An Ecosystem-based Framework for Assessing and Managing Sediment Quality Conditions in Tampa Bay, Florida

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Abstract. A Comprehensive Conservation and Management Plan has been developed to facilitate the protection and restoration of Florida's largest open-water estuary. The plan, developed cooperatively by the Tampa Bay Estuary Program and its partners, recognizes that sediment contamination has the potential to compromise beneficial water uses and adversely affect aquatic-dependent wildlife and human health. As such, protecting relatively uncontaminated areas of the bay from contamination and reducing the amount of toxic chemicals in contaminated sediments have been identified as high priority sediment management objectives for Tampa Bay. The purpose of the paper is to present an ecosystem-based framework for assessing and managing sediment quality conditions to support the sediment management program. The framework includes five key elements, including identification of sediment quality issues and concerns, development of ecosystem goals and objectives, selection of ecosystem health indicators, establishment of metrics and targets for key indicators, and incorporation of key indicators, metrics, and targets into watershed management plans and decision-making processes. The process that was used to select and evaluate numerical sediment quality targets and to apply the targets to identify three types of sediment management areas is also described. In addition, the sediment management options that should be considered for each of the three types of sediment management areas are described.

Key words: Ecosystem Sediment Quality Targets Assessment Management Contamination

Introduction

Tampa Bay is a large, urban estuary that is located in west central Florida (Figure 1). As Florida's largest open-water estuary, Tampa Bay covers an area of almost 400 square miles and receives drainage from a 2,200 square mile watershed (TBNEP 1996). The estuary, which is surrounded by the cities of Tampa, St. Petersburg, Clearwater, and Bradenton, provides a variety of benefits to residents and visitors to the area alike. While portions of the bay system are still relatively undeveloped (e.g., Little Manatee River basin), other areas are highly industrialized and urbanized (e.g., Hillsborough River basin).

Tampa Bay receives contaminant inputs from a wide range of sources, including urban runoff, industrial point sources, municipal wastewater discharges, atmospheric deposition, accidental spills, illegal dumping, pesticide applications, and agricultural practices (Long *et al.* 1994). Upon release to aquatic systems, many contaminants adhere (or adsorb) to particulate matter (e.g., suspended sediments) and become associated with bottom sediments. In Tampa Bay, several classes of toxic substances have been identified in bedded sediments, including trace metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides (Long *et al.* 1991). The results of previous studies indicate that contaminant concentrations are highest near large urban centers, ports, and marinas, particularly in upper Hillsborough Bay, Boca Ciega Bay, and Bayboro Harbor (Long *et al.* 1994; Zarbock *et al.* 1996). Several major studies in Tampa Bay have identified specific chemicals of potential concern (COPCs), based on exceedances of sediment quality guidelines (SQGs) for the protection of aquatic organisms, wildlife, and/or human health. These COPCs include eight trace metals (cadmium, copper, chromium, lead, mercury, nickel, silver, and zinc), PAHs, PCBs, and eleven organochlorine pesticides (Long *et al.* 1991; 1994).

At elevated concentrations, sediment-associated contaminants have been linked to a number of adverse effects on the organisms that live in and on bedded sediments. For example, tests conducted with field-collected sediment samples have demonstrated that contaminants may be acutely and chronically toxic to benthic and/or pelagic species (e.g., Swartz *et al.* 1986; 1991; Ferraro *et al.* 1991). In addition, benthic invertebrate community alterations have been observed in association with elevated sediment contaminant concentrations (e.g., Swartz *et al.* 1985; 1994; Anderson *et al.* 1988). Furthermore, many of the substances that accumulate in sediments can also accumulate in the tissues of fish and shellfish. At elevated levels, these tissue-borne contaminants may represent significant hazards to humans and wildlife that consume aquatic organisms (Ingersoll and MacDonald 1999). Therefore, accumulation of toxic substances in bedded sediments represents an important concern that needs to be addressed by environmental managers.

The Tampa Bay Estuary Program (TBEP) and its partners are addressing concerns regarding sediment quality conditions in several ways, including the development of sediment quality targets (SQTs; i.e., physical, chemical, and biological benchmarks that can be used to assess the status of sediment quality conditions) that can be used in conjunction with monitoring data to support sediment management initiatives within the Tampa Bay ecosystem (e.g., monitoring, assessment, source control, remediation). Over the past six years, three workshops have been convened to obtain advice and guidance on the selection of indicators of sediment quality conditions and associated numerical targets. In addition, a number of focused studies have been conducted to obtain the information needed to evaluate the SQTs. As such, the requisite information is now available for establishing SQTs for Tampa Bay.

The purpose of this paper is to describe the ecosystem-based framework that has been developed for assessing and managing contaminated sediments in Tampa Bay, Florida (Figure 2). Accordingly, the ecosystem goals and objectives that have been established to guide the management of sediment quality conditions in Tampa Bay are described. In addition, the sediment quality indicators and metrics that have been selected to support assessments of sediment quality conditions are identified. Furthermore, numerical SQTs were derived based on the concentration-response relationships that were developed for two key indicators of sediment quality conditions, including sediment toxicity and benthic community structure. The resultant SQTs are intended to support the identification of three types of sediment management areas, based on the probability of observing specific types of biological effects. Finally, the applications of the selected SQTs for defining sediment management areas and for considering sediment management options within such areas are presented.

Methods

Development of Ecosystem Goals and Sediment Management Objectives

Ecosystem goals are broad narrative statements that describe the long-term vision that has been established for the ecosystem under consideration (CCME 1996; Crane *et al.* 2000). Because it is difficult to evaluate the extent to which ecosystem goals have been attained directly, sediment management objectives (SMOs) that are more closely linked to ecosystem science are also needed to clarify the scope and intent of the ecosystem goals (DOE 1996). To support the development of ecosystem goals and SMOs that provide a basis for assessing and managing sediment quality conditions, the TBEP convened a series of workshops with key stakeholder groups (i.e., representatives of government, industry, and academia) from the area and practitioners in the field of sediment quality assessment. Subsequently, workshop participants evaluated a suite of candidate ecosystem health indicators and associated metrics to identify the ones that would provide the information needed to determine if the ecosystem goals and SMOs were being met in Tampa Bay (MacDonald 1995; 1997; 1999; Table 1).

Selection of Sediment Quality Metrics and Targets

The ecosystem health indicators and associated metrics that are selected to support the sediment quality assessment process determine what types of data are to be collected in monitoring programs (i.e., high priority indicators and metrics identified in Table 1). While such data can be used directly to evaluate trends in sediment quality conditions, assessment of the status of the ecosystem relative to the SMOs necessitates the development of SQTs that apply to key indicators and metrics (e.g., a SQT of 18.7 mg/kg dry weight could be used to support the evaluation of copper concentrations in estuarine sediments; MacDonald *et al.* 1996). Such chemical and biological targets need to provide a basis for determining if aquatic habitats are not impacted (i.e., Impact Level A), moderately impacted (i.e., Impact Level B), or highly impacted (i.e., Impact Level C) due to chemical contamination. Such a classification scheme then supports the identification of sediment management areas and options that can be used to protect and/or restore the beneficial uses of aquatic habitats.

In order to identify the candidate SQTs, the workshop participants first established ecosystem-based biological SQTs. More specifically, biological SQTs that corresponded to the three impact levels were established for sediment toxicity and benthic invertebrate community structure. Aquatic habitats were considered to be not impacted if incidence of acute toxicity, chronic toxicity, or benthic community impairment within an area was below 10% (i.e., if fewer than 10% of the samples showed evidence of impairment; Impact Level A). By comparison, aquatic habitats were considered to be moderately impacted if the incidence of acute toxicity, chronic toxicity, or benthic community impairment within an area was between 10 to 20%, 10 to 50%, and 10 to 50%, respectively (i.e., Impact Level B). Finally, aquatic habitats were considered to be highly impacted if the incidence of acute toxicity, chronic toxicity, and benthic community impairment within an area was >20%, >50%, and >50%, respectively (Table 2; i.e., Impact Level C). These biological targets then provided a basis for establishing candidate chemical targets for classifying sediments into the three impact categories (i.e., in terms of classifying sediment samples as having low, moderate, or high potential for being associated with specific types of adverse biological effects).

Published numerical SQGs provided sources of candidate chemical SQTs for assessing sediment chemistry data. A number of approaches have been developed to support the derivation of numerical SQGs for assessing sediment chemistry data (MacDonald *et al.* 2000). In this investigation, two types of numerical SQGs were considered for establishing SQTs for COPCs in Tampa Bay, including the effects level SQGs that were derived for Florida coastal waters (MacDonald *et al.* 1996) and the effects range SQGs that were formulated under the National Oceanic and Atmospheric Administration's (NOAA) National Status and Trends Program (NSTP; Long *et al.* 1995). Using effects level approach, MacDonald *et al.* (1996) derived a threshold effect level (TEL) and a probable effect level (PEL) for nine trace metals, total PCBs (tPCBs), 13 PAHs, bis(2-ethylhexyl)phthalate, and six organochlorine pesticides (Table 3). Similarly, Long *et al.* (1995) formulated an effects range-low (ERL) and an effects range-median (ERM) for nine trace metals, tPCBs, 13 PAHs, and five organochlorine pesticides (Table 3). These two sets of SQGs can be used to identify three ranges of chemical concentrations, including a low range, within which adverse biological effects are unlikely to occur (e.g., below the TEL or ERL values), a middle range, within which adverse biological effects are possible (e.g., between the TEL or ERL and PEL or ERM values), and an upper range, within which adverse biological effects are likely to occur (e.g., above the PEL or ERM values). As the narrative intent of these SQGs was generally consistent with the biological targets, they were selected as candidate SQTs for sediment chemistry in Tampa Bay. The bioaccumulation-based SQTs for Tampa Bay were adopted directly from New York State Department of Environmental Conservation (NYSDEC 1999) and are presented in Table 4.

Evaluation of the Candidate Chemical Targets

The candidate chemical SQTs were evaluated to determine if they would provide effective tools for assessing sediment quality conditions in Tampa Bay (i.e., tools that could be used to accurately classify sediments in a manner that was consistent with the biological targets). In this study, predictive ability is defined as the ability of the various SQTs to correctly classify field-collected sediments as impacted or unimpacted. The predictive ability of the candidate effects-based chemical targets for COPCs was evaluated using a two-step process (MacDonald *et al.* 2000), including development of the project database and evaluation of the incidence of adverse biological effects within the ranges of contaminant concentrations. Due to limitations on the availability of information on the bioaccumulation of sediment-associated contaminants in Tampa Bay, no attempt was made to evaluate the chemical targets for bioaccumulative substances.

The first step in the SQT evaluation process involved the acquisition and evaluation of matching sediment chemistry and biological effects data. Both matching sediment chemistry and toxicity data (i.e., synoptically-collected) and matching sediment chemistry and benthic invertebrate community structure data from Tampa Bay were compiled to support the evaluation of the predictive ability of the candidate chemical targets. The primary sources of such data included NOAA (i.e., data collected under the NSTP; Long *et al.* 1994; Carr *et al.* 1996), Environmental Protection Commission of Hillsborough County (Grabe 1997; Grabe and Barron 2002; EPC, unpublished data), and the University of South Florida (USF; unpublished data; Table 5). Each study was evaluated to assure the quality of the data that were to be used in subsequent analyses. The acceptance criteria that were applied to individual studies provided a basis for determining if experimental designs, measurement endpoints, sample collection and handling procedures, toxicity testing protocols and environmental conditions, control responses, and analytical methods were consistent with established procedures (Long *et al.* 1995; MacDonald *et al.* 1996; Long *et al.* 1998; Field *et al.* 1999; MacDonald *et al.* 2000; USEPA 2000; Ingersoll and MacDonald 2002). The sediment chemistry and biological effects data used in this investigation were evaluated against the acceptance criteria were found to meet the project data quality objectives.

All of the data that met the acceptance criteria were incorporated into the project database in Microsoft Access™ format. The data were compiled on a per-sample basis, with each record including the reference citation, a brief description of the study area (i.e., water body and reach), a description of the sampling locations, georeferencing information (i.e., latitude and longitude coordinates), information on the toxicity tests (e.g., species tested, endpoint measured, and test duration) or benthic invertebrate community structure analyses that were conducted, type of material tested (i.e., whole sediment, or pore water), the total organic carbon (TOC) concentrations (if reported), and the chemical concentrations (expressed on a dry weight basis). Other supporting data, such as simultaneously extractable metal (SEM) concentrations, acid volatile sulfide (AVS) concentrations, and particle size distribution, were also included in the individual data records, as available. The total concentrations of PAHs, PCBs, DDTs, and chlordane were determined for each sediment sample using the methods described USEPA (2000). All of the data that were compiled in the database were verified against the original data source (i.e., on a number for number basis) to assure the accuracy of all data entry and translation activities.

Because sediments in Tampa Bay are known to contain complex mixtures of contaminants (Zarbock *et al.* 1996), four widely used indices of overall chemical contamination were derived to support the predictive ability assessment. Thus, predictive ability is likely to increase when the chemical targets are used together to classify sediments from this geographic area. For this reason, mean SQG-quotients (i.e., PEL-Qs) were calculated for each of the sediment samples represented in the database to provide an index of overall chemical contamination using the United States Environmental Protection (USEPA) method (USEPA 2000). First SQG-Qs for each metal were calculated by dividing the measured concentration of each metal by its respective SQG. Next, the mean SQG-Qs for metals, an SQG-Q for tPAHs , and an SQG-Qs for tPCBs were calculated. Finally, the mean SQG-Q was calculated by determining the average of the mean SQG-Q for metals, the SQG-Q for tPAHs, and the SQG-Q for tPCBs (USEPA 2000).

The data on the chemical composition of Tampa Bay sediments were not consistent throughout the project database. In some cases, for example, only the concentrations of trace metals were measured in sediments. In other cases, the concentrations of trace metals, PCBs, PAHs, and organochlorine pesticides were measured (termed the 'full suite of analytes'). In certain sediment samples, only the concentrations of trace metals and organochlorine pesticides were quantified. In the predictive ability analysis, all mean SQG-Qs were treated as equivalent regardless of the number of analytes measured (as per Ingersoll *et al.* 2001).

The biological effects data that have been generated for Tampa Bay sediments were used to designate individual sediment samples as impacted or unimpacted. Sediment samples were designated as acutely toxic to sediment-dwelling organisms based on the results of 10-day toxicity tests with the amphipod *Ampelisca abdita*. Sediment samples for which amphipod survival was significantly reduced compared to that in control samples and outside the normal range for uncontaminated Tampa Bay sediment samples were designated as acutely toxic (i.e., using a reference envelope approach; Reynoldson *et al.* 1995; Hunt *et al*. 2001). The normal range of amphipod survival was determined by calculating the 95% prediction limits (i.e., mean $\pm$ 2 standard deviations; Reynoldson *et al.* 1995) for uncontaminated Tampa Bay sediment samples (i.e., those with mean PEL-Qs, calculated using the USEPA method, of <0.1; Long and MacDonald 1998; Ingersoll *et al.* 2001).

The results of 1-hour toxicity tests with the sea urchin, *Arbacia punctulata* (endpoint measured: fertilization), using undiluted pore water were used to evaluate the chronic toxicity of Tampa Bay sediments. In this application, sea urchin gamete fertilization was used as a surrogate for reproduction in sediment-dwelling organisms. Although this approach provides a rapid, worst-case scenario for the potential exposure of benthic organisms, it may not be ecologically realistic for many sediment-dwelling organisms that are provided some measure of protection from their tube or burrow while ventilating overlying water into their oxic microenvironment. While some infaunal organisms move freely within the sediment, many species of infaunal crustaceans, polychaetes, and bivalves inhabit tubes and burrows which are actively ventilated, thereby greatly reducing their exposure to the adjacent interstial water and associated contaminants. For example, the infaunal clam, *Macoma nasuta*, has been observed to have its siphon below the sediment surface more than 75% of the time but pore water constituted only 4% of the water ventilated based on dye studies (Specht and Lee 1989; Winsor *et al.* 1990). For organisms with porous tubes or burrows made of loosely consolidated sediment (e.g., the ghost shrimp, *Callianassa californiensis*), a greater portion of the ventilated water may be interstial water (Winsor *et al*. 1990). By exposing organisms to the undiluted pore water, the effects of confounding factors may mask contaminant-induced responses (Nipper *et al.* 2002). For this reason, the results of toxicity tests conducted with undiluted and diluted pore water were used to assess chronic toxicity. Sediment samples with significantly reduced fertilization relative to control samples and control-adjusted fertilization rates of <81% in undiluted or diluted pore water were designated as chronically toxic to sediment-dwelling organisms (Carr *et al.* 1996).

A total of seven metrics were considered for evaluating the status of the benthic invertebrate community, including: total abundance of benthic organisms; abundance of amphipods; abundance of capitellid polychaetes; abundance of gastropods; abundance of tubificid oligochaetes; Shannon-Wiener Diversity Index (SWDI; Shannon and Weaver 1949; Cook 1976; Hughs 1978; Washington

1984; Coastal Environmental Inc. 1995; 1996); and, Tampa Bay Benthic Index (TBBI; Coastal Environmental Inc. 1995; 1996). The SWDI was selected as the primary metric for assessing the status of the benthic community because it provided the most reliable basis for discriminating among impacted and unimpacted sediment samples (i.e., the lower 95% prediction limit was not a negative value). Sediment samples were considered to be impacted relative to benthic invertebrate community structure if the SWDI was less than the lower 95% prediction limit of 1.23 for relatively clean sediment samples (mean PEL-Q <0.1; i.e., using the reference envelope approach; Hunt *et al.* 2001). All three types of biological effects data (i.e., acute toxicity, chronic toxicity, and benthic community impairment) were used independently to determine if Tampa Bay sediments were impacted or unimpacted.

In the second step of the predictive ability evaluation, an assessment was conducted to determine the extent to which the candidate chemical targets were consistent with the biological targets that had been previously established. As the reliability of the TELs and PELs, had been previously evaluated (MacDonald *et al.* 1996; Long *et al.* 1995), the performance of the individual SQGs was not assessed in this investigation. Rather, the predictive ability evaluation focused on determining the extent to which the PELs, when used together in mean PEL-Qs, accurately classified sediment samples into the three categories defined by the biological targets (i.e., A, B, and C Impact Levels).

Several approaches for defining the impact levels relative to sediment chemistry were evaluated in this study. First, two different methods of calculating the mean SQG-Qs were evaluated to determine which was more appropriate for use in Tampa Bay. In addition, various ranges of mean SQG-Qs were evaluated for establishing A, B, and C impact levels (Table 2). For each of these approaches, the incidence of sediment toxicity and benthic invertebrate community impairment was determined within various ranges of the SQTs (i.e., <0.1, 0.1-1.0, and >1.0 for mean PEL-Qs and mean ERM-Qs; <0.1, 0.1-2.3, and >2.3 for mean PEL-Qs; <0.1, 0.1-1.5, and >1.5 for mean ERM-Qs, calculated using the NSTP and USEPA methods). Then, the incidence of adverse biological effects within each impact level category was compared to the biological targets that were established for that category (e.g., incidence of toxicity of <10% for impact level A; see Table 2). A predictive ability score of 0 or 2 was assigned based on whether or not the observed incidence of effects was within the range of effects that was established for that category (MacDonald *et al.* 1996). These scores were then summed for each category and biological endpoint to determine a total evaluation score for each approach. The approach with the highest total evaluation score was selected for identifying sediment management areas in Tampa Bay.

More specifically concentration response relationships were generated for each biological effects metric (Field *et al.* 1999). To facilitate the new development of such relationships, the matching sediment chemistry and biological effects data for Tampa Bay were used to determine the incidence of sediment toxicity or benthic community impairment for groups of sediment samples. The points shown on these plots represent the geometric mean of the PEL-Qs and the fraction of the samples that was identified as toxic or impaired (e.g., Figures 3, 4, and 5). Each point represents a minimum of 10 and a maximum of 40 individual samples (depending on the plot; USEPA 2000; Field *et al.* 1999; 2002). The relationship between concentration (i.e., mean PEL-Q) and response (probability of observing sediment toxicity or benthic community impairment) was determined by fitting a logistic regression model to the data points using Sigma Plot 2000 (for Windows Version 6; USEPA 2000; Field *et al.* 2002). The resultant models provide a basis for estimating the probability of observing biological effects at any level of sediment contamination (as indicated by mean PEL-Qs) represented by the underlying data. As such, these models were used to identify the levels of sediment contamination that corresponded to a 10%, 20%, 50%, and 80% probability of observing acute toxicity, chronic toxicity and benthic community impairment (i.e., P_{10}, P_{20}, P_{50}, and P_{80} values, respectively).

Identification of Sediment Management Areas

Classifying areas within the bay relative to the potential for observing adverse biological effects represents an important element of the overall sediment management strategy for Tampa Bay. In this study, sediment chemistry data were used to identify sediment management areas. The sediment chemistry data that were used in the predictive ability evaluation represent a substantial portion of the data that were used to identify sediment management areas. In addition, data sets that included sediment chemistry data only or non-matching sediment chemistry and biological effects data were assembled (FDEP 1994; Grabe 1997; Grabe and Barron 2002; EPC unpublished data; Table 5). The acceptance criteria that were applied to these additional individual studies were similar to those that were applied to the matching sediment chemistry and toxicity data sets. However, the age of the data were also considered in the latter data evaluation process to ensure that the most relevant data were used in the process. While all acceptable data were compiled, only data collected within the past 10 years were used to identify sediment management areas.

Three types of sediment management areas were identified in Tampa Bay, including Impact Level A Areas (i.e., unimpacted areas), Impact Level B Areas (moderately impacted areas), and Impact Level C Areas (highly impacted areas). These areas were identified using the chemical benchmarks (i.e., SQTs) that corresponded to the narratives that were established for indicators of sediment quality conditions. More specifically, sediment samples with mean PEL-Qs below the P_{10} value for acute toxicity to amphipods, chemical toxicity, and benthic community impairment were considered to be unimpacted (Table 2). By comparison, sediment samples with mean PEL-Qs above the P_{20} value for acute toxicity to amphipods or P_{50} value for chronic toxicity and benthic community impairment were considered to be highly impacted (Table 2). Moderately impacted sediment samples were considered to be those that had mean PEL-Qs between the P_{10} and P_{20} values for acute toxicity to amphipods or between the P_{10} and P_{50} values for chronic toxicity and benthic community impairment. Although it is important to consider the potential for effects on aquatic-dependent wildlife and human health in the identification of sediment management areas, the current evaluation considered potential effects on sediment-dwelling organisms only.

Results and Discussion

A Framework for Ecosystem-based Sediment Quality Management

The TBEP and its partners have agreed to utilize an ecosystem-based approach to the assessment and management of sediment quality conditions in Tampa Bay. Implementation of the ecosystem approach requires a framework in which to develop and implement management policies for the ecosystem. This framework consists of five main elements, including (Figure 2):

- *Identification and assessment of the issues and collation of the existing ecosystem knowledge base;*
- *Development and articulation of ecosystem health goals and objectives*;
- *Selection of ecosystem health indicators to gauge progress toward ecosystem health goals and objectives;*
- *Conduct directed research and monitoring*; and,
- *Make informed decisions on the assessment, conservation, protection, and restoration of natural resources.*

The first three elements of the framework are discussed in the following sections of this manuscript. More detailed information on these three and the subsequent two elements of the framework are provided in MacDonald and Ingersoll (2002).

Identification of Sediment Quality Issues and Concerns

The first element of the framework is intended to provide all participants in the ecosystem management process with a common understanding of the key issues and the existing knowledge base. While various types of information were collected, reviewed, evaluated, and collated at this stage of the process, emphasis was placed on assembling the available information on the structure, function, and status of the ecosystem, on the socioeconomic factors that influence environmental management, and on historic land and resource use patterns in Tampa Bay. The information that was assembled at this stage of the process was disseminated to process participants in a series of technical reports (Long *et al.* 1991; 1994; Coastal Environmental Inc. 1996; Grabe 1997) and through a number of technical workshops (e.g., MacDonald 1995; 1997; 1999). This information provided participants with an understanding of existing sediment quality conditions in the bay and, hence, a basis for identifying sediment quality issues and concerns. The accumulation of toxic and/or bioaccumulative substances in bay sediments and associated effects on ecological receptors and human health were identified as the principle sediment quality issues and concerns by participants (who were identified by MacDonald 1995).

Ecosystem Goals and Objectives for Tampa Bay

The development of ecosystem goals and objectives is a fundamental component of the overall ecosystem-based management process. In recognition of the importance of developing a long-term vision for the future, TBEP and its partners convened a series of workshops with representatives of key stakeholder groups and with experts in the sediment assessment process (MacDonald 1995; 1997; 1999). Workshop participants indicated that the protection and restoration of Tampa Bay's natural resources was the most important goal that needed to be addressed under the TBEP. As this goal was too general to support meaningful sediment assessment and management initiatives, two SMOs were also developed to translate this goal into a vision that is linked more directly to sediment quality conditions, including:

SMO1: *Maintain environmental conditions in Tampa Bay sediments such that the benthic community, including epibenthic and infaunal species, is protected and, where necessary, restored; and,*

SMO2: *Maintain and, where necessary, restore environmental conditions in Tampa Bay sediments such that fish and other aquatic organisms are safe to consume, both by humans and wildlife.*

These ecosystem objectives are now reflected in the Comprehensive Conservation and Management Plan (CCMP) for Tampa Bay (TBNEP 1996). More specifically, the goals and priorities for sediment quality in Tampa Bay include 'reducing the amount of toxic chemicals in contaminated sediments and protecting relatively clean areas of the bay from contamination' (TBNEP 1996). In areas with contaminated sediments, minimizing the risks to marine life and humans has been identified as a priority under the CCMP (TBNEP 1996).

Sediment Quality Indicators and Metrics

Long-term ecosystem goals and SMOs are essential for establishing agreement among the partners regarding sediment management priorities. However, they do not directly support the development of monitoring programs for assessing the current status of the bay or evaluating the efficacy of management actions (i.e., it is difficult to identify monitoring program elements that would provide information for determining if the goals and objectives are being attained). For this reason, the participants at the 1997 sediment management workshop also developed a number of recommendations that could assist the TBEP in the establishment of natural resource protection and restoration targets that address concerns related to sediment-associated contaminants (MacDonald 1997). Importantly, workshop participants concluded that concerns relative to sediment contamination are primarily associated with the potential for direct effects on sediment-dwelling organisms and the bioaccumulation of sediment-associated contaminants in the food web.

Based on the input provided by workshop participants, the highest priority indicators for assessing the health of Tampa Bay sediments included the three elements of the sediment quality triad (which includes sediment chemistry, sediment toxicity, and benthic invertebrate community structure); physical characteristics of sediments; chemistry of overlying water and pore water; tissue chemistry; and, biomarkers in fish (Table 1; MacDonald 1997). The highest priority metrics for measuring the status of the recommended ecosystem health indicators were also identified by workshop participants (Table 1). The indicators and metrics that provide information for assessing attainment of each sediment management objective (i.e., SMO1 and SMO2) are also identified in Table 1. From the list of candidate indicators and metrics, five were selected for further evaluation, including sediment chemistry (mean ERM-Qs and mean PEL-Qs), sediment toxicity (10-day amphipod survival and 1-hour sea urchin fertilization), and benthic invertebrate community structure (SWDI).

Predictive Ability of Candidate Chemical SQTs

Matching sediment chemistry and biological effects data were used to evaluate the predictive ability of the candidate chemical SQTs (i.e., PELs, relative to the protection of sediment-dwelling organisms;

SMO1). In total, two sets of SQGs (i.e., PELs and ERMs; Table 3), two procedures for calculating mean SQG-Qs (i.e., the USEPA and NSTP methods), and three ranges of mean SQG-Qs were evaluated to identify the chemical targets that most closely corresponded with the biological targets (Table 2). The predictive ability of the chemical targets was evaluated using the information on three indicators of adverse biological effects, including benthic invertebrate community structure, acute sediment toxicity, and chronic sediment toxicity. The chemical SQTs for bioaccumulative substances (i.e., for the protection of aquatic-dependent wildlife and human health are listed in Table 4; SMO2).

The evaluation of the matching data on sediment chemistry and benthic invertebrate community structure (i.e., using the SWDI) provide important information for selecting SQTs for Tampa Bay. The results of this evaluation indicate that the incidence of impairment of benthic invertebrate communities generally increases with increasing chemical concentrations (as indicated by mean SQG-Qs). Benthic community structure evaluation scores ranged from 2 to 4 among the various approaches that were evaluated (Tables 6 and 7). The NSTP approach to the derivation of PEL-Qs, using SQTs of <0.1, 0.1-1.0, and >1.0 to define the A, B, and C impact levels, provided the most accurate basis for classifying sediment samples as impaired and unimpaired relative to benthic invertebrate community structure.

The matching sediment chemistry and toxicity data also provide relevant information for selecting targets for sediment chemistry in Tampa Bay. As was the case for the benthic invertebrate community structure data, the incidence of sediment toxicity generally increases within increasing levels of chemical contamination. Evaluation scores for amphipod toxicity ranged from 4 to 6 among the various candidate approaches for selecting numerical SQTs. By comparison, evaluation scores calculated using the data on sea urchin fertilization were low (i.e., 2) and did not vary for the various procedures.

Total evaluation scores were calculated by summing the evaluation scores that were calculated using the benthic invertebrate community structure, acute toxicity, and chronic toxicity data. Overall, total evaluation scores ranged from 8 to 12 among the various approaches that were used to establish candidate targets for sediment chemistry (Table 6 and 7). These results demonstrate that the mean PEL-Qs generally provided a more reliable basis for classifying sediment samples as toxic or not toxic and impaired or not impaired, when compared to the mean ERM-Qs. However, the method for calculating the quotients and the ranges of mean PEL-Q considered appeared to have little influence on the results of the predictive ability evaluation. Because it provided a marginally better basis for assessing the incidence of biological effects within ranges of mean SQG-Qs, the USEPA method for calculating mean PEL-Qs was used to develop the concentration-response relationships for Tampa Bay.

The relationships between concentration (i.e., mean PEL-Qs) and response (i.e., incidence of sediment toxicity or benthic community impairment) are shown in Figures 3, 4, and 5. These relationships (i.e., logistic regression models) provide a means of estimating the mean PEL-Qs that correspond directly to the narrative targets that were established previously for Tampa Bay (Table 2). Using the data from 10-day toxicity tests with amphipods, a mean PEL-Q of 0.28 corresponds to a 10% probability of observing acute toxicity to sediment-dwelling organisms (i.e., P_{10} value); the corresponding P_{20} and P_{50} values for acute toxicity to amphipods were 0.54 and 1.3 respectively (Table 8). By comparison, the P_{10} and P_{50} values for benthic community impairment were 0.05 and 0.34 respectively (Table 8). For sea urchin fertilization, the results of toxicity tests conducted in 25% pore water yielded P_{10} (0.10) and P_{50} (0.55) values that corresponded most directly to the narrative intent of the SQTs, suggesting it may be more relevant to use the results of toxicity tests conducted using diluted pore water to assess effects on sediment-dwelling organisms (i.e., these results more closely correspond to those for benthic community impairment; Table 8).

The site-specific concentration-response relationships that were developed for Tampa Bay sediments appear to be consistent with those that have been developed using other data sets. For example, Long and MacDonald (1998) reported that the incidence of acute toxicity to amphipods was roughly 50% at mean PEL-Qs of 1.5 to 2.3 (compared to 1.3 in this study). Similarly, Long *et al.* (1998) reported that 56% of the sediment samples with mean PEL-Qs of >1.0 were acutely toxic to amphipods. As such, it appears that acute toxicity thresholds for Tampa Bay are similar to those that have been observed elsewhere in North America. The results of this study suggest that benthic invertebrate community impairment can occur at relatively low levels of sediment contamination. In this study the P_{50} for benthic impairment was roughly a factor of 3.8 lower than the P_{50} for acute toxicity to amphipods. This is not surprising since the duration of exposure to contaminated sediments is likely to be >10-days for *in situ* benthic invertebrate communities. Ingersoll *et al.* (2001) compared the P_{50} values for acute (10-day) and chronic (28- to 42-day) toxicity to the amphipod, *Hyalella azteca* (measuring survival and growth) and concluded that acute-to-chronic ratios (ACRs) for that species were in the order of six. Therefore, the relationship between acute toxicity and benthic impairment thresholds for marine invertebrates in Tampa Bay sediments is similar to the ACR that was reported for freshwater invertebrates.

That thresholds for benthic community impairment can occur at relatively low levels of sediment contamination has also been reported for marine sediments. For example, Hyland *et al.* (2002) reported that the likelihood of observing benthic community impairment increased substantially (i.e., to roughly 75%) when mean PEL-Qs exceeded 0.1 in sediments from the Carolinian province, confirming that adverse effects on benthic communities are likely to occur at lower levels of contamination than is the case for acute toxicity. Similarly, Long *et al.* (2002) observed that species richness was reduced by roughly 50% when mean ERM-Qs exceeded 0.1 in sediments from Biscayne Bay. As benthic communities are the principal receptors that require protection, sediment management strategies should explicitly consider the potential for effects on benthic macroinvertebrates. However it should be noted that benthic invertebrate communities can be adversely affected by both physical and chemical stressors.

It was not possible to fully evaluate the effects of physical factors on the structure of benthic communities in Tampa Bay. For example, data on salinity or the levels of dissolved oxygen measured when sediment samples were collected provide only a snapshot of potential stressors on the benthic community. As TOC was only poorly correlated with SWDI ($r^2 = 0.23$; $p = <0.001$), the levels of organic carbon in sediments was not a good predictor of benthic impairment. Nevertheless, it is possible that effects thresholds would be higher if physical stressors on the benthic community could be accounted for. Janicki Environmental, Inc. (2002) provides an evaluation of the relative importance of salinity and sediment particle size on benthic health in Tampa Bay.

Sediment Management Areas

Data on the chemical composition of Tampa Bay sediments were available on 821 samples, that were distributed throughout the estuary (Figure 6). These data (i.e., mean PEL-Qs) were used, in conjunction with the contouring model (i.e., ESRI ArcView and Spatial Analyst), to identify Impact Level A, B, and C areas based on the potential for observing acute toxicity to amphipods (Figures 7 and 8) or benthic community impairment (Figures 9 and 10). Comparison of the results of these data interpolations reveals that the SQTs that are selected can dramatically influence the identification of sediment management areas. While the areal extent of Impact Level C levels is similar regardless of which SQT is used, the proportion of the bay that is classified as Impact Level B varies substantially. Using the SQTs derived form the benthic community data, McKay Bay, most of Hillsborough Bay, and portions of Old Tampa Bay, middle Tampa Bay, lower Tampa Bay, Boca Ciega Bay, Terra Ceia Bay, and the Manatee River would be classified as Impact Level B sediment management areas (Figures 5 and 6). In contrast, relatively small portions of these bay segments would be so classified using the SQTs derived from the acute toxicity data (Figures 9 and 10). As benthic macroinvertebrates are key receptors that require protection in Tampa Bay and sediment-dwelling organisms can be exposed to contaminated sediments for extended periods of time (i.e., >10-days), the SQTs derived from the benthic community data are considered to be most appropriate for identifying sediment management areas (i.e., mean PEL-Q of <0.05 for identifying areas classified as Impact Level A and >0.34 for identifying areas classified as Impact Level C). The biological conditions that have been measured in sediment samples that fall into the three classifications are shown in Table 9. The concentration-response relationships that were developed using the matching sediment chemistry and biological effects data provide a basis for classifying sediment samples based on the probability of observing specific types of adverse effects. For example, sediment samples with a low (i.e., <10%), moderate (10 to 20%), and high (>20%) probability of being acutely toxic to the amphipod, *Ampelisca abdita*, can be identified using the mean PEL-Q (i.e., <0.28, 0.28-0.54, and >0.54, respectively; Table 8). Likewise, it is possible to use the sediment chemistry data to identify sediment samples with a low (i.e., <10%), moderate (i.e., 10 to 50%), and high (i.e., >50%) probability of being associated with benthic community impairment (i.e., those with mean PEL-Qs of <0.05, 0.05-0.34, and >0.34, respectively; Table 10). These SQTs for acute toxicity to amphipods and benthic community impairment can also be used to identify sediment management areas in Tampa Bay.

Three types of sediment management areas were identified in Tampa Bay, based on the potential for observing specific types of adverse biological effects, including Impact Level A, B, and C areas. Consistent with the underlying narrative intent, areas in which there is a low potential for observing acute toxicity to amphipods or benthic community impairment were those with mean PEL-Qs of predominantly <0.28 or <0.05, respectively (Figures 7 to 10; Table 8). The areas in which there is a moderate potential for observing acute toxicity to amphipods or benthic community impairment were identified as those with mean PEL-Qs of 0.28 to 0.54 or 0.05 to 0.34, respectively. Finally areas with mean PEL-Qs of >0.54 or >0.34 were considered to have a high potential for acute toxicity to amphipods or benthic community impairment, respectively (Table 8).

Using the benthic community SQTs (i.e., mean PEL-Qs of 0.05 and 0.34, which correspond to a 10% and 50% probability of observing benthic community impairment) most of the Tampa Bay ecosystem is classified as having a low potential for observing adverse biological effects (i.e., roughly two-thirds of the surface area of the bay; Figures 7 and 8). However, there is a moderate potential for observing adverse biological effects in a number of areas (representing roughly one-third of the surface area of the bay), include, Boca Ciega Bay (BCB2), the St. Petersburg Waterfront, the eastern, northern, and westerly portions of Old Tampa Bay (i.e., in the vicinity of Allen Creek), Hillsborough

Bay (HB1) and McKay Bay, Terra Ceia Bay (TCB1), the middle portion of the Little Manatee River, and the lower and middle portions of the Alatia River. The areas with the highest potential for observing adverse biological effects primarily include Bayboro Harbor, St. Pete Marina, Port of Tampa and Ybor Channel, the lower and middle portions of the Hillsborough River, a portion of Hillsborough Bay and the lower and middle portions of the Palm River. Together, these areas represent roughly 3% of the surface areas of the bay. Examination of the data presented in Table 10 indicates that certain bay segments have mean PEL-Qs that are inconsistent with the predominant impact level (e.g., HB4). In these cases, it is likely that sediment hot spots exist within the sediment management area, suggesting that further investigation is warranted to assess the areal extent of the contamination. In this study, contaminants of concern were identified as those substances that occurred in one or more sediment samples within a sediment management area at concentrations in excess of the corresponding PEL. These substances, which are identified in Table 10 for each sediment management area, are considered to be the ones that are associated with the effects that have been observed. As such, these substances need to be considered in further assessments that are conducted within the various management areas.

While these classifications are considered to be broadly applicable for Tampa Bay (i.e., see Table 11 for a description of the range of physical characteristics that the SQTs are considered to apply to; i.e., the normal range for the underlying data), caution should be used in applying this framework directly to other geographic areas. Previous evaluations have demonstrated that the degree of chemical contamination and the incidence of toxicity tends to be much lower in Tampa Bay than in many other urban estuaries throughout the United States (Long *et al.* 1994). Therefore, this type of framework would likely require some refinement (e.g., by including additional impact levels; Long and MacDonald 1998) to provide the degree of discrimination among sediment samples that is needed in more contaminated estuaries (MacDonald 1999).

It is important to note that the SQTs that were selected for Tampa Bay do not consider the potential for bioaccumulation of persistent toxic substances in the food web nor associated effects on aquatic-dependent wildlife or human health. As bioaccumulation-based SQTs could be lower than the effects-based targets, different and/or more areas might have been identified as having a moderate or high potential for adverse biological effects had bioaccumulation-based targets been used in the identification of sediment management areas. Therefore, further investigations are needed to characterize the hazards posed to aquatic-dependent wildlife and human health associated with contaminated sediments in Tampa Bay.

Sediment Management Options

Among the major urban estuaries in the United States, Tampa Bay is one of the least contaminated (Long 2000a). In addition, only 0.5 km^2 of the bay, or 0.1% of the area, of the bay is considered to be acutely toxic to amphipods (Long 2000b). Nevertheless, effective environmental management in Tampa Bay will necessitate the identification and implementation of sediment management options and remedial alternatives to maintain and where necessary restore sediment quality conditions. To facilitate this process, candidate sediment management options for each of the three types of sediment management areas (i.e., Impact Level A, B, and C areas) have been identified based on the potential for adverse effects on sediment-dwelling organisms (Table 12).

In the Impact Level A sediment management areas, sediment quality conditions have not been adversely affected by anthropogenic activities. As the potential for observing adverse biological effects is low in such areas, protecting these areas of the bay from contaminations represents a high priority sediment management objective (TBNEP 1996). In such areas, management initiatives should focus on evaluating the confidence in the existing data, determining the potential for false negative results, and assessing spatial and temporal trends in sediment quality conditions. Some of the management options that could be considered for such areas include (Table 12):

- Reviewing and evaluating the available data to identify any substances that pose potential concerns in these areas (i.e., the COPCs that are present at concentrations that are approaching the SQTs; see Table 10);
- Identifying the likely local and more remote sources of any COPCs that are identified;
- Limiting physical disturbances (such as dredging) in such areas to maintain benthic productivity;
- Assessing historic and ongoing land use practices to identify additional substances that could be contaminating sediments;
- Ensuring that the sediment-associated COPCs are considered in the development of total maximum daily loadings (TMDLs) for the water courses that could contribute to contaminant loadings to the area;
- Conducting periodic chemical and biological monitoring to confirm that sediment quality conditions are not deteriorating over time; and,
- Acquiring adjacent lands or securing conservation easements to limit the potential for future development of adjacent shoreline areas, particularly when such sediment management areas coincide with critical fish and wildlife habitats (e.g., sea grass beds, mangrove stands).

Sediment quality conditions are considered to have been moderately impacted by anthropogenic activities in the Impact Level B sediment management areas. The potential for observing adverse biological effects is moderate in such areas; therefore, protecting these areas of the bay from further contamination is a primary sediment management objective (TBNEP 1996). Management initiatives in these areas should focus on evaluating the confidence in the existing data, assessing spatial and temporal trends in sediment quality conditions, and determining if contaminated sediments pose potential risks to ecological receptors or to human health. There are a number of sediment management options that should be considered for Impact Level B areas, which include (Table 12):

- Reviewing and evaluating the available data to identify COPCs, to evaluate the level of confidence that can be placed in the data (i.e., based on quality, areal coverage, and age of the data), and to better characterize sediment quality concerns;
- Identifying the likely local and remote sources of any COPCs that are identified;
- Conducting a preliminary site investigation to evaluate the magnitude and areal extent of sediment contamination and the concentrations of bioaccumulative COPCs in fish and shellfish tissues (whole body and edible tissues), if bioaccumulative substances are present;
- Comparing the data collected in the preliminary site investigation to the SQTs, bioaccumulation-based SQG, and tissue residue guidelines to determine if risks to sediment-dwelling organisms, aquatic-dependent wildlife, or human health exist in the area;

- Conducting follow-up investigations, such as human and ecological risk assessments, if potential risks to ecological receptors or human health are indicated by the results of the preliminary site investigation; and,
- Exploring mechanisms for reducing the loadings of COPCs into affected water courses, including developing and implementing TMDLs, evaluating compliance of point source discharges with National Pollutant Discharge and Elimination System (NPDES) permits and increasing enforcement, as necessary, and identifying and controlling non-point sources of COPCs.

In the Impact Level C sediment management areas, sediment quality conditions are considered to have been highly impacted by anthropogenic activities. As the potential for observing adverse biological effects is high in such areas, reducing the amount of toxic chemicals in contaminated sediments and minimizing risks to bay wildlife and humans are the primary SMOs (TBNEP 1996). Management initiatives in these areas should focus on identifying the chemicals that are contributing to toxicity, reducing inputs of contaminants to aquatic ecosystems, and reducing exposure to sediment-associated contaminants. There are a number of sediment management options that should be considered for Impact Level C areas, including (Table 12):

- Reviewing and evaluating the available data to identify COPCs, to evaluate the level of confidence that can be placed in the data (i.e., based on quality, areal coverage, and age of the data), and to better characterize sediment quality concerns;
- Identifying the sources of the COPCs;
- Reducing the loadings of COPCs into affected water courses, potentially by developing and implementing TMDLs, evaluating compliance of point source discharges with NPDES permits and increasing enforcement, as necessary, and identifying and controlling non-point sources of COPCs (e.g., using voluntary measures, RCRA actions);
- Conducting a detailed site investigation to evaluate the magnitude and areal extent of sediment contamination, the biological effects on contaminated sediments, and the concentrations of bioaccumulative COPCs in fish and shellfish tissues (whole body and edible tissues), if bioaccumulative substances are present;
- Conducting toxicity identification evaluation (TIE) investigations and/or sediment spiking studies to identify the factors that are causing sediment toxicity;
- Utilizing the data collected in the detailed site investigation to conduct screening level ecological and human health risk assessments;
- Conducting baseline human and/or ecological risk assessments (BHHRA and BERA) if the results of the screening level risk assessments indicate that potential risks exist to ecological receptors or human health;
- Conducting a Natural Resource Damage Assessment (NRDA) to evaluate the nature and extent of injury to sediment, sediment-dwelling organisms, and aquatic-dependent wildlife;
- Conducting remedial investigations and feasibility studies (RI/FS) to evaluate the various remedial alternatives for restoring the beneficial uses of the aquatic ecosystem (e.g., natural recovery, sediment capping, sediment removal and disposal, sediment removal and treatment); and,
- Developing remedial action plans (RAP) to guide remedial and restoration activities within the area.

In considering the various options that are available for managing contaminated sediments, it is important to remember that the weight of the decision should dictate the weight of the evidence that is needed to support the decision (MacDonald and Ingersoll 2002). For instance, it is likely to be expedient and cost-effective to move directly to remedial action planning at sites with limited volumes of highly contaminated sediments (i.e., the costs associated with removal and disposal of contaminated sediments are likely to be lower than the costs associated with conducting further investigations). In contrast, further investigations are warranted at larger and more complex sites, where resolving uncertainties regarding the risks associated with exposure to contaminated sediments will ensure that limited resources can be targeted on sediment management priorities. Consideration of sediment chemistry data in conjunction with biological effects data provides a sound basis for selecting the sediment management options that are appropriate for specific situations (Table 12).

Future Directions

The ecosystem-based framework for Tampa Bay is intended to provide environmental managers with practical tools for assessing and managing contaminated sediments. However, its utility is likely to be enhanced by conducting a number of follow-up investigations in the bay. Some of the key recommendations for refining the framework include conducting further field validation of the SQTs using acute and chronic sediment toxicity data, assessing tissue residue levels in sessile invertebrates and fish, in impacted areas, preparing a guidance manual to support sediment quality assessment activities, validating the applicability of the framework in regulatory and land-use planning decision-making processes, developing sediment management plans for sediment hot spot areas, and implementing pollution prevention and watershed management activities throughout the bay.

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References

Anderson JM, Bay SM, Thompson BE (1988) Characteristics and effects of contaminated sediments from southern California. SCCWRP Contribution No. C-297. Southern California Coastal Water Research Project, Long Beach, California, 120 pp.

Carr RS, Long ER, Windom HL, Chapman DC, Thursby G, Sloane GM, Wolfe DA. 1996. Sediment quality assessment studies of Tampa Bay, Florida. Environ Toxicol Chem 15:1218-1231.

CCME (Canadian Council of Ministers of the Environment) (1996) A framework for developing ecosystem health goals, objectives, and indicators: Tools for ecosystem-based management. Prepared by the Water Quality Guidelines Task Group of the Canadian Council of Ministers of the Environment, Winnipeg, Manitoba, 24 pp.

Coastal Environmental, Inc. (1995) User's guide for the Hillsborough County Tampa Bay National Estuary Program benthic program analysis software. Prepared for Tampa Bay National Estuary Program, St. Peterburg, Florida.

Coastal Environmental, Inc. (1996) Statistical analysis of the Tampa Bay National Estuary Program 1993 benthic survey. Technical Publication #11-95. Tampa Bay National Estuary Program, St. Peterburg, Florida.

Cooke SEK (1976) Quest for and index of community structure sensitive to water pollution. Environ Pollut 11: 269-288

Crane JL, MacDonald DD, Ingersoll CG, Smorong DE, Lindskoog RA, Severn CG, Berger TA, Field LJ (2000) Development of a framework for evaluating numerical sediment quality targets and sediment contamination in the St. Louis Area of Concern. EPA 905-R-00-008. Great Lakes National Program Office, Chicago, Illinois.

DOE (Environment Canada) (1996) The ecosystem approach: Getting beyond the rhetoric. The Task Group on Ecosystem Approach and Ecosystem Science, Ottawa, Canada.

FDEP (Florida Department of Environmental Protection) (1994) Florida coastal sediment contaminants atlas. Office of Water Policy, Tallahassee, Florida.

Ferraro SP, Swartz RC, Cole FA, Schults DW (1991) Temporal changes in the benthos along a pollution gradient: Discriminating the effects of natural phenomena from sewage-industrial wastewater effects. Estuar Coast Shelf Sci 33:383-407.

Field LJ, MacDonald DD, Norton SB, Severn CG, Ingersoll CG (1999) Evaluating sediment chemistry and toxicity data using logistic regression modeling. Environ Toxicol Chem 18:1311-1322.

Field LJ, MacDonald DD, Norton SB, Ingersoll CG, Severn CG, Smorong DE, Lindskoog RA (2002) Predicting amphipod toxicity from sediment chemistry using logistic regression models. Environ Toxicol Chem 21:1993-2005

Grabe SA (1997) Trace metal status of Tampa Bay sediments. Environmental Protection Commission of Hillsborough County, Tampa, Florida.

Grabe SA, Barron J (2002) Status of Tampa Bay sediments: Polycyclic aromatic hydrocarbons, organochlorine pesticides, and polychlorinated biphenyls (1993 and 1995 to 1999). Environmental Protection Commission of Hillsborough County, Tampa, Florida.

Hughs BD (1978) The influence of factors other than pollution on the values of Shannon's diversity index for benthic macroinvertebrates in streams. Wat Res 12:359-364.

Hunt JW, Anderson BS, Phillips BM, Newman J, Tjeerdema RS, Fairey R, Puckett HM, Stephenson M, Smith RW, Wilson CJ, Taberski KM (2001) Evaluation and use of sediment toxicity reference sites for statistical comparisons in regional assessments. Environ Toxicol Chem 20:1266-1275.

Hyland, JL, Balthis WL, Engle VD, Long ER, Paul JF, Summers JK, Van Dolah RF (2002) Incidence of stress in benthic communities along the U.S. Atlantic and Gulf of Mexico coasts within different ranges of sediment contamination from chemical mixtures. Environ Monitor Assess (In press).

Ingersoll CG, MacDonald DD (1999) An assessment of sediment injury in the West Branch of the Grand Calumet River. Volume I. Prepared for United States Department of Justice, Washington, District of Columbia, 161 pp.

Ingersoll CG, MacDonald DD (2002) A guidance manual to support the assessment of contaminated sediments in freshwater ecosystems. Volume III - Interpretation of the results of sediment quality investigations. Prepared for the Great Lakes National Program Office, United States Environmental Protection Agency, Chicago, Illinois, 198 pp.

Ingersoll CG, MacDonald DD, Wang N, Crane JL, Field LJ, Haverland PS, Kemble NE, Lindskoog RA, Severn CG, Smorong DE (2001) Predictions of sediment toxicity using consensus-based freshwater sediment quality guidelines. Arch Environ Contam Toxicol 41:8-21.

Janicki Environmental, Inc. (2002) Tampa Bay sediment quality targets physical parameters assessment. Tamp Bay Estuary Program Technical Memorandum. Tampa Bay Estuary Program, St. Petersburg, Florida.

Long ER (2000a) Degraded sediment quality in U.S. estuaries: A review of magnitude and ecological implications. Ecol Appl 10:338-349.

Long ER (2000b) Spatial extent of sediment toxicity in U.S. estuaries and marine bays. Environ Monitor Assess 64:391-407.

Long ER, Morgan LG (1991) The potential for biological effects of sediment-sorbed contaminants tested in the National Status and Trends Program. NOAA Technical Memorandum NOS OMA 52. National Oceanic and Atmospheric Administration, Seattle, Washington, pp. 175 + appendices.

Long ER, MacDonald DD (1998) Perspective: Recommended uses of empirically derived sediment quality guidelines for marine and estuarine ecosystems. Human Ecol Risk Assess 4:1019-1039.

Long ER, MacDonald D, Cairncross C (1991) Status and trends in toxicants and the potential for their biological effects in Tampa Bay, Florida. NOAA Technical Memorandum NOS OMA 58. National Oceanic and Atmospheric Administration, Seattle, Washington, 77 pp.

Long ER, Wolfe DA, Carr RS, Scott KJ, Thursby GB, Windom HL, Lee R, Calder FD, Sloane GM, Seal T (1994) Magnitude and extent of sediment toxicity in Tampa Bay, Florida. NOAA Technical Memorandum NOS ORCA 78. National Oceanic and Atmospheric Administration, Seattle, Washington, 86 pp. + app.

Long ER, MacDonald DD, Smith SL, Calder FD (1995) Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environ Manage 19:81-97.

Long ER, Field LJ, MacDonald DD (1998) Predicting toxicity in marine sediments with numerical sediment quality guidelines. Environ Toxicol Chem 17:714-727.

Long ER, Hameedi G, Sloane G, Read L (2002) Chemical contamination, toxicity, and benthic community indices in sediments of the Lower Miami River and adjoining portions of Biscayne Bay, Florida. Estuar (Submitted).

MacDonald DD (1995) Science advisory group workshop on sediment assessment in Tampa Bay: Summary report. Technical Publication #06-95. Prepared by MacDonald Environmental Sciences Ltd., Prepared for the Tampa Bay National Estuary Program, St. Petersburg, Florida.

MacDonald DD (1997) Tampa Bay sediment quality workshop: Setting targets and defining management strategies. Final summary report. Technical Publication #06-97. Prepared by MacDonald Environmental Sciences Ltd.,Prepared for the Tampa Bay National Estuary Program, St. Petersburg, Florida.

MacDonald DD (1999) Tampa Bay sediment quality workshop: Establishing impact levels and setting sediment quality targets. Workshop summary report. Prepared by MacDonald Environmental Sciences Ltd. Prepared for the Tampa Bay National Estuary Program, St. Petersburg, Florida.

MacDonald DD, CG Ingersoll (2002) A guidance manual to support the assessment of contaminated sediments in freshwater ecosystems. Volume 1: An ecosystem-based framework for assessing and managing contaminated sediments. Prepared for the Great Lakes National Program Office, United States Environmental Protection Agency, Chicago, Illinois. Under contract to Sustainable Fisheries Foundation, Snohomish, Washington.

MacDonald DD, Carr RS, Calder FD, Long ER, Ingersoll CG (1996) Development and evaluation of sediment quality guidelines for Florida coastal waters. Ecotox 5:253-278.

MacDonald DD, Ingersoll CG, Berger TA (2000) Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Arch Environ Contam Toxicol 39:20-31.

Nipper M, Burton GA Jr, Chapman DC, Doe KG, Hamer M, Ho K (2002) Issues and recommendations for porewater toxicity testing: methodological uncertainties, confounding factors and toxicity identification evaluation procedures. *In:* Porewater Toxicity Testing: Biological, Chemical, and Ecological Considerations Methods, Applications and Recommendations for Future Areas of Research, Carr, R.S. and M. Nipper (eds), SETAC Press (In press).

NYSDEC (New York State Department of Environmental Conservation) (1999) Technical guidance for screening contaminated sediments. Division of Fish, Wildlife and Marine Resources, Albany, New York.

Reynoldson TB, Day KE, Bailey RC, Norris RH (1995) Methods for establishing biologically-based sediment guidelines for freshwater quality management using benthic assessment of sediment. Austral J Ecol 20:198-219.

Shannon CE, Weaver W (1949) The mathematical theory of communication. The University of Illinois Press, Urbana, Illinois pp. 19-27, 82-83, 104-107.

Specht DT, Lee H II (1989) Direct measurement technique for determining ventilation rate in the deposit-feeding clam, *Macoma nasuta* (Bivalvia, Tellinaceae). Mar Biol 101:211-218.

Swartz RC, Schults DW, Ditsworth GR, DeBen WA, Cole FA (1985) Sediment toxicity, contamination, and macrobenthic communities near a large sewage outfall. *In:* Validation and Predictability of Laboratory Methods for Assessing the Fate and Effects of Contaminants in Aquatic Ecosystems. ASTM STP 865. T.P. Boyle (ed.) American Society for Testing and Materials, Philadelphia, Pennsylvania. 1985:152-175.

Swartz RC, Cole FA, Schults DW, DeBen WA (1986) Ecological changes in the Southern California Bight near a large sewage outfall: Benthic conditions in 1980 and 1983. Mar Ecol - Prog Ser 31:1-13.

Swartz RC, Schults DW, Lamberson JO, Ozretich RJ (1991) Vertical profiles of toxicity, organic carbon, and chemical contaminants in sediment cores from the Palos Verdes Shelf and Santa Monica Bay, California. Mar Environ Res 31:215-225.

Swartz RC, Cole FA, Lamberson JO, Ferraro SP, Schults DW, DeBen WA, Lee H II, Ozretich RJ (1994) Sediment toxicity, contamination, and amphipod abundance at a DDT- and dieldrin-contaminated site in San Francisco Bay. Environ Toxicol Chem 13:949-962.

TBNEP (Tampa Bay National Estuary Program) (1996) Charting the course for Tampa Bay: The comprehensive conservation and management plan for Tampa Bay. St. Peterburg, Florida.

USEPA (United States Environmental Protection Agency) (2000) Prediction of sediment toxicity using consensus-based freshwater sediment quality guidelines. EPA 905/R-00/007. Great Lakes National Program Office, Chicago, Illinois.

Washington HG (1984) Diversity, biotic and similarity indices: A review with special relevance to aquatic systems. Water Res 13:88-92.

Winsor MH, Boese BL, Lee H II, Randall RC, Specht DT (1990) Determination of the ventilation rates of interstitial and overlying water by the clam *Macoma nasuta*. Environ Toxicol Chem 9:209-213.

Zarbock HW, Janicki AJ, Logan DT, MacDonald DD (1996) An assessment of sediment contamination in Tampa Bay, Florida using the sediment quality triad approach. Prepared by Coastal Environmental, Inc. and MacDonald Environmental Sciences Ltd. Prepared for the Tampa Bay National Estuary Program, St. Petersburg, Florida.

Table 1. Candidate ecosystem health indicators and metrics for assessing sediment quality conditions in Tampa Bay, Florida (MacDonald 1997; 1999).

Ecosystem Health Indicator	Candidate Metrics	Relative Priority/ SMOAddressed[1]
Sediment quality triad	Triad evaluation table	High; SMO1
Sediment chemistry	Concentrations of contaminants of concern	High; SMO1/SMO2
	% Incidence of predicted toxicity	High; SMO1
	Mean PEL quotient[2]	High; SMO1
	Mean ERM quotient[3]	High; SMO1
	SEM-AVS (on a molar basis)[4]	Low; SMO1
Sediment toxicity	Amphipod survival	High; SMO1
	Sea urchin embryo fertilization	High; SMO1
	Sea urchin embryo development	Low; SMO1
	Microtox/Mutatox	Low; SMO1
	Polychaete growth	Low; SMO1
	Seagrass seed germination	Low; SMO1
	Seagrass growth	Low; SMO1
	Cytochrome P450 assays	Low; SMO1
	Hazard quotients	Low; SMO1
Benthic invertebrate community structure	Shannon-Wiener Diversity Index	High; SMO1
	Evenness	High; SMO1
	Biomass	Low; SMO1
	Tampa Bay Benthic Index	High; SMO1
	Presence/absence of indicator species	High; SMO1
	Abundance of various taxa	Moderate; SMO1
Physical characteristics	Grain size	High; SMO1
	Total organic carbon	High; SMO1/SMO2
	Sediment settling rate	High; SMO1
	% Depositional area	High; SMO1
Water chemistry	Concentrations of contaminants of concern	High; SMO1/SMO2
	Dissolved oxygen in overlying water	High; SMO1
	Dissolved oxygen in pore water	Low; SMO1
	Ammonia in pore water	High; SMO1
	Hydrogen sulfide in pore water	High; SMO1
	Biological oxygen demand in pore water	Low; SMO1

Table 1. Candidate ecosystem health indicators and metrics for assessing sediment quality conditions in Tampa Bay, Florida (MacDonald 1997; 1999).

Ecosystem Health Indicator	Candidate Metrics	Relative Priority/ SMOAddressed[1]
Tissue chemistry	Concentrations of bioaccumulative contaminants	High; SMO1/SMO2
	Number of fish advisories	High; SMO2
	Hazards quotients	High; SMO2
Biomarkers in fish	# of preneoplastic and neoplastic lesions in fish livers	High; SMO2
	Internal parasite loads in fish	Low; SMO2
	External parasite loads in fish	Low; SMO2
	Cytochrome P450 activity	Low; SMO2

[1]SMO = sediment management objective.
[2]PEL = probable effect level.
[3]ERM = effects range median.
[4]SEM-AVS = molar concentration of simultaneously extracted metals minus molar concentration of acid volatile sulfides.

Table 2. Narrative intent of the sediment quality targets for assessing sediment quality conditions in Tampa Bay, Florida.

Type of Sediment Quality Target	Potential for Adverse Biological Effects	Target Level of Biological Effects		
		Acute Toxicity[1]	Chronic Toxicity[2]	Benthic Community[3]
Impact Level A	Low (relatively uncontaminated sediments)	<10% of samples acutely toxic	<10% of samples chronically toxic	<10% of samples impacted
Impact Level B	Moderate (moderately contaminated sediments)	10-20% of samples acutely toxic	10-50% of samples chronically toxic	10-50% of samples impacted
Impact Level C	High (highly contaminated sediments)	>20% of samples acutely toxic	>50% of samples chronically toxic	>50% of samples impacted

[1]As indicated by the results of 10-day whole sediment toxicity tests with the amphipod, *Ampelisca abdita* ; survival endpoint.
[2]As indicated by the results of 1-hour porewater toxicity tests with the sea urchin, *Arbacia punctulata* ; fertilization endpoint.
[3]As indicated by the Shannon-Wiener Diversity Index.

Table 3. Sediment quality guidelines (SQGs) that were evaluated to support the establishment of numerical sediment quality targets (SQTs) for Tampa Bay, Florida.

Substance	Effects Level SQGs[1]		Effect Range SQGs[2]	
	TEL	PEL	ERL	ERM
Trace Metals (mg/kg)				
Arsenic	7.24	41.6	8.2	70
Cadmium	0.68	4.21	1.2	9.6
Chromium	52.3	160	81	370
Copper	18.7	108	34	270
Lead	30.2	112	46.7	218
Mercury	0.13	0.7	0.15	0.71
Nickel	15.9	42.8	20.9	51.6
Silver	0.73	1.77	1	3.7
Zinc	124	271	150	410
Polycyclic Aromatic Hydrocarbons (PAHs; µg/kg)				
2-Methylnaphthalene	20.2	201	70	670
Acenaphthene	6.71	88.9	16	500
Acenaphthylene	5.87	128	44	640
Anthracene	46.9	245	85.3	1100
Fluorene	21.2	144	19	540
Naphthalene	34.6	391	160	2100
Phenanthrene	86.7	544	240	1500
Total LMW-PAHs	312	1442	552	3160
Benz(a)anthracene	74.8	693	261	1600
Benzo(a)pyrene	88.8	763	430	1600
Chrysene	108	846	384	2800
Dibenz(a,h)anthracene	6.22	135	63.4	260
Fluoranthene	113	1494	600	5100
Pyrene	153	1398	665	2600
Total HMW-PAHs	655	6676	1700	9600
Total PAHs	1684	16770	4022	44792
Polychlorinated Biphenyls (PCBs; µg/kg)				
Total PCBs	21.6	189	22.7	180

Table 3. Sediment quality guidelines (SQGs) that were evaluated to support the establishment of numerical sediment quality targets (SQTs) for Tampa Bay, Florida.

Substance	Effects Level SQGs[1]		Effect Range SQGs[2]	
	TEL	PEL	ERL	ERM
Organochlorine Pesticides (µg/kg)				
Chlordane	2.26	4.79	0.5	6
Dieldrin	0.72	4.3	0.02	8
Lindane	0.32	0.99	NG[3]	NG
Sum DDD	1.22	7.81	2	20
Sum DDE	2.07	374	2.2	27
Sum DDT	1.19	4.77	1	7
Total DDT	3.89	51.7	1.58	46.1
Phthalates (µg/kg)				
Bis(2-ethylhexyl) phthalate	182	2647	NG	NG

[1]TEL = threshold effect level; PEL = probable effects level (from MacDonald *et al.* 1996).

[2]ERL = effects range low; ERM = effects range median (from Long and Morgan 1991; Long *et al.* 1995).

[3]NG = no guideline.

Table 4. Bioaccumulation-based sediment quality targets (SQTs) for assessing and managing sediment quality conditions in Tampa Bay, Florida (from NYSDEC 1999).

Chemicals of Concern	Piscivorous Wildlife SQTs	Human Health-Based SQTs
Polycyclic Aromatic Hydrocarbons (PAHs; µg/kg OC[1])		
Benzo(a)pyrene	NG[2]	700
Benzo(a)anthracene	NG	700
Benzo(b)fluoranthene	NG	700
Benzo(k)fluoranthene	NG	700
Chrysene	NG	700
Indeno(1,2,3-cd)pyrene	NG	700
Polychlorinated Biphenyls (PCBs; µg/kg OC)		
Total PCBs	1400	0.8
Pesticides (µg/kg OC)		
Chlordane	6	1
Dieldrin	NG	100
Dieldrin + Aldrin	770	100
Total DDT	1000	10
Heptachlor + Heptachlor epoxide	NG	0.8
Hexachlorocyclohexane - all isomers	1500	60
Mirex	3700	70
Toxaphene	NG	20
Dioxins (µg/kg OC)		
2,3,7,8-TCDD	0.2	10

[1]OC = organic carbon. [2]NG = no guideline.

Table 5. Sources of sediment chemistry and biological effects data for Tampa Bay, Florida.

Data Source[1]	Sediment Chemistry Data	Biological Effects Data			Reference
		Acute Toxicity[2]	Chronic Toxicity[3]	Benthic Community[4]	
Matching Data					
NOAA-NSTP/USF	141	96	141	49	Long *et al.* (1994); USF (unpublished data)
EPC	486	0	0	486	Grabe (1997)
Non Matching Data					
EPC	194	0	0	92	Grabe (1997)
FDEP	110	0	0	0	FDEP (1994)

[1]NOAA-NSTP = National Oceanic and Atmospheric Administration - National Status and Trends Program; EPC = Environmental Protection Commission; USF = University of South Florida; FDEP = Florida Department of Environmental Protection.

[2]Amphipod survival; 10-day toxicity tests.

[3]Sea urchin fertilization; 1-hour toxicity tests.

[4] Shannon-Wiener Diversity Index.

Table 6. Evaluation of PEL-based candidate sediment quality targets (SQTs) for assessing and managing sediment quality conditions in Tampa Bay.

SQT Type[1]	Derivation Procedure[2]	Categories of Mean SQG-Qs	Incidence of Benthic Impairment[3]	Score	Incidence of Acute Toxicity[4]	Score	Incidence of Chronic Toxicity[5]	Score	Total Evaluation Score
PEL-Q	USEPA	≤0.1	5.2% (21 of 402)	2	2.8% (1 of 36)	2	59.5% (25 of 42)	0	
		>0.1 - 1.0	43.9% (54 of 123)	2	13.7% (7 of 51)	2	75.0% (63 of 84)	0	
		>1.0	40.0% (4 of 10)	0	77.8% (7 of 9)	2	100.0% (15 of 15)	2	
				4		6		2	12
PEL-Q	NSTP	≤0.1	6.6% (25 of 381)	2	2.8% (1 of 36)	2	59.5% (25 of 42)	0	
		>0.1 - 1.0	34.5% (49 of 142)	2	14.3% (7 of 49)	2	74.4% (61 of 82)	0	
		>1.0	41.7% (5 of 12)	0	63.6% (7 of 11)	2	100.0% (17 of 17)	2	
				4		6		2	12
PEL-Q	USEPA	≤0.1	5.2% (21 of 402)	2	2.8% (1 of 36)	2	59.5% (25 of 42)	0	
		>0.1 - 2.3	44.2% (57 of 129)	2	20.7% (12 of 58)	0	78.4% (76 of 97)	0	
		>2.3	25.0% (1 of 4)	0	100.0% (2 of 2)	2	100.0% (2 of 2)	2	
				4		4		2	10
PEL-Q	NSTP	≤0.1	6.6% (25 of 381)	2	2.8% (1 of 36)	2	59.5% (25 of 42)	0	
		>0.1 - 2.3	35.3% (53 of 150)	2	19.3% (11 of 57)	2	77.7% (73 of 94)	0	
		>2.3	25.0% (1 of 4)	0	100.0% (3 of 3)	2	100.0% (5 of 5)	2	
				4		6		2	12

[1]PEL-Q = probable effects level quotient from MacDonald *et al.* (1996).
[2]USEPA = United States Environmental Protection Agency; NSTP = National Status and Trends Program.
[3]Based on Shannon-Wiener Diversity Index less than 95% prediction limit for uncontaminated sediment samples.
[4]Based on significantly reduced survival of amphipods and survival less than 95% prediction limit for uncontaminated sediment samples.
[5]Based on significantly reduced fertilization in sea urchins and control adjusted fertilization of less than 81%, in 100% pore water.

Table 7. Evaluation of ERM-based candidate sediment quality targets (SQTs) for assessing and managing sediment quality conditions in Tampa Bay.

SQT Type[1]	Derivation Procedure[2]	Categories of Mean SQG-Qs	Incidence of Benthic Impairment[3]	Score	Incidence of Acute Toxicity[4]	Score	Incidence of Chronic Toxicity[5]	Score	Total Evaluation Score
ERM-Q	USEPA	≤0.1	8.3% (38 of 458)	2	5.3% (3 of 57)	2	63.9% (46 of 72)	0	
		>0.1 - 1.0	54.3% (38 of 70)	0	20.6% (7 of 34)	0	93.7% (59 of 63)	0	
		>1.0	42.9% (3 of 7)	0	100.0% (5 of 5)	2	100.0% (6 of 6)	2	
				2		4		2	8
ERM-Q	NSTP	≤0.1	9.1% (42 of 460)	2	5.5% (3 of 55)	2	64.2% (43 of 67)	0	
		>0.1 - 1.0	51.4% (36 of 70)	0	19.4% (7 of 36)	2	90.9% (60 of 66)	0	
		>1.0	20.0% (1 of 5)	0	100.0% (5 of 5)	2	100.0% (8 of 8)	2	
				2		6		2	10
ERM-Q	USEPA	≤0.1	8.3% (38 of 458)	2	5.3% (3 of 57)	2	63.9% (46 of 72)	0	
		>0.1 - 1.5	54.8% (40 of 73)	0	22.9% (8 of 35)	0	93.8% (61 of 65)	0	
		>1.5	25.0% (1 of 4)	0	100.0% (4 of 4)	2	100.0% (4 of 4)	2	
				2		4		2	8
ERM-Q	NSTP	≤0.1	9.1% (42 of 460)	2	5.5% (3 of 55)	2	64.2% (43 of 67)	0	
		>0.1 - 1.5	50.7% (36 of 71)	0	25.6% (10 of 39)	0	91.7% (66 of 72)	0	
		>1.5	25.0% (1 of 4)	0	100.0% (2 of 2)	2	100.0% (2 of 2)	2	
				2		4		2	8

[1] ERM = effects range median from Long *et al*. (1995)

[2] USEPA = United States Environmental Protection Agency; NSTP = National Status and Trends Program.

[3] Based on Shannon-Wiener Diversity Index less than 95% prediction limit for uncontaminated sediment samples.

[4] Based on significantly reduced survival of amphipods and survival less than 95% prediction limit for uncontaminated sediment samples.

[5] Based on significantly reduced fertilization in sea urchins and control adjusted fertilization of less than 81%, in 100% pore water.

Table 8. Summary of sediment quality targets generated using matching sediment chemistry and biological effects data from Tampa Bay.

		Sediment Quality Targets (expressed as mean PEL-Qs[1])				
Endpoint Measured	**n**	P_{10}	P_{20}	P_{50}	P_{80}	**Logistic Model Parameters[2]**
Acute toxicity to amphipods	96	0.28	0.54	1.3	2.0	a = 15983.8265; b = -1.0589; x_0 = 296.1373 (r^2 = 0.91; n = 10; p = <0.001)
(endpoint: survival)						
Chronic toxicity to sea urchins (endpoint: fertilization)						
100% pore water	141	NA[3]	NA[3]	NA[3]	0.38	a = 336.9413; b = -0.2043; x_0 = 116.0202 (r^2 = 0.90; n = 7; p = <0.05)
50% pore water	141	NA[3]	0.04	0.24	0.83	a = 136.1706; b = -0.7167; x_0 = 0.5095 (r^2 = 0.89; n = 7; p = <0.05)
25% pore water	141	0.10	0.19	0.55	1.2	a = 126.6869; b = -1.1760; x_0 = 0.7868 (r^2 = 0.90; n = 7; p = <0.05)
Benthic community impairment	535	0.05	0.10	0.34	NA[3]	a = 74.2956; b = -1.3634; x_0 = 0.1989 (r^2 = 0.97; n = 13; p = <0.0001)
(endpoint: Shannon-Wiener Diversity Index)						

[1]PEL-Q = probable effects level quotient from MacDonald *et al.* (1996).

[2]Logistic Model Equation: $y = a/[1+(x/x_0)^b]$

[3]NA = not applicable; concentration-response data did not support calculation of the P value.

Table 9. Biological conditions that occur within the three types of sediment management areas in Tampa Bay, Florida, identified using the sediment quality targets for benthic community structure.

Benthic Metric/Toxicity Test	Endpoint Measured	Impact Level A mean ± SD (n)[a]	Impact Level B mean ± SD (n)	Impact Level C mean ± SD (n)
Mean PEL-Q		0.025 + 0.0099 (342)	0.15 ± 0.078 (157)	1.3 ± 2.5 (36)
Range		0.0044 to 0.050	0.050 to 0.33	0.34 to 15
Benthic Invertebrate Community Structure				
Shannon-Wiener Diversity Index	NA	3.46 ± 0.974 (342)	2.01 ± 1.30 (157)	1.09 ± 1.09 (36)
Abundance of all benthic organisms	# organisms/m^2	9620 ± 13000 (342)	7200 ± 11900 (157)	3070 ± 4900 (36)
Abundance of amphipods	# organisms/m^2	1820 ± 5050 (340)	1610 ± 5540 (157)	71.7 ± 194 (36)
Abundance of capitellid polychaetes	# organisms/m^2	335 ± 763 (342)	335 ± 1010 (157)	18.4 ± 52.0 (36)
Abundance of gastropods	# organisms/m^2	953 ± 2040 (342)	195 ± 412 (157)	39.8 ± 130 (36)
Abundance of tubificid oligochaetes	# organisms/m^2	396 ± 1150 (342)	376 ± 1400 (157)	281 ± 624 (36)
Sediment Toxicity				
Amphipod survival (%)	% survival	91.5 ± 5.78 (29)	86.7 ± 4.88 (42)	78.0 ± 14.1 (25)
Sea urchin fertilization (100% pore water dilution)	% fertilization	48.3 ± 30.6 (33)	40.9 ± 34.9 (66)	8.29 ± 18.9 (42)
Sea urchin fertilization (50% pore water dilution)	% fertilization	78.3 ± 25.73 (33)	68.4 ± 30.6 (66)	23.9 ± 30.7 (42)
Sea urchin fertilization (25% pore water dilution)	% fertilization	82.8 ± 22.65 (33)	81.6 ± 19.9 (66)	42.8 ± 33.3 (42)

[a]SD = standard deviation; n = number of samples.
[b]NA = not applicable.

Table 10. Identification of sediment management areas and contaminants of concern in Tampa Bay, Florida, as determined using the PEL-based sediment quality targets for protection of the benthic community.

Bay Segment	Sediment Management Area	n[1]	Impact Levels <0.05	Impact Levels 0.05 - 0.34	Impact Levels >0.34	Predominant Impact Level	Mean PEL-Q[2]	Contaminants of Concern[3]
Old Tampa Bay	Eastern Old Tampa Bay (EOTB)	5	0	5	0	B	0.126	Cr, Pb, Chlordane
	Northern Old Tampa Bay (NOTB)	3	1	2	0	B	0.131	None
	Old Tampa Bay (Other Areas; OTB)	95	89	6	0	A	0.0291	None
	Western Old Tampa Bay (WOTB)	22	5	16	1	B	0.196	Cr, Lindane
Hillsborough Bay	Hillsborough Bay 1 (HB1)	72	19	48	5	B	0.144	Cr, Cu, Zn, PAHs, Chlordane, Lindane
	Hillsborough Bay 2 (HB2)	11	10	1	0	A	0.0316	None
	Hillsborough Bay 3 (HB3)	10	10	0	0	A	0.0232	None
	Hillsborough Bay 4 (HB4)	21	19	2	0	A	0.0324	None
	Hillsborough Bay 5 (HB5)	11	7	3	1	A	1.40	Cr, Cu, Zn
	McKay Bay	12	1	6	5	B	0.475	Cd, Cr, Cu, Pb, Zn, PAHs, PCBs, Chlordane, DDTs, Lindane
	Port of Tampa & Ybor Channel	28	0	5	23	C	1.52	Cd, Cu, Pb, Zn, PAHs, PCBs, Chlordane, DDTs, Dieldrin, Lindane
Hillsborough River	Lower Hillsborough River (LHR)	13	0	2	11	C	0.936	Cu, Pb, Zn, PAHs, PCBs, Dieldrin, DDTs, Chlordane
	Middle Hillsborough River (MHR)	8	1	2	5	C	1.04	PAHs, PCBs, Chlordane, DDTs, Dieldrin
Palm River	Lower Palm River (LPR)	15	4	4	7	C	0.464	Cd, Cr, Pb, Zn, PAHs, PCBs, Chlordane, DDTs
	Middle Palm River (MPR)	5	0	0	5	C	1.36	Cd, Cr, Pb, Zn, PAHs, PCBs, Chlordane, Dieldrin
Alafia River	Lower Alafia River (LAR)	16	2	14	0	B	0.116	Cd, Cr, Zn
	Middle Alafia River (MAR)	6	0	6	0	B	0.146	Cd, Cr, Chlordane
	Upper Alafia River (UAR)	3	2	1	0	A	0.0331	None

Table 10. Identification of sediment management areas and contaminants of concern in Tampa Bay, Florida, as determined using the PEL-based sediment quality targets for protection of the benthic community.

Bay Segment	Sediment Management Area	n[1]	Impact Levels <0.05	Impact Levels 0.05 - 0.34	Impact Levels >0.34	Predominant Impact Level	Mean PEL-Q[2]	Contaminants of Concern[3]
Middle Tampa Bay	Bayboro Harbor (BH)	3	0	1	2	C	0.513	Pb, Zn, PAHs, Chlordane, DDTs, Dieldrin, Lindane
	Middle Tampa Bay (MTB)	149	132	17	0	A	0.0328	Cr, PAHs, Lindane
	St. Pete Marina (SPM)	7	0	3	4	C	0.522	Cu, Pb, Ag, Zn, PAHs, Chlordane, DDTs, Dieldrin, Lindane
	St. Petersburg Waterfront (SPW)	21	7	13	1	B	0.143	Chlordane, DDT, Lindane
Little Manatee River	Lower Little Manatee River (LLMR)	13	12	1	0	A	0.0263	Ag
	Middle Little Manatee River (MLMR)	5	2	3	0	B	0.0624	None
	Upper Little Manatee River (ULMR)	1	1	0	0	A	0.0154	None
Lower Tampa Bay	Lower Tampa Bay (LTB)	101	91	10	0	A	0.0304	Cu, Chlordane, Lindane
Terra Ceia Bay	Terra Ceia Bay 1 (TCB1)	4	0	4	0	B	0.0641	None
	Terra Ceia Bay 2 (TCB2)	20	17	3	0	A	0.03194	None
Manatee River	Lower Manatee River (LMR)	22	16	6	0	A	0.0424	Zn, Chlordane
	Middle Manatee River (MMR)	19	15	4	0	A	0.0326	None
Boca Ciega Bay	Boca Ciega Bay 1 (BCB1)	25	15	10	0	A	0.0838	Lindane
	Boca Ciega Bay 2 (BCB2)	23	7	14	2	B	0.179	Cu, Pb, PAHs, Chlordane, DDTs, Dieldrin, Lindane
	Boca Ciega Bay 3 (BCB3)	9	9	0	0	A	0.0252	None
	Boca Ciega Bay 4 (BCB4)	28	26	2	0	A	0.0266	None
Gulf of Mexico	Gulf of Mexico	15	15	0	0	A	0.0190	None

[1]n = number of samples. [2]PEL-Q = probable effects level quotient from MacDonald et al. (1996). [3]Identified based on one or more exceedances of PELs (Table 3).

Table 11. Physical characteristics of sediment samples used in the evaluation of the predictive ability of sediment quality targets.

Variable	Number of Samples	Range	Mean	Standard Deviation	Normal Range[1]
Water Depth (m)	196	0.475 - 14.5	4.49	3.05	0 - 10.6
Total Organic Carbon (%)	141	0.08 - 7.86	1.85	1.64	0 - 5.14
Fines (%)	516	0.2 - 96.6	10.1	15.3	0 - 40.7
Bottom Salinity (ppt)	658	0 - 36.0	23.1	7.84	7.42 - 36.0

[1]Mean $\pm$ 2 standard deviations.

Table 12. Options for managing contaminated sediments in Tampa Bay.

Chemistry / Biology	**Impact Level A: mean PEL-Q[1] <0.05**	**Impact Level B: mean PEL-Q of 0.05 to 0.34**	**Impact Level C: mean PEL-Q >0.34**
Impact Level A: Benthic community impairment and/or acute toxicity to amphipods observed or predicted in <10% of sediment samples	Review and evaluate data; Conduct periodic monitoring	Review and evaluate data; Identify sources of COPCs[2]	Review and evaluate data; Evaluate the factors influencing bioavailability; evaluate bioaccumulation potential
Impact Level B: Benthic community impairment and/or acute toxicity to amphipods observed or predicted in 10-50% and 10-20% of sediment samples, respectively	Characterize nearby land uses; Identify additional COPCs; Conduct additional sampling including expanded suite of COPCs	Conduct preliminary site investigation; assess potential risks; Consider source control measures	Conduct a detailed site investigation; Conduct screening level ERA[3] and HHRA[4];
Impact Level C: Benthic community impairment and/or acute toxicity to amphipods observed or predicted in >50% and >20% of sediment samples respectively	Conduct load analysis for COPCs by source; Conduct TIEs[5] to identify causal factors; Control COPC inputs from key sources;	Conduct TIEs to identify causal factors; conduct screening level ERA and HHRA; Implement source control measures, as needed	Implement source control measures; Conduct baseline ERA and HHRA; Conduct RI/FS[6]; Conduct NRDA[7]; Develop RAP[7]

[1]PEL-Q = probable effects level quotient from MacDonald *et al.* (1996).
[2]COPC = contaminant of potential concern. [3]ERA = ecological risk assessment. [4]HHRA = human health risk assessment.
[5]TIE = toxicity identification evaluation procedures. [6]RI/FS = remedial investigation and feasibility study.
[7]NRDA = natural resource damage assessment. [8]RAP - remedial action plan.

Figure Captions

Figure 1. Map of study area.

Figure 2. A framework for ecosystem-based management (CCME 1996).

Figure 3. The relationship between mean PEL-Qs and the incidence of toxicity in 10-day whole sediment toxicity tests with the amphipod, *Ampelisca abdita* (data points generally represent 10 samples).

Figure 4. The relationship between mean PEL-Qs and the incidence of toxicity in 1-hour pore-water toxicity tests with sea urchins (based on fertilization endpoint; data points generally represent 20 samples).

Figure 5. The relationship between mean PEL-Qs, and the incidence of benthic community impairment using the Shannon-Wiener Diversity Index (data points generally represent 40 samples).

Figure 6. Distribution of sediment sampling locations in Tampa Bay.

Figure 7. Distribution of sediment management areas in Old Tampa Bay, Hillsborough Bay, and associated riverine systems, using the SQTs derived from benthic community structure data.

Figure 8. Distribution of sediment management areas in Middle and Lower Tampa Bay, Boca Ciega Bay, and associated riverine systems, based on SQTs derived from benthic community structure data.

Figure 9. Distribution of sediment management areas in Old Tampa Bay, Hillsborough Bay, and associated riverine systems, based on the SQTs derived from data on acute toxicity to amphipods.

Figure 10. Distribution of sediment management areas in Middle and Lower Tampa Bay, Boca Ciega Bay, and associated riverine systems, based on SQTs derived from data on acute toxicity to amphipods.

Figure 1.

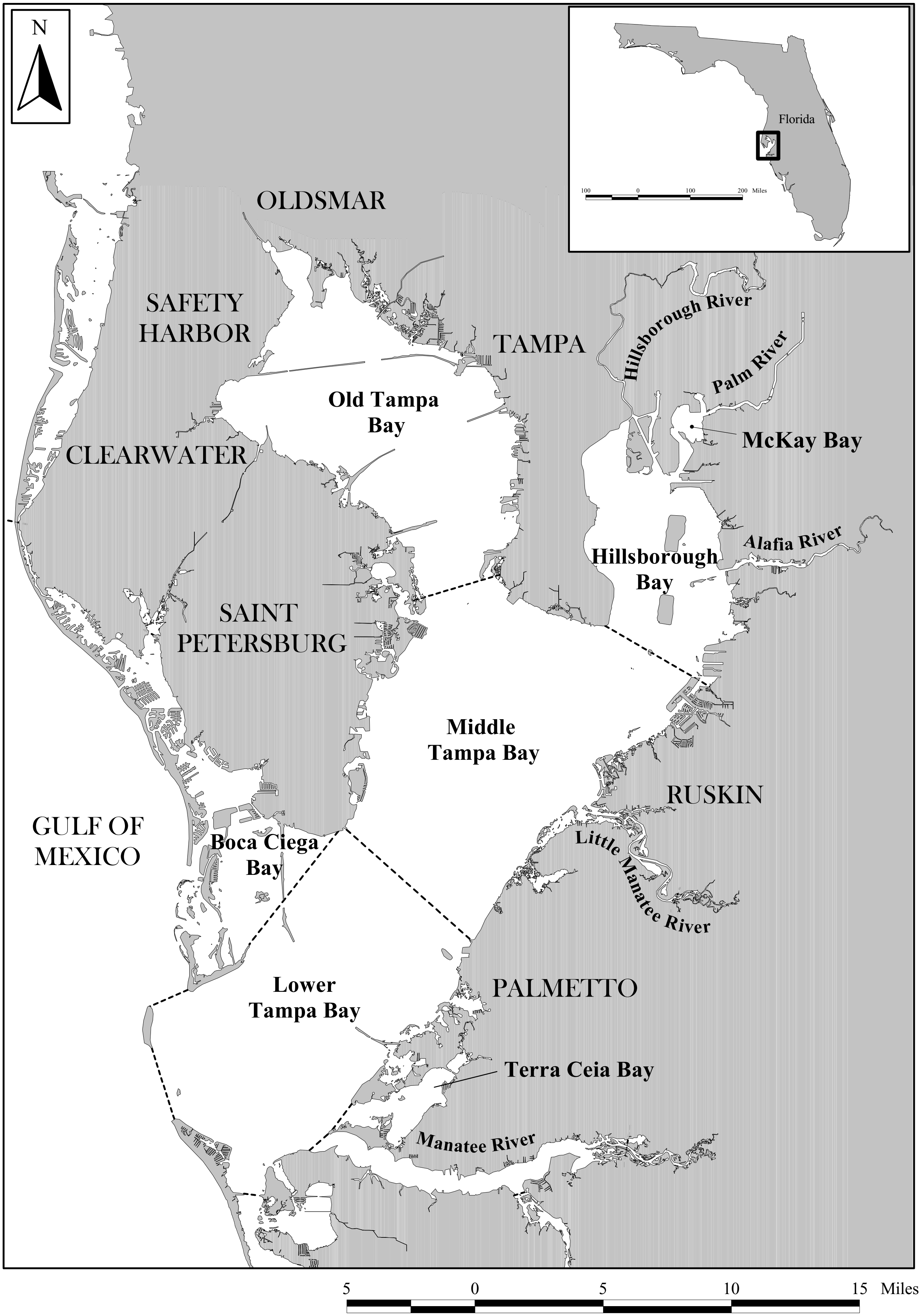
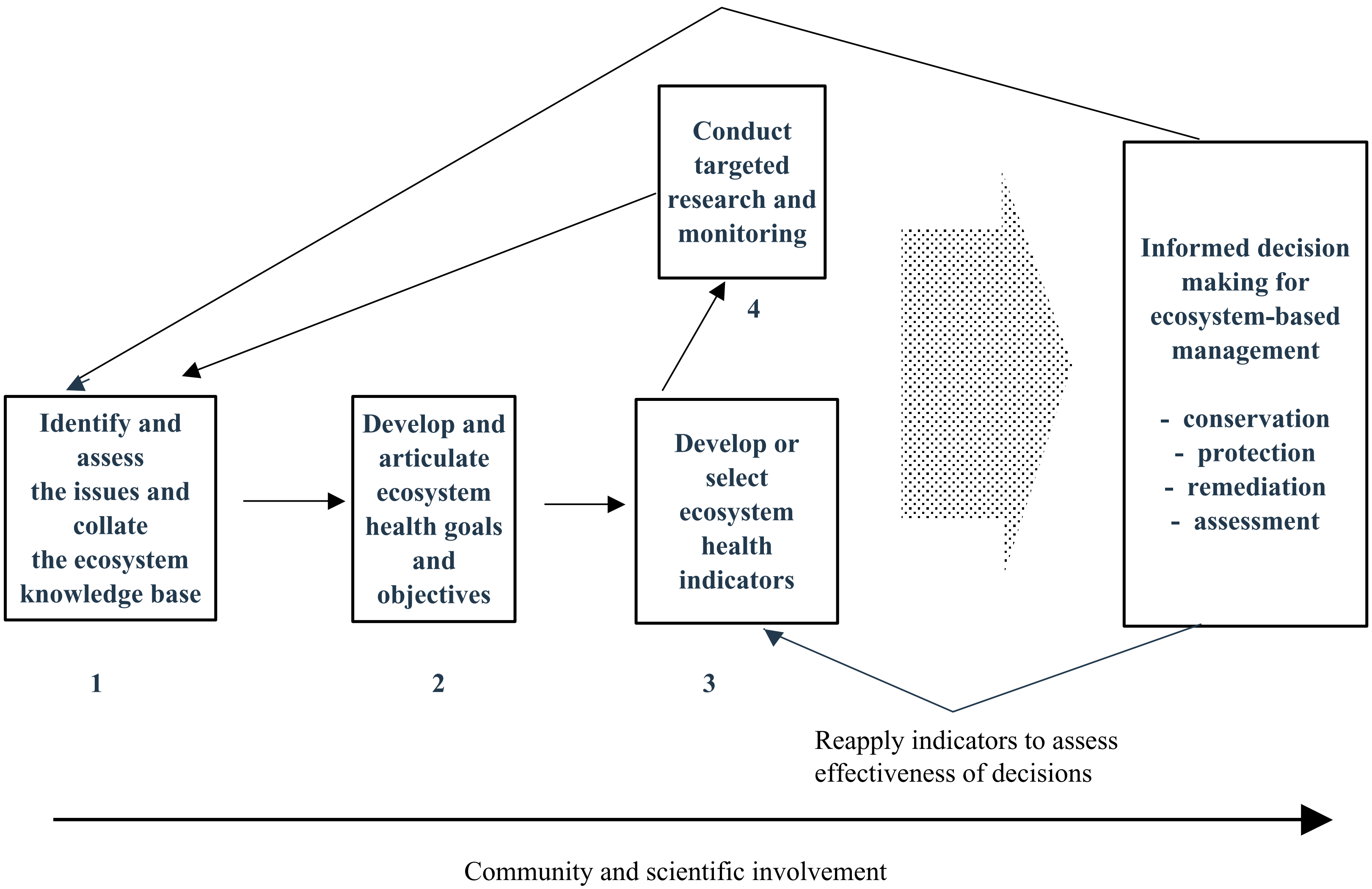
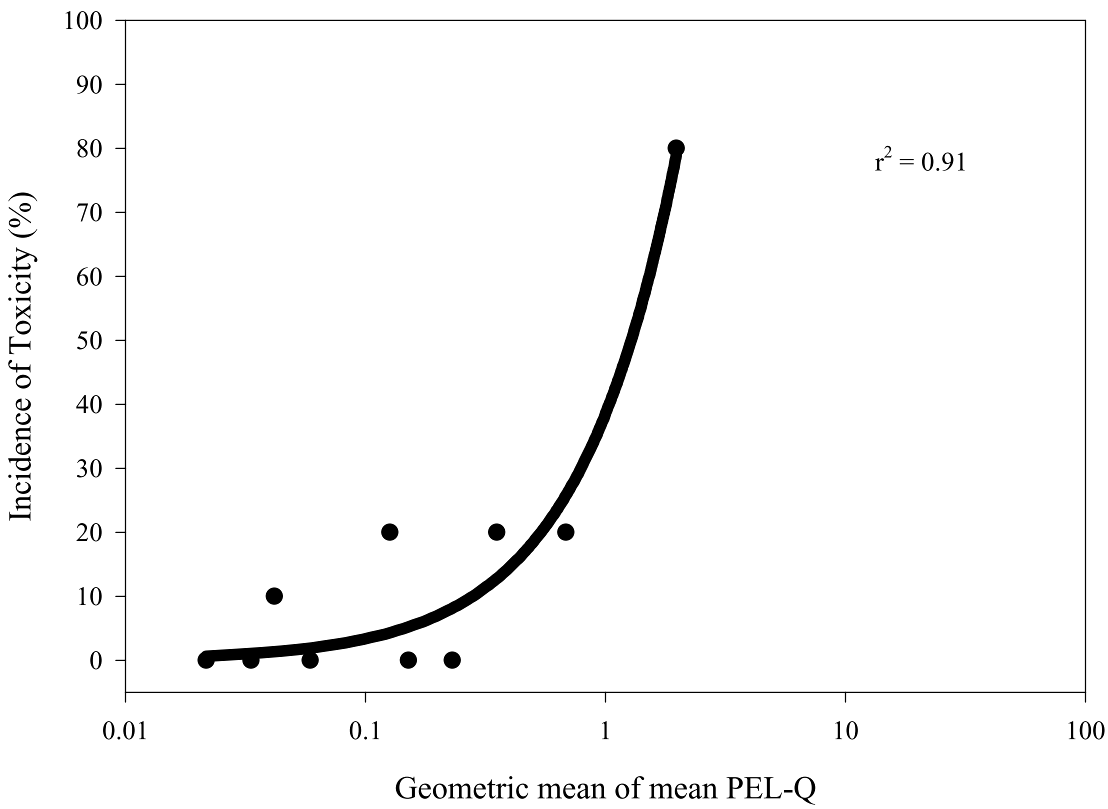

N
Florida
100 0 100 200 Miles
OLDSMAR
SAFETY HARBOR
TAMPA
Hillsborough River
Palm River
Old Tampa Bay
McKay Bay
CLEARWATER
Alafia River
Hillsborough Bay
SAINT PETERSBURG
Middle Tampa Bay
RUSKIN
GULF OF MEXICO
Boca Ciega Bay
Little Manatee River
Lower Tampa Bay
PALMETTO
Terra Ceia Bay
Manatee River
5 0 5 10 15 Miles

Figure 2.



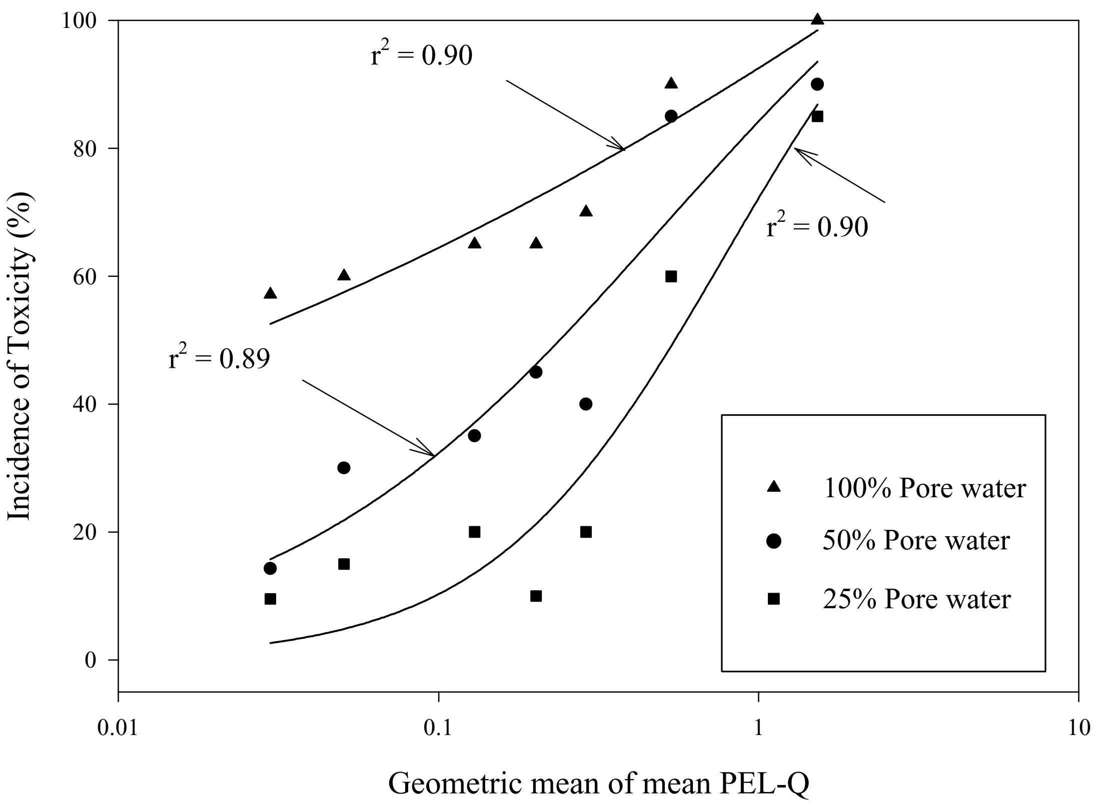
Conduct targeted research and monitoring
4
Identify and assess the issues and collate the ecosystem knowledge base
Develop and articulate ecosystem health goals and objectives
Develop or select ecosystem health indicators
Informed decision making for ecosystem-based management
- conservation
- protection
- remediation
- assessment
1
2
3
Reapply indicators to assess effectiveness of decisions
Community and scientific involvement

Figure 3.



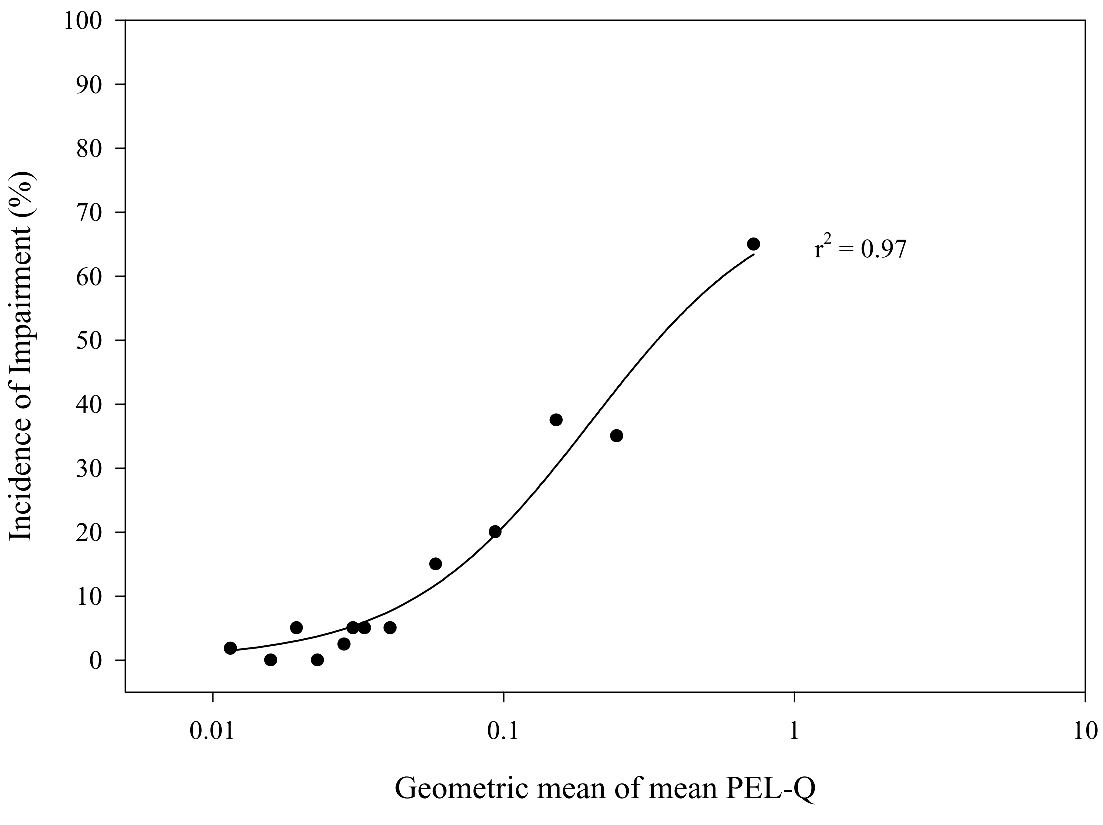
100
90
80
70
60
50
40
30
20
10
0
Incidence of Toxicity (%)
r2 = 0.91
0.01
0.1
1
10
100
Geometric mean of mean PEL-Q

Figure 4.



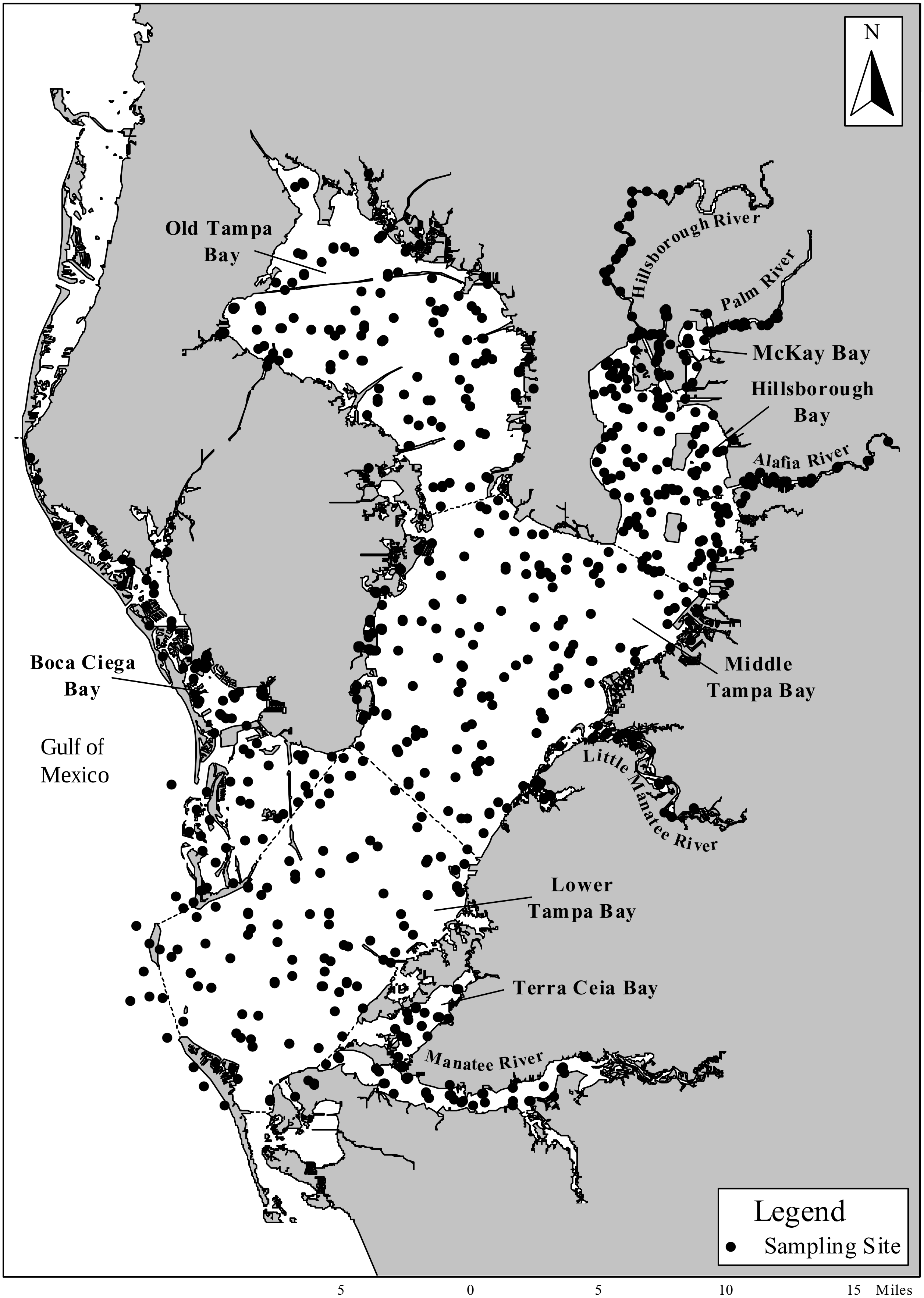
100
80
60
40
20
0
0.01
0.1
1
10
Incidence of Toxicity (%)
Geometric mean of mean PEL-Q
r2 = 0.90
r2 = 0.90
r2 = 0.89
100% Pore water
50% Pore water
25% Pore water

Figure 5.



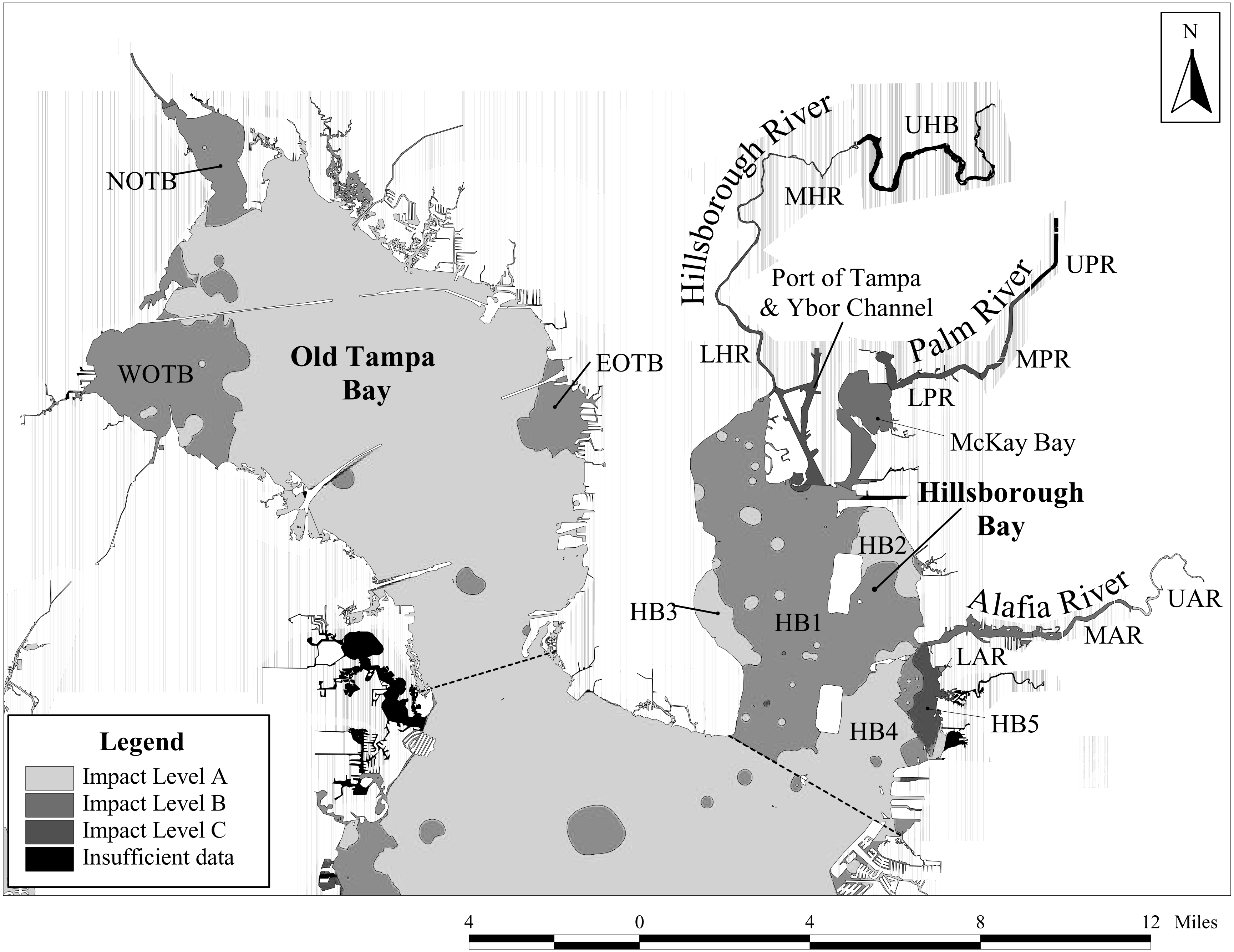
100
90
80
70
60
50
40
30
20
10
0
Incidence of Impairment (%)
r2 = 0.97
0.01
0.1
1
10
Geometric mean of mean PEL-Q

Figure 6.



N
Old Tampa Bay
Hillsborough River
Palm River
McKay Bay
Hillsborough Bay
Alafia River
Boca Ciega Bay
Middle Tampa Bay
Gulf of Mexico
Little Manatee River
Lower Tampa Bay
Terra Ceia Bay
Manatee River
Legend
Sampling Site
5 0 5 10 15 Miles

Figure 7.



N
Hillsborough River
UHB
MHR
LHR
Port of Tampa
& Ybor Channel
Palm River
UPR
MPR
LPR
McKay Bay
Hillsborough
Bay
HB1
HB2
HB3
HB4
HB5
Alafia River
UAR
MAR
LAR
NOTB
WOTB
EOTB
Old Tampa
Bay
Legend
Impact Level A
Impact Level B
Impact Level C
Insufficient data
4
0
4
8
12 Miles

Figure 8.

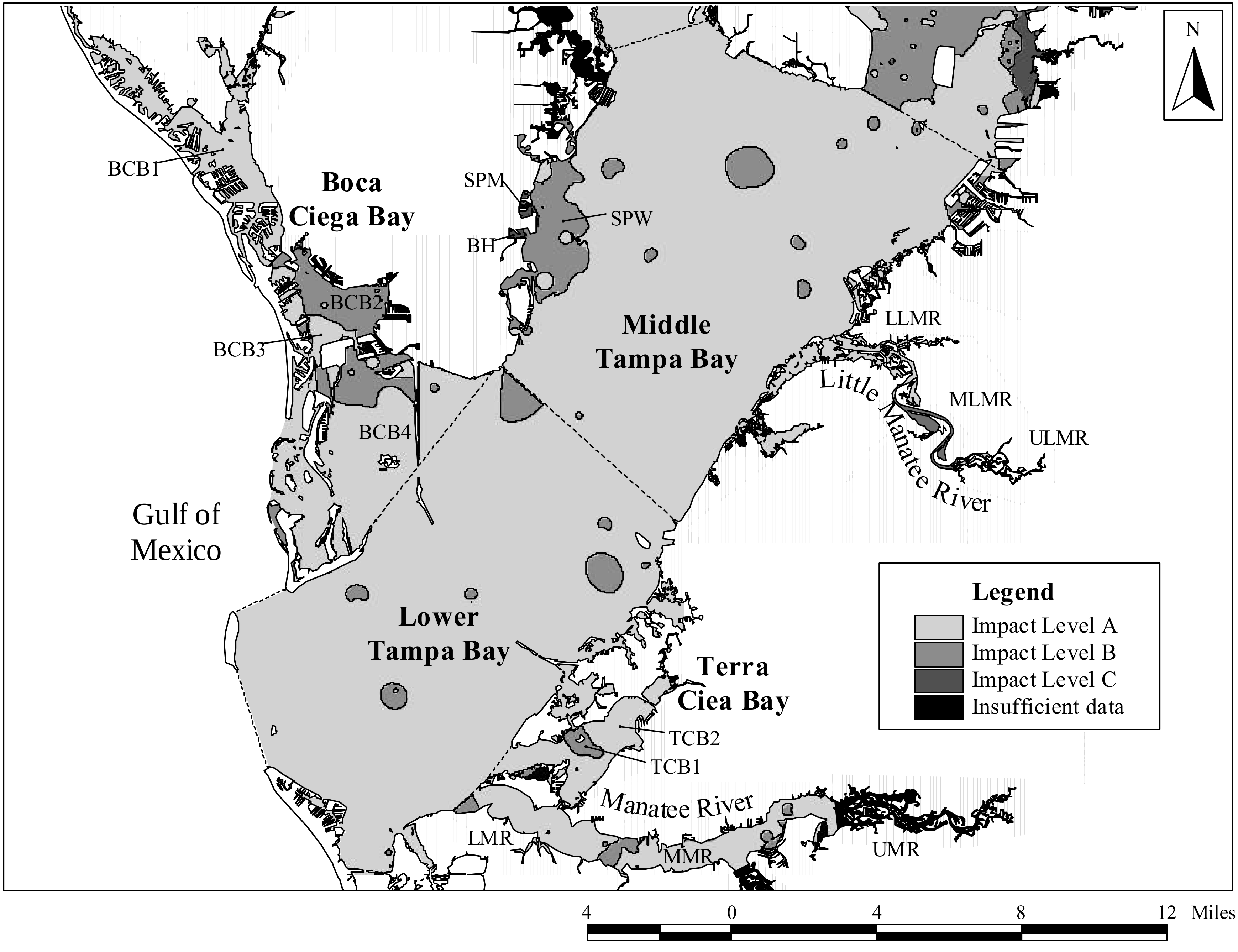

N
BCB1
Boca
Ciega Bay
SPM
SPW
BH
BCB2
BCB3
Middle
Tampa Bay
LLMR
Little Manatee River
MLMR
ULMR
BCB4
Gulf of
Mexico
Lower
Tampa Bay
Terra
Ciea Bay
TCB2
TCB1
Manatee River
LMR
MMR
UMR
Legend
Impact Level A
Impact Level B
Impact Level C
Insufficient data
4
0
4
8
12 Miles

Figure 9.

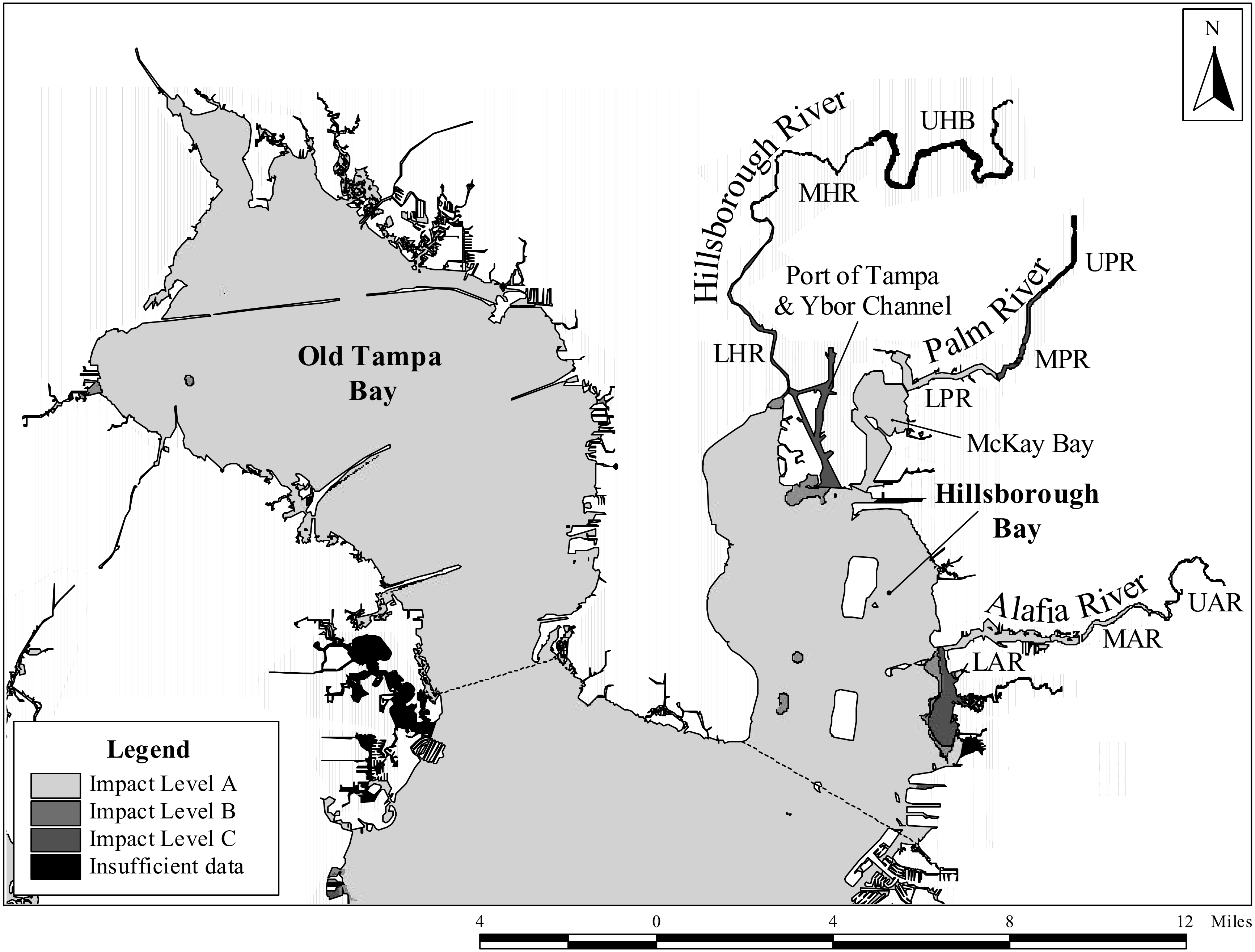
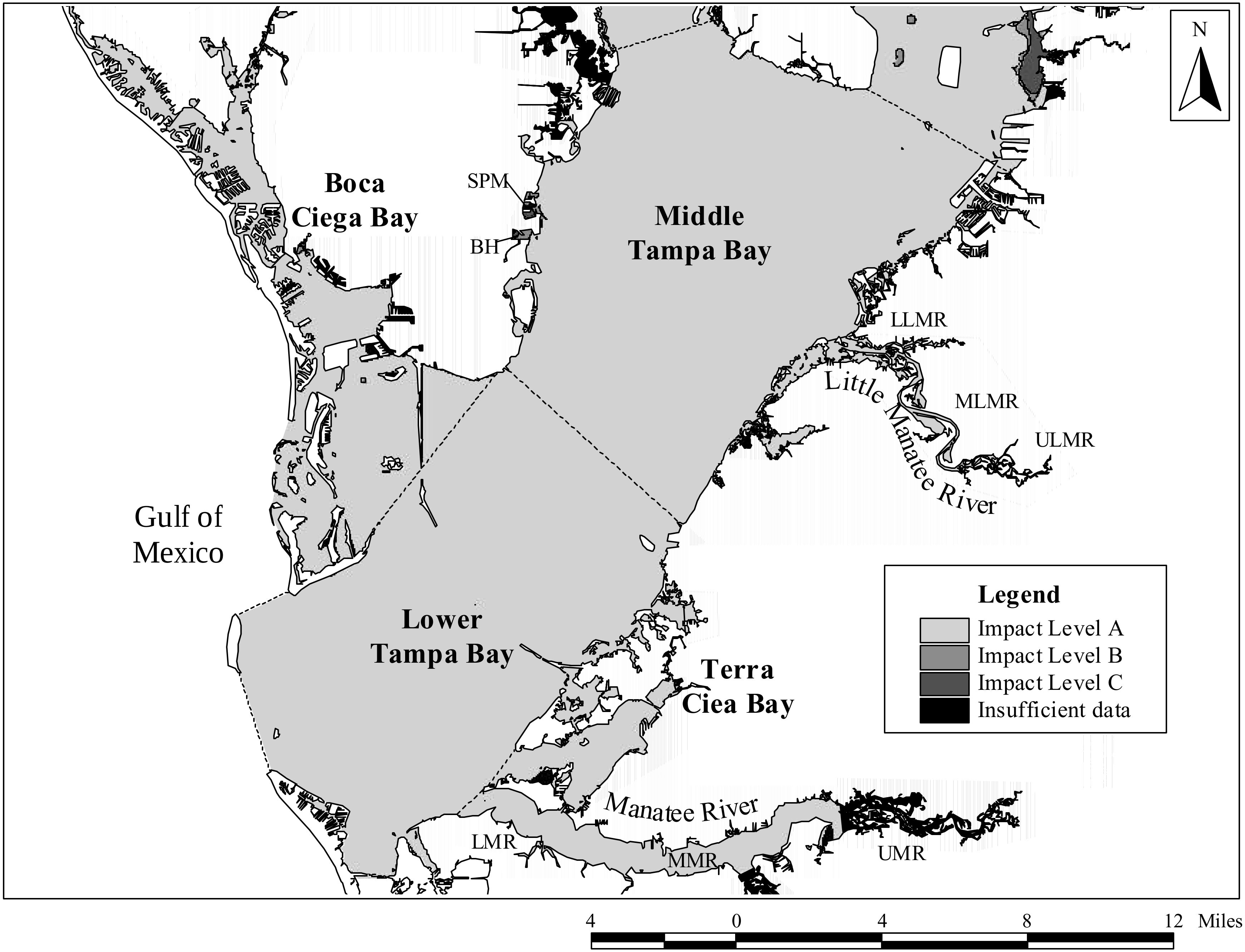

N
Old Tampa
Bay
Hillsborough River
UHB
MHR
LHR
Port of Tampa
& Ybor Channel
Palm River
UPR
MPR
LPR
McKay Bay
Hillsborough
Bay
Alafia River
UAR
MAR
LAR
Legend
Impact Level A
Impact Level B
Impact Level C
Insufficient data
4
0
4
8
12 Miles

Figure 10.


N
Boca
Ciega Bay
SPM
BH
Middle
Tampa Bay
LLMR
Little Manatee River
MLMR
ULMR
Gulf of
Mexico
Lower
Tampa Bay
Terra
Ciea Bay
Legend
Impact Level A
Impact Level B
Impact Level C
Insufficient data
Manatee River
LMR
MMR
UMR
4 0 4 8 12 Miles