Appendix M

Development of Water Quality Indexes for Drainage

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Ranking tributaries for setting remediation priorities in a TMDL context

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Abstract

The San Joaquin River (SJR) in the Central Valley of California has been designated an impaired waterbody based on its loss of fisheries-related beneficial uses and the river is now subject to regulation under total maximum daily load (TMDL) rules. For impaired waterbodies, numeric standards alone may not be sufficient to establish remediation priorities and priorities must be established by comparing drainages to each other. Data collected as part of regional water quality (WQ) studies in the SJR Valley were not normally distributed, so nonparametric methods based on ranking were used to compare the WQ of individual tributaries and drainages. Normalized rank means (NRMs) were calculated from ranked data and NRMs were mapped to identify priority drainages for WQ improvement activities. NRMs for individual parameters were combined into indexes that are useful for examining the relative importance of different drainages for multiple parameters simultaneously. Indexes were developed for eutrophication and overall WQ. This ranking approach is being proposed as an easily understood, transparent, and scientifically rigorous method to assess the relative WQ impact of individual drainages and set watershed remediation priorities.

Keywords: Eutrophication; TMDL; Chemometric; Water quality index; Wilcoxon–Mann–Whitney; Diffuse pollution

1. Introduction

The San Joaquin River (SJR) in the Central Valley of California was once a vibrant ecosystem that supported forty species of native fish, many unique to California, and spring and fall runs of chinook salmon that were estimated to number hundreds of thousands of fish (Moyle, 2002). The SJR drainage has undergone a series of development actions since the late 1800s that have resulted in the over-utilization of the river and significant impairment of the rivers ability to support native fishes and other wildlife (Brown and Moyle, 1994; Moyle, 2002; Smith, 2004). More recently, the SJR was listed as an impaired waterbody based on its loss of fisheries-related beneficial uses and the river is now subject to regulation under total maximum daily load (TMDL) rules for a number of water quality (WQ) parameters including dissolved oxygen and salt (Central Valley Regional Water Quality Control Board, 1998; Gowdy and Grober, 2003). The implementation of a TMDL requires stakeholders to develop basin-wide management actions to improve WQ.

Implementation of an effective regional TMDL response requires the setting of priorities. Watersheds and drainages (locations) with the most need, and potential for, improvement must be identified. One approach to setting priorities is to establish numeric standards for WQ and determine which sites are better or worse than the numeric standard (Lam et al., 1994; Benner, 2004). There are drawbacks to this approach, including the scientific uncertainty of how to establish numeric goals and the lack of numeric standards for many WQ constituents of concern

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(Lijklema, 1995; Shabman and Smith, 2003; Karr and Yoder, 2004; Jia and Culver, 2006). Additionally, the use of standards developed for one purpose for an unrelated purpose may not provide benefit. For example, optimization of fish habitat is unlikely to be achieved by setting goals based on drinking water standards (Walters and Collie, 1988; Ranta and Lindstrom, 1993; Bauer and Ralph, 2001). There is often lack of agreement among stakeholders and regulators as to what the numeric goals should be and that any actual improvement in environmental conditions may be delayed until final numeric standards are established.

An alternative method for setting remediation or restoration priorities is to compare locations within a watershed to each other. If WQ in the watershed needs improvement, then it follows that taking action toward improvement is rational, even if there is not agreement as to what final level of improvement needs to be reached. By comparing locations in the watershed to each other, priorities for action can be set even in the absence of specific regulatory targets. Comparative methods are obviously useful tools for the TMDL process.

There are numerous ways to compare WQ between locations. Common methods involve comparing the means of locations using parametric statistical techniques, such as ANOVA (Vega et al., 1998). It is widely recognized that WQ data are not normally distributed, so frequently environmental data is transformed to log-values or in other ways before analysis (Sokal and Rohlf, 1995; Vega et al., 1998; Novotny, 2004). Arithmetic or geometric means of individual measurements can be combined into "pollution index" calculations which can be weighed to account for differences in level of activity or toxicity (Khanna, 2000; Jarvie et al., 2002). These types of comparisons are often supplemented with chemometric analysis, which provide additional information, such as the minimum number of measurements required to characterize sites (Vega et al., 1998; Alberto et al., 2001; Kowalkowski et al., 2006; Terrado et al., 2006; Kannel et al., 2007; Terrado et al., 2007).

Parametric statistical techniques have some drawbacks in the context of the TMDL process and setting watershed remediation priorities using monitoring data. Parametric statistical methods assume that data has a normal distribution and the application of parametric analysis to non-normal data can lead to erroneous conclusions (Sokal and Rohlf, 1995; Zar, 1999). Data collected at most locations in the SJR watershed was not normally distributed, even after transformation (Stringfellow et al., 2007). The non-normal distribution of data biases the means, which can be skewed by outlying measurements, particularly in the case where a limited number of values are recorded (Sokal and Rohlf, 1995; Zar, 1999). If zero or non-detect results are ignored when data transformations are applied, biasing will result against locations with only transient poor WQ events. Consequently, analysis based on parametric means are subject to challenge and rejection by the stakeholder community of the SJR and other impaired waterbodies.

In this paper, nonparametric statistical methods are applied as an alternative approach to comparing WQ between locations. In nonparametric analysis, scores (1, 2, 3, ..., n) are substituted for actual numeric data and comparisons are made using sums of score (rankings) rather than the measurements themselves (Sokal and Rohlf, 1995; Lehmann, 2006). Nonparametric methods are less biased by outlying data and are applicable to data that is not normally distributed as well as data that is normally distributed (Sokal and Rohlf, 1995; Lehmann, 2006). Normalized rank means (NRM) are calculated from the rankings and are used to compare WQ between drainages and combined into WQ indexes. This ranking approach, combined with mapping and geographical information system (GIS) analysis, is being proposed as an easily understood, transparent, and scientifically rigorous methods for assessing the relative WQ impact of individual drainages and setting watershed remediation priorities.

2. Methods

2.1. Study area

The project study area is south of Stockton, CA, upstream of the Sacramento San Joaquin Delta, and includes the confluences with the Stanislaus, Tuolumne, and Merced Rivers, as well as a number of smaller tributaries (Fig. 1). Water quality data were collected from all major and most minor tributaries in the SJR upstream of the tidal estuary (Sacramento-San Joaquin River Delta) and below the confluence with Bear Creek (Fig. 2, Table 1). River flow is subject to diversion for agricultural use and in the dry-season the SJR often has no flow for many miles upstream of Bear Creek, therefore the SJR immediately downstream of the confluence with Bear Creek (at Lander Avenue) was chosen as the upstream limit of the study area.

Environmental conditions differ for lands on the western and eastern sides of the San Joaquin River and theses differences influence WQ. On the westside, soils are derived from the Coast Range, which is overlain by Cretaceous marine and continental sediments, and are high in salts and minerals such as selenium and boron (McNeal and Balisteri, 1989; Gronberg et al., 1998). The western side of the watershed is largely occupied by irrigated farmland which receives much of its water from canals that convey pumped water south (up-gradient) from the Sacramento-San Joaquin Delta. Diversions from the SJR are also an important source of water for the westside. The water used for irrigation returns to the SJR and in westside tributaries dry-season flows typically consist entirely of agricultural drainage. High soil concentrations of selenium and other salts on the westside of the San Joaquin Valley have been long recognized as causing agricultural drainage management problems (Johns and Watkins, 1989; McNeal and Balisteri, 1989; San Joaquin Valley Drainage Program, 1990). Major drainages for the westside include Del Puerto Creek, Orestimba Creek, Mud Slough, and Salt Slough (Fig. 1).

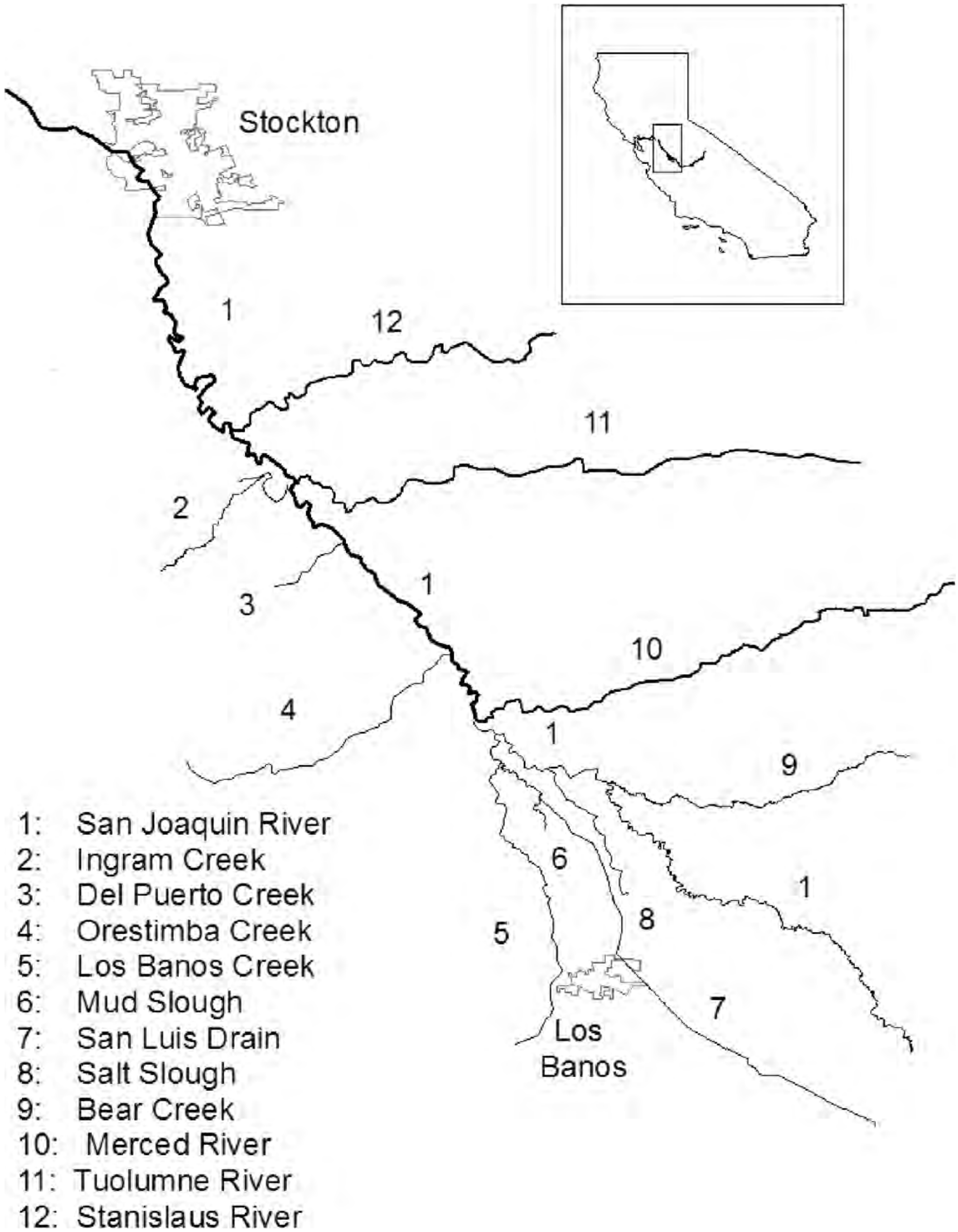

Fig. 1. San Joaquin River study area with major tributaries shown.

On the eastside, soils are derived from the weathered granite of the Sierra Nevada Mountains, which are non-marine in origin. On the eastside, irrigated farmland is mostly supplied by diversions from the Stanislaus, Tuolumne, and Merced Rivers, which convey high quality water from the Sierra Nevada Mountains. Drainage entering the SJR from eastside agricultural activities consists of both agricultural return flows and "spill" or excess unused supply-water discharged as part of water delivery practices. Additionally, both eastside and westside drainages may be impacted by urban activities from communities such as Turlock, Modesto, and Los Banos.

2.2. Sample collection and measurement

Sample collection and measurement of WQ parameters followed procedures described in Stringfellow (2005) and standard methods for the examination of water and wastewater (American Public Health Association, 1998, 2005). Field measurements were made for specific conductance (EC), pH and turbidity (NTU) with handheld sondes and WQ measurement devices, including a YSI 6600 sonde, HACH turbidometer, and Myron combination Ultraprobe. Water samples were collected from mid-channel and depth integrated where possible and kept in the dark

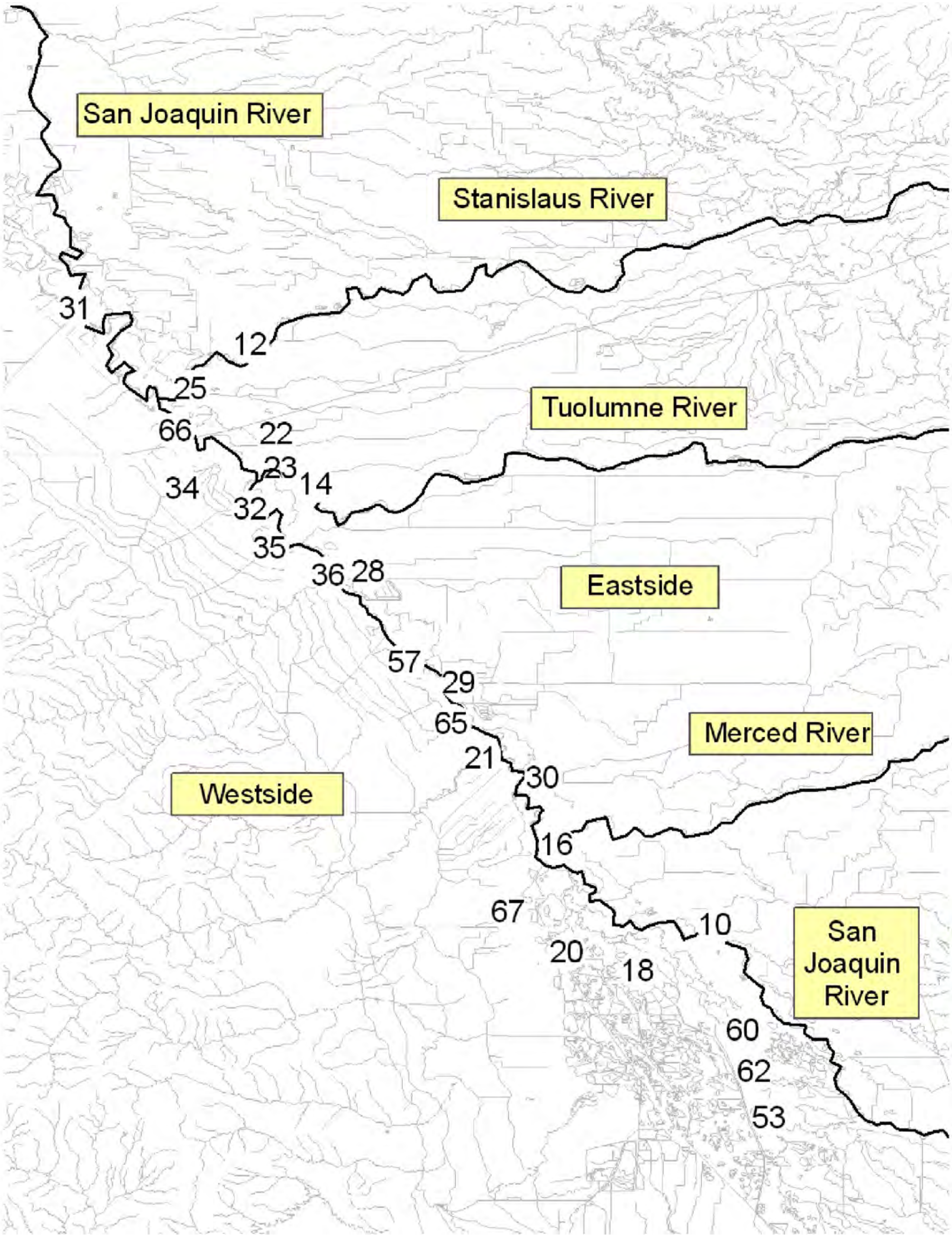

Fig. 2. San Joaquin River study area with water quality sampling locations shown. Site numbers correspond to locations listed in Table 1.

at 4 °C until analyzed or further processed and preserved. All analyses were run within the allowed holding time applicable to the preservation method used (Stringfellow, 2005).

Total organic carbon (TOC) was measured by high temperature combustion according to standard method (SM) 5310 B. Dissolved organic carbon (DOC) was measured after filtration through a GF/F glass-fiber filter by the same method. Total suspended solids (TSS) and volatile suspended solids (VSS) were analyzed by SM 2540 D and E, respectively. Mineral suspended solids (MSS) was determined by subtracting VSS from TSS. Chlorophyll-*a* (chl-*a*) was extracted and analyzed using spectrophotometric absorption (SM 10200H). *Ortho*-phosphate P (oPO_4-P) was determined on samples filtered through a glass-fiber filter (0.7 μm). Nitrate nitrogen (NO_3-N) was measured by as nitrate and nitrite (NO_3-N + NO_2-N) spectrophotometrically after reaction with a V(III)/Griess reagents to form

Table 1
Tributaries and drainages included in normalized rank mean (NRM) analysis

Site no.	Tributary name	Tributary relation to San Joaquin River	Predominate characteristic[a]
10	Lander Avenue	Upstream limit of study area	Agricultural and Sierra drainage
12	Stanislaus River	Eastside	Sierra drainage
14	Tuolumne River	Eastside	Sierra drainage
16	Merced River	Eastside	Sierra drainage
18	Mud Slough	Westside	Agricultural and wetland drainage
20	Los Banos Creek	Westside	Agricultural and wetland drainage
21	Orestimba Creek	Westside	Agricultural drainage
22	Lateral 4	Eastside	Agricultural drainage
23	Lateral 5	Eastside	Agricultural drainage
25	Miller Lake	Eastside	Agricultural and wetland drainage
28	Westport Drain	Eastside	Agricultural drainage
29	Harding Drain	Eastside	Agricultural and urban drainage
30	Lateral 6 and 7	Eastside	Agricultural drainage
31	New Jerusalem Drain	Westside	Agricultural drainage
32	Grayson Drain	Westside	Agricultural drainage
33	Hospital Creek	Westside	Agricultural drainage
34	Ingram Creek	Westside	Agricultural drainage
35	Westley Wasteway	Westside	Agricultural drainage
36	Del Puerto Creek	Westside	Agricultural drainage
38	Marshall Road Drain	Westside	Agricultural drainage
53	Salt Slough	Westside	Agricultural drainage[b]
57	Ramona drain	Westside	Agricultural drainage
60	Moffit One	Westside	Wetland drainage
61	Deadman's Slough	Westside	Wetland drainage
62	Mallard Slough	Westside	Wetland drainage
64	Moran Drain	Westside	Agricultural drainage
65	Spanish Grant Drain	Westside	Agricultural drainage
66	Maze Drain	Westside	Agricultural drainage
67	Newman Wasteway	Westside	Agricultural drainage

Data from each location are pooled, ranked and compared to prioritize tributaries for TMDL management actions.
[a] Agricultural drainage can include tailwater runoff, tile drainage, and operational spill; urban drainage includes wastewater treatment plant effluent and storm runoff.
[b] Salt Slough can also contain seasonal wetland drainage.

a colored product. Ammonia nitrogen (NH_4-N) was quantified using the Nessler Method. Biochemical oxygen demand (BOD) was analyzed on unfiltered samples by SM 52101 B with a modification for measurement of oxygen demand at 10 days rather than 5 days. Previous studies in the SJR have used 10-day BOD analysis as a standard procedure and this data set is consistent with prior studies (Volkmar and Dahlgren, 2006).

2.3. Calculation of NRM indexes

Data from 2005 and 2006 were compiled and analyzed using both parametric and nonparametric statistical methods (Sokal and Rohlf, 1995; Zar, 1999; Lehmann, 2006). Included in this paper are data collected at 29 major and minor tributaries of the SJR in 2005 and 2006. Only locations with complete results from four or more samples were included in this analysis. For normalized rank means (NRM) analysis, the WQ data for all locations to be compared were pooled by parameter and assigned a rank according the method of Wilcoxon (Wilcoxon, 1945; Mann and Whitney, 1947; Lehmann, 2006). For each location, the expected rank under the null hypothesis (that all locations have equal rank) was subtracted from the actual rank sum of that location and the result divided by the standard deviation of pooled data, yielding a NRM expressed in units of standard deviation.

$$\mathrm{NRM} = \frac{(R_j - R_0)}{(\mathrm{SD})}$$

where R_j is the actual rank sum of WQ at location j; R_0 is the expected rank sum for a location under the null hypothesis (that all locations are equal); and SD is the standard deviation for the polled ranks. The NRM is equivalent to the variously called '*C*', '*Z*' or '*z*' Wilcoxon–Mann–Whitney statistic (Sokal and Rohlf, 1995; Zar, 1999; Lehmann, 2006). Statistical calculations were preformed using JMP statistical software (SAS Institute, Research Triangle Park, NC).

For the calculation of an overall WQ index for each location, the average of the NRMs for EC, chl-*a*, TOC, VSS, MSS, NH_4-N, NO_3-N, *o*PO_4-P, and BOD was taken. For an eutrophication index, the average of the NRMs for chl-a, NO_3-N, NH_4-N, and *o*PO_4-P was calculated. The parameters used in the calculation of the eutrophication ranking were previously shown to have a positive correspondence to phytoplankton growth in this system (Herr and Chen, 2006; Stringfellow et al., 2006).

Table 2
Mean concentration of water quality parameters[a] for San Joaquin River tributaries included in normalized rank mean (NRM) analysis

Site no.	Site name	EC (mS/cm)	pH	NTU	Chl-*a* (μg/L)	TOC (mg/L)	DOC (mg/L)	VSS (mg/L)	MSS (mg/L)	NH_4-N (mg/L)	*o*PO_4-P (mg/L)	NO_3-N (mg/L)	BOD (mg/L)
10	Lander Avenue	0.556	8.0	28.9	32.3	6.4	5.2	7.1	33.5	0.28	0.17	1.06	5.3
12	Stanislaus River	0.097	7.5	7.2	3.5	2.7	2.4	2.0	11.3	0.15	0.13	0.21	1.3
14	Tuolumne River	0.103	7.8	6.2	3.7	2.6	2.2	2.1	15.9	0.15	0.10	0.67	1.3
16	Merced River	0.104	7.5	11.4	2.6	3.1	2.6	2.9	20.1	0.17	0.07	0.79	1.7
18	Mud Slough	2.462	8.1	39.5	59.6	11.2	9.3	13.8	58.3	0.37	0.15	4.79	9.0
20	Los Banos Creek	1.263	7.7	78.5	41.5	12.8	11.2	13.8	86.4	0.68	0.42	0.72	9.1
21	Orestimba Creek	0.525	8.0	125.8	12.3	5.5	4.8	14.0	148.4	0.37	0.18	2.58	3.0
22	Lateral 4	0.190	8.7	1.9	7.3	2.7	2.4	1.7	4.2	0.21	0.14	1.32	2.3
23	Lateral 5	0.123	8.3	7.0	6.4	4.2	3.1	2.9	14.3	0.28	0.16	1.39	2.3
25	Miller Lake	0.363	7.6	19.6	25.4	10.0	8.8	9.7	22.8	1.77	0.76	1.12	7.0
28	Westport Drain	0.695	8.0	12.0	7.7	4.8	4.0	2.9	15.0	0.33	0.50	12.81	2.4
29	Harding Drain	0.655	7.8	17.7	8.6	6.0	5.1	5.0	35.9	0.57	1.82	8.78	5.0
30	Lateral 6 & 7	0.694	7.7	10.1	25.8	7.8	7.0	2.4	14.2	0.34	0.62	14.28	3.4
31	New Jerusalem Drain	2.391	7.4	11.7	7.5	2.1	7.3	0.6	5.8	0.14	0.17	13.85	0.4
32	Grayson Drain	0.545	7.9	653.9	32.5	21.6	10.3	58.1	863.7	0.62	0.26	1.29	10.0
33	Hospital Creek	0.455	8.0	524.3	31.4	13.1	6.7	61.8	1007.7	0.56	0.30	1.06	9.3
34	Ingram Creek	0.767	7.9	436.6	28.0	9.5	4.2	31.6	503.1	1.16	0.20	5.33	5.9
35	Westley Wasteway	0.629	8.4	329.9	26.5	12.4	3.6	38.7	676.6	0.41	0.16	1.60	6.8
36	Del Puerto Creek	0.687	8.2	100.8	20.0	7.2	4.7	15.7	142.5	0.69	0.23	3.22	6.4
38	Marshall Road Drain	0.614	7.7	84.0	20.4	5.9	11.8	11.4	68.7	0.38	0.22	2.34	7.2
53	Salt Slough	1.219	7.5	44.5	14.6	7.7	6.3	8.7	64.2	0.36	0.20	0.96	4.0
57	Ramona Drain	1.145	7.9	97.6	81.0	11.0	7.3	19.4	138.5	0.68	0.11	2.36	12.8
60	Moffit One	0.894	7.2	1.8	13.4	11.9	11.4	2.2	1.6	0.46	0.14	0.08	5.4
61	Deadman's Slough	1.075	7.3	14.2	21.4	11.5	10.5	5.7	22.9	0.39	0.21	0.39	5.6
62	Mallard Slough	1.784	7.2	8.5	20.8	11.7	10.9	4.2	9.8	0.50	0.46	0.11	3.9
64	Moran Drain	0.552	7.9	119.2	18.0	7.2	4.4	13.7	155.6	0.81	0.05	0.75	5.8
65	Spanish Grant Drain	0.627	7.9	227.2	20.1	7.7	4.7	23.7	273.0	0.41	0.14	4.45	5.5
66	Maze Drain	0.488	8.5	378.8	21.6	10.5	4.0	27.6	466.2	0.23	0.11	0.74	3.2
67	Newman Wasteway	1.309	7.4	87.6	18.4	7.0	20.7	9.4	76.7	0.67	0.16	3.27	6.4

[a] See Section 2 for analyte abbreviations.

Table 3
Normalized rank means (NRM) results for water quality parameters[a] for San Joaquin River tributaries

Site no.	Site name	EC NRM	pH NRM	NTU NRM	Chl-*a* NRM	TOC NRM	DOC NRM	VSS NRM	MSS NRM	NH_4-N NRM	*o*PO_4-P NRM	NO_3-N NRM	BOD NRM
10	Lander Avenue	−0.76	3.22	1.38	4.41	0.60	1.06	1.99	0.95	−1.96	−1.01	−2.97	2.36
12	Stanislaus River	−7.83	−4.06	−5.51	−6.73	−7.66	−7.72	−6.22	−5.06	−5.60	−3.49	−6.74	−7.51
14	Tuolumne River	−8.25	−0.55	−6.58	−7.56	−8.11	−8.42	−6.87	−5.30	−5.77	−5.01	−3.75	−7.09
16	Merced River	−8.19	−5.26	−4.12	−7.78	−6.80	−6.72	−4.40	−2.91	−4.70	−6.90	−3.32	−5.93
18	Mud Slough	9.80	4.75	3.25	7.84	6.64	6.47	5.75	3.84	0.81	−2.11	5.34	6.62
20	Los Banos Creek	6.36	−2.26	5.52	6.54	7.81	8.25	5.16	4.36	5.97	5.47	−2.75	6.59
21	Orestimba Creek	−0.78	3.03	6.56	0.11	−1.21	−1.42	4.44	6.24	0.14	−0.50	1.98	−2.19
22	Lateral 4	−2.23	3.52	−3.22	−1.00	−2.21	−2.65	−2.31	−3.07	−1.08	−0.82	−1.14	−0.86
23	Lateral 5	−6.58	4.33	−5.46	−4.37	−4.19	−4.86	−3.91	−5.28	−2.82	−3.08	−3.31	−3.48
25	Miller Lake	−2.41	−2.09	−0.91	2.46	2.36	3.25	−0.64	−1.90	1.45	2.57	−1.35	3.01
28	Westport Drain	1.23	3.01	−3.77	−3.50	−2.42	−1.74	−3.48	−4.04	−1.01	4.37	7.44	−3.19
29	Harding Drain	0.95	0.07	−1.59	−3.20	−0.45	0.76	−0.80	−0.95	1.83	9.82	8.26	2.34
30	Lateral 6 & 7	0.78	−0.83	−2.83	−0.66	1.39	2.12	−2.77	−2.79	0.32	4.19	5.75	−0.86
31	New Jerusalem Drain	3.14	−2.06	−0.79	−1.57	−2.99	0.93	−3.35	−2.75	−1.94	−0.72	3.53	−2.81
32	Grayson Drain	−0.18	0.42	2.60	0.60	2.37	1.40	2.29	2.30	1.20	0.87	0.10	1.27
33	Hospital Creek	−1.16	1.63	4.93	2.73	2.73	1.25	3.68	4.63	0.91	0.92	−0.63	2.23
34	Ingram Creek	1.09	1.77	5.18	2.31	1.28	−1.53	3.81	4.82	3.10	0.29	3.53	0.42
35	Westley Wasteway	0.39	3.10	2.60	1.19	0.61	−1.12	1.78	1.83	0.47	−0.98	−0.09	0.57
36	Del Puerto Creek	1.52	5.32	4.24	1.84	−0.42	−1.23	3.05	4.22	2.32	1.04	3.28	2.41
38	Marshall Road Drain	0.18	−0.47	2.11	1.02	−0.04	0.70	1.63	1.61	0.05	0.40	0.91	1.28
53	Salt Slough	4.88	−4.39	2.61	1.16	2.04	2.55	2.84	3.40	1.11	−0.30	−1.25	0.86
57	Ramona Drain	3.69	0.46	4.05	3.71	3.41	2.62	3.43	4.05	2.91	−2.05	1.61	4.47
60	Moffit One	2.31	−5.16	−5.27	0.27	3.93	4.70	−3.50	−5.36	2.43	−1.61	−5.35	1.26
61	Deadman's Slough	3.46	−4.83	−2.56	1.65	3.70	4.29	−0.56	−2.22	1.18	0.33	−4.13	1.31
62	Mallard Slough	4.44	−5.11	−3.22	1.21	3.19	4.41	−1.78	−4.17	1.92	1.36	−4.94	−0.59
64	Moran Drain	−0.11	0.71	2.03	0.98	0.48	−0.39	1.71	2.23	2.01	−2.00	−0.57	0.53
65	Spanish Grant Drain	0.27	0.67	2.35	1.24	0.48	−0.24	2.02	2.38	0.98	−0.65	1.84	0.29
66	Maze Drain	−0.54	2.67	1.31	0.40	0.58	−0.76	−0.16	0.23	−0.76	−1.23	−0.69	−0.43
67	Newman Wasteway	2.27	−2.02	2.20	0.94	0.35	1.98	1.05	1.41	1.89	−0.35	1.54	1.05

[a] See Section 2 for analyte abbreviations.

3. Results and discussion

A key component to the application of NRM analysis is the careful selection of what locations are going to be included in the analysis so that an appropriate comparison can be made. For this paper, it was hypothesized that the watershed would be managed by the stakeholders as a unit and the stakeholders would need to determine what are the locations that deserve priority attention, given a limited remediation budget. It was assumed that, either there were no regulatory targets [as is currently the case for suspended sediments and nutrients], or each drainage was given the same regulatory priority [as is the case with the salt and boron TMDL, where all drainages with a 30 days average

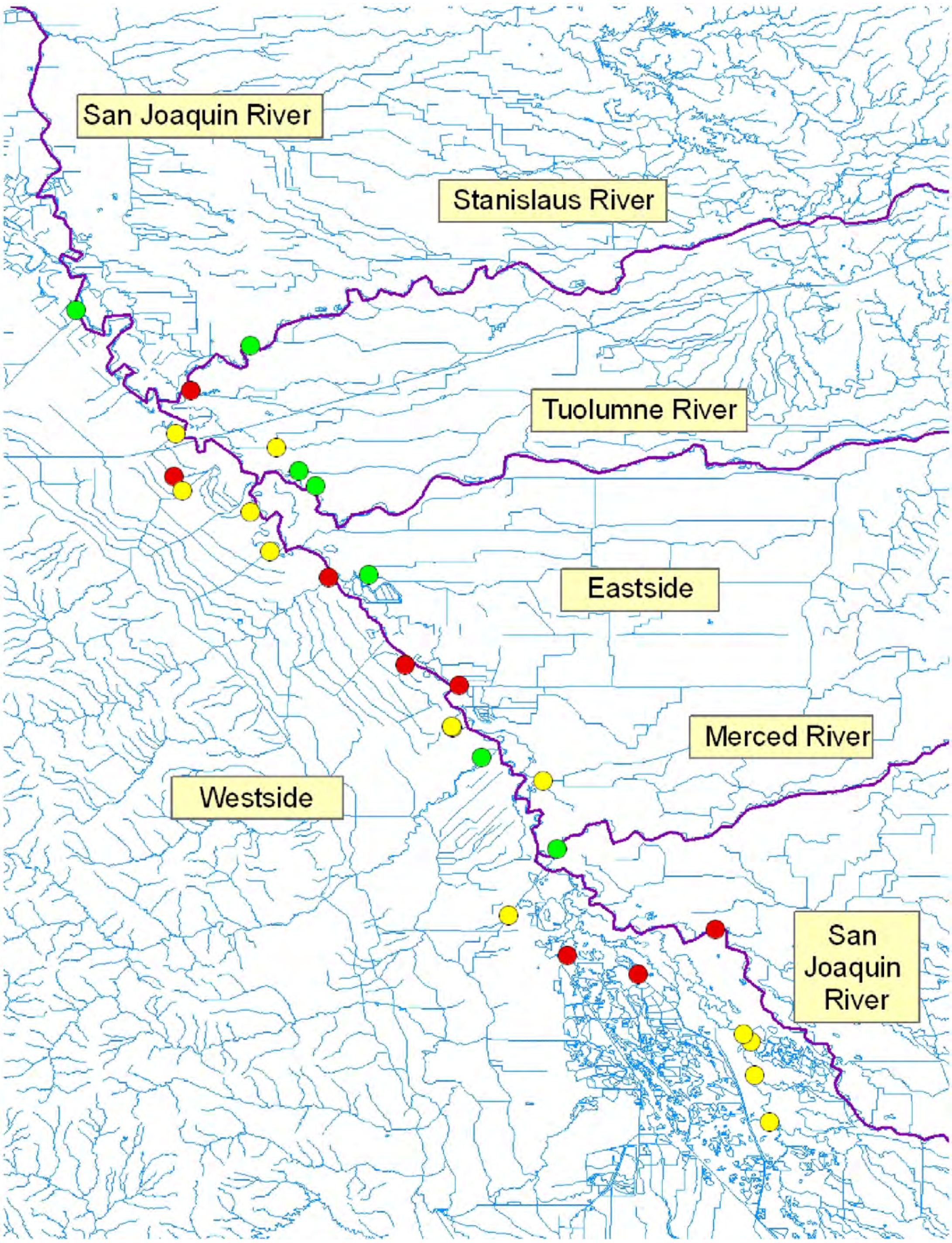

Fig. 3. Geographical analysis of biochemical oxygen demand (BOD) in tributaries of the San Joaquin River using normalized rank mean (NRM) analysis. Sites displayed in red have poorer BOD water quality compared to the other tributaries combined (90% probability). Sites in green are significantly better than the mean for BOD water quality. Yellow locations are not different from the mean.

EC above 0.315 mS/cm are subject to the same regulatory pressure (Central Valley Regional Water Quality Control Board, 2004)]. The locations (Table 1) are all primary tributaries of the SJR, meaning that measurements made at each location represent water that is directly discharging to the SJR without passing another monitoring location (i.e. no drainage is being represented twice). The analysis does not include any river locations, except the upstream limit of the study area (Site 10, Lander Avenue).

The mean values for major WQ parameters of concern for each drainage are presented in Table 2. Eutrophication is a significant issue in the SJR and NH_4-N, $o$$PO_4$-P, and NO_3-N influence algal growth rates and yields (e.g. Beardall et al., 2001; Stringfellow and Quinn, 2002; Shostell

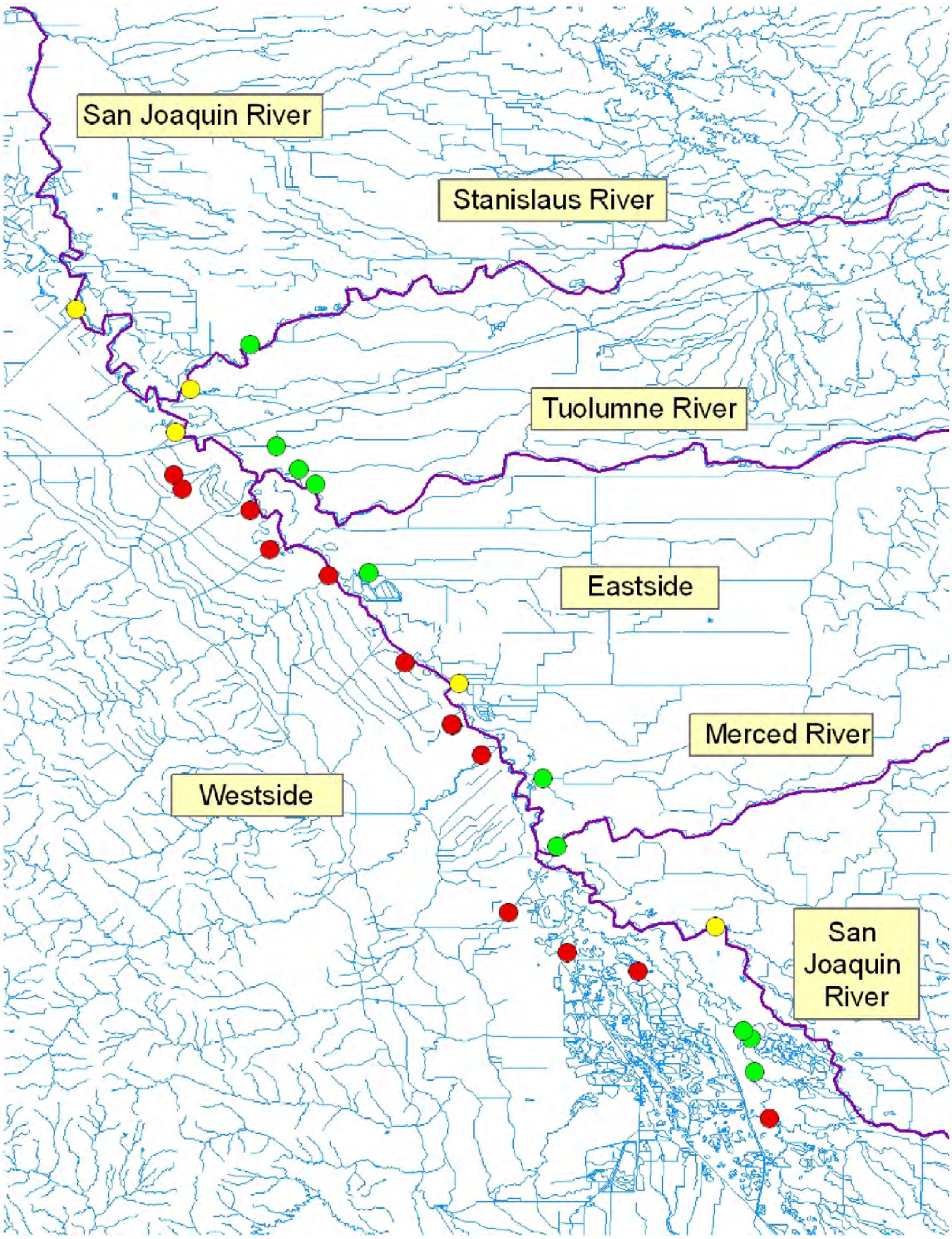

Fig. 4. Geographical analysis of turbidity (NTU) in tributaries of the San Joaquin River using normalized rank mean (NRM) analysis. Sites displayed in red have higher turbidity compared to the other tributaries combined (90% probability). Sites in green are significantly better than the mean for turbidity. Yellow locations are not different from the mean.

and Bukaveckas, 2004; Hilton et al., 2006). Inoculum of planktonic algae (measured as chl-*a*) has been implicated as a potential contributing factor to high yields of biomass in the SJR (Foe et al., 2002). The parameters pH, NTU, MSS, TOC, DOC, VSS, and BOD are important components for a variety of SJR TMDLs under development. Drainage salinity (here reported as EC) is a very important overall WQ parameter for this region (Johns and Watkins, 1989; McNeal and Balisteri, 1989; San Joaquin Valley Drainage Program, 1990) and is used as a calibration parameter for mass balance models of the SJR (Quinn and Karkoski, 1998; California Department of Water Resources, 2006; Herr and Chen, 2006; Stringfellow et al., 2007).

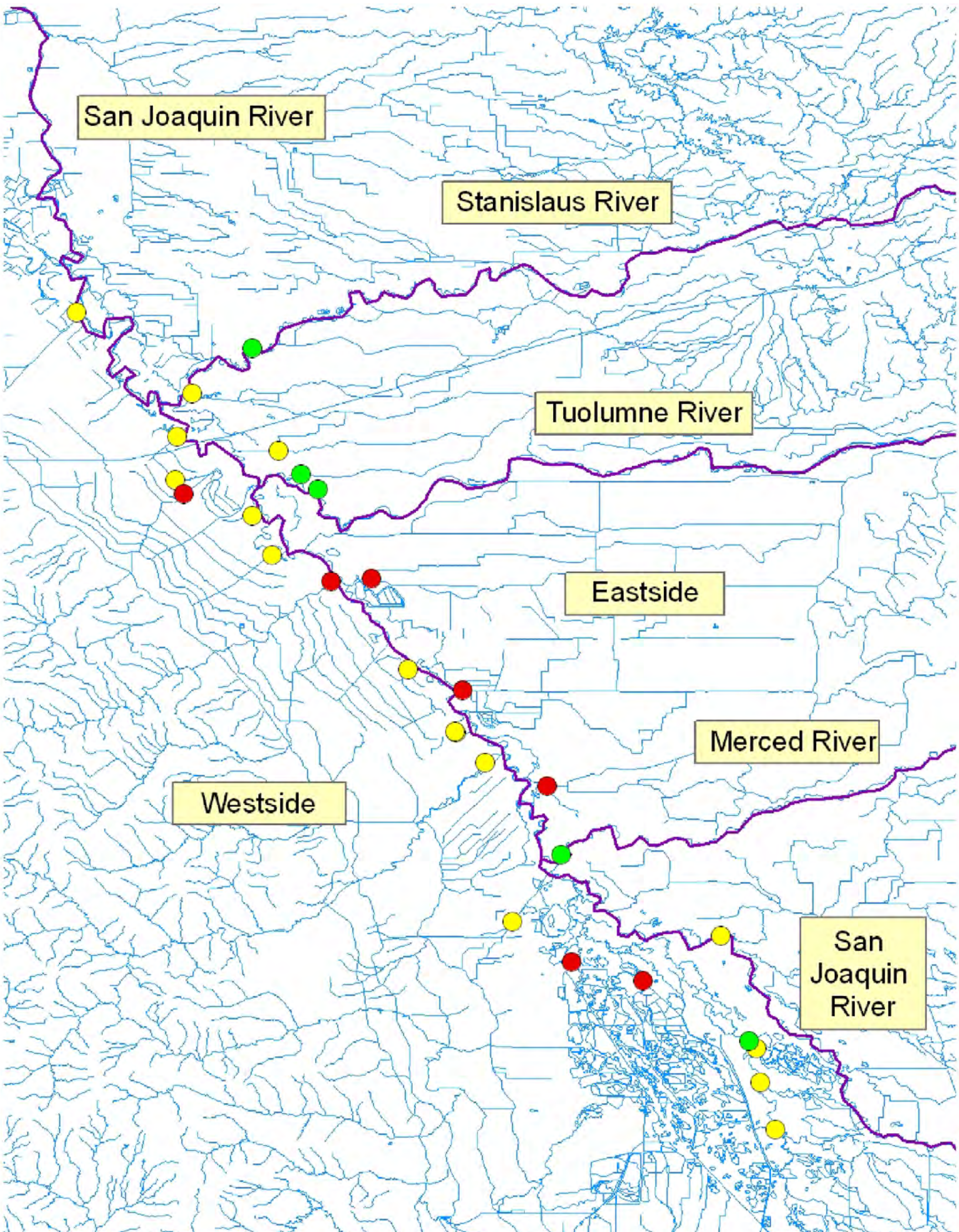

Fig. 5. Geographical analysis of the eutrophication index created using normalized rank mean (NRM) results for nutrients and algal biomass. Sites displayed in red have an index value greater than the group mean (90% probability). Sites in green are significantly better than the mean and yellow locations are not different from the mean.

NRMs (Table 3) were calculated for each location and each WQ parameter shown in Table 2. Negative values indicate that the location has a been ranked as having better WQ than the mean of all the other tributaries included in the analysis, a positive value means the site has poorer WQ than the group. If all locations had an NRM of 0.0, it would indicate that there was no difference between the WQ of any of the drainages. NRMs values follow a normal distribution (Lehmann, 2006), so locations with NRMs greater than 1.65 or less than −1.65 (for example) have a 90% likelihood of being different from the mean of all the tributaries taken as a group. The calculated NRMs have

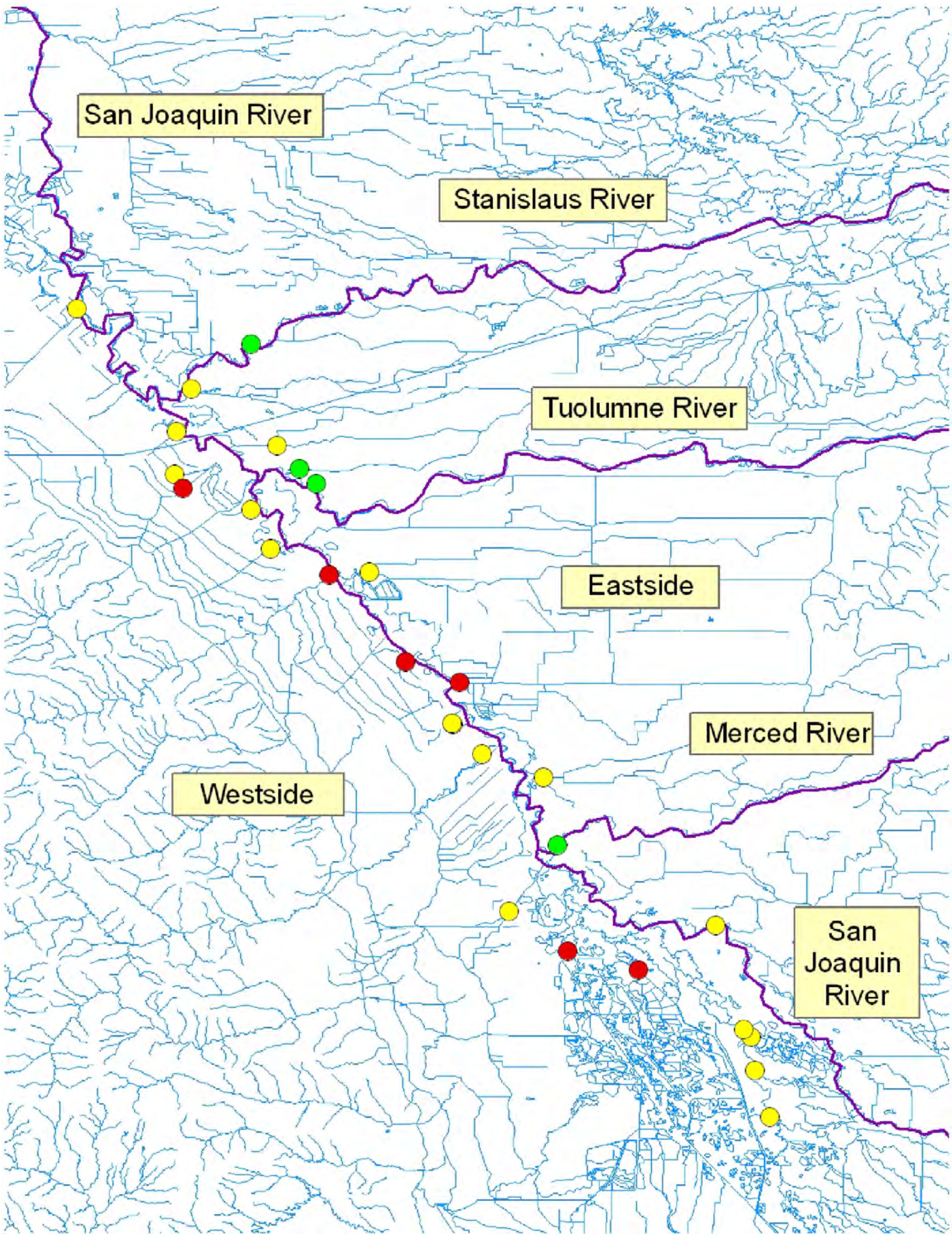

Fig. 6. Geographical analysis of the water quality index created using normalized rank mean (NRM) results for nine water quality parameters as described in the methods. Sites displayed in red have index values greater than the group mean (90% probability). Sites in green are significantly better than the mean and yellow locations are not different from the mean.

several applications and are proposed as a robust method for indexing WQ and a useful tool for setting remediation priorities.

NRMs for individual WQ parameters can be used evaluate watershed WQ and set remediation priorities. For example, the NRMs for BOD (Table 3) are mapped to determine if there are regional patterns for lower BOD WQ (Fig. 3). Locations with a NRM significantly greater ($\alpha = 0.10$) than the mean are marked in red, locations with a BOD NRM similar to the mean are marked in yellow, and those less than the mean are green. Five of the eight highest ranked BOD sites are on the westside, there is significant BOD entering from upstream of the study area, and the eastside has two locations with BOD rankings higher than the mean (Fig. 3, Table 3). Describing the sources of BOD in individual watersheds is beyond the scope of this paper, but westside BOD is often associated with the growth of planktonic algae in agricultural drains. Eastside drains have low turbidity and support benthic algae, not planktonic algae, and have mixed input from urban sources, ranching, dairy, orchards and row crops. The relative importance of each of these sources is under investigation.

This "stoplight" analysis can be applied to any individual WQ parameter. A stoplight analysis of NRM results for suspended sediments (measured in this case at NTU) demonstrates that sediment runoff is predominantly a westside WQ problem (Fig. 4). NRM analysis using MSS yields the same results. This parameter was chosen to illustrate an extreme case, where application of scarce resources to control sediments on the eastside would obviously be a low priority. This result is consistent with the occurrence of highly erodable soils on the westside of the SJR (Gronberg et al., 1998; United States Department of Agriculture, 2006).

A powerful application of NRM analysis is the combining of individual NRMs into WQ indexes. The combination of NRM data into NRM indexes is possible because all NRMs are expressed in common units. Indexes allow the stakeholder to examine multiple parameters simultaneously. As an example, a eutrophication index was calculated using NRMs for phytoplankton biomass, nitrogen compounds, and soluble phosphate (see methods). How the index is calculated can be varied, depending on what the applicable science and modeling determine are controlling factors (Herr and Chen, 2006; Stringfellow et al., 2006), but in this example all variables are weighted equally. Each parameter included in the index will not result in an algal bloom individually, but must be combined (in the presence of light) to result in excess planktonic growth. The resulting eutrophication index, analyzed geographically in Fig. 5, suggests that controlling eutrophication will require stakeholder action on both east and west sides of the SJR and that specific problem areas can be prioritized for action.

The specific NRMs included in a WQ index can be changed depending on any number of priorities or goals. An overall WQ index, created by combining NRMs for chl-*a*, NO_3-N, NH_4-N, *o*PO_4-P, MSS, EC, TOC, and BOD is plotted in Fig. 6. NRM indexes that could be calculated in addition to the eutrophication and WQ indexes include a sediment (VSS, MSS, NTU) and organic carbon (VSS, TOC, DOC, chl-*a*) indexes. Other indexes could including any number of parameters, including pH or temperature, if adjustments are made to account for the non-linearity of those parameters. Which NRMs to include in a specific index and whether to assign weights to individual NRMs would need to be determined based on scientific evidence and program or stakeholder goals.

4. Conclusions

Impaired water bodies are subject to regulation under TMDL programs. Regional stakeholders are expected to develop appropriate, scientifically based WQ management programs to meet TMDL goals. Implementation of an effective regional TMDL response requires the identification of problem areas and setting of priorities for remediation. Stakeholders need rigorous, yet easily understandable, tools for integrating scientific information and setting remediation priorities.

WQ data collected in the SJR of California was not normally distributed, even after transformation. The use of parametric statistical methods on non-normal data can be misleading, so nonparametric methods, based on ranking, were applied to the analysis of WQ monitoring data collected in the San Joaquin Valley.

Ranking results for pooled data were used to calculate NRMs and compare drainages to each other. Mapping NRM results is a scientifically rigorous but easily understood method for setting remediation priorities on a watershed scale.

The application of NRM calculations to WQ data is proposed as a useful method for comparing WQ between locations, even in the absence of specific regulatory goals. NRM results are being combined to create WQ indexes which allow locations to be evaluated for multiple parameters simultaneously.

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