Ranking methods to set restoration and remediation priorities on a watershed scale

William T. Stringfellow

ABSTRACT

The establishment of a total maximum daily load (TMDL) is part of management process that results in the institution of watershed-based controls of otherwise unregulated sources of pollution. In California (USA), the implementation of a TMDL is driven forward in a process where watershed stakeholders are expected to cooperate on actions needed to improve ecosystem health. In the TMDL process, methods are needed for synthesizing complex scientific data into actionable management information. Where pollutant load analysis may be misleading or perceived as unfair, non-parametric statistical methods can be applied to flow and water quality data to guide the selection of drainages for remediation. The calculation of normalized rank means (NRMs) for flow and water quality can be used to set priorities for the implementation of TMDL management actions. Drainages can be classified into one of four categories (quadrants) based on the relationship between flow and water quality NRMs. Drainages can be included or excluded from management action based on their quadrant classification. Although there are many possible alternative approaches, this "quadrant analysis" is suggested as a scientifically rigorous methods for identifying priority watersheds in the often contentious, stakeholder driven TMDL implementation process.

Key words | Central Valley, diffuse pollution, dissolved oxygen, San Joaquin River, TMDL, water quality index

William T. Stringfellow
Ecological Engineering Research Program,
University of the Pacific,
School of Engineering & Computer Sciences,
Sears Hall,
3601 Pacific Ave, Stockton, CA 95211,
USA
E-mail: *wstringfellow@lbl.gov*

INTRODUCTION

In the United States, there has been a new emphasis on establishing and achieving ambient water quality criteria in rivers and other waterbodies that are still impaired even after the implementation of "point of discharge" control programs (National Research Council 2001). Waters that are identified as impaired are given a specific ambient water quality objective, called a total maximum daily load (TMDL). In California, the establishment of a TMDL is part of a planning and management process that results in the institution of watershed-based, best management practices (BMPs) for the control of "diffuse" or "non-point" sources of pollution. The implementation of a TMDL is driven forward in an open process where stakeholders (including farmers, water suppliers, regulatory agencies, municipalities, federal land managers, and environmental groups) are expected to cooperate on actions needed to achieve improvements in ecosystem health.

In the San Joaquin River Valley, irrigated agricultural is the predominant land-use (Figure 1) and the predominant source of diffuse pollution. Farmers and other stakeholders are under new regulatory and economic pressure to implement water conservation and pollution control practices. Watershed BMPs may include activities as diverse as installing drip-irrigation systems, the construction of regional water recycling facilities, or the installation of riparian wetlands for nutrient and sediment removal. Construction or implementation of BMPs may be funded in part by State and Federal grants, but responses to TMDL requirements are

doi: 10.2166/wst.2008.567

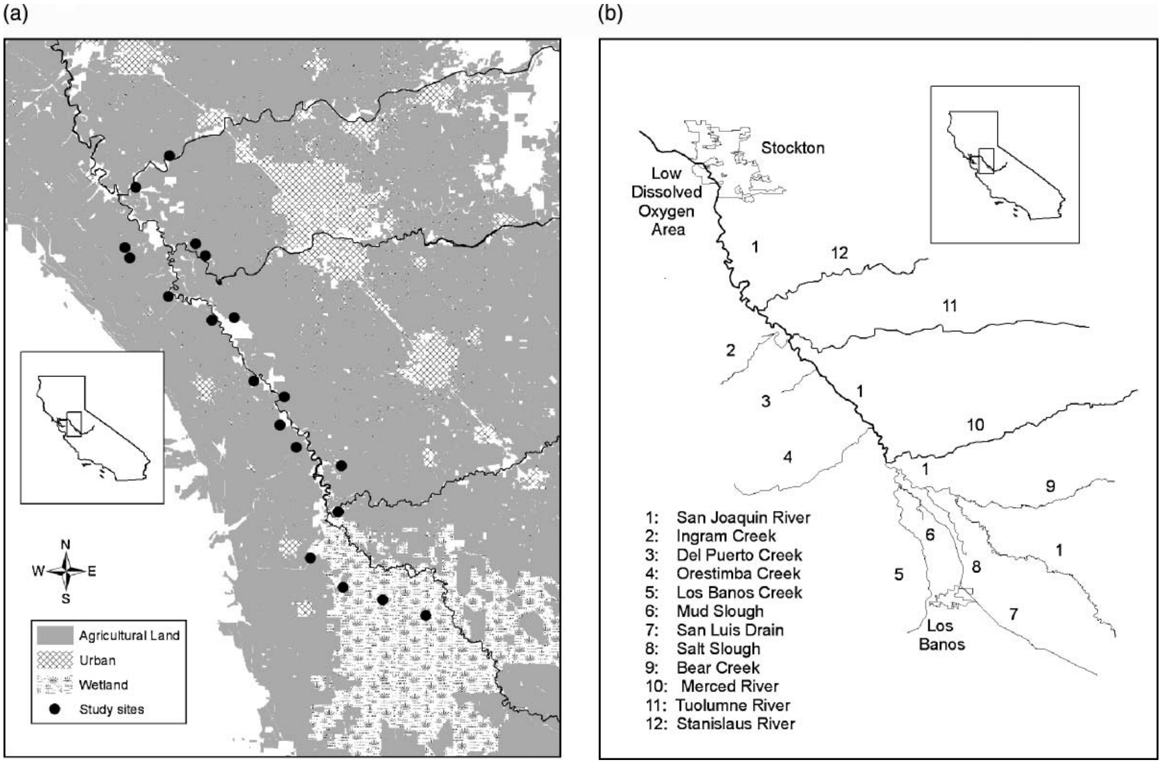

Figure 1 | (a) Land use in the San Joaquin River dissolved oxygen TMDL area and location of water quality and flow measurement sites. (b) The dissolved oxygen TMDL area of the San Joaquin River with major drainages shown. The major eastern tributaries have large flows and hence convey significant loads of nutrients and oxygen demand into the San Joaquin River, despite having low concentrations of pollutants. The San Joaquin River is located in the Central Valley of California, USA.

largely paid for by stakeholder groups. There are limited resources available for implementation of BMPs and analytical tools are needed to help set priorities on the watershed scale. In order to maintain stakeholder cooperation, it is important that methods for selecting individual drainages for action not be perceived as arbitrary or unfair.

Parts of the San Joaquin River (Figure 1) have had a long-term problem with low DO conditions and portions of the San Joaquin River now have a TMDL for dissolved oxygen concentration (McCarty 1969; Bain *et al.* 1970; Gowdy & Grober 2003). The San Joaquin River is part of a historically important salmon migration route and resolution of the low DO condition of the San Joaquin River is a major focus of ecosystem restoration efforts in California (Lehman 2001; Gowdy & Grober 2003; Jassby & Van Nieuwenhuyse 2005; Stringfellow *et al.* 2008).

The first hurdle to setting priorities on a watershed scale is the collection of sufficient information on individual drainages to provide an accurate picture of diffuse pollution sources in the watershed. The San Joaquin River has been the subject of intensive monitoring and the watershed is well characterized in relation to constituents of concern for dissolved oxygen (Kratzer *et al.* 2004; Volkmar & Dahlgren 2006; Stringfellow *et al.* 2008). Significant challenges remain as to how this information will be used to implement BMPs in response to the dissolved oxygen TMDL, particularly in the absence of ambient water quality criteria for nutrients and oxygen demanding materials, typically measured as biochemical oxygen demand (BOD).

It has been shown that large sets of water quality (pollutant concentration) data can be simplified and interpreted using nonparametric statistical methods (Stringfellow 2008). Water quality information for individual drainages can be used to calculate normalized rank means (NRMs) and the NRMs can be combined into water quality indices. The water quality NRMs and indices can be used to compare drainages, identify drainages with the poorest water quality, and set priorities for remediation activities (Stringfellow 2008).

Setting remediation priorities based on pollutant load is more challenging than setting priorities based on pollutant concentration. High flow drainages can have very good water quality and still be identified as the major sources of pollutant load in a drainage. Setting remediation priorities based on loading, as is suggested under TMDL regulations, would require resources to be directed at removing already low levels of pollutants in high flow systems, an approach that is economically, if not technologically, unfeasible.

In this paper, a method to identify drainages with optimal potential for remediation is proposed. It is shown that water quality NRMs can be used in combination with flow measurements to identify drainages with optimal combinations of flow and water quality for implementation of BMPs.

METHODS

Flow and water quality data were collected at major and minor drainages throughout the San Joaquin River Valley between March 2005 and December 2007 (Stringfellow *et al.* 2007). Flow and water quality data was collected in accordance with rigorous QA/QC procedures (Puckett 2002; Stringfellow 2005; California Department of Fish and Game 2007).

Unfiltered samples were analyzed for biochemical oxygen demand (BOD) by Standard Method (SM) 5210 B (American Public Health Association 2005) 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 will be consistent with prior studies (Kratzer *et al.* 2004; Volkmar & Dahlgren 2006; Stringfellow 2008). BOD was measured without seed, as in previous studies. Nitrate nitrogen (nitrate) was quantified using a TL-2800 ammonia analyzer (Timberline Instruments, Boulder, CO). Total phosphorus (total-P) was determined on 5.0 mL of unfiltered sample by persulfate digestion and colorimetric determination by the

Table 1 | Mean flow and loading of nitrate as nitrogen (Nitrate), total phosphate as phosphorus (Total-P), and 10-day biochemical oxygen demand (BOD) for major and minor drainages in the San Joaquin River Valley as measured between 2005 and 2006. The major eastern tributaries contribute the most loading, but are impractical targets the TMDL implementation process

Drainage	Flow (m^3 per day) Mean	Nitrate load (kg/d) Mean	Total-P load (kg/d) Mean	BOD load (kg/d) Mean
Tuolumne River	4,505,437	1,757	399	7,324
Merced River	2,913,088	2,101	193	4,565
Stanislaus River	2,753,013	438	179	3,243
Salt Slough	617,348	907	215	2,020
Mud Slough	337,527	1,284	101	2,569
Harding Drain	96,168	882	177	441
Orestimba Creek	81,936	121	37	160
Westport Drain	63,837	752	23	141
Los Banos Creek	60,622	50	37	552
Ramona Drain	48,937	125	20	628
Lateral 5	48,279	56	20	97
Lateral 6 & 7	41,659	664	34	106
Del Puerto Creek	28,854	127	16	199
Spanish Grant Drain	27,039	143	16	331
Ingram Creek	23,863	139	21	286
Miller Lake Drain	22,847	67	41	201
Newman Wasteway	22,721	58	13	92
Grayson Drain	11,465	54	10	174
Hospital Creek	10,046	30	17	132
Marshall Road Drain	7,557	41	13	132

ascorbic acid method, adapted from SM 4500-P B, E (American Public Health Association 2005).

Monitoring data were pooled and ranked according to nonparametric methods as described previously (Stringfellow 2008). Briefly, for each monitoring location a normalized rank mean (NRM) is calculated for flow or a water quality parameter. NRMs are expressed in units of standard deviation from the mean (e.g. mean of 0 and standard deviation of 1), as

$$\mathrm{NRM} = (R_j - R_o)/(\mathrm{SD})$$

where R_j is the actual rank-sum of water quality at location j; R_o 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 pooled ranks. The NRM is equivalent to the variously called 'C', 'Z', or 'z' Wilcoxon-Mann-Whitney statistic (Sokal & Rohlf 1995; Zar 1999; Lehmann 2006).

RESULTS AND DISCUSSION

Flow and water quality data were collected at major and minor drainages that discharged directly to the San Joaquin River (Figure 1). Average loads of nitrate, total-P, and BOD were calculated for 20 drainages. The major loads of these constituents are entering the river from the three major east-side tributaries, the Tuolumne, Stanislaus and Merced Rivers (Figure 1, Table 1). These rivers convey generally high quality water from the Sierra-Nevada Mountains and are characterized by concentrations of nutrients and oxygen demanding materials significantly lower than other drainages entering the San Joaquin River (Stringfellow 2008). Although these rivers are the largest sources of load to the river, it is obviously impractical to focus remediation efforts on improvement of systems with already, relative to adjacent drainages, low concentrations of pollutants.

One approach is to ignore the major drainages and to concentrate remediation efforts on drainages with less flow. It is not clear from loading and flow calculations (Table 1) how selections of priority sites should be made. TMDL implementation requires the cooperation of farmers and other stakeholders and it is important, if not imperative, to successful implementation efforts that individual drainages be characterized fairly and with scientific rigor. Selection of smaller drainages and not larger drainages for priority action should not be arbitrary and will be resisted by stakeholders if perceived as unfair.

One method for evaluation of drainages is to combine flow information with concentration information independently of a load analysis. In Figure 2, the NRM for nitrate is plotted against the NRM for flow for individual drainages and four quadrants are defined by the rank means (0 on the x and y axes). Sites with flows lower than the mean, but concentrations above the mean of the group are found in quadrant 2 (Figure 2). Sites with lower flows, but high concentrations are typically good candidates for implementation of engineered treatment systems, such as constructed wetlands.

Table 2 lists the NRMs for drainages in the San Joaquin River and their quadrant assignments based on their flow and concentration relationships. In this analysis, it is assumed that the BMP will be a treatment system and maximum engineering efficiency will be achieved at sites with lower flows and higher concentrations. For other BMPs, it may be that sites with high flows and high

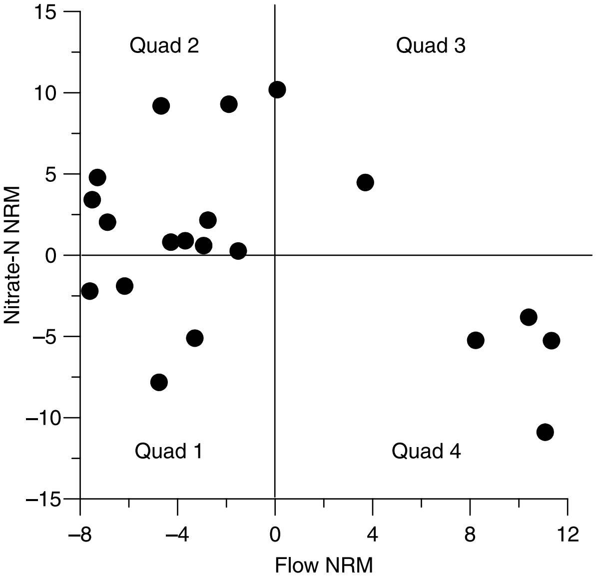

Figure 2 | Quadrant analysis of San Joaquin River drainages using normalized rank means (NRMs) of flow and nitrate. Quadrant analysis provides an alternative method for setting remediation priorities in systems where load analysis is not leading to practical development of TMDL implementation priorities.

Table 2 | Normalized rank mean (NRM) for flow and concentration of nitrate as nitrogen (Nitrate), total phosphate as phosphorus (Total-P), and 10-day biochemical oxygen demand (BOD) for major and minor drainages in the San Joaquin River Valley as measured between 2005 and 2006. The concentration NRMs are plotted against the flow NRM to calculate quadrants. In this analysis, drainages classified as in quadrant 2 are considered the most likely to present practical targets for TMDL implementation activities

Drainage	Flow NRM	Total-P NRM	Nitrate NRM	BOD NRM	Quad. Total-P	Quad. Nitrate	Quad. BOD
Del Puerto Creek	−7.51	1.52	3.41	3.45	2	2	2
Grayson Drain	−3.69	1.55	0.89	2.39	2	2	2
Hospital Creek	−6.17	2.36	−1.90	2.72	2	1	2
Ingram Creek	−7.29	2.49	4.78	3.43	2	2	2
Los Banos Creek	−4.76	7.90	−7.82	9.09	2	1	2
Marshall Road Drain	−4.28	1.41	0.81	2.27	2	2	2
Merced River	10.40	−10.97	−3.82	−8.17	4	4	4
Miller Lake Drain	−7.60	1.71	−2.21	4.44	2	1	2
Lateral 5	−3.30	−5.40	−5.11	−3.89	1	1	1
Mud Slough	3.70	−2.42	4.48	8.87	4	3	3
Newman Wasteway	−2.93	0.17	0.59	0.81	2	2	2
Orestimba Creek	−6.88	−0.11	2.03	−2.14	1	2	1
Ramona Drain	−1.51	2.06	0.26	4.52	2	2	2
Salt Slough	8.23	3.54	−5.24	0.48	3	4	3
Spanish Grant Drain	−2.76	−0.02	2.16	1.52	1	2	2
Stanislaus River	11.08	−10.34	−10.89	−9.68	4	4	4
Tuolumne River	11.34	−8.76	−5.26	−9.28	4	4	4
Harding Drain	0.09	12.28	10.19	2.78	3	3	3
Lateral 6 & 7	−4.68	6.01	9.19	−1.79	2	2	1
Westport Drain	−1.90	−0.49	9.29	−4.08	1	2	1

concentrations (quadrant 3) will be most practical or economical targets for achieving maximum ambient water quality benefits. In all cases, there is a clear rationale and method for defining low-flow, low-concentration drainages (quadrant 1) and high-flow, low-concentration drainages (quadrant 4) that can be excluded as priorities for implementation of TMDL management actions.

CONCLUSIONS

Setting watershed management priorities based on pollutant load analysis can be misleading, even in the context of a regional TMDL. High-flow, low-concentration drainages need to be excluded from implementation actions, but the method of exclusion cannot be arbitrary or perceived as unfair by cooperating stakeholders. TMDL implementation is a stakeholder driven process and methods for identifying problem drainages in a regional watershed need to be fair, easily understood, and scientifically rigorous. In the San Joaquin River Valley, sufficient data has been collected on individual drainages to insure that the inputs to the river system are well characterized, but the plethora of information presents challenges for analysis. Methods are needed for synthesizing complex scientific data into actionable management information.

It is proposed that application of non-parametric statistical methods, particularly the calculation of NRMs, can be used to set priorities for the implementation of TMDL management actions. NRMs for water quality constituents can be combined with NRMs for flow to classify drainages into four categories (quadrants). Drainages can be included or excluded from management action based on their quadrant classification. Although there are many possible alternative approaches, this “quadrant analysis” is suggested as a scientifically rigorous methods for identifying priority watersheds in the often contentious, stakeholder driven TMDL implementation process.

REFERENCES

American Public Health Association 2005 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, DC.

Bain, R. D., McCarty, P. L., Robertson, J. A. & Pierce, W. H. 1970 Effects of an oxidation pond effluent on receiving waters in the San Joaquin River Estuary. 2nd International Symposium for Waste Treatment Lagoons. University of Kansas, pp. 168–180.

California Department of Fish and Game 2007 Marine Pollution Studies Laboratory–Department of Fish and Game (MPSL-DFG) Standard Operating Procedures (SOPs) for Conducting Field Measurements and Field Collections of Water and Bed Sediment Samples in the Surface Water Ambient Monitoring Program (SWAMP). California Department of Fish and Game, Sacramento, CA, p. 64.

Gowdy, M. J. & Grober, L. F. 2003 *Total Maximumm Daily Load for Low Dissolved Oxygen in the San Joaquin River*. Regional Water Quality Control Board Central Valley Region, Sacramento, CA.

Jassby, A. D. & Van Nieuwenhuyse, E. E. 2005 Low dissolved oxygen in an estuarine channel (San Joaquin River, California): mechanisms models based on long-term time series. *San Francisco Estuary & Watershed Science* **3**(2), article 2 (http://repositories.cdlib.org/jmie/sfews/vol3/iss2/art2).

Kratzer, C. R., Dileanis, P. D., Zamora, C., Silva, S. R., Kendall, C., Bergamaschi, B. A. & Dahlgren, R. A. 2004 Sources and Transport of Nutrients, Organic Carbon, and Chlorophyll-a in the San Joaquin River Upstream of Vernalis, California, during Summer and Fall, 2000 and 2001, Report Number 2003-4127. Water-Resources Investigations Report. US Geological Survey Information Services, Denver, CO, p. 124.

Lehman, P. 2001 The Contribution of Algal Biomass to Oxygen Demand in the San Joaquin River Deep Water Channel, Final Draft Report, San Joaquin River Dissolved Oxygen TMDL Steering Committee. California Department of Water Resources Sacramento, CA.

Lehmann, E. L. 2006 *Nonparametrics: Statistical Methods Based on Ranks*. Springer, New York, NY.

McCarty, P. L. 1969 *An Evaluation of Algal Decomposition in the San Joaquin Estuary (Research grant DI-16010 DL)*. Federal Water Pollution Control Administration, Washington, DC.

National Research Council 2001 *Assessing the TMDL Approach to Water Quality Management*. National Academy Press, Washington, DC.

Puckett, M. 2002 Quality Assurance Management Plan for the State of California's Surface Water Ambient Monitoring Program. California State Water Resources Control Board, Sacramento, CA, p. 144.

Sokal, R. R. & Rohlf, F. J. 1995 *Biometry: The Principles and Practice of Statistics in Biological Research*. W.H. Freeman & Co, New York, NY.

Stringfellow, W., Borglin, S., Hanlon, J., Graham, J. & Burks, R. 2008 Scientific studies supporting the development of a dissolved oxygen TMDL. *Water Pract.* **2**, 1–10.

Stringfellow, W. T. 2005 Up-Stream Dissolved Oxygen TMDL Project Quality Assurance Project Plan. Ernest Orlando Lawrence Berkeley National Laboratory Formal Report No. LBNL-59937. Berkeley National Laboratory, Berkeley, CA.

Stringfellow, W. T. 2008 Ranking tributaries for setting remediation priorities in a TMDL context. *Chemosphere* **71**, 1895–1908.

Stringfellow, W. T., Borglin, S. E., Dahlgren, R., Hanlon, J. S., Graham, J., Burkes, R. & Hutchinson, K. 2007 San Joaquin River Up-Stream DO TMDL Project (ERP-02D-P63) Task 4: Monitoring Study Interim Task Report # 3. Ernest Orlando Lawrence Berkeley National Laboratory Formal Report No. LBNL-63243. Lawrence Berkeley National Laboratory & The University of the Pacific, Berkeley, CA.

Volkmar, E. C. & Dahlgren, R. A. 2006 Biological oxygen demand dynamics in the lower San Joaquin River, California. *Environ. Sci. Technol.* **40**, 5653–5660.

Zar, J. H. 1999 *Biostatistical Analysis*, 4th Edition. Prentice Hall Inc, Upper Saddle River, NJ.