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Effects of an invasive isopod on erosion rates at Elkhorn Slough, California

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**EFFECTS OF AN INVASIVE ISOPOD
ON EROSION RATES
AT ELKHORN SLOUGH, CALIFORNIA**

A Thesis

Presented to

The Faculty of the Department of Environmental Studies

San Jose State University

In partial fulfillment

Of the Requirements for the Degree

Master of Science

By

Shannon Bane

May 2002

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ABSTRACT

EFFECTS OF AN INVASIVE ISOPOD ON EROSION RATES AT ELKHORN SLOUGH, CALIFORNIA

By Shannon Bane

Elkhorn Slough is experiencing high rates of erosion and extensive loss of salt marsh habitat as a result of introduced tidal scour processes. Understanding the factors that contribute to or exacerbate tidal scour Elkhorn Slough is important for the management and conservation of the habitats that occur there.

This study examined the potential contribution of *Sphaeroma quoyanum*, an exotic, burrowing isopod, to marsh erosion and bank loss at Elkhorn Slough, California. Results showed no relationships between *S. quoyanum* organisms, burrow density, and erosion rates for: (1) the entire Elkhorn Slough system, (2) subsets of sites such as tidal creeks, or (3) sites classified as having “high” rates of erosion. *Sphaeroma quoyanum* are currently not contributing to erosion rates in Elkhorn Slough. It appears that other factors such as tidal current, wave action, and tidal prism are the more significant contributors to Elkhorn Slough’s high erosion rates.

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PROBLEM STATEMENT

Importance

Anthropogenic influence on mid-sized estuarine systems has been documented throughout central California, including Elkhorn Slough, Morro Bay, and Bolinas Lagoon (Haltiner and Thor 1991). Changes to these systems have been the result of activities to serve the needs of a developing coastline and include activities such as: diking, draining, filling, breaching, diverting upstream water, and dredging to accommodate small craft harbors, agriculture, and development.

Although these slough and lagoon systems still support a diverse array of marine and estuarine wildlife, they are no longer self-sustaining. Unable to accommodate anthropogenic changes within their natural floodplains, the result is accelerated and ongoing loss of habitat. Losses occur either by deposition of sediment from upstream sources as in Bolinas and Morro Bay, or by substantially increased erosional processes like those occurring in and Elkhorn Slough.

Elkhorn Slough is an important estuary in the Monterey Bay region. Elkhorn Slough is located in Watsonville, California, midway between Santa Cruz and Monterey (Figure 1). Elkhorn Slough is approximately 7 miles long and drains a significant portion of the Pajaro Valley. It empties into the Monterey Bay at Moss Landing, a man-made harbor located at the apex of the Monterey Submarine Canyon. Habitat loss due to erosion began after the creation of Moss Landing Harbor in 1946 when the Army Corps of Engineers breached the sand dunes in front of the mouth of Elkhorn Slough (Elkhorn Slough National Estuarine Research Reserve 1997, Oliver et al. 1988, Crampton 1994,

Figure 1. Location of Elkhorn Slough

Clark 1972, Wong 1989, and Philip Williams and Associates 1992). Prior to this, Elkhorn Slough had been a quiet, seasonal estuary supporting expansive salt marsh and freshwater wetlands. What exists today is essentially a broad coastal lagoon flushed by strong, swift tidal currents and bordered by low and receding intertidal mud flats. The vegetation and habitats throughout the Slough have diminished and continue to be lost to erosional processes.

A recent study by Malzone (1999) quantified the erosional changes in Elkhorn Slough over the past decade using aerial photographs, field ground truthing, and comparison of various physical measurements within the Slough. This study documented very high erosion rates that continue to increase. Malzone found the most extensive erosion in the vicinity of Parson Slough and the back regions of Elkhorn Slough; aerial photos showed increases of channel width greater than 40% since 1980 in some areas. Ground truthing confirmed these figures, documenting losses at rates greater than 1m/year over a six month period at some sites.

Malzone (1999) found that other parts of the Slough are suffering as well. Width increases have been documented along the entire length of the Slough. Increases in depth, however, were restricted to its back regions. Depth increases and other data indicate greater tidal prism and water storage in the upper parts of the Slough. The increased volume of stored water increased the velocity of the ebb flow and subsequently hastened the erosion of accumulated sediment bank at the head of the Slough.

Other studies have documented the effects of erosion on physical and ecological processes within the Slough (Oliver et al. 1988, Crampton 1994, Clark 1972, Wong 1989,

and Philip Williams and Associates 1992). Efforts focused on identifying factors contributing to erosion, quantifying processes and losses.

Although erosion is a physical process that occurs naturally in estuarine systems, the radical changes that Malzone and other researchers observed are not typical of this system or other similar ones along the California Coast. Until the creation of Moss Landing Harbor, the system only received saltwater input once a year when the sand dunes at the mouth of the Slough were breached from heavy winter storm flows. In addition, upland land uses have diverted water from local creeks, resulting in substantial reduction of fresh water inputs and depositional processes that deliver sediment to the Slough.

The introduction of daily tidal movement into the system has caused large amounts of material to be swept from the Slough banks into the ocean. Because the natural sediment transport of the system has been substantially altered, the end result is a net loss of bank, salt marsh, and mud flat habitat within the Slough. As these habitats are lost, the physical and biological functions of the Slough are also lost.

In addition to physical changes to the Slough, biological changes have also ensued; among these is the introduction of an exotic burrowing isopod, *Sphaeroma quoyanum*. The relationship between *S. quoyanum* and erosion has not been documented in Elkhorn Slough. However, the burrowing behavior of this species is well-documented (Schmitt 1965, Talley et al. 2001, Hass and Knott 1998), and its contributions to erosion have been observed in the San Francisco and San Diego Bays (Talley et al. 2001). With the increases in erosion rates at Elkhorn Slough, questions about the effect of *Sphaeroma*

quoyanum, and/or the movement of water through burrows in the marsh banks of the Slough is a concern. The National Oceanic and Atmospheric Administration (NOAA), the California Department of Fish and Game (DFG), and the Elkhorn Slough Foundation are responsible for the management of Elkhorn Slough National Estuarine Research Reserve and the surrounding watershed, and are very interested in the factors causing high rates of erosion in the system. This study is designed to evaluate the potential contribution of *S. quoyanum* to erosion at Elkhorn Slough.

Generality

Loss of habitat in wetland areas has been extensive throughout the United States. Less than half of the original 215 million acres of wetland present at the time of European settlement remain today (Kusler and Kentula 1990). Losses in recent years have been particularly devastating; nine million acres of wetland habitat were drained, filled, and cleared from the mid-1950s to the mid-1970s. Rates of loss continue at 450,000 acres per year.

A wide range of factors contribute to the loss and degradation of wetlands. One such factor is the presence of non-native species. Introduced species are a concern in wetland habitats, where they become well-established soon after invasion (Carlton 1989, Carlton 1992, Carlton and Geller 1993, Chapman and Carlton 1994, Cohen and Carlton 1995). Introduced marine species are already known to be abundant or predominant in many estuaries of the world. The San Francisco Bay/Estuary is now recognized as the most invaded aquatic ecosystem in North America, with 212 recorded introduced species (Cohen and Carlton 1995). All shallow water habitats within this system have been

invaded by exotic species. In some regions of San Francisco Bay, it is difficult to find native species in any abundance.

Ecological and economic consequences of introductions are severe in the few aquatic environments where their effects have been studied (Carlton, Thompson, and Nichols 1990; Nichols, Thompson, and Schemel 1990; Carlton 1992). Introduced clams, especially the Japanese clams *Venerupis* and *Musculista* and the Atlantic clam *Gemma*, are so numerous that they are capable of filtering the entire volume of the South San Francisco Bay and Suisun Bay for food once per day (Cohen and Carlton 1995). Other predatory species, such as the Asian Clam (*Potamocorbula*) the Atlantic Mudsail (*Ilyanassa*) and the Atlantic Green Crab (*Carcinus maenus*) alter the diversity, abundance, size distribution, and recruitment of prey, which in turn affects the survival and persistence of native species (Carlton, Thompson, and Nichols 1990; Cohen and Carlton 1995; Monterey Bay National Marine Sanctuary 1999; Dukes and Mooney 2001). Losses due to a fouling organism, the shipworm (*Teredo navalis*) caused \$615 million (in 1992 dollars) in structural damage to maritime facilities in three years in the early 20th century (Cohen and Carlton 1995).

The proximity of Elkhorn Slough to the highly invaded and disturbed San Francisco Bay system raises questions as to its susceptibility to invasion (Figure 1). Wasson et al. (2001) identified over 55 invasive invertebrate species in Elkhorn Slough, including almost half of the species that were identified in San Francisco Bay by Cohen and Carlton (1995). These data were preliminary, so it is likely that even more species would have been detected with more time or effort. Wasson et al. (2001) suspect that

most of these species arrived at the Slough through one of two methods: the oyster culturing business that was active in the Slough from the 1900-1970s, or through regional transport from San Francisco Bay on boats or natural currents.

S. quoyanum is an invasive species in northern California that burrows into mud banks and is thought to increase erosion (Cohen and Carlton 1995, Talley et al. 2001). The ecological and economic costs due to this species, and others, that cause erosion have been inadequately studied. To date, only one paper has examined the density and erosional impact of *S. quoyanum* in California wetland habitats similar to Elkhorn Slough. Talley et al. (2001) recorded densities and burrow structure of these isopods in both San Francisco and San Diego Bays. They found large populations and complex burrow structures of *Sphaeroma quoyanum* in areas of high erosion. In addition, their experimental data indicate that the presence of isopod burrows caused increases in erosion at their sites.

Focus

This research focused on the possible relationship between the presence of *Sphaeroma quoyanum* and erosion rates in Elkhorn Slough. Specifically, I tested for relationships between densities of isopod burrows, densities of animals, and physical parameters such as bank height, horizontal bank loss, undercutting, and bank angle.

Using data from the study by Malzone (1999), which quantified tidal scour, study sites were chosen and the horizontal bank loss data provided a baseline from which current data could be compared. In addition, cores and quadrats were taken as a part of this study and the resulting densities of *Sphaeroma quoyanum* populations and burrows

were compared to the results from the study by Talley et al. (2001) for San Francisco and San Diego Bays. Canonical correlation and tests of independence were used to identify possible relationships between these variables.

This study has provided only a “snapshot” of the condition of the Slough banks. A longer study, documenting erosion rates and changes in population size of the isopod over a number of years would provide more accurate data with which to the relationship at Elkhorn Slough between *Sphaeroma* and erosion. However, the preliminary results of this research have answered several questions about the status of the *Sphaeroma* population in the Slough and have provided baseline information that will benefit Slough managers without the efforts and costs associated with a multi-year project.

RELATED RESEARCH

Elkhorn Slough History

Elkhorn Slough is a tidal embayment located midway between the California coastal communities of Santa Cruz and Monterey. It is divided into four regions: Lower Slough, Mid-slough, Upper Slough, and the Elkhorn Slough National Estuarine Research Reserve (Reserve) (Figure 2). The slough is a remnant of an ancient river valley that had been flooded by the sea after the last ice age. When Europeans arrived, freshwater and saltwater marsh habitats were abundant here, and supported a wealth of wildlife such as great blue herons (*Ardea herodias*), grizzly bear (*Ursus arctos*), salt-marsh harvest mouse (*Reithrodontomys raviventris*), and California clapper rail (*Rallus longirostris obsoletus*).

The main channel of the Slough runs seven miles inland from the coast and encompasses over 2,500 acres of marsh and tidal flats (Estuary Net 1998) (Figure 2). Although Elkhorn Slough lacks a permanent river flowing through it today, winter rains create a seasonal estuary. The entire watershed that drains into Elkhorn Slough covers nearly 43,600 acres (Estuary Net 1998). It includes drainage tributaries Carneros and Watsonville Creeks. In addition, the southern fifth of the watershed drains into Moro Cojo Slough, which joins Elkhorn Slough just upstream of the outlet to the ocean.

About 100 years ago the mouths of Elkhorn Slough and the Salinas River were connected and opened to the ocean approximately 1 mile north of the present day harbor

Figure 2. Regions within Elkhorn Slough

(Elkhorn Slough National Estuarine Research Reserve 1997, Malzone 1999, Crampton 1994, Philip Williams and Associates 1992, Oliver et al. 1988). At that time, the Elkhorn Slough system was influenced by depositional processes that brought sediment downstream into the wetlands (Oliver et al. 1988).

Some of the first modern habitat changes included diking off areas of the lower Slough to create salt ponds. Then the Salinas River mouth was opened south of Moss Landing in about 1908 (Elkhorn Slough National Estuarine Research Reserve 1997, Malzone 1999, Crampton 1994, Philip Williams and Associates 1992, Oliver et al. 1988). Later, in the 1920s, farmers began diking and dredging the wetlands for agriculture. This practice continued and increased as agriculture increased in importance in the Watsonville and Salinas Valley areas.

The most drastic and influential change occurred in 1946 when the Army Corps of Engineers created Moss Landing Harbor (Malzone 1999, Crampton 1994, Philip Williams and Associates 1992, Oliver et al. 1988). Original plans called for local cost sharing and the construction of tidegates near the mouth of the Slough to prevent excessive erosion due to the new tidal influx; neither happened. Unchecked tidal scour and erosion began then and continues to change the Slough today.

Oliver et al. conducted the first tidal scour study in 1988. They found that the four tidal creeks flowing into Elkhorn Slough had increased in width by an average of 72% between 1931 and 1980. A more recent study by Malzone (1999) included a quantitative examination of the current and historical rates of erosion in Elkhorn Slough. His results stated that the tidal scour process has yet to reach a steady state; scour rates

are still increasing. He found that over 10 years, from the mid-1980s to mid-1990s, the tidal volume of the Slough increased by 43% and surface area covered with salt water had increased by 48%. Tidal currents were found to be at the highest rates ever at 3 knots, an increase of 50% since the 1970s. Tidal channel widths had increased by as much as 40%. Field measurements in the last year of study showed bank losses of more than one meter per year in some areas.

In general, the opening of the harbor entrance had initiated major changes in Elkhorn Slough. Introduction of a tidal prism and the resulting influx of water began to erode away at the banks, convert freshwater marsh areas to saltwater areas, convert emergent salt marsh into intertidal mud flats, cause saltwater intrusion into nearby fields, and cause dike and levee breaches. The result was conversion of a seasonal estuary supporting expansive salt marsh habitat into a broad coastal lagoon flushed by tidal currents.

To study the magnitude of change in the Slough, Malzone (1999) recorded width and depth increases since 1988 for five regions or areas of Elkhorn Slough: the main channel, the mouth (Lower Slough region), Mid-slough, back slough (east of Kirby Park, also known as Upper Slough region), and the entrance to Parson Slough (Figure 2). Specifically, he found that erosion losses were most dramatic in the vicinity of the Parson Slough mouth and the back region of Elkhorn Slough. Losses of up to 40 meters of pickleweed (*Salicornia virginica*) habitat laterally and one meter vertically were recorded here. Most depth increases occurred in these two areas of the Slough as well.

Malzone (1999) concluded that the back slough and the Parson Slough mouth suffered the highest erosion rates because over 30% of the tidal volume passes through these areas. Increases in the tidal prism and tidal heights indicate that a large percentage of the water in the Slough is stored in its upper regions. This increase in the volume of stored water increased ebb flow velocity, and therefore increased erosion of accumulated sediment bank at the head of the Slough.

Erosion rates remained high or increased from 1980-1992 for the rest of the stations. Lateral expansion ranged from 2-4 meters at the mouth of the Slough, and 10-20 meters at the two Mid-slough stations (Malzone 1999).

In addition to Malzone's study, other studies quantifying erosion rates in Elkhorn Slough have been conducted in the past. In 1988, Oliver et al. documented historical changes to the system, examined tidal creek widths using aerial photography, and attempted to describe the bathymetry of the Slough. Wong (1989) discovered that phase lags of high and low water within the Slough had doubled from 1976 to 1988, and currents had increased by 55% since 1982. Philip Williams and Associates (1992) described the tidal scour problem in detail, and proposed possible remedies, including the construction of a tidal sill near the mouth of the Slough designed to dampen tidal flows.

Crampton (1994) quantified numerous erosion rates, including vertical channel degradation at the Slough mouth of 5.8 meters from 1946-1993, losses of $0.42 \times 10.6 \text{ m}^3$ from the main channel from 1988-1993, and average horizontal losses (retreat) of salt marsh habitat of 18 cm/year since 1946. He estimated average rates (in 1993) of horizontal bank loss to be 39 cm/year, with rates in some areas as high as 188 cm/year.

Crampton also estimated average losses of 41 cm/year for major tributaries to Elkhorn Slough. He measured the average lateral increment of salt marsh bank loss at 50 cm. He hypothesized that the mechanism for bank loss begins with notching of the banks from high-velocity tidal currents, followed by undercutting of the bank, and eventual bank collapse. Crampton (1994) also felt that the vertical bank loss often affected the banks of the Slough incrementally, producing a short-lived but substantial horizontal loss. He specifically mentioned crab burrows as a possible contributor.

Ongoing work relating to tidal scour rates and processes includes a geographic information system-based study of horizontal bank losses that utilizes historic aerial photography and a bathymetry study designed to detect erosion of subtidal regions of the Slough (Wasson pers. comm. 2001). These studies will yield more information that can be used by managers to analyze the erosional processes affecting the Slough and may help identify possible management techniques to counteract them.

Sphaeroma quoyanum

Scientists at Elkhorn Slough feel that the high erosion rates may be the result of more than just increased tidal volume and velocity. The banks of the Slough are riddled with holes from an exotic burrowing isopod, *Sphaeroma quoyanum*. It is possible that the integrity or stability of the banks may be compromised due to water movement in and out of these holes.

Sphaeroma quoyanum is a crustacean, belonging to the order Isopoda, infraorder Flabellifera, family Sphaeromatidae (Schram 1986, Brusca et al. in press). It was originally described by Milne Edwards in 1840 (Bishop Museum 2000). In general,

isopods are dorso-ventrally flattened, with one set of antennae, coxae developed as plates with a tendency to fuse to the body, and legs set distally (Schram 1986, Brusca et al. in press) (Figure 3). Their bodies are segmented, and some abdominal segments contain pleopods, which they use for swimming and for respiration. Isopods form a large and diverse taxonomic group. They are ubiquitous, easily collected, and easy to work with in the field or laboratory. As a whole, isopods are basically omnivores. Sexual dimorphism is subtle.

Although no research has focused on the life cycle of *Sphaeroma quoyanum* in particular, studies of similar species may provide insight into the reproduction, survival, and dispersal of this species. A study of *Sphaeroma serratum* and *S. rugicauda* by Harvey (1969) in Britain sampled the greatest number of juveniles in August, suggesting that breeding and dispersal of young occur from mid- to late- summer. In addition, he found the life span of *S. serratum* and *S. rugicauda* to be 2.5 years and 1.5 years, respectively. Breeding occurred in the 2nd year for *S. serratum* and in the 1st year for *S. rugicauda*. Borowsky (1996) found brood sizes of *S. quadridentatum* in lab conditions ranging from 14-67, with an average brood size of 34 (± 11.3). Survival of juveniles to maturity was 48%.

Sphaeromatid isopods inhabit a wide range of aquatic habitats. Their ability to tolerate changes in salinity and their resistance to desiccation allow them to colonize unstable, physically demanding environments like estuaries. Hass and Knott (1998)

Figure 3. Examples of (A) General Isopod Anatomy, (B) Sphaeromatid Isopod Carapace, and (C) Generalized Pleopods

found *Sphaeroma quoyanum* in Australian estuaries at salinities of 5-40 ppt, with the uppermost specimens subject to desiccation during low tides. Of the species studied, they found that *S. quoyanum* was the most successful species in adapting to the changing distribution and quality of hard substrates. They believe that the range of salinities that *S. quoyanum* tolerates is so wide that it probably can inhabit an entire estuary at any tide or season. In Australia, it is often more prevalent in lower salinities because it can be outcompeted in near-seawater salinities by other species.

Sphaeromatid isopods, and *Sphaeroma quoyanum* in particular, are known for their activities as burrowers and bioeroders (Talley et al. 2001, Carlton 1979a, Carlton 1979b, Rehm and Humm 1973). *S. quoyanum* occurs naturally in estuaries in eastern Australia, New Zealand, and Tasmania (Marsden 1982, Carlton and Iverson 1981, Hass and Knott 1998, Cohen and Carlton 1995). This burrowing, filter-feeding isopod is one of the most widely distributed of the estuarine isopods, and was therefore once thought to be native to this area. Scientists have since realized that *S. quoyanum* is an introduced species. It was first collected in San Francisco Bay in 1893 (Cohen and Carlton 1995). Because of its propensity to burrow into wood, it probably arrived in North America via ship fouling on ships delivering men and goods from Australia during the gold rush (Talley et al. 2001, Carlton 1979a, Carlton 1979b, Cohen and Carlton 1995). By the late 1920s and early 1930s *S. quoyanum* populations had been found north to Humboldt and south to San Diego Bay. In San Francisco Bay it is reported as common to frequently abundant (Miller 1926, Cohen and Carlton 1995, Talley et al. 2001).

Burrowing isopod populations create a network of burrows in the substrate in which they live. *S. quoyanum* burrow into all types of soft substrate: clay, peat, mud, sandstone, soft or decaying wood, and wood that has been bored by shipworms and gribbles. Within the substrate, *Sphaeroma* burrows have been shown to form a network; almost all of the burrows examined by Talley et al. (2001) were connected to at least one other burrow. On average, the burrows they measured were 2.2 cm long, with a maximum depth of 5.6 cm, and had an average width of 0.5-0.7 cm. And although *Sphaeroma* remove sediment from the banks of the marshes and sloughs, researchers feel that they do not eat the sediments into which they burrow, but rather excavate and maintain the burrows and filter feed from within (Rotramel 1975, Talley et al. 2001).

The preferred habitat of *Sphaeroma quoyanum* in California salt marshes is the peat and mud walls of tidal creeks and marsh edges (Talley et al. 2001). Its burrowing behavior creates characteristic “*Sphaeroma* topography” in the mud banks and bay shores, with many linear meters of fringing mud banks riddled with its burrows (Figure 4). It is thought that these holes weaken the banks and facilitate their removal by wave or tidal action (Talley et al. 2001, Carlton 1979, Josselyn 1983). In addition, permanent burrows may alter habitat properties above and below ground, including nutrient and gas exchange, movement of organic matter, and permeability and strength of the substrate (Meadows and Meadows 1991, Ray and Aller 1985).

Carlton (1979a, 1979b) and Josselyn (1983) suggested that *S. quoyanum*'s burrowing could be responsible for substantial erosion of intertidal sediments, which

Figure 4. "*Sphaeroma* Topography". The small holes in this photograph are typical of the burrowing pattern created by *Sphaeroma quoyanum* in marsh banks at Elkhorn Slough.

Carlton estimated as possibly amounting to the loss of tens or hundreds of meters of land along many kilometers of shoreline in San Francisco Bay.

The burrowing behavior of *Sphaeroma* has also caused problems in other parts of the world. In Hawkes Bay, New Zealand, *S. quoyanum* bores into clay stone used in harbor works so extensively that the sea wall in many places virtually disappeared. Blocks of concrete which overlaid the rock sank several feet (Schmitt 1965). In Florida, *S. terebrans* is impacting the red mangrove by burrowing into the prop roots, compromising the support of the trees (Carlton and Ruckelshaus 1997). Similar behavior by *S. terebrans* was reported in the mangrove swamps of Singapore (Lim et al. 2001).

No measurements of *S. quoyanum*'s topographic impact had ever been made and no one had quantified or related the number of *Sphaeroma* burrows to animals until Talley et al. (2001) identified a positive correlation between *S. quoyanum* density and marsh edge erosion for the period between the summer and winter seasons in 1998 for San Diego Bay. The densities of organisms were 2,936/0.25m² in San Francisco Bay and 1,153/0.25m² in San Diego Bay. In addition, Talley et al. (2001) demonstrated the ability of *Sphaeroma quoyanum* to increase erosion rates in a manipulative experiment in San Francisco and San Diego Bays. The use of enclosures resulted in the loss of 2.4 times the wet bank sediments than at control sites.

Although a few *S. quoyanum* burrows have been recorded in dock floats and foam buoys (Wasson pers comm.), most of the burrows created by this species in Elkhorn Slough have been seen in the mud banks. *S. quoyanum* has little or no competition at

Elkhorn Slough because, aside from crabs, *Sphaeroma* is the largest burrowing animal within the system.

Two species of native burrowing crabs, *Hemigrapsus oregonensis* (Dana) and *Pachygrapsus crassipes* Randall co-occur with *S. quoyanum* within the banks of Elkhorn Slough (Sliger 1982). *Hemigrapsus oregonensis* typically burrows in to the lower region of the bank, while *Pachygrapsus crassipes* is found in the upper regions. The average carapace size of these crabs ranges from 7.3 mm for *H. oregonensis* to 13.5 mm for *P. crassipes*, which results in the creation of large, conspicuous burrows within the banks of the Slough (Sliger 1982). These burrows may also exacerbate erosion rates within the Slough, as proposed by Crampton (1994). Because the crabs are native to the area, their interactions within the ecosystem are considered to be within normal limits and they are not considered a problem species.

OBJECTIVES

The objectives of this thesis were to investigate current rates of erosion in Elkhorn Slough, as well as to examine the status and possible relationship of erosion with *Sphaeroma quoyanum* presence and density. To this end, permanent erosion measurement stations were established. Data about *Sphaeroma quoyanum* were collected to document their distribution and abundance in Elkhorn Slough and these data were compared to erosion rates to determine any likely relationships between *S. quoyanum* and erosion. This thesis tested the following null hypotheses concerning rates of erosion and relative density of *Sphaeroma quoyanum* burrows and individuals in Elkhorn Slough:

1. There is no correlation between the density of *Sphaeroma quoyanum* burrows and the density of *Sphaeroma quoyanum* isopods at each site.
2. There is no relationship between the density of *Sphaeroma quoyanum* burrows, density of *Sphaeroma quoyanum* isopods, and erosion rates, including horizontal and vertical bank loss, vegetation loss, changes in bank angle, and bank height.
3. There are no dependencies among *Sphaeroma quoyanum* burrow density, crab burrow density, and erosion variables in Elkhorn Slough.

METHODS

Materials

Equipment and materials used to collect data in the field included: Trimble GeoExplorer GPS unit for recording the locations of the study sites; 25 meter tape for setting the ten meter transects parallel to the axis of the Slough and taking measurements from the transect to the bank edge and edge of the vegetation; two PVC poles (½ inch diameter) for marking each end of the transect; 10-meter piece of rope with meter marks and loops on both ends for stretching between the two poles; chaining pin for holding the end of the tape steady during measurements; quadrat measuring 0.25 meter x 0.25 meter for measuring density of burrows; Canon 35mm camera for recording the number of burrows via photographs; penetrometer for measuring substrate density; inclinometer for measuring bank angle; large corer (4" diameter) for *Sphaeroma* animal density analysis; 2 meter measuring sticks for measuring the bank height and undercut; 1 mm screen for

sifting core material; jars for preserving specimens; and 90% isopropyl alcohol for preserving specimens.

Site Selection

Forty-one sites were chosen for this study using Malzone's research as a guide (Malzone 1999). Malzone had originally chosen 57 sites (Figure 5), however not all of them were included in this study because many were repetitive (paired or triple sites, where a transect was extended from 10 to 20 or 30 meters in length) or difficult to access. Sites for this study were placed at or as close as possible to the location where Malzone had placed his sites. The first attempt to locate Malzone's sites was conducted using a GPS, however only a few of the sites were still intact. I used a map from his thesis to approximate locations of sites that no longer were marked with PVC poles.

Additional sites were added in areas in Elkhorn Slough that were underrepresented in Malzone's study. Site selection was stratified based upon the presence of burrows within the banks. However, the inaccessibility of many areas of the Slough prevented random selection of sites. A total of 41 sites were established throughout Elkhorn Slough, 7 in the Lower Slough, 24 in the Mid-slough, 4 in the Upper Slough, and 6 in the Reserve (Figure 6).

Two PVC poles were used to mark either end of a permanent 10-meter transect by inserting them into the substrate at each site. Transects were set parallel to the axis of the

Figure 5. Approximate Location of Erosion Study Sites from Malzone (1999) – Sites with 2 or 3 numbers are "paired" sites, where the transect was extended from 10 m in length to 20 or 30 m in length

Slough or tidal creek channel, approximately 2 meters from the “edge” (see definition of edge below) of the bank. Poles were marked and given a unique number; Malzone’s numbering system was used where sites approximated his original site locations. New unique site numbers were given to new site locations.

Parameters Measured

Five locations were chosen using a random numbers table along the 10-meter rope stretched between the two PVC markers. At these randomly chosen locations along the transect, six measurements of physical characteristics and two measurements of *S. quoyanum* activity were recorded. All measurements were taken at a right angle from the transect towards the center channel (either the main channel or tidal channel).

Measurements taken included:

Physical Parameters.

1. Distance from the transect to the edge of the bank. The measuring tape was stretched at a right angle from the transect to the slough channel, and the measurement was taken where the edge of the bank was identified. Usually, the “edge” was defined by a sharp change in topography (e.g., a “cliff”, “drop-off”, or steep bank). In areas where the change in topography was not as obvious, the edge was determined to be either (1) the location where the change in the angle of the bank became greater than 15°, or (2) the edge of the vegetation, where the change in angle would not equal 15° within 2 meters of the edge of the vegetation.

2. Distance from the transect to the edge of the vegetation. The edge of the vegetation was measured in a way similar to item 1, except the distance was noted where the last rooted vegetation (dead or alive) was located.
3. Cliff height. If a “drop-off” or “cliff” existed, its height was measured and recorded. The measuring stick was placed at the base of the cliff, and held perpendicular to the ground. A second measuring stick was used to identify the height of the cliff by placing it perpendicular to the vertical stick and along the ground of the higher section where the ground was stable and level (occasionally, the higher sections sloped down towards the cliff edge because of severe undercutting of the bank).
4. Bank undercut. If a cliff had been formed from past erosional processes, the amount of undercutting was recorded. The measuring stick was oriented parallel to the ground and used to find the maximum amount of undercutting at that point. All measurements were read from directly above the cliff edge.
5. Bank angle. An inclinometer was used to measure the angle of the bank. The middle of the bottom edge of the inclinometer was placed at the “edge” of the bank, and a measurement was recorded.
6. Substrate density. A penetrometer was used to measure the density of the substrate. At sites where substrate stability varied, five measurements were taken and an average was recorded.

Biological Parameters.

1. **Burrow density.** The 0.25 meter x 0.25 meter quadrat was used to record burrow density. The measurement was taken where the highest density of burrows was represented at the randomly chosen transect point. Because of the difficulty of counting the burrows in the field, a camera with a macro lens was used to take a photograph of the quadrat to aid in counting burrows later.

To record the number of burrows within each quadrat, a clear plastic sheet was placed over the photograph, and all of the burrows were marked with a pen. The number of *Sphaeroma* and crab burrows was determined and recorded. A scale was prepared on the edge of the quadrat to help measure the size of burrows after the photographs were developed. Burrows within the size range of *Sphaeroma quoyanum* (1 cm or less) (Talley et al. 2001) were counted as “*Sphaeroma* burrows”, while any holes larger than 1 cm were labeled as “crab burrows”. Crabs and *Sphaeroma* are typically the only animals in the Slough that leave substantial burrows in the mud banks.

2. ***Sphaeroma* density.** Cores were taken at sites that contained *Sphaeroma*-sized burrows. A large (4” diameter) corer was used to take a sample core of the bank just up or downstream of the transect. Cores were not taken within the banks directly in front of the transect because the large size of the core could inadvertently cause error by contributing to higher levels of erosion in those areas.

Twenty-three cores were taken throughout Elkhorn Slough. Each core was taken at a point in the bank that was similar in structure and number of burrows to where the quadrats for that site had been placed. The banks are almost always homogeneous within a few meters of the transects, so finding similar habitat did not present a problem. The contents of the core were placed into a plastic bag and preserved with 90% isopropyl alcohol. Later, the contents of the core were sifted over the 1 mm screen, and the plant and animal material separated and preserved. The specimens were preserved in isopropyl alcohol (90%). Density of isopods within the banks was determined based upon the surface area of the corer, extrapolated to square meters.

All measurements except burrow density and *Sphaeroma quoyanum* isopod density were taken twice; once at time zero and again after approximately 3 months. Field visits include the following dates in 2001: June 16, 17, 24; July 2, 4, 21, 30; September 16, 17; and October 1, 15.

Data Preparation

The values of the physical measurements taken at each of the stations were entered into a spreadsheet. The five sets of measurements for each site were averaged into one number per variable, per field visit. Next, the averaged data from the first set of measurements (time zero) were compared with data from the second set of measurements (three months later) to estimate erosion rates. This difference is the erosion measurement, which represents the amount of change detected in the physical characteristics of the site. Physical measurements were imported into SPSS version 10 or

Systat version 10 as the independent variables measured at the site, while *Sphaeroma* organism and burrow density as well as and crab-related data functioned as the dependent variables.

The data were analyzed and classified into 2 classes, “high” or “low” for the following variables: erosion rate, crab burrow density, and *Sphaeroma* burrow density. Class separation was performed to create a discrete data set in the event that continuous data did not readily show a conclusive relationship. Often, statistics involving discrete data sets can identify a weaker relationship in the data.

“High” and “low” values were determined by taking the total range of values for those variables, and dividing them in half. Sites with values falling in the upper half of the range were labeled as “high”, and sites with values falling in the lower half of the range were labeled as “low”. These classes were analyzed using SPSS version 10 or Systat version 10.

Canonical Correlation

An SPSS version 10 or Systat version 10 canonical correlation analysis was used to test for relationships between continuous variables (Tabachnick and Fidell 1996). The following steps were taken to run this analysis.

1. Highly correlated variables were eliminated. Highly correlated variables must be eliminated to avoid redundancy in the analysis. A simple correlation is run between all variables. A correlation of $p=0.6$ or higher is considered highly correlated. One of the two variables must be eliminated; the other is retained for further analysis. Retention is based upon biological importance or

relevance to the study, or the value of the coefficient of dispersion (cd). If the cd comparison is used, the variable with the higher value is retained.

2. Data that were not normally distributed were transformed. After conducting a skewness evaluation of each variable, variables with an absolute value greater than 2 were transformed into a normal distribution before including them in the canonical correlation. Positive skewness values were transformed using the natural log (ln). Negative skewness values were transformed using the reciprocal of the skewness value (Tabachnick and Fidell 1996).

One problem encountered in this analysis was the presence of negative values within the data sets. The values used in this analysis are based upon the difference between two measurements, at time zero and after 3 months. Some of the differences indicated erosional trends (positive numbers indicate bank loss) and depositional trends (negative numbers indicate gains in bank material). In this case, a typical formula for normalizing the distribution would not have been successful, because all the numbers must be positive in order to change them using the natural log. So, the minimum value was shifted by the minimum negative number in the range plus 1 so that all of the data were greater than zero.

Any data sets that were transformed were used in place of the original variable data sets in the canonical correlation analysis. Otherwise, all normally distributed data sets were retained.

Specific applications of this methodology were used to look at the relationships between variables of four sets of data: all regions of Elkhorn Slough, main channel sites, tidal creek sites, and “high” erosion sites. The methodology for each is discussed below.

All regions of Elkhorn Slough combined. The first canonical correlation compared data collected along the entire slough (all regions combined). The initial simple correlations, detected two pairs of highly correlated variables:

1. Distance from transect to bank edge and distance from transect to vegetation edge (0.692), and
2. Inclinator and cliff height (0.653).

Of the 2 variables in the first pair, the distance from transect to bank edge was retained because this measurement seemed more relevant to the analysis of the data. It is more easily measured in the field, creating less error in measurements, and is more relevant when discussing erosion rates than transect to vegetation edge measurements.

For the second pair of variables, inclinometer and cliff height, an analysis of the coefficient of dispersion (cd) was conducted, because increased relevance to the data of one variable over another was not readily apparent. The cd for the inclinometer variable (143.3) was much greater than the cd for cliff height (15.1), so the inclinometer variable was retained.

Correlation analyses between the two dependent variables, crab burrow density and *Sphaeroma* burrow density, revealed that these two variables were not correlated (0.487), so both variables were retained for the analysis.

Upon examination of the skewness of the variables that were to be included in the canonical correlation test, two variables needed to be transformed: inclinometer (2.745) and distance from the transect to the bank edge (-2.862). Positive values (inclinometer) were transformed using the natural log (ln), and negative values were transformed using the reciprocal (distance from transect to bank edge) before running the canonical correlation. However, the natural log cannot be applied to negative numbers, so in order to transform the inclinometer variable values, the range minimum plus one was added to the values so that they all became greater than zero. For example, the minimum value of the inclinometer variable was -25, so 26 was added to all of the numbers before taking the natural log.

Main channel sites. The second canonical correlation included only sites that were sampled along the main channel of Elkhorn Slough. When the initial simple correlations were run, three sets of highly correlated variables were detected:

1. Cliff height and inclinometer variables (0.676),
2. Density of *Sphaeroma quoyanum* burrows and density of crab burrows (0.631), and
3. Density of *Sphaeroma quoyanum* burrows and density of *Sphaeroma quoyanum* in cores (0.673).

For the first pair of variables, the cliff height variable was retained because it had a greater coefficient of dispersion than the inclinometer variable. For the second and third pair of variables, the density of *Sphaeroma quoyanum* burrows was retained

because it has more biological significance to this study than the density of crab burrows, and because core samples were not taken at every site.

When examining the skewness of the variables to be included in the analysis, one variable needed to be transformed: distance from transect to bank edge (-2.773). This negative skewness value was transformed using its reciprocal. The newly transformed values were then included in the canonical correlation.

Tidal creek sites. The third canonical correlation included only sites that were sampled along tidal creeks in Elkhorn Slough. When the initial simple correlations were run, two sets of highly correlated variables were detected:

1. Distance from transect to bank edge and distance from transect to vegetation edge (0.782), and
2. Penetrometer and inclinometer variables (0.679).

As with previous canonical correlation tests, the distance from the transect to the bank edge variable was retained based upon its biological significance to the study relative to the distance from the transect to vegetation edge variable. For the second set of variables, the inclinometer variable was retained instead of the penetrometer variable based upon the fact that the equipment allowed a more reliable inclinometer measurement in the field. I expected that these data would yield a more reliable result when included in this analysis.

When examining the skewness of the variables to be included in the analysis, only one, the density of *Sphaeroma* burrows, needed to be transformed (2.502). Values were transformed using natural log, and then included in the canonical correlation.

Sites classified as having “high” erosion. The last canonical correlation included sites that were classified as having “high” erosion rates in Elkhorn Slough. When the initial simple correlations were run, eight sets of highly correlated variables were detected:

1. Distance from transect to bank edge and amount of undercut (0.663),
2. Distance from transect to bank edge and inclinometer variable (0.726),
3. Distance from transect to bank edge and penetrometer variable (0.636),
4. Cliff height and inclinometer variable (0.842),
5. Cliff height and penetrometer variable (0.714),
6. Undercut and inclinometer values (0.679),
7. Inclinometer and penetrometer variables (0.833), and
8. Density of *Sphaeroma quoyanum* burrows and density of *Sphaeroma quoyanum* isopods (0.706).

Based on biological significance, the distance from transect to bank edge was retained in lieu of undercut, inclinometer, and penetrometer variables. Because of this decision, the cliff height variable was also retained because of the previous elimination of inclinometer and penetrometer. The distance from transect to vegetation edge variable was included in the canonical correlation because it had no significant simple correlations with any other variables. The density of *Sphaeroma quoyanum* burrows variable was retained rather than density of *Sphaeroma quoyanum* isopods because cores (which detected the presence of isopods) were not taken at every site, so the reliability of the burrow data was much higher.

Based upon examination of the skewness of the variables to be included in the analysis, no transformations were required. All values were included in the canonical correlation “as is.”

Tests of Independence

The tests of independence examined the relationship between “high” and “low” classifications of *Sphaeroma quoyanum* burrows, crab burrows, and erosion rates to test for variable dependencies. Discrete variables (erosion rate, crab burrow density, and *Sphaeroma* burrow density) were analyzed for independence using two different tests. One test examined the dependencies for all three discrete variables, and the second analyzed dependencies of variables among only the “high” erosion sites within Elkhorn Slough (Tabachnick and Fidell 1996).

“High” and “low” classifications were chosen for the discrete variable statistical testing (log linear), unlike the “high”, “medium”, “low” classification that was used for comparison purposes only. A “medium” category was not feasible for the tests of independence used in this study based upon the statistical “rule of 5”, in which each level or combination must have at least 5 observations. When split into “high” and “low” categories for three variables, the log linear required three 2x2 comparisons, which, in turn, required a minimum of 5 observations each for a total of 40 sites. With 41 data points, this study barely qualified. Adding a “medium” category would require more observations than were available to have sufficient statistical power. All discrete variable data were imported and analyzed using Systat version 10.

LIMITATIONS

Corers are common tools used to provide good data per sampling effort (Hass and Knott 1998, Cummins 1962, Longhurst 1959). Past research has found that a large number of samples are needed to get accurate numbers for total population size and distribution when using a corer (Cummins 1962, Needham and Usinger 1956, Lackey 1961). This is because most corers can collect only a small sample of the substrate at one time. The sampling strategy of this research did not include enough randomly chosen sites with which to make a truly accurate population estimation for Elkhorn Slough. The data were used to compare relative population densities at a limited number of sites for comparison and to test for relationships between burrows, population density, and erosion rates, rather than inventory the entire system.

This study is limited both spatially and temporally. The analysis of the data applies to Elkhorn Slough and its unique habitats, and should be used cautiously to make recommendations or assumptions about other systems. In addition, extrapolation of erosion rates taken over a series of months to represent yearly rates may misrepresent the true physical processes the Slough. However, studies of Elkhorn Slough and San Francisco and San Diego Bays collected data similarly and therefore could provide adequate comparisons to this data.

The topography, ownership, and accessibility of the Slough did not allow equal representation of different regions of the Slough in the analysis. However, the data serve their purpose in collecting information from all of the areas of the Slough, and function adequately for a preliminary-type study like this. For future efforts, a study that could

analyze the erosion and population changes using comprehensive, random sampling techniques within the Slough over a series of years would be ideal.

RESULTS

Physical Parameters

The average erosion rates over the 3-month study period for Elkhorn Slough were 9.7 cm horizontal bank loss, 5.1 cm vertical loss, 0.2 cm increase in undercutting, and 3.4° bank angle increase (Table 1). These results reflect the differences between the two sets of measurements taken at each site, and time zero and after 3 months. The large standard deviation values demonstrate the heterogeneity in erosion rates among sites along the length of the Slough.

Table 1.— Average Rates of Erosion for Elkhorn Slough Over the 3-Month Study Period

Variable	Average Change	Standard Deviation	Range
Horizontal Loss	9.7 cm	61	-296-76
Vertical Loss	5.1 cm	9	-10-35
Undercut	0.2 cm	4	-11-9
Bank Angle	3.4°	22	-25-102

Table 2 compares average erosion rates for two types of channels found within the Slough, the main channel and tidal creeks, and for a subset of “high” erosion sites. Erosion rates of main channel sites were much higher than those of tidal creek sites. Average horizontal and vertical bank losses for main channel sites were 12.5 cm and 6.2 cm respectively (n=31), compared with 1.14 cm and 1.9 cm for tidal creeks (n=10).

Average losses from undercutting were also larger among main channel sites (0.65 cm) than tidal creek sites (0.2 cm), resulting in larger changes to the bank angle (5.4° versus 3.4°). In comparison, “high” erosion sites (n=15) show much larger horizontal and vertical losses than all other data sets. Average losses of 11.6 cm of vertical loss and 52.9 cm of horizontal losses are between 2 and 4 times larger than other values in the table.

Table 2.— Average Erosional Changes in Salt Marsh Banks During the 3-Month Study Period for Elkhorn Slough and Selected Subsets of Data

Variable	Elkhorn Slough	Tidal Creeks	Main Channel	High Erosion Sites
Horizontal Bank Loss (cm)	9.7	1.1	12.5	52.9
Vertical Bank Loss (cm)	5.1	1.9	6.2	11.6
Undercut (cm)	0.2	-1.1	0.7	-1.6
Bank Angle (°)	3.4	-2.6	5.4	0.1

Over the entire Slough, 68% of the sites exhibited horizontal bank losses and 32% of the sites had depositional processes occurring (Table 3). When separated into discrete classes as described in the methods section, 15 of the 41 sites were classified as having “high” levels of erosion, while 26 of the sites were classified as “low” erosion sites.

Table 4 shows the rankings for the different regions within the Slough. The Upper Slough had the highest relative percentage of “high” erosion sites (50%), followed by the Mid-slough (38%), Reserve (33%), and Lower Slough (29%) regions.

Table 3.— Frequency of Erosion Processes Occurring within Elkhorn Slough

Erosion Process	Number of Sites	Percent of Sites
Bank Loss	28	68
Deposition (Bank Gain)	13	32

Table 4.— Frequency of “High” Erosion Classes for Different Regions of the Slough

Region	Number of Sites Ranked “High”	Total Number of Sites Sampled	Percent Sites “High” per Region
Lower Slough	2	7	29
Mid-Slough	9	24	38
Upper Slough	2	4	50
Reserve	2	6	33
Total	15	41	n/a

Substrate density measurements supported these findings with the softest substrates reflected in the regions of the Slough with the greatest percentage of “high” erosion sites. The sediment in the Upper Slough sites had an average penetrometer reading of $1.7 \text{ lb/in}^2 \pm 0.4$, followed by Mid-slough sites ($2.0 \text{ lb/in}^2 \pm 0.8$), Reserve sites ($2.9 \text{ lb/in}^2 \pm 0.9$), with the densest substrate occurring in the Lower Slough ($3.2 \text{ lb/in}^2 \pm 1.1$). Although these trends are interesting to note, they are not significantly correlated (see results of the canonical correlation tests below).

Biological Parameters

For the entire Slough, the average number of *Sphaeroma* holes per site was $121/\text{m}^2 \pm 159$ (range 0-624/ m^2), and the average number of crab holes was $111/\text{m}^2 \pm 264$ (range 0-264) (Table 5). The large standard deviation results reflect sizable differences in the distribution of isopod densities within Elkhorn Slough. It appears that *Sphaeroma* are fairly abundant where they occur, but are not distributed equally.

Table 5.— Average Densities of *Sphaeroma quoyanum* and crab burrows in Elkhorn Slough

Burrow Type	#/ m^2	Standard Deviation	Range
<i>Sphaeroma quoyanum</i>	121	159	0-156
Crab spp.	111	78	0-66

Only 13 of the 23 core samples taken in Elkhorn Slough contained *Sphaeroma quoyanum*. Table 6 shows the resulting densities of the cores. When comparing only the 13 cores that contained *Sphaeroma*, the average density was 882/ m^2 isopods. For all of the sites at which cores were taken (23 sites), including those at which no *Sphaeroma* were found, the average density of *Sphaeroma* was 498/ m^2 . When all of the sites of the Slough were averaged (all 41 sites), the average number of *Sphaeroma* per square meter dropped to 279. The highest number of *Sphaeroma* found within any one core was 18 (per 4 inch diameter core) at site 68, which was located on the Elkhorn Slough National Estuarine Research Reserve Property.

Table 6.— Average Density of *Sphaeroma quoyanum* Isopods Found within Core Samples

Sample Type	#/m²	Standard Dev.	Range
Sites with cores containing <i>Sphaeroma quoyanum</i> (13 sites)	882	713	123–2,344
Sites at which cores were taken (with or without <i>Sphaeroma</i>) (23 sites)	498	676	0–2,344
All Elkhorn Slough Study Sites	279	571	0–2,344

Table 7 shows the average densities of both *Sphaeroma quoyanum* animals and burrows by region. Animal and burrow densities were highest in the Reserve sites, with values of 264/m²±143 and 1,295/m²±686, respectively, followed by Lower Slough sites (215/m²±234 and 288/m²±409), Mid-slough sites (78/m²±108 and 145/m²±503), and Upper Slough sites (41.3/m²±77 and 82/m²±201). Large standard deviation values were caused by very large variation in the number of organisms and burrows found per sample.

Table 7.--Average Densities of *Sphaeroma quoyanum* Isopods and Burrows by Region

Region	Isopods			Burrows		
	Density (per sq m)	Std. Dev	Range	Density (per sq m)	Std. Dev	Range
Lower Slough	215	234	0-624	288	409	0-986
Middle Slough	78	108	0-388	145	503	0-2,343
Upper Slough	41	77	0-192	82	201	0-493
Reserve	264	143	136-404	1,295	686	616-2,220

Canonical Correlation

Canonical correlation analysis was used to examine possible relationships between biotic data (e.g., population density of *Sphaeroma*, the density of *Sphaeroma* burrows, and the density of crab burrows), which were the dependent variables, and erosion rates (e.g., distance from transect to bank edge, inclinometer, cliff height, etc.), which were the independent variables. The analysis generates roots that show characteristics of the sites using relationships between dependent and independent variables. When analyzing the results of a canonical correlation, the strongest relationships are identified in Root 1. A relationship, if found in the second root, would have less power than the first root, and so on.

The canonical correlation analysis indicated that, for all of the study sites along Elkhorn Slough, there is no relationship between *Sphaeroma* burrow density and physical variables that were measured. For the first canonical correlation, Root 1 had a p-value of 0.782, which is greater than the alpha level used here, which was 0.025. This lower alpha level was chosen (rather than 0.05) to increase the power of the result of this test, ensuring that only a significant result could reject the null hypotheses chosen. The null hypothesis was accepted, meaning that the data show no relationship between the biotic variables (density of *Sphaeroma* burrows) and the physical/erosion variables that were measured. For Root 2, the p-value was 0.814, which is also greater than alpha (0.025). The null hypothesis was accepted again. There is no relationship between the burrow density and the other variables that were measured.

The second canonical correlation analysis included only sites that were sampled along the main channel of Elkhorn Slough. The canonical correlation produced roots that were greater than alpha (0.025). Root 1 generated a score of 0.045, and root 2 generated a score of 0.875. The root 1 value for this particular test was the closest to a significant value than in any other of the canonical correlation tests of this study. However, in both cases the null hypothesis was accepted, finding no relationship between physical characteristics or erosion rates and the number of crab or isopod burrows at sites located in the main channel of Elkhorn Slough.

The third canonical correlation included only sites that were sampled along tidal creeks in Elkhorn Slough. The canonical correlation produced roots that were greater than alpha (0.025). Root 1 generated a score of 0.105, and root 2 generated a score of 0.249. In both cases the null hypothesis was accepted, finding no relationship between physical characteristics or erosion rates and the number of crab or isopod burrows at sites located in tidal creeks throughout the Slough.

The last canonical correlation included sites that were classified as having “high” erosion rates in Elkhorn Slough. The canonical correlation produced roots that were greater than alpha (0.025). Root 1 generated a score of 0.376, and root 2 generated a score of 0.493. In both cases the null hypothesis was accepted, confirming no relationship between physical characteristics or erosion rates and the number of crab or isopod burrows at sites located in “high” erosion sites throughout the Slough.

Basic statistical tests performed for the early stages of the canonical correlation (see “Highly correlated variables were eliminated” in the statistical analysis description in the

methods section) revealed a correlation (0.646) between the density of *Sphaeroma quoyanum* burrows and the distance from transect to bank edge (horizontal bank loss) within the “high” erosion sites of Elkhorn Slough (Figure 7). Thus, among sites within the upper range of erosion rates, the density of *S. quoyanum* burrows correlates with horizontal bank erosion rates. No other statistical tests detected relationships between these two variables.

Figure 7. Correlation Between Sphaeroma Burrow Density and Horizontal Bank Loss within "High" Erosion Sites ($r=0.646$)

Tests of Independence

The log linear analysis indicated that *Sphaeroma* burrows, crab burrows, and erosion rates were independent. A fully-saturated model for all of the sites sampled in Elkhorn Slough was examined for relationships between *Sphaeroma quoyanum* burrows, crab burrows, and erosion rates. Terms were eliminated and the probability of the resulting model was compared to alpha (0.025). The most complex term was eliminated from the model ($p=0.240$), then the three 2 x 2 terms were eliminated from the model ($p=0.488$, 0.156, and 0.515), then the single terms were eliminated from the model ($p=0.084$, 0.035, and 0.030) (Table 8). No significant results were found.

Table 8.—P-values for Terms Used in the 3-term Log Linear Analysis (alpha=0.025)

Term ^a	P-value
SQ*CRAB*EROS	0.240
SQ*CRAB	0.156
SQ*EROS	0.488
CRAB*EROS	0.515
SQ	0.035
CRAB	0.084
EROS	0.030

^aSQ represents the density of *Sphaeroma* burrows variable, CRAB the density of crab burrows variable, and EROS the erosion rate variable.

The second log linear analysis indicated that *Sphaeroma* burrows and crab burrows are independent in “high” erosion sites. The probability generated by this test was 0.033, which is greater than alpha (0.025). The null hypothesis was accepted, finding no dependencies among variables. However, these values are within 0.008 of

each other, which could indicate that with a larger sample size, the relationship between these two variables might be significant.

DISCUSSION

Erosion Rates

Results of the erosion measurements suggest that the erosion rates are continuing to increase throughout the Slough, as predicted by Malzone (1999). The average bank losses throughout the Slough were very high, 148 cm/yr. However, it is important to realize that the test sites were chosen to examine high erosion rates. Preliminary data collected by Elkhorn Slough managers to compare slough widths using historical aerial photographs also indicate similar findings (Wasson pers. comm. 2001).

The overall rate of erosion at the Slough showed a loss of 48 cm/yr. These results are nearly double Malzone's erosion rate of 27 cm/yr for Elkhorn Slough six years ago. Although the higher number in this study may truly reflect a large increase in the erosion rates, care should be taken in interpreting these results. The additional sites that were chosen in this study were picked based upon the presence of burrows, which often were associated with the presence of a cliff, and possibly higher levels of erosion. Thus, overall rates of erosion in the Slough as measured in this study may be inflated when compared to Malzone's rates.

In addition, the large differences between these results and Malzone's may reflect seasonal differences in erosion rates. Malzone's first measurements were taken in April (spring), while the first measurements for this study were taken in June (summer). The

second sets of measurements for both studies were taken around October. Although the actual differences in erosion rates between spring and summer months at Elkhorn Slough have not been determined, it is possible that they may vary enough to influence the erosion rates that were calculated.

The erosion rates measured in this study are also much higher than the results reported by Talley et al. (2001) for San Francisco Bay (27 cm/yr) and San Diego Bay (15 cm/yr) using similar data collection techniques (Table 9). However, these results are still much lower than Josselyn's findings of losses of 95 cm/yr in San Francisco Bay (Josselyn 1983). However, differences in rates measured in this study may vary from Josselyn's study based upon variations in erosion sampling techniques and seasonal sampling periods.

Table 9.— Comparisons of Horizontal Bank Loss by Location and Author

Location	Author (Year)	Horizontal Bank Loss (cm/yr)
Elkhorn Slough	Bane (2002) (This Study)	48
Elkhorn Slough	Malzone (1999)	27
San Francisco Bay	Talley et al. (2001)	27
San Diego Bay	Talley et al. (2001)	15

Sphaeroma quoyanum Density

The data show that at Elkhorn Slough, there is no relationship between the density of *Sphaeroma* burrows and the population density of *Sphaeroma quoyanum*. Talley et al. (2001) found that their data indicated the presence of a relationship between burrow class and isopod density; the relationship was strongest in the summer, when *Sphaeroma*

densities are highest. They also found that at many sites, isopod densities at “high” and “medium” burrow density classes were not always significantly different from one another, but were distinguishable from low burrow density areas. These data indicate that there may be a correlation between burrows and *Sphaeroma quoyanum* densities in San Francisco or San Diego Bays. However, their findings were based upon visual, qualitative estimation rather than quantitative counts of burrows. It is possible that their qualitative findings might not be supported by quantitative analyses.

A fairly strong correlation between *Sphaeroma quoyanum* burrows and *Sphaeroma quoyanum* in the cores along the main channel of Elkhorn Slough may give insight into methodology for estimation of *Sphaeroma* populations within that system (0.673). Talley et al. (2001) found that generally, the size of the *Sphaeroma* populations at their sites was related to the visual density class of the burrows. However, the relationship between the presence of the burrows versus the presence of *Sphaeroma quoyanum* in the cores and erosion rates is not clear. In addition, the utility of determining the relationship between animals and burrows may not be high unless a definitive relationship between the density of isopods and erosion rates can be established. In addition, because the burrows are more persistent than the isopods themselves, burrows may be a good indication of permanent effects to the Slough caused by *Sphaeroma*'s structural engineering of marsh banks.

Talley et al. (2001) collected data over two seasons, summer and winter. Numbers of organisms may fluctuate by season. Therefore, the data in this study, which were collected during summer months (July-early September), were only compared to the

data collected by Talley et al. in summer. Talley et al. (2001) found much higher densities of *Sphaeroma* isopods than this thesis research. The results of each study are compared in Table 10. Where *Sphaeroma quoyanum* were present, Talley et al. found average densities of 2,936 *Sphaeroma* per 0.25m² in San Francisco Bay, and 1,153 *Sphaeroma* per 0.25m² in San Diego Bay. In Elkhorn Slough, where *Sphaeroma quoyanum* were present, the density of *Sphaeroma*/0.25m² was 221, much lower than either San Francisco or San Diego Bays.

Table 10.— Comparisons of Densities of *Sphaeroma quoyanum* Isopods and Burrows by Location and Author

Location (Author)	Isopods/0.25m ²	% “High” and “Med” Burrow Densities
Elkhorn Slough (Bane)	221	29
San Francisco Bay (Talley et al.)	2,936	71
San Diego Bay (Talley et al.)	1,153	58

Rather than counting burrows, Talley et al. (2001) classified burrow density data into ranks of “high”, “medium”, and “low” based on visual observation. They found that 71% of the sites in San Francisco Bay and 58% of the sites in San Diego Bay were classified as having visual burrow densities of “high” or “medium” (Table 10). When the data from this study are classified similarly, only 29% of the sites are “high” or “medium” density, much lower than in San Francisco or San Diego Bays.

These data indicate that Elkhorn Slough’s population of *Sphaeroma quoyanum* is smaller than either San Francisco or San Diego Bay’s. This population difference is probably due to the fact that *Sphaeroma* was introduced much earlier into those systems

by boats (fouling). Talley et al. (2001) and Cohen and Carlton (1995) estimate the arrival of *S. quoyanum* in San Francisco Bay between 1850 and 1870, reaching San Diego Bay in about 1920. Elkhorn Slough was not directly open to the Pacific Ocean until the dunes were breached in 1947 to create Moss Landing Harbor. Therefore, the *Sphaeroma* population in Elkhorn Slough could only have become established much more recently. In addition, at Elkhorn Slough, the physical characteristics of the smaller slough system, a more highly eroding tidal regime and/or a higher percentage of native biota at Elkhorn Slough as compared with the other bays may be holding *Sphaeroma quoyanum* populations at levels that do not contribute to erosion.

Other circumstances within Elkhorn Slough may also be contributing to the relatively low densities of *Sphaeroma*. For instance, high rates of erosion may remove the bank substrate before *Sphaeroma* has an opportunity to burrow into the banks. Erosion rates due to tidal scour may be so high that the contribution from *Sphaeroma* burrows is negligible. Biological factors may provide resistance to invasion by *Sphaeroma*, including high levels of predation or competition for substrate from burrowing crabs.

Comparing Erosion Parameters and Biological Parameters

Results using both canonical correlation (continuous data) and log linear and 2x2 tests (discrete data) showed no relationship between the density of burrows and multiple measurements of erosion rates in Elkhorn Slough.

The canonical correlation tests yield the statistically strongest results because these tests are conducted using continuous data rather than discrete data as in the log

linear tests. The fact that no relationship was detected for the entire Slough or regions of the Slough means that the data shows, fairly strongly, that there is no relationship between the *Sphaeroma* burrows or populations and erosion rates at Elkhorn Slough.

Despite the fact that the canonical correlations and independence tests showed no relationships between variables, one of the simple correlations that was run in the preliminary process (to facilitate elimination of highly correlated variables) of a canonical correlation showed an important relationship. A simple correlation between *Sphaeroma quoyanum* burrows and horizontal bank loss at sites labeled as having “high” erosion was significant ($p=0.046$ where any correlation over 0.6 is significant). So, for “high” erosion sites, the presence of burrows is correlated with high bank losses. This relationship is only significant for this one variable. The correlation does not provide any information that may point to a causal relationship between the two.

Although the final canonical correlation result did not reveal a significant relationship between any variables, this preliminary correlation may provide some information as to the relationship of high erosion rates and *Sphaeroma quoyanum* burrow density. For example, it could indicate that there is a critical density of *Sphaeroma* that, when reached, could result in a significant contribution to erosion. This may be the case, as Talley et al. (2001) found correlations between *S. quoyanum* animals and erosion at their sites, where density of *Sphaeroma* was much higher than in Elkhorn Slough. The results of this study of Elkhorn Slough only detected a correlation between the two factors in areas of “high” erosion. Alternately, *Sphaeroma* may prefer burrowing into banks that are already weakened and/or experiencing high erosion rates.

Crabs

Crabs were found throughout the Slough. Their burrows were present in all but four of the quadrats measured in this study. Burrow shape and size were extremely varied, but were always larger than *Sphaeroma* burrows. This study was not designed to provide complete quantitative information describing crab populations within the Slough. However, inclusion of crab data in the canonical correlation and log linear analyses showed that, for this study, the density of crab burrows is not related to erosion rates within Elkhorn Slough.

Comparing Regions of the Slough

Comparisons of regions of Elkhorn Slough are limited by the differences in the number of sites sampled within each of the regions, and by the non-random selection of sites for this study. However, the results of the comparisons are included here to provide some guidance for future studies or monitoring programs.

Several factors may explain the distribution of “high” erosion sites in the Upper Slough region in combination with low *Sphaeroma* burrow densities. The density of substrate in this area is low, possibly making the bank more susceptible to erosion processes, but less susceptible to *Sphaeroma* invasion. The soft substrate in the banks probably would not support extensive burrowing of *S. quoyanum* in this region. In addition, Malzone (1999) identified the Upper Slough region as supporting the majority of the tidal prism of the Slough. With a large volume of water moving in and out of that region, the speed and force of the tidal flow are probably responsible for the high erosion rates.

The Lower Slough region is exposed to more boat traffic and wave action than other regions of the Slough, which may contribute to erosion rates in that area. Water traveling through this narrow area must flow at higher velocities than the Upper Slough region. However, to protect against bank loss, many parts of the Lower Slough have been strengthened with fill in the past, which may have reduced the losses due to erosion in this area. *Sphaeroma* is much less abundant in these areas. It is likely that animals cannot burrow into the compacted, rocky fill. Where the banks are more mud than fill, and the substrate becomes softer, *Sphaeroma* are more abundant. This patchy distribution of erosion and *Sphaeroma* may explain why erosion rates are high, but not as high as in the Upper Slough regions.

The Mid-slough region had a large number of sampling sites (24), at least 3 times more than any region. This is the largest region of the Slough. Much of the bank on the Santa Cruz (north or west) side of the Slough is on the inside of a large curve, and has sloping banks that do not have high erosion rates (some sites are undergoing depositional processes). The Monterey (south or east) side is on the outer part of the sweeping curve and tends to have higher and steeper “cliffs” for banks. The main channel of the Slough is wide here and it seems that the combination of deposition and erosion sites may mute the effects of erosion and *Sphaeroma* burrow densities in this region.

The Reserve sites are protected from wave action, swift tidal flows, and boat traffic that affect the main channel of the Slough. This may be why it exhibits fewer “high” erosion sites than the Upper and Mid-slough regions. This area has the highest relative numbers of *Sphaeroma quoyanum* animals and burrows in the Slough. It also

seems to contain large numbers of other introduced species, such as the Japanese horn snail (*Battelaria attramentaria*). Perhaps the lower rates of tidal flow and erosion in this region, in combination with relatively stable substrate, allow the banks to be retained long enough for these species to become established there. Also, with such few sampling sites in some of the regions of the Slough, the data may not be representative of the general conditions of those areas.

General Observations During Research

In addition to the quantitative data measurements that were taken over the course of 2001, general observations of the condition of Elkhorn Slough were recorded during field visits. General trends and observations, as well as sudden changes were noted informally, providing anecdotal information regarding erosion processes in the Slough.

Seals. Harbor seals are common residents of Elkhorn Slough. During initial establishment of the study sites throughout the Slough, they were most often seen at the downstream end of Seal Bend, on the north bank (the side closest to Santa Cruz). These sites have traditionally shown signs of heavy use, but have been reinforced with rock and other added substrate. Toward the end of the field season, when the second set of physical measurements was being collected, the seals began to congregate frequently at the mouth of Parson's Slough, from the main channel to the railroad trestle. With the increased use of this area by seals, signs of rapid erosion became evident, even over just a few weeks (Figure 8).

During the initial measurements for these sites, signs of erosion included a high cliff with a fairly vegetated, even edge and some undercutting. But when the seals began

using the site, vegetation on and near the cliff edges became trampled and removed.

Heavy use of the site indicated areas of high bank loss where seals would slide back into the water during low tides. These areas, used as seal slides, deteriorated and caused a convoluted bank edge that appeared to be more susceptible to erosion. Areas that became separated from the original bank edge were surrounded by water at high tide, and crumbled or were worn down from use.

Cliff failure. Erosion tends to be constant along the vertical face of the bank until it causes severe undercutting that can no longer support the weight of the vegetation and soil above. Then, the entire bank fails at one time, dropping the top of the bank into the main channel or tidal creek flows, as suggested by Crampton (1994) (Figure 9). It appears that much of the horizontal bank losses occur this way. During the field season in which these data were collected, it appeared that a large amount of cliff failure occurred during the latter period of data collection (late August through October). Long stretches of overhanging banks tended to fall within days or weeks of each other, leaving large chunks of vegetation and soil that were previously part of the salt marsh vegetated banks in the channels of the Slough. From the results of this study, it does not appear that cliff erosion is related to *Sphaeroma* burrow or population density.

Figure 8. Erosion to salt marsh banks caused by harbor seals (*Phoca vitulina*) at Elkhorn Slough. Note the claw marks in the mud banks caused by seals entering the water.

Figure 9. Example of large-scale bank failure at Elkhorn Slough. The banks are undercut from the high volume and velocity of tidal currents until the weight of the vegetation and soil above causes the bank to collapse.

CONCLUSIONS AND RECOMMENDATIONS

Erosion and salt marsh losses still remain large concerns at Elkhorn Slough. Malzone (1999) found that the system was still exhibiting increasing erosion rates and had not reached equilibrium. This study supports these findings.

The findings from this research of no significant correlation between *Sphaeroma quoyanum* and erosion measurements indicate that this organism is not, at the current time, a significant factor contributing to erosion rates at Elkhorn Slough. It is possible that, in the future, burrow numbers may reach critical densities that cause significant erosion effects. However, currently, it appears that other factors such as tidal current, wave action, and tidal prism are the more significant contributors to Elkhorn Slough's high erosion rates. At this point, attention is best focused on these hydrological factors in order to address the erosion issue. Research on the most important factors and the extent of their erosional effects would be valuable. In the past, a range of solutions have been proposed to limit tidal exchange and reduce wave energy within the system. Research on the benefits of such approaches is in order.

To help keep track of *Sphaeroma quoyanum* effects on physical parameters, the 41 sites established for this study, or a subset of these sites, should be monitored on a regular basis. These results should be analyzed and discussed in conjunction with other erosion studies and monitoring activities that are ongoing, including efforts using geographic information systems to track horizontal bank losses over time using aerial photography, and bathymetry studies that measure losses to subtidal or channel areas within the Slough. When analyzed together, these data will give a larger and more

complete picture of erosional processes and may help to identify or quantify factors that contribute to these losses.

Monitoring should occur at least yearly or more often depending on the resources available to the managers at Elkhorn Slough. Significant physical changes became apparent at some sites over a period of only 2 or 3 months, although any changes in this short of a time period may not have been large enough to significantly change results for the entire Slough. A schedule that allows data collection once or twice a year should yield enough data for an ongoing study and would also help to refine the erosion rates that were extrapolated from the short time frame of this study. Keeping a good record of temporal and spatial changes, including *Sphaeroma* burrows or populations, is necessary. If the population of *Sphaeroma quoyanum* and the erosion rates increase substantially at the same time, a study similar to the one conducted here would indicate if a critical density of *Sphaeroma* had been reached and was contributing to erosion.

Many of the sites that were included in this study may not be easily accessible and this fact should be considered in creating a long-term monitoring plan. A subset of these sites, including easily accessible sites and sites of special concern, would be appropriate for volunteers to monitor, or when the resources for sampling are limited to a few people or a short period of time. Although this type of abbreviated sampling strategy would produce biased results, it may provide adequate information for Slough managers to identify significant changes in either erosion rates or *Sphaeroma* populations.

Other recommendations include conducting additional studies. It would be valuable to know if there is a critical density of *Sphaeroma quoyanum* that may begin to

affect the erosion rates of the Slough. This may be approached experimentally with altered or constructed banks or with exclosure/enclosure manipulations with *Sphaeroma*. An equally useful study may be to look specifically at the possible contributions of crab burrows to erosion. Although *Sphaeroma* burrows are very numerous, they are small and superficial. Crab burrows are much larger and deeper, and may possibly affect erosion rates. This study did not specifically study crab burrows, so although I did not find any relationships between crab burrows and erosion rates, it may be worthwhile to examine this situation specifically.

LIST OF REFERENCES

- Bishop Museum. 2000. *Subphylum Crustacea*. Retrieved October 8, 2001 from the World Wide Web: <http://www2.bishopmuseum.org/HBS/invert/isopoda.htm>.
- Borowsky, B. 1996. Laboratory observations of the life history of the isopod *Sphaeroma quadridentatum* Say, 1818. *Crustaceana* 69(1):94-100.
- Brusca, R.C., S. Taiti, and V. Coelho. In press. Isopods. In *Light's Manual, 4th Edition*, ed. J. Carlton. Menlo Park: Stanford University Press. Available electronically at: http://phylogeny.arizona.edu/tree/eukaryotes/animals/arthropoda/crustacea/isopoda/isopod_lichen/bruscapeet.html.
- Carlton, J. T. 1979a. *History, Biogeography, and Ecology of the Introduced Marine and Estuarine Invertebrates of the Pacific Coast of North America*. Ph. D. diss., University of California, Davis. 904 pp.
- _____. 1979b. Introduced invertebrates of San Francisco Bay. In: *San Francisco Bay: The Urbanized Estuary*, ed. T. J. Conomos, 427-444. San Francisco: Pacific Div./Amer. Assoc. Adv. Science.
- _____. 1989. Man's role in changing the face of the ocean: biological invasions and implications for conservation of near-shore environments. *Conservation Biology* 3:265-273.
- _____. 1992. Introduced marine and estuarine mollusks of North America: an end-of-the-century perspective. *Journal of Shellfish Research* 11:489-505.
- Carlton, J.T. and J.B. Geller. 1993. Ecological roulette: the global transport of nonindigenous marine organisms. *Science* 261:78-82.
- Carlton, J.T. and E. W. Iverson. 1981. Biogeography and natural history of *Sphaeroma walkeri* Stebbing (Crustacea: Isopoda) and its introduction to San Diego Bay, California. *Journal of Natural History* 15:31-48.
- Carlton, J.T. and M.H. Ruckelshaus. 1997. Nonindigenous marine invertebrates and algae. In: *Strangers in Paradise: impact and management of nonindigenous species in Florida*, eds. D. Simberloff, D.C. Schmitz, and T.C. Brown, 87-210. Washington, D.C.: Island Press.

- Carlton, J.T., J.K. Thompson, and T. H. Nichols. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian Clam *Potamocorbula amurensis*, vol I. Introduction and Dispersal. *Marine Ecology Progress Series* 66:81-94.
- Chapman, J.W. and J.T. Carlton. 1994. Predicted discoveries of the introduced isopod *Synidotea laevidorsalis* (Miers, 1881). *Journal of Crustacean Biology* 14(4):700-714.
- Clark, L.R. 1972. Long period wave characteristics in Moss Landing Harbor and Elkhorn Slough. M.S. Thesis, San Jose State University. 73 p.
- Cohen, A.N. and J.T. Carlton. 1995. *Nonindigenous Aquatic Species in a United States Estuary: A Case Study of the Biological Invasions of the San Francisco Bay and Delta*. A report for the USFWS and the National Sea Grant College Program (Connecticut Sea Grant). Retrieved March 3, 1999 from the World Wide Web: <http://nas.er.usgs.gov/publications/sfinvade.htm>.
- Crampton, T.A. 1994. Long term effects of Moss Landing Harbor in the wetlands of Elkhorn Slough. M.S. Thesis, University of California, Santa Cruz. 81 p.
- Cummins, K.W. 1962. An evaluation of some techniques for the collection and analysis of benthic samples with special emphasis on lotic waters. *American Midland Naturalist* 67(2):477-501.
- Dukes, J.S. and Mooney, H.A. 2001. Biological invaders disrupt ecosystem processes in western North America. In: *How Landscapes Change: Human Disturbance and Ecosystem Disruptions in the Americas*, ed. G. Bradshaw, et al. Berlin: Springer-Verlag.
- Elkhorn Slough National Estuarine Research Reserve. March 28, 1997. Historical perspective of change in the slough. Watsonville, California: Elkhorn Slough National Estuarine Research Reserve..
- Estuary Net. 1998. *Elkhorn Slough National Estuarine Research Reserve, General Description*. Retrieved November 13, 1998 from the World Wide Web: http://www.inlet.geol.sc.edu/elk/gen_info.html#GEN_DESCRIPTION.
- Haltiner, J.P. and D. Thor. 1991. Sedimentation processes in Morro Bay, California. In: *Coastal Sediments '91 Proceedings, Specialty Conference/Water Resources*, 831-845. Seattle, Washington: Division/ASCE.
- Harvey, C.E. 1969. Breeding and distribution of *Sphaeroma* (Crustacea: Isopoda) in Britain. *Journal of Animal Ecology* 38:399-406.

- Hass, C.G. and B. Knott. 1998. Sphaeromatid isopods from the Swan River, Western Australia: diversity, distribution, and geographic sources. *Crustaceana* 71(1):36-46.
- Josselyn, M. 1983. *The Ecology of San Francisco Bay Tidal Marshes: A Community Profile* (FWS/OBS-83/23). Washington, D.C.: U.S. Fish and Wildlife Service, Division of Biological Services
- Kusler, J.A. and M.E. Kentula. 1990. *Wetland Creation and Restoration: the status of the Science*. Washington, D.C.: Island Press.
- Lackey, J.B. 1961. Bottom sampling and environmental niches. *Limnology and Oceanography* 6:271-279.
- Lim, K.K.P., D.H. Murphy, T. Morgany, N. Sivasothi, P.K.L. Ng, G.C. Soong, H.T.W. Tan, K.S. Tan, and T.K. Tan. 2001. A Guide to Mangroves of Singapore. In: *Volume 1: The Ecosystem and Plant Diversity, and Volume 2: Animal Diversity*, eds. P.K.L. Ng and N. Sivasothi. Singapore: Singapore Science Center.
- Longhurst. A.R. 1959. The sampling problem in benthic ecology. *Proceedings of the New Zealand Ecological Society* 6:8-12.
- Malzone, C. 1999. *Tidal Scour and its relation to erosion and sediment transport in Elkhorn Slough*. M.S. Thesis, San Jose State University.
- Marsden, I.D. 1982. Population biology of the commensal asellotan *Iais pubescens* (Dana) and its Sphaeromatid host *Exophaeroma obtusum* (Dana)(Isopoda). *Journal of Experimental Marine Biology and Ecology* 58:233-257.
- Meadows, P.S. and A. Meadows. 1991. The environmental impact of burrowing animals and burrows. In: *Symposia of the Zoological Society of London*, no. 63, 327-338. Oxford: Oxford University Press.
- Miller, R. 1926. Ecological relations of marine wood-boring organisms in San Francisco Bay. *Ecology* 7(3):247-254.
- Monterey Bay National Marine Sanctuary. 1999. *Ecosystem Observations for the Monterey Bay National Marine Sanctuary: Exotic Species*. Retrieved October 8, 2001 from the World Wide Web: <http://www/bonita.mbnms.nos.noaa.gov/Educate/newsletters/2000Eco/pages/exotic.html>.
- Needham, P.R. and R.L. Usinger. 1956. Variability in macrofauna of a single riffle in Prosser Creek, California, as indicated by the Surber Sampler. *Hilgardia* 24:383-409.

- Nichols, F.H., J.K. Thompson, and L.E. Shemel. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian Clam *Potamocorbula amurensis*. In: *Marine Ecology Progress Series, Volume II: Displacement of a Former Community*, 66:95-101.
- Oliver, J.S., J. King, M. Hornberger, and D. Schwartz. 1988. *Erosion of Wetland Habitats by Increasing Tidal Currents from Harbor Construction and Breaching Dikes in Elkhorn Slough, California*. Draft Final Report Submitted to Division of Marine and Estuarine Management.
- Philip Williams and Associates. 1992. Elkhorn Slough tidal hydraulics erosion study. Technical Report prepared for the U.S. Army Corps of Engineers, San Francisco District. 34 p.
- Ray, A.J. and R.C. Aller. 1985. Physical irrigation of relict burrows: implications for sediment chemistry. *Marine Geology* 62:371-379.
- Rehm, A. and H.J. Humm. 1973. *Sphaeroma* terebrans: a threat to the mangroves of southwestern Florida. *Science* 182:173-174.
- Rotramel, G. 1975. Filter feeding by the marine boring isopod *Sphaeroma quoyanum*, H. Milne Edwards, 1840 (Isopoda: Sphaeromatidae). *Crustaceana* 28:7-10.
- Schmitt, W.L. 1965. *Crustaceans*. Ann Arbor, Wisconsin: University of Michigan Press.
- Schram, F.R.. 1986. Chapter 12: Isopoda. *Crustacea*. New York: Oxford University.
- Sliger, M.C. 1982. Distribution and microhabitat selection of *Hemigrapsus oregonensis* (Dana) and *Pachygrapsus crassipes* Randall in Elkhorn Slough, Monterey County, California. M.S. Thesis, California State University, Hayward.
- Tabachnick, B.G. and L.S. Fidell. 1996. *Using Multivariate Statistics, Third Edition*. New York: Harper Collins College Publishers.
- Talley, T.S., J.A. Crooks, L.A. Levin. 2001. Habitat utilization and alteration by the invasive burrowing isopod, *Sphaeroma quoyanum*, in California salt marshes. *Marine Biology* 138: 561-573.
- Wasson, K, C.J. Zabin, M.C. Diaz, L. Bedinger, and J.S. Pearse. 2001. Biological invasions of estuaries without international shipping: the importance of intraregional transport. *Biological Conservation* 102(2001):143-153.

Wasson, K. Research Coordinator, Elkhorn Slough. Personal Communications via phone and conversations. February 2001- February 2002.

Wong, C. 1989. Observations of tides and tidal currents in Elkhorn Slough. M.S. Thesis, San Jose State University. 108 p.

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March 20, 2002

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Sincerely,

Richard C. Brusca
Director of Conservation and Science

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