling times in the regular monitoring program occur before the maximum daily temperature and after the minimum DO (Figure 3.3).

Note also that the 1998–2006 TN:TP (molar) ratio in loading at Nixon is 20. This value is close enough to the average phytoplankton molar ratio of 16 and cannot, by itself, be said to favor either N or P limitation in growth rate or biomass of Pyramid Lake phytoplankton.

## 5.3 Seasonal loads

Now we focus on loading summaries more relevant to water quality conditions in the river itself, as opposed to the lake, particularly with respect to DO and periphyton problems. We examine the "characteristic" contributions of TMWRF and other sources during the times when problems manifest. In particular, we look at the median percentage contribution to the daily load during summer, the season of highest temperature and biological metabolism [26] and lowest DO (Figure 5.4). The summer season is not, of course, completely problematical, nor is it the only season where problems may occur. It is used here as a convenience because problematic days differ among years and stations.

The calculation requires estimating TMWRF effluent loads for days of missing observations, much as we did for river loads. In the case of TMWRF, however, there is no reason to expect a dependable relationship between flow and constituent levels, nor did we find one. So missing observations are estimated simply by interpolating between measured values. We checked this procedure by repeating calculations with and without interpolated values and found little difference in terms of interpretation. But the interpolated values are probably less biased and are used here. Table 5.2 lists median daily loads during summer.

Although these can be used directly to estimate median contributions of different sources upstream of *lockwood*, it is more accurate to calculate the median daily ratio of TMWRF to TMWRF + *mccarran* + *steamboat* + *ntd* during this same period. The latter ratio is shown in Table 5.3. TMWRF provides most of the ammonium upstream of *lockwood* but little of the nitrate or nitrite; the total DIN contribution is 22%. TN, TP and TDS contributions range from 22 to 29%. These are substantially higher than contributions to the total 1998–2006 loading (Table 5.1 but the *mccarran* load is still the dominant one, especially for TN and TDS (Table 5.2).

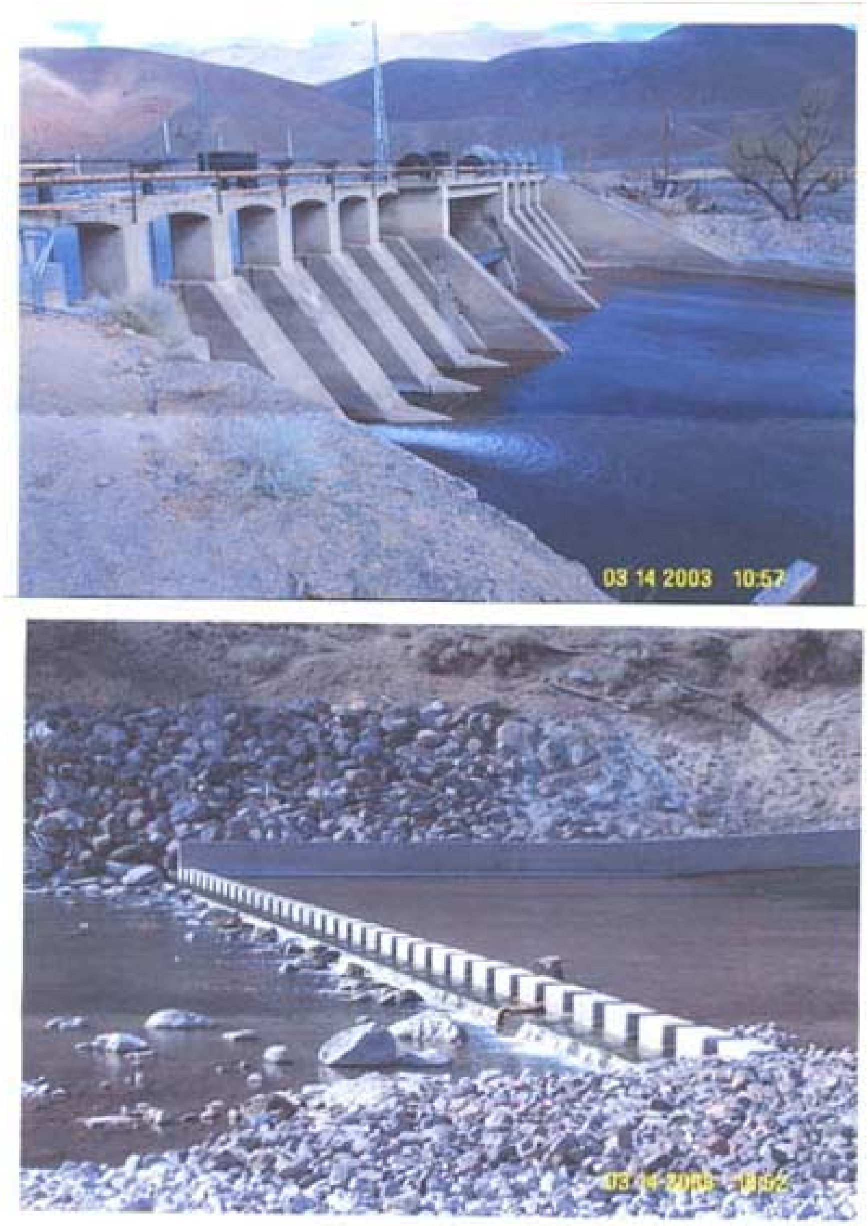
It is interesting to note that the median DRP values at *lockwood* and downstream are about 1 $\mu$mol $L^{-1}$ (Figure 3.6). Studies have shown "that phosphate concentrations of unperturbed turbid rivers (SPM $>$ 50 mg $L^{-1}$) are controlled near the dynamic equilibrium phosphate concentration of their particles ($EPC_0$ = 0.2-1.5 $\mu$M)" [4]. The median behavior of DRP at *lockwood* and downstream is largely consistent with this mode of control. It would be informative to investigate the $EPC_0$ in more detail because it shows whether river-bed sediments have the potential for net DRP uptake or release [9]. River-bed sediment P can be taken up directly by rooted plants but is not significant for nuisance algae proliferation if DRP exceeds $EPC_0$. Conversely, if sediments have the potential for release, then this indicates that particulate P (PP = TP - DRP) loads are probably contributing to P bioavailability. In the former case, emphasis should be on control of DRP; in the latter, emphasis should be on TP. The TMWRF contribution is similar in both cases (Table 5.3), but the $EPC_0$ can tell

Table 5.2: Median daily loads (kg $d^{-1}$) of water quality constituents in summers of 1998–2006.

| | $NO_3$-N | $NO_2$-N | $NH_4$-N | DON | TN | DRP | TP | TDS |
|---|---|---|---|---|---|---|---|---|
| tmwrf | 6.4 | 0.33 | 4.6 | 120 | 180 | 15.0 | 29.0 | 40000 |
| mccarran | 25.0 | 1.60 | 0.7 | 220 | 410 | 19.0 | 36.0 | 85000 |
| steamboat | 24.0 | 1.20 | 2.3 | 52 | 120 | 14.0 | 23.0 | 34000 |
| ntd | 16.0 | 1.00 | 1.1 | 31 | 60 | 5.6 | 8.5 | 21000 |
| lockwood | 73.0 | 5.70 | 9.9 | 390 | 680 | 53.0 | 93.0 | 160000 |
| clark | 62.0 | 7.40 | 7.7 | 330 | 570 | 41.0 | 76.0 | 160000 |
| derby | 16.0 | 1.60 | 2.3 | 130 | 200 | 16.0 | 30.0 | 56000 |
| wadsworth | 17.0 | 1.90 | 2.3 | 220 | 360 | 23.0 | 46.0 | 93000 |
| nixon | 11.0 | 0.66 | 3.4 | 220 | 360 | 25.0 | 52.0 | 130000 |

Table 5.3: Median ratio of daily TMWRF loads to daily combined loads of TMWRF + *mccarran* + *steamboat* + *ntd* in summers of 1998–2006.

| $NO_3$-N | $NO_2$-N | $NH_4$-N | DIN | DON | TN | DRP | TP | TDS |
|---|---|---|---|---|---|---|---|---|
| 0.084 | 0.079 | 0.51 | 0.22 | 0.29 | 0.23 | 0.28 | 0.29 | 0.22 |




Above and below Derby Dam, showing dewatering of Truckee River.

us which to emphasize in terms of nutrient management.

Although sources between *lockwood* and *clark*, and between *wadsworth* and *nixon*, have an impact on the the total load to Pyramid Lake, they do not appear to be important in governing instream conditions during the season of periphyton development and low oxygen. Most of the total annual load occurs in winter and spring when streamflow is higher (Figure 2.4). In contrast to the total load for 1998–2006, there is little or no increase in summer median load between *lockwood* and *clark*, and between *wadsworth* and *nixon*, for TN and TP.

# 6

# Concluding remarks

Any revision of TMDLs and WLAs need to take into account the relevant time scales for the resources that they are intended to protect. Traditionally, the relative importance of different sources has been estimated from annual loads, often dominated by diffuse inputs in storm runoff from intensively managed agricultural or high-density urban areas. But river habitat quality is more closely tied to characteristic concentrations during ecologically sensitive seasons. As far as the lake is concerned, the appropriate scale is the integrated load over at least a year. The annual or even biennial average should suffice. As far as hypoxia in the lower river is concerned, the appropriate scale is the daily load. Moreover, the daily WLAs should be seasonal, lowest during the summer season or perhaps late spring–early autumn, which is the period having a high probability of including all low-oxygen conditions.

TN exceeded the Nevada water quality standards at Lockwood only 9% of the time during 1998–2006. Moreover, TN values are very close to ambient conditions for this ecoregion. This contrasts strongly with the 1980s and largely reflects tertiary treatment processes at TMWRF that have dramatically reduced inorganic N. As a result, the TMWRF 1998–2006 contribution to TN loading above Lockwood Bridge was 17% and its median summer contribution was 22%. The treatment plant did experience WLA exceedances during this period. But aside from the anomalous 2001 conditions, these were few and relatively small. Moreover, experimental evidence regarding wastewater DON suggests that the actual bioavailable TN was less than the WLA in all but one case.

The strong downriver decrease in summer N:P ratios shows that periphyton metabolism and resulting hypoxia may be sensitive to the N supply; N control is therefore indeed important for the lower river. Given that (1) TMWRF appears to meet the “spirit” of the TN WLA in terms of bioavailability, and almost the “letter” of the WLA; (2) TMWRF TN effluent concentrations are close to the best achievable with current technology; and (3) TMWRF does not dominate TN river loads above Lockwood; treatment plant improvements do not appear to be an effective way to control TN loads to the lower river and the lake. Indeed, there may be far better opportunities elsewhere. Steamboat Creek currently contributes an amount similar to TMWRF and the river upstream two to three times as much, depending on whether integrated load or summer median load is the measure. Moreover, the trend tests showed that TKN is increasing in Steamboat Creek upstream of TMWRF and in the North Truckee Drain, as well as possibly in the upstream Truckee River itself. In terms of the integrated river load to the lake, there also appear to be large sources downstream between Lockwood and Clark, and especially between Wadsworth and Nixon, that need to be identified and assessed for possible mitigation. A priority should be to map these watershed areas for potential sources and, if necessary, to design a synoptic study that can then compare their actual contributions.

The record shows that TMWRF would probably meet current WLAs if the recalcitrant DON, as typically defined, were excluded. This may be especially important in the future because effluent DON concentration and loading is increasing, although the latter trend is not (yet) statistically significant.

Of the TMDL water quality constituents, TP levels most often exceeded the Nevada standards at *lockwood*. In fact, the standard of 0.05 mg $L^{-1}$ annual average was exceeded every year by a median of about 50%. TP also was elevated about two-fold with respect to ambient stream and river water quality conditions in the region. TP and especially DRP loading from TMWRF has increased since 1995. At least for TP, the increase is similar to the population increase. The TMWRF 1998–2006 contribution to TP loading above Lockwood Bridge was 22% and its median daily contribution in summer was 29%, more than for TN. Exceedances of the TP WLA were not uncommon during 1998–2006 although they were rare in summer.

Despite the low N:P ratios downstream in summer, the potential for nitrogen-fixing periphyton to provide their own N supply means that restricting P may ultimately be the way to ensure limitation of periphyton biomass. TMWRF P loading has increased, but TP and DRP have also increased in the Truckee River upstream of the plant as well as in the North Truckee Drain. In terms of integrated loads during 1998–2006, TMWRF contributed about the same as Steamboat Creek and half as much as the upstream Truckee River. In terms of median daily loads during summer, TMWRF contributed about three-quarters as much as much as the upstream Truckee and more than Steamboat Creek. Once again, the contribution between Wadsworth and Nixon to the integrated load exceeded the TMWRF contribution although the increase between Lockwood and Clark was not as dramatic. In contrast, the downstream contributions to the median daily load in summer seemed unimportant. In terms of integrated TP loads to the lake, then, all of the main sources—upstream Truckee, Steamboat, TMWRF, Lockwood-Clark watershed increment, Wadsworth-Nixon watershed increment—merit examination. In terms of summer median loads, the first three sources are the most useful ones to consider in terms of mitigation. The inclusion of tests for equilibrium phosphate concentration may help to pinpoint further which P fractions, DRP or PP or both, should have priority for management.

TMWRF experienced no WLA exceedances for TDS, and the river at Lockwood met the NAC standards. There were no detectable long-term trends either in TMWRF loading or river concentrations after correcting for flow. The major opportunity for reducing integrated salt load to the lake appears to be upstream of East McCarran Bridge.

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# Appendix A

# Water quality summary

Table A.1: Summary of the best-sampled variables in the TMWRF river monitoring database. All records summarized here end between 2006-09-19 and 2006-10-19. Temperature is in °C, pH in standard units, and concentrations in mg $L^{-1}$. *Num.,* number of samples; *Cens.,* fraction censored; 0.25 and 0.75, respective quantiles.

| | Num. | Cens. | Start | Min. | 0.25 | Med. | 0.75 | Max. |
|---|---|---|---|---|---|---|---|---|
| *McCarran:* | | | | | | | | |
| Temp. | 399 | | 1985-04-23 | 0.1 | 4.85 | 9.2 | 14.3 | 25 |
| DO | 398 | | 1985-04-23 | 6.6 | 9 | 10.4 | 11.6 | 14.8 |
| pH | 395 | | 1985-04-23 | 6.2 | 7.6 | 7.8 | 8.1 | 9.2 |
| Alk. | 183 | | 1993-06-21 | 27 | 38 | 43 | 48 | 76 |
| NH4-N | 393 | 0.8 | 1985-04-23 | 0.001 | 0.001 | 0.001 | 0.02 | 0.327 |
| NO2-N | 392 | 0.97 | 1985-04-23 | 0.001 | 0.001 | 0.001 | 0.001 | 0.012 |
| NO3-N | 397 | 0.2 | 1985-04-23 | 0.001 | 0.007 | 0.026 | 0.052 | 0.384 |
| DKN | 308 | 0.36 | 1985-04-23 | 0.001 | 0.1 | 0.18 | 0.21 | 1.44 |
| TKN | 391 | 0.13 | 1985-04-23 | 0.001 | 0.2 | 0.3 | 0.4 | 1.44 |
| DRP | 397 | 0.02 | 1985-04-23 | 0.001 | 0.01 | 0.013 | 0.018 | 0.097 |
| DTP | 310 | 0.01 | 1985-04-23 | 0.001 | 0.011 | 0.015 | 0.023 | 0.2 |
| TP | 397 | 0 | 1985-04-23 | 0.001 | 0.023 | 0.032 | 0.044 | 0.395 |
| TDS | 307 | 0 | 1985-04-23 | 4 | 68 | 80 | 95 | 175 |
| DOC | 277 | 0.01 | 1985-04-23 | 0.003 | 1.26 | 1.56 | 1.91 | 11.4 |
| *Steamboat:* | | | | | | | | |
| Temp. | 299 | | 1985-04-22 | 0.1 | 6.4 | 12.7 | 18.6 | 26.5 |
| DO | 298 | | 1985-04-22 | 4.1 | 7.5 | 8.9 | 10.6 | 15.3 |
| pH | 296 | | 1985-04-22 | 6.7 | 7.8 | 8.1 | 8.3 | 9.3 |
| Alk. | 186 | | 1993-06-21 | 73 | 132 | 160 | 183 | 271 |
| NH4-N | 300 | 0.49 | 1985-04-22 | 0.001 | 0.001 | 0.03 | 0.06 | 0.5 |
| NO2-N | 299 | 0.31 | 1985-04-22 | 0.001 | 0.001 | 0.009 | 0.014 | 0.11 |
| NO3-N | 299 | 0.01 | 1985-04-22 | 0.001 | 0.18 | 0.334 | 0.546 | 1.99 |
| DKN | 212 | 0 | 1988-11-07 | 0.14 | 0.4 | 0.515 | 0.64 | 2.3 |

*continued*

*Table A.1 continued*

| | Num. | Cens. | Start | Min. | 0.25 | Med. | 0.75 | Max. |
|---|---|---|---|---|---|---|---|---|
| TKN | 297 | 0 | 1985-04-22 | 0.1 | 0.7 | 0.9 | 1.12 | 2.7 |
| DRP | 301 | 0 | 1985-04-22 | 0.041 | 0.12 | 0.145 | 0.178 | 0.345 |
| DTP | 214 | 0 | 1988-11-07 | 0.059 | 0.128 | 0.159 | 0.196 | 0.394 |
| TP | 301 | 0 | 1985-04-22 | 0.134 | 0.215 | 0.256 | 0.308 | 0.799 |
| TDS | 212 | 0 | 1988-11-07 | 27 | 280 | 353 | 457 | 698 |
| DOC | 186 | 0 | 1993-06-21 | 1.49 | 3.51 | 4.51 | 5.47 | 40 |
| *NTD:* | | | | | | | | |
| Temp. | 300 | | 1985-04-22 | 3 | 8.78 | 12.8 | 16.7 | 24 |
| DO | 299 | | 1985-04-22 | 4.6 | 7.9 | 9.5 | 10.8 | 17.2 |
| pH | 295 | | 1985-04-22 | 6.1 | 7.8 | 8 | 8.3 | 9.3 |
| Alk. | 186 | | 1993-06-21 | 86 | 145 | 193 | 245 | 374 |
| NH4-N | 298 | 0.56 | 1985-04-22 | 0.001 | 0.001 | 0.001 | 0.05 | 0.73 |
| NO2-N | 300 | 0.19 | 1985-04-22 | 0.001 | 0.008 | 0.013 | 0.021 | 0.287 |
| NO3-N | 299 | 0 | 1985-04-22 | 0.001 | 0.465 | 0.691 | 1.25 | 2.63 |
| DKN | 212 | 0.02 | 1988-11-08 | 0.001 | 0.4 | 0.52 | 0.7 | 7 |
| TKN | 297 | 0.02 | 1985-04-22 | 0.001 | 0.5 | 0.7 | 0.94 | 2.23 |
| DRP | 300 | 0 | 1985-04-22 | 0.015 | 0.064 | 0.084 | 0.119 | 0.381 |
| DTP | 214 | 0 | 1988-11-07 | 0.027 | 0.081 | 0.117 | 0.166 | 0.459 |
| TP | 300 | 0 | 1985-04-22 | 0.01 | 0.1 | 0.146 | 0.212 | 0.467 |
| TDS | 212 | 0 | 1988-11-07 | 11 | 290 | 393 | 534 | 1040 |
| DOC | 186 | 0 | 1993-06-21 | 0.935 | 3.45 | 4.75 | 5.8 | 13 |
| *Lockwood:* | | | | | | | | |
| Temp. | 564 | | 1985-04-23 | 0.1 | 6.9 | 11.2 | 17.5 | 25.7 |
| DO | 564 | | 1985-04-23 | 4.8 | 9.1 | 10.3 | 11.5 | 14.2 |
| pH | 557 | | 1985-04-23 | 6.5 | 7.7 | 8 | 8.3 | 9.1 |
| Alk. | 180 | | 1993-06-28 | 32 | 54 | 68 | 76.3 | 173 |
| NH4-N | 555 | 0.39 | 1985-04-23 | 0.001 | 0.001 | 0.04 | 0.191 | 2.68 |
| NO2-N | 561 | 0.55 | 1985-04-23 | 0.001 | 0.001 | 0.001 | 0.014 | 0.682 |
| NO3-N | 562 | 0.01 | 1985-04-23 | 0.001 | 0.073 | 0.151 | 0.325 | 9.55 |
| DKN | 306 | 0.05 | 1985-04-23 | 0.001 | 0.25 | 0.375 | 0.6 | 3.01 |
| TKN | 551 | 0 | 1985-04-23 | 0.11 | 0.47 | 0.6 | 0.907 | 3.33 |
| DRP | 560 | 0 | 1985-04-23 | 0.004 | 0.028 | 0.041 | 0.057 | 0.45 |
| DTP | 310 | 0 | 1985-04-23 | 0.007 | 0.036 | 0.05 | 0.07 | 0.364 |
| TP | 559 | 0 | 1985-04-23 | 0.022 | 0.07 | 0.092 | 0.124 | 0.606 |
| TDS | 304 | 0 | 1985-04-23 | 12 | 107 | 146 | 176 | 440 |
| DOC | 272 | 0 | 1985-04-23 | 0.46 | 2.06 | 2.52 | 3.05 | 15.4 |
| *Clark:* | | | | | | | | |
| Temp. | 409 | | 1985-04-23 | 0.6 | 7.1 | 12.3 | 17.2 | 26.4 |
| DO | 409 | | 1985-04-23 | 4.5 | 8.3 | 9.8 | 11 | 16.5 |
| pH | 404 | | 1985-04-23 | 6.2 | 7.6 | 7.9 | 8.2 | 9.4 |
| Alk. | 185 | | 1993-06-22 | 36 | 54 | 68 | 77 | 156 |
| NH4-N | 408 | 0.5 | 1985-04-23 | 0.001 | 0.001 | 0.028 | 0.16 | 3 |

*continued*

*Table A.1 continued*

| | Num. | Cens. | Start | Min. | 0.25 | Med. | 0.75 | Max. |
|---|---|---|---|---|---|---|---|---|
| NO2-N | 410 | 0.53 | 1985-04-23 | 0.001 | 0.001 | 0.001 | 0.019 | 0.428 |
| NO3-N | 408 | 0.14 | 1985-04-23 | 0.001 | 0.023 | 0.102 | 0.398 | 6.68 |
| DKN | 307 | 0.04 | 1985-06-19 | 0.001 | 0.28 | 0.36 | 0.56 | 2.6 |
| TKN | 402 | 0.01 | 1985-04-23 | 0.1 | 0.403 | 0.6 | 0.889 | 3.6 |
| DRP | 409 | 0 | 1985-04-23 | 0.007 | 0.024 | 0.034 | 0.047 | 0.237 |
| DTP | 314 | 0 | 1985-06-19 | 0.016 | 0.032 | 0.042 | 0.062 | 0.32 |
| TP | 411 | 0 | 1985-04-23 | 0.026 | 0.059 | 0.081 | 0.102 | 0.566 |
| TDS | 307 | 0 | 1985-07-16 | 13 | 107 | 145 | 178 | 400 |
| DOC | 277 | 0 | 1985-06-19 | 1 | 2.01 | 2.52 | 3.22 | 36.3 |
| *Derby:* | | | | | | | | |
| Temp. | 281 | | 1985-04-24 | 0.2 | 6.7 | 11.8 | 17.5 | 25 |
| DO | 280 | | 1985-04-24 | 5.1 | 8 | 9.5 | 10.7 | 15 |
| pH | 279 | | 1985-04-24 | 6.7 | 7.7 | 7.9 | 8.2 | 9.2 |
| Alk. | 177 | | 1993-07-14 | 36 | 57 | 69 | 78 | 154 |
| NH4-N | 279 | 0.56 | 1985-04-24 | 0.001 | 0.001 | 0.001 | 0.1 | 3.01 |
| NO2-N | 280 | 0.59 | 1985-04-24 | 0.001 | 0.001 | 0.001 | 0.014 | 0.268 |
| NO3-N | 280 | 0.17 | 1985-04-24 | 0.001 | 0.017 | 0.078 | 0.261 | 5.3 |
| DKN | 191 | 0.05 | 1985-05-13 | 0.001 | 0.23 | 0.32 | 0.485 | 2.69 |
| TKN | 277 | 0 | 1985-04-24 | 0.1 | 0.41 | 0.59 | 0.8 | 5.8 |
| DRP | 280 | 0 | 1985-04-24 | 0.01 | 0.025 | 0.035 | 0.047 | 0.209 |
| DTP | 194 | 0 | 1985-05-13 | 0.017 | 0.031 | 0.042 | 0.058 | 0.095 |
| TP | 281 | 0 | 1985-04-24 | 0.025 | 0.06 | 0.076 | 0.098 | 0.352 |
| TDS | 193 | 0 | 1985-05-13 | 13 | 120 | 146 | 180 | 395 |
| DOC | 178 | 0 | 1985-05-13 | 1.05 | 2.06 | 2.42 | 2.96 | 16.6 |
| *Painted:* | | | | | | | | |
| Temp. | 177 | | 1989-09-08 | 1.7 | 7.2 | 12.2 | 17.7 | 25.4 |
| DO | 177 | | 1989-09-08 | 6.4 | 9 | 10.1 | 11.5 | 16.7 |
| pH | 177 | | 1989-09-08 | 6.8 | 7.9 | 8 | 8.2 | 9 |
| Alk. | 175 | | 1993-07-28 | 36 | 57 | 70 | 79 | 134 |
| NH4-N | 178 | 0.78 | 1989-09-08 | 0.001 | 0.001 | 0.001 | 0.001 | 1.39 |
| NO2-N | 178 | 0.71 | 1989-09-08 | 0.001 | 0.001 | 0.001 | 0.007 | 0.117 |
| NO3-N | 178 | 0.16 | 1989-09-08 | 0.001 | 0.011 | 0.034 | 0.121 | 0.632 |
| DKN | 176 | 0.07 | 1989-09-08 | 0.001 | 0.21 | 0.3 | 0.41 | 1.64 |
| TKN | 175 | 0.01 | 1989-09-08 | 0.001 | 0.375 | 0.48 | 0.6 | 3.65 |
| DRP | 178 | 0 | 1989-09-08 | 0.012 | 0.026 | 0.035 | 0.049 | 0.09 |
| DTP | 177 | 0 | 1989-09-08 | 0.018 | 0.032 | 0.045 | 0.057 | 0.127 |
| TP | 178 | 0 | 1989-09-08 | 0.032 | 0.057 | 0.07 | 0.085 | 0.98 |
| TDS | 176 | 0 | 1989-09-08 | 16 | 120 | 151 | 173 | 343 |
| DOC | 174 | 0 | 1993-07-28 | 0.82 | 1.97 | 2.29 | 2.72 | 5.31 |
| *Wadsworth:* | | | | | | | | |
| Temp. | 294 | | 1985-04-24 | 0.3 | 6.4 | 12.1 | 18.3 | 26.8 |
| DO | 293 | | 1985-04-24 | 4.8 | 8.9 | 10 | 11.4 | 15.8 |

*continued*

*Table A.1 continued*

| | Num. | Cens. | Start | Min. | 0.25 | Med. | 0.75 | Max. |
|---|---|---|---|---|---|---|---|---|
| pH | 291 | | 1985-04-24 | 6.8 | 7.8 | 8 | 8.3 | 9.4 |
| Alk. | 176 | | 1993-06-22 | 36 | 56.8 | 71 | 80 | 136 |
| NH4-N | 292 | 0.65 | 1985-04-24 | 0.001 | 0.001 | 0.001 | 0.041 | 0.912 |
| NO2-N | 290 | 0.71 | 1985-04-24 | 0.001 | 0.001 | 0.001 | 0.008 | 0.166 |
| NO3-N | 290 | 0.26 | 1985-04-24 | 0.001 | 0.005 | 0.03 | 0.2 | 1.89 |
| DKN | 203 | 0.09 | 1988-11-15 | 0.001 | 0.2 | 0.3 | 0.4 | 1.5 |
| TKN | 289 | 0 | 1985-04-24 | 0.001 | 0.32 | 0.46 | 0.656 | 4.4 |
| DRP | 291 | 0 | 1985-04-24 | 0.002 | 0.018 | 0.027 | 0.041 | 0.118 |
| DTP | 203 | 0 | 1988-11-15 | 0.013 | 0.028 | 0.038 | 0.053 | 0.3 |
| TP | 292 | 0 | 1985-04-24 | 0.012 | 0.045 | 0.062 | 0.083 | 0.473 |
| TDS | 202 | 0 | 1988-11-15 | 16 | 108 | 148 | 173 | 324 |
| DOC | 174 | 0 | 1993-06-22 | 0.79 | 1.98 | 2.25 | 2.63 | 5.03 |
| *Nixon:* | | | | | | | | |
| Temp. | 540 | | 1985-04-25 | 0.1 | 6.28 | 12.6 | 17.7 | 28.1 |
| DO | 537 | | 1985-05-14 | 1.3 | 8.6 | 10 | 11.5 | 14.7 |
| pH | 535 | | 1985-04-25 | 6.2 | 7.9 | 8.1 | 8.4 | 9.3 |
| Alk. | 187 | | 1993-06-17 | 39 | 58 | 78 | 92 | 193 |
| NH4-N | 536 | 0.62 | 1985-04-25 | 0.001 | 0.001 | 0.001 | 0.04 | 0.604 |
| NO2-N | 538 | 0.84 | 1985-04-25 | 0.001 | 0.001 | 0.001 | 0.001 | 0.153 |
| NO3-N | 537 | 0.46 | 1985-04-25 | 0.001 | 0.001 | 0.007 | 0.07 | 1.07 |
| DKN | 441 | 0.12 | 1985-07-18 | 0.001 | 0.2 | 0.23 | 0.3 | 1.13 |
| TKN | 527 | 0.03 | 1985-04-25 | 0.001 | 0.3 | 0.4 | 0.5 | 3.26 |
| DRP | 537 | 0 | 1985-04-25 | 0.001 | 0.014 | 0.02 | 0.03 | 0.096 |
| DTP | 448 | 0 | 1985-07-18 | 0.005 | 0.02 | 0.028 | 0.041 | 0.6 |
| TP | 538 | 0 | 1985-04-25 | 0.008 | 0.035 | 0.055 | 0.083 | 0.87 |
| TDS | 440 | 0 | 1985-07-18 | 62 | 179 | 317 | 509 | 812 |
| DOC | 418 | 0 | 1985-07-18 | 0.001 | 1.79 | 2.2 | 2.65 | 13.8 |

# Appendix B

# Loading summary

Table B.1: Loading (kg $d^{-1}$) of water quality constituents during 1998–2006. *Num,* number of daily estimates available; *Mean,* mean of all available estimates; *Lower,* lower 0.95 confidence level; *Upper* 0.95 confidence level.

| | Num | Mean | Lower | Upper |
|---|---|---|---|---|
| *Ammonium-N:* | | | | |
| mccarran | 3287 | 3.8 | 1.8 | 7.1 |
| ntd | 3172 | 1.4 | 1.0 | 2.1 |
| steamboat | 3173 | 6.7 | 4.6 | 9.4 |
| lockwood | 3287 | 35.2 | 20.5 | 56.6 |
| clark | 3287 | 119.0 | 58.5 | 215.0 |
| derby | 3287 | 91.4 | 43.3 | 171.0 |
| wadsworth | 3287 | 65.2 | 32.7 | 117.0 |
| nixon | 3287 | 24.9 | 16.8 | 35.5 |
| *Nitrite-N:* | | | | |
| mccarran | 3287 | 3.2 | 1.9 | 5.0 |
| ntd | 3172 | 1.0 | 0.8 | 1.1 |
| steamboat | 3173 | 2.2 | 1.9 | 2.7 |
| lockwood | 3287 | 8.3 | 4.4 | 14.3 |
| clark | 3287 | 15.2 | 7.8 | 26.6 |
| derby | 3287 | 9.2 | 4.9 | 15.7 |
| wadsworth | 3287 | 13.1 | 6.7 | 23.0 |
| nixon | 3287 | 13.6 | 6.7 | 24.6 |
| *Nitrate-N:* | | | | |
| mccarran | 3287 | 99.4 | 73.9 | 131.0 |
| ntd | 3172 | 20.6 | 18.1 | 23.4 |
| steamboat | 3173 | 142.0 | 102.0 | 193.0 |
| lockwood | 3287 | 137.0 | 116.0 | 160.0 |
| clark | 3287 | 396.0 | 227.0 | 642.0 |
| derby | 3287 | 333.0 | 178.0 | 570.0 |

*continued*

*Table B.1 continued*

| | Num | Mean | Lower | Upper |
|---|---|---|---|---|
| wadsworth | 3287 | 279.0 | 154.0 | 467.0 |
| nixon | 3287 | 650.0 | 190.0 | 1640.0 |
| *DRP:* | | | | |
| mccarran | 3287 | 32.9 | 29.4 | 36.6 |
| ntd | 3172 | 4.7 | 4.4 | 5.1 |
| steamboat | 3173 | 21.1 | 19.9 | 22.3 |
| lockwood | 3287 | 70.1 | 63.4 | 77.2 |
| clark | 3287 | 67.3 | 61.2 | 73.8 |
| derby | 3287 | 44.6 | 40.8 | 48.8 |
| wadsworth | 3287 | 53.4 | 47.9 | 59.4 |
| nixon | 3287 | 60.3 | 53.9 | 67.2 |
| *DKN:* | | | | |
| mccarran | 3287 | 417.0 | 352.0 | 490.0 |
| ntd | 3172 | 26.2 | 23.5 | 29.2 |
| steamboat | 3173 | 76.1 | 69.9 | 82.7 |
| lockwood | 3287 | 660.0 | 572.0 | 757.0 |
| clark | 3287 | 692.0 | 614.0 | 777.0 |
| derby | 3287 | 439.0 | 384.0 | 499.0 |
| wadsworth | 3287 | 521.0 | 449.0 | 600.0 |
| nixon | 3287 | 509.0 | 454.0 | 569.0 |
| *TKN:* | | | | |
| mccarran | 3287 | 651.0 | 571.0 | 739.0 |
| ntd | 3172 | 37.3 | 34.0 | 40.9 |
| steamboat | 3173 | 135.0 | 125.0 | 147.0 |
| lockwood | 3287 | 947.0 | 854.0 | 1050.0 |
| clark | 3287 | 1040.0 | 938.0 | 1150.0 |
| derby | 3287 | 745.0 | 665.0 | 832.0 |
| wadsworth | 3287 | 826.0 | 732.0 | 929.0 |
| nixon | 3287 | 896.0 | 806.0 | 993.0 |
| *TP:* | | | | |
| mccarran | 3287 | 67.5 | 60.7 | 74.9 |
| ntd | 3172 | 7.8 | 7.2 | 8.5 |
| steamboat | 3173 | 35.1 | 33.4 | 36.9 |
| lockwood | 3287 | 135.0 | 125.0 | 146.0 |
| clark | 3287 | 156.0 | 144.0 | 169.0 |
| derby | 3287 | 104.0 | 96.0 | 113.0 |
| wadsworth | 3287 | 134.0 | 121.0 | 149.0 |
| nixon | 3287 | 176.0 | 159.0 | 193.0 |
| *TDS:* | | | | |
| mccarran | 3287 | 170000 | 153000 | 189000 |
| ntd | 3172 | 21300 | 18300 | 24500 |
| steamboat | 3173 | 56000 | 51300 | 60900 |

*continued*

*Table B.1 continued*

| | Num | Mean | Lower | Upper |
|---|---|---|---|---|
| lockwood | 3287 | 263000 | 240000 | 287000 |
| clark | 3287 | 272000 | 247000 | 298000 |
| derby | 3287 | 160000 | 150000 | 171000 |
| wadsworth | 3287 | 178000 | 171000 | 185000 |
| nixon | 3287 | 201000 | 192000 | 211000 |