Integrating probabalistic and targeted compliance monitoring for comprehensive watershed assessment

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ABSTRACT

Environmental monitoring typically falls into one of two broad categories. Targeted designs, utilizing fixed stations, focus on describing and quantifying impacts, tracking trends, and assessing compliance with regulatory guidelines or limits. Probabilistic designs, in contrast, draw sampling stations at random from an area or region, and the stations are used to describe conditions in the region of interest based on a subpopulation of sites. These two design approaches are usually viewed as mutually exclusive, with randomized designs used for broader regional assessments of overall ambient condition and targeted designs for demonstrating regulatory compliance and/or characterizing specific, localized impacts. Combining elements of both approaches into a single design provides benefits not available from either design alone. Embedding targeted monitoring within the framework of a probabilistic design enables data from targeted stations to be viewed in a more accurate regional context and provides a consistent background against which to identify characteristic regional patterns of contamination and impact. We use the San Gabriel River Regional Monitoring Program, recently implemented in southern California, to illustrate the structure of a hybrid design and how it enables data analyses and assessments that provide a more complete picture of conditions in the watershed. For example, the hybrid design showed that approximately 80% of the metals levels at compliance sites were below the 25th percentile of the overall watershed condition as indicated by the probabilistic sampling.

INTRODUCTION

Environmental monitoring typically falls into one of two broad categories. Targeted designs, utilizing fixed stations, focus on describing and quantifying localized impacts, tracking trends, and assessing compliance with regulatory guidelines or limits. Targeted designs for such purposes have a relatively long history and a well-developed set of technical methods for specifying hypotheses, optimizing sample allocation, and evaluating the statistical power of alternative designs. Most regulatory-mandated monitoring falls into this category.

Randomized or probabilistic designs, in contrast, draw sampling stations at random from an area or region, and stations are re-randomized for each survey or iteration of the design. Probabilistic designs (McDonald 2003, Stevens and Olson 2004) are most often used for broader regional assessments of overall ambient condition and enable statements about the population of sampling sites (e.g., X% of the miles of flowing streams in the region have copper values above Y). Where clearly defined subpopulations exist (e.g., effluent dominated streams vs. natural streams), the design can include two or more sampling strata. Examples of monitoring programs based on probabilistic designs include USEPA's Environmental Monitoring and Assessment Program (EMAP; Stevens 1997; USEPA 2002, 2007), the Bight Program in southern California (SCCWRP 2003), and water quality and aquatic life assessment programs conducted by several states (e.g., Indiana, Maryland, Nebraska, South Carolina, West Virginia). The USEPA's Aquatic Resources Monitoring Website (USEPA 2006a) and its Environmental Monitoring and Assessment Program (EMAP) website (USEPA 2007) provide detailed information about the design and use of probabilistic surveys nationwide. While randomized designs have become more widespread, particularly over the past decade, the detailed statistical aspects of their design remain unfamiliar to many practitioners, and USEPA often provides technical

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support to regional and statewide design efforts.

Targeted and probabilistic design approaches are often viewed as an either-or choice that is inherently a zero-sum game. Interest in improving knowledge of regional conditions is thus seen as coming at the expense of monitoring compliance with key regulatory conditions or tracking important impacts, while an emphasis on compliance and impact monitoring is seen as reducing the ability to assess resources and describe ambient conditions on a regional scale. In reality, each approach, used alone, has limitations and drawbacks that can be remedied by a hybrid design that integrates both approaches. Targeted designs can leave large areas unmonitored, provide no context for interpreting site-specific results, and cannot generalize their results to support conclusions about larger areas. Probabilistic designs are less useful at describing localized impacts and monitoring regulatory compliance.

This paper describes the structure of a hybrid monitoring design at the watershed scale in southern California. Results from the San Gabriel River Regional Monitoring Program's (SGRRMP) first year of monitoring are used to illustrate data summarization and analysis methods that combine the best features of both targeted and probabilistic designs. This hybrid design, created by a collaborative workgroup of stakeholders in the watershed, leads to new insights about the spatial pattern of contamination and impacts in the watershed, and questions about the processes that create these patterns. As data accumulate over time, the SGRRMP will have the ability to track changes in these larger-scale patterns. Furthermore, this model can be replicated in other watersheds to expand the capacity of monitoring throughout the region.

METHODS

San Gabriel River Watershed

Watershed description

The 1,785 km^2 (689 mi^2) San Gabriel River watershed (Figure 1) in southern California is typical in many ways of watersheds in urbanized coastal areas. Its upper reaches consist of natural creeks and streams flowing through relatively undeveloped riparian, chaparral, and woodland habitats of the San Gabriel and San Bernardino Mountains, while its lower reaches are mostly channelized and flow through a heavily urbanized coastal plain before terminating in the San Pedro Bay at its southern end.

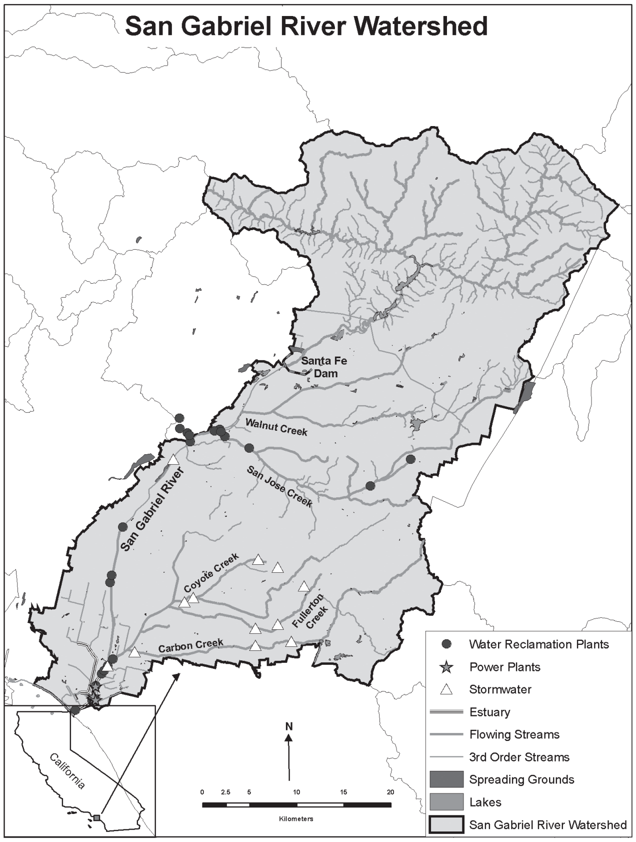

Figure 1. Distribution of permit-mandated, fixed sites focused on monitoring whether discharges were meeting water quality objectives. This represents the distribution of monitoring effort in the watershed prior to implementation of the regional monitoring program.

The watershed's hydrology is highly modified, with a series of flood control and water conservation dams in the upper watershed and large spreading grounds for water reclamation in the central watershed, with the result that there is little hydrologic connectivity between the upper and lower portions of the river. The lower part of the river and its major tributaries flow primarily in concrete-lined or armored soft-bottom channels through heavily urbanized areas, becoming a soft bottom channel once again near the ocean in the city of Long Beach. As with most watersheds, the majority of the approximately 1,300 km (808 mi) of streams are comprised of 1st and 2nd order drainages, which make up 59% and 19% of the total watershed stream length, respectively. Approximately 44% of the land area of the watershed is developed, with an additional 5% in agricultural use, with virtually all of the developed area in the lower watershed.

Tertiary-treated effluent from five publicly-owned treatment works enters the river in the lower part of the watershed while two power generating stations discharge cooling water from Alamitos Bay into the river's estuary. In addition to the National Pollution Discharge Elimination System (NPDES) permits for these discharges, the watershed is covered under two NPDES municipal stormwater permits (for Los Angeles and Orange Counties) and straddles two water quality regulatory jurisdictions. Separate from the county permits, there is also a municipal stormwater permit for the City of Long Beach. There are also over 100 additional, mostly industrial, NPDES permittees in the watershed, half of which discharge directly to the San Gabriel River or its major tributaries.

Monitoring in the Watershed

Program focus

As in many urban watersheds, monitoring in the San Gabriel River watershed was largely unbalanced (LACSD 2005), with numerous agencies independently collecting data, mostly for permit compliance purposes around discharges in the lower watershed, while much of the remainder of the watershed went unmonitored. The lack of coordination among these separate monitoring programs resulted in limited data comparability, redundancies between programs, and key data gaps. Figure 1 clearly shows the clustering of monitoring by multiple entities around a few large discharges in the lower watershed and the resultant lack of information from the upper watershed and large portions of major tributary watersheds.

Realization of these deficiencies led to the development of a coordinated watershed monitoring program with the related goals of expanding monitoring of ambient conditions throughout the watershed, establishing long-term trend monitoring sites, improving coordination and cost-effectiveness of disparate monitoring efforts, developing consistent quality assurance (QA) and data management approaches, and providing a framework for periodic and comprehensive assessments of watershed conditions (LACSD 2006). A key design goal of the program was to integrate targeted monitoring of discharge compliance and trend sites of unique interest (e.g., valued habitat, key confluences), with probabilistic monitoring of the entire watershed. Through a collaborative process, a broad range of stakeholders (permitted dischargers, local cities, state and federal regulatory agencies, conservation organizations, research entities) identified five core questions around which to restructure surface water quality monitoring:

- What is the condition of streams in the watershed?
- Are conditions at areas of unique interest getting better or worse?
- Are receiving waters near discharges meeting water quality objectives?
- Is it safe to swim?
- Are locally caught fish safe to eat?

Program design

Table 1 summarizes the overall program design; however, only Questions 1 - 3 were addressed during the first year of monitoring (2005) because the program is being phased in over a three-year period. In contrast with the prior monitoring approach (Figure 1), the resulting design (Figure 2) covers the entire watershed with a rotating network of probabilistic sites allocated to the upper watershed, the lower watershed, and the mainstem river. These three areas consist primarily of natural streams, channelized tributaries, and a larger channelized river, respectively. The target population for the probabilistic component of the design was all natural and constructed stream channels that have at least intermittent flow in spring/early summer. The sampling frame, which is a representation of the target population used to select the sampling sites, encompassed all streams greater than 2nd order with at least intermittent flow through late spring/early summer. Limiting the sampling frame to exclude 1st and 2nd order streams was necessary because the majority of low order streams are ephemeral and only flow for very short periods following moderate to heavy rain. This is common for headwater streams in the arid western United States, which are often hydrologically isolated from downstream areas and are dry for most of the year (Izbicki 2007). The majority of indicators in this program (e.g., benthic macroinvertebrates, water chemistry, water toxicity) cannot be used in ephemeral systems; therefore, in the absence of new indicators, there was no choice but to exclude these streams. This approach is also taken by the California Statewide Ambient Monitoring and Assessment Program, which excludes ephemeral streams from its assessments for similar reasons.

The sampling frame was based on the US Geological Survey National Hydrographic Dataset

Table 1. Summary of the SGRRMP watershed monitoring program design to address each of the five core management questions. Highlighted sites are those sampled in 2005.

Question	Approach	Site Breakdown	Indicators	Frequency
Q1: Stream condition	Randomized design for streams in entire watershed, except 1st and 2nd order streams*	30 in Year 1 and 10 new in each following year	Triad (bioassessment, water chemistry, toxicity) and Riparian habitat condition	Annually, in spring
Q2: Trends at unique areas	Fixed stations in estuary and freshwater	12 in Freshwater (4 - High value**; 5 - Confluence of Tribs/Mainstem; 3 - Background)	Triad (bioassessment, water chemistry, toxicity) and Riparian habitat condition	Annually, in spring
		4 in Estuary	Conventional water quality; Full suite water quality; Sediment chemistry, toxicity, infauna	Annually, in spring; Not determined; Annually
Q3: Discharges	Improve coordination Improve efficiency Reduce overlap	Defined by discharge permit	Defined by discharge permit	Defined by discharge permit
Q4: Safe to swim	Focus on high-use areas Defer to Health Departments	6 in Lakes and Rivers; 6 in Background; 1 in Estuary	*E. Coli* and fecal coliform	Based on degree of use and proximity to sources
Q5: Safe to eat fish	Three-year pilot study focusing on popular fishing sites, commonly caught species, and high-risk chemicals	Minimum 2 each in Lakes, Rivers, Estuary	Commonly caught fish at each location (mercury, DDTs, PCBs, arsenic, selenium)	Annually, in fall

* Stream order is defined by a tributary's position in the branching network, with 1st order streams being headwater streams, 2nd order streams those with one tributary above them

** High value sites are locations of relatively isolated and unique habitat

enhanced stream classification (http://nhd.usgs.gov/index.html), which was updated to include the workgroup's knowledge of non-flowing segments and non-contiguous channels. Potential sampling sites were then selected at random from the GIS map of the stream network. However, the random selection was constrained to ensure that a minimum number of sites were allocated to three predetermined sub-populations of interest: the upper watershed, the lower watershed, and the mainstem. This was necessary because the overall proportion of stream miles represented by the mainstem was so small that a strictly random site selection process would likely have included few if any mainstem sites. Potential random sites were then evaluated through a field reconnaissance effort to ensure that the stream contained flowing water and that it was feasible to access the site. In many instances, upper watershed sites were only accessible after hiking several miles into the back country. In other cases, prior arrangements were necessary to obtain access to flood control channels and US Forest Service roads.

The probabilistic component of the watershed design (Figure 2a) is based on a minimum sample size of 30 for conducting an assessment. This sample size reflects the workgroup's judgment about the adequate size of the confidence limit around the 50% proportion in the binomial distribution. A sample size of 30 provides a confidence limit of about +15%, while a sample size of 50 provides a small marginal improvement to +12% (see USEPA 2006b for a detailed explanation). Thirty sites were sampled in the program's first year, to furnish the basis for an immediate assessment. Ten additional random sites are being sampled in subsequent years, to enable a complete watershed assessment to be completed on a three-year schedule.

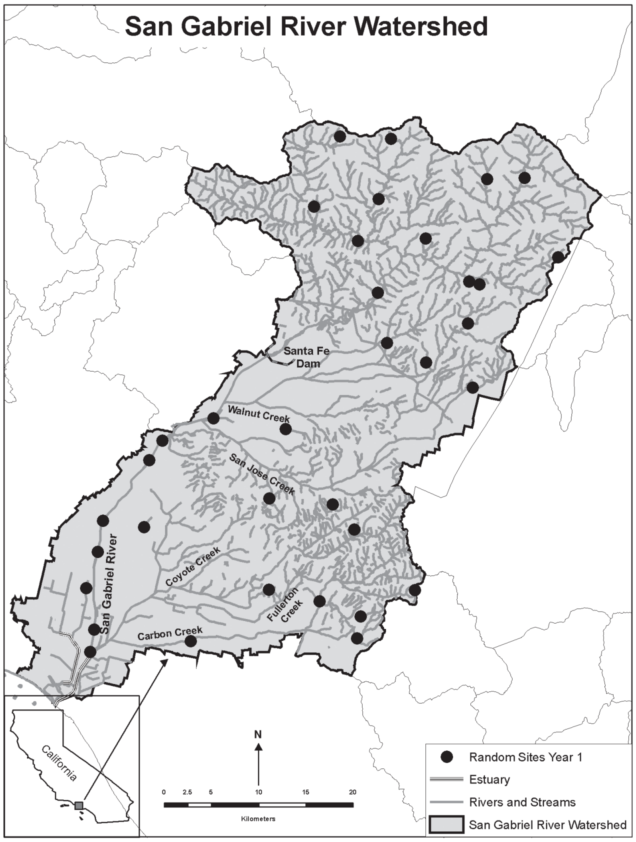

Figure 2a. Location of the 30 probabilistic watershed sites sampled during the first year (2005) of the program. Together with the additional targeted sites (Figure 2b) focused on trend sites of unique interest, this represents the additional regional monitoring effort implemented at the watershed scale.

Fixed targeted sites at locations of unique interest (Figure 2b) were also identified, to ensure monitoring of background pristine locations, and to track trends in condition at key confluences and at areas of high habitat value and/or public concern. These sites were selected based on the consensus of the workgroup and are sampled annually. The third and final program component is represented by the fixed permit mandated monitoring sites (Figure 1), which were revised to reduce redundant sampling, eliminate ineffective monitoring locations, remove monitoring parameters that were not useful to management, and reduce sampling frequency at several sites from weekly to monthly. This last adjustment was based on careful inspection of time series of data that demonstrated weekly sampling provided no additional utility for management.

As described more completely in LACSD (2006), adjustments to the overall monitoring system were cost neutral, with the new watershed elements financed by improving the focus and efficiency of existing compliance monitoring, cooperating on data collection and analysis, and by reducing redundancy between monitoring entities.

There are two important elements of the new watershed design that deserve emphasis. First, the design explicitly integrates both probabilistic (random) and targeted (fixed site) monitoring. Second, the design involves the simultaneous collection of multiple indicators of condition: water chemistry, aquatic toxicity, instream benthic community structure using the southern California Index of Biotic Integrity (IBI; Ode *et al*. 2005), and physical and biological habitat structure using the California Rapid Assessment Method (CRAM; Collins *et al.* 2006). This multimetric approach allows for a more comprehensive description and interpretation of watershed condition and the processes affecting it.

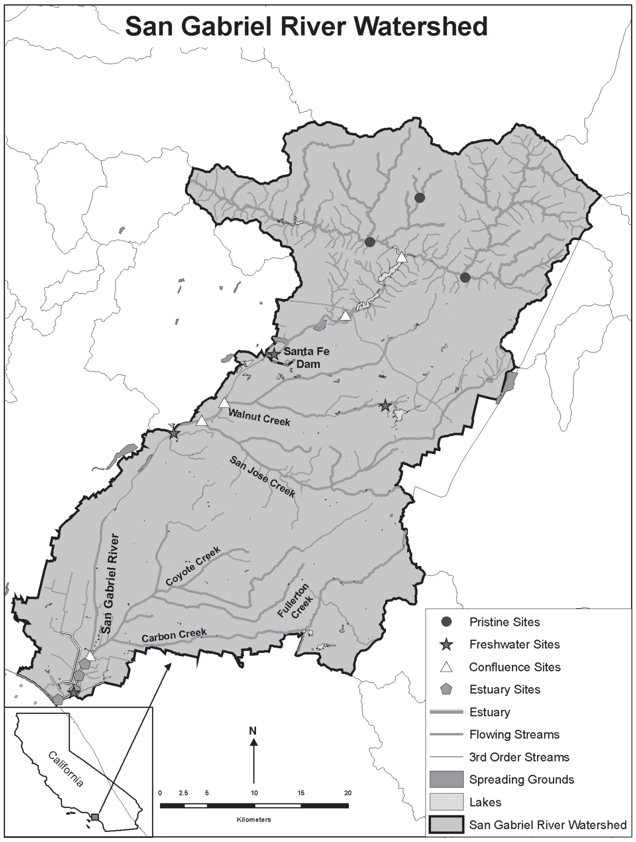

Figure 2b. Location of the additional targeted sites focused on trend locations of unique interest. Together with the 30 probabilistic sites (Figure 2a), this represents the additional regional monitoring effort implemented at the watershed scale.

RESULTS

Integrating Data from Targeted Sites into a Watershed Context

Complete results of the watershed assessment can be found in LASGRWC (2007). This paper focuses specifically on demonstrating the methods used to integrate the analysis of monitoring data from the targeted and probabilistic sites. Data from targeted sites are typically compared to relevant regulatory standards or guidelines. Consequently, data analyses in traditional monitoring programs tend to focus on the percentage of discrete samples exceeding such standards and on the trends in exceedance rates over time. When probabilistic data from the entire watershed are also available, these data can be used to provide additional context for comparison and interpretation of data generated by targeted monitoring. This can produce insights about patterns of impact and contamination that are not available from either targeted or probabilistic designs alone.

Three characteristic watershed scale patterns

Figure 3 uses cumulative frequency distributions to illustrate the pattern typical of metals concentrations in the watershed. Cumulative frequency distributions are useful for providing a means of visualizing the overall distribution of data values for each monitored parameter. Figure 3 shows that copper concentrations at representative NPDES permitted discharge compliance sites generally fell within the lower 25% of conditions observed throughout the watershed as a whole, as defined by data from the probabilistic sites. That is, over 80% of the data values from the targeted compliance sites were below the 25th percentile value for the probabilistic sites - approximately 9 µg/L. Similarly, concentrations at most of the targeted sites were also within the lower 25% of ambient conditions. This pattern was consistently observed for most metals sampled. Despite concerns that might exist about the elevated levels of metals in a few compliance samples, Figure 3 (and similar figures for other metals) document that levels of metals just below discharges are well below those typical of conditions for the watershed as a whole.

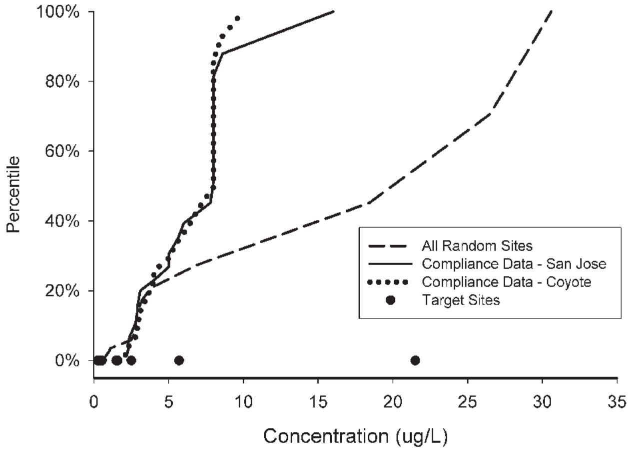

Figure 3. Cumulative frequency distribution of copper concentrations for probabilistic sites (dashed line) relative to distribution of copper concentration at two permit compliance monitoring sites (solid and dotted lines) and to trend sites (dots).

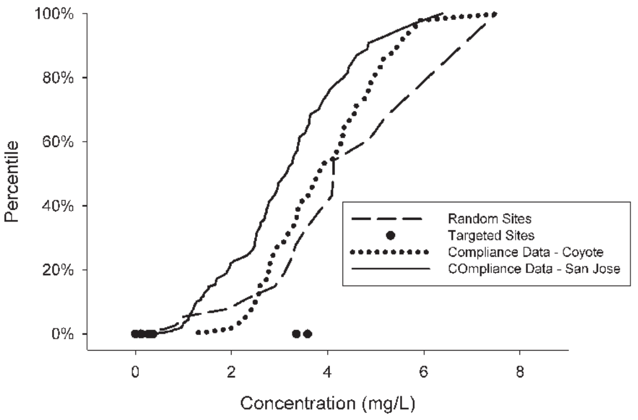

Figure 4. Cumulative frequency distribution of nitrate + nitrite concentrations for probabilistic sites (dashed line) relative to distribution of nitrate + nitrite concentration at two permit compliance monitoring sites (solid and dotted lines) and to trend sites (dots).

The watershed-scale picture for nutrients was quite different. Figure 4 shows that concentrations of nitrate + nitrite, which were representative of other nutrients in the watershed, at compliance sites were similar to distributions in the watershed as a whole. The difference between the distributions of metals and nutrients provide insights into, and raise questions about, watershed-scale patterns and processes. Most discharge compliance monitoring occurs on the mainstem river, whose flow is comprised predominantly of treated wastewater effluent. Past studies (Stein and Ackerman 2007) have shown such effluent is very low in metals but relatively high in nutrients. In contrast, the overall watershed (from the probabilistic survey) includes more broadly distributed sites that also reflect the contaminant signature of stormdrain discharges, which include elevated levels of both metals and nutrients that stem primarily from dry season nuisance flow. While this explains why the compliance sites are lower in metals than the watershed as a whole (Figure 3) it does not explain why nutrient values below the discharges have distributions so similar to the overall watershed. Thus, the hybrid design's ability to provide a watershed-scale context for compliance monitoring data raises interesting questions about the processes underlying the characteristics of nutrient values in the mainstem.

Yet a third pattern was observed for IBI values (Figure 5), a measure of the health of the macroinvertebrate community in streams. In this case, biological communities at the compliance monitoring sites were much more impacted than communities of the overall watershed. This reflects the fact that the compliance sites were all in heavily modified channels while the probabilistic sites were distributed across the watershed (Figures 1 and 2). In contrast to the compliance sites, the wide spread of IBI values at the targeted sites reflects the range of habitat conditions that these trend sites were selected to represent.

Biological patterns and habitat modification

Further examination of the macroinvertebrate species data also reveals differences among the major portions of the watershed. A cluster analysis (Barbour *et al.* 1996, Roth *et al*. 1998, LASGRWC 2007) of the species data from the probabilistic sites defined four site groups that reflect consistently different patterns of species distribution and abundance.

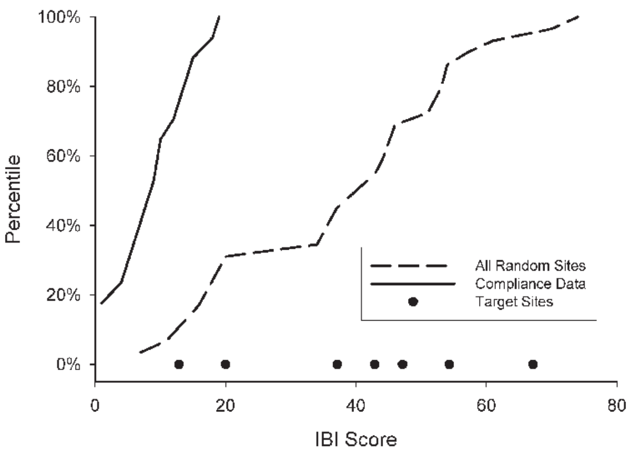

Figure 5. Cumulative frequency distribution of Index of Biotic Integrity (IBI) scores for probabilistic sites (dashed line) relative to distribution of IBI scores at permit compliance monitoring sites (solid line) and to trend sites (dots).

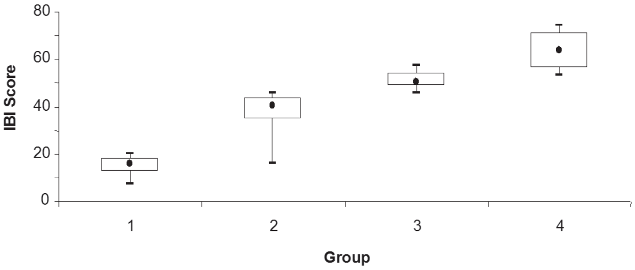

Figure 6. Box and whisker plots showing IBI scores for each of the four site groups from the cluster analysis. Dot = median value; box edges = 5% and 95% confidence intervals; and whiskers = range of all values for each site group.

The IBI scores within each of these site groups (Figure 6) reflect the clear biological differences described by the cluster analysis. The four site groups roughly correspond to the three subareas of the watershed sampled. Site group 4 (with the highest IBI scores) contains the upper watershed sites, and site group 1 (with the lowest IBI scores) contains only lower watershed sites. Site groups 2 and 3 contain a mix of lower watershed and mainstem sites, with group 3 having relatively more soft-bottom channels with available substrate for benthic communities.

This biological pattern can be explained by the much higher habitat scores for channel alteration and epifaunal substrate available cover in site groups 3 and 4 compared to site groups 1 and 2 (LASGRWC 2007). Channels in the lower watershed and along the mainstem are much more likely to lack natural substrate and riparian vegetation and to be routinely maintained for flood control purposes. Such factors have been shown to impact IBI scores in other areas (Collier 1995, Downes *et al*. 2000, Suren and McMurtrie 2005). Site groups 1 and 2, in the lower watershed and mainstem, have higher average temperatures, which are likely due to channel modification and the lack of riparian vegetation, which may also affect IBI scores (Collier 1995, Quinn *et al.* 1997, Lepori *et al*. 2005). Additional insight into patterns in benthic macroinvertebrate communities across the watershed can be inferred by the positive correlation between CRAM and IBI scores, indicating that biotic integrity (as indicated by the benthic macroinvertebrate community) is higher at sites with more intact wetland and riparian communities. As described above, the majority of sites monitored for permit compliance had very low IBI values and are all in heavily modified channels.

The cluster analysis' grouping of sites into four categories based on benthic community structure parallels the four site classes identified for the proposed Biological Condition Gradient (BCG) as part of the Tiered Aquatic Life Use (TALU) process being developed for southern California coastal streams (Diamond 2006). Although generally consistent, the four categories identified by this effort are more distinct than those identified by the TALU process. This may be because the former is based solely on probabilistically sampled sites from a single watershed, while the latter represents a combination of sites from probabilistic and targeted sampling across multiple watersheds. This suggests that groupings based on probabilistic sampling can provide context for interpreting regulatory compliance at fixed sampling sites.

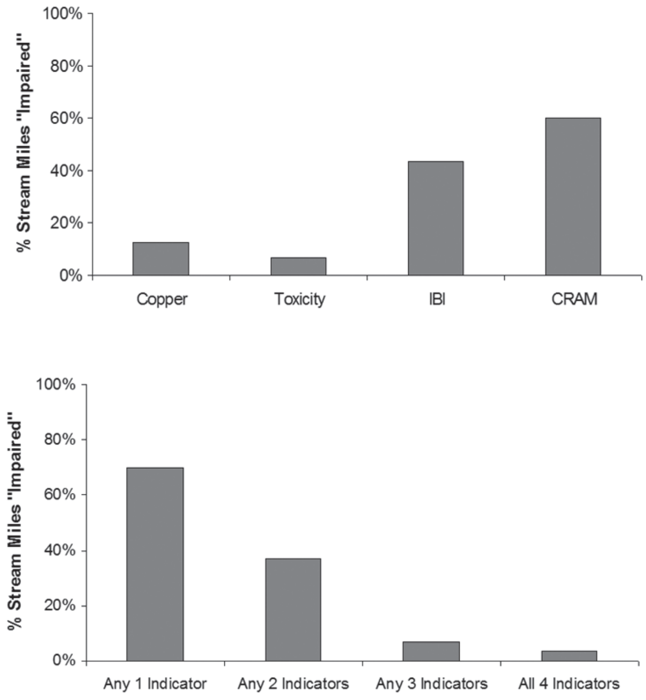

Figure 7. The percentage of watershed stream miles impaired for each of four separate indicators (top panel) and for combinations of the indicators (bottom panel). Impairment was defined as: dissolved copper concentration above the hardness adjusted California Toxics Rule (CTR) criterion; a positive toxicity result on either the chronic or acute test; an IBI score less than 40, the threshold of poor conditions in southern California; a score of less than 54 on the California Rapid Assessment Method (CRAM), a measure of habitat condition. Histograms lack error bars because the percentage of impairment is based on exceedance of a threshold value.

Overall extent and severity of impact

Probabilistic watershed data can be used to estimate the percentage of total miles of flowing streams in the watershed impacted for various indicators (Figure 7). This is possible because results from probabilistic designs can be generalized to the larger sampling frame they represent (Stevens 1997). This is, in fact, one of the principal strengths of such designs. Figure 7 shows the percent of stream miles in the watershed impaired in terms of the values of each of four distinct indicators: chemical contamination, toxicity, biological condition (IBI), and habitat condition (CRAM). The top panel shows that relatively few of the watershed's stream miles are impaired for traditional indicators of chemical contamination or toxicity, while a much greater percentage of stream miles are impaired for indicators of biological and habitat condition. The bottom panel provides a measure of the relative severity of overall impairment by showing the percentage of stream miles simultaneously impaired for more than one indicator.

Use of multiple indicators allows for more in-depth data analysis and interpretation over a range of sensitivities and time scales (Cuffney *et al*. 2000, Adams *et al*. 2002). For example, none of the toxicity observed in the San Gabriel watershed was due to high copper concentrations, which is often assumed to be the source of impairment. In contrast, biological impairment appears to affect a greater proportion of the watershed. Such information can provide managers with insight into key stressors that affect watershed condition, and can help guide priorities for future monitoring and assessment.

Discussion

Watershed-scale environmental monitoring programs that utilize hybrid designs combining both targeted and random sites provide useful insights about patterns of condition and characteristics of impairment that are not available from either type of design alone. Using results from a hybrid watershed design in southern California, we show that compliance monitoring data from discharge sites display distinct patterns in relation to overall watershed conditions. The permit mandated compliance sites have substantially lower metals values than ambient conditions, nutrient values that are well within the range of ambient conditions, and biological conditions, as measured by bioassessment, that are much worse than ambient. In addition, the ability to use probabilistic data to estimate the percentage of stream miles impaired for a range of different indicators furnishes a more comprehensive assessment of overall condition than is typically available from targeted monitoring designs.

Expanding and adapting the hybrid monitoring approach for this and other watersheds should include additional attention to developing tools to better assess headwaters streams. As stated above, 78% of the total stream miles were not evaluated under this program because they were ephemeral and could not be assessed using existing indicators and tools. Consequently, the conclusions of this assessment can only be applied to 3rd order streams and larger. It is well established that headwater streams can have high biodiversity (particularly of benthic communities) and contribute to a range of ecosystem functions (Beschta and Platts 1986, Meyer *et al*. 2007). In wetter climates headwater streams can contribute approximately 70% of the volume and 65% of the nutrient flux to downstream areas (Alexander *et al*. 2007). In arid climates these streams are often hydrologically isolated from downstream areas, yet can still contribute to the overall ecologic function of the watershed (Dietrich and Dunne 1993). Future assessments could benefit by incorporating indicators of general habitat condition, headwaters catchment characteristics, or geomorphic condition that capture the ecologic function of headwater streams.

Despite being limited to 3rd order streams and larger, the types of results illustrated here are useful for managers because they help to prioritize concern and attention by putting monitoring results in the larger context of overall watershed condition. In addition, they provide a basis for interpreting monitoring results that are unavailable from either type of design used alone, thereby demonstrating the value of integrating NPDES compliance and ambient monitoring programs.

Even in its short lifespan, the SGRRMP has begun to demonstrate important benefits for its participants. All have agreed on a core set of questions that will motivate monitoring and management and have agreed that these should be addressed at the watershed scale. While monitoring for compliance purposes continues to be a high priority, these results are now being evaluated in the larger context of overall watershed conditions. As a result, managers are better able to interpret results and prioritize their concerns. For example, the overall extent and magnitude of impairment based on various indicators is beginning to be understood. This overall assessment suggests that while the focus on monitoring along the mainstem of the San Gabriel River is justified, there is as much or more impairment along small tributary channels, which are currently not monitored. This may help guide future monitoring priorities. In addition, the availability of watershed-scale information for multiple metrics that describe physical, chemical, and biological condition is helping to improve understanding of fundamental processes in the watershed. The multiple-indicator approach suggests that managers may need to look beyond the traditional sources of impairment (e.g., copper concentrations) to identify the mechanisms and processes resulting in biological impairment. This insight will in turn continue to enhance the knowledge base for evaluating compliance monitoring results and linking stressors with indicators of condition.

Integrated monitoring, such as the SGRRMP, provides additional benefits to its participants in terms of improved logistical coordination across a wide range of generators and users of monitoring data, greater return on the investment in monitoring effort, and improved cooperation. By working together, the partners on this program have improved the efficiency of their monitoring programs. The cost-savings realized through reduced redundancy and joint data analysis have provided the funding for ongoing implementation of the larger program in a cost-neutral manner. Finally, shared quality assurance procedures (QA) and data management provide all participating agencies and the public with a robust, common dataset for making future management decisions.

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