A Review of

The Practicality of Cultivating Puerulus
of the
Western Rocklobster, *Panulirus cygnus*

in

Western Australia

Prepared for

The Western Australian Fishing Industry Council

Compiled By

Tim Meagher BSc.[Hons] Ph.D

September 1994

ROCK LOBSTER PUERULUS ENHANCEMENT PROGRAM

CONTENTS

LIST OF FIGURES

ROCK LOBSTER PUERULUS ENHANCEMENT PROGRAM

EXECUTIVE SUMMARY

It is known that puerulus of the Western Rock Lobster *Panulirus cygnus* can be reared through to a marketable size of 250-300 grams in 18-24 months, under laboratory conditions. Field and laboratory observations indicate the puerulus of *Panulirus cygnus* can be mass-cultured commercially, without undue complication.

The distribution of puerulus returning to the coast from the plankton is not uniform throughout the fishery. There are areas along the coast where habitat for puerulus and early juveniles is either inadequate, or limited. Recruitment to the fishery at such locations is ineffective. This excess could be harvested and cultured without causing a reduction in the existing sustainable yield of the fishery. Indeed culture of the excess will expand the sustainable yield of the Rock Lobster fishery.

It is known that puerulus can be collected in the wild at the time of its natural settlement. The precise habitat of natural puerulus settlement still remains unknown. However the habitat of the post-puerulus and early stages of juvenile animals, in shallow coastal areas is documented. It is also known that pueruli occasionally settle successfully in deeper water.

Preliminary estimates have been made of the cost of capture and rearing Western Rocklobster puerulus. The data available at the present time indicate that capture and cultivation will be profitable. A hypothetical, commercial-sized farm of 1000 tonne per year, based on reasonably conservative operating parameters, indicates a return on investment of 24.5% Internal Rate of Return (IRR) before tax, which is acceptable. A sensitivity analysis of the IRR, which enables simple variations of market costs and revenue, within ranges known to have routinely occurred in recent years, suggests commercial returns are likely to be better than the base 24.5% IRR.

Western Rocklobster culture thus appears to be a good commercial prospect. It is recognised that the project will not proceed without the support of the rocklobster industry and government, regardless of scientific merit and profitability. The commercial entity proposed for the venture provides inducement and benefit to all participants in the existing wild-capture fishery. It is also equitable to government and enables private sector investment.

Other countries such as New Zealand, Cuba and the United States (Florida) are examining the commercial cultivation of wild-caught rock lobster puerulus. It is essential that the Western Rock Lobster is similarly evaluated, so that the industry has the relevant strategic information on its own Rocklobster resource.

The project as proposed, will not detract from the existing wild-catch fishery. It will not proceed unless the Research and Development program demonstrates that the puerulus harvested and cultured, are excess to those required for maintenance of

the existing wild-catch fishery. The project if successful, will result in a substantial expansion of the sustainable yield of the fishery, and enable the sale of smaller sized lobster, continuously through the year.

The conversion rate of food to body mass, by the early juvenile Western Rock Lobster is good. It is equivalent to, or better than, other marine crustacean and fish species which are profitably cultured.

The animal's behaviour is known to be conducive to mass culture under commercial conditions because it is gregarious and therefore economical to rear, in terms of pond and farm size. It will forage for food thereby separating feed and shelter areas, which in turn leads to a reduction in disease susceptibility. The animal is considered to be resilient to both disease and habitat stress.

Predation at puerulus settlement appears to be high, but is insufficiently documented. It is considered to be largely due to predation, which in turn is likely to be due to lack of refuge habitat. Early juvenile stages appear to have a further 60%- 90% mortality over a three year period. Techniques for improved efficiency in the collection of puerulus from the wild are known and are likely to improve greatly with research. It is concluded that collection of puerulus on a large scale will be commercially viable.

Alternate concepts for the enhancement of the wild-capture fishery are briefly canvassed. However puerulus capture and culture remains the focus of this report.

Research and Development for the project should be supported by the Commonwealth Government's Research and Development Plan for fisheries, currently administered by the Fisheries Research and Development Corporation. Funds available through that agency, and complemented by funds from the Fisheries Trust Fund, should be adequate to fully evaluate and formulate a program for commercial rearing of the Western Rock Lobster.

It is recommended that the project proceed in two phases. The first phase will identify research objectives so that the program is mission-orientated. It will also develop protocols for trials and experiments. The conduct of the research will be costed and scheduled. Discussions with the Government as to the acceptability of the project, and the legislative changes required to accommodate it, will be negotiated. In the second phase of the project, staff will be recruited and the research programs will be conducted over a three year period.

It is recommended that the Western Australian Fishing Industry Council be the Manager or Administrator of the project. Specific components of the Research and Development programs as detailed in the individual protocols will be contracted for and conducted by experienced specialists obtained from a variety of organisations, such as the CSIRO, Australian Institute of Marine Sciences, the Western Australian Government Fisheries Department, Universities and private sector consultants. It is anticipated that the second half of the three year program will involve pilot plant trials and market evaluation.

INTRODUCTION

Current Harvest Level

Records of catch-weight have been kept by the Fishery Department, West Australian Government, since 1944, (FIGURE 1). In the early 1960's combined export and domestic demand became so large that it was necessary to regulate the fishery to the maximum sustainable yield. For the 16 years from 1960 to 1976 it was approximately 9,200 tpa, and for the last 16 years it has been 11,100 tpa. Natural variation in annual harvest during the past 16 years has ranged between 8,400 and 13,500 TPA, under present management conditions.

The WRL Industry has accepted that the *sustainable yield* of WRL is approximately 10,500 TPA. Part of the increased average yield over the past 16 years has undoubtedly come from the altering age-structure of the WRL population. Removal of large-sized, slow-growing animals, and their replacement by an increased number of smaller, faster growing juveniles and early adults has lead to an increase in harvestable biomass. This is a fairly general biological phenomenon. However removal of the larger-sized brood-stock animals can, in turn, lead to a significant reduction in population fecundity. There are current management concerns that this may have occurred and regulations have recently been put in place to reduce fishing pressure on the brood-stock.

The purpose of this report is to briefly review a number of suggested techniques to increase the sustainable yield of the fishery, and to consider in detail both the commercial and biological practicality of rearing WRL puerulus through to marketable size.

Focus of Industry Research

The WRL industry has been competently researched and managed since product demand rose in the early 1960's. The industry has enjoyed both stability in yield, and strong market support for a premium product. R & D programs have been consistently refined over the years to support the industry. Throughout the late 1980's research confidence in forecasting yield from settlement success at the puerulus stage, led to a comfortable expectation that enough was known about the WRL industry to ensure yield could be sustained at its present level. However in recent years increased harvest capability, due to new technology, combined with the acquired skills and efficiency of operators, has been cause for concern to fishery managers.

Department of Fisheries research has recently indicated that harvesting at the *sustained yield* may be selectively altering the age structure within the population, thus modifying the reproductive potential of the overall fishery. The concern of WRL fishery managers is, that the number of eggs being produced by the brood-stock, may fall to risk levels under current harvest practice. Elimination of this risk by increasing larvae production, has been the principal focus of recent Fisheries Department R&D programs and reduction in fishing effort.

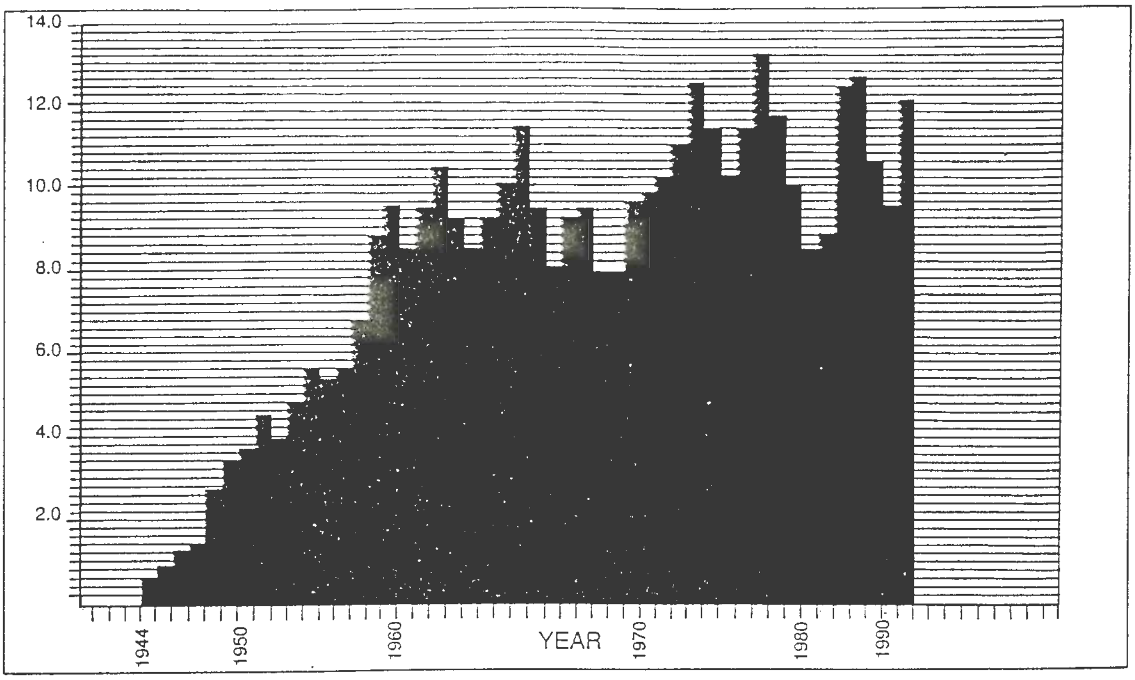


FIGURE 1.
The annual catch of Rock Lobster in millions of kilograms from the beginning of the Fishery in 1944, through to 1992. Data source, Western Australian Fisheries Department. (In Gray, 1992 as FIGURE 40)

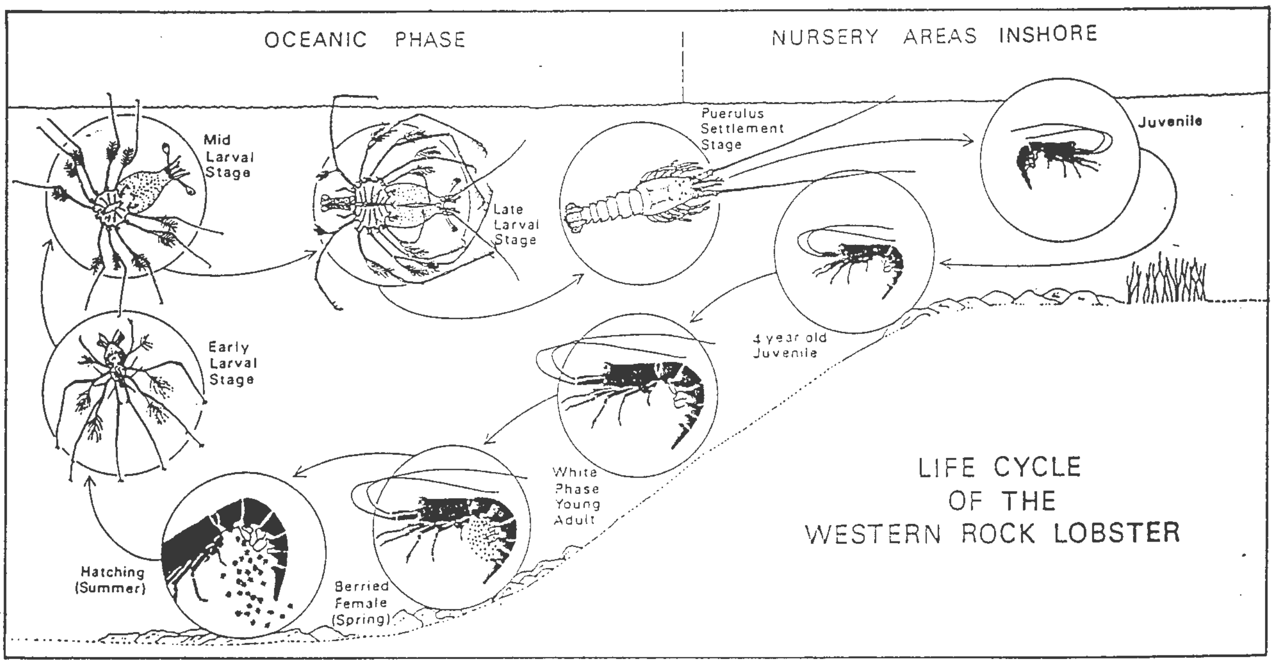


FIGURE 2.
The life cycle of the Western Australian Rock Lobster *Panulirus cygnus* showing its passage through several major stages in its life history. These include the series of Phyllosoma larvae, a Puerulus, followed by Juvenile and Adult stages. After hatching during the summer, Phyllosoma larvae undergo a 9-11 month planktonic life. The surviving Phyllosoma metamorphose to Puerulus which then swims across the Continental Shelf, and settles in the shallow coastal areas. The younger juveniles aggregate on limestone reef areas which occur at depths to about 10 metres with some larger juveniles still being found on reef down to 20 metres. At about 4-5 years of age the juveniles migrate in what is called a white phase from shallow reef areas into depths of between 30-150 metres. Here maturity is reached, mating takes place and the life cycle is completed.

On the advice of the Rock Lobster Industry Advisory Committee (RLIAC) the Minister has modified fisheries regulations for the 1993-94 and 1994-95 seasons in order to significantly increase the number of breeding females in the WRL population.

It is understood from discussion with Fisheries Research Scientists, that the 1993/94 restrictions have been biologically effective and appear to be having the desired effect of increasing brood-stock level.

Segregation of WRL Research Programs

WRL research over the period 1970-1990 was segregated into two components.

* The Western Australian Government Department of Fisheries, focussing on fishery management research programs.

* CSIRO Division of Fisheries and Oceanography, undertook the more broadly based, strategic R&D programs into biology, behaviour and the effect of ocean circulation on larval dispersal and juvenile recruitment.

Towards the end of the 20 year R&D period, the CSIRO was making a substantial contribution to knowledge of the fishery by investigating the relationship of both larval dispersal and settlement of early juveniles, to the structure and intensity of the Leeuwin Current.

CSIRO Fisheries and Oceanography Division changed its research orientation in the mid 1980's. As a consequence there is now no significant ecological research into the puerulus and early juvenile components of the fishery. In the mid 1980's the CSIRO re-allocation of resources was a reasonable outcome. However the more recent query over adequacy of WRL brood-stock level, and a growing international interest in rocklobster cultivation, require a refocussing of research effort into post-larval recruitment and ecology. The recent review by Phillips et al, (1994) indicates that such information is generally lacking.

The FRDC/Industry funding provides an opportunity to support research into post-larval ecology and the efficiencies in recruitment, thereby continuing the previous strategic contribution made by CSIRO. This report collates information to assist in the consideration of funding support for research and development of ways to enhance recruitment and best utilisation of WRL post-larvae.

Requirement for Continued Puerulus - Juvenile WRL Research

The empirical relationship between the density of puerulus settlement on collectors and catches of juveniles some four years later, has enabled the assumption that post-puerulus mortality is sufficiently consistent, to enable competent prediction of subsequent sustainable harvest. Thus management is oriented to ensure that there is a surfeit of eggs in the plankton, so that every year the optimal recruitment potential is provided. The main variables to influence recruitment success, are known to be the vagary of the Leeuwin Current and occurrence of storm events in spring. These two environmental factors facilitate the return of the puerulus stage from oceanic plankton to coastal nursery areas. Subsequent juvenile mortality is presently considered to be a constant and largely unmanageable factor, its evaluation has therefore been somewhat ignored.

Studies by Chittleborough (1970), indicated that juvenile mortality on coastal reefs is in the order of 60-90% over the first three years. Later studies by Ford, Phillips and Joll (1988) acknowledged a high mortality, but described some of the difficulties, particularly migration, which affect estimates of juvenile mortality. This suggested that Chittleborough's estimate is likely to be a maximum.

However there is an additional phase of possibly massive, but inadequately documented mortality, which occurs prior to that considered by Chittleborough. It occurs at puerulus settlement, post-puerulus recruitment and through the early post-puerulus instars. This mortality thus occurs well before that considered by Chittleborough (1970) or Ford et al (1988). The only study to assess components of this mortality, did so by examining the predatory effect of local fish, and concluded mortality is in the order of thousands per hectare on coastal reefs, Howard (1988). However, Howard's study in practice only examined mortality of early post-puerulus juveniles. The puerulus to post-puerulus mortality itself, has not been investigated.

The indications are that there is significant, if not massive, mortality at both settlement and early juvenile instars. However insufficient research has been completed to determine whether this wastage can be utilised.

The preferred or successful, natural habitat where puerulii settle throughout the fishery remains unknown. We only know for certain that they settle on artificial collectors. That is simply not good enough for thorough management of Australia's major fishery. The habitat of WRL post-puerulus was only found in the mid-1980's, Jernakoff (1990). Insufficient ecological research has been conducted on this phase of the life-cycle.

The situation is further complicated by occasional settlement and recruitment of juveniles, and presumably the earlier puerulus, in deeper water. This recruitment may be substantial, but is not currently taken into WRL management consideration. It also tends to confuse the generally accepted life-cycle story, which accepts that settlement and juvenile recruitment occurs in shallow coastal areas. Therefore much remains to be done, to enable a comprehensive understanding of the WRL fishery. Many questions remain, as to whether or not the habitat available for puerulus settlement, subsequent availability of food for early juveniles, and predation on early juveniles are significantly limiting the recruitment of juveniles to the commercial population, (and thus limiting the sustainable yield of the fishery).

At present, the number of puerulus settling in acknowledged nursery areas, is considered to be the significant limiting factor to harvest some 3-4 years later. Manipulation of brood stock numbers, is the fundamental management lever being used to optimise the sustainable yield. It is obviously very good, but is it enough ?

This proposal considers the additional areas of stock management, in order to see whether aquaculture has a place in ongoing management strategies. These are:-

* What is the relative impact of present puerulus/juvenile mortality (as compared to settlement intensity) on sustainable yield ? Can natural mortality be reduced by post-larval harvest and subsequent culture.

* If puerulus and early juvenile mortality is as substantial as supposed, is there a practical method to reduce this mortality ?

To answer these unknowns, it is essential to find out just how fundamental ecological factors such as shelter, food and predation are to puerulus success at settlement, and to early juveniles following settlement. This in turn leads to two further considerations:-

* If the availability of adequate nursery habitat is found to be a limiting factor, can excess puerulus settlement be harvested and better husbanded?

* Can ecological conditions and habitat be managed, or enhanced to reduce early juvenile mortality, after settlement?

This approach requires a slight conceptual shift in how the WRL fishery is viewed. The sustainable yield becomes the number of puerli that can be recruited and utilised for both the subsequent wild-capture fishery and aquaculture.

Through the same 1980-1990 period in which the WRL fishery has matured, there has been a vast increase in the technological understanding and capability of aquaculture of marine species. Overseas researchers, particularly those in Japan, have recently shown that it is technically possible to rear both Jasiid and Panulirid species from egg to mature adult. Whether this technology can become commercially competitive to the ocean-capture WRL industry, has yet to be determined. However it is strategically important to continue to conduct research into the late larval and early juvenile stages to ensure that our local industry does not fall behind technologically, as was the case in regard to the rearing of prawns.

Many other countries are researching capture and rearing of their puerulus and juvenile rock lobster stock. The WRL fishery is obliged to do likewise, for strategic reasons, if no other.

There are also a number of fisheries where a mix of wild-capture and aquaculture have greatly increased the sustainable yield of the population. This logical extension has not been considered in adequate detail for the WRL fishery, and is the basic issue considered throughout this paper.

Report Content

This report has been compiled to assess proposals to harvest and rear a portion of the WRL puerulus stock at settlement. It additionally canvasses, in less detail, a number of suggestions for improving the sustainable yield of the wild-capture fishery by manipulation of late juvenile and commercial size portions of the stock. The report does not contribute new data. It is a synthesis of existing knowledge. The report examines whether there is an excess of pueruli in some locations and in some years which are subsequently lost, due to limited habitat or limited carrying capacity in settlement areas.

It is generally accepted, that mortality in the period from puerulus settlement to one year old juveniles although unknown, is likely to be significant in some areas. The report therefore considers whether or not some areas of the coast are presented with surfeit puerulus settlement, because they do not have a proportionate amount of habitat to enable efficient transition from puerulus through to late-stage juveniles.

The report then considers whether

* There is genuine puerulus wastage in some areas, which could be better utilised.

* Harvesting such excess pueruli, and raising them through the early juvenile stages by mariculture, conveys any advantage to the WRL industry.

* WRL aquaculture of wild-caught puerulii is commercially attractive.

* WRL aquaculture of puerulii can be conducted in a way which is both acceptable to the existing industry and politically and socially acceptable to the Western Australian community.

The report does not revisit biological detail given in the book *"Western Rock Lobster Natural History and Biology"* compiled by Howard Gray in 1992. Gray's book provides pre-requisite knowledge of those assessing this current proposal. It is referred to frequently because of the detailed nature of the text, illustrations, figures and diagrams it contains. It is further acknowledged, that definitive reviews of some technical aspects canvassed by this present paper, are given by acknowledged international experts, in the recently published text, *"Spiny Lobster Management"*, edited by Phillips, Cobb and Kittaka, (1994).

THE PUERULUS PROPOSITION

It is not uncommon for scientific research to be developed and undertaken, on the simplistic basis that relevant information is unavailable and should be found, regardless of the practicality of subsequent commercial application. This proposal not only says - "Do we have the necessary information" ? It also considers at outset, the implementation of the findings, if the research is successful. To do this a range of questions needs be posed and answered now. The questions are essentially :-

* Do we know the WRL life cycle adequately?
* Why not grow the WRL from the egg?
* Are there really years in which excess puerulus settle on the coast?
* Are there areas of the coast in which puerulus settle unsuccessfully?
* Is it possible to catch or harvest puerulus commercially?
* Can we grow puerulus to marketable size?
* What will it cost to grow puerulus and will it be profitable?
* Where and how would puerulus be reared?
* Who would have rights to harvest, rear and share in the profitability?
* Will the overall sustainable yield of the WRL industry improve, or decrease as a result of puerulus harvest?
* Are there any other successful aquaculture models upon which to base the concept?
* How would the R&D program be implemented?

Each of these questions is briefly answered below. Some components are later considered in more detail. It is evident that the answers to many of the questions are known, but significantly there are others for which knowledge is inadequate.

The questions for which there is an obvious lack of information, are reviewed in more detail subsequently in this proposal. They will constitute the basis of the proposed research program.

Do We Know the Life Cycle ?

The answer to this is yes. It has been the subject of detailed research by the Department of Fisheries and the CSIRO Division of Fisheries and Oceanography for the past 30 years. The 1992 publication by Gray, *"The Western Rock Lobster Panulirus Cygnus - A Natural History"*, synthesises that research into a very readable format. It describes how the natural history of the Rock Lobster was gradually revealed by research, and traces the life cycle from egg to adult. It also describes the habitats in which individual stages in the life cycle are completed.

In general terms there are few gaps in the information, but if the puerulus stage is to be harvested for aquaculture, additional and much more detailed information will be required in regard to settlement characteristics such as, preferred location, behaviour and mortality.

It is significant to note the preferred habitat for natural settlement of WRL pueruli has still not been found. The preferred post-puerulus habitat is known to be in small holes and crevices on seagrass covered, shallow reef, and plate corals at the Abroholos Islands, Jernakoff (1990). The translucent (unpigmented) pueruli are readily obtained from collectors, but only 2-3 have been found in the shallow reef areas surrounding collector sites. (Jernakoff, pers comm.) Their natural habitat is certainly not the same as that of the pigmented post-puerulus. Thus there is no realistic estimate of mortality at this vital transition from puerulus to early juvenile. Howard (1988) suggests that subsequent mortality of early post-puerulus juveniles may be in the order of thousands per hectare, per annum.

Why Not Grow The Rock Lobster From The Egg ?

An international conference on Rock Lobster held at Sanriku in Japan in July 1993, was attended by research scientists from the Western Australian Fisheries Department. Proceedings confirmed that Japanese researchers have been able to culture some panulirid and jasiid rocklobsters from egg through to early juvenile stage and then on to adult. The status of this research is reviewed by Kittaka, in Phillips et al (1994). At the present time Japanese research is restricted to growing animals in small numbers, under intensive laboratory culture conditions. Mortality at the moult from phyllosoma to puerulus is very high, compared to that of wild caught phyllosoma.

Cost and complications of live-food production tend to mitigate against commercial rearing of the larval phases of many marine animals, particularly those with long larval phases.

The early larval stages of all rock lobster species require specialised live food. Although Kittaka (1994) does not say as much, the food species in turn must have nutrient enrichment, (to overcome the high mortality at the puerulus transitional moult). This means that early stage aquaculture of phyllosoma is not simply a matter of growing and maintaining the health of the target species, but also ensuring that a range of other food species are grown and maintained by sophisticated aquaculture techniques. Phyllosoma stages of *Panulirus* species are known to be more complicated and more difficult to grow than the phyllosoma stages of the *Jasus* rock lobster species, Western Australian Government Fisheries, (pers comm).

It is now known that the later phyllosoma stages can be fed a simple fresh, but not necessarily live diet, such as chopped up mussel. However to ensure the phyllosoma randomly comes in capture range of the food particle, phyllosoma must be kept in suspension with the chopped up food. If there is a dense culture of phyllosoma larvae, they tend to tangle with each other. Therefore mass culture of the phyllosoma larvae, maintaining food supply for early stages, whilst suppressing disease, will most likely require rearing of rock lobster larvae in intense laboratory culture conditions, over the long larval period of some six to eleven months.

I understand from my discussions with Fisheries Department research scientists that rearing *Panulirus cygnus* from the egg stage through phyllosoma stages will remain commercially unattractive in the foreseeable future, because of the factors outlined above.

Are There Years In Which There Is Excess Puerulus Settlement ?

This question has not been adequately resolved. The numerical relationship between the number of pueruli found settling on the artificial collectors on the coast and the subsequent recruitment level of juveniles into the commercial stock, three to four years later is valid, Phillips et al (1991). The *"puerulus settlement index"* (PSI), has therefore become a very useful management tool.

However the empirical relationship between egg production, settlement and juvenile recruitment may be far more complicated. There is a good correlation between change in mean sea level at Fremantle and puerulus settlement numbers each year. The mean sea level variation at Fremantle is in turn directly related to the *"Southern Oscillation Index"* (which is an indication of the strength of the driving force for the southward flowing Leeuwin Current), Phillips and Pearce (1989), Caputi and Brown (1993).

The correlation between the Puerulus Settlement Index (PSI) and catch level 3-4 years later, suggests the density of puerulus settlement is directly reflected in subsequent harvest. The current conventional wisdom in the WRL industry is therefore; *No puerulus or juveniles can be removed for aquaculture because it may reduce the subsequent WRL catch.* However, this conclusion is an over-simplification, and is subsequently considered in detail

It is more relevant to consider whether there are areas of the coast, where it is demonstrably evident that puerulus settlement is adequately in excess of the subsequent carrying capacity of that area for juvenile WRL.

Mortality at settlement, when thoroughly researched, is likely to be high in some areas is high, so it is likely that there are locations in which there is substantial "wastage" of puerulus settlement every year. If this is found to be the case, it will provide the rationale for puerulus cultivation.

Are There Areas Of Coast Where Puerulus Settlement Is Unsuccessful ?

Areas and locations which are referred to throughout this report are shown on FIGURE 3A. It gives the location at which the intensity of puerulus settlement is monitored by collection on standardised artificial habitat, Phillips and Hall (1978), Phillips Pearce and Litchfield (1991).

Information obtained from the puerulus collectors shows that puerulus settlement can be highly variable between locations only 30-40 km apart,(eg. Cliff Head and Seven Mile Beach). This variation occurs at the macro-geographic scale and as well as the local level. For example, the puerulus collectors at South Passage in

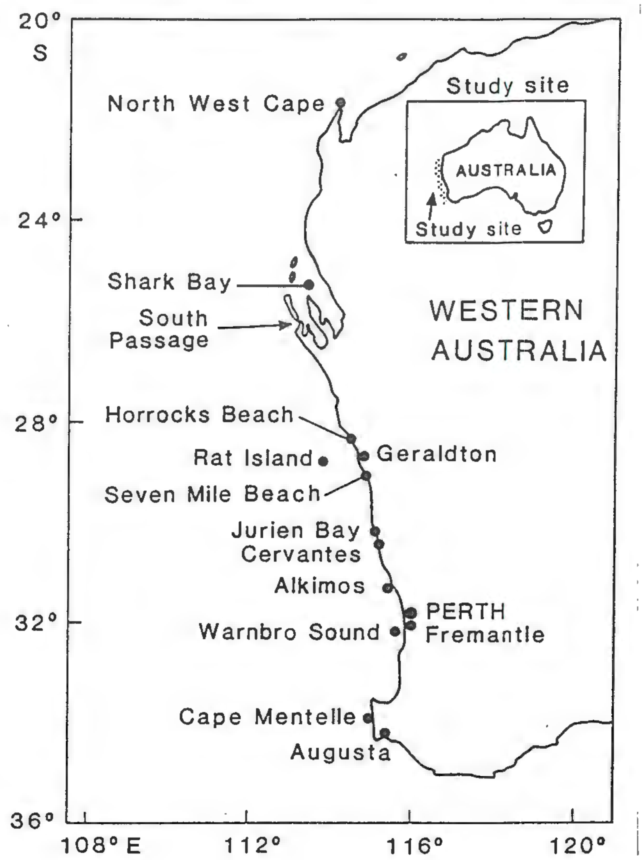


FIGURE 3A
A Map of Western Australia showing sites at which puerulus settlement of the Western Rocklobster is sampled.

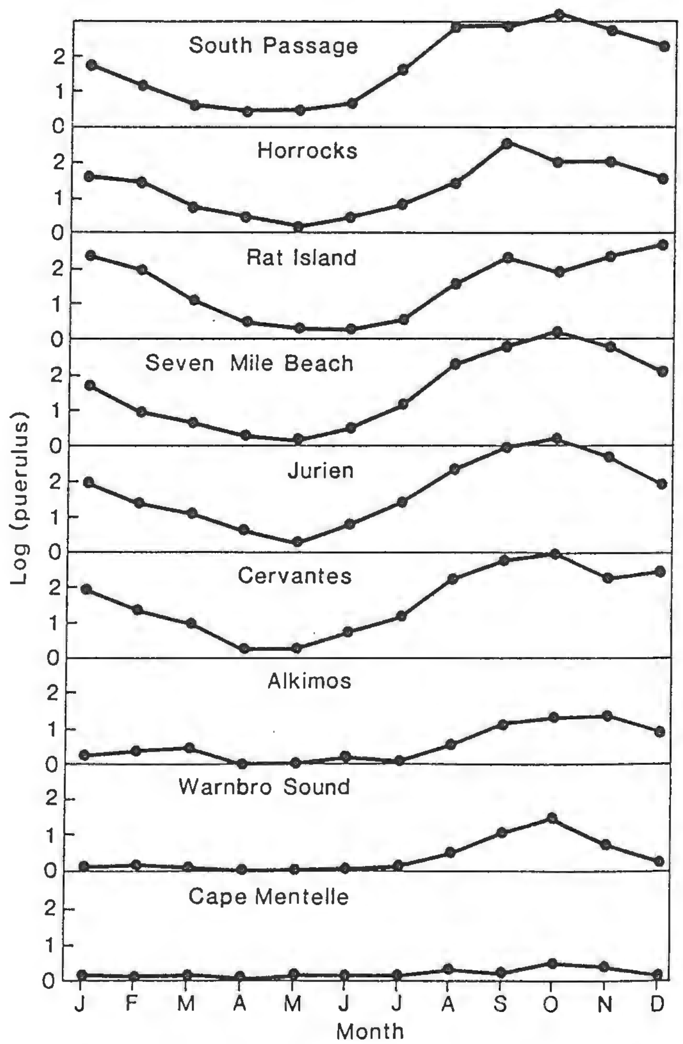


FIGURE 3B
Average monthly settlement of WRL puerulus. The values are given logarithmically. In general terms, the results show that northern areas receive approximately 80 pueruli, per collector, per month. Southern areas receive only 2-4 pueruli per collector, per month.

Shark Bay indicate it is an area of optimum puerulus settlement on collectors. Puerulus settlement on collectors is more intense and extends over a longer season at South Passage in Shark Bay than at any other location, FIGURE 3B. Phillips et al (1991) figs 2a, 2b. However there is not a commensurate sized WRL fishery in the Shark Bay area.

Settlement per collector, at Shark Bay is equivalent to, or higher than that which occurs at the most prolific juvenile areas such as Seven Mile Beach, Jurien and Cervantes,FIGURE 3B. It is twenty times higher than that which occurs at the Alkimos, Garden Island or Warnbro Sound, FIGURE 3C

The difference in settlement levels on collectors in the southern areas such as Alkimos, Warnbro, [and Garden Island, Phillips and Hall (1978)] when compared to the more northern areas such as Cervantes and Jurien, is not commensurately reflected in the subsequent WRL fishery yield.

Interpretation of puerulus collector data is complicated by the accepted view of research scientists that it is only a useful "index", and not a direct measurement of abundance.
It would appear that, if settlement density is directly related to subsequent sustainable yield, under-settlement routinely occurs in the southern areas of the fishery. Conversely over-settlement routinely occurs in the Shark Bay area.

There are no published records of collectors placed further north than South Passage at Shark Bay. However it is known that adult WRL (and occasional undocumented reports of substantial stranding of WRL pueruli) occur as far north as Coral Bay. Plankton hauls of phyllosoma larvae indicate they occur at sea well to the north of Norwest Cape. Thus there is an area from Kalbarri northward, in which substantial proportions of settling pueruli are unlikely to be reflected in the subsequent juvenile and adult population.

The hypothetical model which underpins the proposal of this report is shown on FIGURE 4. It shows in diagrammatic form the density distribution of pueruli settling along the coast and intensity of WRL catches along the coast. The two bell-shaped distributions are offset. The excess puerulus density is well to the north. The distribution suggests substantial numbers of settling pueruli could be harvested in areas to the north of Kalbarri without having any influence on the existing WRL fishery, [on the reasonable assumption that there is no southward migration of early juveniles].

Is It Possible To Harvest Wasted Puerulus ?

Puerulus research has focused on standardising the intensity of settlement at selected areas along the coast. The objective is to compare the settlement between years and between locations, in order to obtain an index of recruitment into the juvenile/adult commercial population. After the collector information was found to be acceptably accurate for diagnostic purposes, [Phillips and Hall (1978)],

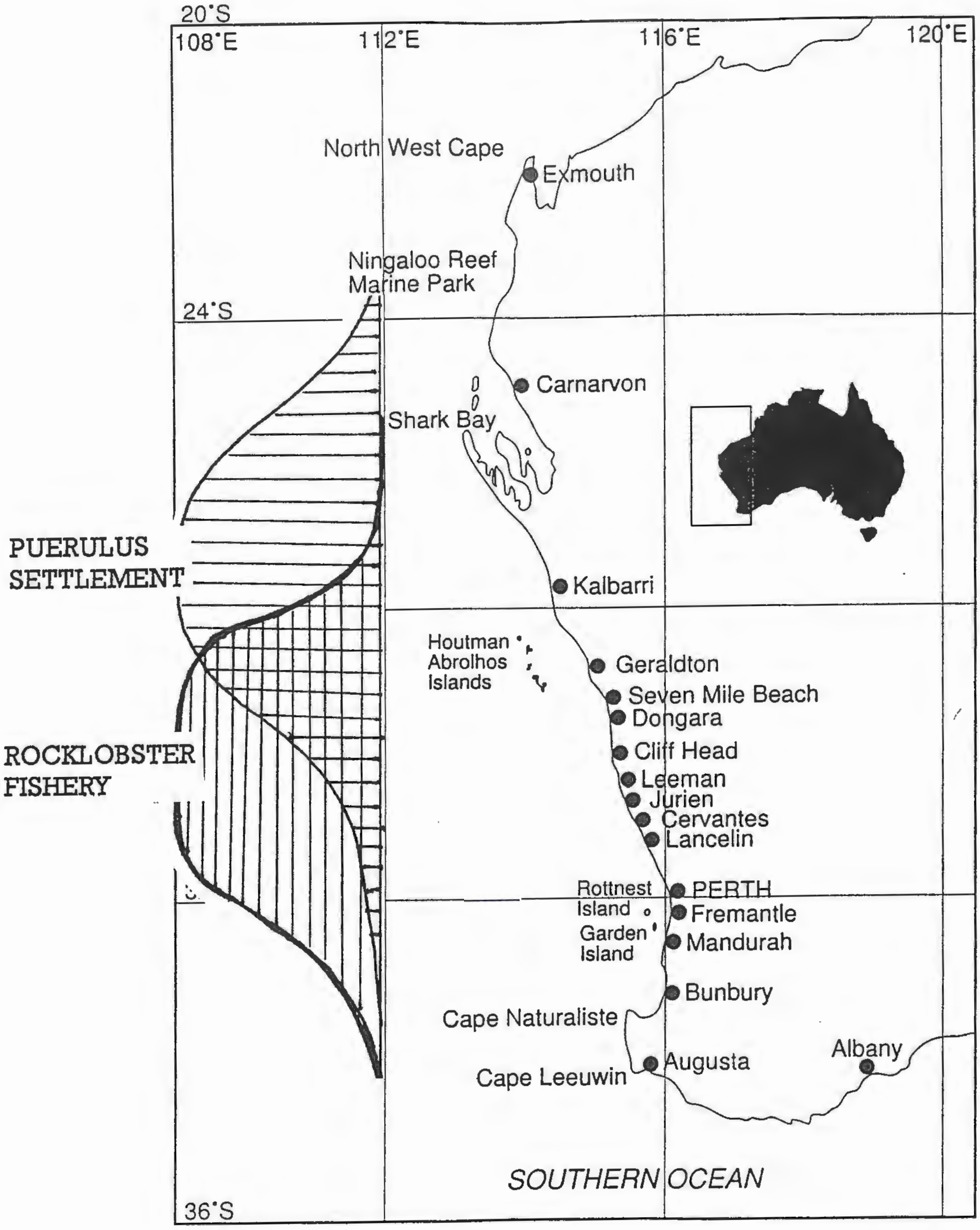


FIGURE 4
A map of Western Australia showing the sites referred to in distribution of the Western Rock Lobster Fishery together with a graph [not to scale], showing the density distribution of the Western Rock Lobster catch and the density distribution of Western Rock Lobster Puerulus collection.

further research to optimise collection efficiency was discontinued. An improvement in the efficiency of collection would have led to complications in comparing previous collections. However a parallel program, wherein collector efficiency is researched, can now be run to investigate aquaculture opportunities, in particular the cost-effective collection of puerulus.

The months of the year and the times of the month at which pueruli settle was found very early in the puerulus collector program, Phillips (1975). It was also known very early in the program, that puerulus collector efficiency increases five times by the simple addition of a 1 watt light, Phillips (1975)

Pueruli can be easily collected for research purposes, but it is not known whether the effort and cost associated with the capture of large numbers of pueruli from the wild for aquaculture is commercially viable. Desk-top estimates given later in this report suggest it may be economically practical to harvest pueruli for culture. However additional research is required to evaluate the economics and ecological consequences of harvesting the pueruli, at the level required for aquaculture.

Even if pueruli are available in substantial numbers, and it can be demonstrated that there is an excess of settlement, compared to effective juvenile recruitment in certain areas, the project will not be successful if harvesting appears to be unduly expensive.

The collection and cultivation of early juveniles is a separate consideration, also reviewed subsequently.

Can We Grow Sea-Harvested Puerulus Through To Marketable Size?

Laboratory rearing, by both the CSIRO and Department of Fisheries, has shown the WRL can be grown from puerulus to market size without substantial difficulty.

Temperature, diet, oxygen levels, and habitat influence growth rate. These factors have been determined under laboratory conditions using relatively small numbers of animals. Comparisons have also been made of differential growth rate between local populations in the field. These show real differences in growth rate, (FIGURE 5) and Chittleborough (1974 a,b,c,d)(1975 a,b)(1976).

More recently Jernakoff et al (1993) have shown differences in the growth rate between local populations of the very early juvenile stages. Realistically the differences can only be due to a combination of food quality, food availability and temperature.

Chittleborough calculated food conversion rate and checked laboratory growth against that of field populations. The work was conducted on juvenile animals, 2-4 years post-puerulus. The results indicate juvenile WRL is an excellent candidate for culture. Chittleborough found a food conversion rate of 3.6:1 which is as good or better than prawns and much better than many marine fish which are cultivated.

Chittleborough was providing premium quality food, as the principal dietary component (abalone). However indications remain that conversion rate under aquaculture conditions will be comparable, if not better, than many marine crustaceans and fish which are cultured.

The animal is remarkably resilient, not only to disease and injury. Chittleborough found it will eat a wide variety of food, including the common Western Australian blowfish, for a considerable period, and can be starved at 2-3 years of age, for up to 42 weeks, before dying, Chittleborough (1975). However Commercial WRL fishermen and processors report unacceptable levels of mortality in animals held for extended periods. Thus further consideration and research is needed on this matter.

WRL are gregarious, with a preference to live in dens and will forage for food. This gives substantial opportunity for efficiency in culture, because feed and shelter areas can be separated and localised. This in turn minimises both food wastage and disease susceptibility. It also means that large grow-out areas are not required.

Chittleborough's classic growth curve from his 1976 paper is given as FIGURE 5. It shows that under optimal food and temperature conditions in the aquarium, the growth rate between early stage juveniles and minimum legal size is effectively double that of field populations. Thus rearing time for a commercial sized, marketable product, of 60mm carapace and approximately 250 gm, will be less than two years.

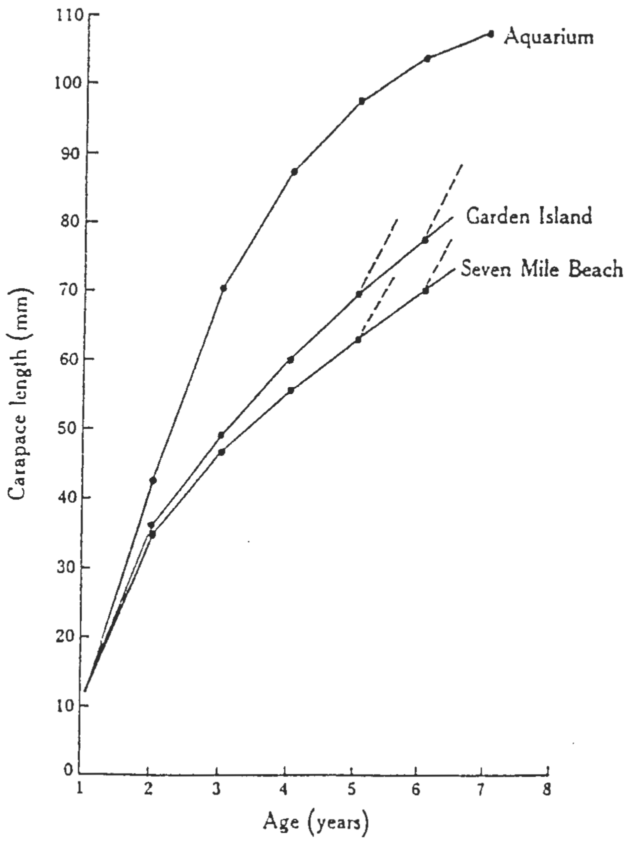


FIGURE 5

Growth of juvenile Western Rock Lobster on Nursery Reefs at both Garden Island and at Seven Mile Beach, as compared to the growth under optimal conditions in the aquaria.(After Chittleborough 1976).

Similar studies to determine food conversion rate, the role of nutritional supplements and survival under intense culture conditions, have not been undertaken on early juveniles. (ie those 1-2 years post settlement). Thus laboratory trials on early juvenile culture will need to be conducted. These will then need to be followed by commercial-sized pilot-plant tests on the culture of both early and late juvenile stages. Therefore additional research is required prior to mass capture of pueruli and mass culture of juvenile stages.

What Will Puerulus Cost To Grow And Will Aquaculture Be Profitable ?

Setting aside R&D costs, which should be available under FRDC/Industry funding, the basic costs associated with the proposal will be - Site acquisition, holding ponds and other structures, capital equipment items, manpower, feed, processing, marketing and transport, administration and environmental approvals.

Evaluation of commercial success will be an essential component of the proposed FRDC funded investigation. There are a number of fundamental parameters which influence aquaculture profitability, which can be considered at outset, in order to obtain a reasonable indication of profitability.

These are:-

* Price of juvenile stock
* Selling price of product
* Feed cost
* Mortality
* Holding density
* Capital works, item and equipment costs
* Transport and marketing
* Manpower and administration

Treadwell, McKelvie and Maguire (1991) compiled a paper on behalf of the Australian Bureau of Agricultural Economics (ABARE) entitled *"Profitability of Selected Aquacultural Species"*. It reviewed Australian aquaculture of, salmon, trout, barramundi, prawns, freshwater crayfish, crocodiles, mussels and Pacific oysters. Components of that review are important background to this report and are attached as Appendix A.

The ABARE study utilised an Internal Rate of Return (IRR) compilation, to enable comparison to routine commercial investment. IRR considers cash flow on total monies invested over a selected time schedule, say 10 or 20 years. In simplicity, IRR enables a percentage return on funds over the period to be calculated, so that the investment can be compared to others, eg a bank deposit. The 20 year return on a bank deposit is presently considered to be 6%. If the project yields more than this, it is better than bank interest. Most investment agencies consider 15-20% IRR before tax, to be the acceptable investment threshold. All investments have varying elements of risk. Business expects returns to be commensurate with risk. IRR can also calculate the probability of the projected rate of return (albeit, theoretically) falling below any particular level, and thus consider the risk factor.

The ABARE study found nearly all the aquaculture projects it analysed to be risky. It recognised that both pearl and edible oyster culture are well established, profitable and substantial industries in Australia. These were not assessed by ABARE.

Any modelling program is only as sensible as its inputs and transformations. A tentative review of the economics of the proposed puerulus program is given below. To go to further detail is inappropriate without practical data which can only be obtained from specific research programs. The figures are intentionally conservative, so the profitability estimate will tend to be low. The objective is to determine whether WRL culture is likely to be profitable, based on parameters most of us would accept as being adequately conservative. Profitability estimates based on such assumptions are calculated as shown overleaf on Table 1

The 20 year schedule of costs and revenue derived from Table 1 and the IRR analysis is then given on the following page. It shows a return of 24.5%. Most companies would consider 12% after tax to be acceptable for the level of risk involved, so an IRR of 18-20% is in the order of acceptability. The project thus appears to be commercially sound. A shorter period of IRR calculation is inappropriate because of the lag between start-up and revenue.

Every person reading the above input assumptions and calculations will find some they definitely "know" are wrong - and you are right. For example, the cost of puerulus collection might be too low, or mortality might be much higher. However we all know the assumed selling price could also be much higher, $27 instead of $21. The only way to get a feel for commercial success and reality, at this stage, is to make a sensitivity analysis.

A sensitivity analysis has been made of the effect of varying the significant cost and revenue parameters on the IRR outcome. This is also shown overleaf. The origin, or base-case of the analysis is shown as"zero". It is an IRR of 24.5%, derived from the nominated input parameters given earlier.

The sensitivity analysis shows the commercial consequence of percentage change to the base-case IRR as a of altering an input parameter. Thus a 10% increment in selling price increases the IRR by 23.7%, that is to 30%. A 10% increase in the cost of puerulus collection reduces the IRR by 4.2%. It is a very useful evaluation tool. You can disagree with any of the input parameters I have adopted and obtain some indication of the outcome. The analysis shows that the most important variables are "sale price" and "feed cost". If sale price is $27 and other parameters remain the same, the IRR would be approximately 39%. The next most influential parameter is the cost of"puerulus collection". Alteration of capital, or contingency cost, have a relatively inconsequential effect on IRR. The analysis enables immediate consideration of the effect of varying any variable, such as selling price, or a change in the cost of contingencies.

INPUT PARAMETERS FOR PROFITABILITY ESTIMATE

Table 1

Cost of puerulus collection, (per puerulus)	=	$0.67
Feed Costs, (trash fish, trash molluscs etc)	=	$2.00kg
Feed Costs, specifically formulated dry pellet	=	$2.00kg
Conversion rate of WRL (Wet feed to WRL product)	=	4:1
Dry Feed to WRL product	=	1.2:1
Selling price of WRL, at say 350gms	=	A$21/kg
Mortality	=	10%
Therefore production costs per kg are compiled as follows:-		
Cost of puerulus (3 animals at 334gm, approx 1kg of WRL product)	=	$2kg
Wet feed cost (of WRL product)	=	$8/kgm
Dry feed cost (of WRL product)	=	$2.40kg
Mix of Dry & Wet feed (of WRL product)	=	$6.00/kg
Mortality	=	10%
Therefore production estimates based on stock price, feed costs and mortality are:		
Wet Feed @ $[(3+8) x 1.1]	=	$12/kg
Dry Feed @ $[(3+2.4) x 1.1]	=	$6/kg
Mixed Wet/Dry feed @ $[(3+6) x 1.1]	=	$10/kg
An IRR model was run on the following parameters:		
Size of farm unit	=	1000 tpa
Number of animals in stock	=	3 million
Stocking density	=	50% @ 10 animals/m² and 50% @ 5 animals/m²
Farm Area	=	50 Hectare
Capital cost of ponds, enclosures, nets, equipment and buildings	=	$3.0million
Labour Costs, 10 operating staff @ $50,000	=	$500,000 pa
Consumables, vehicles, & equipment	=	$200,000 pa
Seed (puerulus)	=	$2.0 million pa
Feed	=	$10 million pa
Contingencies, processing, marketing, insurance	=	$500,000 pa
Selling Price (Farm gate)	=	$21/kg
Start-up to cash flow period	=	2.5 years
Investment period	=	20 years

ROCK LOBSTER AQUACULTURE

CASHFLOW & INTERNAL RATE OF RETURN

BASE CASE

YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
									CASHFLOW $ MILLION											
CAPITAL	-3.0																			
LABOUR		-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
CONSUMABLES		-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
SEED		-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
CONTINGENCIES		-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
FEED		-3.0	-7.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0
SALES				10.5	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
ANNUAL CASHFLOW	-3.0	-6.2	-10.2	-2.7	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
CUMULATIVE CASHFLOW	-3.0	-9.2	-19.4	-22.1	-14.3	-6.5	1.3	9.1	16.9	24.7	32.5	40.3	48.1	55.9	63.7	71.5	79.3	87.1	94.9	102.7

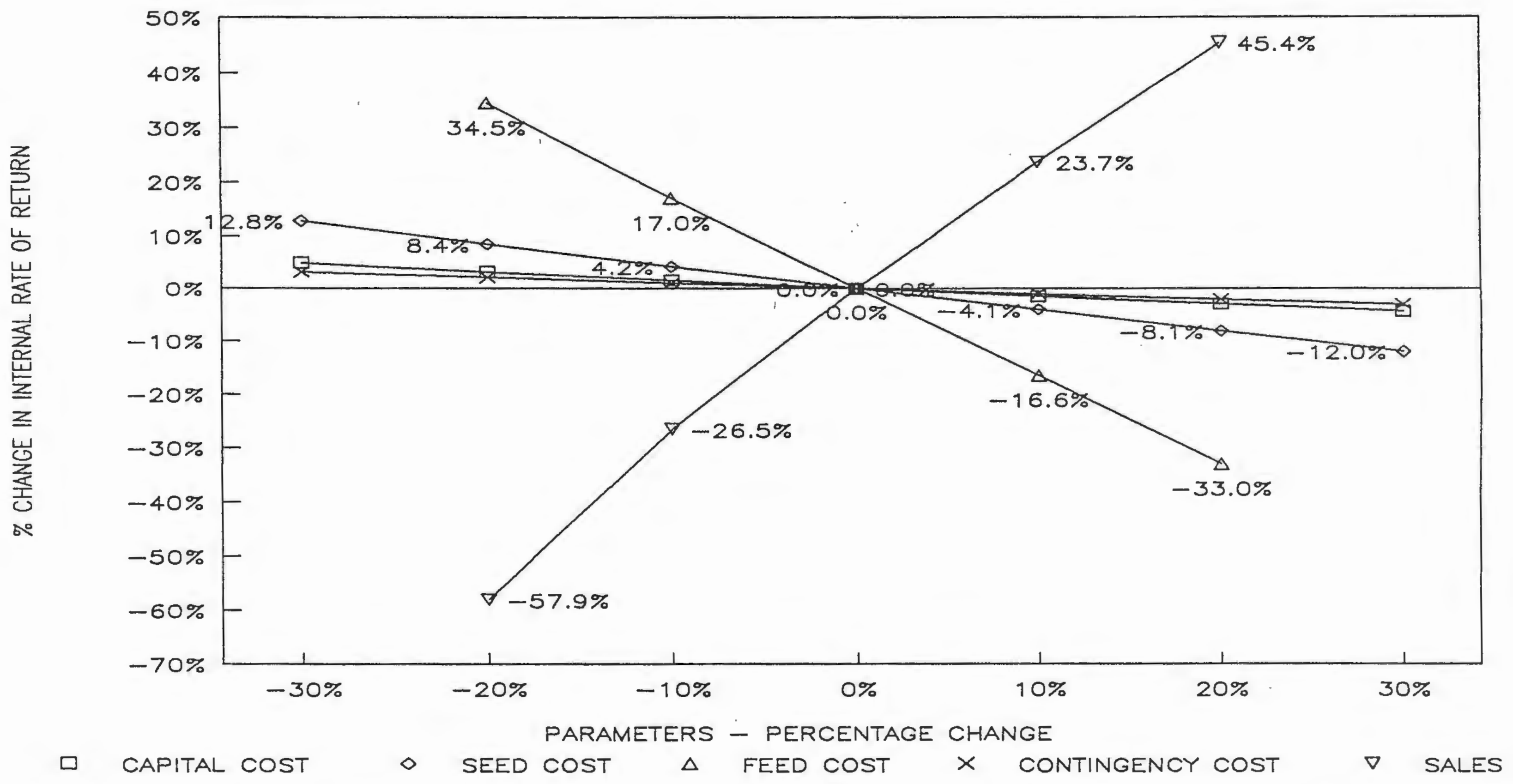
INTERNAL RATE OF RETURN (IRR)	24.6%
OVER 20 YEARS, BEFORE TAX, REAL	

NOTE: MAXIMUM CUMULATIVE OUTGOINGS IS $22.1 MILLION
PRE-TAX "PAYBACK PERIOD" IS 7 YEARS

ROCK LOBSTER AQUACULTURE

INTERNAL RATE OF RETURN (IRR)

GRAPHS OF SENSITIVITY OF BASE CASE IRR TO KEY FINANCIAL PARAMETERS



Obviously more detailed and accurate models will be run, if the project proceeds any further, but for the present level of knowledge and consideration it is evident that, if reasonable changes are made to any of the input parameters, the project still remains commercially attractive.

Figures are given before tax. There are probably some tax advantages in the initial years of negative cash flow. The negative cash flow is quite high in the early years. The effect of debt funding in the early years would also need to be taken into account. However, given the conservative nature of the parameters the project would on balance appear to be a commercially profitable venture.

Successfully reared marine fin-fish such as Yellow-tail Kingfish, salmonoids, turbot and bream all have wet weight food conversion rates of 8:1 or thereabouts, (much depends on factors such as temperature, stress and exercise in captivity). Crab conversion rates are about 3:1. Cultured prawns are now usually given dry-pellet feed and have a dry weight conversion ratio of 1.8:1. With a wet weight conversion ratio in the order of 4:1 and anticipated dry weight conversion ratio of about 1.2:1, the WRL is much the same, or possibly a better food converter, than commercially reared prawns and fish. Feed costs are thus about the same or less than for these alternative animals, but the selling price of WRL is much higher. Thus WRL should be commercially viable.

If the cost of stock collection, plus feed cost is adequately small, when compared to selling price, then the project is very likely to be profitable.

The WRL is known to be disease resistant, easily fed, wide ranging in its diet and gregarious after the early post puerulus phases. It is therefore likely that a marketable animal of 250-300gms could be obtained with 18 months of cultivation, from collection at the puerulus phase. A fairly reasonable price has been allowed for puerulus acquisition, which is probably the most substantial unknown parameter.

Given the established reputation and quality consistency of the *Panulirus cygnus* product in the rock lobster market, together with the inability of competitors to obtain pueruli for culture, plus the significant differential between feed cost and product price, it is evident that the rearing of *Panulirus cygnus* pueruli to market size should be adequately profitable.

The major limitations to the project will be the availability of puerulus stock and the ability to catch them in sufficient numbers at a commercially competitive price. To be successful the project has to expand the sustainable yield of the existing fishery substantially and offer commercial inducement to those already in it. Without security over the existing wild-capture fishery and commercial inducement, there will be a natural tendency for existing licence holders to boycott the proposal. These aspects should be the major focus of the proposed research and development program.

Where And How Will WRL Puerulus Be Reared

All commercially successful animal husbandry falls into three categories, regardless of whether it be culture of cattle, sheep, chickens, fish or pigs. -

Open Range.

In this situation animals are simply captured from the wild, processed and sold. There is little or no feed supplementation, and minimum disease and predator control. The animal is cost-effective to harvest and the level of harvest is usually managed for sustainability.

Semi-Intensive Cultivation.

Animals are contained in an extensive enclosure, and their diet is supplemented. Disease, predation and competition are adjusted or controlled.

Intense-Cultivation.

Animals are fully contained. All feed, and habitat requirements are provided, in an environment that is free of competition and predation. Every effort is made to contain disease and promote efficient growth.

Aquaculture is no different in principle, it is just more recent in Australia. The major difference between agriculture and aquaculture is ecological. In agriculture, the animal, its food and its excreta are all in air. In aquaculture they are all in water. Water has a much greater tendency to become a pathogenic soup. Thus husbandry in aquaculture needs to be far more sensitive.

At the present time, the Western Australian Rock lobster industry is based on harvesting a free-range animal which is naturally contained by habitat preference, and easily captured by feeding behaviour.

Historically, animal domestication has always proceeded through the sequence of wild-capture, followed by incremental steps in semi-intense husbandry. Later, as experience and research information is obtained, there is an inevitable progression to intensive husbandry in those species which are amenable to domestication. In the case of the proposed WRL Research and Development program, it is reasonable to assume that the project would be initiated on the basis of semi-intensive aquaculture. The puerulus would be obtained from the wild and reared in semi-intensive ponds rather than an intensive mass culture facility.

The Research and Development program will, however be obliged to review both semi-intense and intense culture strategies. The more likely successful outcome being, semi-intensive aquaculture in ponds, or cages. The farms could be established along the Western Australian Coast.

Who Should Have Access To Participate In The Project?

Eligibility for participation in the commercial project to rear WRL puerulus will need to be studied as an integral component of the proposed research and development program. However, it is appropriate to consider the following premise and conceptual model at outset.

The Western Australian Rocklobster resource is a *"Commons Resource".* It is the property of the Western Australian Government. Licenses are granted by the Government to harvest components of the WRL *"Commons Resource"*, subject to the Fisheries Act 1905, and its Regulations. Thus the people of Western Australia, through the State Government are the ultimate proprietors of the WRL resource.

The State Government enables prescribed access to the resource to both commercial and recreational fisherman, by way of licence with appropriate conditions. The State Government has the power to adjust the conditions, terms and structure of those licences as it sees fit, without making compensation to licence holders. This type of adjustment has occurred on a number of occasions in recent years, when government has seen fit to amend Fisheries Regulations which are directly relevant to the WRL catch-effort. Thus the principal in the proposed project must be the Government of Western Australia.

The WRL commercial fishery is complicated by the fact that it is a *"Limited Entry"* fishery. The total number of pots is limited. When and where those pots may be placed is also regulated. Under the current Fisheries Act, a commercial WRL licence holder has an expectation of consistent renewal and eligibility for licence transfer, provided the parties have demonstrated reasonable compliance with the Fisheries Act and its Regulations.

Thus there is a definite element of proprietorship by the 700 commercial WRL licence holders in the WRL stock. This should be properly reflected in aquaculture use of the WRL stock. There is also a reasonable expectation of continued access to the fishery by the 20,000 recreational WRL licence holders.

The objective of this proposal is to expand the existing WRL fishery rather than remove a useable component from the wild-capture fishery and culture it in competition with the existing fishery. The project will be based on harvesting pueruli occurring at locations, where it can be demonstrated that such harvest would be excess to optimal recruitment of juveniles into the wild-capture WRL fishery.

It is envisaged that a corporate body would be established by the Government within the framework of The Fisheries Act. Equity and participation in the project would be available in a number of categories.

1. Existing WRL commercial licence holders would automatically have an equity in the project. That equity would be proportionate to the number of pots for which they hold a licence.

2. An entitlement to equity could be also available to recreational licence holders, WRL processors and ancillary services, based on a formula which recognises prior participation in the industry

3. A component of the equity could be available to the public.

On the basis of this proposal, existing commercial rocklobster fishermen and rocklobster processors will have automatic access to the venture without up-front costs. Their licences would earn a "carried interest". The viability of the project will have been demonstrated and tested through the Research and Development program.

The Western Australian Government has the ability to optimise the commercial return from utilisation of its "Commons Resource" by subsequently adjusting license fees. These could be based upon composite return from both wild-catch and aquaculture components of the expanded WRL fishery. It is envisaged that equity obtained by way of commercial pot or commercial process license would be transferable only upon license transfer and thus be reflected in pot licence value. A private sector component enables a market capitalisation value to be put upon the project.

A similar mechanism for equity participation is envisaged for recreational licence holders, with limitation to entry by set by a prior interest in the WRL fishery. Those recreational fishers demonstrating a long term interest in the fishery, by way of holding a recreational WRL licence, could have access to equity participation by way of their licence. It too could be transferred only under specific conditions. The fee for those licensees who chose to participate in the WRL aquaculture project would be calculated differently to those with access to a recreational WRL catch but have no entitlement to equity in the project. In simplicity, if commercial fishers obtain a carried interest into the project by way of their licence, a similar opportunity should be granted to recreational licence holders.

The proposal is therefore essentially "risk-free" to existing commercial and recreational WRL fishers. The project will only proceed if demonstrated to work technically, and is proven to be commercially viable. All participants will benefit from profit and the added security obtained by expanding the WRL sustainable yield. The only contribution WRL licence holders will make, is an allocation of their licence fee to the R&D program and government revenue,to the extent considered appropriate.

Will The Sustainable Yield Of the WRL Fishery Increase ?

The project, if shown to be successful through the Research and Development program, must increase the output of lobster product and the maximum sustainable yield of the WRL stock. Unless a successful outcome is proven by project research and pilot plant trials, the project will not proceed further. The aquaculture project will only harvest the puerulus excess, that component which is currently lost by predation, lack of food and availability of specific habit.Thus pueruli harvested and cultured by the project, will produce in a net increment in sustainable yield.

There are a number of strategic opportunities for use of the product. The most likely outcome is for the cultured stock to be reared through to market size. There will be adequate techniques for identifying and marking husbanded animals so that they cannot be confused with the wild stock, [e.g. pleopod or telson clipping in the moult prior to harvest. The partially healed wound would be impractical to mimic in the wild catch fishery]. Under these circumstances there can be an expansion of the product range. Smaller animals could be sold. Cultured WRL could also be marketed over the whole year, thus not only diversifying product range but also increasing market stability and taking opportunity to supply at optimal price time. Sales and prices could thus be maximised during the present closed season.

There are alternative aquaculture scenarios to expand the sustainable yield of WRL. Pueruli and early juveniles could be harvested from those locations at which it is known that recruitment to the existing fishery is either very low or does not occur naturally. These otherwise wasted animals could be cultured for a period, and returned to the wild at locations known to have under-utilised WRL habitat. The culture period would protect and maintain the animal during a phase of known high predation, Howard (1988).

The objective of this secondary proposal will be to supplement areas of low recruitment and under-used WRL productivity. Because of the faster growth capable under culture conditions, captured pueruli and early juveniles could be used to provide buffering in years of poor recruitment. Thus in years of excess recruitment when natural habitat cannot carry the additional load, it would not be lost. The effect of "domestication" on partially reared animals would need be tested to determine subsequent survival on return to the "wild". Who pays for the rearing, and who has the right to harvest would be a commercial and administrative nightmare.

The commercial reality is however, that industries tend to be viable when product supply is consistent. Thus an aquaculture industry dependent on a stop-start relevant to excess years is impractical. The capital, processing, marketing and manpower costs associated with a stop-start aquaculture project would make it impractical. Similarly, returning expensively caught and reared animals to the wild, for grow-out and recapture will also tend to be impractical.

There are two valid propositions likely to be raised by opponents of this proposal, which need more detailed evaluation by research. The first is, that because the puerulus settlement index [PSI], is subsequently reflected in the amount of catchable stock, there is never any excess in puerulus settlement. The second is whether the local yield of catchable stock is empirically related to the local PSI, (refer FIGURE 4). The two observations conflict and should be resolved.

In summary, the proposed Research and Development program must enhance management knowledge in important areas, and if successful will increase the sustainable yield.

Are There Equivalent Aquaculture Models ?

The concept of this type of project is not entirely new to Australian fisheries; value adding by tuna cage-culture has similarities. However, in concept the project is largely modelled upon one of the world's most successful long term aquaculture production systems. The proposal is remarkably similar to the capture and culture of the Yellowtail kingfish (*Seriola quinqueradiata*), in Japan. The development history of that fishery is outlined in Kafuku and Ikenoue (1983).

The Yellowtail Kingfish forms the mainstay of the sashimi market in Japan, and has done so on a tried and proven basis, for the past thirty years. It has been cultured since the 1930's. Major "Net-cage" cultivation began in 1965. FIGURE 6 shows the increase in aquaculture production of Yellowtail Kingfish, during the transition period 1968-77. Annual production from floating, net-cage, culture is approximately 150,000-180,000 tpa. Culture has routinely supplied between 3 and 5 times the amount taken from the wild-catch fishery since the late 1970's. The success story is the overall 4-fold increment in the sustainable yield, with gradual reduction in the wild-capture component as fishing effort shifted to farming the product.

Fingerlings of the Yellowtail Kingfish school naturally to the south of Japan, between Japan and Taiwan each year. They aggregate with floating seaweed. The Japanese have consistently harvested the fingerlings and returned them live to holding cages located at farms located on the Inland Sea of Japan and at protected coastal areas. They are fed a diet predominantly comprised of trash-fish, together with purse-seine caught pilchard and sardine, and sold into the relatively high-priced Japanese sashimi market. The feed conversion rate is approximately 8:1 [wet weight feed/wet weight product], which is only half the food conversion efficiency of the WRL.

Japan has been able to maintain the Yellowtail kingfish aquaculture industry, based on capture of fingerlings in international waters, because it not only has had the technological capability to catch the fingerlings, but also natural geographic advantages for grow out-sites, and proximity to market.

The fingerlings occur close to Japan and make themselves available for capture through their schooling behaviour on a seasonal basis. The Inland Sea of Japan and some of the coastal embayments provide extremely deep near-shore, sea water protected from wind, wave and swell. To rear the fish successfully there needs be a substantial separation between the bottom of the cages and the sea floor to prevent disease through accumulation of faeces and detritus. There also needs to be good seawater circulation, protection from wave action and predators.

The temperatures in the Inland Sea are near optimum, on a seasonal basis, for the cage rearing of the animal, [in terms of the balance between growth and disease

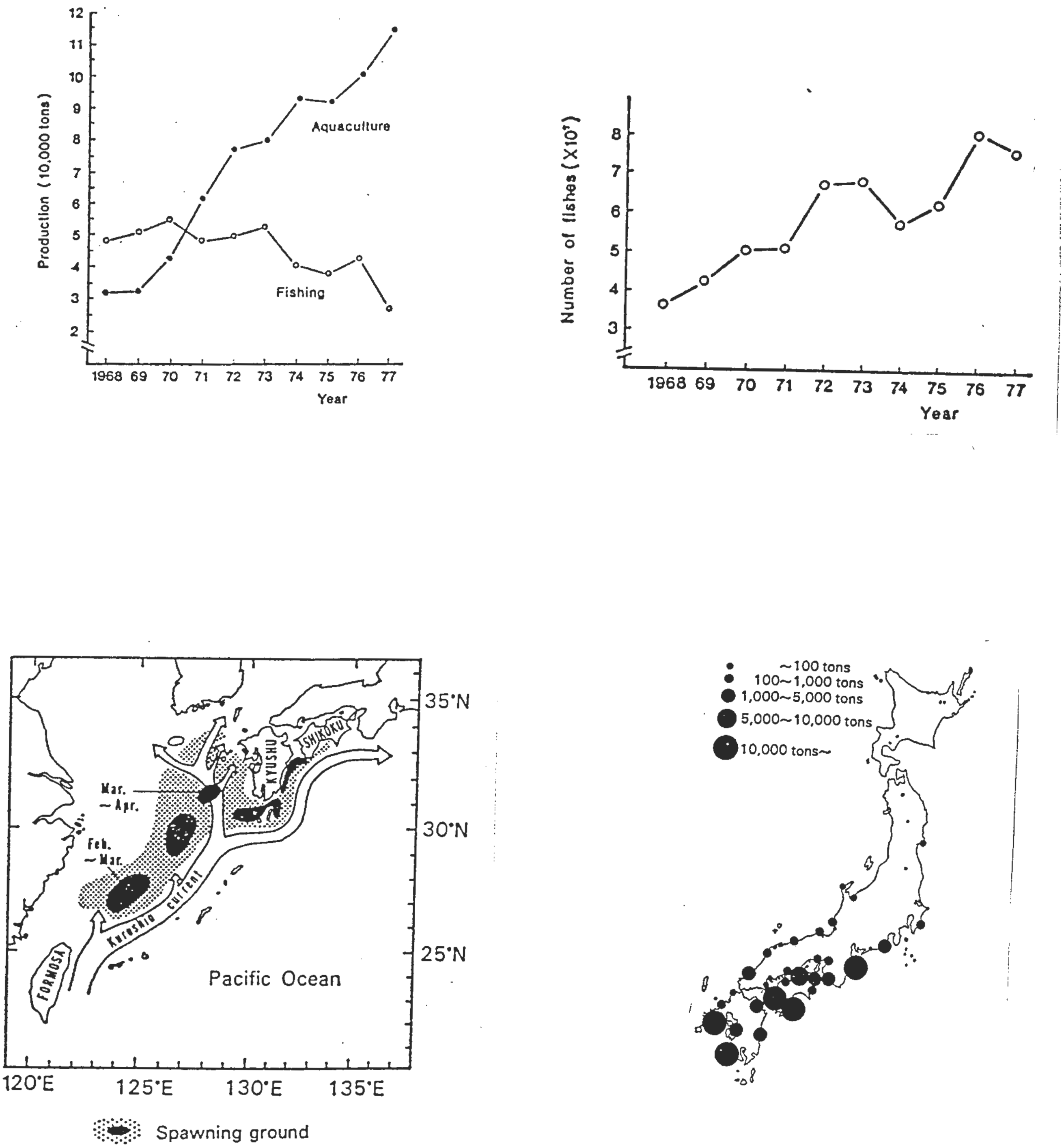


FIGURE 6.

Graphs showing:

(a) The annual production of Yellowtail Kingfish in Japan from both wild-capture fishery and aquaculture.

(b) The number of fingerlings used in aquaculture over the period 1966-77.

(c) The spawning grounds and the areas in which juvenile Yellowtail Kingfish are captured.

(d) The distribution of Yellowtail Kingfish production from aquaculture in Japan in 1979.

(Reproduced from "Modern Methods of Aquaculture in Japan". Kafuku & Ikenoue. 1983) management]. The Japanese grow-out locations have it all, so the success is not simply due to Japanese innovation. It is a mix of available market, biological and geographic serendipity, plus good management.

Thus the Japanese, Yellowtail-Kingfish industry is effectively quarantined from competition. Taiwanese and other nearby neighbours who could also harvest the fingerling resource simply do not have the combination of geographic locations that are required for the grow-out phase, the demand for sashimi, and proximity to market. Insulation from competition enables good control over the supply to the market, and the market price.

The most significant technical factor in the Yellowtail Kingfish program is that, even though the Japanese control the market and have had experience in the cultivation of the animal for more than thirty years, the industry is still predominantly based on fingerling capture rather than rearing of fingerlings from the egg. The Japanese have for many years, [at least ten to fifteen], had the technology and the practical know-how to grow the Yellowtail Kingfish from the egg through to the fingerling stage. However, this is not done on a large scale and there are sound economic reasons for this.

Marine fish are very different to those with fresh water larval and juvenile phases. In general terms, marine fish require live-food in their early larval stages, where salmonoids for example, will eat food pellets. Marine fish also require nutritional supplements to be in their live-food, particularly the *"highly unsaturated fatty acids"*(HUFA). In addition to these pre requisites, many marine fish have long larval cycles and specific spawning triggers. Thus marine fish fingerlings are very expensive to rear, compared to the freshwater species.

Cultivation of marine fish fingerlings usually requires that there also be cultivation of a substantial array of live-feed for the animal larvae. This involves mass-culture of a variety of live food organisms under intensive laboratory conditions (rotifers, copepods). Thus there is requirement for high-quality, habitat control, disease control, complicated routines of nutrient enhancement of the feed species, and maintenance of a wide variety of live cultures, to support the larvae and early juvenile stages.

The necessity for biological, commercial, market, and geographic factors to all be in place, in order for an aquaculture project to be successful, was reflected in the Mahi Mahi (*Coryphaena hippurus*, often called the dolphinfish) program. It was initiated in Western Australia in 1986, and subsequently continued in Queensland until 1993.

Technological advances made during the Mahi Mahi project have brought sophisticated marine fish-rearing research and development capabilities to Australia which should not be underestimated. There is no doubt that Australian technology can grow Mahi Mahi from the egg to a 10 kg animal in a year, and do it better than any other country. However technological competence is not enough in aquaculture, profitable marketing is essential.

The cost of rearing the Mahi larvae through the juvenile stages compared to the product selling price, currently inhibits the profitability of the Mahi project in Australia. To be marketed successfully it must be air-freighted, on ice to the USA where fresh Mahi Mahi is a premium table fish. Even if it was grown in the USA, the project would be commercially tight. The Japanese and Chinese do not like the fish, so it is no good trying to export it to Asia. The alternative is to promote the local Australian market, and that is not easy.

Thus being technologically competent is only one component of the equation. It is strategically essential to avoid the high-cost areas of husbandry wherever possible (eg. larval rearing). It is also highly desirable to have widespread market demand, a premium selling price, and be insulated from competition.

The proposed WRL puerulus cultivation program has all the essential features of the successful Yellowtail Kingfish industry in Japan.

(1) A relatively high product price is effectively guaranteed.

(2) The project is insulated from competition because no other country, or Australian state has the capability to collect the WRL puerulus phase.

(3) Cultivation of the early and late larval phases (phyllosoma) will be prohibitively expensive in the foreseeable future.

(4) It is known the puerulus phase of the animal aggregates near shore, at the new-moon and can be caught.

(5) It is also known that Western Australia has a number of locations which will provide optimum water quality conditions for rearing early juvenile WRL in culture.

Thus the real limitations to the WRL project are

(1) Can the animal be caught in sufficiently large numbers at an adequately low cost?

(2) Are there areas of our coast where pueruli settle in numbers which are excess to those needed for the wild-capture fishery ?

(3) Can the early juvenile stages be provided with cost-effective habitat and diet to ensure both survival and growth rates that are commercially attractive?

(4) Is there WRL industry and Government support to optimise utilisation of the excess puerulus resource?

It is concluded that the project, if accepted and implemented, could provide major benefits to the existing WRL industry and to the State of Western Australia.

Existing scientific information has been reviewed to ascertain whether there is sufficient justification to proceed with the Research and Development program. The essential question to be ascertained from existing knowledge is whether there truly is a substantial excess of pueruli at specific locations, on a regular basis, to warrant the R&D project.

PUERULUS RECRUITMENT

Migration, Moulting and Settlement

Information available from programs undertaken by both the CSIRO and the Department of Fisheries, Western Australian Government, have been reviewed in the context of this present proposal. The essential information on puerulus recruitment to the WRL fishery is as follows:-

* The late stage phyllosoma larvae are distributed extensively off-shore in the Indian Ocean, from the edge of the Continental Shelf westward some 600 nautical miles and between Barrow Island in the north to Cape Leeuwin in the south. (FIGURE 7)

* Throughout the larval stages the phyllosoma modify their vertical migratory behaviour in relation to depth and light. This enables the larval stages to utilise different water currents in the Indian Ocean to effect a distinct migratory pattern. Rimmer and Phillips 1979. (FIGURE 8)

* The early stage phyllosoma behaviour in relation to prevailing wind and current results in the widespread, offshore dispersion. The late stage phyllosoma adjust their diurnal vertical migration in relation to light intensity to position themselves within currents that optimise transportation eastward towards the coast.

* As the later stage phyllosoma approach the Continental Shelf they increasingly come within the influence of the Leeuwin Current. The Leeuwin Current is essentially a warm water, surface, southward flowing current with internal eddies and gyres. The phyllosoma has the opportunity to rise towards the surface and enter the Leeuwin current or stay low and avoid the influence of the Current. The phyllosoma can thus board or exit a gyre which will transport it toward the coast.

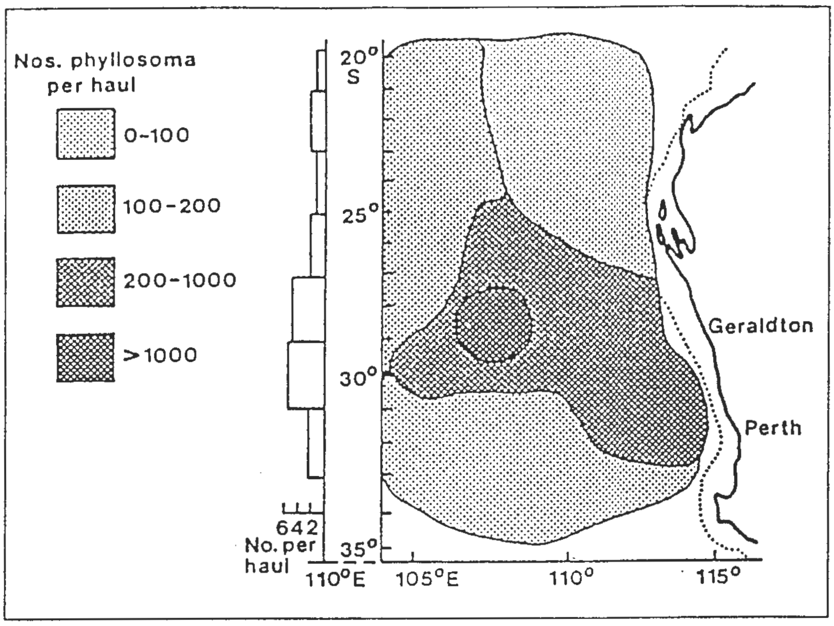
  This hypothesis has been recently revised to include the assistance considered to be provided by the incidence of westerly storm events in late winter and spring.

* It is known that as the late stage phyllosoma approaches the edge of the Continental Shelf it moults to the puerulus stage. At this moult there is a distinct morphological change from an animal having a flat leaf-like shape, designed predominantly for vertical migration in the plankton, to the nektonic puerulus, which resembles prawn morphology.

* The puerulus is transparent and does not feed on its migration (as it does not have functional mouth parts). The puerulus is capable of strong directional swimming. Antennae are positioned straight out in front and the animal swims forward using the pleopods on its abdomen, just like a prawn. It has been observed to obtain swimming speeds of up to 0.5 metre a second. At a

FIGURE 7.

The distribution and density of Phyllosoma during June and July 1976. The Continental Shelf is shown as a dotted line. The distribution pattern varies from month to month and in subsequent years due to variation in spawning intensity and dispersal by current. (After Phillips,1981).



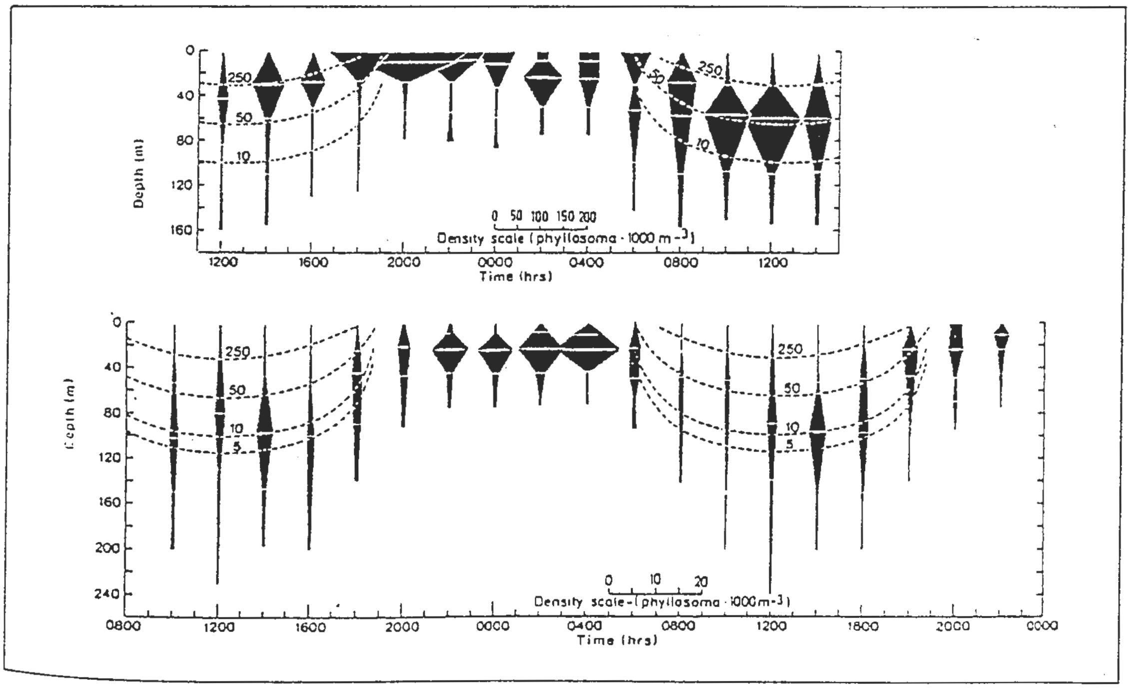


FIGURE 8.
Diurnal Variation in Phyllosoma migration through the water column. The width of the lines indicate the density of larvae at different depths as shown by the bar scale. The dotted lines show depths of equal light intensity. (Adapted from Rimmer & Phillips, 1979). The upper graph shows early stage larvae during full moon indicating movement to the surface by midnight and falling to depths of between 60-100 metres during the day time. The lower diagram shows the distribution of late-stage larvae also near the full-moon period, indicating avoidance of bright moonlit surface water during the night and a descent to an even greater depth during the daylight period.

swimming speed of approximately 1.5 kilometres an hour, the animal is capable of crossing the Continental Shelf and arriving at the coast over a period of 2-3 days.

* It is known that the puerulus has good directional capabilities and proceeds eastward towards the shallow coastal areas. It is assumed that the puerulus sinks during day time and swims actively during the night.

* Recruitment of puerulus from the plankton has a marked periodicity, related to moon-phase. Phillips, (1975) reported that CSIRO plankton hauls made off-shore from the Seven Mile Beach study area during the period from July to November, 1974 obtained 48 puerulus from 71 hauls during the New Moon phase compared to only 1 puerulus from 48 hauls during the Full Moon phase.

* Plankton samples taken within the Seven Mile Beach collection area around the time of New Moon obtained puerulus. Samples taken at the Full Moon, or during daylight at the time of the new Moon, did not yield puerulus.

* The puerulus collectors located in protected shallow water along the Western Australian coastline have clearly established that puerulus settle preferentially in near-surface collectors rather than near-seafloor collectors.

* It is also well-known that puerulus occasionally cling to pot-lines in offshore areas of the fishery, but the significance and opportunity provided by this observation has not been researched.

  Recent observations confirm that settlement, and effective recruitment to juvenile stages, occurs in some years in some offshore areas of the fishery, [WRL fishermen and Fisheries Department, pers. comm.].

* Settlement occurs from three days before the New Moon, peaking at the new Moon and extending some eight days after the New Moon period. There is essentially no settlement during the Full Moon period.

Behaviour and Habitat Requirements

The information that is available reveals a number of significant clues in the WRL recruitment strategy. Collector data show that the intensity of puerulus settlement is directly related to the seasonal intensity of the southward flow of the Leeuwin Current. Plankton hauls confirm the behavioural ability of the phyllosoma and puerulus phases to take advantage of the return transport mechanism provided by eddies in the Leeuwin Current and westerly storms. However the moult from phyllosoma to puerulus and subsequent migration to the coast is highly structured and distinctly cued to moon phase. It is neither a continuous nor random recruitment.

The late-stage phyllosoma are both strongly predatory and vertically migratory within the plankton. However the puerulus does not feed, it does not have functional mouth parts, it is transparent, but is no longer within the plankton. It is an active nektonic swimmer.

The puerulus is a very specific stage of the life cycle. It is obligated to make a strong swim across the Continental Shelf and to find a suitable habitat prior to exhausting its energy reserves (which cannot be replenished) and undertake the moult to the post-puerulus phase during the following full-moon period.

It must find a habitat that is optimal for post-puerulus survival when it makes its moult to post-puerulus. There is a major morphological change at this moult from the non-eating, nektonic, prawn-like puerulus to the benthic, cryptic, browsing post-puerulus juvenile.

Information from the collector program shows that pueruli settle preferentially in near surface habitat at the new moon and moult to the post-puerulus (first juvenile stage) during the following full moon period. In the period between settlement and moulting the transparent puerulus gradually becomes deeply pigmented. At moult it actually reduces slightly in size.

On becoming the post-puerulus, or first stage juvenile it has the overt structural characteristics of the juvenile rocklobster. The post-puerulus is no longer nektonic in behaviour or morphological characteristics, it is characteristically benthic. The successful post-puerulus selects sea- floor habitat in a cryptic environment. Research has shown a post puerulus preference for small holes, fissures and caves in shallow coastal water reefs covered by *Amphibolis* sea grass. Settlement is also known to occur among *Acropora sp* plate-coral at the Abrolhos Islands. The deeper, offshore areas in which Pueruli settle have not been described in detail, as yet.

Artificial Puerulus Collectors

Observations recorded by Phillips (1972) (1975) (1978), Phillips and Olsen (1975) provided the initial information in regard to settling behaviour and the capability of the artificial collectors. The collectors function by providing shelter-habitat rather than food. The collectors have a zone of influence that facilitates capture from an area more extensive than the collector itself. The pueruli do not have to collide physically with the collector in the course of swimming. They can be attracted to a collector when they are within a radius of approximately 1 metre of it.

Collectors located adjacent to each other, have similar catching rates. Interestingly, pairs of collectors located at different portions of the same coastal lagoon or back-reef area have short-term variability in comparative catch rates due to weather. Phillips (1978) made the observation that the less turbulent areas of the Seven Mile Beach test site, as dictated by the prevailing wind at the time, collected more effectively than those downwind, where wave action and turbulence was greater. This preference was observed to change in response to orientation of the wind. Therefore it would appear that the puerulus has a preference for quite-water when settling. This should not be confused with the recent observation of Caputi and Brown (1993), that trans continental shelf migration appears to be assisted by westerly storms in late winter and early summer.

It was established very early in the collector program that the puerulus settles on collectors close to the surface not those collected close to the sea floor even though both the habitat offered and turbulence is similar. The depth at collector sites is quite shallow, approximately 2 metres [Phillips (1972)]. At this range the puerulus would detect both collectors. Thus there is a strong behavioural preference for a near surface habitat at the time of settlement. This is consistent with the surface swimming behaviour of puerulus observed by Phillips. The occasional recruitment of substantial populations of juveniles in deeper water therefor needs further consideration. These populations are presumably derived from puerulus that have settled in deeper water.

Phillips (1975), also observed that artificial light had a marked effect on settlement rate on collectors. In a series of tests, Phillips positioned a small overhead light [illumination = 1 watt] on the collector and found that its collecting rate was five times that of a control collector at the same location. This is an interesting anomaly that has implications for further research. The animals obviously avoid the full moon, or lit periods of the moon phase, to moult from the phyllosoma, migrate and settle. However they are still attracted to collectors with illumination during the new moon phase.

Phillips (1975) also made the observation that a light held over the side of a boat did not attract all pueruli. Some kept going past the light even though they were within its influence, whilst others remained, attracted to light.

It is evident that pueruli settling in the shallow reef areas have to find a habitat that avoids predation, for the 6-10 day period in which they undergo their moult to the post-puerulus juvenile. The post-moult juvenile also needs be in a habitat that provides adequate protection from predators.

Pueruli which settle on the collectors do not eat, and remain there until they have moulted. It is also known that post-puerulus juveniles also remain within the fibres of the collector after their transitional moult. Whether this is because of a reluctance to swim or walk from the collector to the sea floor, is an aspect that requires further evaluation.

Pre-Requisites for Successful Settlement.

In natural conditions, optimal recruitment requires there be a continuity in shelter provided by a juxtaposition of the preferred habitat of both the puerulus and the post-puerulus, in order to avoid predation.

The preferred habitat of the puerulus, and early post-puerulus juvenile phases do not appear to be the same. There has been substantial underwater observation of the post-puerulus and early juveniles in holes, crevices and caves, Fitzpatrick et al (1990). The study noted a combined 188 post-puerulus and early instar juveniles. However only 3 pueruli were found, (2 of these were pre-moult because they were pigmented). Being transparent the newly settled pueruli are of course more difficult to observe, but none the less would have been observed, had they been in the same habitat as post-puerulus juveniles, Jernakoff (pers comm). **Therefore the preferred natural habitat for puerulus settlement has not been found yet.**

In the discussion section of their report to FIRDC Fitpatrick et al (1990) said:-

> "The investigation at Seven mile Beach and Cliff Head was successful in identifying the habitats used by western rock lobsters from the time of puerulus settlement through the post-puerulus stage. The pueruli and the early post-pueruli inhabit small holes in the reef, usually on the reef face and where there is some algae or seagrass growing on the reef. The reef face is covered in dense growth of algae and seems to provide very similar habitat to the artificial seaweed collectors. This supports Phillips' (1972) suggestion that puerulus settlement on the collectors simulates natural settlement. For some time after settlement the post-pueruli continue to inhabit small holes in the reef, however the relationship between carapace length and hole size suggests that they move to larger holes as they grow."

The statement is unfortunately contradictory. It suggests the puerulus habitat is both the algae and the holes. However, it really recognises that two different habitats in juxtaposition are required. Deep within the hairy filaments of reef-face algae is the most logical habitat for puerulus. In such locations the animal has shelter until it moults and is in juxtaposition to the holes and crevices of the reef preferred by the early juvenile stages.

It is important to confirm that while fine filamentous algae on reef and *Amphibolis* seagrass,[being very similar in habitat to the collectors], is the most likely natural habitat for puerulus - it has yet to be proven.

Those pueruli settling in the same algae attached to *Amphibolis sp* in open meadows, rather than on reef-face, have to run the gauntlet of high fish predation (once they moult to post-puerulus juveniles and begin to move about in areas that do not provide small reef-hole or crevice shelter). This may explain some of the high post-puerulus predation reported by Howard (1987) (1988).

There has always been an assumption that puerulus do not settle in seagrass meadow away from reef. If you look at this proposition underwater in areas where there are artificial collectors, then it is difficult to accept. The immediate settling habitat provided by seagrass and associated algae are identical in both reef and adjacent meadow situations. In practical terms the puerulus would need proceed to the seafloor, test the substrate and move on until it finds rock. If this is the case then the artificial collectors should not work.

On the basis of information obtained from collectors it is clear that the puerulus must settle somewhere in the reef area, presumably in a habitat that mimics that provided by the collectors. The animals are presumably there, for the 6-10 day period prior to their moult to the post-puerulus stage, after which their pigmentation and their long antennae enable easier detection and observation.

As noted earlier, discussion with WRL fishermen, and Fisheries Department scientists, indicates that there is also occasional puerulus settlement and juvenile recruitment in deeper offshore water. These observations are plausible and probably result from either the fortuitous settlement of exhausted puerulus in habitats that enable survival, or the animals may routinely settle in such locations, but only rarely survive through to the catchable juvenile stages. Alternatively, it may be that migrating puerulus settle during daytime, and thus diurnally leap-frog toward the coast. If they transiently settle to the seafloor in suitable habitats along the way, they may remain there. If for example, puerulus stop on the seafloor in an area of suitable filamentous material, adjacent refuge habitat, adequate food and low predation do they move on? Do they only settle in such localities if exhausted ? The reports should be investigated in detail.

Howard (1988) found that approximately 20% of the post-pueruli obtained in gut samples of predatory fish were collected from open seagrass meadow areas, 80% were found in fishes collected at or around reef areas. Whether the fish collected in the open were transient between reef areas when caught, or hunting in the open areas, is not known. The information currently available suggests that some post-pueruli do occur in seagrass meadow areas, but are very susceptible to predation in those meadows.

Howard's work, like that of Fitzpatrick et al, also appears to have focused on post-pueruli, because he notes most animals were 8-15 mm carapace. Pueruli are 6-7 mm carapace.

Howard's collections were made on three occasions, on 16th-17th and 18th-19th October 1984 and again on 13th-14th March 1985 (pers comm). Bureau of Meteorology records indicate that Howard's collections were made in the week after full moon on both occasions. Thus it was biologically unlikely for pueruli to have been present in the samples.

Howard's fish collections included Australian Herring, but none of these fish contained pueruli or post-pueruli. It is known that Australian Herring *(Arripis georgianus)* occasionally gorge on WRL puerulus.

Therefore it is still not known whether the translucent puerulus settles in seagrass meadows and is eaten rapidly by the array of bottom-feeding fish collected in Howard's study, or whether it is also hunted by surface fish such as herring, tailor and snook, while swimming over seagrass meadows during its settling period.

The conventional wisdom is that puerulus do not settle in seagrass meadow because they have not been found there. But they have not been found anywhere

other than collectors as yet. Were translucent puerulus missed? One would not expect
settled puerulus or post-puerulus to last long, if they started to move about in open seagrass meadow.

Howard (1988) calculated that mortality of 8-25 mm carapace length post-pueruli may be in the order of 2500/hectare of reef per year. For this current proposal it is essential to consider both puerulus and post-puerulus mortality.

The Howard (1988) estimates of puerulus mortality appear to be consistent with extrapolation which can be made from the observations made by Phillips (1972)(1975) and Phillips and Olsen (1975). The following hypothetical case is interesting to consider.

* Puerulus settlement occurs monthly for at least six months of the year (usually it is six to eight months in southern areas of the fishery and all year round in northern areas, FIGURE 3B)

* Collectors have an effective radius of about a metre, or 3 square metres of area. They also operate in a stream situation, thus the amount of water travelling past may also have an effect on catch rate.

* Pueruli swim directionally toward the shore. They have not been observed to swim in random direction. Thus if they do not settle in favourable habitat en route, they should end up at the beach, or surf zone.

* Collectors at locations from Jurien Bay to South Passage tend to collect about 10 animals a month, per collector (or 3 per square metre).

* Therefore by simplistic calculation, there are 6 x 3 = 18 per square metre, or 180,000 individuals settling per hectare, per year.

* However, such a calculation makes no allowance for the configuration of the hectare, or stream flow past the collector. Even if the hectare was 1 metre by 10 kilometres in configuration it still means there would be at least 18 pueruli per linear metre per year reaching the coast.

  Moreover Phillips and Hall (1978) found that collectors placed outside reef areas fished far less than those inside. Therefore distribution is not spatially uniform.

* The indications are that mortality due to lack of habitat and predation is very high.

* Howard's estimates of predation must be in addition to that on the surface-swimming and settling puerulus. At present there are no realistic data, on which to make reasonable calculations of puerulus mortality.

However a suite of predators is certainly present, their biology in relation to WRL is unexplained and uninvestigated.

* There are occasional reports of substantial numbers of exhausted pueruli washing into shallows, particularly in the Coral Bay area (Fisheries Department pers comm).

* There are no estimates of pueruli wastage on open shorelines which do not provide post-puerulus habitat.

It is concluded that there is insufficient information to estimate density of puerulus recruitment from the nekton to near shore reef habitat.

What does the "puerulus settlement index" really mean ? As we shall see later, the fact that collection rate is 20-40 times less in southern areas of the fishery, when compared to those in the middle and northern portion, is not commensurately reflected in the density of commercial sized animals. However to add to the complexity, settlement index, with appropriate transformations, is an accepted and reliable indicator of future stock levels.

Post-Puerulus Distribution and Behaviour.

Jernakoff (1990) studied the distribution of early post-puerulus juveniles on settlement reefs. A number of artificial shelters were trialled as collectors, most of which proved unsuccessful. Jernakoff also trialled the use of local limestone blocks, of rectangular shape (60x30x25cm), into which holes were drilled (8,10,12,14mm diameter and either 25 or 50 mm depth).

Two trials were undertaken, the first in which 6 of the limestone blocks were placed among *Amphibolis* sea grass meadow habitat, (equivalent to that which occurs on the reefs in which the juveniles were found to settle naturally). The second trial group was some 750 metres away and the equivalent 6 limestone blocks were placed in a clear sand area. Jernakoff found as follows:-

> "All 35 post-puerulii found in holes in the limestone blocks were between 7 and 12 millimetres in carapace length. The post-puerulii preferred holes in those blocks with sea grass cover compared to bare shelters - 335 were found with sea grass and none were found in those blocks that did not have sea grass cover.
>
> In addition there was a strong preference for the deeper holes. For example 34 were found in those which were 50 mm deep and only one was found in a hole 25mm deep. The factor of hole size, that is the diameter of the hole size, was analysed by pooling the data and showed that there was a highly significant trend for the smaller-sized post-puerulii being found in the smaller holes."

Jernakoff concluded that holes drilled in the limestone blocks provide a suitable habitat for the post-pueruli and therefore may be an important experimental tool for future research. His results suggest that **post-pueruli require a very specific habitat for successful recruitment. The indicative configuration being - a hole 8-10mm in diameter and 50mm deep, on a shallow, *Amphibolis* covered reef, (or plate coral). Prior to this the puerulus must have found a suitable settlement habitat**, possibly algae attached either to shallow reef or *Amphibolis* on shallow reef. The puerulus must have survived until moult, then sought the new habitat. Thus it has to be very close to the post-puerulus "hole" habitat.

Jernakoff certainly showed pueruli do not settle into the post-puerulus "little hole" habitat. They must moult, then migrate to the "holy" habitat.

A number of other important observations were made by Jernakoff in regard to the post puerulus behaviour.

* There is no foraging from the safety of burrows during the day time.

* All feeding activity and foraging activity is nocturnal. Movement of the post-pueruli between shelters overnight seems to be common.

* 50% of the occupied shelters were vacated after only a one day period.

It is not known where the individual lobsters moved, because they could not be individually marked. However they are likely to remain on isolated reef patches where there is shelter because if they move between reefs they will be exposed to a high risk of predation.

An added conclusion which may be drawn from Jernakoff's successful placement of limestone blocks in seagrass meadows [*sans* reef], and unsuccessful placement of blocks in open sand areas, is that pueruli are not attracted to reef areas *per se*. They actually settle in to seagrass plus algae beds, but must have suitable holes in juxtaposition for recruitment of the post-pueruli. In practice, it is the seagrass/algae on reef which provides the required combination.

Jernakoff (1993), studied the diet and feeding behaviour of post puerulus WRL. He found that the post-pueruli forage mostly at night among the *Amphibolis* sea grass and sea grass detritus on the reefs in which they had settled. They also foraged among the algal cover on the face of the reef and in the ledges and the caves. No post-pueruli were observed foraging in *Amphibolis, Heterozostera or Halophila* sea grass meadows, surrounding the reefs. Therefore early juveniles remain very close to shelter. As a consequence the carrying capacity of nursery reefs is strictly limited by a mix of availability of shelter and food.

The diet of early juveniles was determined from collection and gut sampling. They are browsers, and it was found that coralline algae, small molluscs, crustaceans and detritus comprise the main diet. Jernakoff et al (1993), made the following observations, "Post-puerulii forage at night amongst *Amphibolis* and macro algae on the reefs on Seven Mile Beach. The reason post-puerulii forage only in these habitats may be that they need to stay close to their shelters to minimise the risk of predation (Howard, 1988). Alternatively the behaviour may be due to specific food requirements (Edgar 1990 a). Regardless of the reason post-puerulii are known to forage in habitats slightly different to those of the 24-45 mm carapace length juveniles which forage both in Amphibolus on the reefs and in the turf on the tops of the reefs. (Edgar 1998). Post puerulii foraging habitat is also different to that of juveniles that are greater than 45 mm carapace length, which generally forage in the sparse Heterozostera and Halophila sea grass meadows away from the reefs at Seven Mile Beach. (Joll and Phillips, 1984, Jernakoff 1987, Edgar 1990a).

Observations were also made on the diet of post-pueruli obtained from the collectors.

"The diet of post-puerulii from the collectors was largely composed of molluscs but also included coralline algae and crustaceans. Although the foraging activity of post puerulii on collectors was not observed these animals probably remained on the collectors from the time of settlement to the time of captured at the monthly examination. The collectors float just below the sea surface and are attached by a chain to an anchor on the sea bed. It is very unlikely that the post-puerulii move off the collectors to forage over the sea bed each night and then return to the collectors. Therefore their diet may be limited by the availability of food types that also settle on the collectors. The low proportion of coralline algae and detritus in the diet of post-puerulii on the collectors compared to the diet of post-puerulii on the reefs as well as the lack of sea grass may thus reflect differences in food availability.

Jernakoff et al (1993) also noted a variation in the diet composition which was related to the moult phase. A higher proportion of coralline algae was found in the gut content of post-moult juveniles as compared to pre-moult juveniles. They also noted that juveniles remained overnight in their burrows close to the moult period.

Jernakoff et al (1993, in press) studied the density and growth in populations of juvenile rocklobsters. Early juveniles have a preference to be solitary but a small proportion were densely aggregated. In each of the habitats (holes, crevices and caves) the density of juveniles at Seven Mile Beach to the north of Dongara was three times those at Cliff Head to the south of Dongara as recorded by diving investigations. (Seven Mile Beach is approximately 40 Km from Cliff Head.)

Juveniles grew faster at Cliff Head than at Dongara, which is consistent with the lower settlement density (if food availability becomes limiting). At Seven Mile Beach juveniles had grown to an average of 35mm by the start of their second year, and 42mm at Cliff Head. The growth rates at Seven Mile Beach may have been lower as a result of stronger competition for food because of the more dense populations that occur at that site.

At Seven Mile Beach the early juvenile component was present in September of both of the years in which the surveys were undertaken, whereas at cliff head there were no newly settled juveniles until November in the first of the two years. It was also found that peaks in the densities of the very early juveniles were fewer at Cliff Head, and occurred later in the season compared to Seven Mile Beach.

There is considerable variation in settlement success and configuration within even the small geographic area that was covered during the survey made by Jernakoff et al (1993, in press). As they note, this fits in with observation, made by Phillips (1991), who also found differences between sites and the timing of peaks in settlement on collectors. Chittleborough and Phillips (1979) also found considerable variation in both larval and juvenile densities on a much larger spatial scale.

It is concluded that the research into puerulus/post-puerulus recruitment and biology, initiated by Phillips, Jernakoff, Howard, Fitzpatrick and Edgar must be continued. The information is essential to an effective understanding of the wild-capture fishery, and fundamental to evaluation of aquaculture potential.

THE SUSTAINABLE YIELD

Changes in Market, Management and Fishing Effort.

Prior to the mid 1950's, the Western Rocklobster was essentially a local product, tied to a small domestic market. It was cheap to buy and in over supply. The WRL industry became export-oriented by the early 1960's with export of frozen tails to the United States. This meant that the price obtained for the product was sufficiently high that what could be caught could be profitable sold. Thus catch was limited only by a concern not to exceed the sustainable yield.

The Department of Fisheries, Western Australian Government recognised at outset of the WRL market expansion, the need to manage and regulate the industry to ensure sustainable yield. Management of the WRL fishery for the subsequent 30 year period has been diligent, astute and effective. The WRL fishery today, is internationally recognised as being one of the best managed in the world.

The thirty-three year period 1960-93 has seen significant improvements in technique and catching efficiency. It has also seen substantial changes in customers. Market emphasis shifted from the United States to Japan, and now to Taiwan and the other burgeoning countries of Asia. The period has also seen changes in the WRL product mix. There has been a shift from predominance of frozen Rocklobster tails toward whole-cooked and live product. The WRL industry has also benefited from by the diminishing fortunes of the Australian dollar. From 1960-1980 for example, the Australian dollar bought approximately $1.2 US and $3.0 Singapore. In the early export market only United States customers could afford rocklobster. The Australian dollar has fluctuated in recent years between $0.65-0.75 US and $1.02-1.15 Singapore. The WRL is now affordable to the growing luxury markets in Asia, as well as Europe and North America.

The current situation in regard to export marketing of Australian and New Zealand Rocklobster is reviewed by Roberts in Phillips et al (1994). A similar review of Rocklobster imports world wide into Japan in terms of amount, price and type of product is given by Oshikata in Phillips et al (1994). It is evident from these reviews that there is a substantial market for cultured WRL in the size range of 250-300gm, particularly if there is continuity of supply and the ability to supply the "live" market in Japan-Asia. Many other countries are actively considering rocklobster aquaculture. Some will undoubtedly shift to puerulus collection and cultivation. The proliferation of *Penaeus monodon* culture has adequately demonstrated that wild-capture fisheries cannot remain complacent. WRL culture must therefore be seriously researched, if for no other reason than to anticipate the effects of aquaculture competition.

Current Management Concern

In the past decade the WRL industry itself has been remarkably pro-active in ensuring regulation and sustainability of the product yield. This is typified by the development and the influence of the Rocklobster Industry Advisory Committee (RLIAC), which is comprised of both the managers and the producers.

The Rocklobster Industry Advisory Committee (RLIAC) and Department of Fisheries researchers are currently concerned by the increase in fishing efficiency of the industry and the structural shift in age-class of the Rocklobster population. Of major concern to the Fisheries Department is the declining biomass of reproductive females in the population. Although the overall level of recruitment and yield has not declined, the biomass of reproductive females has.

This structural change is occurring partially in response to selective fishing pressure. This has recently been assisted by improved technology enabling more efficient capture of the larger animals, in deep water.

The concern is that female brood stock-numbers are now diminishing toward levels, traditionally considered by scientists, to be unstable for maintaining marine crustacean populations. The question arises as to whether the Western Australian Rocklobster conforms to the traditional fishery model, or is it a special case ? Is indeed, the current level of brood-stock limiting population size (and therefore sustainable yield), or is some other component of the WRL life cycle of greater significance to the limitation of the population size ?

The controversy has to be recognised and discussed, because any proposal to harvest pueruli for aquaculture will meet with objection unless the biology is sufficiently understood and documented to support puerulus harvest for subsequent aquaculture.

In 1993 the Fisheries Department expressed concern at WRL broodstock levels and outlined remedial action in a paper which was presented to, and discussed with, the WRL industry. (Fisheries Management paper No. 54, July 1993).

The paper made the point that broodstock levels were becoming sufficiently low, to significantly influence recruitment levels in those years when a weak Leeuwin Current also inhibited recruitment.

Measures were subsequently introduced to increase the size limit slightly (by 1mm carapace length), thus enabling more "whites" to move offshore, and disperse before capture. A reduction in pot numbers also reduced fishing effort.

The strategy was to reduce the catch, in what was predicted to be a good season, and thus enable broodstock numbers to be increased, without disproportionate financial hardship to the industry. It reduced the catch of readily captured, but lower priced "whites", and recognised that most of the animals would still be out there to catch later in the season, some would also survive for capture in later years, [if revised estimates warranted increased capture levels].

The strategy has proven to be effective. The price increased for the product, so overall return to the industry was unaffected. Reproductive potential has increased markedly (Fisheries Department, pers comm). Most importantly, a weak Leeuwin current during the 1993 winter/spring, was complemented by a very low puerulus settlement, [50-60% below average]. However, it must be recalled that the puerulus settlement index has been just as low, on a number of previous occasions, notably the years 1969-72, 1982, and 1986-87, (FIGURE 9).

Egg Production, Puerulus Settlement and Sustainable Yield

The completion of this assignment has taken considerably longer than anticipated. The reason for this is an endeavour to deal with information in regard to the relationships between spawning and recruitment of puerulus and early stage post-puerulus juveniles. In simple terms, if there is not a demonstrable excess of puerulus recruits to some areas of the wild-capture fishery, then the project will be logistically impractical. It is not possible to make such an assessment without considering the long-term spawning and recruitment data.

Even though WRL fishing statistics and biology have been well managed and researched, there are always anomalies in some aspects of such data. The anomalies in regard to WRL data are of concern to some WRL fishermen, largely because of pot reductions and alteration of fishing pattern, to enable improved biomass of reproductive females. I found there are some anomalies, and acknowledge that I may be incorrect in my interpretation. Recent papers by Caputi Brown and Chubb (1994),in press, and Caputi Chubb and Brown (1994), in press, address these matters in some detail. In any event the anomalies should not be used to suggest alteration of the management strategy recently put in place by the Department of Fisheries.

The only significant point at issue is the reliability of calculation of spawning stock index in the period from 1950 to the mid 1970's when records were not as reliable.

FIGURE 10 presents data from "Fisheries Management Paper No.54" (1993). It shows a reduction in the spawning index over the period 1970 through to 1992. The data indicate that the reduction is greater in the northern areas of the fishery

FIGURE 9A.
The Puerulus settlement over the period 1966/67 through to 1992/93 as calculated by the Western Australian Fisheries Department for Jurien Bay and Seven Mile Beach. (After Fisheries Department Management Paper No.54.)

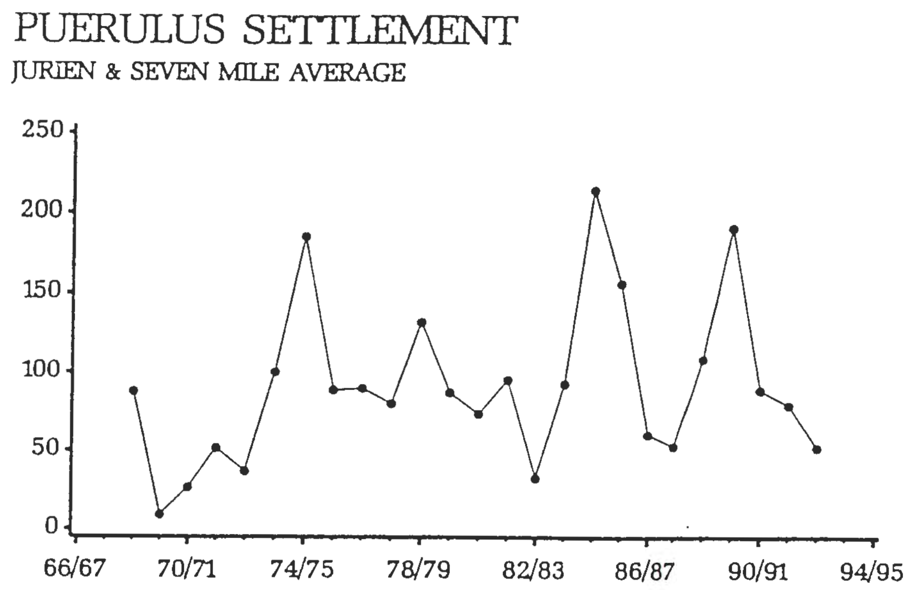


FIGURE 9B
The puerulus settlment at the Abroholos, Alkimos, and Dongara sites. Calculated by Western Australian Fisheries Department. (After Fisheries Department Management Paper No. 54)

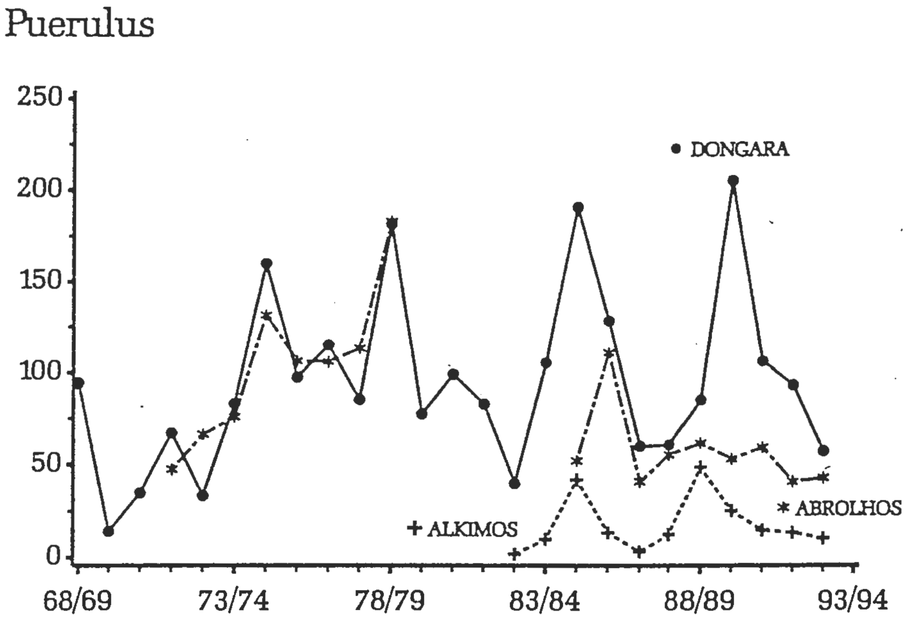
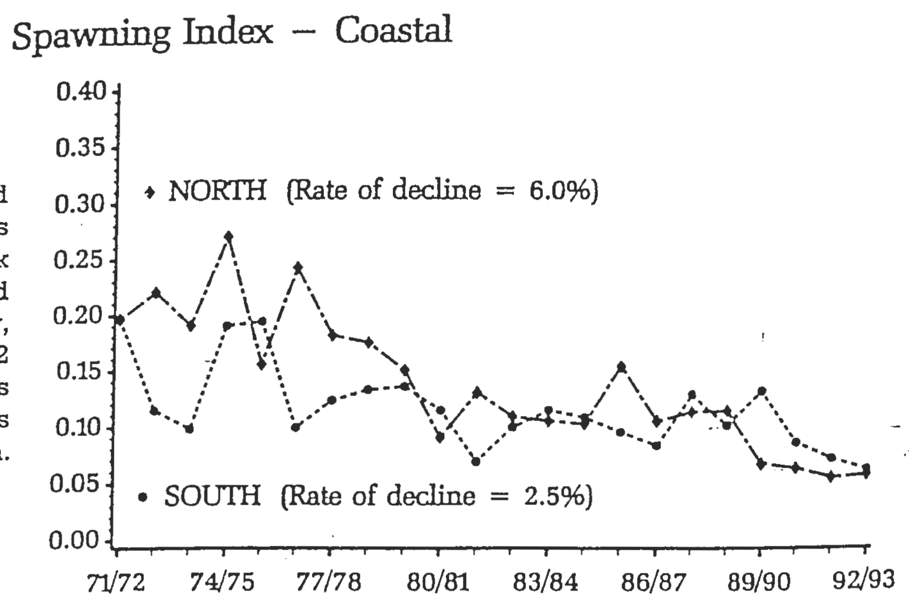


FIGURE 10
The Spawning Index, as calculated by the Western Australian Fisheries Department for Western Rock Lobster, in both northern and southern sections of the fishery, over the period from 1971/72 through to 1992/93. (After Fisheries Management Paper No.54. Fisheries Department of Western Australia. 1993).



(Dongara/Jurien) than in the southern portion of the fishery (Lancelin/Fremantle). The reduction in both sectors was most pronounced over the period 1974-80.

* In the three year period 1971/72 to 1973/74 the spawning index for the southern fishery halved while the northern fishery remained unchanged. If the index directly represents reproductive biomass this equates to catching every breeding female presently in the southern fishery in two seasons, which is difficult to accept as a realistic result.

* The southern fishery then recovered the following year, 1974/75. It remained at that level for one year then halved again in one year.

* In the years after the southern fishery recovered (in 1974/75) and remained stable (1975/76) the spawning index of the northern fishery fell by 46%. It recovered above 1971/74 levels the next year.

* In the 1976/77 season the spawning index for the southern fishery halved once again. However, the northern fishery did the opposite and increased by 66% (back to pre-1971/72 levels.).

* Fluctuations in some individual years were larger than the calculated total reproductive capacity of the present WRL fishery.

The massive short-term fluctuations of spawning index for the early 1970's compared to the more consistent figures from 1980 onward, suggest that there may have been some difficulty in collection and compilation of data used for the earlier calculations.

The trend in the index of puerulus settlement (PSI) over the twenty year period is given as Figures 1.1 and 1.2, in Department of Fisheries, Management Paper No.54. (FIGURE 9). This index does not show a similar trend to spawning index over the same period, (FIGURE 10). The index of puerulus settlement has been gradually rising over the twenty five year period 1968-92, and is, if anything, slightly higher in recent years than it was at outset. The data therefore suggest that present spawning levels (fecundity) have not yet fallen to levels that affect the sustainable yield of the WRL fishery. That does not mean that spawning may not be approaching critical levels.

The need for caution is indicated in the Abroholos Island data of FIGURE 9. Puerulus settlement at the Abroholos Islands was similar to Dongara over the period 1972-1978. Sampling was then discontinued for logistic reasons by CSIRO researchers. The Fisheries Department re-introduced sampling in 1984, and the subsequent results are different. From 1986 to the present, the Abroholos PSI has been half the 1972-78 level.

The significance of this reduction is discussed by Caputi Chubb and Brown, in press. Their view is that all areas of the fishery contribute to the larval pool from which Abroholos recruitment occurs. Because the Abroholos is in the path of the

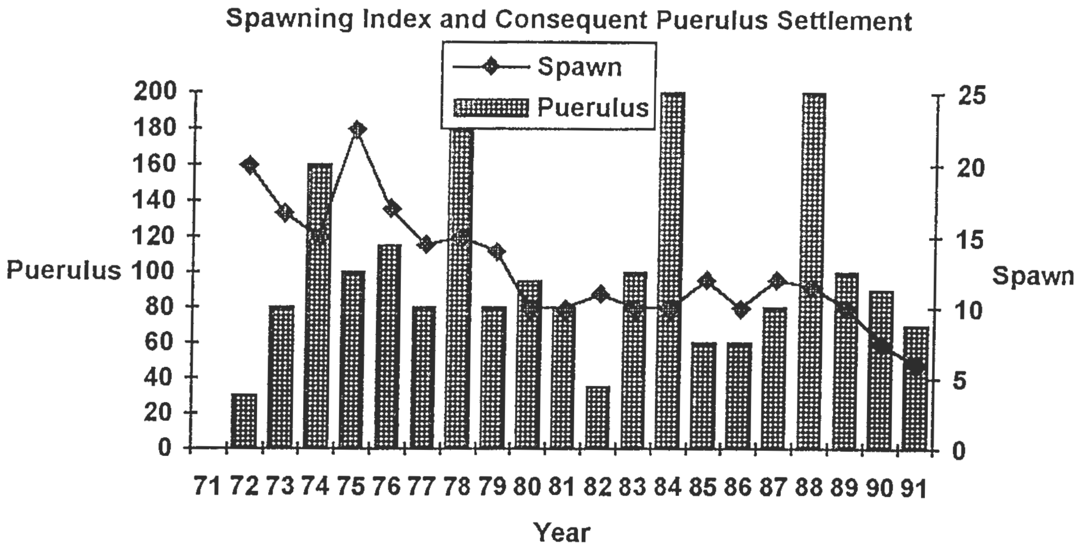


FIGURE 11.

Graphs showing the spawning index and consequent Puerulus settlement for the years 19971/2 through to 1992/93. The graphs are constructed from information presented in Fisheries Management Paper, No.54

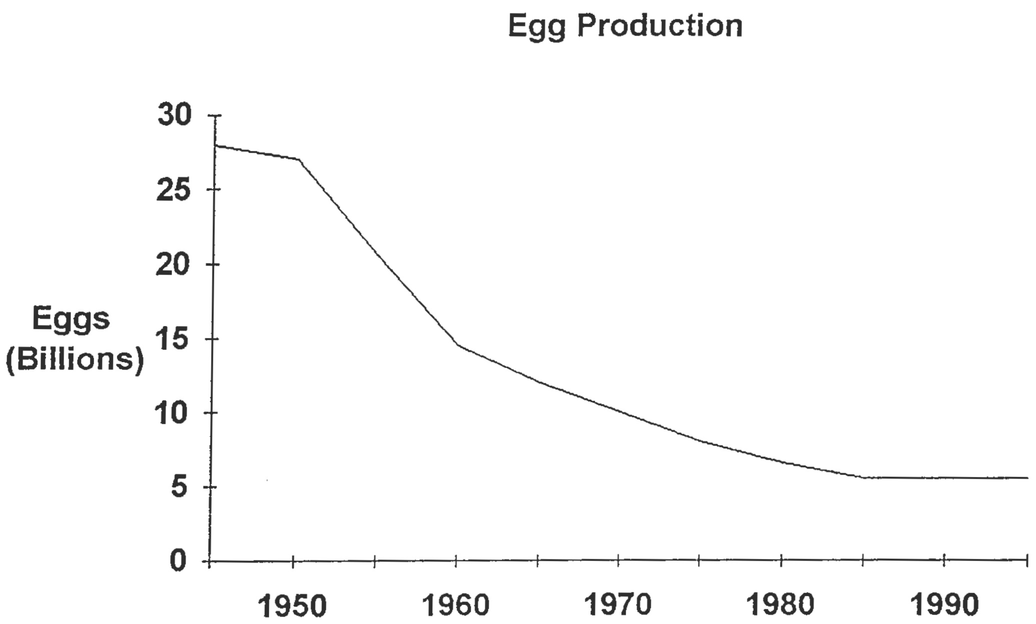


FIGURE 11 B

Egg production from the Western Rock Lobster fishery, over the period 1940 through to the year 2010. This shows computer simulation of the original egg production from the inception of the fishery in 1940 projected through on the basis of current management to the year 2010. (Data obtained Fisheries Department 1993).

Leeuwin Current, it is less dependant on environmental induced fluctuation in recruitment. **Thus the 50% reduction in settlement at the Abroholos may represent a real reduction in overall egg production in the fishery.**

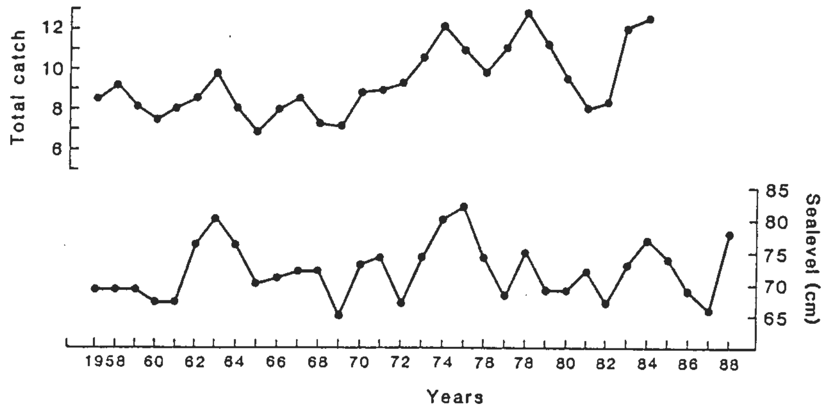
Both the spawning index and puerulus settlement index have been shown to substantially fluctuate annually. The spawning index for a given year, and subsequent recruitment, the following year (as represented by the puerulus index) was graphed for the 21 year period. The results are given on FIGURE 11. It shows there is no direct relationship between spawning index and subsequent recruitment of puerulus the following year.

FIGURE 12 shows a direct time relationship between height of mean sea level at Fremantle and the puerulus settlement index. Mean sea level and size of the puerulus settlement index are also time related to the Southern Oscillation Index (SOI). Both the Fremantle mean sea level variation and the southern oscillation index are known to reflect the intensity of the southward flowing Leeuwin Current, Phillips and Pearce (1989).
More recently Caputi and Brown (1993) have demonstrated a link between the incidence of strong westerly storms in late winter and spring to subsequent intensity of puerulus settlement. They suggest that the strong westerly component helps returning oceanic phyllosoma (known to take advantage of surface-wind driven currents) to migrate eastward toward the coast. Their calculations are also consistent with the finding by Phillips that very high abundance of late-stage phyllosoma were found in surface plankton levels during storm conditions.

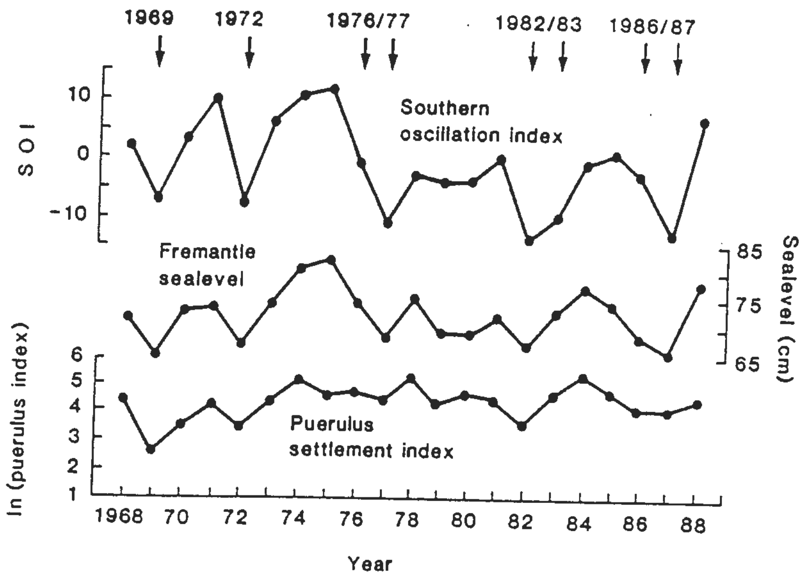
Fisheries Department scientists consider the Leeuwin Current explains about 35% of puerulus recruitment and westerly storm events about the same influence. Together these factors account for approximately 70% of the known variation in puerulus settlement Caputi and Brown,(1993). On the basis of the available evidence it would appear that the influence and structure of the Leeuwin Current, together with storm events during the Spring-Autumn period, have a substantial effect on the intensity of puerulus settlement along the coast.

Fisheries Management Paper No.54 presents data which show that the puerulus settlement index is directly related to the commercial catch 3-4 years later, FIGURE 13. The corollary of this suggests, that any reduction in puerulus settlement should lead to a measurable reduction in catch.

The graphs given in FIGURE 13, suggest the following outcomes. A reduction of 50% in puerulus settlement at the Abrolhos should result in a 10% reduction in the Abroholos WRL yield.



Fremantle sea level and total catch of Panulirus cygnus (lagged by four years). Catch units are 1000 tonnes.



Annual mean data for the Southern Oscillation Index, Fremantle sea level, and index of puerulus settlement at Seven Mile Beach, Dongara. ENSO years are indicated by arrows.

FIGURE 12.

Relationships between mean sea-level at Fremantle, ENSO events and subsequent catches, 4 years later in the Western Rock Lobster Fishery. (After Phillips and Pearce, 1989.)

Figure 2.1 (a)
CATCH (ABROLHOS) – PUERULUS (ABROLHOS)
Millions of kg

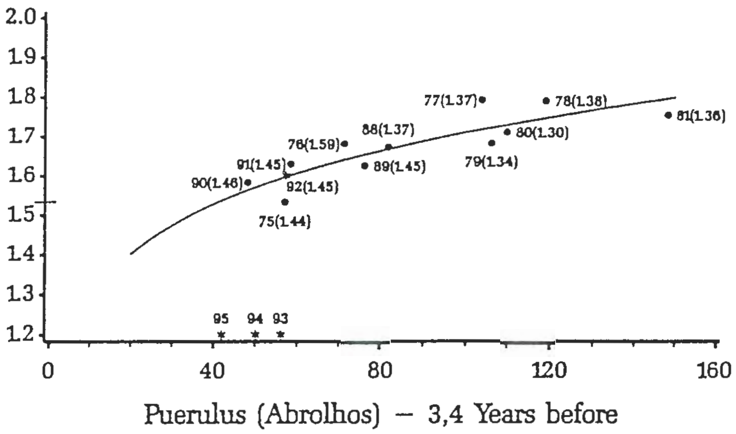


Figure 2.1 (b)
CATCH (ZONE B) – PUERULUS (DONGARA)
Millions of kg

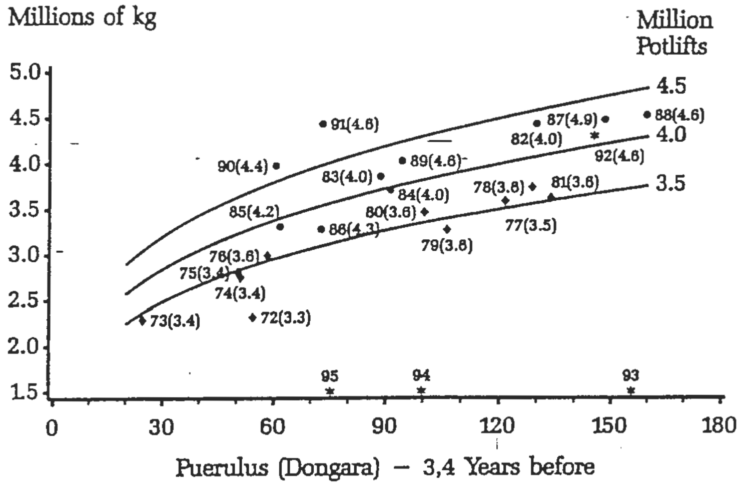


Figure 2.1 (c)
CATCH (ZONE C) – PUERULUS (ALKIMOS)
Millions of kg

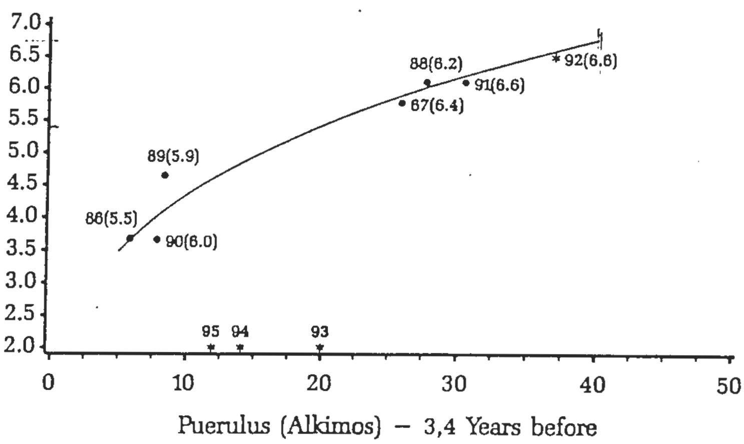


FIGURE 13 A,B,C.

Catches of Western Rock Lobster, in millions of Kilograms, compared to preceding Puerulus settlement index.

In the Zone B fishery, a 50% puerulus reduction would result in a 14% WRL reduction. In Zone C a 50% reduction would cause 20% WRL catch reduction. Thus level of puerulus settlement and WRL catch are not directly proportionate, nor is the relationship consistent between different "Zones" of the fishery, Caputi (pers comm).

Phillips, Pearce and Litchfield (1991) considered the seasonal and geographic variation in settlement of puerulus along the Western Australian coastline from Shark Bay in the north, to Cape Mentelle in the south. Two significant graphs from their paper are given as FIGURES 3B & 3C. The data show that settlement, in terms of puerulus collection, falls into two major geographic groupings,

(1) Shark Bay to Cervantes in the north,
(2) Alkimos (Yanchep) to Cape Mentelle in the south.

In general terms the northern group of collectors has 20 times the settlement of the southern group of collectors. Over the 5 year study period average monthly settlement per collector was 80 for all the northern sites and 2-4 for the southern sites. Phillips and Hall (1978), compared collector data for the seven year period 1970/71 to 1976/77 from Rat Island, Seven Mile Beach, Jurien Bay and Garden Island. The northern areas all had a monthly average in the order of 80, but Garden island averaged only 2. The numerical differences can not be explained by habitat variation. It is not possible to say that reef habitat and water depth is really different between the Garden Island sampling sites and either Jurien Bay or Seven Mile Beach.

The puerulus collectors have been constructed to ensure they are of uniform size, structure and components. They are in effect artificial clumps of seaweed moored into fixed positions, sampling the near-surface water [refer pages 61-62 of Gray (1992) for details]. They primarily provide shelter, not food. In practice the samplers have a similar radius of collection which is probably 1-2 metres, Phillips and Olsen (1975). Thus collection made by the samplers is a composite of the density of animals going past the collectors, and intensity of their urge to settle at that time. It is known that puerulii do not have to collide with the collector. They can detect it at a small distance and will, on occasion, swim toward the collector, Phillips and Olsen (1975).

Information obtained from the collector program shows that pueruli only settle during the period close to the new moon, (2-3 days before to 6-7 days after the new moon). There is also a distinct seasonality in density of settlement, Phillips and Hall (1978), Phillips, Pearce and Litchfield (1991). FIGURE 3B. The main period of settlement is from August to March, reflecting settlement of the previous years spawning.

The important consideration in regard to the collector index of puerulus settlement is the distinct twenty-fold difference between collections on settling frames in the central and northern areas of the fishery, compared with those in the south. The settlement recorded does not directly reflect consequent adult density, or yield from those same local areas of the fishery.

For example if a simple comparison is made between the values given in FIGURE 13, then the same index of puerulus settlement translates to considerably different WRL yields in each area of the fishery. For example; the predicted yield three to four years after the same puerulus index of 40 would yield 6,750 tonnes for the Alkimos area, it would be 3,000 tonnes for the Dongara area, and 1,500 ton for the Abrolhos area. This shows there is no simple translation of the puerulus index to actual abundance and therefore fishery yield. The Alkimos area has more than double the commercial yield of the Dongara area, yet it records only a 1/20th of the number of settling pueruli (according to the collector data).

Thus there is much more to be known about both puerulus settlement and efficiency of juvenile recruitment to the fishery. It is not simply the number of pueruli per collector, that determines juvenile recruitment, it is also the availability of suitable habitat in terms of shelter, predation and availability of food. Mortality between puerulus settlement and one year of age appears from Howard (1987), to be very substantial. Hence there is a need to undertake further research into this aspect.

The best example of settlement excess is the collector located at South Passage at Shark Bay. Collector data indicates that the Shark Bay area receives the highest catch per collector along the entire coast, yet the WRL fishery in the Shark Bay area is comparatively small. [The collectors in South Passage may be in more intense stream flow, and thus sample more than other sites]. Clearly there is a substantial loss between puerulus settlement and recruitment to the commercial fishery in the Shark Bay area. Reefs between Lancelin and Mandurah yield much the same density of WRL to harvest as those between Cervantes and Geraldton. However the southern reef areas receive only 1/20th the number of pueruli as indicated by settlement on collectors, in the northern area of the fishery, during a similar period.

The Leeuwin Current and Recruitment

Phillips (1981) showed that the phyllosoma larvae of the Western Rocklobster are distributed up to 600 nautical miles to the west of the coast and occur in the plankton from Cape Leeuwin in the south to Barrow Island in the north, FIGURE 7. More recent studies show that late stages of the phyllosoma larvae in the Indian Ocean are obliged to re-enter and traverse the Leeuwin Current as it moves south, Phillips et al (1991). Final stage phyllosoma and puerulus appear to be able to detect both the water of the Leeuwin Current and the edge of the Continental Shelf. The Puerulus makes a direct west/east swimming migration to the coast without feeding. The usual traverse distance is in the order of 40 nautical miles.

Metaphorically, the Leeuwin current is similar to putting a garden hose with warm water into one end of a swimming pool. When the hose is running weakly, the warm current trickles along the side of the pool on the surface, with minor turbulence. When the flow is strong, the jet not only creates a more substantial stream, it meanders and larger circulatory eddies are produced. With strong flow there is substantial rotation of the surface water as it proceeds along the wall of the pool. Transferring this concept back to the Leeuwin Current and the known larval biology of the WRL illustrates many observations in regard to density of puerulus settlement.

In years when the Leeuwin Current is stronger it provides the circulatory transport mechanism further to the west of the coast. The opportunity to provide ample chemical and physical signals to the late stage phyllosoma larvae is extended well to the west in the Indian Ocean.

Satellite images obtained and researched in recent years directly support the mechanism outlined above, Pearce (1988)(1992) and Phillips et al (1991). The structure and influence of the current on WRL recruitment is well-known to the industry, *Western Fisheries*, Spring 1992, and *FINS* Vol.21 No.1 1988

Gray (1992) provides an excellent summary of phyllosoma and puerulus distribution together with behaviour during the return migration to the coast. It is also supplemented by very illustrative diagrams and plates. On page 36 of Gray (1992), there are winter and summer satellite images, illustrating the seasonal change in intensity and structure of the Leeuwin Current. Those photographs illustrate two points:-

firstly the containment of the Leeuwin Current closer to the coast during the winter period and its stronger penetration south along the coast. Secondly they show that the more intense eddies with widest diameter of circulation, occur northward from Jurien.

In other words, Leeuwin Current eddies are dissipating in strength as they proceed south along the coast. The collection capability of the Leeuwin Current to rotate phyllosoma back toward the coast is both stronger and wider in diameter in the northern areas of the fishery when compared to the southern areas. This, in part, may explain the more dense settlement of larvae in northern sections of the fishery. The effect of strong south to south west wind on surface water current throughout the afternoon and evening of the spring-summer period, may also be a significant factor in sweeping surface swimming puerulus northward.

ALTERNATE ENHANCEMENT TECHNIQUES

There is a wide range of techniques which could be tested in regard to expansion of the sustainable yield of wild capture rock lobster. It has also been suggested that puerulus, when reared to early juveniles by aquaculture could be replaced on reefs, in areas of naturally low recruitment, but under utilised carrying capacity.

All such suggestions have merit and should be considered further. However, it is not the focus of this assignment.

Some possible opportunities discussed in the course of compiling this report are outlined below, however the range considered is by no means exhaustive.

Feeding Juveniles in Nursery Areas

It has been suggested that known WRL in nursery areas could be given supplemental feed. Chittleborough (1976) showed that provision of food in surfeit significantly reduced the moult interval in juveniles. He also showed they tend to be intermittent in their feeding behaviour, and reduce intake in the latter half of the moult interval.

The main problems with this suggestion are cost, equity and outcome. Firstly who would pay for the feed distributed in the wild and have the right to the subsequent commercial-size stock, some years later.

The second is ensuring the food is effectively used by WRL. Scattering of feed is more likely to sustain an enlarged number of predators such as shark, octopus and rays who will in turn feed opportunistically on WRL, when not artificially fed.

The WRL may not eat the food. It would need to be distributed in late afternoon or during night and would need to be carefully targeted to known high density areas. Reef fish and other scavengers will eat the food before WRL emerge from their dens to forage.

WRL do not eat all the time, they are not consistently attracted to bait or food. If this were the case every WRL would be in pots within a few weeks of the season opening. There are many well known cases of baited pots being ignored by resident WRL.

Translocation of Juveniles

It has been suggested that areas in which there are too many juveniles in relation to food and shelter could be fished, and translocated to under-recruited areas.

This may well work and could be trialled. Deciding on equity and cost sharing could prove difficult. A cooperatively funded operation within a zone might work.

Additional Habitat for Juveniles and Adult WRL

During the late 1950's the remains of the anti-submarine boom fences in Cockburn Sound were major refuges for WRL (T. Meagher pers. comm). The booms were simply 25mm diameter pipe held in a lattice configuration by scaffold clips, at approximately 30cm centres. After the war the fence which was approximately 4-5 metre high, and a few kilometres in length, was simply pushed over onto the seagrass meadow in water 3-4 metres deep. Marine life grew prolifically on the pipe work. In some places it lay on the seafloor in others, it was 30-40cms clear. It provided refuge within an extensive seagrass meadow and was a very effective WRL habitat. The artificial reef habitat presumably enabled WRL to browse otherwise unused meadows. The Garden Island Causeway was built over the southern boom fence in the 1970's and the boom at the northern end of Garden Island gradually rotted away, in the late 1960's.

The old lattice work boom was remarkably successful as WRL habitat, even though it did not mimic natural refuge habitat. It provided shelter in an area of feed.

The same opportunity for additional refuge may apply at many areas along the coast, particularly Shark Bay.

Additional Habitat for Post-Puerulus

This report has found that availability of specific refuge for post-puerulus in juxta-position to that for puerulus is likely to be a major factor in WRL recruitment. Early post puerulus require holes of preferred size and configuration. There are many areas of reef where the pre-requisite habitat is not provided.

Drilling holes in reef, or providing artificial settlement reef does need further consideration.

Predator Control

The Howard (1987) study was really only the tip of the ice-berg in regard to predation and there must be further studies. If fish are substantial and effective predators on early WRL then it is reasonable to assume that commercial and recreational fishing affects WRL recruitment.

Recreational fishing has increased greatly over the past 20 years and may in part have assisted improved WRL settlement, by covering the number of natural predators.

In the case of surface and mid water fish such as tailor. Australian herring, snook, skipjack (and squid), these are all extensively fished and thus there is some degree of predator reduction.

Bottom feeding fish such as wrasse, rock cod, king george whiting, skipjack, flathead (and octopus) are all removed by recreational fishing.

It is important that some basic fish sampling by netting at appropriate moon phases is conducted near puerulus collectors to determine whether or not recreational fish species are significant predators. When recreational fishers take target species they also tend to remove trash fish.

If fish are significant predators then trap programmes to reduce fish such as wrasse and trumpeter which are known to patrol nursery areas, may have a significant effect.

Cage Culture

This is being pursued in a number of localities around Australia and overseas. There are reports that mortality and feed cost outweigh the incentive of weight gain and price opportunity.

However, in most instances holding cages are simply just that - and may be causing unwarranted stress. Shelter and substrate are important for long term holding.
When holding large numbers of blue-swimming crab (*Portunus pelagicus*) in captivity it was found density that could be increased threefold by providing a layer of sand in which the animal could bury itself, (T. Meagher pers. comm). The same principle will apply to long-term lobster holding, in terms of habitat items such as light and shelter. Much more could be done to research long term holding and feeding of WRL.

CONCLUSIONS

The WRL puerulus can be reared to a marketable size of 250-300 gms without undue technical difficulty. Food conversion rate, mortality, growth rate and stocking density are sufficiently known to enable basic calculation of the commercial profitability of rearing captured WRL puerulus.

Internal Rate of Return (IRR) calculation based on fair and reasonable assumptions indicates a base case return of 24.5%. A sensitivity analysis which varies the fundamental parameters, shows these can be varied within ranges that most people conversant with the industry would accept as being reasonable, and the project will remain commercially attractive. The project therefore warrants detailed consideration as commercial venture.

The two main parameters which substantially affect the profitability are selling price of the product and feed cost. The next important variable is the cost of obtaining pueruli.

In practical terms the aquaculture of WRL will be limited by the ability to cost-effectively catch sufficient pueruli, on a regular basis, without reducing the sustained yield of the WRL wild-capture fishery.

WRL aquaculture must be based on utilising the puerulus stage that is currently subject to substantial mortality and probably wasted. This review indicates that there are many areas of substantial wastage, which if used for aquaculture could support a major expansion of the WRL industry.

There are portions of the coast toward the northern limits of the fishery where there appears to be excess pueruli, which are currently wasted. If this is proven to be the case by field research, and the excess could be cost-effectively harvested, there is a substantial case for WRL aquaculture.

The specific localities, habitats, number of pueruli and methods of capture will need to thoroughly researched to ensure the aquaculture industry is optimally designed and the wild-capture fishery is fully protected.

There are well-proven examples of successful fisheries where juveniles are harvested and reared without detracting from the wild-capture yield. In such fisheries, the overall sustainable yield of the individual fishery has increased by factors of between 2 and 4 fold. The Japanese, Yellow-tail Kingfish is shown to be a relevant model for case study.

Cultivation of the WRL and other rocklobster species from egg to marketable size is now technically feasible. It is generally accepted as being commercially impractical in the foreseeable future. However a number of countries have recognised the commercial prospect of capturing and rearing rocklobster puerulus. Trials have been undertaken and aquaculture will undoubtedly occur, to varying degrees, in a number of rocklobster fisheries. It is therefore strategically essential for Australia to consider the aquaculture of its most significant commercial marine species in adequate detail.

Western Australia is strategically well-placed to implement WRL cultivation because:-

* The WRL is a premium priced rocklobster product with an established market share and reputation.
* The pueruli can only be collected and reared in Western Australian waters.
* There is sufficient background knowledge to design and implement an effective and acceptable R&D program.
* There are a range of available locations which will provide optimal rearing conditions

The State Government has the ability to control and manage WRL aquaculture without the competition which would occur internationally, if the animal could be commercially raised from the egg. Thus WRL aquaculture cannot be compared to prawn aquaculture. It is more relevant to consider the successful Japanese Yellow tail-kingfish model.

Re-assuring commercial and political interests of the project's potential benefits and the absence of risk to the existing wild-capture fishery, is essential to obtaining the necessary legislative and community acceptance.

A conceptual model which provides equity to existing industry participants and recreational WRL fishers is outlined. The model also provides for revenue improvement to Government and a commercial opportunity for the private sector. The overall objective of the model is to entice all sectors currently involved in the fishery to support its expansion and security of sustainable yield.

The project should proceed. Recommendations for the next phase of the project are given.

RECOMMENDATIONS

It is recommended that the project now proceed in two distinct stages.

* A detailed identification of research and development objectives, description of individual research programs and protocols, forecast of most likely outcomes, costing of individual programs.

* Implementation of approved Research and Development programs over a 3 year period

A feature of this project which makes it different to most others is that a great amount of the pre-requisite information is well-known and well researched. Equally the portions of information which are missing are obvious. It is therefore a project in which mission-statements can be detailed, specialist staff recruited, and resources identified at outset. Finally, the project has sound prospects of being financially attractive and nationally significant.

Research protocols to be planned and costed in the first phase should be assigned to the following categories.

Biological

Location and description of the natural habitat in which WRL pueruli settle. Evaluation of puerulus mortality, at a range of natural habitats.

Identification of those habitats in which pueruli settle, but whose characteristics preclude subsequent recruitment to post-puerulus juvenile stages.

Identification of methods and locations so that pueruli can be cost-effectively harvested, without reducing the wild-capture WRL stock.

Estimation of the safe level of puerulus harvest for aquaculture. Estimation of the success rate of puerulus settlement through to harvestable stock, in the wild-capture fishery.

Improve the translation of puerulus collector data to enable recruitment density estimates.

Capture Technique

Determine spatial, and density distribution of puerulus settlement, at surface, and at depth, across the extent of the fishery. Correlate results to satellite definition of the Leeuwin Current and sea surface temperature.

Trial alternate types of puerulus collectors and variations of the present collector system.

Test the effect of:-

artificial light
chemical and physical attractions
tactile response-sound.
exhaustion and energy depletion
temperature.
seafloor texture and reflectance.

on aggregation and collectability of pueruli

Aquaculture Technique

Trials will need to be conducted on the early stages of post-puerulus juveniles, to determine the influence of the following variables on optimum growth, survival and product quality.

Provision of food and shelter.
Micro-nutrient and pigment requirement in diet.
Effect of physical parameters on growth behaviour and survival.
Influence of physical and chemical parameters,[Temperature,dissolved oxygen, carbon dioxide,ammonia and nitrate,light intensity,turbidity]
Substrate
Depth
Mortality due to cannibalism, nutrient deficiency and disease.
Pond design, layout of food and shelter
Feeding regimes and corresponding food conversion rate
Selection of optimal pilot-plant and commercial development sites.
Staff recruitment, training and deployment.

Corporate Structure

In the event that the R&D program is as successful as anticipated, the project will then proceed to commercial development. However commercialisation will need to be configured so that the project is commercially attractive, non-threatening to the wild-capture WRL fishery, politically desirable and fair to all participants.

The model proposed in this report, along with alternatives will need to be carefully researched, accepted and promoted. Items which will need be researched and developed into a business model are as follows:-

Production costs
Selling price
Market volume and price sensitivity
Competitors
Capital cost
Optimum production unit size
Management, or Regulatory structure (Government, industry and private sector components).
Corporate Structure
Equity, profit sharing, cash flow and risk analysis
Business strategy.

Legislation

There will need to be legislature change for the project to proceed to pilot-plant trials and commercial operation. Even the research and development phases may require changes to Regulations under the fisheries Act 1906.

However the major consideration will be the basic structure under which government would wish to operate WRL aquaculture. Consideration as to whether the Government would want to issue licences, be a proprietor, or call for bids for private sector developers to undertake leasehold development, all need to be considered. The legislative implications must be researched during the project.

Public Awareness and Public Information

The WRL fishery currently has about 630 commercial licence holders and 20,000 recreational licence holders. Each licence holder, their business associates, family and friends has an intense personal interest in the fishery.

The WRL is a quasi-emblem of Western Australia. The average Western Australian probably has much more knowledge of, and far more practical affection for the WRL than the Numbat. It is also recognised as a stable, profitable industry. There will be resistance to innovation or change.

If the project is handled and promoted correctly, it will gain both industry and public support. This will require professional polling as to aspects of public concern, and delivery of information in a way that satisfies those concerns.

Staffing

It is recommended that a contract be let by FRDC for the first phase of the project. This will be the identification and scoping of research and development priorities, and the construction of research protocols to complete identified tasks. The work should be undertaken by a group of specialist consultants, rather than a Steering Committee. The group should be comprised of representatives of the Fisheries Department and the industry, (WAFIC), academic scientists, and private sector consultants. It should have commercial, biological and legal expertise. The consultants should formally incorporate the advice of agencies such as AIMS and CSIRO.

It is anticipated that when the protocols are completed, they will demonstrate the project will require a mix of professional staff, comprised of specialists from the private sector, academic institutions and government agencies. The overall project should be funded and managed through WAFIC.

BIBLIOGRAPHY

Aldrich,J. 1989 Gross habitat selection and survivorship of small juvenile. WRL in the laboratory. Abstract in : B.F.Phillips,[157]

Anonymous. Unlocking the Leeuwin Current. Western Fisheries, Spring 1992.

Anonymous. 1990. Redclaw, A Hot New Prospect. Australian Fisheries. Nov 1990. pp2-27.

Anonymous. Research on Puerulus Rock Lobsters. Fins. Vol.20 No.5. Sept 1987.

Berrill,M. 1976 Aggressive behaviour of the post-puerulus larvae of WRL Aust. J.Mar. Freshwater Res.,27:83-8

Caputi N, Brown R.1993.The effect of Environment on puerulus settlement of the Western RockLobster(Panulirus cygnus) in Western Australia Fish Oceanogr.2:1 1-10.

Caputi,N. Brown R. & Phillips B. Forecasting Rock Lobster Catches Check and Double check. fins Vol.21 No.2. 1988.

Caputi,N. Brown, R. and Chubb, C. Regional Prediction of the Western Rock Lobster Panulirus cygnus, Commercial Catch in Western Australia. Crustaceana, [in press]

Caputi,N. Chubb,C and Brown, R. Relationships Between Spawning Stock, Environment, Recruitment and Fishing Effort for the Western Rock Lobster Panulirus cygnus, Fishery in Wesrtern Australia., Crusaceana [in press]

Chittleborough,R.G. 1974 Home range, homing, and dominance in juvenile WRL. Aust.J.Mar.Fresh Water Res, 25:227-234

Chittleborough,R.G. 1974 WRL reared to maturity.Aust.J.Mar. Fresh Water Res, 25;221-25.

Chittleborough,R.G. 1964 Review of prospects for rearing rock lobsters. Aust. Fish, 33:4-8.

Chittleborough,R.G. 1974 How to double growth rate of captive rock lobster. South African Shipping News and Fishing Industry review,Vol 29(12),pp 40-46.

Chittleborough,R.G. 1975 Environmental factors affecting growth and survival of juvenile rock lobster. Aust.J.Mar Fresh Water R,26:177-96.

Chittleborough,R.G. 1976 Growth of juvenile Panulirus longipes cygnus on coastal reefs compared with those reared under optimal environmental conditions Aust. J.Mar. Freshwater Res, 27:279-95.

Chittleborough,R.G. 1976 Breeding of Panulirus longipes cygnus under natural and controlled conditions, Aust.J.Mar Fresh Wat Res, 27:499-516.

Chubb, C. Studies of the Breeding Stock of The Western Rock Lobster Panulirus Cygnus. Fins Volume 20. No.5 Sept 1987.

Crossland, C.J. 1988. Towards a Diet for Rock Lobsters in Mariculture. Proceedings First Australian Shellfish Aquaculture Conference, Perth. 1988.

Ford, R.F., Phillips, B. & Joel L. 1988. Experimental Manipulation of Population Density and Its Effects on Growth and Mortality on Juvenile Western Rock Lobsters, Panulirus cygnus George. Fishery Bulletin. Vol 86. No.4. 1988.

Howard, R.K., 1987. Predators of Rock Lobsters. Fins Vol.20. No.5. Sept. 1987.

Jernakoff, P., Phillips, B. and Fitzpatrick J. 1993. The Diet of Post-Puerulus Western Rock Lobster, Panulirus Cygnus George at Seven Mile Beach, Western Australian. Aust. J. Mar. Fresh Wat. Res. 1993. (in press).

Jernakoff, P. Fitzpatrick, J., Phillips, B., & DeBoer, E., 1993. Density and Growth in Populations of Juvenile Western Rock Lobster, Panulirus cygnus George. Aust. J. Mar Fresh Wat Res. (in press).

Jernakoff, P.,Phillips,B.,Fitzpatrick,J. 1993 The Diet of Post-puerulus Western Rock Lobster, Panulirus cygnus George, at Seven Mile Beach, Western Australia. Aust. J. Mar. Freshwater Res, 1993, 44 in press.

Jernakoff,P. 1990 Distribution of newly settled western rock lobster Panulirus cygnus. Mar.Ecol.Prog.Ser. 66:63-74.

Jernakoff,P., Phillips,B.F. and Maller,R.A.,1987 A quantitative study of nocturnal foraging distances of the WRL.Aust.J.Esp.Mar.Ecol.:113-21.

Kafuku T. & Ikenoue H. 1983. Modern Methods of Aquaculture in Japan. Elsevier Scientific Publishing Company.

Morgan,G.R., Phillips,B.F., and Joll,L.M., 1982 Stock and recruitment relationships in Panulirus cygnus, the commercial rock lobster of WA. Fish. Bull. 80(3) 475-486.

Pearce A. 1988. New Developments in Satellite Technology Should Help Studies of the Leeuwin Current. Fins. Vol 21. No.1. 1998.

Pearce,A.F., Phillips,B.F., 1988 ENSO events, the Leeuwin current, and larval recruitment of the WRL.J.Cons.Int.Explor.Mer. 45:13-21.

Phillips, B.F., Cobb,J.S., and Kittaka, J, Spiny Lobster Management, 1994, Blackwell Scientific Publications.

Phillips B.F. 1984. Aquaculture Potential for Rock Lobsters in Australia. Australian Fisheries. Vol.44. No.6.

Phillips, B.F., MacMillan, D.C., 1987 Antennal receptors in puerulus and post-puerulus of the WRL and their potential role in puerulus navigation. J.Crust.Biol.7(1):122-135.

Phillips, B.F. & Pearce A.F. 1989. Interannual Variability in Ocean Circulation and Rock Lobster Recruitment in the South Eastern Indian Ocean. Reprinted from Long Term Variability of Pelagic Fish Populations and their environment Proceedings of the International Symposium , Sendai, Japan, 14-18th November, 1989. Pergamon Press.

Phillips,B.F. 1975 The effect of water currents and the intensity of moonlight on catches of puerulus larval stages of the WRL Rep.Div. Fish. Aceanogr.CSIRO, Cronulla, Rep.63.

Phillips,B.F. 1990 Estimating the density and mortality of juvenile WRL (Panulirus cygnus) in nursery reefs. Can.J.Fish.Aquat. Sci.47:1330-1338.

Phillips,B.F. 1981 The circulation of the south-eastern Indian Ocean and the planktonic life of the WRL. Ocean.Mar.Biol.Ann.Rev.:19,11-39

Phillips,B.F. 1972 A semi-quantitive collector of the puerulus larvae of the WRL. Crustaceana, 22(2): 147-84.

Phillips,B.F. 1975 The effect of nocturnal illumination on catches of Puerulus larvae of the WRL.Aust. J.Mar Freshwater Res. 26:411.

Phillips,B.F. 1977 A review of the larval ecology of rock lobsters in Phillips and Cobb[160] :175-85.

Phillips,B.F. and Hall,N.G. 1978 Catches of puerulus larvae on collectors as a measure of natural settlement of the WRL. Rep. Div. Fish. Oceanogr. CSIRO, Cronulla, Rep.98 (18pp).

Phillips,B.F., Rimmer, D.W., and Reid, D.D. 1978 Ecological investigations of the late stage phyllosoma and puerulus larvae of the WRL. Mar.Biol., 45:347-57.

Phillips,B.F., Campbell,N.A., and Rea, Wa 1977 Laboratory growth of early juveniles of WRL. Mar.Biol., 39:31-9.

Phillips,B.F., and Olsen,L. 1975 The swimming behaviour of the puerulus stage of WRL. Aust. J.Mar. Freshwat.Res.26:415-7

Phillips,B.F., Pearce, A.F., and Litchfield, R.T. 1991 The Leeuwin Current and larval recruitment to the rock (spiny) lobster fishery of Western Australia. J.Roy.Soc W.A., 74, 93-100.

Phillips,B.F., Penrose,J.D., 1985 The puerulus stage of the spiny rock lobster and its ability to locate the coast. Tech Rept SPG 374/1975/AP92, Sch of Ph * Geosci, WA Inst.Tech. pp1-35.

Phillips,B.F., and McWilliam,P.S., 1986 The pelagic phase of spiny rock lobster Development Canad. J.F. and Aquatic Sci 43:2153-2163.

Phillips,B.F.(Ed) 1989 Workshop on rock lobster ecology and management CSIRO Marine Laboratories Report 207.

Rimmer,D.W. 1980 Spatial and temporal distribution of early stage phyllosoma of WRL. Aust. J.Mar. Freshw. Res. 31:485-97.

Rimmer,D.W. 1977 Vertical distribution and diurnal vertical movements of phyllosoma larvae of the WRL. Abstract in:Phillips and Cobb[160] pp26-27.

Rimmer,D.W., Phillips,B.F. 1979 Diurnal migration and vertical distribution of phyllosoma larvae of the WRL. Mar.Biol., 54:109-24.

Ritz,D.A. 1972 Behavioural response to light of newly hatched phyllosoma larvae of Panulirus longipes cygnus J.Exp. mar.Biol. Ecol., 10:105-14.

Rock Lobster Advisory Committee. 1993. Mnagement Proposals for the 1993/94 and 1994/5 Western Rock Lobster Season. Fisheries Management Paper. No.54. Fisheries Department of Western Australia.