DYMNAMIC GEOMORPHOLOGY AND COASTAL ENGINEERING
OF YANGPU HARBOUR, HAINAN ISLAND, CHINA

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ABSTRACT

Yangpu Harbour is located in the northwest of Hainan Island. It is constituted by Yangpu Bay and Xinying Bay. During 1983-1989 we carried out a series of research work for building deepwater harbour, and studied sedimentation of the embayments. This paper presents a summary of the work on the dynamic geomorphology and coastal engineering of the embayments.

COASTAL GEOMORPHOLOGY

The area of Yangpu Harbour includes three structural systems. Consequently, this location has been subject to a large number of tectonic movements since Pliocene. The major structural system trends toward the northeast. The northern part of Hainan Island borders on a large east-west trending graben feature and Yangpu Bay lies within the southern part of the associated trough feature. During Pliocene and Quaternary, 3000 m of sediment have deposited in the graben as a shallow nearshore facies called the Zhanjiang Formation. There is a substantial amount of volcanic activity associated with the tectonic movements that have occurred in this part of the island. This is evidenced by the rocks, primarily basaltic, exposed on the north side of the bay. The rocks on the south side of the bay are part of the Zhanjiang Formation and consist mostly of gravel, sand and clay in various proportion. The embayment is the topographic expression of the fault that separates the basalt from the Zhanjiang Formation sediments. The area north of the embayment has been subject to neotectonic movements since early Holocene that have continued to the present (Ding, 1964).

Yangpu Harbour consists of two embayments - Yangpu and Xinying. Xinying Bay is a tidal embayment with an area of 50 km². Two rivers enter in the embayment, the Dashui River from the east, and the Spring River from the southeast. Their combined drainage basin area is 1419.44 km² (Figure 1).

The mouth of the embayment is 550 m wide and has a cross-section area of about 5000 m². The mouth area is referred to as the Baimajing Strait. Fluvial sediment carried into the eastern side of the embayment by the two rivers has formed two distinct river deltas. During each tidal cycle, the fine fractions of the delta sediment is eroded and transported seaward during the ebb tide. Near the deltas, more than 90% of the residual sediment in tidal channel and lower beach environments is coarser than 0.1 mm. Muddy sediments are carried onto the tidal flats during flood where they are trapped by the mangrove vegetation. Consequently, the coastline is migrating seaward. According to historical records, the towns of Zhonghe and Xinzhou were the sites of seaport 1000 years ago, during the Tang Dynasty. Currently, however, they are landlocked. In Qing Dynasty, seaport moved to Xinying Town. But now, even a small 20-ton boat can only navigate to Xinying only during high tide time.
Figure 1. Coastal dynamic geomorphologic map of Yangpu Harbour
The northern part of Yangpu Bay is developed on a basalt platform. There were two periods of volcanism. The first one occurred in the late Pleistocene, dating back to 52,000 YBP. It formed a lava field which covered a sand deposit. Another eruption took place 25,000 YBP. And the latest eruption occurred in the Holocene (Wang, 1990). The lava which emitted at that time consists of olivine basalt and tholeiite basalt. It is the olivine basalt of oceanic crust, and the tholeiite of mid-ocean ridge. So it may be an interesting phenomenon if there was/is sea floor spreading in the Beibu (Tonkin) Bay (Nicholls and Ringwood, 1973; Wang, 1990).

The north shore of Yangpu Bay consists of a series of basalt cliff. In the inner part deposits muddy sediment and grows up mangrove while the outer part is presently in erosion.

On the south side of the bay, cliffs that were developed in the Zhanjiang Formation are presently eroded. The Zhanjiang Formation supplies sand and silt for the embayment.

The main tidal channel from Baimajing strait to the ebb tidal delta (block gate shoal) is 10 km long, 400-500 m wide and about 5-25 m deep. The bottom sediment of the main channel consists of three distinctive layers. The upper layer is muddy marine sediment. The middle layer is composed of sand and gravel deposited by river currents. The lower layer consisted of Zhanjiang Formation sediments (silt and clay). The main channel is an ancient river valley that was eroded along two major faults in pre-Holocene river valley. The upper and lower reaches of the channel became the sites of sediment deposition that eventually infilled those parts of the ancient river valley. However, the channel was kept open because of daily erosion of sediment by tidal currents.

The ebb tidal delta at the western end of the tidal channel is currently an area of shoals with maximum water depths of about 5 m. This shallow area is about 400 m long and 80-150 m wide. The ebb tidal delta stratum consists of three layers. The top layer is primarily marine mud (0-3 m). The middle layer is about 7 m thick and consists of sand and gravel deposited by river currents. The lower layer consists of Zhanjiang Formation sediments (indurated silt and clay). The ebb tidal delta developed in three stages. Firstly, before 8500 YBP, the channel was cut by river currents which eroded the Zhanjiang Formation and deposited a 7 m thick layer of sand and gravel. Secondly, during the Holocene sea level rise, the entire embayment was flooded. Finally, tidal currents which developed in the bay deposited marine mud resulting in a gradual shoaling of the ebb tidal delta to its present depth of about 5 m. Core 14C data suggest that this water depth has been maintained over the past 2000 years with net deposition of only about 70 cm since that time.

The sand bank area forms the south side of the Yangpu Bay. The area of the bank lying about the zero contour is about 2.5 km². Between 1955-1980, this area has increased by about 0.7 km². An area of less than 2 m water depth represents about 40% of the total area of the bay. This area also shows an enlargement of about 0.7 km² between 1955-1980, i.e. an increase of <5%. The sand bank is developed on erosion platform of Zhanjiang Formation. Its sediment forms a thin veneer about 0-2 m thick on the platform surface.

COASTAL DYNAMICS

Wind and Wave

Wind variation shows two dominant modes. One of these blows NNE-ENE off the land. This wind is relatively strong but does not produce large waves because of the
shelter effect of land, i.e., there is a short wave fetch with respect to the outer bay. The other major component blows from the sea in a SSW-WSW direction. Because of the exposed nature of the outer harbour, this mode of wind produces the largest waves and is responsible for most sediment transport in the harbour, and of coastal erosion. It can also have a disturbing influence on ships that use the harbour as an anchorage.

The components of the tidal wave climate include wind-generated waves (78%) and sea swell (12%). The most frequent waves entering the harbour are from the southwest. Waves propagating from this direction are also among the largest that enter the harbour. The average height of SW propagating wave is 0.83 m with an average period of 4.5 second. Because the breaking depth of the 4.5 second waves is only 0.8 m, their effect on the erosion of sediment is felt primarily on the southwestern edge and top of the sand bank.

Tide

Tides in Yangpu Bay are of the irregular diurnal type. The mean tidal range is 1.81 m. During the survey of November, 1988, the measured range was 3.8 m. Observations over several tidal cycles show that the ebb portion is shorter (12 hours) than the flood portion (13 hours). This difference is reflected in ebb current velocities with tend to be higher than those observed during the flood. Mean flood velocity (Vf) is above 22 cm/s, and mean ebb velocity (Ve) is 27 cm/s (Table 1). There are differences in flood and ebb velocity depending on water depth. During flood, mean surface water velocity (Vf,s) is above 23 cm/s. Middle water velocity (Vf,m) and bottom water velocity (Vf,b) reach 24 cm/s. During the ebb, surface water currents (Ve,s) have a mean velocity of 31 cm/s. Middle water (Ve,m) and bottom water (Ve,b) flows are respectively 27 cm/s and 24 cm/s. During the ebb, tidal current velocities show a decreasing trend from east to west starting at the mouth of the inner harbour near Baimajing. At Baimajing, surface velocities during the flood reach 51 cm/s. Middle and bottom water velocities are considerably high reaching values of 88 and 84 cm/s, respectively. During the ebb, the surface water flows have a maximum velocity of 84 cm/s while middle and bottom water velocities flow at a rate of 86 and 97 cm/s, respectively.

<table>
<thead>
<tr>
<th>Station</th>
<th>Surface</th>
<th>Middle</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baimajing</td>
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<td>51</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>ebb</td>
<td>84</td>
<td>86</td>
</tr>
<tr>
<td>Main Channel</td>
<td>flood</td>
<td>42</td>
<td>67</td>
</tr>
<tr>
<td>(Yangpu Vill.)</td>
<td>ebb</td>
<td>68</td>
<td>53</td>
</tr>
<tr>
<td>Ebb Tidal Delta</td>
<td>flood</td>
<td>57</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>ebb</td>
<td>54</td>
<td>75</td>
</tr>
</tbody>
</table>

At the main channel (Yangpu Village), maximum surface water flow during the flood stage of the tide is 42 cm/s. Middle water and bottom water flows are 67 and 56 cm/s. During the ebb cycle, surface, middle and bottom water maximum velocities are 68, 53 and 45 cm/s. At the mouth of the outer harbour, in the ebb tidal delta, the maximum velocity of surface water during the flood stage is 57 cm/s. And middle and bottom water
velocities are 49 and 22 cm/s. And during the ebb stage, the surface water maximum flow is 54 cm/s. Middle is 54 cm/s. Bottom is comparable to surface values 56 cm/s.

All of the bottom water velocities are above the threshold value necessary for the erosion and transport of silt and fine sand particles. Maximum ebb velocities are generally higher than flood values so that the modal transport direction of sediment is from the inner to the outer bay.

Residual flow presents water velocities and directions in the absence of tidal flow. These flow are important in understanding sediment distribution patterns (Table 2). The residual flow of surface water has a large river component and tends to follow a direction parallel to the axis of the tidal channel. During the wet season there is less coherency of the residual flows between surface and bottom water (Wang and Aubrey, 1987).

<table>
<thead>
<tr>
<th>Station</th>
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<th>Bottom</th>
</tr>
</thead>
<tbody>
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<td>3/95</td>
<td>3/102</td>
</tr>
<tr>
<td>Main Channel</td>
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</tr>
<tr>
<td>Ebb Tidal Delta</td>
<td>7/230</td>
<td>5/164</td>
<td>8/215</td>
</tr>
</tbody>
</table>

**Table 2. Residual flow velocities (cm/s) and direction**

**Suspended Particulate Matter**

In general, the concentration of suspended particulate matter (SPM) in the water column of Yangpu Harbour is about 0.1 kg/m³. Near Baimajing the integrated (surface, middle and bottom water) SPM concentration during the flood stage average 0.088 kg/m³ (Table 3). During the ebb cycle, this value increased to 0.103 kg/m³. At Yangpu Village, SPM during the flood is somewhat higher than at Baimajing and is similar to the ebb value. SPM measurements at the swash platform station are slightly lower than those observed at Yangpu Village and are comparable to the ebb value noted for the Baimajing station.

<table>
<thead>
<tr>
<th>Station</th>
<th>Flood</th>
<th>Ebb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baimajing</td>
<td>0.088</td>
<td>0.103</td>
</tr>
<tr>
<td>Yangpu Village</td>
<td>0.116</td>
<td>0.119</td>
</tr>
<tr>
<td>Ebb Tidal Delta</td>
<td>0.102</td>
<td>0.102</td>
</tr>
</tbody>
</table>

**Table 3. Suspended particulate matter concentration (Kg/m³)**

**SEDIMENT SOURCES**

There are three major sources of sediment in the Yangpu Bay area. The most important source is material derived from the Dashui River. The drainage basin of this river is 648.3 km². The annual discharge of sediment from the basin into the inner bay (Xinying Bay) is about 74,000 tonnes per year. The Spring River enters the bay from the
southeast. Its drainage basin has an area of 577.8 km². The river's annual sediment discharge is about 67,000 tonnes per year. All of other small rivers draining into the bay have a total drainage basin area of about 81.3 km² and account for an annual sediment discharge of 15,000 tonnes per year. So the total discharge from all river sources is 156,000 tonnes per year. The weight equates to a sediment volume of about 62,000 m³ per year.

The second most important sediment source is from coastal erosion. Most of the coastal erosion occurs in the Zhanjiang Formation along the southern coast of the outer harbour. Each year this source contributes 22,000 m³ of sediment. The northern basaltic coastline is also being eroded but at a significantly slower rate than the southern coast. Its annual contribution of sediment is about 2,000 m³ of sediment. The total contribution of sediment from coastal erosion processes is 24,000 m³ each year.

The third source of material is from coral reefs that are established on offshore islands, at the northwestern end of the bay, and at various locations along the south coast (Figure 1). Sediments in the ebb tidal delta area contain about 33% CaCO₃, those along the subtidal areas of the south shore contain about 22-23% CaCO₃. In the inner bay, the sediments contain only about 0.6-0.9% CaCO₃. The distribution of CaCO₃ in outer bay sediments is consistent with the distribution of reefs along the coastline. It also shows that the sediment from the outer bay is not transported too far into the inner bay. The total amount of sediment from this biogenic source is estimated to be not greater than about 4,000 m³ per year. The total amount of sediment supplied to the bay area from all sources is about 91,000 m³ per year.

COASTAL ENGINEERING

Yangpu Harbour is a natural harbour. The main channel is 10-23 m deep and 500-800 m wide. The huge water and large currents are major factors for keeping channel open. The Northern, Eastern and Southern parts of the harbour are 10m-deep marine terraces that stop the wind wave from north, northeast, east and south. The frequency of strong winds is a little, >6 wind (force) scale only 0.42%. Wave heights H₁/₁₀ < 0.5 m are 99%, H₁/₁₀ ≤ 0.8 m are 99.88%, but those H₁/₁₀ ≥ 1 m are only 0.06%. The frequency of wave height ≥ 1.2 m is zero. So, Yangpu Harbour is a good harbour. The harbour area, geologically, is a platform of basalt and the Zhanjiang Formation. The geologic base is quite good. And an abundant rocks material, broad land area. But now, the problem is only a blocked gate shoal and shallow waters, requiring dredging for a navigation channel.

Yangpu Harbour is a tidal inlet, in which Xining Bay is a tidal water trap: the main channel is the tidal water pass; the block gate shoal is the ebb tidal delta. Core data and regional geomorphological analysis show: the main channel and block gate shoal were originally a fossil river valley 8,500 YBP. The valley's elevation is minus 25-30 m. The top surface of the river deposits has a minus 20 m elevation. The ancient river's gradient was 0.07%. The ancient Dashui River and Spring River joined the ancient river valley in the area of today's Xining Bay, which finally entered the open sea at the -20 m contour through the main channel and block gate shoal. With the post-glacial sea level rise, the coastal plain was drowned as Yangpu Harbour and ancient river valley were filled with marine sediment while the ancient river valley was kept as today's deep water channel because of the tidal flushing and scoring of tidal prism. But, the section of the block gate shoal disappeared due to siltation.
Dating data (according to $^{14}$C) from the block gate shoal show: the average sedimentation rate was 0.16 cm/a during the last 8500 years. And during the last 3000 years the rate was 0.10 cm/a, which is consistent with the world wide sea level change processes and now (according to $^{210}$Pb inventory analysis) is 0.52-1.06 cm/a. Hence, the natural formation process of the block gate shoal is shown.

We have worked out the erosion and siltation budget for the last decades of the area by comparing the six 1947-1983 navigation maps and the bathymetric maps. In this work, we transferred the different depth bases of various maps into a same theoretical depth base, and then calculated the volumes of the block gate shoal, the main channel at different periods. We find the block gate shoal with an erosion rate 2-10 cm/a during 1947-1974, a siltation rate 7.2-4.5 cm/a during 1974-1983; and the main channel with an erosion rate of 1.2-5 cm/a during 1947-1974, a siltation rate of 5 cm/a during 1974-1983. In general, however, the block gate shoal and main channel were both subjected to slight erosion during last fifty years. The total erosion volume of the block gate shoal is one million cubic meters and that of the main channel is 0.7 million cubic meters.

Therefore, for the past 8000 years, the sedimentation rates of the area have been very small and the submarine reliefs are nearly stable although sometimes there was slight erosion or siltation, which does not interfere with constructing a harbour and digging a navigation channel in the area.

Tides in Yangpu are irregular diurnal type. The mean tidal range is 2 m and tidal prism is 200 million cubic. Tidal cycles show that the ebb current velocities are above the threshold value necessary for the eroding and transporting silt and fine sand particles (Figure 2).

According to dynamic geomorphology analysis, the paper verified the advantageous conditions for construction of Yangpu Harbour, suggested the optimum direction as 45°-225° of navigation channel passing through the block gate shoal (ebb tidal delta), and predicted that the siltation rate following digging the channel will be about 0.5 m/y.

REFERENCES


SYSTEMS CONCEPT FOR AN OFFSHORE MARICULTURE FACILITY

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ABSTRACT

As the world's population rapidly increases and changes its dietary habits, tremendous demands will be placed on mariculture (aquaculture in the marine environment) to produce large quantities of fishes, crustaceans, mollusks, and seaweeds. Meanwhile, floating platform technology now provides the capability of working on and below the surface of the ocean many miles from the nearest coastline. Horizontal positioning of the platform, with respect to geographical location and orientation, can be achieved utilizing the renewable energy sources available. Proposed applications for large floating structures include international airports, military bases, ocean mining, industrial facilities, waste treatment plants, ocean energy conversion, weather stations, recreation centers, and offshore mariculture.

The use of floating platforms for offshore mariculture appears to have many advantages over conventional mariculture techniques. Mariculture will become more and more restricted in coastal areas due to increasing population densities, land usage, oxygen depletion, waste disposal, and agricultural-industrial-domestic runoff. Offshore mariculture offers advantages due to the large mixing and dilution ratios of the containment area to adjacent water masses, which increases productivity and the associated economic benefits. Another potential advantage involves the ability to use deep ocean water, which is nutrient-rich and pathogen-free, to further improve productivity and systems design.

INTRODUCTION

Mariculture is a term used to designate aquaculture within the marine environment. Since the marine environment includes bays and estuaries, as well as the world's oceans, offshore mariculture is used to distinguish cultivating activity in unprotected marine waters, regardless of its distance to the nearest coastline. Offshore mariculture is a relatively new concept. Although much of the fundamental technology that it requires is already well advanced, new applications will be needed in the future.

Some advantages from locating a mariculture facility in the offshore environment include (P2M, 1991):

1. A virtually unlimited supply of water available at different temperatures.
2. Avoidance of coastal-zone use conflicts.
3. Increased survival, growth rates, stocking densities, and product quality.
4. Facility mobility and the ability to change location seasonally.
In addition, an offshore mariculture facility can be developed in conjunction with artificial upwelling of nutrient-rich water, electrical power production, deep seabed mining, and other ocean resources utilizing a large floating platform for a base of operations (Takahashi and Yuen, 1991). This concept is illustrated in Figure 1.

Figure 1. Systems concept for an ocean resources platform

Although the benefits mentioned above are important to consider, the offshore environment remains a more uncertain legal and political environment to operate in than the coastal zone. Moving away from the overlapping jurisdictions of local, state and federal governments is an appealing prospect; however, constraints of a more international nature will be encountered. While an enormous amount of time and money is required to satisfy the numerous regulations concerning the use of near-shore waters, at least they are discernable. The requirements to be satisfied in offshore waters are yet to be determined, as well as the extent to which a mariculture facility operating offshore could be legally protected (Hanson, 1974).
OFFSHORE PLATFORMS

The base of operations for an offshore mariculture facility should be designed according to the type of species to be cultivated, containment methods, harvesting and processing needs, geographic location, and other appropriate factors (Ribakoff, 1974). Options can be broadly categorized into coral atolls, bottom-supported structures, and floating platforms.

Coral atolls occur naturally in many parts of the Pacific Basin and would require a minimum amount of modification and capital investment due to their natural morphology. Pacific Basin atolls can be grouped into six major chains: the Marshalls, Gilberts, Carolines, Marianas, Line Islands, and the Hawaiian Archipelago. Any development of mariculture in these areas should give serious consideration to the following characteristics of atolls:

1. Enclosed basins or lagoons of various depths and diameters occur naturally in many cases.
2. Because of a volcanic foundation, atolls are usually in close proximity to deep water where phytoplankton nutrients are abundant.
3. Atolls are highly stable and survivable, and require little regular maintenance.
4. Many atolls lie within inhabited island areas where some type of economic development is desired.

The majority of bottom-supported structures have been constructed by the offshore oil and gas industry. The basic design of these platforms consists of a flat deck, a supporting framework, and pilings or legs which are embedded or anchored in the sea floor. Since the platform is moored and rigid, it is considered to be highly stable and no motions other than vibrations resulting from wave impact are usually discernible on deck. The major disadvantage, with respect to offshore mariculture applications, is that this type of structure is generally limited to water depths of approximately 100 meters (300 feet).

Floating platforms, including conventional ships and barges, as well as semisubmersible platforms, appear to be the most promising concept for offshore mariculture development. The chief advantages of semisubmersibles are a high level of motion stability and high survivability in extreme environmental conditions. The major disadvantage results from the fact that water-plane area is minimal giving relatively little buoyancy force per unit of submersion. Overturning moments and added loads must be compensated for by ballast adjustments, in contrast to the spontaneous compensation occurring in ships and barges (Ribakoff, 1974).

Another concept, which is especially applicable for large floating structures in turbulent seas is indirect displacement. Indirect displacement with pneumatic stabilization has the following advantages over conventional direct displacement vessels (Innis, 1991):

1. Simpler on-shore construction of smaller modules.
2. Greatly reduced forces at module junctions.
3. Reduced draft and mass.
4. Greater ability to absorb impact loads.
5. Greater ability to utilize the energy causing destabilization.

The principle behind indirect displacement is that the vessel is supported on a compressible bubble of air rather than incompressible water. The bubble acts as a shock absorber to mitigate pitch and heave motions due to changes in the surface conditions of the ocean.

**CONTAINMENT SYSTEMS**

Potential species for offshore mariculture can be broadly categorized into the following groups:

1. Fish
2. Crustaceans
3. Mollusks
4. Seaweeds
5. Marine mammals and reptiles

The type of containment system to be designed is highly dependent upon the species chosen to be cultured.

Containment systems for fish involve either physical enclosures or aggregation devices (passive containment). Submersible cages appear to be the only type of physical containment having any potential for the offshore environment. Since water movement produced by waves is largely a surface phenomenon and the water particles rotate in circular orbital motions, a submerged cage is less susceptible to damage from waves than conventional cages. In deep water, the wave motion at a depth of one-half the wave length is considered to be negligible.

Optimal cage volume is believed to be approximately 4000 square meters (40,000 square feet); however, analysis based on the biological behavior of the particular fish species to be cultured should be conducted on an individual basis. The cage should also be designed so that it is possible to operate it safely from the surface even under unfavorable weather conditions, which are common in the offshore environment. The final design of a submersible cage system, including the number, size, shape, materials, mooring, and ballasting of cages will also depend on other systems to be used in conjunction with the containment system.

It is anticipated that, in the future, cage-culture will become obsolete. The combination of economics and severe weather conditions will lead to methods of passive containment. Passive containment is defined as a system that keeps fish in the vicinity of a desired area without the use of walls or cages. With any passive containment system there exists the possibility of losses due to emigration; however, systems can be established which require little maintenance and will attract and hold natural fishery resources (Brock, 1991).
Passive containment systems capitalize on the behavior of fish and include attraction to light, sound, and shelter. Pneumatic barriers (bubble fences) appear to have potential for offshore mariculture applications. Assuming an enclosure several hundred meters in diameter could be deployed at a depth of 600 meters (2000 feet), the advantages of such a system would be numerous. The system would be survivable in any weather, no biofouling would occur, bubbles would automatically oxygenate the enclosed water column, surface waters would remain calm within the enclosure since the bubbles act as wave absorbers, and a degree of artificial upwelling could occur by entraining deep water with the rising bubbles. Furthermore, if hydrogen production systems could be integrated with offshore mariculture, the bubble fence concept would be an attractive use for the waste oxygen that this process produces (Hanson, 1974).

**ARTIFICIAL UPWELLING**

The offshore environment is believed to have tremendous potential for mariculture. Since the majority of oceanic surface waters are practically nutrient deserts, the most promising concept for offshore mariculture is artificial upwelling. More than 40% of the world’s fisheries catch comes from 0.1% of the ocean’s total surface area, where natural upwelling occurs. Artificially upwelled fisheries may actually create a new maritime industry, as deep ocean water at depths from 200 meters (700 feet) begins to increase in nutrient-rich and pathogen-free characteristics.

It has been demonstrated that fish can be conditioned to congregate at a feeding site. With offshore mariculture, artificial upwelling of deep ocean water offers the opportunity to capitalize on this behavior. Deep ocean water, at a depth of 600 meters or 2000 feet (nominally) contains two orders of magnitude more nitrates (NO₃, NO₂) and a magnitude more phosphates (PO₄), compared to surface waters (Table 1). As the majority of the nitrogen and phosphorus contained in deep ocean water is derived from the decay of previous biological production from the upper layers of the world’s oceans, deep ocean water represents an ideal source of nutrients for photosynthesis and mariculture production (McKinley and Takahashi, 1991).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface Water</th>
<th>Deep Ocean Water</th>
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</thead>
<tbody>
<tr>
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<td>8.9</td>
</tr>
<tr>
<td>Nitrogen (NO₃ plus NO₂)</td>
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</tr>
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<td>Nitrogen (NH₄)</td>
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</tr>
<tr>
<td>Phosphorus (PO₄)</td>
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Maintaining relatively dense, artificially upwelled water at or near the surface is a significant engineering challenge. The three ways to achieve surface retention are through physical containment or by lowering its density through dilution or solar heating. Creative engineering design, which makes efficient use of the natural energy fluxes available, is essential to establishing the feasibility of any artificial upwelling system. In addition, an offshore mariculture system could utilize nutrient concentrations or temperature differential barriers as a means of passive containment to retain stock.
RENEWABLE ENERGY SOURCES

The oceans are the world's largest solar energy collector and storage system. Incident solar radiation is stored either directly or indirectly in various forms within the global ocean system. Specifically, solar energy is stored directly in the form of thermal heat, and indirectly as wind, waves, and currents created by the temperature differences between the oceans and the surrounding atmosphere.

Types of direct solar energy systems include passive solar heating, active water and space heating, photovoltaics, and thermal electrical systems. While solar energy conversion techniques appear to have low conversion efficiencies (5 to 20%), this is offset by the fact that the energy resource is free and infinitely renewable. The important technical benefits of an ocean-based, solar energy conversion system would be the proximity to an excellent thermal sink and source of working mass, mobility of rotation and translation, space available for large solar collector areas, and logistical ease in initial construction and maintenance.

Another major source of renewable energy is the wind. Wind energy has considerable application potential in the offshore environment. This is due to the fact that wind patterns are more consistent over and near large bodies of water. In addition, many offshore areas have consistently high average wind speeds. A preliminary concept, integrating solar and wind power to produce electricity for an offshore floating platform is illustrated in Figure 2.

Figure 2. Preliminary concept integrating solar and wind power
The two basic types of wind machines are mechanical and electrical. Recent interest has focused on electricity production. In general, the larger the wind machine, the more power it can extract from the wind; however, there are limiting factors which must be considered in designing these machines. These include blade balance and vibrations, effect of wind gusts, gravitational and gyroscopic forces, and the blocking effect of the tower itself. Costs rise geometrically with size, and blade diameters in excess of 100 meters (300 feet) can develop excessive amounts of stress. Under high wind conditions, there is also potential for excessive stress to be placed on the blades. Protective measures must be designed to automatically shut the systems down by folding the blades or tilting the tower back under these conditions (Pryde, 1983).

The most potentially valuable source of renewable energy associated with the ocean is ocean thermal energy conversion, commonly known as OTEC. This is because the waste effluent from OTEC systems can be utilized as the nutrient source for mariculture systems. The basic concept of OTEC is to extract energy from the temperature difference between surface and deep ocean water (at approximately 1000 meters or 3000 feet). Solar energy absorbed and stored as heat in the upper layer of the ocean and cold water transported from the polar regions provide the source of this temperature differential. In equatorial areas, the temperature differential is sufficient (20 degrees centigrade) for OTEC operations year-round.

The open-cycle OTEC system uses seawater as the working fluid and has the advantage of producing desalinated fresh water as a by-product. In addition, refrigeration and mariculture systems could be designed based on the availability of cold, nutrient-rich water which would be available for use at no extra cost. The major components still undergoing development for OTEC systems are open-cycle turbines and flexible cold water pipes using bottom-mounted pumps. While there have been numerous development projects over the past decade, none have reached commercial fruition to date. Utilization of small-scale OTEC in conjunction with offshore mariculture systems may prove to be essential to the continuing development of such technology.

CONCLUSION

Current technology has reached a level in which the construction of an offshore mariculture facility based on a large floating platform appears to be technically feasible; however, since any project of this magnitude also needs to be justified economically and socially, other factors besides the state of the existing technology must also be considered. In the case of offshore mariculture, large floating platforms, containment systems, artificial upwelling concepts and renewable energy systems need to be designed, integrated, and analyzed for overall costs and benefits to society as a whole. While the cost of producing food from agriculture and fisheries are expected to continue to rise exponentially due to decreasing land, fossil-fuels, and natural fish stocks, mariculture costs should continue to decline with technological improvements and become increasingly competitive with time.

ACKNOWLEDGMENT

The authors would like to acknowledge the assistance of Dr. Cengiz Ertekin in the development of this paper.
REFERENCES


SYSTEMS FOR CONTROL OF ENVIRONMENTAL CONDITIONS IN REGIONAL MARINE ECOSYSTEM - A FUNDAMENTAL STUDY

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*National Research Institute of Fisheries Engineering
Yamaguchi, Japan

ABSTRACT

This study is being executed as a part of the consolidated research carried out by Nihon University. The study is being developed basically by two main research groups: the first group working on the development of a structure comprising marine control systems and on the investigation of geographical conditions, and the second group researching the repercussion effects caused by these marine control systems as well as various peripheral techniques.

INTRODUCTION

In Japan, where about one-third of fishery is imported from various foreign countries, techniques for increasing and nurturing fishery resources are required, in order to enhance productivity in the seas controlled by Japan. This need results from an increase in demand and coastal fishery restrictions in these foreign countries. Furthermore, the development of optimal utilization of ocean space has also become necessary. Through marine observation, the authors have decided to evaluate changes in both the physical and biological environments by installing a structure at Futaoi Island, Shimonoseki City, Yamaguchi prefecture.

The overall aims of this project included:

1) Development of recreation space, which efficiently uses coastal areas,

2) Increased efficiency of fishing along coastal areas, and

3) Establishment of a marine area control system and evaluation of the effect of creating ocean space.

OUTLINE CONDITIONS FOR TEST AREA

Outline of Area

Futaoi Island is situated at Hibiki-Nada, 12 km offshore to the northwest of Shimonoseki City (Figures 1 and 2). Futaoi Island occupies a small area of 2.32 km², and has 41 households and a population of 164.
The coast line has a total length of 13.31 km, and is gently curved towards the south. The main industry is fishing. Its climate is comparatively warm as a result of the Tsushima Warm Current and its annual average air temperature is 16.1°C. Its rainfall is 1.715 mm.

TEST OUTLINE

Results of Preliminary Test on Marine Area

Tests at Futaoi Island bay showed that the seabed topography inside the bay has a comparatively gentle slope to about 10 m depth, but past this area, the slope drops away sharply to create many undulations. The seabed geology indicated substantial gravel and reefs from the shore to about 15 m depth. Further out, large-grain sand, medium-size sand, and fine-grain sand were widely distributed (Regional Fishery Plan for Futaoi Island, 1985; Hydrographic Dept. of Maritime Safety Agency, 1985).

Inside the bay, a tidal current was flowing, forming a large vortex. The water temperature at the 15 m depth layer had a maximum of 25.0°C at low tide, and a minimum of 24.38°C at high tide. The salt content was a maximum of 33.5%, and a minimum of 32.5%. Both above values were measured at high tide.

Sunken Structure

The Ocean Conditions Control Structure used in the present study and installed in the marine area was the Rock Reef Type-12, whose shape is shown in Figure 3. At positions 1.5 m away from both ends of concrete frame measuring 10.4 m in width, 6.6 m in length and 3.85 m in height, two pieces of natural stone 70 to 80 cm long were placed, and at their center (3.6 m), natural stones with diameters of 20 to
40 cm were piled up. This structure has two functions. The first is the function of an artificial reef allowing fry and young fish to shoal and reside there. The second is the function of a spawning ground where fry and young fish can shoal, grow and spawn.

In addition, natural stones have the power to activate living things, and through their use, a living environment is created which is conducive to habitation by living organisms (Ocean Fisheries Experimental Station of Yamaguchi Pref., 1988; Sakuta, et al., 1987).

The structure was installed on October 23, 1989, in a marine location 100 m offshore at depth of 12 m as shown in Figure 4. The structure was installed at a right angle to the predominant flow in the bay, and visual observation of the aggregation of living organisms was made by diving surveys (Sugawara, et al., 1989).

DIVING SURVEY RESULTS

After the structure was sunk, visual diving surveys were carried out five times in order to evaluate biological aggregation conditions in the period February to December, 1990. The investigation method used was camera and video photography. For the quantitative evaluation of living organisms, the area separation method was used.

Installation Conditions

The installation conditions of the structure were maintained in a satisfactory state without excavation due to bottom-layer flow and sinking of the structure by its own weight. Furthermore, no damage to the natural stones due to currents was observed, and the required quantity of natural stones was piled up.
The west side of the artificial reef is mainly formed by the boulder zone. The east side features many natural reefs, and is severely undulated. The highest location is 7.0 m.

Aggregation Conditions of Living Organisms

Viewed from the results of the diving survey carried out during the period from February to December, 1990, the fish distribution expanded as the days elapsed, and the body length of fish and the apparent quantity also increased.

In particular, the aggregation of Trachurus japonicus, Apogon semilin eatus and Chromis rotatus notatus was conspicuous, and these three kinds of fish were found in shoals in the area surrounding the artificial reef. Useful fish such as Parapristipoma trilineatum, Pagus major, Girella punctata, Epinephelus awoara, etc., have now been confirmed to be present. Since there is no significant current on the west side of the artificial reef, and the topography is quite uniform, many kinds of fish are to be found such as Girella punctata, Chromis rotatus notatus, Suezichthys gracilliss, etc., because the vicinity of the artificial reef was favorably affected by the Structure. On the east side, which is greatly affected by the natural reefs found there, many kinds of fish such as Suezichthys gracilliss, Thamnaconus modeatus, Stephanolepis cirrhifer, Oplegnathus fasciatus, and Trachurus japonicus were gathered around the artificial reef and natural reefs.

Furthermore, regarding shore-grown organisms, the number of Turbo cornutus with a shell height of 70 mm or more and of Haliotis discus with a shell height of 90 mm or more, both found on and inside the artificial reef, were 0.07 pcs/m² and 0.29 pcs/m², respectively.

However, in December 1990, there were found to be 0.29 pcs/m² each of Turbo cornutus and Haliotis discus, thus indicating that the number of living Haliotis discus is tending to increase.

Biological Four Compartments Model

This study examines an predict method which first evaluated the changes in wave patterns, currents and other aspects of the physical marine environment, then attempts to clarify the impact these changes will have on biological production. If a regional environmental impact system relies totally on-side observations, there are limitations in scale.

Thus development of a predict method which incorporates a quantitative analysis-based 'structural model' of the coastal zone region is desirable (Administration Inspection Bureau, 1985).

We attempt here to construct a biological model and to consider the characteristics of the model (Kishi, et al., 1981).

This model is based largely upon Kishi's producer, PO₄-P as a limiting nutrient, zooplankton as a predator of chlorophyll-a and detritus as particles produced the mortality of plankton and by egestion. The dissolved detritus is not considered as a first step because its variation with time is very slow.
Phytoplankton: $P$

$$\frac{dP}{dt} = V_1(T,N) \cdot V_2(I(t)) \cdot P - \beta \cdot P - \alpha \cdot P - P/(P + D)g(P,D) \cdot Z$$  \hspace{1cm} (1)

Zooplankton: $Z$

$$\frac{dZ}{dT} = g(P,D) \cdot Z - \gamma \cdot g(P,D) \cdot Z - \delta \cdot Z - \varepsilon \cdot Z$$  \hspace{1cm} (2)

Detritus: $D$

$$\frac{dD}{dt} = \beta \cdot P + \alpha \cdot P + \delta \cdot Z - \phi \cdot D$$  \hspace{1cm} (3)

Nutrient: $N$

$$\frac{dN}{dt} = -V_1(T,N) \cdot V_2(I(t)) \cdot P + \beta \cdot P + \phi \cdot D + \varepsilon \cdot Z$$  \hspace{1cm} (4)

where the formation of Eqs. (1) to (4) are indicated in Table 1.

**Discussions about Stability and Uniqueness**

If the systems of biomass represented by Eqs. (1) to (4) have solutions, biomass will in time oscillate diurnally. The integrated value of each biomass during one day will not vary.

We replace such mean values of $P$, $Z$, $D$, and $N$, respectively, and $P' + Z' + D' + N'$ equals constant, and call such values the “steady state solutions.” The steady state solutions will satisfy the following equations

$$[V_1(T,N') \cdot V_2(I(t))dt - \beta - \alpha] \cdot P' - g(P',D') \cdot Z = 0$$  \hspace{1cm} (5)

$$[(1 - \gamma) \cdot g(P',D') \cdot \delta - \varepsilon] \cdot Z' = 0$$  \hspace{1cm} (6)

$$\phi \cdot D' - [V_1(T,N') \cdot V_2(I(t)) - \beta] \cdot P' + \varepsilon \cdot Z' = 0$$  \hspace{1cm} (7)

$$P' + Z' + D' + N' = M = \text{const.}$$  \hspace{1cm} (8)

we may conclude from Eqs. (5) to (8) that:

(i) The system is stable for any parameter values.

(ii) If $P' + Z' + D' + N'$ is constant, then $P'$, $Z'$, $D'$ and $N'$ will be independent of the initial values and will take the fixed values.

(iii) If we can decide the value of $P'$, $Z'$, $D'$ and $N'$ based upon observations, the values of any there parameters can be decided (e.g., we solve Eqs. (1) to (4) numerically for two different initial values under the values of parameters shown in 4-3). Figure 5-a shows the time-dependent values of $P$, $Z$, $D$ and $N$ for the initial values; $P=3.0$, $Z=7.54$, $D=0.374$, $N=0.05$; these values are selected to be near values observed in large tank test in 1988. Figure 5-b shows the time-dependent values of $P$, $Z$, $D$ and $N$ for the initial values; $P=0.374$, $Z=0.05$, $D=3.0$, $N=7.54$. 

-375-
Table 1. Formation of biological terms in the four compartments model

<table>
<thead>
<tr>
<th>Term</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth of phytoplankton</td>
<td>$V_f(T,N) = V_m \cdot N / (K_S + N)$</td>
</tr>
<tr>
<td></td>
<td>$V_x(I(t)) = a \cdot I \cdot \exp(1 - a \cdot I)$</td>
</tr>
<tr>
<td></td>
<td>$I = I(t)$</td>
</tr>
<tr>
<td></td>
<td>$= I_{opt} \cdot \sin^3(\pi/12)t \cdot \exp(-kd)$ (day time)</td>
</tr>
<tr>
<td></td>
<td>$= 0$ (night time)</td>
</tr>
<tr>
<td>Extracellular release</td>
<td>$\beta \cdot P$</td>
</tr>
<tr>
<td>Grazing</td>
<td>$g(P,D) = Z$</td>
</tr>
<tr>
<td></td>
<td>$g(P,D) = R_{max} (1 - \exp(-\lambda \cdot P \cdot \lambda \cdot P^<em>))$ (if $P &gt; P^</em>$)</td>
</tr>
<tr>
<td></td>
<td>$g(P,D) = 0$ (if $P &lt; P^*$)</td>
</tr>
<tr>
<td>Natural death of P</td>
<td>$\alpha \cdot P$</td>
</tr>
<tr>
<td>Egestion of Z</td>
<td>$\gamma \cdot g(P,D) \cdot Z$</td>
</tr>
<tr>
<td>Natural death of Z</td>
<td>$\delta \cdot Z$</td>
</tr>
<tr>
<td>Bacterial decomposition of D</td>
<td>$\phi \cdot D$</td>
</tr>
<tr>
<td>Urine of Z</td>
<td>$\epsilon \cdot Z$</td>
</tr>
</tbody>
</table>

where $V_m$ : maximal photosynthetic rate

$K_S$ : half saturation constant

$I_{opt}$ : maximal light intensity on sea surface

$a$ : constant in light-photosynthetic curve

$k$ : light extinction coefficient

$d$ : water depth

$\beta$ : extracellular release rate

$R_{max}$ : maximal grazing rate

$\lambda$ : constant in grazing curve

$P^*$ : threshold of $P$ in grazing

$\alpha$ : natural death rate of $P$

$\gamma$ : excretion rate of $Z$

$\delta$ : natural death rate of $Z$

$\phi$ : bacterial decomposition rate of detritus

$\epsilon$ : urine by $Z$
These two time-dependent features of four biomass systems show that, for the same parameter, the solutions of this system approach to the same points for different initial values.

This fact shows that the solutions of this system are stable.

Figure 5. Time-dependent features of P, Z, D, and N (integrated with \( t \) in Eqs. (1) to (4)). Initial values are different in (a) and (b), but in the time solutions they reach the same values.
FUTURE ACTION TO BE TAKEN

As diving investigation on the structure was repeated, it has been confirmed that fish and shellfish are aggregating to the structure to the same degree as on the natural reef on the east side, which has already become good fishing ground.

From this, it is expected that if, in the future, this structure is provided with a feeding environment and the biological effects improve, the function of the structure as a breeding ground and the awareness and feeling towards the "Fisheries Controlled for Resource Management" by fishermen at Futaoi Island will be enhanced, with a positive attitude being developed.

Regarding the future schedule, the authors will undertake investigation and examination into the following:

1) Continuous investigation into changes in awareness of fishermen by the formation of a fishing ground.

2) Continuous investigation into the biological effects due to installation of the structure.

3) Continuous measurement of growth rate of seaweed presently introduced on the structure, and investigation into activity characteristics of infant abalone by stocking abalone seeds.

4) Examination of selectivity of stones as living areas for seaweed and abalone.

5) Examination of the relation between the light quantity and the growth quantity, and the feeding environment formation method.

6) Examination of the possibility of realizing marine stock farming through fishing ground formation by dumping natural stones into the marine area.

7) Examination of the environmental predict method of the regional marine taking into consideration biological productivity.

REFERENCES


REDUCING THE RISK OF PEARL OYSTER DISEASES
IN POLYNESIAN LAGOONS

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ABSTRACT

Pearl oyster diseases have become endemic in most major pearl culture areas. Poor oyster health and farm mortalities have profound impacts on the profitability of individual farms, result in increased pressure on already depleted natural stocks, and cause instabilities in the pearl market. This paper discusses management approaches to disease prevention in new pearl culture areas in the Pacific Islands.

The etiology of pearl oyster diseases is often poorly understood, and the available literature is meager. Commensal organisms, parasites, pathogens and secondary infections are difficult to distinguish in bivalves, and the taxa associated with pearl oyster diseases in different culture areas are diverse. It is therefore inappropriate to base farm size limits on estimates of the original stock abundance, phytoplankton production and oyster filtration rates, or lagoon water turnover, particularly where no disease has yet been identified. Histories of disease patterns, farming practices and farmed stock numbers in different lagoons could provide useful guidelines, but such information is carefully protected.

Management must be based on the understanding that there is a continuum of increasing disease risk with increasing farm numbers and densities. The industry itself must determine its own acceptable limits on the number of farms in any enclosed body of water, the number of oysters on farms, spacing and cleaning regimens, and restrictions on stock transfers. The short-term rewards of higher production must be balanced against the increased risk of disease. No ecologically determined limit can provide any assurances.

INTRODUCTION

The culturing of pearls is often described as "more art than science." Indeed, outside of a solid body of Japanese and Indian work on the Akoya oyster (Pinctada fucata), there has been little publicly-funded research into the techniques of growing pearl oysters and culturing pearls. Pearl farmers perhaps prefer to cultivate the mystique of the trade, but this condemns much research to overly-protective proprietary concerns.

In the last few decades, however, independent pearl culture has become established throughout S.E. Asia, Australia and the atolls of the Pacific (Table 1). Particularly in the small island countries of Polynesia and Micronesia, pearl culture developments have the potential for dramatic improvements to rural economies, previously reliant on copra, pearl shell and fisheries resources, and the vagaries of these commodity markets. Pearl culture brings lucrative returns, and wider socio-economic benefits: reversing rural-urban drift and revitalising atoll economies by providing stable employment and demand for support industries. The best example is in French Polynesia, where 2,300 people are directly employed in an industry worth US$41 million
Table 1. Pearl culture areas throughout the world

<table>
<thead>
<tr>
<th>AREA</th>
<th>SPECIES CULTURED</th>
<th>EXPORTS$^{(1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAPAN</td>
<td><em>P. f. martensii</em></td>
<td>Domestic production 1988: $476 million$^{(2)}</td>
</tr>
<tr>
<td>OKINAWA</td>
<td><em>P. margaritifera</em></td>
<td>One farm only. Hatchery-bred.</td>
</tr>
<tr>
<td></td>
<td><em>Pteria penguin</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>P. maxima</em></td>
<td>Hatchery-bred.</td>
</tr>
<tr>
<td>FRENCH POLYNESIA</td>
<td><em>P. margaritifera</em></td>
<td>$41 million in 1989</td>
</tr>
<tr>
<td>N.W. AUSTRALIA</td>
<td><em>P. maxima</em></td>
<td>$71 million in 1989</td>
</tr>
<tr>
<td>W. AUSTRALIA (Shark Bay)</td>
<td><em>P. albina albina</em></td>
<td>Four farms.</td>
</tr>
<tr>
<td>N.E. AUSTRALIA (Gt Barrier Rf)</td>
<td><em>P. margaritifera</em></td>
<td>Several farms. Experimental.</td>
</tr>
<tr>
<td></td>
<td><em>P. radiata</em></td>
<td></td>
</tr>
<tr>
<td>CHINA</td>
<td><em>P. f. martensii</em></td>
<td>$8 million in 1988</td>
</tr>
<tr>
<td>TAIWAN</td>
<td><em>P. f. martensii</em></td>
<td>$2 million in 1988</td>
</tr>
<tr>
<td>KOREA</td>
<td><em>P. f. martensii</em></td>
<td>$0.3 million in 1988</td>
</tr>
<tr>
<td>INDONESIA</td>
<td><em>P. maxima</em></td>
<td>$12 million in 1989</td>
</tr>
<tr>
<td>PHILIPPINES</td>
<td><em>P. maxima</em></td>
<td>$4 million in 1989</td>
</tr>
<tr>
<td>MALAYSIA</td>
<td><em>P. maxima</em></td>
<td>$1 million in 1988</td>
</tr>
<tr>
<td>THAILAND</td>
<td><em>P. maxima</em></td>
<td>$1 million in 1988</td>
</tr>
<tr>
<td>BURMA</td>
<td><em>P. maxima</em></td>
<td>$0.6 million in 1989</td>
</tr>
<tr>
<td>INDIA</td>
<td><em>P. fucata</em></td>
<td>$3 million in 1989</td>
</tr>
<tr>
<td>COOK ISLANDS</td>
<td><em>P. margaritifera</em></td>
<td>Manihiki. Others developing.</td>
</tr>
<tr>
<td>PALAU</td>
<td><em>P. maxima?</em></td>
<td>One farm.</td>
</tr>
<tr>
<td>FIJI</td>
<td><em>P. margaritifera</em></td>
<td>One farm only.</td>
</tr>
<tr>
<td>MEXICO (Pacific coast)</td>
<td><em>P. margaritifera</em></td>
<td>Experimental. Now defunct?</td>
</tr>
<tr>
<td>SUDAN</td>
<td><em>P. margaritifera</em></td>
<td>Fluctuates. For shell only.</td>
</tr>
</tbody>
</table>

NOTES:  
(2) May include re-exports and processed products. Source: Gervis and Sims, in press.
in exports per annum (1989 data, Table 1; Coeroli, 1991). Black pearl culture has also become rapidly established in the Cook Islands, where the first harvest occurred only in 1989, yet the current value is around NZ$6 million (US$4 million).

Other Pacific Island governments and development agencies are keen to emulate these successes in French Polynesia and the Cook Islands. Pilot programs have recently begun in the Marshall Islands, Federated States of Micronesia, Tonga, the Solomon Islands, Kiribati, and Tuvalu, assessing pearl oyster resources, and initiating spat-collection and grow-out trials. While wild pearl oyster stocks are often scarce, research advances with pearl oyster hatchery technology offer scope for expansion of pearl culture to lagoons with depleted stocks, or none at all.

This bright prospectus is somewhat dimmed by the Damoclean Sword of pearl oyster diseases. These have, at some time or another, decimated pearl farm stocks in almost every established pearl culture area in the world (Table 2). Mass mortalities among pearl farms usually have unknown etiology, but invariably result in poor quality pearls, directly reducing farm profitability, and damaging the market price and the industry's reputation. Greater pressures are placed on wild stocks to replenish the farm losses, and oyster transfers from one region to another become increasingly risky. Mortalities can also spread to wild pearl oysters and other bivalves (P. maculata, Tridacna maxima, Arca ventricosa, and Spondylus varius) (Coeroli, 1983; M. Coeroli, pers. comm.), decimating the pool of natural broodstocks and subsistence resources.

The threat of pearl oyster diseases makes pearl culture less attractive to private investors, governments and aid agencies, adding an air of uncertainty to what is otherwise a stable, lucrative development option. The highly protective nature of the industry means that technology and capital assistance programs are essential for fostering locally-owned and operated farms, with their broader-based benefits. However, governments and international aid donors are wary of the economic dislocation and political costs of association with boom-and-bust development. Prevention and control of pearl oyster diseases will remove these uncertainties, providing for the long-term growth of pearl culture across the Pacific, and ensuring the economic viability of otherwise-impoverished atolls.

**REVIEW**

**Pearl Oyster Diseases: Causes**

Earliest records of pearl oyster disease were from wild *P. fucata* stocks in Ceylon, where around 10% were infected with an unidentified "yellow disease" (Herdman, 1903). Most pearl culture industries have at some time suffered from persistent, heavy mortalities among farmed stocks. Disease and pollution problems have plagued the Japanese industry since 1962 (Hollyer, 1984), with "very high mortalities" and "low quality pearls" (George, 1978, p 41). North-Western Australia, and French Polynesia also suffer farm mortalities, with low retention rates and poor quality pearls.

Pollution and over-production are usually blamed first. Poor quality Japanese pearls are sometimes attributed to the continual farming of the same area. The depletion of nutrients or essential trace metals from the water or substrate has been suggested (Matsui, 1958), but not proven. Pearl farm management in Japan therefore moves spat, juveniles and seeded oysters between several different locations (Matsuda, 1979).
<table>
<thead>
<tr>
<th>AREA</th>
<th>SPECIES</th>
<th>YEAR</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAPAN</td>
<td>martensii</td>
<td>1962-present</td>
<td>Undescribed disease and pollution problems (Hollyer, 1984; George, 1978)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nutrient or trace metal depletion (Matsui, 1958)</td>
</tr>
<tr>
<td>FRENCH POLYNESIA</td>
<td>margaritifera</td>
<td>1984-present</td>
<td>Mortalities up to 82% in some lagoons (Cabral, 1989)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Due to detrital build-up on farms, and overcrowding? (Reed, 1985; Low, 1986)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vibrio isolated, not proven pathogenic (Parc, 1980, in Coeroli, 1983)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Protozoan parasite in intestinal tract (unconfirmed reports)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slow growth indicates physiological weakening? (Lachhar-Cheffort and Intes, 1989)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Abnormal lysosomes due to stresses (Grizel, 1986, in Cabral, 1989)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Due to cyclone-induced changes? (Anon., 1987)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Due to increase in water temperatures? (Anon, 1987; Porter, 1991)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spread to wild <em>P. margaritifera</em>, <em>P. maculata</em>, <em>Tridacna maxima</em>, etc. (Coeroli, pers. comm.)</td>
</tr>
<tr>
<td>AUSTRALIA</td>
<td>maxima</td>
<td>1960's-present</td>
<td>Due to oil spills? (Yamashita, 1986)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Virus-like particles in digestive gland cells (Pass, et al., 1988)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bacteria: <em>V. harveyi</em>, others - primary or secondary pathogen? (Dybdahl and Pass, 1985; Pass, et al., 1987)</td>
</tr>
<tr>
<td>SUDAN</td>
<td>margaritifera</td>
<td>1910-20's</td>
<td>Detrital build-up on farms, overcrowding (Crossland, 1957).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1980's</td>
<td>Spherical bodies in the digestive gland epithelia (Nasr, 1982)</td>
</tr>
<tr>
<td>SRI LANKA</td>
<td>fucata.</td>
<td>1900's</td>
<td>Unidentified &quot;yellow disease&quot; (Herdman, 1903)</td>
</tr>
<tr>
<td>MEXICO (Pacific coast)</td>
<td>margaritifera</td>
<td>1960-70's</td>
<td>No details</td>
</tr>
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</table>
Build-up of detritus under farms (Crossland, 1957; Reed, 1985; Lowe, 1986) has also been associated with epidemics. Crossland (1957, p 124) reported heavy mortalities of cultured P. margaritifera in the Red Sea due to overcrowding, causing "poisoning from excreta or lack of oxygen". Oil spills were blamed for the extensive mortalities on Australian pearl farms from the late 1960's onwards (Yamashita, 1986; Kearney, 1976, in Uwate, et al., 1984), only because no likely pathogen or parasite was identifiable (Wolf and Sprague, 1978). Hynd (unpubl., in Potter, 1983) surmised that physiological stresses are contributing factors, but rarely causes of diseases.

Disease problems are often associated with bacteria or protistans, but these could be either pathogens, commensals or saprophytes. Bacteria build-ups in recirculating tanks on transfer vessels, and on oyster holding grounds were associated with diseases in Western Australia (Dybdahl and Pass, 1985; Pass, et al., 1987). Three bacteria isolated from moribund or dead P. maxima (Vibrio harveyi, V. alginolyticus and Pseudomonas putrefaciens) were shown to be pathogenic by experimental inoculations, but their actual role in the mortalities remains unclear (Dybdahl and Pass, 1985).

Anomalous structures in histological preparations are difficult to isolate and culture, and symptoms are usually non-specific. The symptoms among infected P. margaritifera in the Red Sea were similar to other epidemics, with shrinking of the mantle and cessation of feeding (Nasr, 1982). Spherical bodies in the digestive gland epithelia were suspected as the causative agent. However, the "extensive host tissue damage" from "protistan parasites" in the digestive gland of P. maxima (Wolf and Sprague, 1978, p 263) was considered by Pass and Perkins (1985) to be necrotic autolysis, and a symptom, rather than a cause, of the mortalities. The common protistan parasite, Perkinsus spp, has been found in P. margaritifera and P. sugillata on the Great Barrier Reef, but these were from wild stock samples, with no symptoms (Goggin and Lester, 1987).

Atrophy of digestive gland cells may be due to reduced food intake in diseased pearl oysters, as recently dead or dying pearl oysters undergo autolysis (ibid). Pass, et al., (1988) described inclusion bodies containing smaller virus-like particles in the enlarged nuclei of digestive gland cells of both normal and diseased P. maxima. The structures were considered lesionous, but it was not possible "to assign any pathological significance to them" (ibid, p 166).

In French Polynesia, mortality rates from seeding to harvest have reached as high as 82% in some lagoons (Cabral, 1989). The problem has proven transferrable between lagoons (Reed, 1985), suggesting some infectious agent. Vibrio alginolyticus and Beneckea vulnifica, were isolated from P. margaritifera from Rikitea lagoon, French Polynesia, but no proof of pathogenicity was found (Parc, 1980, in Coerlo, 1983). There are also unconfirmed reports of a protozoan parasite found in the intestinal tract of diseased oysters.

Gradual physiological weakening of pearl oysters is inferred from evidence of decreased growth during the time of heaviest mortalities in French Polynesia (Lachhar-Cheffort and Intes, 1989). Again, it was not clear, however, whether this was a cause or a symptom. Grizel (1986, in Cabral, 1989) reported abnormal lysosomal activity due to physiological stresses. Others suggest that the rash of cyclones in French Polynesia during 1983 (Anon., 1987) or a slight increase in water temperatures (ibid; Porter, 1991) may be associated with the mortalities. However, Cabral (1989, p. 217) asserts that "no satisfactory explanation has been found," and the best response is "management of cultured areas" and "improvement of cultivation techniques" (ibid, p. 223).
Losses on farms in French Polynesia have been improved by better handling and farming practices, but once the disease becomes endemic, it is difficult to eradicate. Excessive mortalities still occur on farms in French Polynesia, and over the last few years have spread to wild stocks of *P. margaritifera*, and other bivalves (e.g. the pipi pearl oyster, *P. maculata*, the small giant clam, *Tridacna maxima*, and *Spondylus* sp: M. Coeroli, pers. comm.).

The pathology of most pearl oyster diseases is still little understood. Nevertheless, the geographical range of disease outbreaks and the taxonomic diversity of suspected pathogens underscores the problem for management of pearl culture lagoons - you never know what will hit you. How then, can you even begin to prevent its outbreak?

**Disease Controls**

A prima facie association of "poor farming practices" with disease outbreaks is based on the assumption that stressed or weakened pearl oysters are more susceptible to infection. Overcrowding on a farm, growing oysters close to the bottom or where circulation is poor, inadequate cleaning of oysters or dumping of tailings from cleaning or pearl slurry back into farm waters are all now widely recognised as increasing the risk of an outbreak of disease, or increasing the resulting mortalities if a disease is already endemic. Management can therefore minimise the chances of disease outbreak or transmission from area to area by regulating farming practices and pearl oyster transfers.

Farming regulations which could be, or are already applied include:

(i) confining farming (or large farms) to areas of adequate circulation or flushing;
(ii) rotation of intensively farmed areas, to allow them to lie "fallow" for a period;
(iii) restricting the discharge of chemical pollutants into farming waters;
(iv) farming on long-lines or rafts suspended well above the substrate;
(v) ensuring adequate spacing of oysters on farm platforms or lines;
(vi) ensuring regular cleaning of oysters to minimise stresses from fouling;
(vii) restricting the build-up of organic material beneath seeding houses or cleaning platforms; and
(viii) limiting the total number of oysters held on a farm or within a lagoon.

This last measure has proven the most problematic. The means of determining the quota level is critical to the entire management debate. Several methods have been used to estimate allowable quotas in Manihiki lagoon, Cook Islands, on the basis of simple ecological models. These are examined below.

**Modelling Pathogen Outbreaks**

Prevention and control of an aquaculture disease is largely based on the ecological characteristics of the parasite or pathogen. The causative organism is first identified, and its abundance correlated with various environmental factors or with different farming techniques. However, even monitoring of bacteria levels has proven difficult enough in the marine environment, without attempting to predict future levels or responses to ecosystem changes (Farley, 1988; Rodrick, et al., 1988; Venkateswaran, et al., 1989).
The models of pathogen prevention proposed for the Cook Islands have been based on estimates of primary productivity, lagoon and ocean water exchange rates, and original wild stock abundance (Table 3). The quota is therefore based on prediction of the critical load point imposed on the lagoon ecosystem by pearl farming. The underlying assumption is that at some certain point, the oysters become stressed and susceptible to disease. There has been little consideration of the relative loadings of different farming methods and different ecological capacities, and no real consideration of the actual cause of the disease outbreaks. If the etiology is unknown it is clearly premature to extrapolate from a few knowns to set a quota. You cannot prevent the unpredictable.

Intes (unpubl.) and Intes, et al., (1990) suggest that lagoon phytoplankton are depleted by farmed *P. margaritifera* in French Polynesia, causing feeding stresses and subsequent mortalities. The concentration of farm stocks in the upper 10 m of Takapoto lagoon increases demands on primary production within this stratum by an estimated 1000% (ibid). However, *P. margaritifera* naturally occurs in greatest abundance in this shallowest stratum, and the increasing pearl oyster abundance with depth in most lagoons is only due to fishing pressure (Sims, 1990 b). Original abundances of pearl oysters in the shallowest strata could therefore have been much higher than current levels of cultured pearl oysters.

Galenon and Coeroli (1991) extrapolate from the pumping rate of termperate-water edible oysters and an estimate of the turnover rate of Manihiki lagoon water. It is presumed that lagoon water can be pumped through a pearl oyster only once before phytoplankton depletion, metabolic wastes or bacterial levels become unsafe. If based on primary production limits, this implies 100% filtration efficiency and no phytoplankton regeneration within the lagoon. If metabolic wastes are the problem, the lagoon's capacity to support nutrient loading needs to be assessed. If bacterial or other pathogen levels are critical limits, the specific microbes need to be identified and monitored.

However, even models of biomass production for edible oyster and mussel culture are still only tentatively proposed (Héral, et al., 1984; Dame, 1990; Carver and Mallet, 1990; Fréchette, 1991; Héral, 1991; Grant, 1992). In these temperate environments, where total primary production and conversion ratios are available, and the food chains are relatively simple, it is still considered "premature to use ... models for predicting the ... trophic capacities of ecosystems" (Héral, 1991, p. 61). In tropical lagoon ecosystems, primary production and energetic pathways are both highly complex and poorly described.

Reports from French Polynesia also suggest that disease problems are greatest in the more enclosed lagoons. Less turnover of lagoon water in enclosed lagoons should allow greater nutrient build-up and greater primary production. It would therefore appear that primary production is not the principal limiting factor.

Similarly, Goldman and Goldman's (1991) use of a wild stock to farmed stock ratio of 2:1 has no ecological basis. Extrapolating from this theory, if the wild stock is fished to extinction it follows that all farming should then be halted. If the wild stock proliferates, however, there are supposedly then no real limits to the number of oysters which could be farmed.

The reliance on stock estimates in this model is also unrealistic. Due to the patchy distribution of pearl oysters, the confidence limits around stock estimates are inherently wide, with 95% confidence limits sometimes three or more times the mean densities (Sims, 1990b).
<table>
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<tr>
<th>AUTHORS</th>
<th>YEAR</th>
<th>MODEL</th>
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| Intes, et al., and Intes (unpublished) | 1989 | Estimated rate of phytoplankton filtration by oysters, and primary production extrapolated from New Caledonia. Concentration of oysters in upper 10 m of water column considered overloading (by 1000%).
|                              |      | **... but primary production will increase with greater nutrient loading by farmed oysters. Also, oysters are naturally at greatest densities in upper 10 m, but fished out there.**                          |
| Goldman and Goldman          | 1991 | Estimated wild stocks, and applied 2:1 ratio of wild to farmed shell.                                                                                                                                 |
|                              |      | **... but stock assessment methods are inherently inaccurate. This model also implies that if wild stock regenerates, then farming can continue to expand.**                                             |
| Galenon and Coeroli          | 1991 | Estimated lagoon water turnover time (8 years) and pearl oyster filtration rate.                                                                                                                                 |
|                              |      | **... but filtration estimates based on edible oysters in temperate waters, assumed oysters only filter water once, and no regeneration of phytoplankton. Also did not distinguish between nutritional, metabolic and pathogenic stresses.** |
DISCUSSION

Preventative management of pearl oyster diseases is not feasible without improving the knowledge of the causative organisms: their identity, and their epidemiology. The current paucity of knowledge is due to two main factors:

(i) bivalve pathology is still a developing science, with disease-causing organisms identified with difficulty among even the most-studied oysters and mussels; and

(ii) pearl farmers are very reluctant to share information about mortality rates on their farms, wanting to prevent any stigma of disease associated with their pearls.

The first problem could be partly addressed by an increased commitment from research organisations and development agencies. Increased funding for research into pearl oyster pathology would be clearly cost-effective, given the opportunity-cost for under-farming a lagoon. The revenues lost are in direct proportion to how much any management model underestimates the sustainable farm quota. In French Polynesia, for example, if the quota underestimates the sustainable level in all lagoons by a factor of two times the present production, "lost" revenues are in the order of US$82 million per year.

The most important advances in pearl oyster pathology, however, require a recognition of the mutual benefits to be gained from greater sharing of information on diseases. There is a particularly strong incentive for French Polynesian farmers and government agencies to assist other Pacific atoll pearl producers in minimising disease problems. International jewellery trade authorities recently bestowed the official trade name "Tahitian black pearl" on all P. margaritifera pearls (Coeroli, 1991). This means that poor quality black pearls produced from diseased areas in other Pacific islands will reflect badly on the French Polynesian product. With the small, lucrative market niche for black pearls, instabilities due to uncertain quality will be to the detriment of all.

Cabral (1989) and Lachhar-Cheffort and Intes (1989) offer some data on mortalities on co-op farms, and among wild stocks. However, a more detailed account is needed of mortalities on all farms in all French Polynesian lagoons. Such an account should specifically include, for each lagoon:

(i) the lagoon size, depth, water turnover rate, and other ecological characteristics,

(ii) estimates of the numbers of farmed pearl oysters, methods of farming employed, and wild stock levels for each year,

(iii) description or data of the epidemiology of the disease, where and when the first outbreaks occurred, what percentage losses were sustained, and when the mortalities began to abate.

Only with this information would it be possible to begin to guess at the numbers and densities at which farmed oysters can be supported in another lagoon before becoming vulnerable to unknown or undescribed pathogens. Management of pearl culture in other developing areas would then have a real basis by which to begin to estimate allowable farm quotas.

There is also a need for management in developing pearl culture areas to reassess their goals. Management efforts in the Cook Islands to date have emphasised an extremely conservative approach, with the goal of ensuring that no pearl oyster diseases
become established (Sims, 1990a, 1991; Goldman and Goldman, 1991; Galenon and Coeroli, 1991). This is an unrealistic expectation.

There is a continuum of increasing disease risk with increasing farm numbers and densities. The only guaranteed assurance of no pearl oyster diseases is if there is no pearl farming. Management must explicitly recognise that there is always a probability of disease outbreaks, and this must be impressed upon the local enforcement authorities and the farmers. Although most pearl farmers in Manihiki recognise the value of setting a quota for farmed oysters in their lagoon, the corollary of individual farm quotas is not well supported (Sims, 1990a). Farmers must decide for themselves the level of risk with which they wish to live.

CONCLUSIONS

The issue of pearl oyster disease prevention is of critical importance to the economic development of many Pacific atolls. There is a need for further research, but there is a greater need for closer co-operation between all pearl producers. With the potential value of this industry to the Pacific atolls, the ultimate returns to all are unquestionable.

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REFERENCES


