Mapping the Fish Fry Feeding Prism in a Saltmarsh-Estuary Ecotone

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***Abstract*- It is a common understanding that coastal wetland plays an important role in marine fisheries recruitment. However, mechanistic detail of the processes that link the two ecosystems is not well defined. This study aims to describe and map ecological landscape features of a saltmarsh-estuary ecotone at the entrance to Mambo Creek in Salamander Bay, at Port Stephens, on the southeast coast of Australia. The creek drains from 175 ha of estuarine-freshwater area which forms part of the Tomaree Wetland complex. Based on field surveyed data and GIS analysis, a dynamical system is depicted of a tidal salt-wedge that results from the interaction of the wetland and estuary water. The creek entrance lies inside the extensive *Posidonia* seagrass beds of Salamander Bay. It is constricted by a shallow sandbar at the entrance and is fringed by mangroves that stabilize the creek channel. Analysis of the ebb-tide outflow from the wetland shows it contains micro-particles (10-100 µm diameter) at densities >20,000 particles ml^{-1}, high levels of H_2S, low pH, low-salinity and low dissolved oxygen and is thus adverse for most fish fry. In the vicinity of the entrance channel to the creek: i) the outflow from the wetland forms a tidal salt wedge and disperses across the water surface where it meets denser saline estuary water; ii) the micro-particles sink out of the surface layer at the tip of the salt wedge in a sharp, readily observable boundary, due to flocculation effects. At this boundary or ecotone, the continuous presence of a "feeding prism" which contains very large numbers of at least three species of marine fish fry <20 mm total length, particularly in warmer months, was observed. The fry remain only within this creek area and feed on the ad-libitum supply of outwelling wetland micro-food particles while swimming in near oceanic condition water below the salt wedge; iii) the seston material varies with season; in warmer months it is principally a mixture of purple and green bacteria coated micro-particles and in cooler months detritus predominates; iv) the location of the halocline is dynamic and is related to the morphology of the creek and tide; and, v) the creek entrance also contains a deeper area in which small numbers of large apparently gravid fish were regularly observed. The fish fry aggregations are mapped in relation to the halocline in space and time during summer and winter seasons and linked to tidal sea-level and the morphology of the creek. The authors suggest the "feeding prism" ecotone is an important link between wetland process functions and marine fish recruitment for at least three commercially and recreationally important coastal fish species and perhaps others. It is this ecotone that needs to be considered as a focus of management measures and environmental impact assessment associated with adjoining developments and landscape modifications that may affect coastal processes in the vicinity of the creek. For example, the sand-dune system surrounding Mambo Wetlands provides a freshwater aquifer reservoir that is recharged by precipitation and discharges over time into the low-lying saltmarsh.**

I. INTRODUCTION

Present knowledge on energy flow in salt-marsh estuary ecosystems came after the work of [1] who calculated 45% of the carbon fixed in a Georgia saltmarsh was exported to the estuary. This work was followed by [2] who in his original work identified the protein enrichment conversion process of low protein dead salt-marsh plant tissue to high protein microbial biomass which was attached to detritus particles exported from the wetland to the adjoining estuary. Further work followed in mangrove wetlands [3, 4, 5] and led to the wetland food chain outwelling model [6]. However, [7] suggested that in spite of many studies the wetland outwelling model was hypothetical and qualitative. Numerous wetland and estuarine flux studies underscore continued debate over the quantitative value of wetlands to marine fisheries [8, 9]. Recent work has quantitatively demonstrated that a great proportion of the primary production in an estuarine wetland is exported to the adjacent estuary ecosystem via a range of predator-prey trophic transfer mechanisms [10] while within the system only a small percentage is grazed or goes to detritus [e.g. 11]. To improve our understanding of estuarine wetland function [9] suggested that a focus of wetland outwelling research should be on material exchange mechanisms between different subsystems in estuary-coastal landscapes; and in particular the process controls that enable this exchange.

Water quality in salt marsh wetlands often exhibit a wide range of environmental conditions in space and time including temperature, salinity, oxygen, pH, water depth, stratification, emergence and a range of parameters that are considered benchmarks of water environmental health [e.g. 12]. In addition, sulfate reduction is the predominant terminal electron accepting process in carbon metabolism in anaerobic marine sediments [13] including salt marshes [14]. Consequently, saltmarsh sediments and pore water are typically highly reduced. Sulfate-reducing bacteria play the major role in the turnover of organic matter, particularly cellulose, under these conditions [15].

The "failure" of wetlands to regularly meet water quality objectives often results in environmental assessment reports that suggest "improved" water quality could be achieved by increasing wetland water exchange rates through engineering

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of artificial entrances and so forth. In many situations this "failure" to meet benchmarks is driven not only by an anthropomorphic idealization of water quality parameters for wetlands, such as safe swimming guidelines and odor preferences, but also by an understanding of important aspects of fisheries biology.

During the last few decades, there have been significant advances in understanding of marine larval fish development and feeding. Conditions conducive to successful fish larval rearing including water quality parameters, pathology and epidemiology have been well documented. This has demonstrated that the widely varying environmental conditions typically encountered in a salt marsh landscape are not ideal for fish larval rearing. Aquaculture research has also led to a detailed understanding of larval fish nutrition including routine methodology for monitoring larval feeding [e.g. 16, 17]; an understanding of optimal physical and chemical parameters of diets during early development [e.g. 17, 18]; composition of gut content of mangrove associated fish larvae [19] and particle size and presentation [e.g. 16, 17, 20].

Where two ecosystems such as a salt marsh and estuary meet, the transition zone or boundary is commonly referred to as a stress line or ecotone [21]. The "edge effect" where ecotones occur is typically characterized by greater species diversity and population density than occur in either of the individual communities [22]. Ecotones are key structures for the functioning of the landscape and fundamentally important to ecosystem integrity and function [23]. An ecotone may be characterized by a gradual blending of the two ecosystems across a broad area, or it may manifest itself as a sharp boundary line [24, 25]. As a result of their temporary nature and scaling properties, ecotones can be difficult components of a landscape to investigate [26]. In many cases because they are scale dependent their distinctive patterns disappear when observed [27].

In this article we investigate the hypothesis that three species of fish fry (defined here as covering the approximate size range of 3 mm to 20 mm total length) distribution within a tidal saltmarsh-estuary ecotone is regulated by the position of a halocline. We focus on the flux of micro-particulates produced in the salt marsh. We describe the shunting mechanism used to deliver this wetland food to the estuary and the landscape processes that control its availability for consumption by fish fry at this critical boundary interface. Finally, we map the ecotone during tidal cycles and develop a simple inductive analytical model [28] to describe its spatial and seasonal response to salinity and bathymetry.

II. METHODS

A. Description of study area

The study site is located on Tomaree Peninsula at the entrance to Mambo Creek, Salamander Bay, New South Wales, Australia (Figure 1). Tomaree Peninsula is located at the eastern end of the Port Stephens Estuary which is approximately 100 km^2. Tomaree Peninsula is characterised by volcanic peaks interspersed by deep windblown sand sheets that contain shallow freshwater aquifers.

Port Stephens is considered an inter-barrier estuary among the geomorphological types of south east Australian estuaries defined by [29]. The intertidal and subtidal area of Port Stephens is protected under the NSW Marine Parks Act (1997) and the study site lies within a designated sanctuary area that prohibits fishing. Salamander Bay, in which Mambo Creek is located, is approximately 90 ha in area and approximately 16 m deep at the outer edge. It is located in the outer more oceanic section of the Port Stephens estuary. Mambo Creek provides a surface water exchange pathway between the Tomaree Wetland complex and estuarine Salamander Bay. The 175 ha saltmarsh which adjoins Mambo Creek, forms part of the Tomaree wetland complex. Mambo creek is tidal at its seaward end (Figure 2). The region is characterised by semi-diurnal tides with a maximum range of approximately 2.8 m.

The catchment of the wetland consists of sandbed aquifers that are recharged by rainfall. Annual average rainfall is 1350 mm and is fairly consistent throughout the year. June is the wettest month with an average of 154 mm. The climate is temperate with average annual maximum and minimum temperature of approximately 23 and 14 °C respectively. July is the coldest month with a minimum average of 8.4 °C.

The saltmarsh functions as a ponded system, separated from Salamander Bay by a stranded beach ridge, in which a large portion of the saltmarsh undergoes daily tidal exchange. The creek entrance from the bay was modified in the 1950's and now operates via five 1.5 m diameter concrete road culverts that cross the beach sand ridge (Figure 2). The wetland supports a range of vegetation communities, including seagrass (*Zostera capricorni, Halophila ovalis, Ruppia* spp.); fringing mangroves (*Avicennia marina and Aegicarus corniculatum*); and saltmarsh including *Sarcocornia quinqeuflora, Sporobolus virginicus, Phragmites australis* and *Juncus kraussii*.

The Salamander Bay area in which Mambo Creek entrance is located contains a well developed seagrass meadow consisting of inner shore *Z. capricorni* and an outer deeper adjoining meadow of *Posidonia australis*.

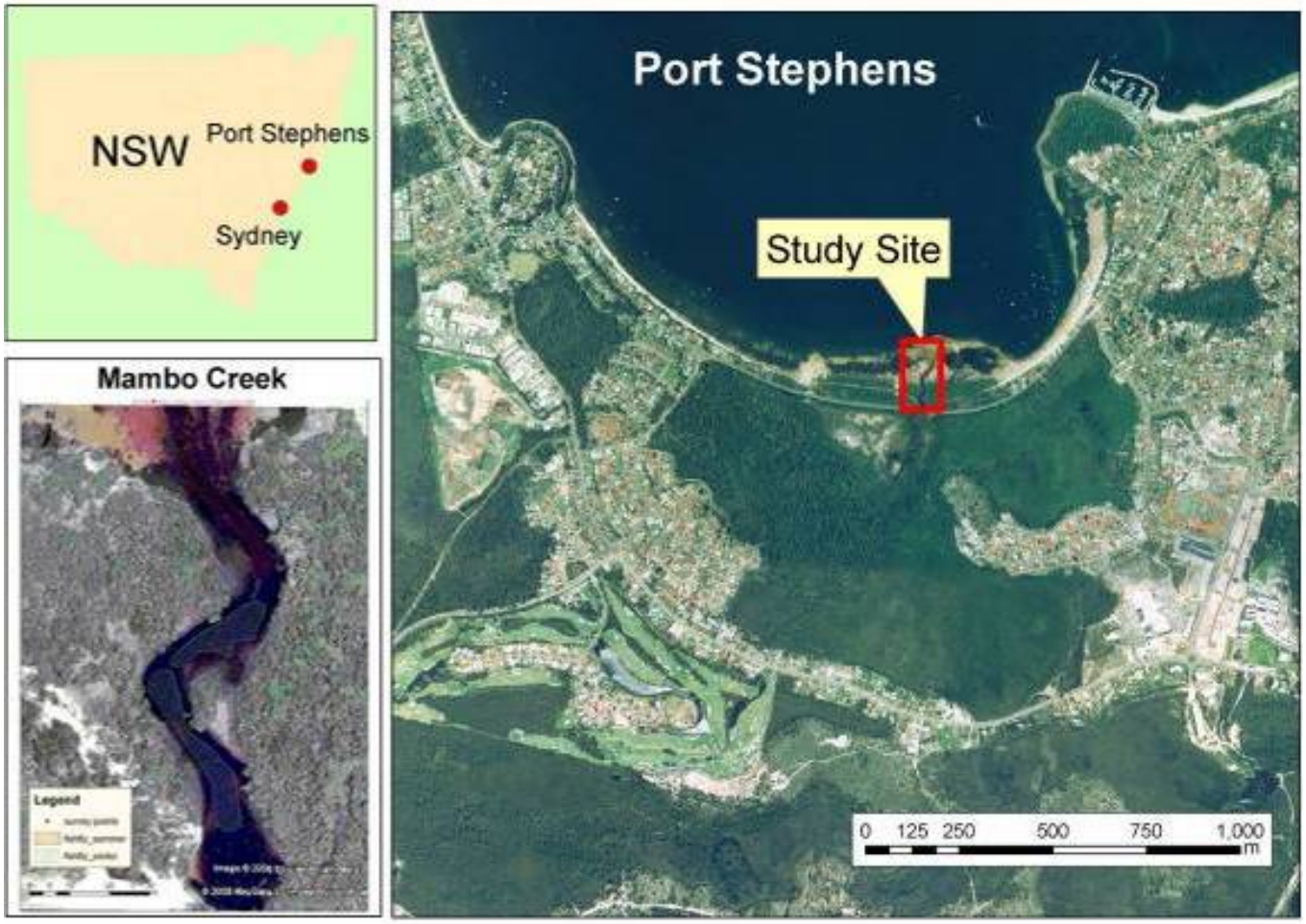

Figure 1. Location map for Mambo Creek and adjoining saltmarsh in Salamander Bay, Australia..

This seagrass meadow extends along almost the entire 3 km of sandy shoreline of Salamander Bay out to approximately 4 m below Australian Height Datum (AHD). Total *P. australis* area is approximately 16.4 ha and averages more than 90% cover [30, 31]. A well developed stand of the mangrove *A. marina* flanks the creek and black she-oaks (*Allocasuarina littoralis*) inhabit the beach ridge above the high tide mark (Figure 2). Salamander Bay is characterized by a marine environment with salinities above 32 ppt and features strong tidally driven oceanic water exchange. The bay benthos is predominantly muddy with water depth ranging up to 15 m. Secchi depth is normally around 2.5 ±1 m in the bay.

B. Study Methods

A survey benchmark was established at the road culvert 200 m south of the entrance to Mambo Creek (Figure 2) to enable approximate water levels (±0.05 m) to be readily determined relative to AHD. A horizontal (N-S: E-W) grid map of the creek with 5 m x 5 m grids northwards of the culvert was developed with surveyors tape using the centre of the roadway culvert benchmark as the origin. The bathymetry of the Mambo Creek channel from the culverts to the sandbar, located at the entrance to the creek (Figure 2), was measured at approximately 5 m intervals, relative to AHD and plotted on a grid map relative to the benchmark (Figure 2).

A sampling program was undertaken to map the location of fish fry on the grid map at approximately 2-hour intervals during tide cycles fortnightly, at intermediate tides, over a six month period from February until August 2008 along Mambo Creek. The sampling period encompassed spawning peaks for three commercially and recreationally important estuarine species in NSW, namely: December to March for flathead – *Platycephalus fuscus* [32] June – July for yellow fin bream - *Acanthopagrus australis* [33]; and September to March for sand whiting - *Sillago ciliata* [34]. Location of the fish fry was determined by swimming passively along the creek and using snorkel and mask to visually detect the location and presence of fry and larger fish which was then recorded on a grid map together with time and approximate

sea level relative to the benchmark. Samples of fry aggregations (> 10 individuals) were collected on site visits using a 0.5 m dip net with 0.5 mm mesh for species identification and gut content analysis. Gut contents were analyzed using a stereo binocular microscope to directly observe the stomach contents of the fry through the transparent gut wall as routinely undertaken in hatcheries to observe micro particle consumption [16].

Samples of water exiting the wetland were taken at the culvert at low tide on a fortnightly basis over the corresponding sampling program period from February until August, 2008. Salinity, temperature and pH of the water were recorded. Water samples were taken back to the laboratory and sub-sampled to a Sedgewick rafter cell. Counts were made of all particles > 10 µm and identified either as phytoplankton or micro-particles and noted where aggregated bacteria on micro-particles was observed.

Salinity profiles were taken at approximately 100 m north of the culvert during a tidal cycle in order to develop a model of the halocline vertical structure under typical wetland flow conditions. The halocline model was calibrated on subsequent tide cycles in order to establish the final invert (bottom) halocline elevations in response to tide level.

During the study interval, a periodic two-month mapping and seagrass monitoring survey of the adjacent seagrass meadows by snorkeling along the entire shore of Salamander Bay (Figure 1) was conducted for a separate environmental monitoring program for a pearl farm development (Ogburn, unpubl.). These extensive seagrass surveys enabled observations to be made regarding the presence of fish fry outside the creek area in Salamander Bay during the study period.

A Digital Elevation Model (DEM) of 20 cm x 20 cm resolution was generated from the field survey transect data, by using the Grid module of ArcGIS [35], with the data interpolation method after [36].

III. Results

A. Water Quality

Mambo Creek is characterized by a turbid brown low salinity surface water plume discharging from the wetland and present in the study area at all times except high tides. Monthly averages from later summer to end of winter for salinity, water temperature and pH for the water discharging from the Mambo Creek wetland at low tide are shown in Figure 3.

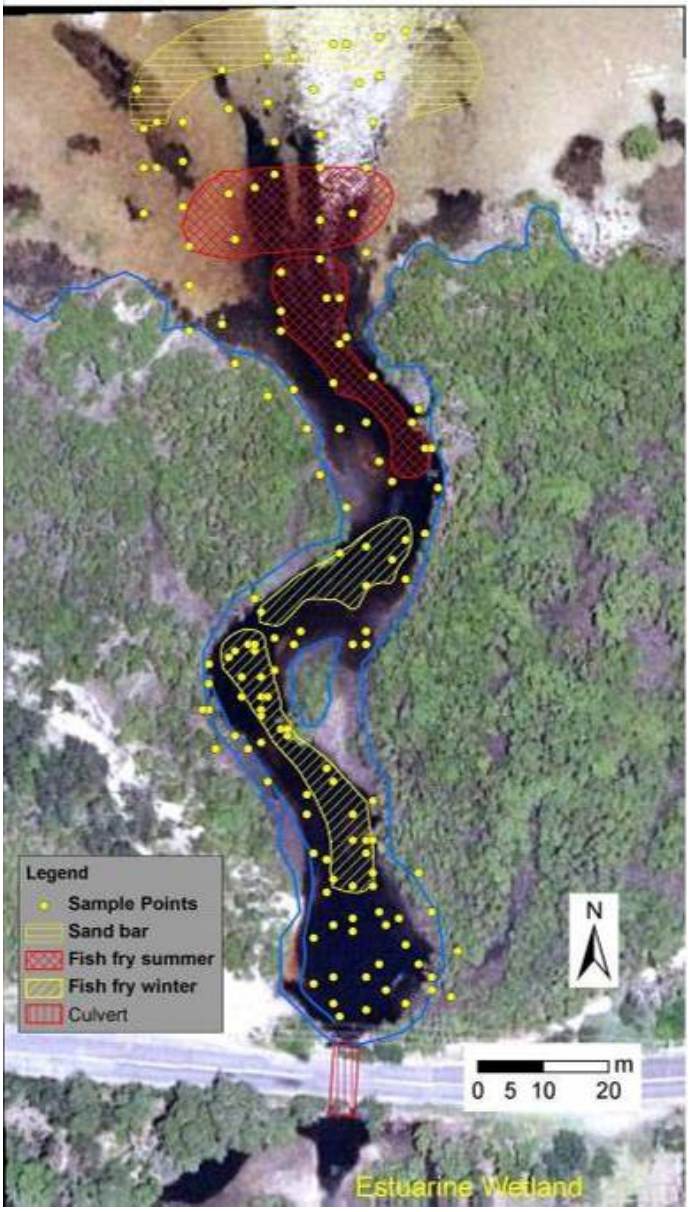

Figure 2. Aerial photograph of Mambo Creek with culvert outlet (S) and Salamander Bay (N).

Water temperature declined significantly during the study. Salinity fluctuated around an overall mean of 1.8 and pH increased approximately 1 pH unit from 5.8 in summer to 6.9 in winter.

Corresponding plankton counts for micro-particles in the size range of 10-100 µm are shown in Figure 4. There is a significant decline in particle counts from warmer to cooler months. The particles consisted almost entirely of fragmented brown flocculent "detrital" particles predominantly in the size range of 20-50 µm.

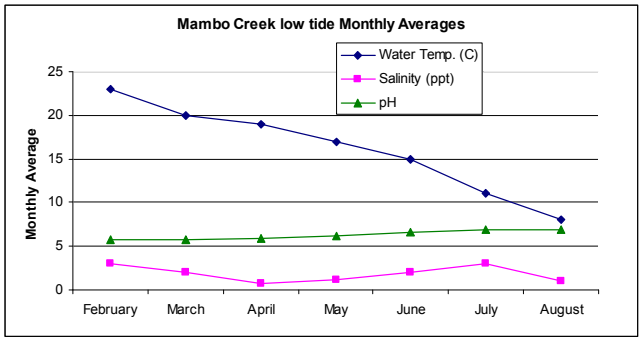

Figure 3. Monthly averages of temperature, salinity and pH of Mambo Creek wetland outflow at low tide.

Occasional flagellates and diatoms (e.g. *Nitzchia* sp.) were also observed in the haemocytometer. What is not shown by the data, however, is the complete disappearance of green and purple bacteria aggregated on the brown flocculent particles, during cooler months when water temperature of low salinity water draining from the saltmarsh at low tide dropped below approximately 16 C.

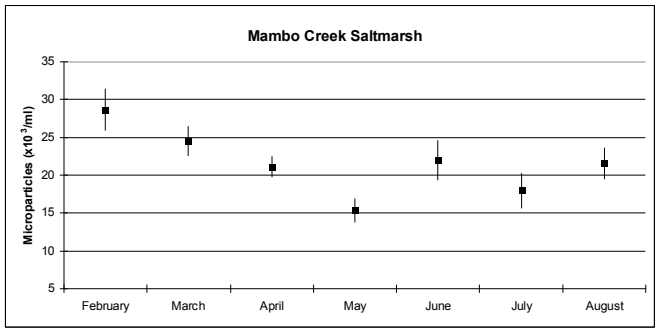

Figure 4. Monthly average seston concentration in Mambo Creek saltmarsh outflow at low tide.

Salinity profiles of the channel at the 100 m sampling station, established for developing the descriptive model, revealed a distinct halocline. The mean and 95% confidence limit for salinity on ebb tide in this surface halocline was 5.3 ± 2.6 ppt from 23 samples collected during the sampling period. Salinity below the halocline was 32.1 ± 1.4 ppt. The resultant values for the invert (bottom) and surface elevation of the low salinity layer are shown in Figure 5. The results, as expected, indicate that the low salinity layer reduces in thickness on an incoming tide due to a salt wedge effect, rises out of the channel and spreads across the wider banks lined with mangrove pneumatophores. At approximately 0.5 m AHD the halocline breaks down.

B. Creek Landscape

The submerged channel at mean low water neap tide (approximately – 0.4 m AHD) in Mambo Creek is depicted in (Figure 6).

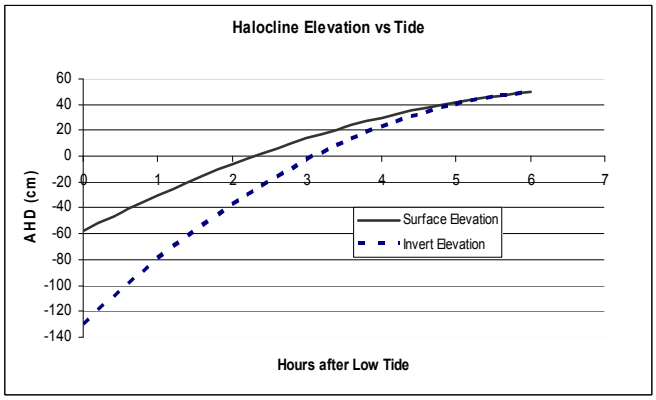

Figure 5. Modelled elevation levels and thickness of halocline as a function of tide 100m north of culvert benchmark in Mambo Creek channel

The channel, with a water surface area of approximately 3,500 m^2, meanders along a south-north axis for approximately 200 m where it is delimited by a shallow estuary sandbar that has a minimum elevation of approximately -0.50 m AHD. Average depth of the channel at mean low water neap is approximately 45 cm and corresponding estimated total volume is 1,575 m^3. The channel is characterized by sharp deep turns, particularly in the region from 60-120 m north of the culverts. These areas have dense mangrove (*A. marina*) root matting that protect and armor the permanently submerged channel banks. Pneumatophores from this vegetation are distributed along the channel boundaries from -0.40 m AHD to approximately 0.3 m AHD. These pneumatophores stabilize the wider boundary of the mouth of Mambo Creek where it enters the estuary (Figure 2). The channel was devoid of seagrass to approximately 130 m north of the culvert during warmer months (February- April). Further north in the channel, sparse and patchy occurrence of *Z. capricorni* was noted. The channel substrate is composed of mud and sand-mud. During the warmer months the channel bottom out to approximately 120 m north of the culvert was highly reduced with *Beggiatoa* sp. evident as white filamentous mats on top of sulfide-rich sediments. The water column in this region remained highly turbid during this period and visibility was extremely poor.

Bathymetry of the channel in Mambo Creek was measured at low tide and transformed to Australian Height Datum (AHD). The bathymetry contour profile of the creek along the north–south axis is shown in Figure 6. The overall morphology of the creek bed (Figure 7) reveals a relatively complex series of deep and shallow sections in the channel that appear to relate to the interaction of the salt wedge and fish distribution discussed below. A relatively large deep pool probably formed due to scouring during flood events occurs immediately north of the culverts (0-20 m on S-N axis). This was approximately 800 m^3 at mean low water neap. It is referred to in this study as “scour pool” (Figure 7).

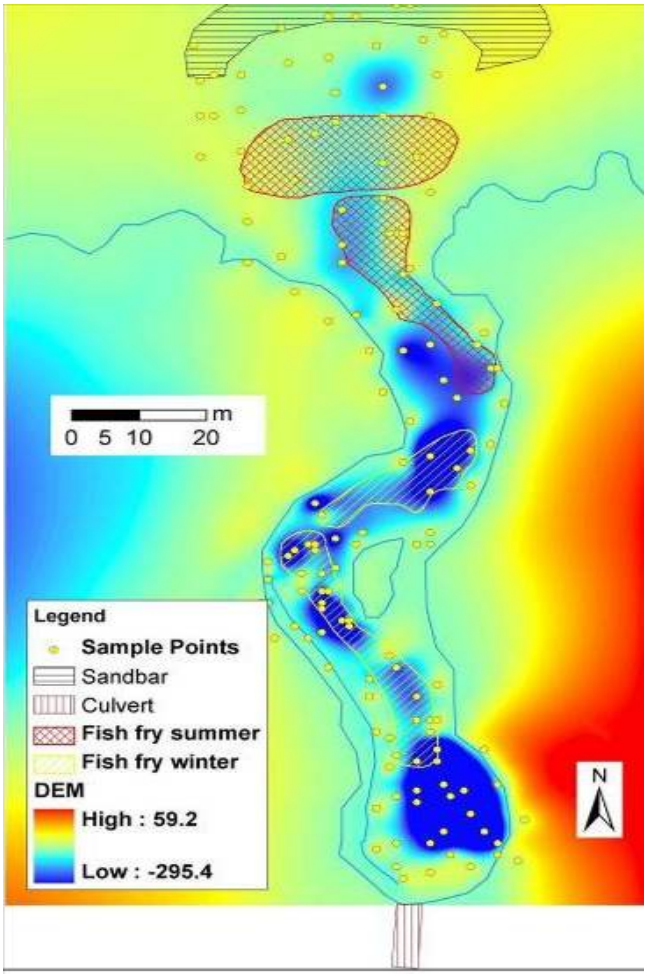

Figure 6. Mambo Creek channel digital elevation model relative to AHD.

C. Fish spawning site

Another large deep pool (~250 m^3 at mean low water neap) occurs at approximately 100 m on S-N axis. During warmer month's, particularly in early morning, adults of a very large size, particularly of *P. fuscus, A. australis*, and *S. ciliata* were observed first-hand on several occasions in the "spawning pool" below the halocline (Figure 8). Their behavior clearly paralleled that observed by the senior author in ready to spawn *P. fuscus* and *A. australis* in broodstock aquaculture tanks. In the case of *P. fuscus* very large females were "attended" by two smaller males just above the creek bottom. *A. australis* female and males remain almost stationary mid-water, approximately 1.5 m below the surface with three or four males facing towards the female who faces opposite them about 2 m apart. On several occasions on early morning high tides in previous years the senior author had collected large *P. fuscus* and *A. australis* with running ripe gonads at this location. These observations suggest that spawning of adults and nursery habitat of these three species can occur within the same functional area of the estuary. This is contrary to previously reported recruitment habit wherein the three species are reported to appear to spawn at the mouth of estuaries and the larvae enter the estuary to grow [37, 32].

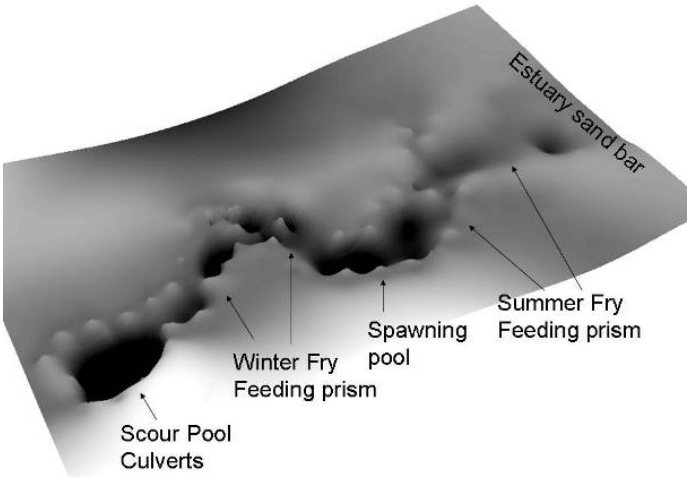

Figure 7. Digital plan model of the channel in Mambo Creek along the north-south axis.

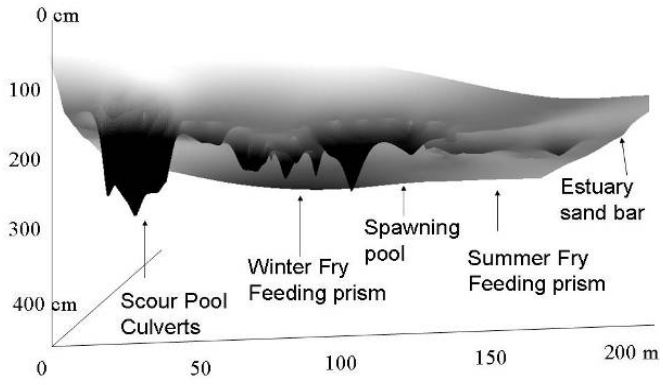

Figure 8. Digital elevation model of the channel in Mambo Creek along the north-south axis.

The brown low-salinity plume discharging from the wetland is characterized by a tidal salt-wedge regime. At the tip of the plume, rapidly flocculating micro-particulate material was observed descending towards the creek bed. Large numbers (multiples of 10^5 in summer and 10^4 in winter) of fish fry less than 20 mm total length were present on all sampling occasions at the tip of the plume, the horizontal location of which was governed by the tidal salt-wedge. Larger fry of *S. cili*ata were observed in very large numbers early in the study period (February – March). *P. fuscus* fry were observed throughout the study period with highest aggregations in March – May and larger size (10-20

mm) observed in winter months. *A. australis* were observed in April – July. During winter months the *Beggiatoa* sp. white filamentous mats disappeared from the creek bed in the vicinity (0-80 m) north of the culverts and the water column in this region became much clearer. During this period the fry of *P. fuscus* and *A. australis* were observed further up the creek, depending on halocline conditions, to approximately 60 m north of the culvert. During the months from February until June the fry aggregations occurred more than 100 m north of the culvert; particularly in the deeper areas between 120-170 m north of the culvert (Figure 8). No fry (< 2 cm) of these 3 species were observed beyond the estuary sandbar 200 m north of the culvert nor were they observed in the 4 surveys conducted in the approximate 27 ha of combined *Z. capricorni* and *P. australis* seagrass area in adjacent Salamander Bay.

Distribution of fry aggregations during a tide cycle showed a distinct pattern. The pattern of fry distribution observed in the summer season during hourly intervals of an example rising 6 hour tide is shown in a plan view in Figure 9. At low tide, in this case -58 cm AHD, the fry were aggregated at the northern end of the creek entrance adjoining the sandbar. As the tide level increased the fry aggregations moved along the creek in a southerly direction until the tide elevation rose up out of the deeper channel and flooded the adjacent flats (approx. 20 cm AHD) lined with *A. marina* pneumatophores. At this point the fry dispersed onto the mangrove flats. The distribution pattern of fish fry at hourly intervals of the example rising 6 hour tide is depicted in an elevation view in Figure 10. The fry were actively feeding on discernible particulate material that was flocculating from the brown surface plume in a precise location at the tip of the salt wedge. The fry were located at variable depth below the wedge tip but always at least 10 cm below the surface. As shown in the figure, the aggregations became slightly more dispersed horizontally as the tide rose. When the tide overflowed the channel bank (approx. 20 cm AHD), the fry aggregations dispersed across the mangrove flats. Fish fry, of a single species, typically schooled in aggregations. These aggregations were estimated to exceed 20 litre^{-1}, in fry less than 5 mm in total length.

Aggregations occurred within one specific region of the creek channel on each occasion. These aggregation regions varied in length from 15-40 m during summer and up to 60 m during winter. Each aggregation consisted of one species and size class. Larger fry, 15-20 mm, in length were less concentrated. Several aggregations of different species and or size classes occurred within the same region of the channel, particularly during February to May. The surveys revealed particularly large aggregations of fish fry in the warmer months of February – April when they appeared as dense clouds of fry

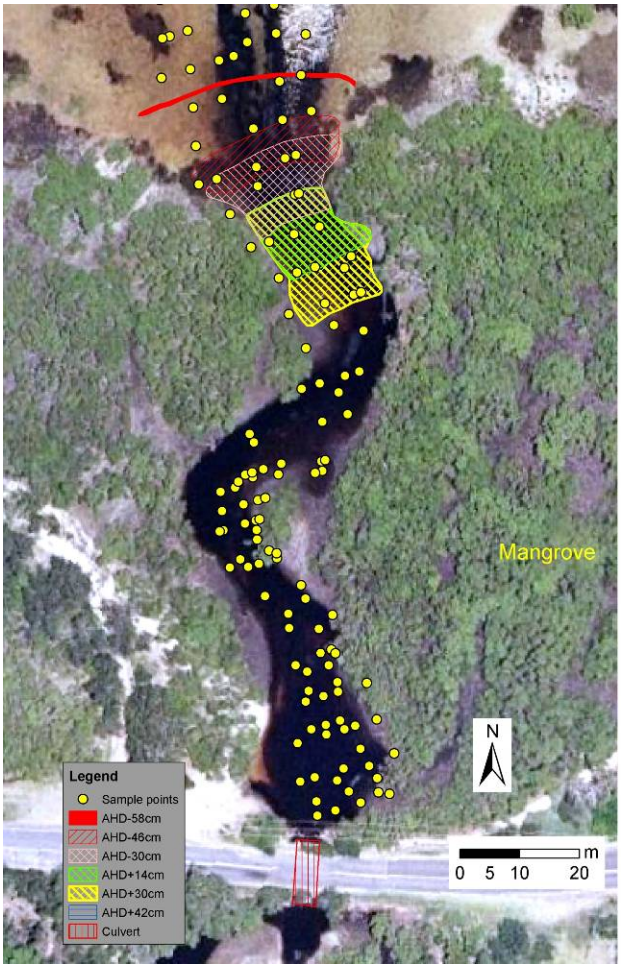

Figure 9. Plan view of fish fry distribution in summer at hourly intervals in a 6 hour tide period measured relative to AHD.

. Estimated aggregations would exceed 50 m^2 and 50 m^3. In cooler months flocculation appeared to occur over a wider area; aggregations of fry were less dense, patchier in distribution and smaller in overall numbers. In overall terms, based on observations and previous hatchery experience of the senior author, the number of fry within the 100 m zone described for Mambo Creek was estimated to vary 4.5 log from approximately 10^3 to 10^7 depending on season.

D. Fish fry gut contents

Gut contents of samples of fish fry of all 3 species were examined under a binocular microscope on sampling occasions. Gut content material consisted of that observed in the Sedgewick counted material taken in samples discharging from the wetland. The micro-particles were clearly discernible packed into the anterior portion of the gut. Fragments of "detritus" material predominated in the gut contents; purple and green bacteria cells could be discerned in the anterior gut region during warmer months; occasional flagellates and diatoms were also observed in the anterior gut region.

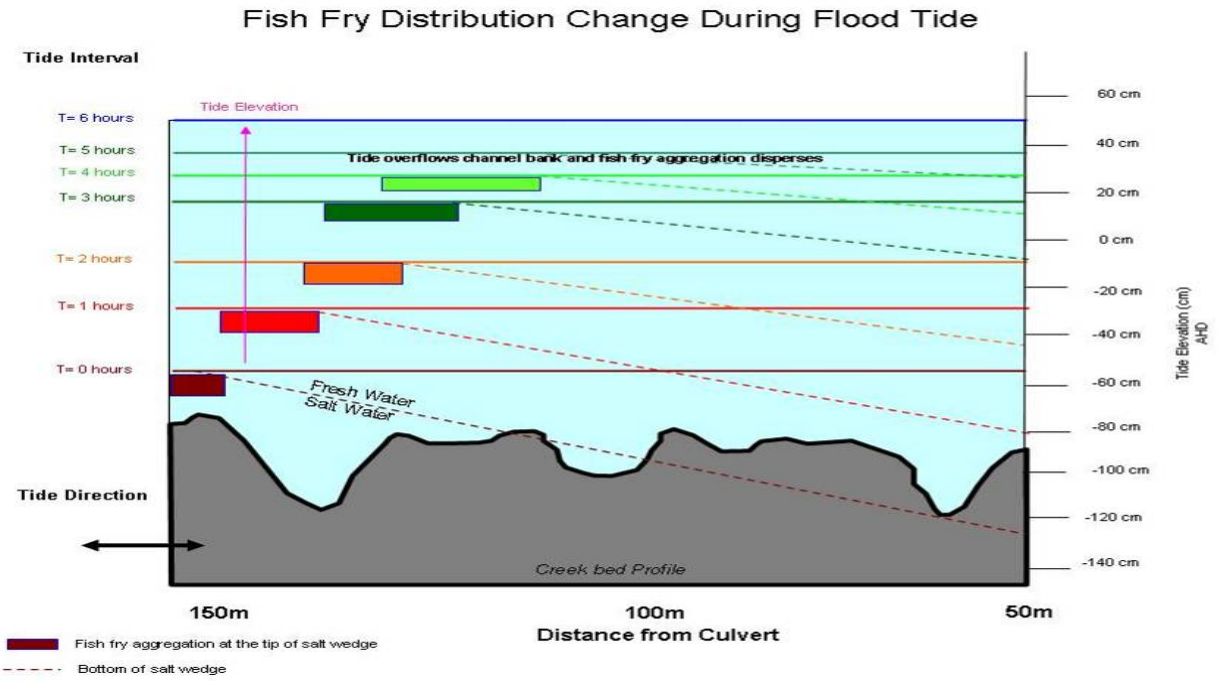

Figure 10. Elevation view of fish fry distribution in summer at hourly intervals in a 6 hour tide period measured relative to AHD.

This confirmed the observations of 'active-feeding' behavior of the fish fry at the leading edge of the halocline. This 'active-feeding' behavior is similar to that observed in fry in the hatchery when micro-particulate feeds are introduced at the surface of fish fry rearing tanks (Ogburn, unpubl. data).

IV. Discussion

Micro-particulate feeds have been a major challenge and an intensive focus of research in hatchery production systems for marine larval fish rearing during the last three decades [16, 17, 20]. These have traditionally relied on "live foods", zooplankton and phytoplankton and artificially manufactured micro-particles. Identifying the sources of micro-particulate food, other than live food, for very early stage fish development in natural systems, is an important element in coastal marine management [3]. In coastal marine wetlands, sulfate reduction is the major form of respiration; this process and the associated fermentation reactions which feed substrates to sulfate-reducing bacteria are responsible for most carbon and nutrient mineralization in the system [13]. Energy is conserved in the reduced sulfur compounds formed during sulfate reduction. Relative to aerobic respiration, approximately 75% of the potential energy in the organic matter consumed is transferred and stored in reduced sulfur during sulfate reduction [38]. Sulfide can be oxidized in the absence of oxygen and nitrate if light is present; a variety of photosynthetic bacteria, including purple and green sulfur bacteria, use sulfide as an electron donor in anoxygenic photosynthesis.

Anoxygenic, photosynthetic bacteria occur in large numbers in the upper layers of anoxic water columns typical of marine wetlands when enough light is present to support their photosynthesis. Photosynthetic sulfur bacteria are also very active in bacterial mats on the surface of sediments receiving light. As with plants and chemosynthetic bacteria, carbon fixation by photosynthetic sulfur bacteria is stoichiometrically coupled to nutrient assimilation.

During decomposition to particulate detritus, the material retains 60-70% organic content and the caloric value either remains the same or increases slightly. Crude fiber, carbohydrate, and fat contents decline but protein shows 96–300% increase from dead plants to particulate detritus stage [39]. It is this bio-processing of organic matter via the sulfate reduction – anoxygenic photosynthetic pathway in salt marsh areas that is critical to the manufacture of protein enriched micro-particles that are then "out-welled" [6] to the estuary. In Mambo Creek wetland these micro-particles range in size from 10-100 µm. They are commonly composed of detritus particles. In summer purple and green bacteria aggregated on brown particles, are a predominant component of the discharge material. This out-welling water is observed as light brown surface water, because of tannins and the micro-particles. Bacteria attached to detrital flocculent brown-coloured particles have also been reported in seston from saltmarsh by [40] and detritus is the predominant gut content of larvae of mangrove delta associated fish species such as *Chanos chanos* [19, Ogburn, unpubl. data) and penaeids [16]. The absence of purple sulfur bacteria, which require hydrogen sulfide and

associated green bacteria in cooler months, is consistent with the findings of [14] who reported a 2 log reduction in sulfate reduction in salt marsh sediments with negligible activity during cool months.

The halocline that results from the difference in salinity of the wetland and estuarine water provides the physical mechanism for locating the observed fry and their feeding behavior. The morphology of Mambo creek channel and in particular, the variation in depth along the creek provides a relatively complex micro-landscape that is closely linked to waterscape properties of a halocline rising and falling in a predictable pattern and location with the tide cycle. The micro-particles that are "channeled" in the out-welling wetland water are observed to flocculate out of the water column at the tip of the halocline where it is beginning to break down. These areas are devoid of significant seagrass habitat. Reference [41] reports a similar flocculation phenomenon at the tip of the salt wedge in a much larger estuary system characterized by a well-developed turbidity front. They report a range of nektonic and in-fauna species that show a spatial distribution pattern that may be taking advantage of the particulate organic material and/or phytoplankton concentrated near the front.

The flux of micro-particles carried from the Mambo Creek saltmarsh are carried in a water column that has low pH (~ pH 5.8) and high levels of sulfides including H_2S. Low pH has been associated with various dermal pathologies in marine fish such as red spot disease [42], particularly during early stages of development when the fish fry typically have no protective scales. Fish fry of many marine fish species are scale-less during the early stages of development. The fry observed in Mambo Creek were predominantly at very early scale-less development stages.

The low salinity water discharging from the wetland is remarkably constant in micro-particle concentration. The dynamic process of halocline evolution and dissolution during a tidal cycle may help explain the phenomena of apparent highly variable changes in concentrations and composition of seston reported in previous salt marsh studies [43]. They suggested an extremely frequent sampling program was necessary to obtain reliable estimates of temporal changes in seston concentration and composition which does not appear to be the case in this study.

Previous work in aquaculture has shown that optimal food particle concentration and size is critical to successful rearing of marine fish fry [20, 16]. The channel morphology and halocline effect provides a mechanism to conserve food particles in a highly localized area at concentrations and size ranges similar to those reported as optimal in hatchery operations for a range of marine fish species [20]. The landscape features of the area in which the halocline breaks down appears to enable the fry to exploit a rich food source in a concentrated area over much of the tide cycle. We term this area the "fish fry feeding prism" to denote the dynamic tidal and salinity effects that regulate the system.

V. Conclusion

Saltmarsh areas are relatively robust environmental systems that have evolved to deal with variable hydrological and catchment inputs. They have also been recognized as important features of estuary systems in terms of their ecosystem services. This paper identifies an important hydrological function of the halocline, in terms of structure and function, between the saltmarsh wetlands and the adjacent estuary. The ecotone that occurs in this seascape appears to provide a critical habitat for regulating distribution and feeding of earliest development stages of at least three important estuarine species of fish in this coastal region. An elucidation of the physical and nutrient composition and digestibility of ingested micro-particles discharging from the saltmarsh, and associated seasonal changes, would appear to be an important facet of this phenomenon for further study, for example using isotopes.

Previous studies have suggested a generalized paradigm in which spawning of these species occurs in the mouth of estuaries and early development stages occur in seagrass habitat. Our study indicates this may not always be the case. Spawning and early larval development stages appear to be able to co-occur in areas largely devoid of seagrass, where a saltmarsh halocline exists such as Mambo Creek.

It is this ecotone that needs to be considered as a focus of management measures and environmental impact assessment associated with adjoining developments and landscape modifications that may affect coastal processes. For example, the sand-dune system surrounding Mambo Wetlands provides a freshwater aquifer reservoir that is recharged by precipitation and discharges over time into the low-lying saltmarsh. The dunes have been extensively urbanized during recent decades and the suburbs rely heavily on un-regulated access to the underlying freshwater aquifer for maintaining domestic gardens, particularly during dry periods. This in turn may increase salinity of outwelling water from the saltmarsh during drought periods which would cause the halocline to be impacted.

Further research on this ecotone in similar saltmarsh areas in other estuary types [29] is needed to confirm and elaborate the structure and function of the system processes associated with this important component of fish recruitment in estuary systems.

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