Freshwater Inflow Biotic Index (FIBI) 
for the Lavaca-Colorado Estuary, Texas

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Freshwater inflow is an important source of physical variability in estuaries. Effects of 
water flow are dynamic, and it is impossible to sample all conditions as they vary over 
space and time. Benthos, however, are fixed in place, continuously sample the overly-
ing water conditions, and demonstrate a variety of consistent responses to multiple 
sources of stress. Benthic indices of biotic integrity (BIBIs) have been particularly use-
ful for assessing aquatic systems. However most indices have focused on assessing 
effects related to changes in water quality rather than water quantity. This study devel-
ops a Freshwater Inflow Biotic Index (FIBI) to determine how changes in freshwater 
inflow affect benthic populations, which in turn reflect the ecological condition of an 
estuary. Based on benthic succession theory and long-term data, 12 biotic metrics 
were chosen that characterized benthic community structure in response to inflow 
regimes. The metrics were ranked and then reduced to one variable using principal 
component analysis (PCA) to form the index. The FIBI and hydrological PC variables 
were significantly correlated, indicating that benthic communities respond to changes 
in salinity and do so in a relatively predictable manner. If inflow is reduced (i.e., salinity 
increased), it will cause upstream communities to take on characteristics of down-
stream communities. The FIBI successfully characterized effects of a salinity gradient 
in the Lavaca-Colorado estuary, and application of the FIBI approach should be suc-
cessful in other estuarine ecosystems.

Keywords  benthos, diversity, hydrology, nutrients, salinity, environmental flows

Introduction

Concern over anthropogenic changes to the environment has grown over recent decades, 
and ever-increasing environmental legislation has brought concern about ecosystem health 
to the forefront of both scientific and political spheres (Lackey 2001, Montagna and others 
2002a, Farber and others 2006). To address these concerns, it is necessary to develop 
new scientific methods to assess, distinguish, and mitigate effects from natural and 
anthropogenic changes (Millennium Ecosystem Assessment 2005). Because ecological 
interactions are complex, it is necessary to explain these relationships in a simple 
and easy-to-understand manner. Methods that both simplify the assessment process and 
are economically feasible are crucial to the success of ecosystem-based management 
strategies.

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Environmental flows, i.e., the hydrologic regimes in rivers, and inflow from rivers to estuaries are one ecosystem service that is particularly vulnerable to water resource development (Kowalewski and others 2000, Rodriguez and others 2001, Kimmerer 2002a). The effects of water flow are dynamic, and it is impossible to sample all conditions as they vary over space and time. Benthos, however, are fixed in place, continuously sample the overlying water conditions, and demonstrate a variety of consistent responses to multiple sources of stress (Pearson & Rosenberg 1978, Bilyard 1987, Weisberg and others 1997). Benthic invertebrates integrate the ephemeral water column conditions over time and provide a long-term record of short-term changes (Montagna and others 2002b). Until recently, most assessments have focused on water or sediment quality, especially to identify the effects of chemical pollutants (i.e., Carr and others 1996, USGS National Water Quality Assessment Program 2008). Water quantity, however, is increasingly under regulatory review and control (Alber 2002, Montagna and others 2002a). As freshwater inflow is a key factor controlling ecosystem health in coastal bays and estuaries worldwide (Copeland 1966, Sutcliffe 1972, Ben-Tuvia 1973, Montagna and Kalke 1992, Longley 1994), an index that could simply and effectively assess the environmental condition based on salinity regimes and other hydrographic variables (as a proxy for measuring the effects of inflow directly) would be useful. Inflow effects indices would be particularly helpful in coastal areas in which population growth, and subsequent freshwater usage, is expected to increase significantly over the next several decades. For example, in Texas, coastal population growth is projected to almost double from 20.9 million to 39.6 million by 2050 and the need for new water projects will increase concomitantly (Texas Water Development Board 2002).

Ecological health can be defined in terms of ecosystem integrity (Costanza and others 1992, Karr 1991), and benthic monitoring is an important tool used often to assess integrity of aquatic ecosystems. One important outcome from benthic monitoring programs of the past few decades is the succession dynamics model where benthic community change with distance from a disturbance is analogous to benthic community change over time after a disturbance (Pearson and Rosenberg 1978, Rhoads and others 1978). Benthic indices of biological (or biotic) integrity (BIBIs) have been particularly useful in the assessment of aquatic systems, which are under increasing levels of environmental stress (Weisberg and others 1997, Carr and others 2000, Llansó and others 2002, Maloney and Feminella, 2006, Qadir and Malik, 2009). Benthic organisms are relatively long-lived and sessile, making them excellent indicators of long-term environmental conditions.

The goal of the current study was to develop a Freshwater Inflow Biotic Index (FIBI) that could be used to determine how changes in freshwater inflow affect benthic populations, which in turn reflect the ecological condition of an estuary as it relates to altered inflow regimes. Development of the FIBI was based on succession theory (Pearson and Rosenberg 1978, Rhoads and others 1978), methodology employed by a variety of indices of biotic integrity (Karr 1991, Weisberg and others 1997, Carr and others 2000, Llansó and others 2002, Maloney and Feminella 2006, Qadir and Malik, 2009), as well as other studies linking environmental variables with biological measures (Green and Montagna 1996, Peterson and others 1996, Long and others 2003). The FIBI was calibrated using a long-term dataset on macrofauna and hydrography in the Lavaca-Colorado Estuary on the central Texas coast in the western Gulf of Mexico.
Methods

Study Area and Index Development

Benthic data used to develop and validate the index were collected from 4 sites in the Lavaca-Colorado Estuary, Texas over a 17-year period (April 1988 to October 2005; Fig. 1). Four stations, A - D, are positioned along a salinity gradient originating from inflow from the Lavaca River to Lavaca Bay and Matagorda Bay, which is connected to the Gulf of Mexico. Stations A and B are mixo-mesohaline (≈5-18 ppt) areas located in the highly freshwater-influenced portion of Lavaca Bay. Station C is a mixo-polyhaline (≈18-30 ppt) area located mid-way between Lavaca and Matagorda Bay, and euhaline (≈30-40 ppt) station D is located nearest to the Gulf of Mexico. Details on the study area and specific sampling locations are described by Kalke and Montagna (1991), Montagna and Kalke (1995).

Continuous, quarterly benthic samples were collected at each site using three replicate cores (6.7 cm dia, 35.4 cm² area) per station. The cores were split vertically into surface (0 – 3 cm deep) and bottom (3 – 10 cm deep) sections. Benthic macrofauna from the core samples were preserved, extracted on a 0.5 mm sieve, sorted using a dissecting microscope, identified to the lowest taxonomic level (usually species), and enumerated. Biomass measures were obtained by combining individual macrofauna into higher taxa levels (i.e., Crustacea, Mollusca, Polychaeta, and others), drying at 50 °C for 24 h, and then weighing. Mollusc shells were removed with 1 N HCl prior to drying and weighing.

Figure 1. Study area and stations. Stations A - D are located along a salinity gradient from fresh to marine from Lavaca Bay to Matagorda Bay.
Several other measurements or samples were collected in conjunction with the benthic samples to characterize the conditions at each station. A multiparameter instrument (Hydrolab Surveyor II or YSI 6 series) was used to measure hydrographic characteristics including: water temperature, pH, dissolved oxygen, redox potential, salinity, and specific conductivity; salinity was also measured with a refractometer. In the laboratory, water samples were analyzed for chlorophyll a (Chl a) and nutrients (dissolved inorganic nitrogen, phosphate, silicate). Inflow data were obtained from Paul Jensen, PBS&J, Inc., and includes gauged flows and modeled flows by the Texas Water Development Board (TWDB) for ungauged areas. Continuous salinity data (for comparison with inflow events) were obtained from the TWDB station in Lavaca Bay (at the Causeway), N 28° 39′ 12″ and W 96° 35′ 44″. Sediment samples were collected during fall quarterly sampling periods from 2001-2003 for geological analyses. Sediment samples were analyzed for percent contribution by weight of rubble, sand, silt, and clay. Percent porewater, total carbon (C), total nitrogen (N), total organic carbon (TOC), $\delta^{15}$N, and $\delta^{13}$C values were also measured.

The benthic and hydrographic data collected from the Lavaca-Colorado estuary were used to develop a freshwater inflow biotic index (FIBI) to determine the primary factors driving macrofaunal community structure in different salinity regimes. The approach is similar to that which has been used in other biological indices, i.e., a set of metrics are chosen based on their ability to reflect biological, chemical, or physical attributes of ecological condition (US EPA 2000). It is desirable to identify metrics that display a consistent response to a given stressor or disturbance (Karr 1991, Weisberg and others 1997, Llansó and others 2002). For development of the FIBI, the stressor was salinity as a surrogate for freshwater inflow effects. In accordance with other index methods, a scoring system for the metrics was used to classify the ecological condition at a specific location and sampling period. Because the variables must be expressed in the same scale for the scoring system to be useful, a ranking system was used.

Twelve different biological metrics (Table 1) were included in the current index: biomass (g m$^{-2}$), abundance (n m$^{-2}$), and Shannon diversity ($H'$) were included as metrics of integrity; % fresh water indicator species, % brackish water indicator species, and % marine indicator species were habitat metrics; % subsurface (3-10 cm below the sediment water-column interface) biomass, % subsurface abundance, and % subsurface species number were vertical metrics, and % predators, % deposit feeders, and % water-column feeders were functional metrics. When considering the integrity of a community, univariate measures (i.e., biomass, abundance, or diversity) are commonly used. These univariate measures, however, lack any information about which species contribute to the diversity. Thus, multivariate measures of community identity were included in the FIBI in addition to the univariate measures.

Marine, brackish, and freshwater indicator species were identified in a long-term study of the sampling stations (Kinsey 2006; Table 2). The Lavaca-Colorado Estuary is a system where biodiversity is driven by rarity; 13% of the species made up 90% of all those found (Kinsey 2006). In developing the FIBI, it was therefore important to decrease the number of species to a subset of indicators so that non-occurrence does not drive the result. The selected species comprise a subset of dominant organisms that are indicators of the three salinity-habitat types (freshwater, brackish, marine). These indicators then each become 1 of 12 metrics included in the index. The salinity ranges assigned to the various indicator species agree with mean salinities of occurrence for these species or genera reported from: 1988 - 2007 for the Texas coast (from the Laguna Madre, Nueces-Corpus, Mission-Aransas, Guadalupe, and Lavaca-Colorado Bay systems from 3,159 samples;
Table 1
List of biological attributes that were used as metrics for the freshwater inflow biotic index. Percent values in each category are with respect to total numbers for that category. Asterisk indicates biological attribute is significantly correlated with Hydrographic PC 1 (all correlations positive except for % brackish indicators and % deposit feeders).

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Benthic metric</th>
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<tr>
<td>Integrity</td>
<td>Abundance (n m$^{-2}$)*</td>
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<tr>
<td></td>
<td>Biomass (g m$^{-2}$)*</td>
</tr>
<tr>
<td></td>
<td>Shannon diversity (H$^\prime$)*</td>
</tr>
<tr>
<td>Habitat</td>
<td>% Freshwater indicators</td>
</tr>
<tr>
<td></td>
<td>% Brackish indicators*</td>
</tr>
<tr>
<td></td>
<td>% Marine indicators*</td>
</tr>
<tr>
<td>Vertical</td>
<td>% Subsurface abundance*</td>
</tr>
<tr>
<td></td>
<td>% Subsurface biomass*</td>
</tr>
<tr>
<td></td>
<td>% Subsurface species*</td>
</tr>
<tr>
<td>Functional</td>
<td>% Predators / omnivores*</td>
</tr>
<tr>
<td></td>
<td>% Deposit feeders*</td>
</tr>
<tr>
<td></td>
<td>% Water column (suspension) feeders*</td>
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</tbody>
</table>

Table 2

<table>
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<th>Indicator type</th>
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<th>Species name</th>
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<th>Mean salinity U.S. coast</th>
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<td>Chironomidae larvae</td>
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<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Insecta</td>
<td>Insecta (unidentified)</td>
<td>0.0</td>
<td>6.8</td>
</tr>
<tr>
<td>Brackish</td>
<td>Crustacea</td>
<td>Ampelisca abdita</td>
<td>26.2</td>
<td>27.2</td>
</tr>
<tr>
<td></td>
<td>Mollusca</td>
<td>Macoma mitchelli</td>
<td>15.4</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>Mollusca</td>
<td>Mulinia lateralis</td>
<td>22.4</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>Polychaeta</td>
<td>Parandalia ocularis</td>
<td>15.0</td>
<td>15.5*</td>
</tr>
<tr>
<td></td>
<td>Polychaeta</td>
<td>Streblospio benedicti</td>
<td>21.3</td>
<td>19.4</td>
</tr>
<tr>
<td>Marine</td>
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<td>Apseudes sp. A</td>
<td>27.2</td>
<td>n.d.</td>
</tr>
<tr>
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<td>Corbula contracta</td>
<td>27.2</td>
<td>32.9</td>
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<tr>
<td></td>
<td>Mollusca</td>
<td>Periploma cf. orbiculare</td>
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<td>33.1*</td>
</tr>
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<td>Ophiuroidea</td>
<td>Amphiodia atra</td>
<td>27.8</td>
<td>31.3</td>
</tr>
<tr>
<td></td>
<td>Polychaeta</td>
<td>Minuspio cirrifera</td>
<td>27.9</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

*mean salinity of occurrence for genera; n.d. = no data available.
Montagna, unpublished data), and from 1991 - 2006 for the U.S. coast (from California, Texas to Mississippi, Florida to North Carolina, and Virginia to Maine from 2,104 samples; National Benthic Inventory 2009; Table 2). Brackish-water indicator species declined and marine indicator species increased continuously along the freshwater to marine salinity gradient. Abundances within each indicator category were summed, and the % abundance in each category with respect to total abundance of all species was calculated. Species-level data were then organized into trophic guilds as defined by Tenore and others (2006).

In long-term analyses (Kinsey 2006), biomass, abundance, diversity, and all trophic groups (interface feeders, predators, and deposit feeders, defined by Tenore and others 2006) were found to be positively correlated with salinity. High diversity is associated with healthy ecosystem function (Thébault and Loreau, 2006). High biomass, abundance, and diversity in the subsurface sediment layer are known to be associated with later successional stages and therefore relatively undisturbed, high-quality communities (Pearson and Rosenberg 1978; Carr and others 2000). All other variables included in the index were either found to be significantly correlated with salinity or were known be associated with changes in salinity or inflow (Kalke and Montagna 1991; Montagna and Kalke 1992, 1995, Ritter and others 2005). Sediment characteristics were not included as metrics because they were not significantly different among stations and were not correlated with any of the biological variables in Lavaca Bay or Matagorda Bay (Kinsey 2006).

Principal Component Analysis (PCA) was used to assess relationships between sediment variables, hydrologic variables, and FIBI metrics. PCA reduces a multivariate data set and creates new variables by extracting variance in order of importance. Results of the analysis are a new set of PC variable loads and sample scores. The PC loads represent the underlying structure of the dataset, and the scores represent the contribution of each sample. The higher the absolute value of the PC loads the more influence the variable has in the new PC variable. Results are presented in plots of the vectors of the PC loads to aid interpretation of the underlying structure, and sample scores to visualize spatial and temporal comparisons. The second output is a matrix of sample scores representing the sample contribution. This allows for spatial and temporal comparisons among the different loading variables, and among stations and sampling periods.

The PROC FACTOR procedure (SAS version 9.1) was used in lieu of PROC PRINCOMP because the former produces data sets of both vector loads and sample scores, while the latter only outputs vector loads (Carr and others 2000, Long and others 2003). Values for each of the FIBI metrics for each sampling period and station were ranked in groups of five (0 - 4) using the PROC RANK procedure in SAS (1996). The metrics were then analyzed using these ranked values. The new PC variables represent the FIBI because all the biological metrics are reduced to just two new variables representing the underlying structure of the dataset due to environmental variability.

To link the sediment and hydrographic data with the biotic data, linear correlations were performed between FIBI metrics and sediment and hydrographic PC factor 1 and PC factor 2 scores, using the PROC CORR procedure (SAS version 9.1). This method of linking reduced environmental variables with reduced biological variables has been used successfully in previous sediment toxicity studies (Green and Montagna 1996; Carr and others 2000), and is described in detail by Montagna in Porewater Toxicity Testing (Long and others 2003).

Results

Salinity ranged from freshwater conditions (<0.5 ppt) to hypersaline (>36 ppt) during the study period. Average salinities ranged from 12.3 to 26.6 ppt, increasing continuously
Freshwater inflow rates ranged from approximately 11,500 ac-ft (1.419 × 10^7 m^3) per month to almost 4,000,000 ac-ft (4.934 × 10^9 m^3) with a mean value of nearly 360,000 ac-ft (4.441 × 10^8 m^3) per month. A significant, negative correlation (p < 0.001, R^2 = 0.69) was found between inflow and salinity (Fig. 2), indicating that salinity levels were affected by inflow. Average dissolved oxygen levels decreased continuously along the increasing salinity gradient from 7.4 to 8.1 mg l\(^{-1}\). Temperatures and sediment characteristics were uniform across all stations; nutrients and chl a declined with increasing salinities. Mean abundance, biomass and diversity generally increased along the salinity gradient from fresh to marine. Over 70% of all species found comprised polychaetes, while crustaceans constituted 5% and bivalves 7%. Out of a total of 227 species, 29 species represented 90% of all of the individuals found over all stations.

The first and second principal components (PC 1 and PC 2) for the FIBI metric ranks explained 46% and 17% (63% total) of the variation within the data set (Fig. 3). The PC 1 variable loads for the FIBI metric ranks had the highest positive values for percent marine indicator (% Mi) species, diversity (H'), and biomass (Bio), and the highest negative values for percent brackish indicator (% Bi) species, and percent deposit feeders (% Dep). Thus, the FIBI PC 1 axis represents freshwater inflow effects; freshwater and brackish water species had negative loads while marine species had high positive loading values. All PC 1 loads except for percent freshwater indicators were above the absolute value of 0.54, indicating that all of the metrics except for freshwater indicators were relatively important. Station loading scores were distributed in a fairly distinct spatial pattern, with station A and B values being most negative (higher proportion of brackish indicators), and station C and D values being most positive (higher proportion of marine indicators). The PC 2 variable loads had the highest positive values for percent deposit feeders (% Dep) and the highest negative values for percent water column feeders (% Wat) and percent brackish indicator species (% Bi). All other metrics’ PC 2 loads were below the absolute

Figure 3. Principal components analysis (PCA) variable loads (top) and station scores (bottom) for FIBI ranks. Abbreviations: % Bi = brackish indicator species; % Mi = marine indicator species; % Fi = freshwater indicator Abund = abundance; Bio = biomass; $H'$ = diversity; BioSub = subsurface (3-10 cm) biomass; AbundSub = subsurface abundance; SppSub = subsurface number of species.
value of 0.5, indicating that those metrics were not as influential. Station loading scores were distributed randomly along the PC-2 axis.

The first and second principal components (PC 1 and PC 2) for sediment variables explained 67% and 31% (98% total) of the variation among all sediment data (Fig. 4). The PC 1 loads for the sediment data had the highest positive values for TOC, percent nitrogen (Npct), and percent carbon (Cpct), and the highest negative values for sand. The PC 1 axis represents sand effects, with low organic content correlated with high sand content. Station D loading scores were generally higher than station C scores along the PC 1 axis, whereas station A and B scores tended to overlap. The PC 2 variable loads had the highest positive values for $\delta^{13}$C, while silt and porosity had the most negative loads. The PC 2 axis is related to inflow because fine material (silt) is transported downstream by flow and deposited in the bay. The $\delta^{13}$C values indicate the carbon source, where land plants have lower values than phytoplankton, and phytoplankton has lower values than seagrass. Freshwater influenced stations A and B tended to have higher proportions of silt and lower $\delta^{13}$C values compared to marine influenced stations C and D.

The PC 1 and PC 2 loads for hydrographic variables explained 44% and 37% (total 81%) of the variation among all hydrographic data (Fig. 5). The PC 1 loads for the hydrographic data had the highest positive values for salinity and the highest negative values for nutrients [dissolved inorganic nitrogen (DIN), phosphate and silicate], but salinity was overwhelmingly the most influential variable. The PC 1 axis clearly represents an inflow effect, where a decrease in salinity (or increase in freshwater inflow) is associated with an increase in nutrients. Station loading scores were distributed in a fairly distinct spatial pattern along the inflow gradient, with stations A and B generally exhibiting the most negative relationship with salinity and stations C and D the most positive. The PC 2 axis represents a seasonal effect, with high temperatures correlated with low dissolved oxygen. Although freshwater inflow was highest in spring and fall, the variability was high enough such that inflow effects and seasonal effects were independent of one another. Station loading scores did not show any seasonal distribution pattern.

A significant correlation ($p < 0.0001$) was found between FIBI PC 1 and hydrographic PC 1 scores, indicating that the biological variables are directly related to the hydrology of the system (Table 3, Fig. 6). The PC 1 axis for both the FIBI and hydrographic variables represented inflow effects. Along the FIBI PC 1 axis, freshwater and brackish water species had negative loads while marine species had high positive loading values. Correspondingly, freshwater influenced stations A and B tended to have more negative values along the FIBI PC 1 axis than marine influenced stations C and D. Along the hydrographic PC 1 axis, low salinity had negative loads while low nutrients had high positive loading values, representing the decrease in salinities and increase in nutrients (from runoff) associated with increased freshwater inflow. Along this axis, freshwater influenced stations A and B also tended to have more negative values than marine influenced stations C and D.

There was a roughly 1:1 relationship between salinity and the hydrographic PC 1 axis, and a breakpoint exists at around 20 ppt (0 on the hydrographic PC 1 axis), representing a shift from freshwater-influenced to marine-influenced communities (Fig. 6). Thus, a 1-2 unit shift along the hydrographic PC 1 axis can lead to a change in community structure. The FIBI PC 1 scores were also significantly correlated with sediment PC 2 scores, further demonstrating the link between freshwater inflow effects (i.e., fine materials and terrestrial-based carbon sources being transported down to the bay) and changes in community structure (Table 3). The FIBI PC 2 scores were significantly correlated with hydrographic PC 2 scores, demonstrating a link.
Figure 4. Principal components analysis (PCA) variable loads (top) and stations scores (bottom) for sediment characteristics, stations A-D. Abbreviations: TOC = percent total organic carbon, d15N = $\delta^{15}$N, C pct = percent carbon, N pct = percent nitrogen, d13C = $\delta^{13}$C.
Figure 5. Principal components analysis (PCA) variable loads (top) and stations scores (bottom) for hydrographic characteristics, stations A-D. Abbreviations: Sal = salinity, ph = pH, do = dissolved oxygen, temp = temperature, sio4 = silicate, po4 = phosphate, din = dissolved inorganic nitrogen, chl = chlorophyll a.
between seasonal effects and changes in community structure represented by changes in benthic feeding modes.

**Discussion**

Multivariate analytical techniques have been used successfully for assessing disturbances to benthic communities (Green 1980, Stull and others 1986, Smith and others 2001). The approach advocated in the present study is to characterize the long-term trend in hydrographic changes using a multivariate analysis of water quality parameters. Multivariate analyses are necessary to assess which variables are most influenced by freshwater inflow, and to predict how a system will change in response to alterations of hydrology. Using PC factor scores is unique in comparison to other index systems that utilize arbitrarily chosen, fixed values to define their respective environments. Principal component analysis groups the variables by their similarity of variance with respect to one another; any change (addition or subtraction) to the data being processed will alter the relationship between the variables. Therefore, the original PC factor values may change for each date-station sample when new data are added. These values will remain similar relative to one another, however, and will still allow for detection of community shifts (towards marine or freshwater-influenced communities) over time.

The ranking and scoring system for the FIBI reflect freshwater inflow effects across the estuary. The lowest PC 1 factor scores and mean rankings are associated with the most freshwater influenced portions of the system; values increase along the salinity gradient, with highest values representing the most marine-influenced environments (Fig. 3). Only two metrics did not follow this trend; brackish indicator species (%) and deposit feeders (%). High biomass, diversity, and marine indicators were the primary variables characterizing the most marine-influenced environment. Two of the three trophic groups increased in abundance along the salinity gradient from fresh to marine; water column feeders and predators/omnivores. High abundances of water column feeders were observed in the marine-influenced environment while deposit feeders were more abundant in highly freshwater-influenced environment. This difference is likely due to the high number of pioneer species, which are known to colonize quickly after a disturbance.

Spatial distributions of estuarine organisms are strongly influenced by the salinity gradient between the landward and seaward boundaries of the estuary (Boesch 1977). Different mechanisms have been discussed for positive effects of freshwater inflow on estuarine populations, including release from bottom-up limitation due to nutrient stimulation

### Table 3

Linear correlations between FIBI (Fig. 3), sediment (Fig. 4), and hydrographic (Fig. 5) PC factor scores. FIBI = Freshwater inflow biotic index, PC = principal component,  
$r$ = Pearson product correlation coefficient, $P$ = probability of the null hypothesis

<table>
<thead>
<tr>
<th>Hydrographic PC 1</th>
<th>Hydrographic PC 2</th>
<th>Sediment PC 1</th>
<th>Sediment PC 2</th>
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<tr>
<td><strong>FIBI PC 1</strong></td>
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<tr>
<td>$r$</td>
<td>0.592</td>
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<tr>
<td>$P$</td>
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<td>$P$</td>
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Figure 6. Linear correlations between FIBI PC 1 (Fig. 3) and hydrographic PC 1 (Fig. 5) factor scores, and between salinity and hydrographic PC 1 factor score, stations A-D. A natural breakpoint between freshwater-influenced and marine communities occurs at around 20 ppt (dashed line).
Pollack, Kinsey, and Montagna (Sutcliffe 1972), or low-salinity suppression of benthic predators (Wilber 1992). In contrast, marine-influenced benthic species may display a negative response to increased freshwater inflow due to seaward displacement of their habitat or osmotic stress (Nichols and others 1990).

The FIBI PC 1 load for % freshwater indicators was below 0.5, suggesting the relative unimportance of this metric (Fig. 3). Insects constituted a very small proportion (< 0.1%) of the total number of organisms collected in this study, and were thus grouped into higher taxonomic levels. All samples containing insects were collected from the lowest salinity station A. The exception was two samples collected from station B either during high inflow periods or preceded by prolonged periods of flood conditions. Similar patterns were observed in 1984, where flood conditions expanded the freshwater zone in Lavaca Bay, increasing the downstream distribution of chironomid larvae from more dense populations upriver (Kalke & Montagna 1991). In the Lavaca-Colorado Estuary, insects as a group are not good indicators of the existence of a salinity gradient but rather are indicators of freshwater conditions.

It is important to be able to identify how many water condition-based habitats exist in the bay system because of proposed water resource development. The relationship between FIBI PC 1 and hydrographic PC 1 factor scores (Fig. 6) demonstrates two distinct salinity habitat zones or water conditions that support characteristic communities. The lower left quadrant represents freshwater and brackish indicators and conditions, and the upper right quadrant represents marine indicators and marine conditions. The A-B and C-D clusters represent the two salinity zones in the estuary, which are driven by freshwater inflow. The variability in the A-B and C-D clusters is due to the stochastic nature of biological communities. It is not uncommon for biological communities in coastal and estuarine areas to be variable. This is partially driven by the regular seasonality of the system, and partially driven by inflow variability. Given this noise, the question remains: is the FIBI a conservative indicator of the long-term inflow/salinity condition of the site, or is it a more sensitive indicator of the transient conditions at the site? The answer is likely that both are true. The contention here is that the FIBI defines salinity habitat zones; if the estuary is dewatered with water resource development or diversions, the water conditions will change such that the estuary may contain only one salinity habitat zone and the conditions in the A-B zone may change to those at C-D. The FIBI would be able to identify these changes over time.

Many indices of pollution or other environmental stressors utilize a system of classification based on threshold values that define specific environments of interest e.g., degraded vs. pristine environments (Weisberg and others 1997, Van Dolah and others 1999, Toham & Teugels 1999, Christman & Dauer 2003, Qadir and others 2008). For the FIBI, PCA scores were continuous and not parsed into distinct categories, allowing for greater sensitivity in detecting small shifts in environmental condition. As FIBI PC 1 values increased, the community increasingly took on marine characteristics. A breakpoint or shift from freshwater to marine-influenced benthic community structure occurred at around 20 ppt. This translated into a 1 - 2 unit shift along the hydrographic PC 1 axis leading to a change in community structure. By using PC scores instead of mean rankings, it was possible to detect trends associated with both season and inflow events by comparing the FIBI and hydrologic and sediment PC scores along each PC axis. This is useful because a shift in community structure during a given sampling period might be primarily due to seasonal differences (i.e., temperature and irradiance) rather than inflow effects, or vice versa. Inflow regimes are complex and comprise the volume, timing, frequency, extent, and duration of inflow events; changes to any of these characteristics of a regime
will likely cause different physical and biological responses (Alber 2002, Kimmerer 2002b). These distinctions are necessary to determine causal relationships and appropriately apply the findings to inflow management strategies.

Benthic indices, although not without limitations, have proven to be important tools for assessing estuarine habitat quality (Weisberg and others 1997, Van Dolah and others 1999). The results presented here indicate the FIBI can be effectively used to link benthic community response to change in salinity habitats (as a proxy for freshwater inflow) in the Lavaca-Colorado Estuary. The FIBI can be applied to other systems, but some metrics may need to be adjusted. For example, in other systems different indicator species or the addition of a sediment substrate metric may be useful. However, the overall methods for such an index should remain relatively similar in other systems. If it is found to be an effective general model, the FIBI could be paired with salinity or inflow models in order to quantitatively predict changes in benthic secondary production (i.e., biomass). This pairing might also allow for the development of models that could predict quantitative trophic changes in estuarine systems. Such models would be important to our understanding of how inflow affects trophic dynamics in these environments, which are strong indicators of ecosystem function and health (Kimmerer 2002a).

The maintenance of environmental health or integrity is a growing priority of environmental legislation and regulation for local, national, and international communities. The FIBI was designed to be a tool to help simplify the process of determining ecosystem health. Because the FIBI contains components of both structural integrity (e.g., abundance, biomass, and diversity) and functional integrity (e.g., trophic guilds and vertical habitat presence), it is a useful tool for detecting important changes within environmentally sensitive estuarine systems. More research and application of the FIBI to other systems is needed to determine the generality and effectiveness of this new approach.

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References


