# Use of probability-based sampling of water-quality indicators in supporting development of quality criteria

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Intensive, site-based data are typically used to establish protective water-quality criteria, but may only exist for few systems in a region. We examine whether or not water-quality indicator data collected from large-scale, probability-based assessments can support the development of regional quality criteria. Because such indicators may be subject to high natural variation over short time-scales, a key question is whether survey values will be sufficiently similar to site-based sampling to merit use in extrapolating quality criteria spatially. Median values for dissolved inorganic nitrogen, phosphorus, and Chl *a* for dry-season data collected within Yaquina Bay (OR, USA) over a 7-year period were compared with dry-season datasets collected from two studies comprising 6 and 14 Oregon estuaries, respectively. A second, reduced dataset (August–September only) was compared with data from 38 estuaries within the same ecoregion. All comparisons were made for marine and riverine salinity zones. Medians for Yaquina Bay were higher than those from the comparison surveys. Stochastic variation of coastal upwelling during sampling appears to cause the contrasts. Further work is required to define upwelling-based adjustments for regional, probability-based survey data before they can be used in regulatory applications. However, even without adjustment, these data may help in determining the appropriate regional context for quality criteria.

**Keywords:** National Coastal Assessment, probability-based sampling, regional water quality, upwelling, water quality criteria, water quality indicators.

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## Introduction

In the USA, states and authorized tribes define designated uses for their waters and must adopt water-quality criteria to protect these designated uses. Although estuaries such as Chesapeake Bay have been extensively studied and support comprehensive datasets that can assist in determining appropriate criteria, few data exist for many other estuarine systems. Therefore, the question of whether or not numeric water-quality criteria developed in systems with adequate data can be extrapolated to other estuaries within the jurisdictional boundaries of the state or tribe, or even across broader areas, is an important one. Relatively limited data exist for most estuaries on the outer coast of the Pacific Northwest region of the USA (Bricker *et al.*, 2007).

One important source of recent data for a suite of water-quality indicators is the National Coastal Assessment (NCA) of the Environmental Protection Agency (US EPA, 2004; Nelson *et al.*, 2005; Hayslip *et al.*, 2006). The NCA programme was instituted with the goals of providing the scientific basis as well as increasing state and tribal capabilities to monitor the status and trends in the condition of coastal ecosystems. A key operational objective has been to collect comparable data to report on the nationwide condition of coastal resources. The programme uses suites of environmental indicators to quantify habitat characteristics, stressor levels, and biological condition (US EPA, 2004), including five measures of water quality: dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), Chl *a*, dissolved oxygen, and water clarity ($k_d$ or Secchi disc depth). The indicators measured represent those recommended in guidance to the states as parameters that can be used as numeric water-quality criteria (US EPA, 2001).

In contrast to many other monitoring programmes, NCA utilizes a probability-based sampling design that selects sampling stations randomly within the total extent of the resource being assessed (e.g. all US west coast estuaries). Although this approach has been optimized for producing quantitative, regional-, and national-scale assessments of environmental condition, aspects of the programme design may limit the utility of these data in informing authorities about the development of criteria protective of waters for which they are responsible. All sampling takes place only during summer, and comprises one-time water samples taken at the surface, in midwater, and near the bottom, irrespective of the tidal stage. For cost and logistical reasons, sampling may be spread over multiple years.

The availability of an extensive dataset from Yaquina Bay (OR, USA) allows a comparison of the median values of key indicators with data collected at larger scales but with shorter temporal extent to determine the potential for using such studies in establishing water-quality criteria. A first set of comparisons was made with datasets restricted to Oregon, because criteria are usually set by the states. Second, Yaquina Bay data were compared with a set compiled from the coastline between the outer coast of

Washington State and central California (EPA Level III-Ecoregion 1; Omernik, 1987). EPA has previously proposed setting freshwater, but not yet estuarine, criteria at the ecoregional level.

## Methods

Yaquina Bay is a small (19 $km^2$) estuary located on the coast of central Oregon (Figure 1). The watershed (660 $km^2$) is ~82% forested, 6% grasslands, <1% highly developed land, with the remainder a mixture of wetlands, open water, and parklands. Population density is relatively low (12 $km^{-2}$). Yaquina Bay (and the Pacific Northwest region in general) is characterized by two distinct hydrological seasons. During the wet, winter season, river flows are high and can be five times greater than during the dry, summer season, and consequently the dominant (74%) source of DIN into the estuary is the watershed (Brown *et al.*, 2007). During summer, coastal upwelling is the major (82%) source of nutrients into the bay (Brown *et al.*, 2007). Based on an analysis of historical and recent water-quality data, hydrodynamic modelling, and stable-isotope analyses of nitrogen sources, Brown *et al.* (2007) divided Yaquina Bay into a marine (≥26 psu) and a riverine zone (<26 psu), which tend to be dominated by differing sources of nutrients. The comparisons of water-quality data were conducted using this criterion for zoning.

The Yaquina Bay data (Y1 set) spanned 7 years (1998–2004) and were collected at 5–36 sites (spanning a ~20 km reach of the estuary) at a frequency ranging from weekly to monthly during the dry season (May–October; for details see Brown *et al.*, 2007). Station locations were selected primarily along the longitudinal axis of the estuary, although in some cases, they were selected randomly within a longitudinal segment.

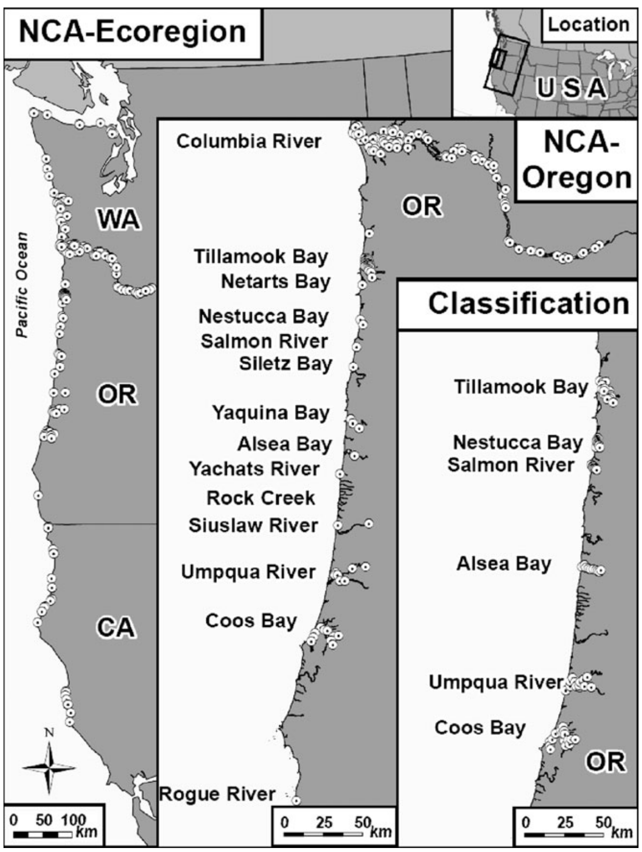


**Figure 1.** Locations of water-quality monitoring stations for NCA-Ecoregion 1 (P2 set), NCA-Oregon (P1 set), and estuarine classification (C set) studies used for regional comparisons with Yaquina Bay.

DIN, DIP, and Chl *a* were selected from the NCA indicator list for analysis. Water clarity was not examined because of methodological differences that limited comparability among studies. The complexities of dissolved-oxygen data will be considered elsewhere.

The Y1 set was compared with data from six estuaries sampled as part of an EPA study to classify Oregon estuarine waters (C set; Brown *et al.*, 2007), and also with data from 14 Oregon estuaries sampled for the NCA (P1 set; for details see Nelson *et al.*, 2004), both carried out during the dry season. The number of samples for each indicator and each dataset are provided in Table 1.

The C set is based on specific estuaries selected for sampling to obtain a cross section of systems within Oregon estuarine management categories, with stations lying at approximately equal intervals along the longitudinal axis (or axes) of each estuary. For this set (156 stations), fewer estuaries and more stations per estuary (10–17; Figure 1) were sampled than for the P1 set, and sampling time was tied to tidal stage (both low- and high-tide cruises). The NCA study used a probability-based, stratified random sampling design (Diaz-Ramos *et al.*, 1996; Olsen *et al.*, 1999), with station locations within a stratum established at random, both in terms of which estuaries received sampling stations and where within the estuary a station was located. Details of the sampling design are provided in Nelson *et al.* (2005). This P1 set (125 stations) spanned a larger geographic extent and was random with respect to tidal stage, with number of samples per estuary ranging from one for small systems to 67 for the large Columbia estuary (Figure 1). Except the Columbia River, all estuaries sampled are similar to Yaquina Bay in that they are relatively small (estuarine area <55 $km^2$), have similar characteristics, e.g. are relatively shallow with strong tidal forcing, and have similar local drivers, e.g. nitrogen-fixing red

**Table 1.** Sample sizes associated with the various datasets used in the comparisons.

| Dataset | Number of estuaries | Number of samples by zone | |
|---|---|---|---|
| | | Marine | Riverine |
| Comparison Yaquina Bay vs. Oregon estuaries | | | |
| Y1 set: Yaquina 1998–2004 | 1 | 1 113 | 915 |
| C set: Classification study 2004/2005 | 6 | | |
| DIN, DIP | | 68 | 88 |
| Chl *a* | | 68 | 78 |
| P1 set: NCA-Oregon 1999/2000 | 14 | 36 | 89 |
| Comparison Yaquina Bay vs. Ecoregion | | | |
| Y2 set: Yaquina August/September 1998–2004 | 1 | | |
| DIN, DIP | | 440 | 111 |
| Chl *a* | | 263 | 183 |
| P2 set: NCA-Level III-Ecoregion 1 1999/2000 | 38 | 76 | 124 |

alder, *Alnus rubra*, in the watershed; influenced by coastal upwelling; and similar land-use characteristics. These watersheds are primarily forested (60–98%), have a small percentage of developed land area ($\leq$2%), and have low human-population densities ($<25\ km^{-2}$; Brown *et al.*, 2007). The watershed of the Columbia River has less forest (56%), more development (low to high intensity = 6% of land area), and a higher population density ($90\ km^{-2}$).

A second comparison was made between the Yaquina Bay data (Y2 set), including only samples collected during August–September (NCA collection period), and the NCA data for 38 estuaries for the whole of Ecoregion 1 (P2 set; for details see Nelson *et al.*, 2005; Hayslip *et al.*, 2006). This comparison was made because ecoregions reflect many ecological factors related to the landscape and watershed, e.g. climate and geology (Omernik, 1987, 1995), and have been used as an appropriate scale for setting stream-nutrient criteria (US EPA, 2000).

Because the data were not normally distributed, the non-parametric Kruskal–Wallis one-way analysis of variance on ranks (SigmaStat version 3.5, Systat Software, San Jose, CA, USA) was used to test differences in the median values among the Y1, C, and P1 sets, whereas Dunn's test was used for pairwise multiple comparisons. The distributions in the Y2 and P2 sets were compared using the Mann–Whitney rank sum (M–W) test. All tests used a significance level of $p < 0.05$.

To evaluate the relative influence of variability in ocean conditions on the estimated medians, we developed regression relationships between water temperature, and $NO_3 + NO_2$, and $PO_4$, using data from the inner continental shelf off Yaquina Bay (Wetz *et al.*, 2005). Nitrate is the primary form of DIN entering the estuary from the ocean (Brown *et al.*, 2007). Previous studies have demonstrated a high coherence in water temperature fluctuations among locations along the Oregon shelf (Hickey and Banas, 2003). In addition, flood-tide water temperatures from Yaquina Bay are correlated with 40 h, low-pass-filtered water temperatures on the inner shelf. Flood-tide water temperatures from Yaquina Bay were assumed to represent ocean conditions along the Oregon coast. To test this approach, the regressions between nutrients and flood-tide water temperature were used to estimate variability in oceanic conditions on the specific dates of estuarine sampling for the Y1 and P1 datasets. Temperature data were obtained from South Beach Station (Station: 9435380, 44.625°N 124.043°W; available online at http://co-ops.nos.noaa.gov), and flood-tide values were extracted from the hourly data using times of predicted high tides. Pearson product moment correlations ($r$) were calculated between observed and predicted nutrients. Differences between predicted and observed median values for each dataset and differences between predicted nutrients for the Y1 and P1 datasets were tested using the M–W test.

## Results

Plots of the NCA data (P2 set) for DIN and DIP measured across the Level III-Ecoregion 1 vs. surface salinity at the sample sites demonstrate two distinct patterns (Figure 2). DIN exhibited a bimodal pattern with highest values at either end of the salinity distribution, although these data did not yield a statistically significant fit to a regression model (second order polynomial, $p = 0.18$). In contrast, DIP had a significant linear relationship with surface salinity ($PO_4 = 0.4 + 0.024 \times \text{salinity}$; $r^2 = 0.44$).

Figure 3 summarizes the various comparisons between the medians of the three indicators for the two zones separately.

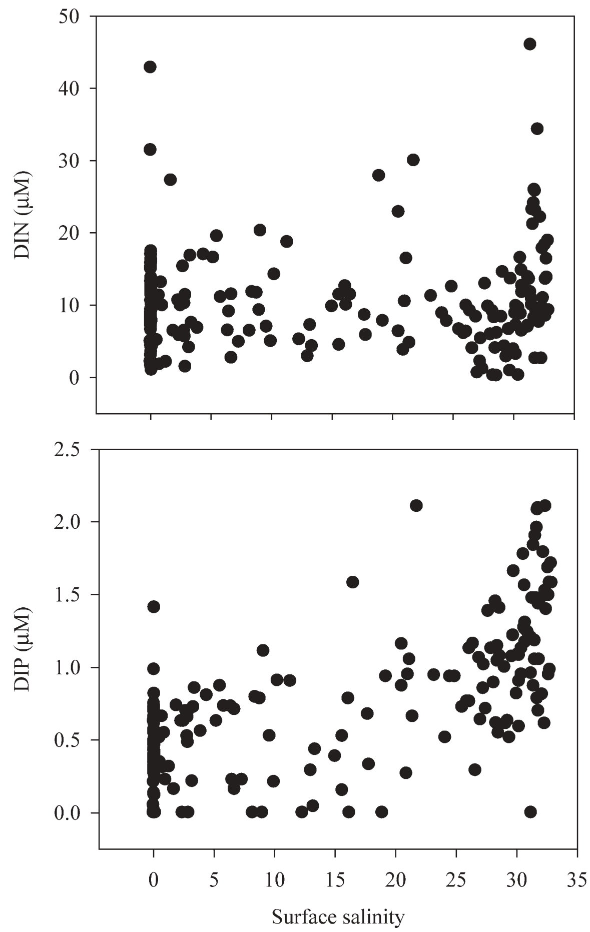


**Figure 2.** Scatterplots of surface DIN and DIP vs. surface salinity for stations sampled by NCA within Level III-Ecoregion 1 (P1 set), 1999/2000.

Median DIN concentration in the Y1 set in the marine zone was significantly greater than the median concentrations in both the C and P1 sets, which did not differ significantly from each other. For the riverine zone, the median DIN value in the Y1 set did not differ from the C set, whereas both values were significantly higher than in the P1 set, and the range of values observed in the first two sets was much greater. The median DIP concentration in the Y1 set in both the marine and riverine zones was significantly greater than the medians of the other two sets, which did not differ significantly from each other. Median Chl *a* concentration in the Y1 set in the marine zone was significantly greater than those for the other two sets, which did not differ significantly from each other. In the riverine zone, the median concentration in the Y1 set was significantly greater than in the P1 set, which in turn had a significantly higher median than the C set.

Similar comparisons of median DIN and DIP-values between the Y2 set and the P2 set gave generally the same pattern of results. For both zones and parameters, Y2-set medians were significantly higher. The median Chl *a* values for the marine zone were not significantly different, whereas the median for the riverine zone in the Y2 set was significantly higher than in the P2 set.

On the inner Oregon shelf, nutrient ($NO_3 + NO_2$, and $PO_4$) levels were significantly correlated with water temperature

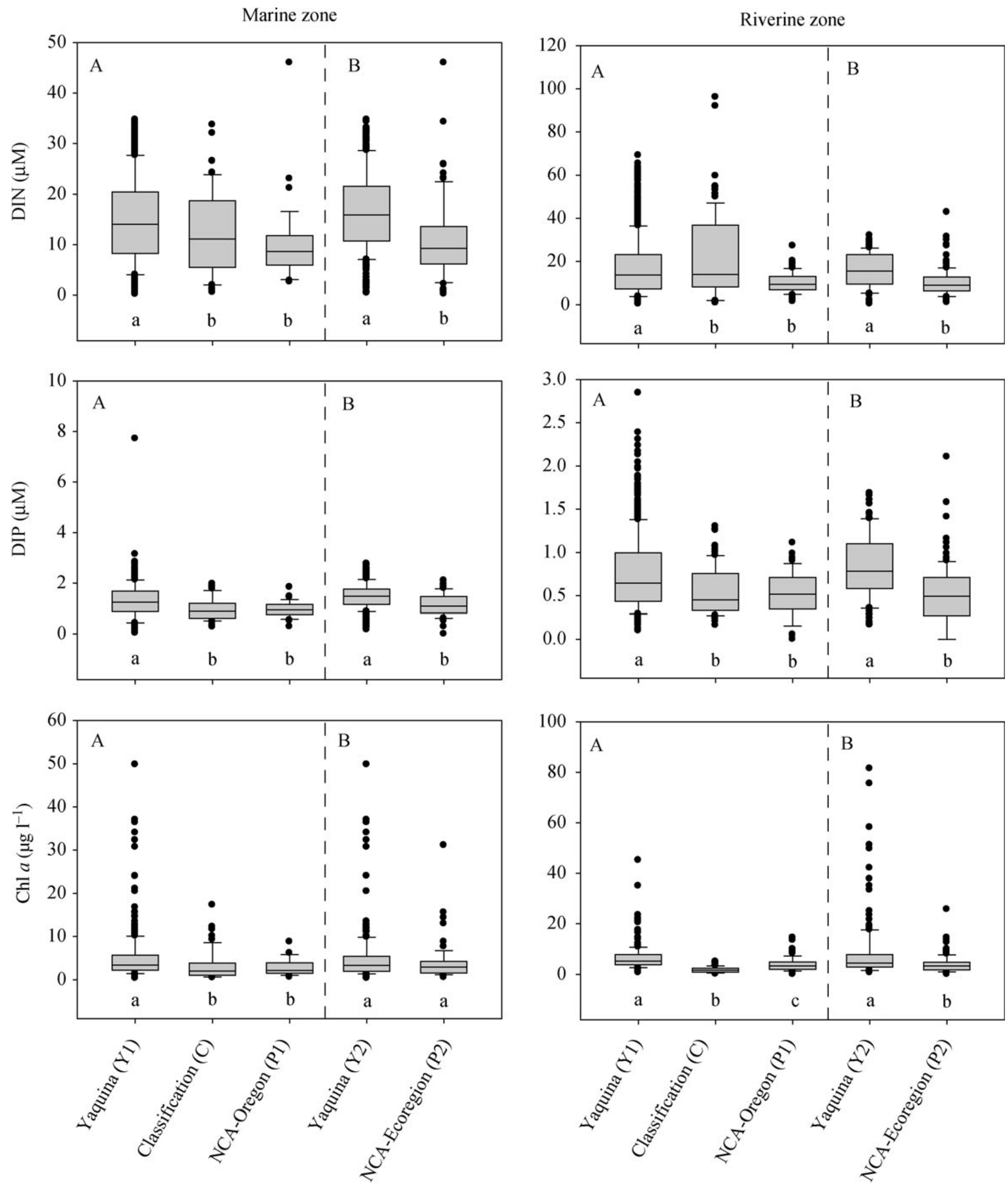


**Figure 3.** Box plots comparing quartiles, 10th and 90th percentiles of DIN, DIP, and Chl *a* for marine and riverine salinity zones for (A) data from Yaquina Bay (Y1 set), Classification (C set), and NCA-Oregon (P1 set); and (B) Yaquina Bay (Y2 set) and the NCA-Level III-Ecoregion 1 (P2 set). Solid points are values beyond the 10th and 90th percentiles. Datasets labelled with different letters within graph sections A or B have significantly different medians ($p < 0.05$).

(Figure 4). Oceanic nutrient concentrations (in μM) can be predicted from water temperature ($T$ in °C) using the following equations (presented in Figure 4):

$$NO_3 + NO_2 = 44.7 - \frac{44.3}{1 + e^{-(T-8.29)/0.996}} (n = 570, r^2 = 0.85) \quad (1)$$

$$PO_4 = 19.5\, e^{-T/3.67}\ (n = 432, r^2 = 0.77). \quad (2)$$

These equations can be used to assess the influence of upwelling on comparisons of medians among datasets. First, we compared the modelled $NO_3 + NO_2$ concentration from July through September 1999 with the dates of the 1999 P1 set of the marine zone (Figure 5), demonstrating that 82% of NCA-Oregon sample dates occurred during periods of low upwelling activity. We then used flood-tide water temperature at Yaquina and Equations (1) and (2) to predict $NO_3 + NO_2$, and $PO_4$ concentrations for each observation in the marine zone of both the Y1

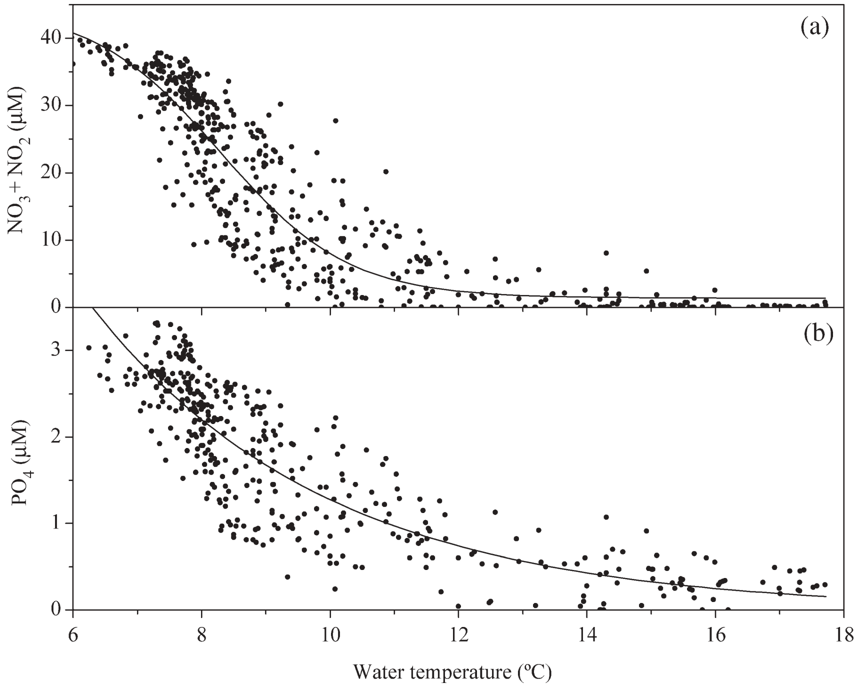


**Figure 4.** Relationship between water temperature and (a) $NO_3 + NO_2$, and (b) $PO_4$, generated using data from Wetz *et al.* (2005).

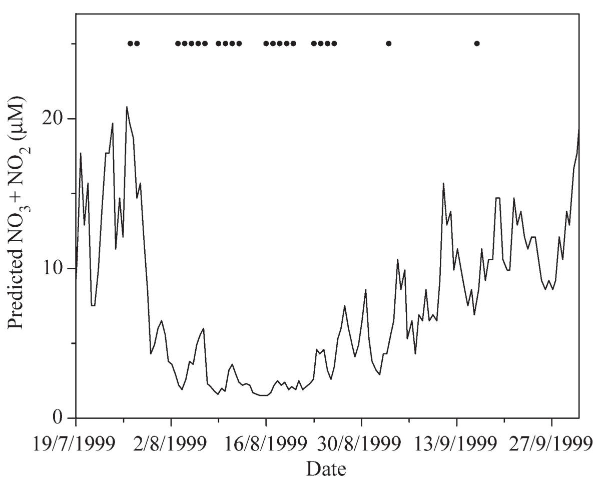


**Figure 5.** Comparison of the 1999 NCA dates of sampling (dots) in the marine zone of Oregon estuaries with the predicted $NO_3 + NO_2$ concentration based on its relationship with water temperature for the inner Oregon shelf.

and P1 datasets. This approach provided an estimate of the nutrient concentration expected if all input came from the nearshore.

The correlations between observed and predicted $NO_3 + NO_2$ and $PO_4$ in the marine zone were significant for both datasets (Pearson product moment correlation $r$, 0.42–0.64, $p < 0.05$; Table 2), suggesting that ocean conditions are influencing nutrient levels in the marine zone. Although observed and predicted values are significantly correlated, there are significant differences in the observed and predicted median values for these parameters. For the Y1 set, differences between observed and predicted median values were significant, with predicted median values being 14% lower than observed for $NO_3 + NO_2$ and 5% higher than the observed for $PO_4$. For the P1 set, observed median $NO_3 + NO_2$ values were significantly higher (66%) than the modelled values. In contrast, there were no significant differences in $PO_4$ between modelled and observed values for the P1 set. The modelled median values for both were significantly higher for the Y1 set than for the P1 set, suggesting that differences in ocean conditions may be the cause of the differences in observed medians between these sets (Table 2).

## Discussion

The patterns of DIN and DIP values vs. salinity found across the Level III-Ecoregion 1, determined from probability-based sampling (Figure 2), were essentially the same as the patterns found by Brown *et al.* (2007) from an intensive study of Yaquina Bay. Although in this study only the DIP relationship was significant for the ecoregional data, both the bimodal DIN and linear DIP relationships vs. salinity within Yaquina Bay were statistically significant (Brown *et al.*, 2007). For DIN, the bimodal pattern reflects oceanic inputs from offshore upwelling at high salinities and watershed inputs, even under low flow conditions associated with nitrogen-fixing red alder within the riparian zone in the watershed (Brown *et al.*, 2007). This similarity initially encouraged the view that water-quality criteria determined from intensive studies within a single estuary might be extrapolated to a broader range of systems. However, of the six statistical comparisons of median values conducted using data collected within Oregon's estuaries (Figure 3), in only one case (DIN, riverine zone) was the median value from the Yaquina study not significantly different from the two spatially broader datasets. Similar results were found for statistical comparisons of the reduced Yaquina dataset (Y2) that matched the ecoregional NCA set (P2) in terms of sampling period (Figure 3), where, of six comparisons, only one (marine zone, Chl *a*) did not differ significantly. In all

**Table 2.** Comparison of observed and predicted median values of $NO_3 + NO_2$, and $PO_4$ for the marine zone for the Y1 and P1 datasets, and Pearson product moment correlation coefficients (*r*) calculated between observed and predicted values (sample sizes in parentheses).

| Dataset | $NO_3 + NO_2$ | | | $PO_4$ | | |
|---|---|---|---|---|---|---|
| | Median (μM) | | *r* (*n*) | Median (μM) | | *r* (*n*) |
| | Observed | Predicted | | Observed | Predicted | |
| Y1 | 10.1 | 8.6 | 0.64 (1 103) | 1.25 | 1.31 | 0.53 (1 104) |
| P1 | 8.4 | 2.8 | 0.42 (36) | 0.95 | 0.81 | 0.45 (36) |

All correlation coefficients are significant at $p < 0.05$.

cases of significant differences, medians of parameters from Yaquina Bay were higher.

Estuaries on the Pacific Northwest coast are next to the California Current system, which exhibits strong interannual, seasonal, and event-scale variability (Hickey and Banas, 2003). Wind-driven upwelling advects relatively cool, nutrient-rich ($NO_3$ and $PO_4$) water to the surface, typically from April to September. A greater amount of the short-term variability in nutrient and Chl *a* concentrations in these estuaries is related to import of oceanic water (De Angelis and Gordon, 1985; Roegner and Shanks, 2001; Brown *et al.*, 2007). Nitrate near the mouth of the Yaquina estuary can vary by as much as 30 μM over a period of days in response to local windforcing (Brown *et al.*, 2007). Because the bay is not being affected by large anthropogenic inputs of nutrients (Brown *et al.*, 2007), the differences observed compared with other datasets, particularly in the marine zone, are likely to have resulted from variability in upwelling conditions during sampling.

Great interannual variation in nutrient and Chl *a* levels on the Oregon shelf also results from variability in upwelling conditions (Corwith and Wheeler, 2002; Huyer *et al.*, 2002; Thomas *et al.*, 2003; Wheeler *et al.*, 2003), as well as from significant delays of the upwelling season during some years (Barth *et al.*, 2007). Hickey and Banas (2003) examined variations in temperature, salinity, and alongshore windstress for three estuaries spanning 400 km along the Oregon and Washington coasts and demonstrated similarity in the fluctuations of specific water properties among these estuaries during summer, resulting from the large-scale patterns of alongshelf windforcing.

The analysis using water temperature and modelled nutrient relationships suggests that the differences between the NCA-Oregon and Y1 datasets may be largely the result of differences in ocean conditions at the times that samples were collected. The water temperature and nutrient relationships performed better at predicting nutrient levels in the marine zone for the Y1 set than for the P1 set, which is not surprising because the relationships were generated using data from the inner shelf near the Yaquina estuary. The large discrepancy between the observed and modelled $NO_3 + NO_2$ levels suggests that the observations from the marine zone of the P1 set may be influenced by additional nitrogen sources. We conclude that the influence of upwelling variability must be accounted for, if data on water-quality indicators collected from short-term, large-scale studies are to be used to extending the spatial scope of water-quality criteria derived from long-term, site-specific studies. We suggest that relationships between water temperature and nutrients offer a potential means of generating correction factors for probability-based data collection in the region. A future refinement of this approach would be to develop temperature–nutrient relationships, using data from multiple stations along the Oregon shelf to predict ocean conditions at the time of sampling.

Although major difficulties appear to arise when directly extrapolating indicator data from probability-based surveys to systems where data are limited, the use of all available data in a regional context for setting criteria that help to protect the environment remains an important issue. For example, the current Oregon Chl *a* criterion for estuaries that must be satisfied is that the average value (based on a minimum of three samples collected over any three consecutive months) must be $<15\ \mu g\, l^{-1}$. However, this value is rarely exceeded within either marine or riverine zones for a system examined over multiple years (Yaquina Bay) or for multiple systems across Oregon, or even across the entire ecoregion. Median Chl *a* levels in all Oregon estuaries sampled were generally in the low ($\leq 5\ \mu g\, l^{-1}$) category as defined by Bricker *et al.* (2003), in terms of eutrophication status. The current criterion is 3–7 times higher than median Chl *a* values observed in any of the datasets examined. If 3-monthly average concentrations of estuaries were to approach the current criterion value routinely, it is likely that trophic status would have altered. Therefore, we suggest that the current criterion may not be adequate to prevent further anthropogenic eutrophication of estuaries in the region and may need to be revised.

A second example of the relevance of regional data to water-quality standards relates to DIP. In both estuarine zones, the median values of all three sets of observations fell between the concentration limits (0.32–3.2 μM) proposed by Bricker *et al.* (2003) as representing a medium eutrophication status. For the larger ecoregion, >75% of the DIP observations in all datasets examined exceeded 0.32 μM. Upwelling appears to be an important source of DIP into the estuaries, suggesting that the reference level for Pacific Northwest estuaries needs to be adjusted upwards to reflect this natural influence.

Probability-based sampling for water-quality indicators appears adequate for defining spatial patterns of nutrient distribution across the estuarine salinity gradient at an ecoregional scale. However, median indicator values in short-term surveys appear to be strongly influenced by temporal variation in upwelling activity extending across the region. This stochastic variability currently hinders the ability to use data derived from probability-based sampling studies for extrapolating water-quality criteria beyond the systems for which they have been developed. Although the use of modelled nutrient and water temperature relationships to correct for upwelling variability may ultimately be useful in improving the use of regional-scale assessment data in a regulatory context, more rigorous analyses are required to reach this goal. The acquisition of additional years of large-scale survey data, as currently in progress, as well as the development of modelled nutrient and water temperature relationships for different parts of the ecoregion, may also help to clarify these issues.

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