School of Physical Sciences

Modelling the Physics of Prawn Trawling For Fisheries Management

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Doctor of Philosophy

of

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

Sign

Date

ABSTRACT

Management of prawn trawling fisheries is a difficult task due to the competing interests of strongly motivated stakeholders and interest groups. This occurs because prawn trawling operations are technically complex, require large capital investments and exhibit high running costs while owners have limited property rights over the resources that they harvest. Prawn stocks are public resources and are managed with a view to provide maximum benefit to the broad community. Additionally their exploitation also involves the incidental capture of significant numbers of other animals of no commercial value (bycatch) and causes impacts on seabed morphologies, which are involved in many diverse ecosystem processes.

At the policy level an intention to manage trawl fisheries in a comprehensive way is backed by a mandated approach that is designed to capture all of the above issues and interests. That approach is termed Ecological Sustainable Development (ESD).

The work in this thesis is designed to produce a prediction tool for prawn trawling performance that is based on modelling the physical nature of prawn trawling activities. It is proposed that the resulting tool is essential for working to manage the multi-dimensional aspects of prawn trawling fisheries.

Three discrete objectives for the thesis are; to expand and improve an existing Prawn Trawling Performance Model (PTPM) so that it is more accurate and relevant to a broader range of questions, to evaluate the capacity of the PTPM to predict the performance characteristics of real prawn trawling operations in terms of both engineering and catching performance and to investigate the problem space surrounding prawn trawl fisheries to identify and develop applications for the model.

A rudimentary PTPM (Sterling 2000b) is expanded through the analysis of further empirical data collected for model and full-scale trawl gear. Eight area of improvement to the PTPM were considered and in all cases significant changes were made.

The accuracy of the new form of the model is here tested by comparing performance predictions with measurements of trawling performance for a variety of industrial trawl systems operated in the Queensland East Coast Trawl Fishery and also through comparing predicted trawling performance with prawn catches returned for trawlers operating in the Northern Prawn Fishery over the years 1970 to 2000.

In the first case, errors in predicting swept area rate, considered an important performance parameter, were less than 5%. Fine scale issues were explored using the available sea trial data and a number of areas of concern within the model are highlighted. These relate to accurately quantifying the forces involved in the interaction of the trawl gear with the seabed and accurately accounting for the interaction between components within trawl systems.

In the second case, the results suggest that between 50% and 60% of the variation in the seasonal catching performance of trawlers in the NPF is explained by predictions of swept area rate derived by the PTPM from the available data for that fishery.

A comprehensive survey of applications for the PTPM is conducted in context with approaching the management of prawn trawling fisheries using the principles of ESD as defined by the National Strategy for ESD (1992). The Northern Prawn Fishery is used as a case study to explore in finer detail applications for the PTPM. Issues arising from the implementation of some of the applications are discussed.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TERMS AND ABBREVIATIONS

Institutional

AFMA	Australian Fisheries Management Authority
AMC	Australian Maritime College
AMECRC	Australian Maritime Engineering Cooperative Research Centre
ESD	Ecological Sustainable Development
FRRF	Fisheries Resources Research Program
GVP	Gross Value of Production
NSESD	National Strategy for Ecological Sustainable Development
NPFAG	Northern Prawn Fishery Assessment Group
PTPM	Prawn Trawling Performance Model
SD	Sustainable Development
SFR	Statutory Fishing Right
TED	Turtle Excluder Device
WCED	World Commission on Environment and Development

Low opening gear

There are two basic types of prawn trawling gear. These are termed low opening and high opening gear depending on the location of the top of the trawl net relative to the seabed. The vertical size of the trawl net is designed with consideration of the likely location of the target species with respect to the sea floor.

Figure 1 shows a set of low opening quad gear with the various parts named. Following is a list of these terms with their definition.

To capture tiger, endeavour and king prawns and scallops it is not necessary to use trawls with high headlines. The fishing height of this low opening gear is governed by the height that the headlines of the nets are connected to the otter boards and sleds in the system and is generally between 0.75m and 1.4m. Of more importance is the lateral spread of the trawl system as this in part determines the area swept by the system for each hour of trawling and for a given headline height also determines the volume of water filtered each hour. Typically, low opening trawl systems are spread to between 65% and 85% of their headline length. Leadahead is an important factor in maintaining high catch efficiency of low opening prawn trawls (but not important for scallops), since the veranda of netting formed over the footline ensures that prawns reacting to the ground chain do not pass over the headline.

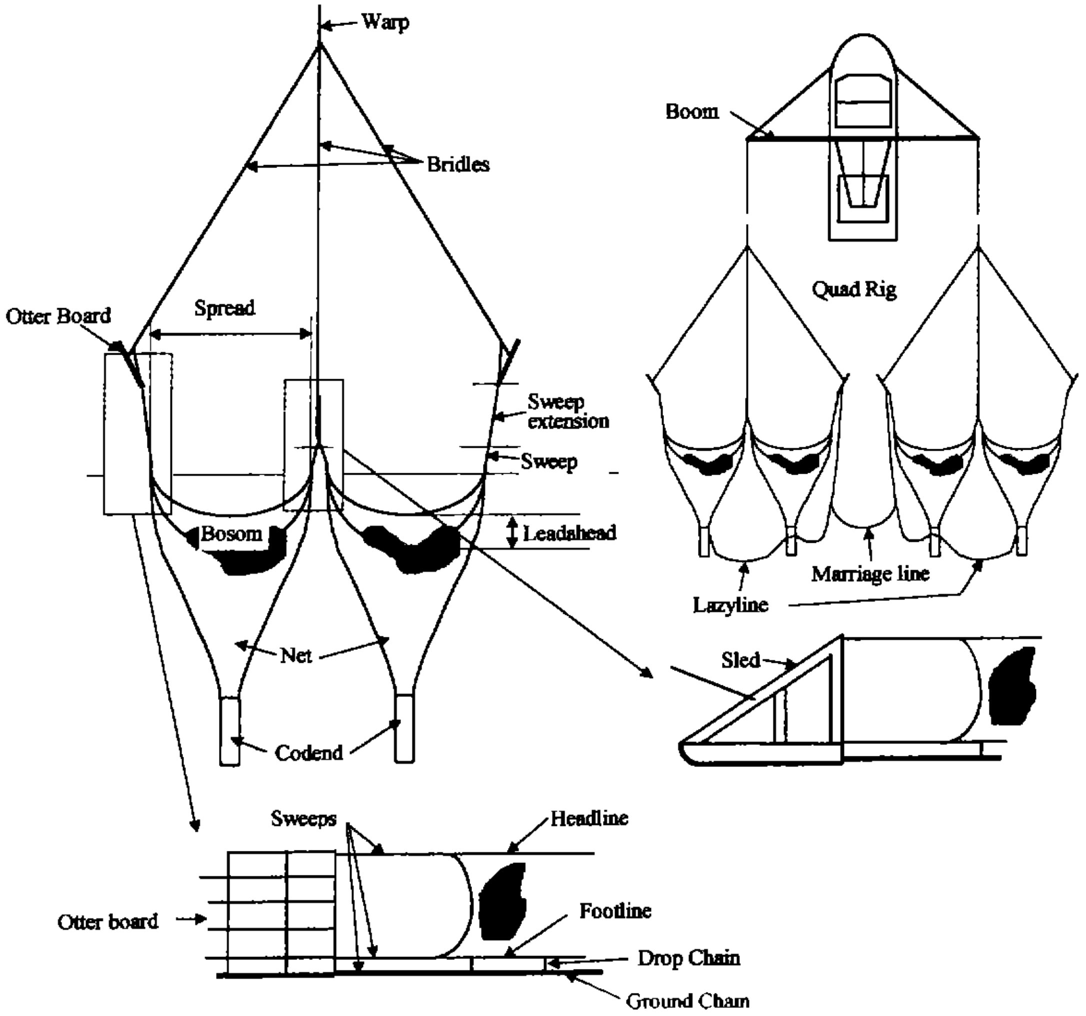


Figure 1. Terminology for low opening prawn trawling gear.

Booms	Steel/aluminium structures to support trawl gear towing points outboard of the vessel's centre line.
Bosom	Central part of trawl net where framelines (headline and footline) work at right angles to the direction of tow.
Bridles	Wire rope connecting otter boards and sleds to towing warp.
Codend	Bag of netting connected to the aft end of the trawl to collect the

	accumulated catch during each tow.
Drop chain	Small length of chain connecting footline to ground chain at about 1m intervals.
Footline	Lower frameline to which netting is connected in a trawl. Also referred to as fishing line.
Ground chain	Of similar length to footline and travels across the sea floor.
Headline	Upper frameline to which netting is connected in a trawl.
Lazy line	Rope permanently connected to the codend to allow it to be hauled on board the vessel.
Leadahead	Where the headline is forward of the footline to form an overhanging veranda of netting.
Marriage line	Small diameter rope connecting together all lazy lines.
Net	Or trawl. Consists of a bag of netting hung between two framelines.
Otter board	Solid device set at an angle of attack to the tow direction to generate a lateral hydrodynamic force (shear) to spread the system of trawls.
Sled	Steel frame used where nets are joined together to provide connection points for the trawls and the towing bridle.
Spread	Is the lateral distance that the headline spans while the gear is working.
Spread Ratio	Lateral spread expressed as a percentage of headline length
Sweep	Trawls are often connected to the appropriate otter board/sled via short lengths (1- 4m) of wire rope and chain of similar specification to the framelines and ground chain.
Sweep extension	Additional sweep on one side of the net to ensure that it is towed square.

Warp	Main towing wire from the booms to the bridles.
Wing	Region of the trawl outermost from its centre line where the body of the net essentially becomes a wall of netting between the two framelines.

High opening gear

Figure 2 shows a schematic diagram of high opening gear with flywires. This type of gear contains some additional components, which are defined below.

Since banana prawn schools can extend many metres above the sea bed, high opening trawl gear is necessary for their capture. Flywires are used to hold the headline at about four times the height (4m) of low opening gear. Lateral spread is of lesser importance in these systems and is typically only 45% to 55% of the headline length.

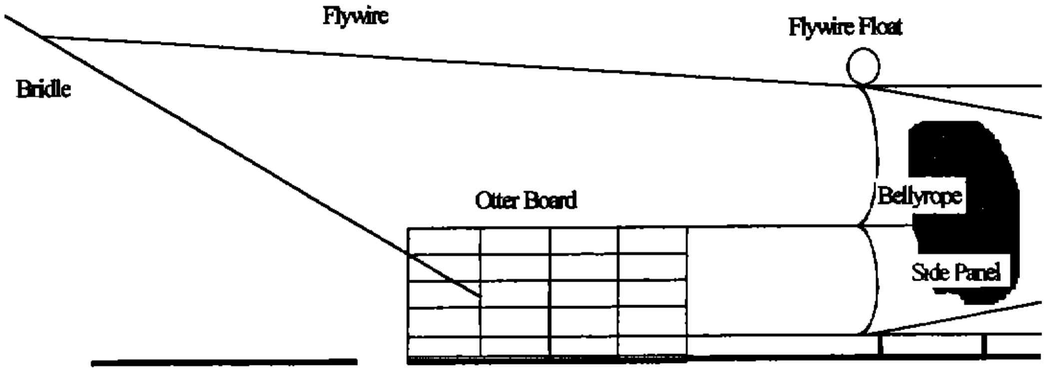


Figure 2. Terminology for high opening trawl gear with flywires

Bellyrope	Rope sewn longitudinally into the side panel of a high opening trawl to transfer netting strain onto the top of the otter board.
Flywires	Wire rope connecting headline of trawl to the bridle at approx. 10 - 20m from the otter board
Flywire float	A float is usually attached to the headline at the flywire connection to improve headline height and to aid setting the gear while shooting away
Side panel	Longitudinal panel of netting incorporated into the side of the trawl to

allow for the degree of separation between the footline and the headline.

Net design

Over the history of prawn and scallop trawling many unique trawl designs have been devised. Figure 3 shows the basic elements of working with net panels to produce a trawl. These elements are defined below along with some performance aspects of trawls.

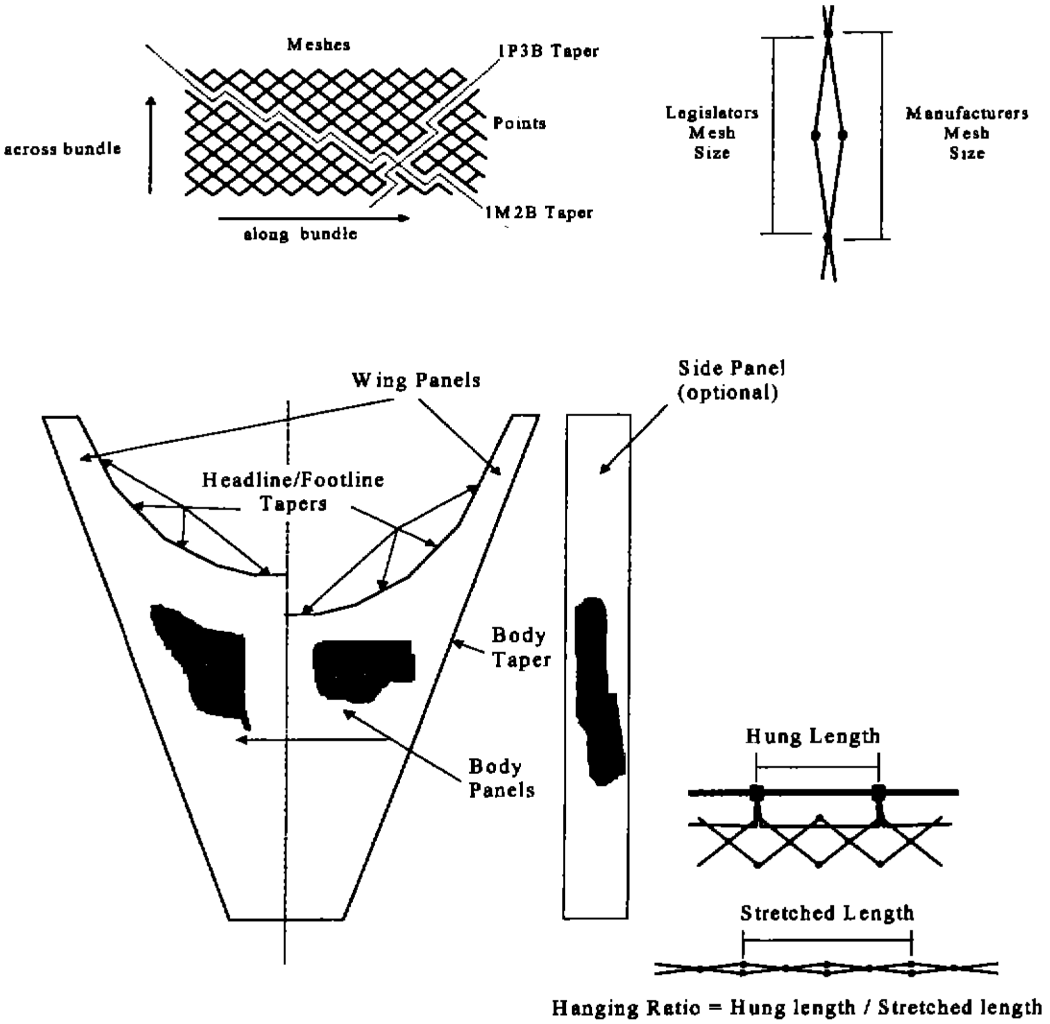


Figure 3. Basic elements of net design.

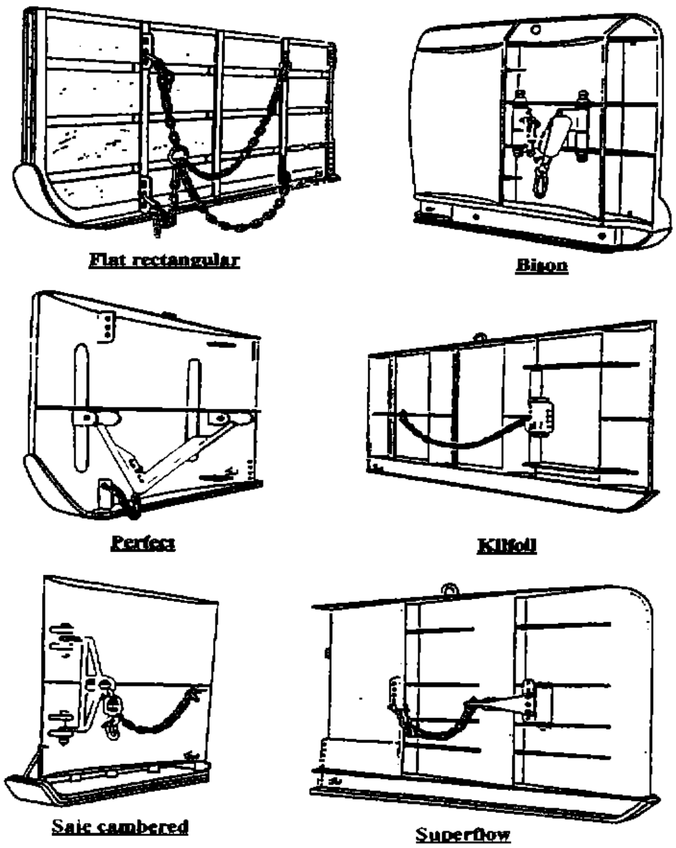
Bars	Twine elements bounded by adjacent knots that form the mesh structure of netting.
Body panel	Two such panels form the majority of the body netting of the trawl. The front side of the body panels contain the headline/footline tapers

	while the body taper forms the sides.
Body taper	This defines the outside extent of the two body panels of the trawl. The required length of the trawl determines the body taper selected.
Bundle	Sheet of netting as supplied by manufacturers, usually 200 points deep (100 deep bundles are available) by 50m long.
Drag	Forces applied to the trawl whilst working that retard its motion along the seabed; principally composed of hydrodynamic forces on the netting and friction/ploughing forces on the ground chain.
Hanging ratio	When attaching netting to the framelines a degree of slack in the netting is attained to ensure an even strain transfer occurs along the edge of the netting. The hung length of the netting is usually expressed as a percentage of its stretched length; this is the hanging ratio.
Inpull force	Due to the generation of drag forces on the trawl and the situation where these are transferred forward through the framelines onto the sleds/otter boards, the wings of the trawl partly apply a closing force against which the otter boards react. This closing force is referred to as the net's inpull force or inward pull.
Mesh size	Length of mesh when the netting is pulled taut along the length of the bundle. Manufacturers specify the distance between knot centres, while fisheries legislation specifies the distance between the knots.
Meshes	Two adjacent bars lying end to end along the length of a netting bundle, also known as transversals. The knot in a mesh can be untied to form a continuous length of twine.
Net plan	Drawing showing detail of netting tapers required to manufacture a particular net design from a bundle of netting.
Points	Two adjacent bars lying end to end across a bundle of net, also known as normals. If the knot within a point is untied the point becomes

	broken into two twine elements.
Side panel	Sometimes incorporated into the wings and between the body panels of a trawl. This produces a net that has two seams down each side (ie. 4 seam net).
Taper	Combination of meshes, points and bars to achieve cuts at various angles in the netting (eg. 1M2B = 1 mesh followed by 2 bars).
Headline/ Footline tapers	Are incorporated along the front edge of the body and wing panels to accommodate the curvature of the framelines to which they will be attached (hung).
Wing panel	Includes those panels of netting forward of the trawl bosom and will include the forward part of the side panel, if present.

Otter board design

There is a wide range of otter board designs, from the conventional flat rectangular to the more modern Bison and Kilfoil designs, that are commonly used in Australian fisheries. Figure 4 shows six contemporary designs.



Flat rectangular

Bison

Perfect

Kilfoil

Saie cambered

Superflow

Figure 4. Six contemporary prawn trawling otter boards.

Figure 5 highlights terms used to describe shape and performance characteristics of otter boards. Below are written definitions of these terms.

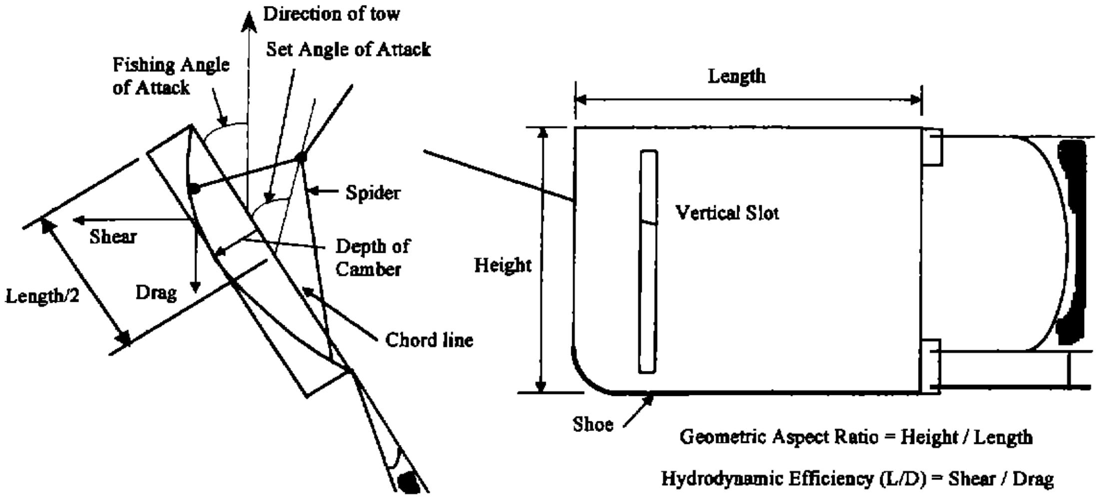


Figure 5. Terminology for an otter board.

Fishing angle of attack	Angle between the direction of tow (assuming no cross currents) and the chord line of the shearing surface of the otter board
Set angle of attack	Angle between the chord line of the shearing surface and a line drawn between the centre of the board and the bridle attachment point.
Aspect ratio	Has two forms, geometric and effective. The geometric form is obtained by dividing the board's height by its length. For plan forms that are not rectangular, it is more correctly given by dividing the square of the board's height by its area. The effective aspect ratio is determined by whether the tips are free or in contact with a boundary plane.
Attitude	Same as fishing angle of attack.
Camber	Longitudinal curvature in the shearing surface of the otter board. Quantified by dividing the depth of the camber by the length of the otter board (chord line length).
Chord line	Line joining leading and trailing edges of the otter board.
Drag	The sum of all forces produced on the otter board that directly resist motion in the direction of tow. These forces include hydrodynamic

	drag and friction and ploughing forces from interaction with the sea floor.
Heel	Equivalent to roll – positive is clockwise roll for port otter board when viewed along direction of tow.
Hydrodynamic efficiency (L/D)	An efficient otter board has a high lateral force (shear) with low drag forces, that is a high shear to drag ratio.
Pitch	See tilt and Figure 6.
Roll	See heel and Figure 6.
Shear	Lateral force produced on an otter board to effect spread of the trawl system.
Shoe	Steel plate (100 - 150mm wide) that is attached to the bottom of the otter board and is in sliding contact with the seabed.
Slots	Gaps in the shearing surface of the otter board. These can either be horizontal or vertical and significantly alter the water flow and hydrodynamic forces acting on the otter board.
Spider	Arrangement of hinged bracket and/or chain that fixes the location of the bridle to otter board attachment point relative to the boards centre.
Tilt	Equivalent to pitch – elevation of front relative to back.
Yaw	See angle of attack and Figure 6.

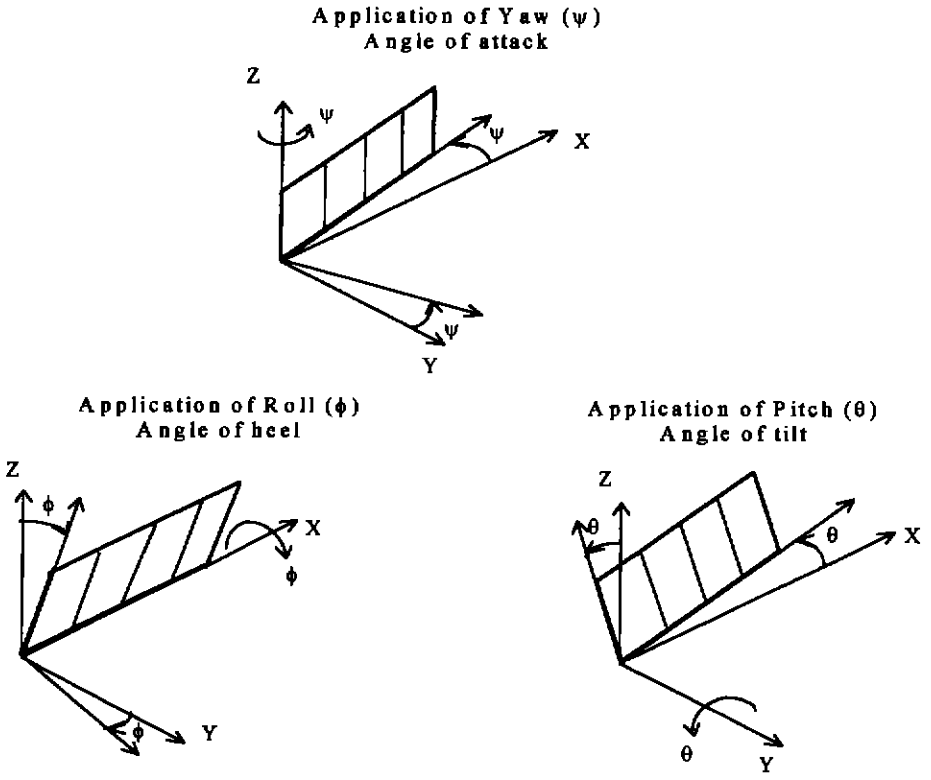


Figure 6. Definition of orientation of port otter board.

Multiple net prawn trawl systems

Figure 7 shows schematic diagrams of four trawls systems commonly used; single, double, triple and quad rig.

Another system commonly used in very deep water is the dual rig. This is identical to one of the two units that make up quad rig. Additionally systems have been devised that incorporate up to six nets, however these systems have not yet been accepted commercially to any great extent.

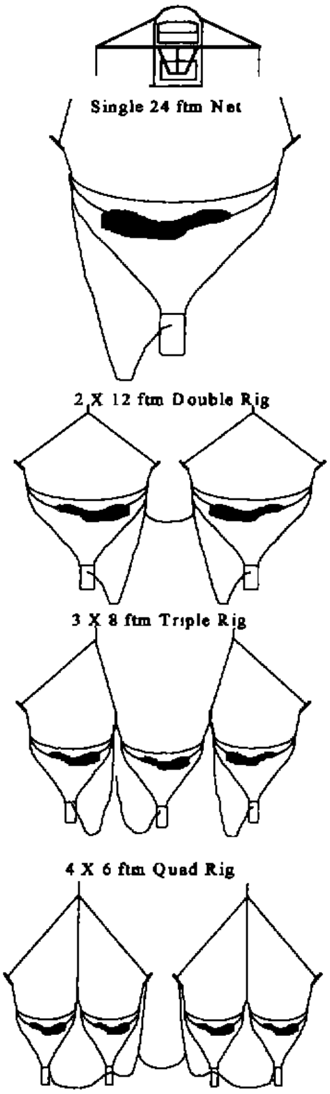


Figure 7. Multiple net prawn trawl systems.

Fisheries management

Biomass (B)	Total mass of fish stock at any point in time.
Catchability coefficient (q)	Proportionality coefficient between Yield (Y) and the product of biomass (B) and fishing effort (f). $Y = q\ B\ f$.
Effort (f)	Fishing effort measured in boat-days for most prawn fisheries.
Effort for MSY (E_{MSY})	Fishing effort that will produce maximum sustainable yield (MSY) in the long term from a fishery.
Recruitment (R)	Biomass of the youngest year class in the fishery when at an age that is first sought by fishers.

Spawning stock (S)	Biomass of the portion of the stock that has reached maturity and contributes to spawning activity.
Spawning stock for MSY (S_{MSY})	Size of spawning stock that on average produces recruitment with maximum in excess of that required to maintain the current stock level.
Yield (Y)	Catch returned from a fishery for a unit of effort (f) and a given level of biomass (B).

NOTATION

Symbol: Definition (Units).. Page first used

a_2: span constant (N) 89

Ab: otter board area (m^2) 26

b_2: span parameter (N/(m/sec)) 89

C/Dw: tow cable to water depth ratio 64

Cd_t': hydrodynamic drag parameter ($N/(m/sec)^2$) 89

Cf': Hydrodynamic force parameter (N@1m/sec) 39

Cl: lift coefficient 26

COP: position of otter board hydrodynamic force from leading edge (fraction of board length) 54

cpflag: control pitch flag 26

ctflag: constant torque flag 24

Df: friction force (N) 89

Dn: trawl net drag (N) 21

Dp: propeller diameter (m) 23

Dt: total gear drag (N) 22

D_V: drag at real speed, V (N) 97

$D_{\overline{V}}$: drag at observed speed, $\overline{V}$ (N) 97

E: propeller performance coefficient 23

F7: vertical reaction force between otter board and seabed (N) 64

F8: otter board ploughing force (N) 54

$F8_{=}$: component of ploughing force tangential to otter board face (N) 64

$F8_{\perp}$:component of ploughing force normal to otter board surface (N) 54

F9: otter board sliding friction (N) 54

$F9_{\perp}$:component of sliding friction normal to otter board face (N) 54

Fb: otter board hydrodynamic force (N) 54

$Fb_{=}$: component of otter board hydrodynamic force parallel to face (N) 54

$Fb_{\perp}$: component of otter board hydrodynamic force perpendicular to face (N) 54

Fn: trawl wingend tension (N) 54

$Fn_{=}$: component of trawl wingend tension parallel to otter board face (N) 54

$Fn_{\perp}$: component of trawl wingend tension perpendicular to otter board face (N) 54

Fw: bridle tension (N) 54

$Fw_{=}$: component of bridle tension parallel to otter board face (N) 54

$Fw_{\perp}$: component of bridle tension perpendicular to otter board face (N)_ 54

HL: headline length (m) 21

In: inpull force of net (N) 21

It: inpull force of system (N) 22

K: Kort nozzle thrust factor 23

Kf: ratio of friction and hydrodynamic forces at 1m/sec 22

L/D: hydrodynamic efficiency (hydrodynamic shear to drag ratio) 17

mesh: knot to knot mesh size (mm) 21

MR: ratio of square mesh wingend height to headline length 67

MT: ratio of headline height to square mesh wingend height 67

Nb: number of otter boards 22

$N_{max\ trawling}$: max RPM during trawling 24

Nn: number of nets 22

$N_{op\ trawling}$: rpm used while trawling 24

N_{rated}: rpm associated with rated power 24

p: maximum continuous rated engine power (kW) 24

P: developed engine power (kW) 23

ply: number of strands in polyethylene netting 21

RPM: engine speed (revolutions/minute) 24

S: trawl gear span (m) 89

S^*: span for standard applied thrust (m) 90

SAR: swept area rate (m^2/sec) 26, 89

SAR^*: swept area per unit time for a standard applied thrust (m^2/sec) 90

SR: spread ratio (fraction of HL) 21, 32

S_V: span at speed, V (m) 98

$S_{\overline{V}}$: span at observed speed, $\overline{V}$ (m) 98

T0: bollard pull (N) 23

T_a: applied thrust (N) 89

T_a^*: standard applied thrust (N) 90

Tapf: side taper drag factor 21

Tv: available thrust or tow force (N) 26

V: trawl speed (m/sec) 21, 89

$\overline{V}$: observed speed (m/sec) 97

V^*: trawl speed for a standard applied thrust (m/sec) 90

Vd: free running speed (m/sec) 26

Wbw: weight of otter board in water (N) 64

wt/m: chain weight per meter of length (N) 63

x,y: position of bridle connection point relative to centre of board (fraction of board length) 54

x2,y2: position of net connection relative to centre of board (fraction of board length) 54

α_2: bridle divergence angle (degrees) 22

μ_k: kinetic friction coeficient 64

μ_{pn}: ploughing force normal component coefficient 65

σ_y^2: variance of y (units of y) 97

Ω: effective wingend angle of net (degrees) 21

ψ: otter board angle of attack (deg) 54

CHAPTER 1 - INTRODUCTION

1.1 Background

The work in this thesis is the continuation of effort by the author to investigate the physical characteristics of low opening prawn trawling systems. A substantial portion of the previous work is reported in Sterling (2000b). That book, titled "The Physical Performance of Prawn Trawling Otter Boards and Low Opening Systems", concentrates on the question of developing improved otter boards for prawn trawling applications. Fundamental to the approach adopted in that work was the notion that otter boards could not be improved in isolation but rather the task needed to be pursued in context with the commercial objectives bound up with the utilisation of prawn trawling gear as a whole. Following this initiative the problem of developing better otter boards was defined in terms of maximising the catch for a given trawler, which is much broader and more complex than simply seeking to maximise the hydrodynamic efficiency of otter boards.

To link the objectives of that research with the commercial goals of trawling required that such goals and the environment in which they are sought needed to be defined and synthesized. That led to a context focussed criteria framework in which to nest and define the specific objectives of the research. The dominant feature of that framework was the notion that the catch of a trawling operation is driven by the area of sea bed swept by the gear. Section 2.1 of Sterling (2000b) defines the magnitude of the area of sea bed swept per unit of time as the "engineering performance" of the operation and goes on to explore how this facet of the trawling operation nests and interacts with other aspects. This conceptual framework is an important basis of that work and the work herein. For that reason it has been updated and reproduced in section 1.4.

Notwithstanding that other aspects of the operation are relevant to the overall catching performance of a trawler (eg. searching capability and minimising escapees), Sterling (2000b) hypothesised that the main connection between gear variables and catch is via the engineering performance mechanism. From that point the work tended to define engineering performance as a proxy to catching performance and then proceeded to develop a Prawn Trawling Performance Model

(PTPM Ver1) that is based on swept area per unit time (chapter 4, Sterling (2000b)) for the purposes of optimising otter board design.

The bulk of the work reported in this thesis seeks to improve and validate the technical accuracy of the PTPM and the assumptions that underpin the work of Sterling (2000b). This includes validating the notion that engineering performance can be practically employed as a proxy to catching performance. Thus one specific objective is to establish the extent that swept area rate, as estimated by the PTPM, is correlated with real catch in a prawn trawling fishery. Motivating this work is the idea that if the PTPM indeed represents a reasonable model of how a dominant factor in catching performance is manifested from the gear's physical characteristics then the model could make a valuable contribution to a range of problems that extends well beyond the development of better trawl gear. These applications relate to the many aspects of prawn trawling that are becoming more intensely managed at industry and government levels.

The importance and relevance of the latter proposition is clearly underlined by the scale of turmoil currently surrounding prawn trawling fisheries worldwide and particularly in Australia. All Australian prawn fisheries are under immense scrutiny on a large number of high profile issues including stock decline, environmental impact, accelerating effort levels and reducing economic and social viability (Minnegal, 2003) (Anon., 2002). Many of the ongoing debates are difficult to resolve because of uncertainty in defining key aspects of the problems (Ludwig, 2001). Perhaps the most crucial of these, because of the way that it is significantly relevant to many of the problematic issues and therefore locks them together with entangling interactions, is the question of how prawn trawling operations work at a mechanistic level. Thus an engineering understanding of prawn trawling systems will help solve these difficult environmental, social and economic problems in addition to the obvious application of improving the operating efficiency of the trawling process itself.

To uncover the potential of the PTPM, part of the thesis is dedicated to exploring the broad management environment of prawn trawling fisheries with the view to recognise and define specific applications.

The attitude of society in the affluent part of the world has changed markedly over the last three decades. It relates to a fundamental mood shift in these communities that is driven by concern for the natural environment against a backdrop of two developing perceptions. Firstly, that the natural systems of the world at all levels have sustained large impacts from human activity and are becoming increasingly stressed, perhaps to the point of imminent collapse. And secondly, that the natural systems of the world are essential for human survival and quality of life (Hawkin et al., 1999). In response to this there has been a global ascendance of policies and legislation at all jurisdictional levels that collectively places conservation and development of the worlds natural systems (natural capital) at a level of importance at least equal to the development of economic and social capital.

The centrepiece of modern governance is a framework for development that recognises three fundamental forms of capital and seeks to form an integrated and complementary strategy for development. This was launched onto the world stage by the release of a report by the World Commission on Environment and Development (WCED) (Anon., 1987). The report introduced the concept of "Sustainable Development" wherein it was described to be:

"development that meets the needs of the present without compromising the ability of future generations to meet their own. It contains within, two key concepts:

- The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- The idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs.

Thus the goals of economic and social development must be defined in terms of sustainability in all countries .... and must flow from a consensus on the basic concept of sustainable development and a broad strategic framework for achieving it."

In Australia, policy makers work with the term "Ecological Sustainable Development" (ESD) and legislators have incorporated the term, with various forms of interpretation, into a large percentage of Australia's legislation, thus closing the democratic loop between the collective sentiment of Australians in respect to their physical and psychological needs and the laws of the nation. Today therefore, the underlying goal of "sustainable development" formally affects in some way many aspects of life for Australian citizens.

To survive into the future all industries to varying extent need to reinvent themselves in a way that caters to the continuously evolving paradigm of sustainable development. The Australian prawn trawling industry has been particularly susceptible to strife flowing from these requirements and due to its structure, culture and history of development has found it immensely difficult to respond in a way that is free from external and internal conflict (Somers, 1994) (Anon., 2000a). Many people in the industry despair as their lives have become surrounded by ongoing turmoil. The author hopes that the work of this thesis, which explicitly attempts to connect with the challenges of Ecological Sustainable Development, will help resolve the difficulties and bring some relief. For the negative impacts on people are surely not consistent with the basic aim of sustainable development, as described by the WCED: "to promote harmony among human beings and between humanity and nature" (Anon., 1987).

1.2 Objectives

The objectives set for this thesis relate to three research areas. Firstly, to expand and improve the PTPM so that it is more accurate and relevant to a broader range of questions. This is addressed in chapter 2. Secondly, to evaluate the capacity of the PTPM to predict the performance characteristics of real prawn trawling operations in terms of both engineering and catching performance. A validation and calibration exercise is undertaken in chapter 3. Thirdly, to investigate the problem space surrounding prawn trawling fisheries to identify and develop applications for the model. This is done in chapter 4.

More specifically the objectives of the thesis are:

1. Expand the structure of the PTPM to produce a more comprehensive and detailed picture of the mechanics of prawn trawling.
2. Develop the sophistication of the model so that it can be applied to a wider range of problems and issues.
3. Make improvements to the model so that operational factors are predicted more accurately.

4. Determine the predictive capability of the model by comparing model predictions with observations of engineering variables and catch.
5. Explore the management environment surrounding prawn trawling fisheries from the perspectives of fisheries managers, industry operators and "public interest" to define applications for the PTPM consistent with the aims and objectives of Ecological Sustainable Development.

1.3 Scope of the work

In relation to the development of the PTPM this work is scoped and segmented in terms of various physical aspects of prawn trawling.

Considering that trawling is an active fishing method, it is recognised that the performance of the prawn trawling system is linked to the magnitude of the tow force, which drives the operation. No direct experimentation was undertaken to underpin the prediction of tow force from the characteristics of the trawl vessel. Instead prediction has relied on published data and a theoretical approach.

It is generally presumed that the response of prawn trawling gear to the driving force is dominated by hydrodynamic considerations, so these were pursued to the greatest extent and empirical data was collected on a range of issues via flume tank testing of model trawl gear. A secondary physical realm is the interaction of the trawl gear with the seabed. In this area no direct experimentation has occurred despite there being a paucity of published information. This was because effort had to be prioritised in the research program and the fact that the resources required to carry out such work were not available. Modelling of ground effect issues has relied on theoretical approaches and reference to the limited published information as a way of supporting and calibrating the theories.

The structure and complexity of the model is determined by not only the important physical processes at work but also by the type of data that is readily procurable and convenient to use. Factors included in the model are those that are practical to measure and/or knowable from industry practice.

Validation data that is independent of that used to construct the model provides an opportunity to check and calibrate various aspects of the model. The validation work in the thesis centred on sea trial data from past research conducted by the Australian

Maritime College and the Australian Maritime Engineering CRC and also catch and vessel configuration information for the Northern Prawn Fishery (NPF) held in CSIRO data bases. The PhD program had limited access to the latter data through collaboration with CSIRO and AMC on a research project funded by the Fisheries Resources Research Program (FRRF) and the Australian Fisheries Management Authority (AFMA) entitled "A new approach to fishing power analysis and its application in the Northern Prawn Fishery". Access was limited for two reasons. Firstly the information is subject to complex and strict confidentiality rules, which means that access is arranged only by notification and agreement with AFMA and secondly there was the practical problem that the database is very large. For the latter reason CSIRO staff were needed to conduct queries of the database and run analyses to aggregate the information.

In relation to the search for applications of the PTPM with respect to prawn trawling fisheries and ESD, the subject matter is almost unbounded due to the broad intentions of ESD - particularly the premise that ESD needs to be devised from a holistic framework of understanding and analysis. Therefore, given that ESD should in a balanced way reflect environmental, economic and social issues organised in a tangible framework that also takes into account values and ethics, there is much opportunity to consider a broad range of points of view, philosophical propositions, connecting academic disciplines and activity occurring at a range of spatial, temporal and social scales.

Methods used to contain the scope of this part of the work were to:

a) Look at the application of the PTPM to the management of prawn trawling fisheries from a single idealised and remote perspective. This was achieved by identifying management priorities from high-level policy documents.

b) Limit the complexity of contextual detail by referring to just one prawn fishery, the NPF, in the case study.

1.4 Factors Affecting the Performance of Low Opening Prawn trawling Systems

The prediction of prawn trawling performance begins with a conceptual framework of the factors that are involved and their function. The following section displays an updated version of such a framework based on that published by Sterling (2000b).

This framework in part shows the outline of a model for the engineering performance of prawn trawling systems based on its measurable physical characteristics and their engineering effects. The work in chapter 2 expands on this to produce a numerical prediction model based on engineering criteria understood in terms of the physical characteristics of the hardware components, their operation and interaction (the PTPM).

This is insufficient for many real world problems because some people are interested in measuring the performance of the system using different indicators. Owners want to use financial indicators (revenue, costs, profits). Economists, ecologists and sociologists have their own unique systems of indicators, while fisheries managers are interested in all of them. To help with this, the framework presented here includes more than engineering performance and conceptualises how the engineering nature of prawn trawling systems connects with other features of the surrounding world.

Given that profitability is a major constraint felt by business owners, and all stakeholders have a basic appreciation of this perspective, it is a useful focus for producing a broad view of a fishing operation. Other important issues like ecological sustainability can be identified and expanded within this framework, in terms of its various components, to produce a view of the industry's ecological footprint within a profit oriented context. It could be argued that this is an appropriate environment to develop ecological objectives because the profit oriented perspective produces direct feedback with respect to economic impact. Clarifying this interaction would help progress the dominant conflict between business profit and nature conservation into successful sustainable development. Such an approach is preferable to decision making processes that are fed by histrionic political debate and which ultimately expose both businesses and the environment to greater harm through the implementation of low quality courses of action.

Factors influencing profitability

A simple profit model for a single fishing unit can be defined as in Figure 8. In this model, factors that give rise to the revenue of the operation are divided into two areas:

- Market factors; where a mix of factors influences revenue through sale price. Manipulating these factors will affect sale price and hence revenue, however the effect on profitability also depends on the costs associated with the manipulating process and any increased investment required.
- Production factors; where the focus is now on revenue being governed by the quantity of prawns caught. This in turn is shown to be influenced by four major factors; local abundance, catch efficiency, engineering performance and trawling time.

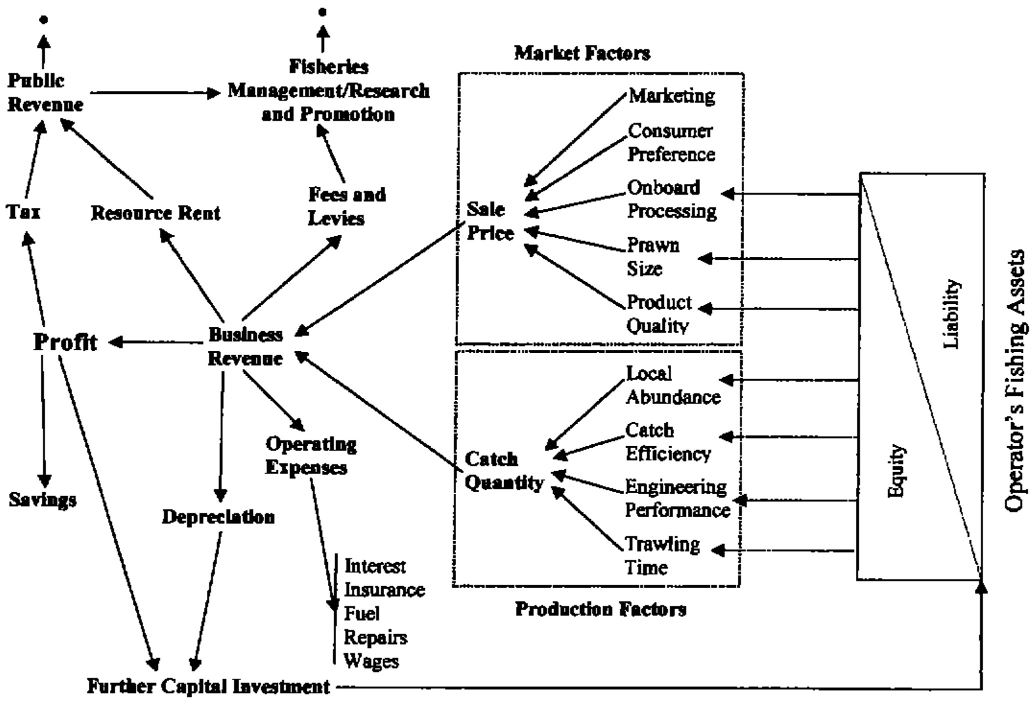


Figure 8. Simple profit model for a prawn trawling operation.

Unfortunately, the two areas above are not completely independent (some of the interactions are not shown). For example, when the catch rate of prawns is very high one can expect some degree of product quality loss and reduction in sale price due to the strain imposed on the product handling facilities onboard the vessel. Another interaction between production and market factors is through the size of the prawns landed. Large prawns have a higher commercial value, but sometimes the quantity of large prawns that can be harvested is less than the quantity of harvestable small prawns. Dependent on the strength of the price premium for large prawns and the relative difference in abundance of different prawn sizes, the targeting of the most profitable catch will be a compromise between sale price and catch quantity. It is entirely possible that operators often face a difficult choice between taking high catches, which is instinctively attractive, or lower catches of larger prawn that have a higher dollar value per unit of catch.

Logically, operators are keen to introduce harvesting initiatives to increase catch quantity and boost revenue and profit. But care needs to be taken. Although all new onboard technology and operating strategies are no doubt adopted with the view to increase profit, not all of such initiatives achieve the objective through increased catches. For example, some technology will be directed towards improving the sale price of the catch through improving quality and adding value by carrying out onboard processing that is carefully aligned to the needs of the market. Additionally, some technology may be aimed primarily at reducing operating cost so that profits can be maximized.

In context with the issue of fishing performance, Figure 8 highlights two background facts:

1. The incentive of operators is to maximise revenue and profit
2. This leads to a first order incentive to increase catch quantity, but this is restrained by a consideration to maximise the sale price of landed catch and optimise operating costs.

Factors affecting catch quantity and their interaction

Figure 9 is a more detailed view of the factors affecting catch quantity. Starting with the same four primary factors shown in Figure 8, these are expanded further into a larger array of influencing factors, many of which are associated with technology and operating strategy. Following is a brief description of some of these influencing factors in relation to the four primary ones. Terms in italics can be found in Figure 9, with connecting lines to mark the interactions described below.

At the top of the diagram is *Biomass,* which depends on the health of the fishery and yearly *Recruitment*. At the bottom of the diagram is *Nominal Time*, which is the number of days that the vessel fishes. The amount of prawns caught for a unit level of biomass and a unit amount of nominal effort (time) depends on all the factors lying in between these terms in Figure 9 and collectively gives rise to the Fishing Power of the operation. Fishing Power is an important term within the management environment of prawn trawling fisheries and is the centre of attention under the topic of ecological sustainability in section 4.2.1.

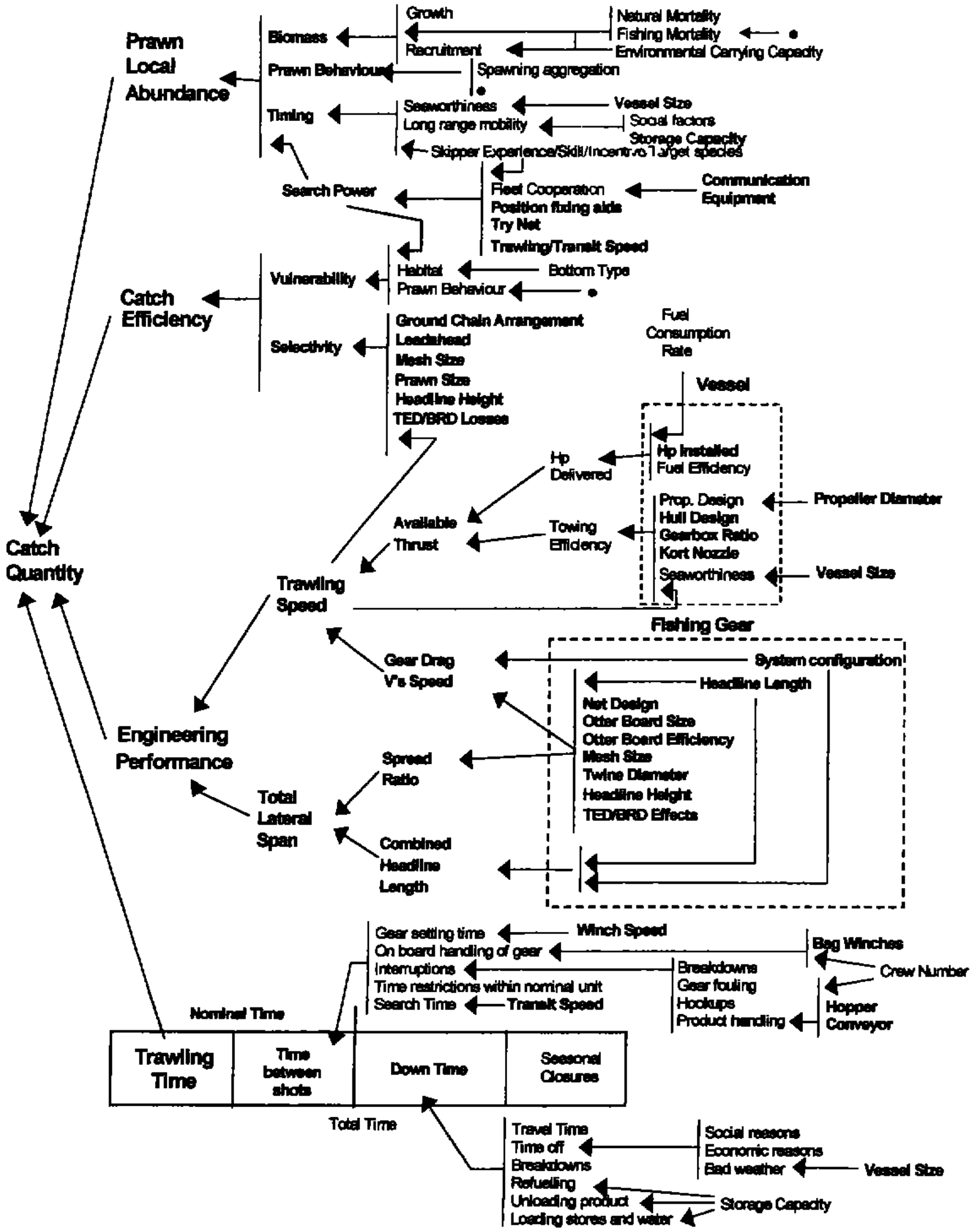


Figure 9. Interaction of factors that affect catch quantity.

Figure 9 indicates the principle factors governing the catch taken by a trawler:

- The abundance of prawns on the trawled seabed (*Local Abundance*).
- The proportion of prawns taken as the seabed is trawled (*Catch Efficiency*).
- The rate at which the seabed is trawled (*Engineering Performance*).
- The amount of time trawling occurs (*Trawling Time*).

Local Abundance is the density of prawns in the area trawled. This parameter depends primarily on *Biomass* as outlined above, but other biological and environmental factors do play a role. This relates to the propensity of the prawns in question to school up and produce geographical areas of greater density. From an operational perspective local abundance also depends on the ability of the skipper to position the trawl in areas of high abundance within the fishery (*Search Power* and *Timing*). Apart from their *Experience* there are a number of aids that help the skipper do this more effectively, for example; the *Try Net*, *GPS* and *Communication Equipment* and in addition the *Transit Speed* of his vessel will also have an effect.

Catch Efficiency is a parameter defined as the proportion of prawns in the path of the trawl that are captured. This can be affected by the environment (*Vulnerability*) and by technology (*Selectivity*). Very little is known about the influencing factors. Vulnerability is known to be influenced strongly by *Prawn Behaviour*; often linked with environmental conditions such as water temperature, time of day and seabed characteristics (Penn, 1981; Hill, 1985). *Search Power* plays a role in determining the instantaneous *Vulnerability* of prawn whilst trawling because the searching process actually targets areas where the density of vulnerable prawns is the highest, which is a combination of local abundance and vulnerability. The searching process does not deliver information on the actual local abundance of prawns or the proportion that are not vulnerable to the gear so to a variable and unknown extent the process helps target areas where the prawns are vulnerable.

Gear factors that affect catch efficiency through *Selectivity* are *Mesh Size* and *Ground Chain Arrangement* (Sterling and Watson, 1989), and *Headline Height* (Eayrs et al., 1996). Some investigations of these factors have already taken place, however there are a multitude of other factors related to net design, otter board size and *Trawling Speed*, which have a completely unknown influence on catch efficiency.

Engineering Performance is a parameter defined specifically as the area trawled per unit of time (swept area rate, SAR). This parameter is labelled engineering performance because it is the end result of the interaction between the forces and the flow of energy in the fishing system and is a measure of the system's trawling capability. In Figure 9 the fishing system is divided into two parts; *Vessel* and *Fishing Gear*. Being an active fishing gear the performance of trawl gear is directly linked to the towing capability (*Available Thrust*) of the vessel. In this respect it would be valid to consider the vessel (or at least its thrust aspects) as part of the fishing gear itself.

Features of the vessel that affect *Available Thrust* are dominated by the *Installed Engine Power* in companion with the effectiveness of the propulsion system, which is largely determined by *Propeller Diameter* and the presence of a *Kort Nozzle*.

It is convenient to estimate the performance effects of specific gear factors in terms of engineering performance (SAR). For any specific trawl system under consideration, its SAR is a result of working from right to left in Figure 9. Firstly, the characteristics of the system determine the *Gear Drag*, *Spread Ratio* and *Combined Headline Length*. This leads to *Total Lateral Spread* and *Trawling Speed* for a given vessel (*Available Thrust*). These variables then combine to give engineering performance or SAR.

Trawling Time is the final parameter shown that determines catch. Of most importance in context with Fishing Power is the difference between *Nominal Time* and actual *Trawling Time*. Certain technology factors can reduce wasted time to some extent, for example those factors that allow the gear to be shot and hauled more quickly. *Transit Speed* can also have an impact on trawling time, particularly under circumstances where the fishery is characterised by having areas of high local abundance and operators carry out a significant amount of searching and targeted fishing.

The *Nominal Time* spent trawling in a year is significantly determined by *Seasonal Closures*, the capacity of the vessel to work rough weather (mainly *Vessel Length*) and on a day-to-day basis at the discretion of the skipper, based on the viability of fishing at that time and location.

CHAPTER 2 – DEVELOPMENT OF THE PRAWN TRAWLING PERFORMANCE MODEL

Overview

Three versions of the Prawn Trawling Performance Model (PTPM) have been produced over the history of its development. Versions 2 and 3 are described in this chapter in a way that explains the input/output and structure of the model and recent improvements made to it. A detailed description of Version 1 is given in Sterling (2000b). That report describes the theoretical approach of the model, relevant background information and the basis of important simplifying assumptions. That material is reviewed in this chapter.

Version 2 of the PTPM is constructed around two fundamental steady state assumptions for prawn trawling:

- Trawler thrust in excess of that required to move the vessel through the water is numerically equal to the total drag of the trawl system.
- The spreading force produced by the otter boards is equal to the inpull force generated by the trawl nets and bridles on the otter boards.

Equations for the four forces mentioned above are the corner stones of the prediction model (equations 4, 5, 8, 9 in section 2.2). These allow solutions for the above mentioned equilibrium conditions to be found, which then define the operational status of the system and therefore its swept area rate (equation 10, section 2.2). Figure 11 and Figure 12 in section 2.2 show the construction and operation of the PTPM in these terms.

Improvements to PTPM ver2 are described in section 2.3 based on eight areas of investigation. The following table indicates the changes that were made and where further details can be found in the body of this chapter.

Model feature	PTPM ver2	PTPM ver3
Hydrodynamic net drag (rel to net drag @ SR = 0.75) = f(SR)	$0.306 + 2.83\,SR - 4.89\,SR^2 + 3.14\,SR^3$ (part of equation 1)	$0.8453 + 0.0095\,\exp^{3.72\,SR}$ (section 2.3.1)

Wingend angle = f(SR)	-58.55 +274.55 SR – 393.07 SR^2 + 241.02 SR^3 (equation 2)	4.444 + 3.427 $\exp^{2.963\ SR}$ (section 2.3.1)
Otter board/net interaction drag correction factor = f(SR)	None	1 + 0.1227 $SR^{2.1449}$ (section 2.3.2)
Otter board/net interaction wingend angle inc.(deg) = f(SR)	None	1.96 $SR^{0.6044}$ (section 2.3.2)
Available Thrust = f(V)	$Tv = T0\ (1 - \frac{V}{2V_d})$ (equation 8)	Tv = T0 (1 - 0.1731 V/Vd – 0.667 $(V/Vd)^2$) (section 2.3.3)
Otter board angle feedback	None	See Figure 30 (section 2.3.4)
Ground chain drag = f(HL, SR, V)	None	HL wt/m 0.8 (1 + b sin(73 SR)) (1 + c V^2) (section 2.3.5)
Otter board ground effect forces	None	F7 = Wbw - (Db + Dn/2) Tan Asin (1/(C/Dw)) $F9 = \mu_k F7$ $F8\perp = \mu_{pn} F7 \sin\psi\ GSF (1 + c V^2)$ $F8_{=} = \mu_k F8\perp \cos\psi$ (section 2.3.6)
Hydrodynamic net drag = f(HL, MR, MT)	39.66 $HL^{1.473}$ (part of equation 1)	A(MR, MT) HL^2 1.095 where: A(MR, MT) = 3.111 + 27.012 MR $\exp^{(1.2205\ MT)}$ (section 2.3.1, section 2.3.7)
Net drag correction factor due to "gape"	None	1 + 0.3866 (gape – 1.53) (section 2.3.8)

2.1 Introduction

This chapter outlines the structure of the Prawn Trawling Performance Model (PTPM) and describes a series of recent improvements made as a result of work done to meet the objectives of the project "A New Approach to Fishing Power Analysis in the NPF". The development of the PTPM to its current form is marked at intervals by the release of three versions, which have increasing capability and are based on greater amounts of supporting experimental data.

The PTPM is a hybrid model that contains theoretical and empirical components. It is a deterministic model in that it does not output any measure of statistical uncertainty.

PTPM ver1 was produced in 1996 by a research project coordinated by the Australian Maritime Engineering CRC (Sterling, 2000b). That work drew on experimental data collected at the Australian Maritime College (AMC) over the previous 10 years and also further data collected by project staff at that time. All the relevant data was obtained from the testing of model trawl gear in the AMC flume tank and were the results of specific studies to understand various features of prawn trawling systems. Namely; multi-net prawn trawl rigs, trawl design, the magnitude of trawl forces at various spread ratios and the lift and drag forces acting on various otter boards. The measurement of trawl gear force in the flume tank was achieved by using specialised trawl and otter board evaluation hardware that was designed and constructed at the AMC.

The PTPM ver1 is described in section 4 of Sterling (2000b) and has a structure that reflects the narrow application and specific questions asked in that work. It serves only to predict the swept area rate of trawl gear based on values specified for a rudimentary collection of system variables. The goal of that version of the model was to provide a link between otter board size and trawl system performance as required by the research objectives of that work, which was focussed on the development of improved otter boards.

PTPM ver2 was a commercial software package developed by the author in 1998. It contained significant changes to the structure of the model to expand its range of application.

Version 2 of the PTPM is described in section 2.2 of this chapter. To broaden the application of the PTPM the structure of the model was expanded to capture more of the fine detail and associated mechanisms that go towards completely describing the character and status of an operating prawn trawling system. The user interface was also developed so that the software provided a more detailed output of the operating features of trawl gear and allowed searches for optimal performance and other specifiable operating goals.

Section 2.3 reports many further improvements made to the PTPM to produce Version 3. This work revisited all aspects of the model and made refinements to improve accuracy and utility either on the basis of collecting superior data or applying more sophisticated model structures.

2.2 The Prawn Trawling Performance Model Ver2

2.2.1 Introduction

Version 2 of the PTPM represents an expansion over Version 1 in six areas.

(1) Prediction of vessel thrust from the characteristics of the propulsion system.

Version 1 (Sterling, 2000b) does not attempt to predict the towing capacity of the towing vessel, but rather considers that the vessel is essentially outside the scope of performance appraisal. In Version 1 the towing performance of the vessel is explicitly specified as a constant thrust value. This is done for the purpose of standardising the input of the vessel when considering questions related to the relative performance of different configurations of the trawling gear. This view regarding the scope of performance comparison is appropriate for investigating different trawling gear options for a given boat (see caption for Figure 10), but is inappropriate in a fisheries management context where there is an overriding interest in the relative Fishing Power of different operations. The Fishing Power of an operator is dependent on the vessel as well as the characteristics of the trawling gear. In fact, since trawling is an active fishing method it is reasonable to presume that the swept area rate of an operation is primarily determined by the rate of energy input and the efficiency of the conversion between fuel and thrust, which are solely related to the characteristics of the tow vessel. Following this logic, one should rightly consider that the boat is manifestly part of the fishing system and the job of predicting the performance of an operation must include the boat in the prediction domain. PTPM ver2 undertakes to include the vessel in the performance prediction calculations and estimates tow force based on the operating parameters of the engine, the characteristics of the propulsion system and the predicted speed of the trawling operation.

(2) Prediction of spread ratio from matching otter board and system characteristics.

In Version 1 the spread ratio of the trawl system was explicitly specified for any given swept area rate calculation. For use as a more general performance prediction method the PTPM needed to be able to predict the resulting spread ratio for any specified system, whereby the characteristics of the otter boards including their area

(Ab), hydrodynamic effectiveness (Cl) and efficiency (L/D) are also specified. PTPM ver2 achieves this and includes otter board parameters in the prediction domain.

(3) Accounting for ground effect at the component level rather than the system level.

In Version 1 the effect of ground contact is estimated during the last stage in the swept area rate prediction process. This does not lend itself well to the task of accurately estimating spread ratio because ground effect forces not only affect the total drag of the system, but also have a bearing on how difficult it is to spread each individual net and the performance of the otter boards themselves. In response to this issue PTPM ver 2 calculates ground effect forces at the component level rather than the system level. Due to the added complexity of modelling the finer details of prawn trawling systems, with its many facets and interactions, the PTPM ver2 utilises Excel Solver™ to search for a status of the system that satisfies all the constraints defined by the physical characteristics of its components.

(4) A detailed system geometry model is incorporated.

Much of the mechanism intrinsically involved in the operation of prawn trawl systems relates to the geometric arrangement of the towing wires. Modelling the geometry of the towing wires, which is part of PTPM ver2, adds valuable insight into the detailed operation of the system and the opportunity to fine-tune its design based on specific design criteria. In particular, the spread ratio of individual nets in multiple net systems can be predicted and the need for sweep extensions can be assessed (to avoid nets being towed out of square).

(5) Each net in multiple net trawl systems is specified explicitly.

A limiting factor in Version 1 is that all the nets in a given multiple net system were considered to be the same. In many multiple net systems more than one net type may exist (eg larger middle net in triple rig). Separate accounting for each net in the system allows the flexibility of having nets of different type used within the one system.

(6) Optimisation carried out using Excel Solver™ rather than graphical methods.

To ascertain optimum spread ratio using PTPM ver1, maps of system performance (speed and swept area rate) were constructed with spread ratio being one of the independent variables as shown in Figure 10 (from section 4.2.2, Sterling (2000b)).

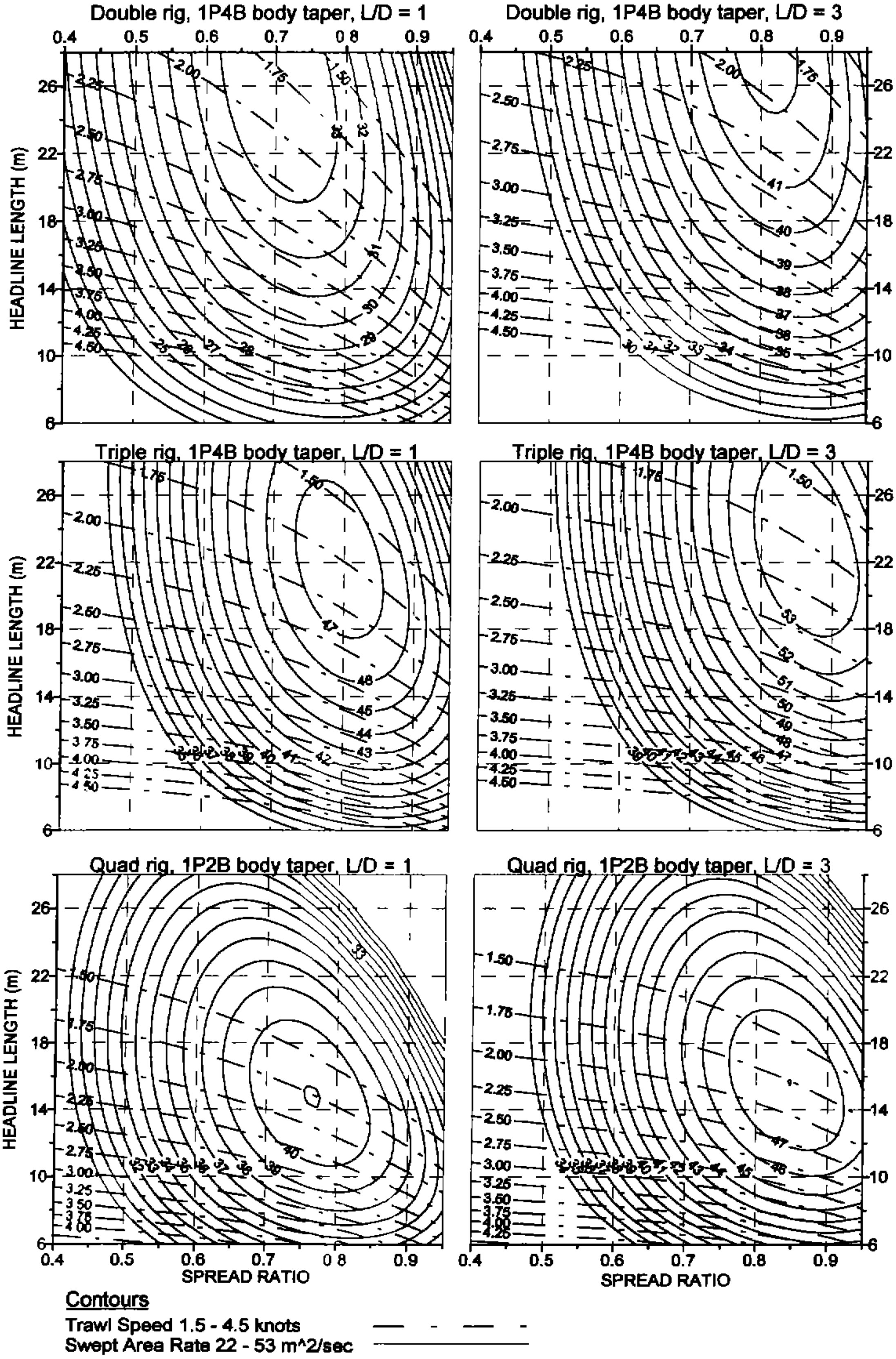


Figure 10. Prawn trawling performance maps from PTPM ver1 for double, triple and quad prawn trawling systems with boards having either low efficiency (L/D = 1) or high efficiency (L/D = 3) for a vessel of 2000kgf bollard pull (Sterling, 2000b).

In this way, the resulting performance map was used to identify the conditions for maximum performance, which included discerning the optimum spread ratio. The graphical approach to trawling gear optimisation shown in Figure 10 had the added benefit of presenting an "eagle eye" perspective of a general system's performance as a function of trawl size and spread ratio. However, production of performance maps is time consuming and calculation intensive. With the increased complexity of the PTPM ver2, as described above, came the necessity to use a numerical search engine to predict that status of the system. Since that calculation overhead had to be incorporated into the model it was cost effective to also use the same facility to search for solutions to any of the wide variety of research questions that can be investigated[1]. The PTPM ver2 has been implemented to use Microsoft Excel and the associated Solver add-in to carry out solution searches as required. It is a positive feature of this software that it is widely available, inexpensive and has extensive customer support, as this will facilitate usage of the PTPM.

2.2.2 The structure of the PTPM ver2

Prawn trawling is an active fishing method that utilises flexible gear. To trawl across the seabed and spread the gear two large and dominant forces need to be applied; namely vessel thrust and otter board spreading force. The prediction of the swept area rate of a prawn trawling operation requires that the magnitude and effect of these two forces be assessed (see Figure 11).

In both cases, steady state equilibrium can be assumed to occur if perturbations in these dominant forces are relatively small. That is, the force applied by the vessel to tow the gear (available thrust) is equal and opposite to the drag of the gear at the resulting trawl speed. And similarly, the spreading force produced by the otter boards is equal and opposite to the inpull force induced in the system at the resulting spread ratio. The characteristics of the vessel and the trawl gear must be used to predict the character of the four forces mentioned above. Iteration is then used to ascertain the resulting trawl speed and spread ratio, which are the only unknowns in predicting swept area rate.

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[1] Questions like; optimum otter board size and optimum net size.

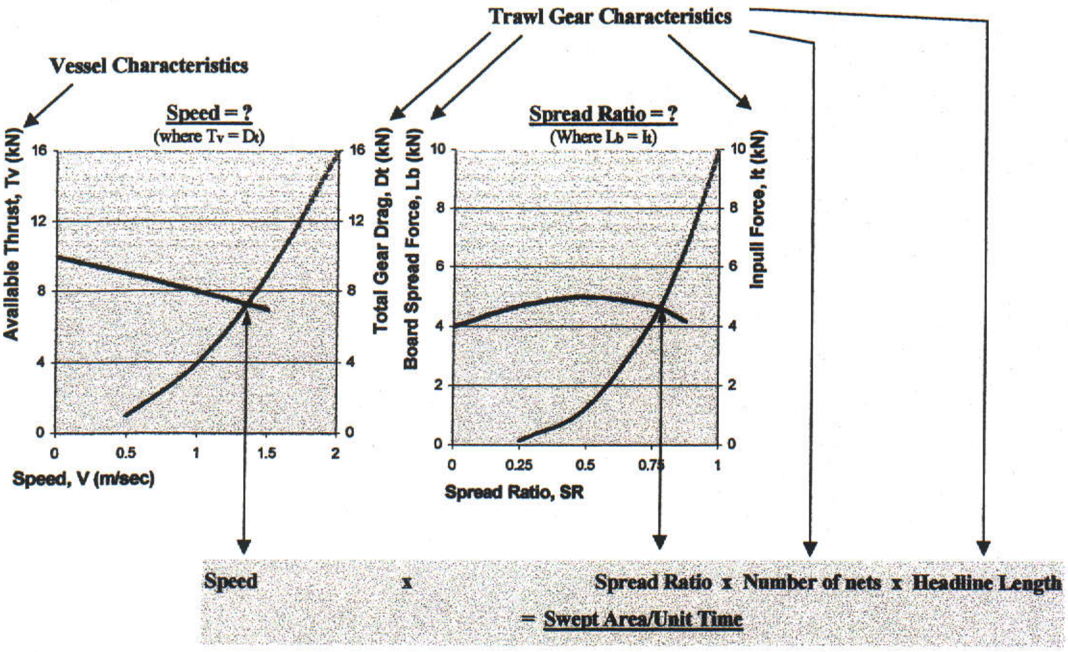

Figure 11. Broad outline of the PTPM ver2 showing the connection between system characteristics, analysis to determine operating parameters and the calculation of performance level.

The PTPM ver2 has six main sub-components as per Figure 12 (in bold). These give rise to the conversion of input data into the four force functions specified above and subsequent processing to predict trawl speed, spread ratio and finally swept area rate. Each sub-component is briefly described below.

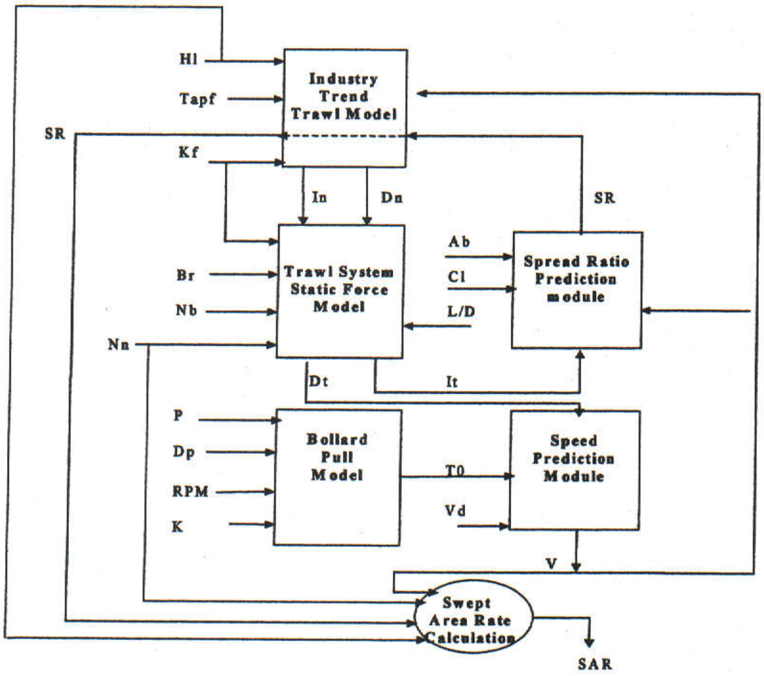

Figure 12. Block diagram of the PTPM ver2 showing six sub-components.

2.2.2.1 Industry trend trawl model

The drag of a trawl net (Dn) of a particular size (HL) and design (Tapf, ply, mesh) and at a particular spread ratio (SR) and trawl speed (V) is given by equation 1.

$$Dn = (39.66\,HL^{1.473})\,(0.306 + 2.83\,SR - 4.89\,SR^2 + 3.14\,SR^3)\,\left(Tapf\left(\frac{ply}{27}\right)^{0.5}\frac{50}{mesh}\,V^2 + Kf\right) \quad (1)$$

The effective wingend angle of a trawl net (Ω), which is the angle between the force vector representing the combined tension in the footline and headline at the wingend and the direction of tow, is given by equation 2.

$$\Omega = -58.55 + 274.55\,SR - 393.07\,SR^2 + 241.02\,SR^3 \quad (2)$$

The inpull force for the wingend of the trawl, In, is given by equation 3 in terms of the drag of the net and the effective wingend angle.

$$In = \frac{Dn}{2}\tan(\Omega) \quad (3)$$

Equations 1-3 are essentially the same as those used in Version 1 and described in Sterling (2000b) section 4.2.1 (equations 19-21). The first two equations are empirically derived expressions from tests conducted in the flume tank on two systematic series of model prawn trawls by Sterling, Bolton et al. (1992). A brief review of these tests is given in sections 2.2.2 and 2.4 of Sterling (2000b). In equation 1, Tapf is a factor that accounts for differences in trawl drag due to various body taper options as calculated in Sterling (2000b) section 2.4 (see Table 1).

Table 1. Trawl Drag Factor for Various Body Taper Options

BODY TAPER	DRAG FACTOR
1P5B	0.953
1P4B	1
1P3B	1.164
1P2B	1.296

Equation 1 contains an extension to Sterling (2000b) equation 19 that allows for variation in mesh size (mesh) and twine thickness (ply) about the deemed standard (50mm mesh, 27ply). Equation 1 also gives rise to the situation where the industry trend trawl model in Version 2 calculates actual trawl forces occurring at the estimated trawl speed and also includes an allowance for ground effect forces, where Kf (ground effect factor) is the ratio of ground effect forces to the hydrodynamic force at unit velocity as defined in Sterling (2000b) section 4.2.1 and is assumed to equally apply to the trawl as to the entire system.

Equation 2 is an update of Sterling (2000b) equation 20 based on the work of Edmondson (1994), which developed an error model for the measurement of inpull forces using the Trawl Evaluation Rig and the "swing arm" method (for schematic drawing see Sterling (2000b) Figure 10) and focussed on the 1P3B 8fathom Florida Flyer net shown in Sterling (2000b) Appendix C as a "standard" design.

2.2.2.2 Trawl system static force model

$$\mathrm{It} = \frac{\mathrm{In} + \frac{\mathrm{Dn}}{2}\,\mathrm{Tan}(\alpha_2)}{1 - \frac{\mathrm{Tan}(\alpha_2)\,(1 + \frac{\mathrm{Kf}}{\mathrm{V}^2})}{\frac{\mathrm{L}}{\mathrm{D}}}} \qquad (4)$$

$$\mathrm{Dt} = \sum_{n=1}^{\mathrm{Nn}} \mathrm{Dn}_n + \mathrm{Nb}\,\frac{\mathrm{It}}{\frac{\mathrm{L}}{\mathrm{D}}}(1 + \frac{\mathrm{Kf}}{\mathrm{V}^2}) \qquad (5)$$

The static force model allows the fundamental building blocks of prawn trawl systems (ie. nets and otter boards) to be assembled to form a variety of rigs and then calculates the system's inpull (It) on the otter boards and total drag (Dt). Equations 4 and 5 are similar in nature to equations 17 and 18 of section 4.2.1 of Sterling (2000b) and come from the same procedure. However unlike the equations of the PTPM ver1, which relate to hydrodynamic forces only, equations 4 and 5 contain ground effect terms (involving Kf) that account for the effect of ground contact forces on the otter boards.

In addition to these equations, Version 2 also contains expressions derived from applying the conditions of equilibrium at all points in the trawl system where nets are joined together (see Figure 13). At these points a towing wire (bridle) is also connected and may have an angle of divergence to the direction of tow depending on the balance of forces between the two nets and the geometry of the bridle system. Such an angle of divergence is calculated for all bridles in the system by ensuring that all conditions of force equilibrium are satisfied at all net junction points and also ensuring that the lateral span of the bridle system equates to the lateral span of the net system. Version 1 of the PTPM did not capture these details and inherently presumed that all trawls in the system were the same size and had the same spread ratio and also that all bridles in the system, other than those connected to the otter boards, had zero angle of divergence.

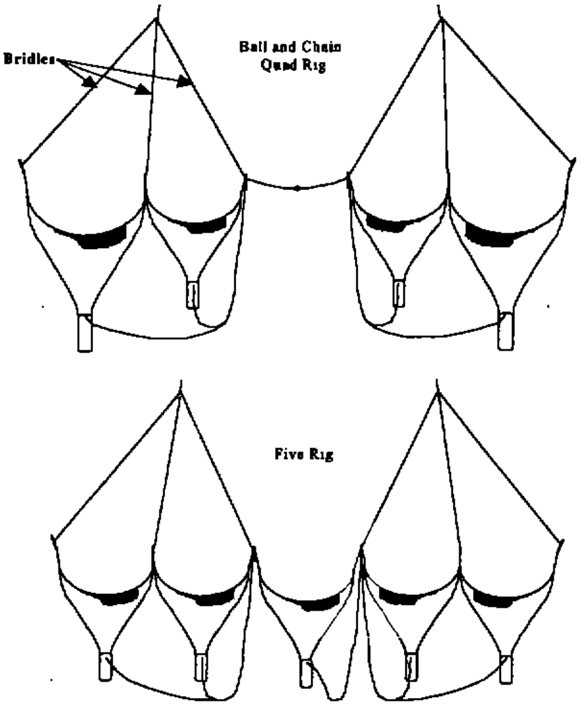

Figure 13. High order multiple net systems with more complex bridle arrangements.

2.2.2.3 *Bollard pull model*

Mathews (1966) provides a thrust formula (Equation 6) that uses quantified developed power (P) and propeller diameter (D_p) to derive bollard pull (T_0).

$$T_0 = E \times (P \times D_p)^{2/3} \times K \tag{6}$$

Where, E is an empirically determined constant that incorporates physical constants and effects that relate to the detailed shape of the propeller and the shape of the hull, and K is a factor that is applied depending on whether or not a Kort nozzle is fitted.

The factors captured by E are of lower significance in determining the thrust of any given trawler than the other variables explicitly included in the equation. The value of E ideally represents the average of these effects for typical trawlers. However there is a paucity of information available to ensure that this is the case and we have assumed a value of 75. This value calibrates the equation to give an estimate of the bollard pull of the trawler and was derived from data given in Moor (1963) for the bollard pull of three different propellers on a 30m tug over a range of developed power.

If a nozzle is fitted K has a value of 1.25 or 1.0 if no nozzle is fitted. This empirical correction is commonly quoted for the estimation of trawler or tug thrust, for example Sedat (1984).

$$P = \left[p \left(\frac{N_{\max\ \mathrm{trawling}}}{N_{\mathrm{rated}}} \right)^{\mathrm{ctflag}} \left(\frac{N_{\mathrm{op\ trawling}}}{N_{\max\ \mathrm{trawling}}} \right)^{2.8} \right]^{(1-\mathrm{cpflag})} \left[p \left(\frac{N_{\max\ \mathrm{trawling}}}{N_{\mathrm{rated}}} \right)^{\mathrm{ctflag}} 0.9 \right]^{\mathrm{cpflag}} \qquad (7)$$

Equation 7 is used in the bollard pull model to calculate the delivered power from a trawler given engine performance information (as rated power, p), details associated with its operation and assumptions about the physics of the propulsion system. The methodology represents a view that the rated output of the motor is not by itself a sufficiently accurate indication of the power applied to a given trawling operation for the purposes of predicting swept area performance. The methodology attempts to capture a range of the most significant factors that culminate in determining the power applied to the propulsion system during trawling. In addition to the installed engine power (continuous rating) consideration is given to how hard the motor is driven and how well the propeller is matched to the engine, that is, whether it loads the motor to its rated output or not.

The latter issue is determined by the ratio $N_{\max\ \mathrm{trawling}}/N_{\mathrm{rated}}$. For a well-matched propulsion system (from the point of view of maximising thrust) this ratio is close to 1. Typically the ratio is less than 1 for fixed pitch propellers so that there is some opportunity to operate the motor at higher rpm while the boat is steaming compared to trawling. This compensates for the reduced propeller load at a higher speed of advance. That factor in the equation is raised to a power of either 0 or 1 depending on the power characteristics of the engine:

ctflag = 0; engine exhibits constant power with rpm.

ctflag = 1; engine exhibits constant torque with rpm.

Figure 14 shows graphically the two different power characteristics. Traditionally, diesel engines had a constant torque character, which determined that maximum engine power output increased with rpm. However, for modern more sophisticated diesel engines the maximum power curve is quite flat over the operating rpm range of the engine. This makes the motor somewhat more flexible in propulsion applications because maximum power can be delivered at engine speeds less than the rated speed. This makes propeller matching less critical and allows full power to be produced for trawlers both while trawling and steaming, for a fixed pitch propeller.

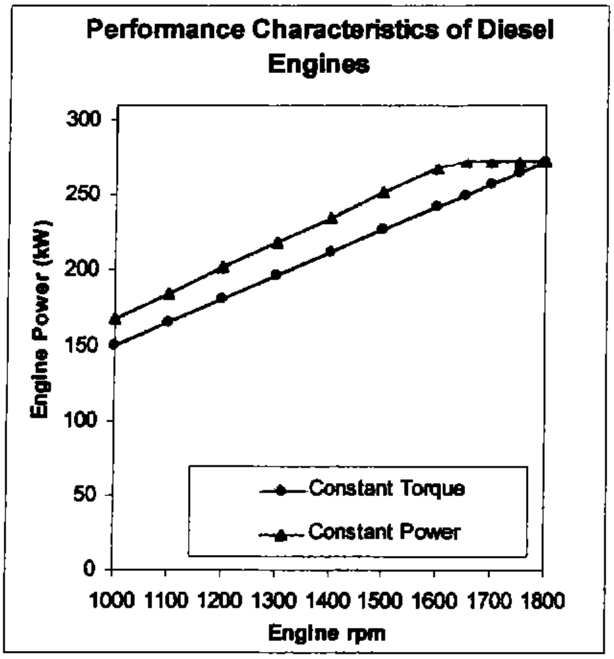

Figure 14. Performance characteristics of illustrative diesel engines (based on Caterpillar engine specification sheets).

The issue of "how hard is the motor driven" is indicated by the ratio Nop trawling/Nmax trawling. This ratio is raised to the power of 2.8, which reflects the sensitivity to which a fixed pitch propeller absorbs power with respect to speed of rotation[1]. For control pitch propellers it is assumed that the motor is loaded such that

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[1] Specification sheets for Caterpillar marine engines use an exponent of 3.0 for fixed pitch props, while Cummins interchangeably use either 2.7 or 3.0. The author suggests that an exponent of 3.0 is probably correct if the speed of advance is held constant while an exponent of less than 3.0 would be appropriate if the speed of the vessel is allowed to increase as more engine power is applied.

it produces 90% of the maximum torque possible for the operating RPM. This is applied in equation 7 using a control pitch flag (cpflag).

2.2.2.4 Speed prediction module

Unlike Version 1, Version 2 of the PTPM calculates actual forces acting in the system at the component level (including ground effects). Because of that it is not possible to find an expression for total system drag that is a simple function of trawl speed. In Version 1 such an expression was available and the trawling speed could be found by equating available thrust to total gear drag and finding the solution to a quadratic equation in speed. In Version 2, Excel Solver is used to find the value of speed that satisfies a constraint that available thrust must equal total gear drag. Similar to Version 1, equation 8 (Ming Yi and Endal 1983) is used to account for the effect of speed on available thrust (Tv), where Vd is the free running speed for the vessel.

$$Tv = To\,(1-\frac{V}{2Vd}) \qquad (8)$$

2.2.2.5 Spread ratio prediction module

The spreading force (Lb) produced by the otter boards is assumed to be constant with respect to spread ratio and given by equation 9, where Cl is the lift coefficient, Ab is the plan area, ρ is the density of sea water and V is the trawling speed.

$$Lb = Cl\,Ab\,\frac{1}{2}\,\rho\,V^2 \qquad (9)$$

Excel Solver is used to find the value of spread ratio that satisfies the constraint that Lb must be equal to the inpull from the system (It) as calculated from equation 4.

For multiple net systems the spread ratios of nets that are not connected to otter boards are found by satisfying constraints that the bridle system, which initially is described by divergence angles as calculated from equations that express the equilibrium of forces at net junctions, must form a connected towing web (see section 2.2.2).

2.2.2.6 Swept area rate calculation

Once the trawl speed and spread ratios for all nets in the system are known the swept area rate (SAR) is calculated using equation 10.

$$SAR = V \sum_{n=1}^{Nn} (SR_n\ Hl_n) \qquad (10)$$

2.3 Improvements to the Prawn Trawling Performance Model

2.3.1 Reflected trawl tests

2.3.1.1 Introduction

The basis of the empirical relationships in the "industry trend trawl model" of PTPM ver2 (equations 1 and 2) is the data collected using the Australian Maritime College flume tank and the Trawl Evaluation Rig (TER) (see Figure 15). The associated methodology is reported in Sterling (2000b) sections 2.3.1 and 2.4. Due to flow irregularities in the flume tank, tests were conducted at that time in midwater utilising a bare trawl (no ground chain) attached to the TER. This has provided what appear to be realistic results, however there is some concern that the shape of the trawl may not be as it should, particularly at high spread ratio. This is because the footline is not held at a fixed location in this testing format. In practice the footline is located relative to the seabed by ballast weight (the ground chain) sliding on the sea floor. To overcome this, it was proposed for the tests reported here to test two trawls simultaneously, such that one is the mirror image of the other (see Figure 16). The two trawls were joined around the footlines so that in each case their footline could not draw towards the headline as hydrodynamic forces act on the net.

In this new test format the two trawls should maintain a shape more representative of full-scale trawls under operational conditions.

In addition to the above concerns, it is also likely that the presence of the seabed in close proximity to the underside of a real trawl might influence the pattern of flow surrounding and through the netting. The seabed boundary in practice could significantly restrict water from flowing through the bottom of the net and cause additional pressure for water to flow out the sides and top of the net. Because of the higher fluid velocities in these regions and the fact that drag is very nonlinear with respect to flow velocity, tests conducted in midwater may produce drag measurements that are too low. It was considered that positioning a second trawl essentially as a reflection of the test trawl about the imaginary seabed boundary should cause a flow regime through the test net identical to that which it would experience if it were on the seabed.

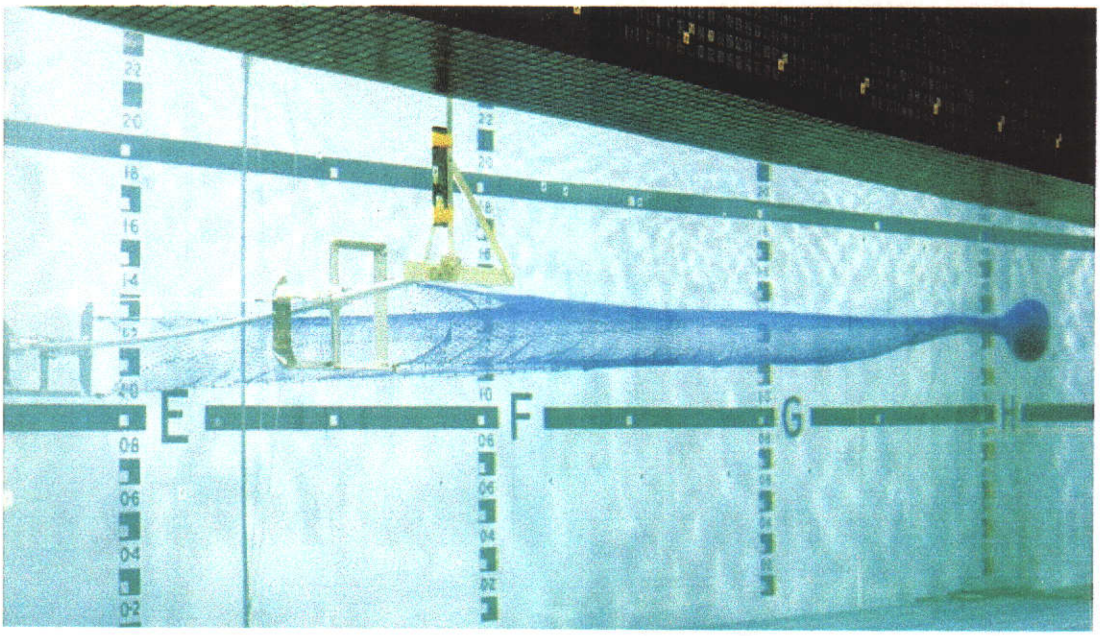

Figure 15. Trawl tested in flume tank using single trawl format as in Sterling (2000b) sections 2.3.1 and 2.4.

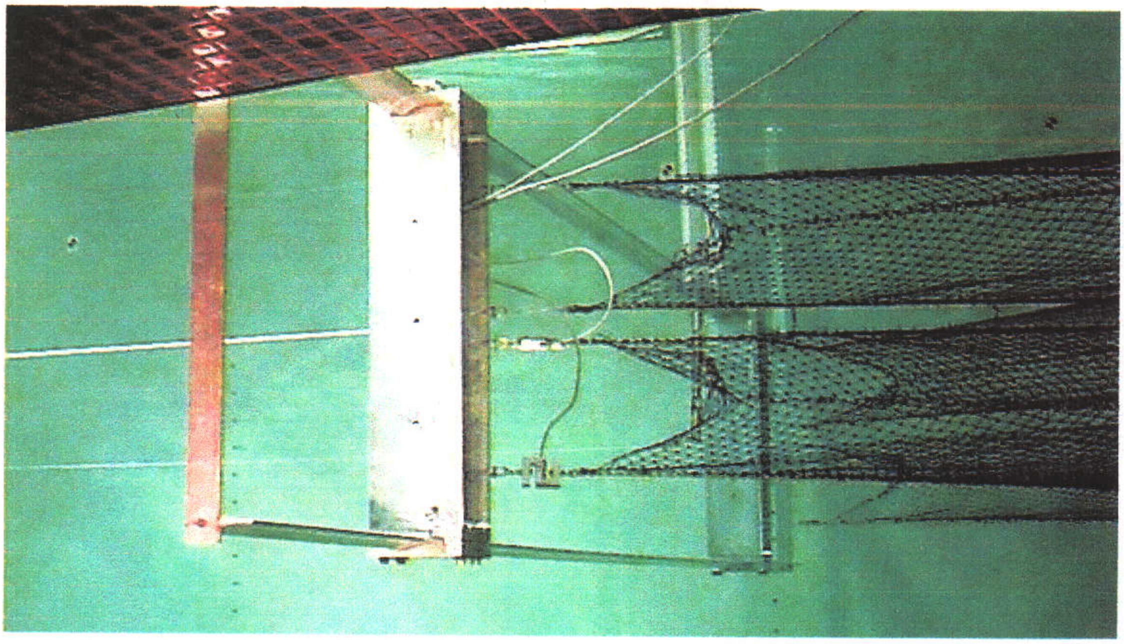

Figure 16. Trawl tested in flume tank using reflected trawl format.

The objective of the trawl tests reported here, which used the new test format, was not to directly assess whether the shape of the trawl or the flow regime through the netting was substantially changed by the change in test format, but rather to measure the trawl forces and adopt new empirical relationships in the PTPM if the resulting data was substantially different from earlier results.

2.3.1.2 Methodology

Equipment

Two 1/4scale 8fathom Florida Flyer trawls (net plan shown in Appendix A) were constructed for testing in the flume tank using the reflected trawl format. The model nets represent the full-scale Florida Flyer trawl shown in Sterling (2000b) Appendix C, which was the subject of much of the investigative work reviewed in Sterling (2000b) sections 2.3.1 and 2.4.

The TER was modified to carry two trawls while suspended in midwater.

Due to the increased availability of economical submersible load cells and improvements in making angular measurements in the flume tank the approach to taking trawl data from the TER has changed from that used by Sterling (2000b). Trawl loads were measured by positioning a load cell on each of the four trawl sweeps and the divergence angle of each sweep was measured using a sweep angle protractor. Drag and inpull data for the tested trawls were obtained by resolving the sweep tensions into the longitudinal and lateral directions with respect to the water flow.

Water speed was measured using an electromagnetic speed log.

All load cells were calibrated immediately before the commencement of testing by attaching a known mass to the device and adjusting the electronic output to produce the correct reading.

The speed log is calibrated from time to time by technical staff at the flume tank and is assumed to be in accurate working order.

Procedure

Model trawls were tested while fitted to the TER at various spread ratios (55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%) at a water speed of 0.775m/sec. For each spread ratio the four sweep tensions of one net and the sweep angles of the other net were measured.

The procedure was repeated for a single net only on the TER so that a direct comparison of results could be made.

Analysis

1. The results from the port and starboard sides of the trawls were averaged to remove the effect of the nets not being exactly square with the flow.
2. The average upper and lower frameline tensions were resolved into drag and inpull components.
3. Force measurements were transformed to an equivalent measure at a water speed of 1m/sec by multiplying by a velocity correction factor, $(1/0.775)^2$.
4. The following trends were investigated using Microsoft Excel:
    - Trawl drag versus spread ratio
    - Trawl inpull versus spread ratio
    - Effective wingend angle versus spread ratio

2.3.1.3 Results and discussion

The raw data from the tests is shown in Appendix A.

Trawl drag

Figure 17 shows the drag measures for the model trawls versus spread ratio. There is a rise in drag as spread ratio increases and the drag of the net for the reflected net format is higher than for the single net format. The average percentage increase in drag for the reflected trawl format is 9.5% (SE = 0.4%[1]). There does not appear to be any noteworthy change in drag difference with spread ratio (see % Dif. Trend in Figure 17).

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[1] SE (standard error) = standard deviation of the mean of the sample.

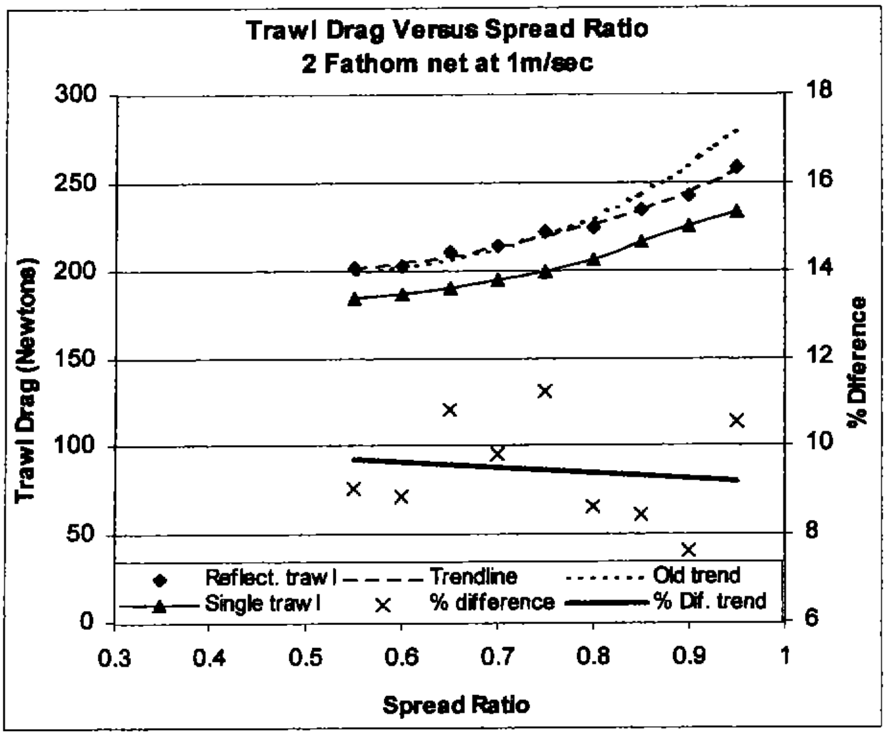

Figure 17. Comparison of trawl drag at different spread ratios for single trawl and reflected trawl test formats.

An exponential trend line with Y-axis intercept was fitted by regression to the reflected trawl format drag data. The resulting trend line is shown in Figure 17 and equation 11 gives the formula for the line, where the drag measure is normalised by the drag at 0.75 spread ratio.

$$\text{Net drag (rel. net drag @ SR} = 0.75) = 0.8453 + 0.0095 \exp^{3.72\ SR} \qquad (11)$$

An exponential model was selected for net drag versus spread ratio because it naturally holds a plausible trend beyond the data points to a greater extent than a high order polynomial. From experience it has been found that high order polynomials can give unstable Solver operation for the PTPM if they are unrealistic outside the range of the calibrating data but inside the range where solution searches are conducted.

Equation 11 has a significantly smaller drag range than the polynomial expression previously used and shown below (and also within equation 1). For comparison the trend associated with the polynomial expression is displayed in Figure 17 as "Old trend"[1].

Net drag (rel. net drag @ SR = 0.75) = $0.306 + 2.83\ SR - 4.89\ SR^2 + 3.14\ SR^3$ Old expression

The proportional rise in drag from SR = 0.55 to SR = 0.9 is 1.21 for the new expression and 1.30 for the old expression. The reason for this difference does not appear to be related to the different mechanics involved in the single trawl and reflected trawl test formats utilised on this occasion because the result for the single trawl format is similarly less sensitive to spread ratio. A possible explanation for this is that the old expression was derived from the data displayed in Sterling (2000b) section 2.4, which was obtained using the methodology described in Sterling (2000b) section 2.3.1. That methodology, although involving the streaming of a single net in the flume tank, is substantially different from the current approach. In the previous work the drag of the net was found by subtracting the assumed drag of the TER from the measured overall drag of the TER plus the net, rather than measure the tension in the connecting frame lines. The drag correction for the TER was measured independently by streaming it in isolation in the flume tank and while set to a spread equivalent to about 75%. It might be that the connection of the net during the testing session induced a slight change in the orientation of the TER, which could be different for each spread ratio, and caused the drag of the TER to be somewhat different from the constant value that was assumed. This would give rise to systematic errors in the drag measurements for the single trawl and might produce an apparent drag trend with respect to spread ratio, which departs from the true trend. It is assumed that the test arrangement that was utilised on this occasion is a more accurate approach to establishing the true drag trend and the new expression therefore more accurately depicts it.

Absolute drag values recorded during the latter tests do not compare well with those from Sterling (2000b) section 2.3.1 Table 4 (data not displayed in Figure 17). The single net results obtained here are about 23% higher than those reported in Sterling (2000b). It appears that the speed setting for the latest test might have been about 0.88m/sec rather than 0.775m/sec. The view that the magnitude of drag

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[1] The old trend is overlayed on the reflected trawl results to aid comparison.

measurements reported here is biased by speed measurement error is supported by drag measurements for the same net taken by Edmondson (1994) and subsequent reflected net format tests reported in the next section. The level of speed inaccuracy suggests that the speed log was not well calibrated for the data reported here. This result does not however make invalid the conclusions described above regarding drag comparisons between the single net and reflected net test formats because the subject of the question is relative drag. Additionally the derivation of a new empirical expression at equation 11 is not invalid because the dependent variable is normalised by the drag of the net at 75% spread ratio. This presumes though that although the speed log was not accurately calibrated the measurements taken in this instance were repeatable.

Effective wingend angle

The effective wingend angle, Ω, is the divergence angle of the resultant force vector applied by the wingend of the net to the direction of tow. This divergence angle can be calculated from the ratio of the inpull force to the share of the net drag applied at the wingend (usually half for each wing). Figure 18 shows the calculated effective wingend angles for both the reflected and single trawl test formats. Also included are two data points obtained from reflected trawl tests reported in the next section on otter board/trawl interaction. A trend line was fitted by regression to all the reflected trawl format data. A weighting factor of 5 was applied to the two otter board/trawl interaction points because each of those points is the average of seven separate sets of data pertaining to different speeds. An exponential model was selected for effective wingend angle versus spread ratio because it holds the trend beyond the data points much better than a high order polynomial and gives more stable Solver operation for the PTPM. The resulting expression is given by equation 12.

$$\text{Wingend angle } (\Omega) = 4.444 + 3.427 \exp^{2.963\ \mathrm{SR}} \qquad (12)$$

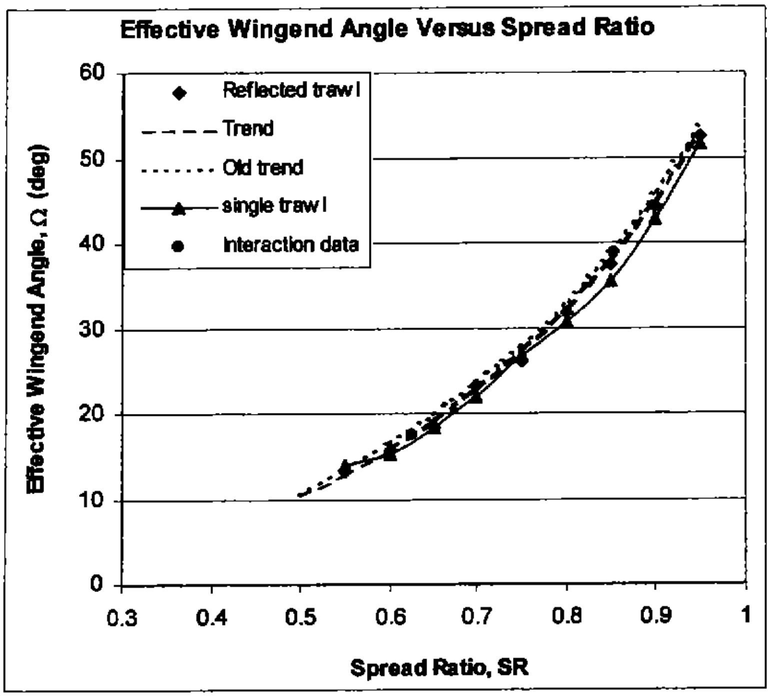

Figure 18. Effective wingend angle, Ω, versus spread ratio, SR, from reflected trawl format and single trawl format tests.

The effective wingend angles for the reflected trawl format are very similar to the single net format. At high spread ratio there is an indication that the single net might have slightly lower effective wingend angles. However, the trend model used in the PTPM ver2 (equation 2 – marked old trend in Figure 18) does not reflect this and has values slightly higher than the new trend model.

2.3.1.4 Conclusions

Based on the trawl drag results from single trawl and reflected trawl test formats it appears prudent to increase trawl drag predictions in the PTPM (equation 1) by 9.5% (average percentage increase in drag for the reflected trawl format) to correct experimental bias associated with previous flume tank testing of prawn trawls in mid water using a single trawl format.

A new model for the effect of spread ratio on trawl drag is implemented in PTPM ver3 to improve accuracy and stability.

A new model for the effect of spread ratio on effective wingend angle is used in PTPM ver3 to improve stability and slightly reduce effective wingend angle predictions.

2.3.2 Otter board/net interaction

2.3.2.1 Introduction

The PTPM generally predicts the engineering performance (swept area rate) of prawn trawl systems by calculating the effect of various input parameters on this performance indicator based on modelling the system's underlying physics and experimentally measuring key characteristics of the system's components. An inherent assumption in the model is that the characteristics and performance of the whole system can be established by summing contributions from its components with due regard to dynamic equilibrium. However, one concern about simple summation is that there might be significant interaction between components within the system. For example, the total drag of the system may not be adequately estimated by summing the drag of the individual components measured in isolation. A specific concern is that the hydrodynamic forces developed within each trawl net may be affected by the presence of the otter boards at the wingends since it is possible that the otter boards could shunt a significant amount of water through the net over and above that which would occur if the net was streamed in isolation.

If the otter boards cause a significant increase in the flow velocity of water through the trawl then higher forces would be induced within the trawl. Such increased forces would cause the drag of the trawl to be higher and the load applied to the otter boards, as they attempt to open the nets laterally, would also be increased.

A more sophisticated conceptualisation of the situation recognises that the circulation around the otter board that gives rise to the lift (spread) force will in general induce fluid flow at the wingend of the trawl which is normal to the direction of tow. This flow component would not necessarily cause the trawl to have increased drag but would cause the net to be harder to spread. Given that prawn trawling otter boards are generally classified as low aspect ratio lifting devices a very significant tip vortex is also a dominant part of the flow structure pertaining to their operation (see Figure 19). It appears feasible that such a strong tip vortex would apply fluid flow to the wingend of a similar nature to that applied by the lift circulation (bound vortex). By considering flow circulations it is reasonable to expect that most of the effect of interaction between the otter boards and the nets within trawl systems might be manifest in the net being harder to spread rather than having more drag.

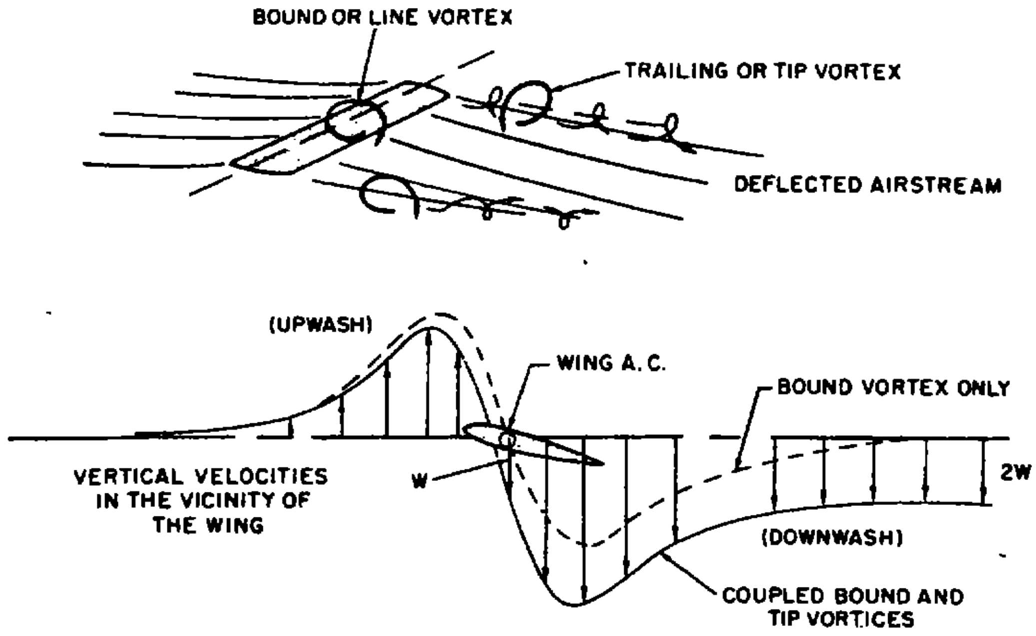

Figure 19. Wing vortex system and induced flow. (Hurt 1960)

2.3.2.2 Methods

The experimental design developed to investigate otter board/trawl interaction in prawn trawl systems was based on measuring the connection tensions for a standard prawn trawl while otter boards were connected to the wingends and while the net was streamed in isolation. Two otter board sizes where tested so that the sensitivity of any measured effect to the size of the otter boards could be determined.

The details of the tested trawl gear was as follows:

- ¼ scale 14.6m (8fathom) Florida Flyer (net plan shown in Appendix A)
- Small otter boards – ¼ scale 1.6m X 1m (5'3" X 3'4") Flat rectangular
- Large otter boards – ¼ scale 3.2m X 1m (10'6" X 3'4") Flat rectangular

Figure 20 shows a picture of the experiment under way while the small boards were used. Tests were conducted in mid water so that uniform flow impinged on the gear. The trawl gear tested consisted of a simple single trawl system connected to a "mirror image". The mirror image system ensures that the shape of the trawl and the water flow through it more accurately reflect the real situation where the trawl system is towed across the sea floor (see section 2.3.1).

Load cells with a rating of 400N were used to measure the tension in the headline

(Hl) and the footline (Fl) at the connection to the otter board (see Figure 21 and Figure 23). From overhead the angles that the connection wires (sweeps) made to the fore/aft direction (see Figure 22) were measured using a vertically oriented telescope mounted at the pivot point of a protractor. Frameline tensions and angles were measured on both sides of the test gear and averaged so that any "out of square" effects were corrected.

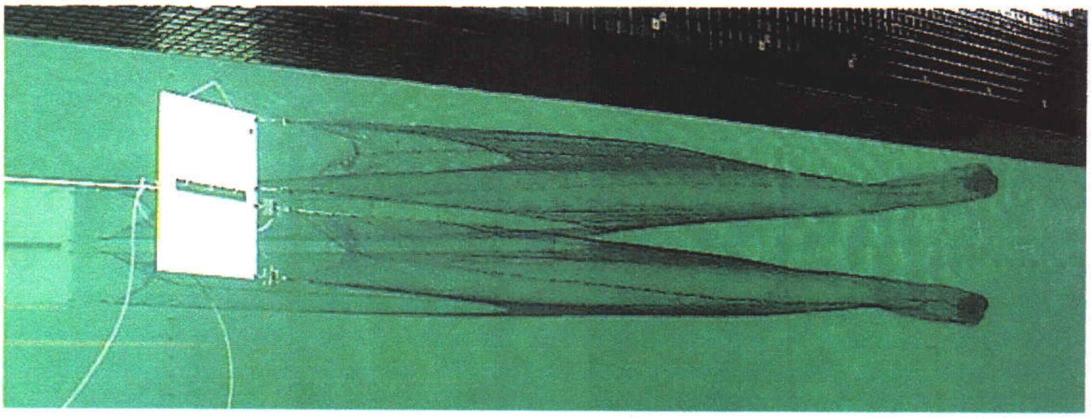

Figure 20. Trawl apparatus tested in the flume tank to allow trawl connection tensions to be measured over a range of flow speeds.

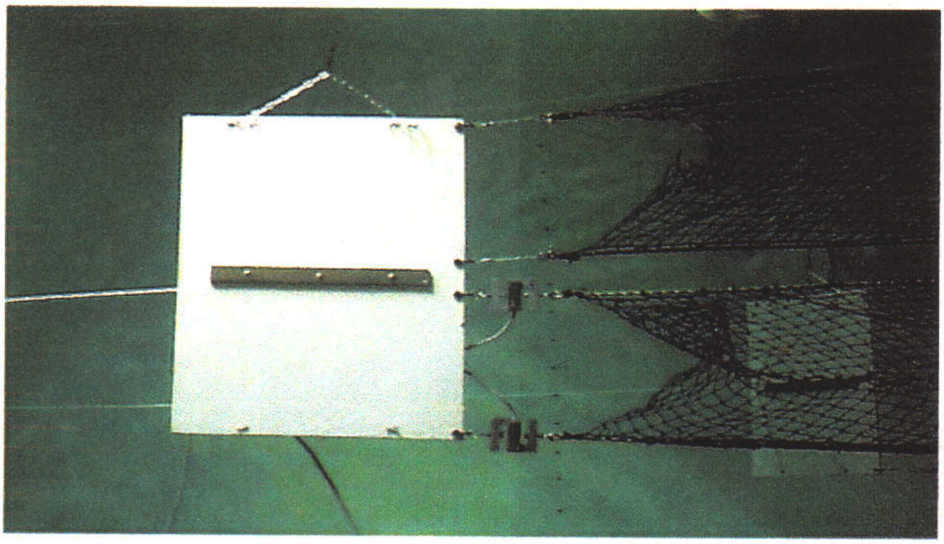

Figure 21. Close up view of small otter board and load cells used to measure trawl connection tensions.

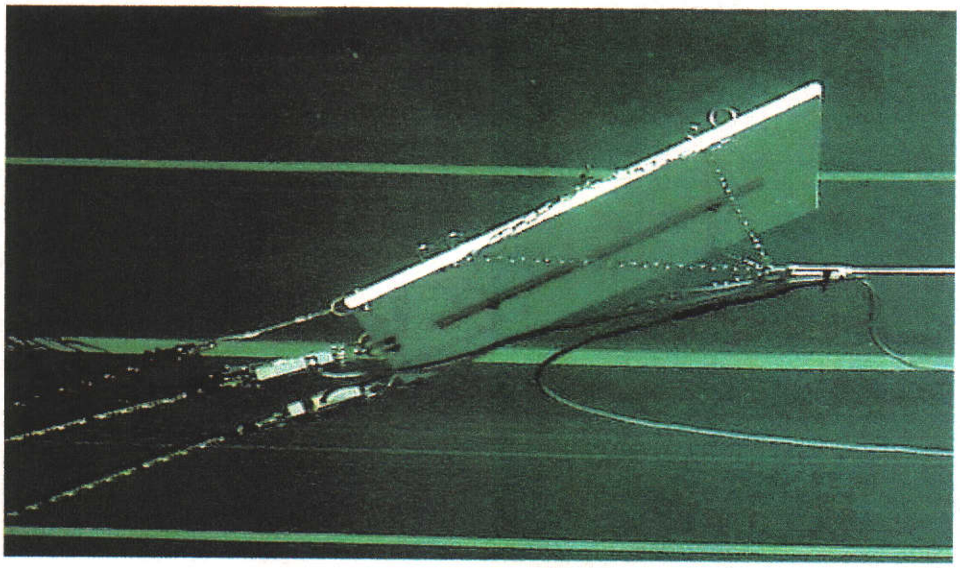

Figure 22. Overhead view of small otter board and tension measuring load cells.

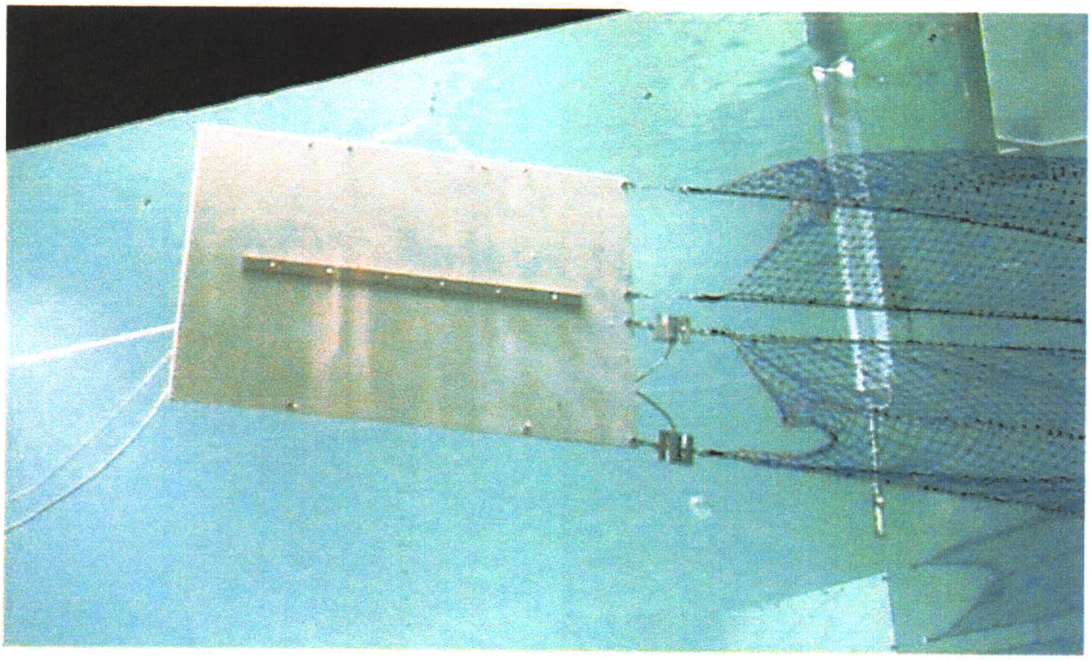

Figure 23. Large otter boards connected to the "mirror" trawl system.

Measurements of tension and sweep angle were taken for each of the four experimental cases over 7 water speed settings. For each speed setting the water speed was measured by taking repeated readings from an electromagnetic log and taking the average. The speed log was positioned in the tank at a fixed location for all tests, which was on the centre line of the trawl and 2.5m forward of the otter boards so that the measured velocity was that of the free stream flow.

For the two cases where the otter boards were used the lateral span of the net was measured. When the nets were connected to the Trawl Evaluation Rig (TER) (see Figure 24) the TER was set to spans which corresponded to that achieved with the otter boards.

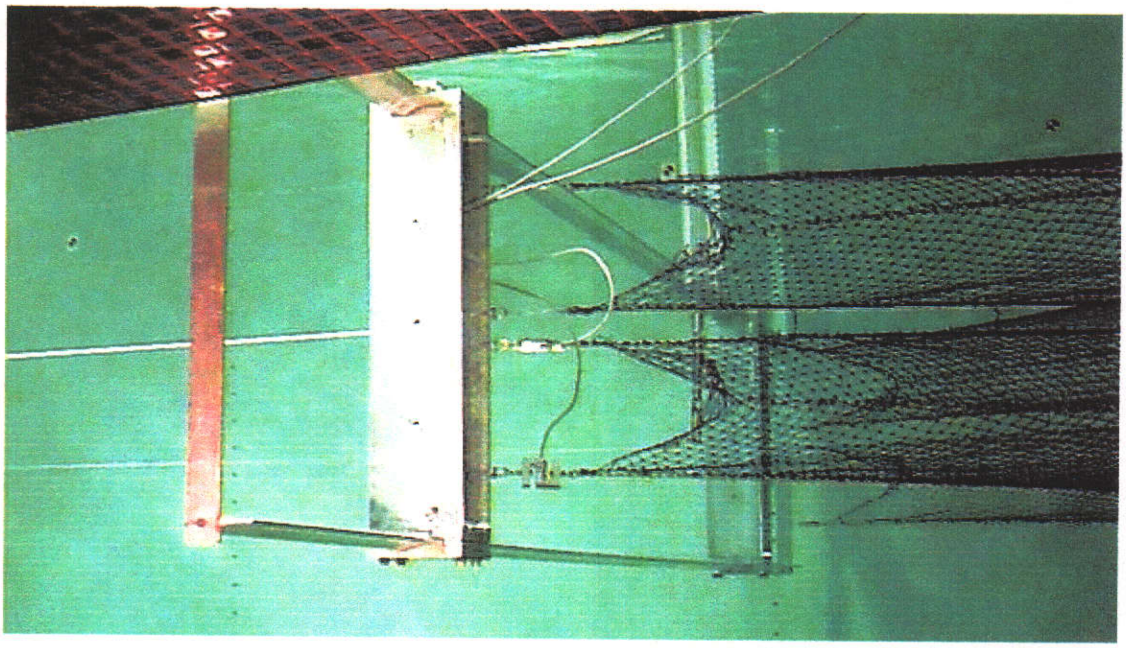

Figure 24. The "mirror" trawl system connected to the Trawl Evaluation Rig (TER).

Statistical analysis, as described below, was used to standardise all force measurements for the effect of flow speed and determine the measured effect due to the presence of otter boards. Flow speed standardisation was achieved by assuming that all measured forces were sensitive to the square of flow speed. For each test case a linear regression between force and the square of flow speed (with intercept = 0) gave a hydrodynamic force parameter, Cf', for each case, which had the units of Newtons at 1m/sec as per the equation below.

Hydrodynamic force = $Cf' \, V^2$

Testing each case over a range of flume tank settings and then standardising the force results for flow speed allowed the process to simultaneously standardise the test conditions (in terms of flow speed) across all cases and provide for each case, results that were in effect the average of 7 replicates (from 7 flume tank settings). Having results for each test case over a range of flow speed also allowed a check on the hypothesis that the results were independent of speed. The indicator used to test that the process under investigation was insensitive to speed was the steadiness of the sweep angle measurements across the speed range.

Drag and inpull at the wingend of the trawl were resolved for each test point by considering the headline and footline tensions and the sweep angle measurements (average of port and starboard in all instances) for each speed. These calculated hydrodynamic force components were then standardised for flow speed to give hydrodynamic force parameters for each of the variables in each of the four test cases.

2.3.2.3 Results

Appendix B shows the raw data collected for all test conditions.

Table 2 shows the result of statistically standardising the hydrodynamic force measurements and the resolved drag and inpull components for flow speed. The spread ratios achieved were 0.626 and 0.853 for the low and high spread cases respectively.

Table 2. Hydrodynamic force parameter results.

	Low SR (0.626)	**High SR (0.853)**
Headline tension parameters (N@1m/sec)		
Nets only	40.98 (SE = 0.38 $R^2 = 0.997$)	71.40 (SE = 0.54 $R^2 = 0.998$)
Boards fitted	43.19 (SE = 0.31 $R^2 = 0.998$)	81.05 (SE = 0.45 $R^2 = 0.999$)
Footline tension parameters (N@1m/sec)		
Nets only	43.59 (SE = 0.50 $R^2 = 0.994$)	44.77 (SE = 0.69 $R^2 = 0.989$)
Boards fitted	45.89 (SE = 0.44 $R^2 = 0.996$)	48.46 (SE = 0.75 $R^2 = 0.989$)
Drag parameters (N@1m/sec)		
Nets only	80.60 (SE = 0.87 $R^2 = 0.995$)	89.62 (SE = 0.87 $R^2 = 0.996$)
Boards fitted	84.21 (SE = 0.73 $R^2 = 0.997$)	97.38 (SE = 0.72 $R^2 = 0.998$)
Inpull parameters (N@1m/sec)		
Nets only	25.38 (SE = 0.15 $R^2 = 0.999$)	72.49 (SE = 0.83 $R^2 = 0.994$)
Boards fitted	28.92 (SE = 0.15 $R^2 = 0.999$)	83.89 (SE = 1.10 $R^2 = 0.993$)

2.3.2.4 Discussion

The general picture of the experimental results can be established from Table 2. Figure 25 shows a vector presentation of these results. The trawl inpull measured for the high spread ratio cases was nearly 3 times that for the low spread ratio cases. This is somewhat surprising because the large otter board has only twice the area and was at an angle of attack of 42 degrees compared to 30 degrees for the small board. It appears that the shear coefficient for the large board was approximately 50% higher compared to the small board (0.823 versus 0.570). It could be that the lower aerodynamic aspect ratio for the large board (0.625 versus 1.25) could be the explanation for this effect; in conjunction with the fact that in both cases the angle of attack occurring is in the region of stall, which for these circumstances could lead to severe reductions in shear force. It could also be that the close proximity of the wall and window to the large otter boards might also have some involvement in determining the exact character of the characteristically unstable flow pattern around the board. If blockage effects are involved in the result it is not known whether or not they will cause the results to be unrealistic. It could be that although the walls of the tank may have caused phenomenon that would not be seen in the field the results measured in the tank might still be representative of the interaction situation for a spread ratio of 85.3%. It might be that in practice a larger otter board is required to achieve this operating condition than observed here. Similarly, if the low shear coefficient for the small boards is due to the aspect ratio being a little greater than typically used then the interaction effect might still be similar in practice for a spread ratio of 62.6%, it may be that in practice a smaller board would achieve this spread condition.

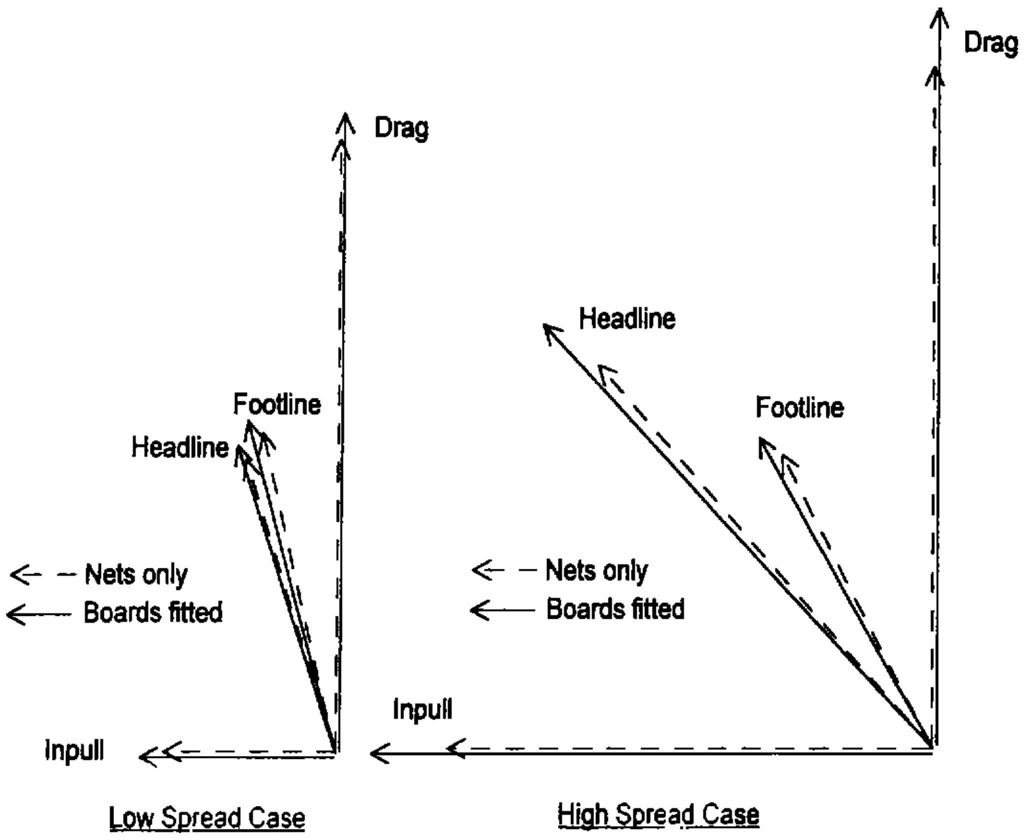

Figure 25. Vector presentation of hydrodynamic force parameters in Table 2.

Table 3 shows the ratio of forces with the boards present compared to when the boards were not present. Load cell tensions were between 5.3% and 13.5% higher when the otter boards were present compared to when they were not (net attached to the TER). When these tensions were resolved into drag and inpull components a similar range of increases were found.

In both cases the inpull parameters seemed to increase by more than the drag. This is consistent with the hypothesis outlined in the introduction (section 3.2.1) that the circulation around the board would tend to increase the inpull of the net rather than the drag.

For the high spread ratio case the headline tension also increased to a greater extent than the footline tension, thus demonstrating that at high spread ratio the forces in the net are biased to the headline and similarly so too are the effects of the otter board/trawl interaction

Table 3. Ratio of hydrodynamic force parameters from Table 2, boards present compared to boards not present.

	Low SR (0. 626)	**High SR (0. 853)**
Headline tension		
Force parameter ratio	1.054 (SE = 0.012)	1.135 (SE = 0.011)
Footline tension		
Force parameter ratio	1.053 (SE = 0.016)	1.083 (SE = 0.024)
Drag		
Force parameter ratio	1.045 (SE = 0.015)	1.087 (SE = 0.013)
Inpull		
Force parameter ratio	1.139 (SE = 0.009)	1.157 (SE = 0.020)

Flowing from the above result where the inpull of the net has increased to a larger extent than the drag, the effective wingend angle of the trawl must increase. This effect is exhibited clearly in the data as depicted in Figure 25 whereby all tension vectors point further away from the direction of flow when the otter boards were present. Therefore the shape of the trawl has been significantly changed by the presence of the otter boards. This is a reasonable proposition since the strength of the interaction effect is likely to be high close to the otter board, that is, at the wingend. The character of the results suggests that the local downwash off the boards has blown the wingends towards the centre line of the trawl as indicated in Figure 26 (see also Figure 19). This effect appears to be more pronounced on the footline than the headline, which could be due to the fact that the footline is at a lower angle to the fore/aft direction.

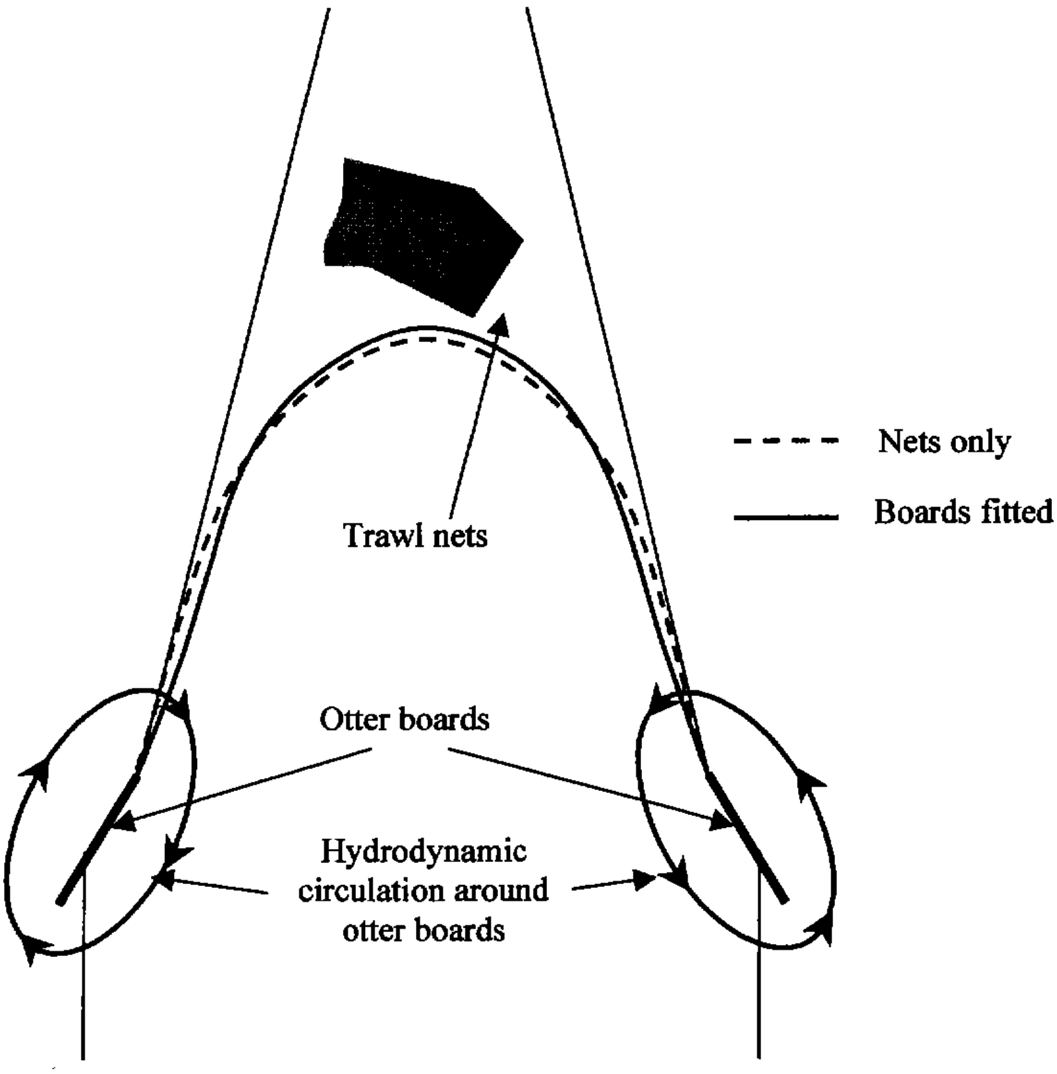

Figure 26. Depiction of trawl distortion due to hydrodynamic interaction with otter boards.

The effective wingend angle can be calculated for each of the four cases from the ratio of inpull and drag parameters. The increase in effective wingend angle occurring because of the presence of otter boards is shown in Table 4. For both spread ratios the size of the trawl distortion is significantly greater than zero and is approximately 1.5°.

Table 4. Effective wingend angle measurements.

	Low SR (0.626)	High SR (0.853)
Dynamic wingend angle (degrees)		
Nets only	17.48 (SE = 0.21)	38.97 (SE = 0.54)
Boards fitted	18.96 (SE = 0.19)	40.74 (SE = 0.56)
Increase	1.48 (SE = 0.28)	1.78 (SE = 0.78)

The interaction effects of interest to the development of the PTPM, namely the extent of drag increase and the degree of wingend angle distortion are shown in Figure 27. These effects have been plotted against spread ratio and power curve relationships have been fitted to the two data points in each case. A power curve has been selected in this case because one presumes that the trend lines will pass through the origin because when the spread ratio is zero the interaction must be zero and the author anticipates that the relationship is smooth. Although the measured interaction effects are significantly different from zero the experiment does not have sufficient resolution to statistically demonstrate that the observed interaction at high spread ratio is larger than the observed interaction at low spread ratio. Nevertheless a mechanistic appreciation of the situation strongly suggests that this should be the case. This coupled with the assertion that the origin is almost certainly another valid data point and that the two measured points lie at each side of the normal operational spread ratio range of prawn trawl systems makes the derived power relationships of functional value to the PTPM and is clearly an advance on applying no correction at all.

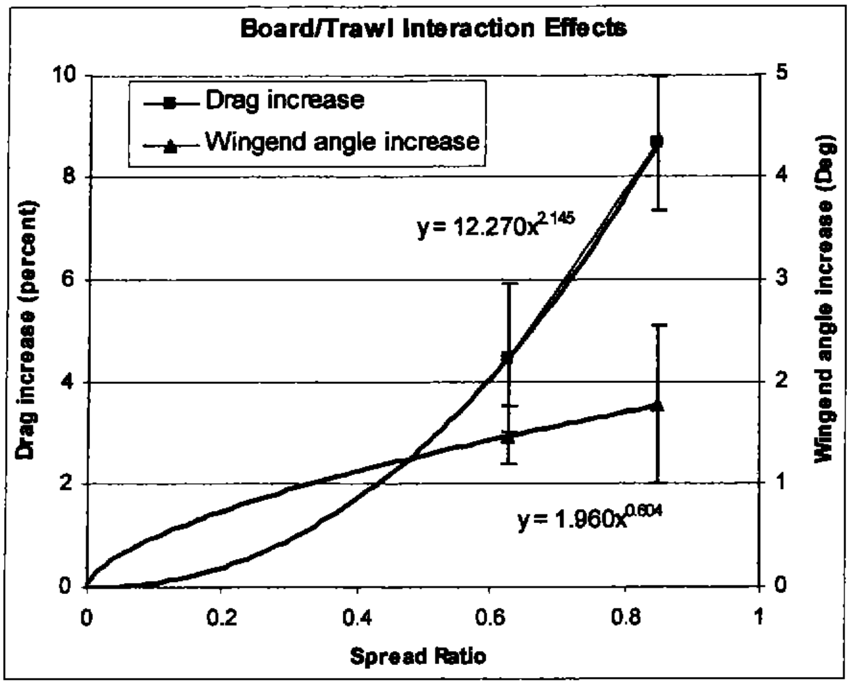

Figure 27. Interaction effects plotted against spread ratio.

2.3.2.5 Conclusions and recommendations

The results show conclusively that there is some interaction between the otter boards and nets within prawn trawl systems.

The data set was used to derive relationships between spread ratio as produced by the application of otter boards to a prawn trawl net and two second order engineering effects induced within the trawl: the change in hydrodynamic drag of the trawl and the change in shape as indicated by effective wingend angle. These relationships are incorporated in PTPM ver3 so that it may take interaction effects into account when predicting trawling performance and will have a particular bearing on the estimation of system span.

To improve confidence in such relationships between spread ratio and the two interaction corrections it would be valuable to obtain more data points. One further data point could be achieved by cutting down the large board to an intermediate size (ie 600mm long) and testing the system for this condition. It is recommended that this be done in further work on this issue.

2.3.3 Thrust calculation

2.3.3.1 Introduction

The relationship between tow force and trawl speed used by the PTPM ver2 is a simple linear one (see equation 8) given by Ming-Yi and Endal (1983). Ming Yi and Endal obtained the expression empirically, based on data from 16 trawlers and claim that in general the equation gives less than 5% error. The expression is very similar to the older and less validated approach published by Prado (1990), which estimates tow force by interrelation between an estimated bollard pull at zero speed and zero force at the free running speed. The only difference between this approach and the expression recommended by Ming Yi and Endal is that the rate of tow force reduction with speed for the latter is one half that of the former. It is claimed that this results in more accurate tow force predictions at typical trawl speeds, however intuitively the formula must over predict tow force as the tow speed approaches the free running speed. It is quite apparent that the Ming Yi and Endayl formula represents the application of a linear approximation to an inherently non-linear system however the degree of variation between different trawlers in terms of their thrust characteristics and the fact that trawl speeds are consistently less than half the free running speed, might make this inconsequential.

The purpose of this section is to report on work to investigate the relationship between tow force and trawl speed with the view to improving the prediction model used in the PTPM. It is felt that a non-linear model might be more appropriate if the necessary data is available to support it.

The problem of establishing a prediction for tow force as a function of tow speed is made difficult on a number of fronts. Firstly the propeller itself is a complicated device to model because the thrust force it produces is a complex function of many variables including size, shape, pitch, speed of propeller revolution and speed of vessel advance. Secondly the tow force that is available to tow the trawl gear is the difference between the thrust developed by the propeller and the resistance of the vessel. Therefore the resistance of the vessel also needs to be known and that itself is the manifestation of a number of complex mechanisms involving skin friction, form drag and wave making resistance.

Lastly there is also the need to be clear about how the engine is to be constrained over the range of vessel speeds considered. Literature on the subject of tow force versus speed covers three different scenarios.

1. Propeller RPM held constant (Caldwell, 1946) (Parker and Dawson, 1962) (Moor, 1963).
2. Shaft torque held constant (Caldwell, 1946) (Moor, 1963).
3. Developed power held constant (Moor, 1963).

Each scenario is an independent option whereby for each variable that is held constant the other two must vary with tow speed for a given propeller and vessel.

In the PTPM, engine speed (hence shaft speed) is specified for the trawling condition and this allows the developed power to be estimated if rated power, rated rpm and maximum possible rpm while trawling are also known (see equation 7). From this the bollard pull of the vessel is estimated for the same developed power from equation 6. With the PTPM structured in this way it becomes necessary to adopt scenario 3 with respect to deriving a useful relationship between tow force and speed since the tow force at zero speed (bollard pull) is linked to the trawling condition by having the same developed power. Once the relationship is established then the trawling speed can be estimated by finding the point where the tow force produced for that given developed power matches the towing resistance of the trawl gear.

How the motor was constrained over the range of speeds for the boats analysed during the derivation of the linear model by Ming Yi and Endal was not specified in their report. It could well be that the motor was run at constant rpm. One problem with such a constraint scenario is that the delivered hp (and fuel consumption[1]) goes down as speed increases. Therefore when the PTPM is used to compare one trawl system against another (for a given vessel input) the comparison may not be entirely fair if the resulting trawl speeds for the two systems are substantially different. As discussed above this scenario would also not be consistent with the basic structure of

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[1] From manufacturers specifications of diesel engines it is apparent that the specific fuel consumption of engines is relatively constant (+- 2.5%) over normal operating ranges.

the PTPM in that it needs to be able to predict the change in tow force with speed while holding the delivered power constant to be able to predict trawl speed accurately for any specific trawl system.

One further complication is the matter of whether or not a Kort nozzle is fitted. Equation 6 makes allowance for the use of a Kort nozzle by adding 25% to the calculated bollard pull (based on (Sedat, 1984)). However it is well known that the thrust advantage of the Kort nozzle is particularly apparent at low tow speed and diminishes towards zero (and often becomes a disadvantage) at free running speed. Therefore one could expect that for a vessel fitted with a Kort nozzle the tow force will decrease more quickly, albeit from a higher initial value, with tow speed than for an open water propeller.

2.3.3.2 Methods

Moor (1963) makes available analytically derived relationships (based on model tests) between tow force and tow speed for three different open water propellers fitted to a 30m tug over a range of developed engine powers. One of the propellers was a standard Troost B.4 series propeller and the resulting relationships for this propeller are plotted in Figure 28. Also shown on the graph is the linear relationship of Ming Yi and Endal. It crosses Moor's tow force predictions at about half the maximum tow speed and for typical trawl speeds (abscissa = 0.3) seems to under predict tow force.

Based on this data it would appear that a more accurate expression could be obtained by fitting a quadratic curve to the part of the thrust data of relevance to the PTPM. Given that the propulsion systems of trawlers are usually designed to continuously use close to the rated power of the engine, the propellers involved are quite heavily loaded and the delivered power involved would drive the hull to quite a high free running speed (making allowance for vessel length) it seem appropriate to focus on the higher engine powers depicted in Figure 28 for deriving a non-linear relationship.

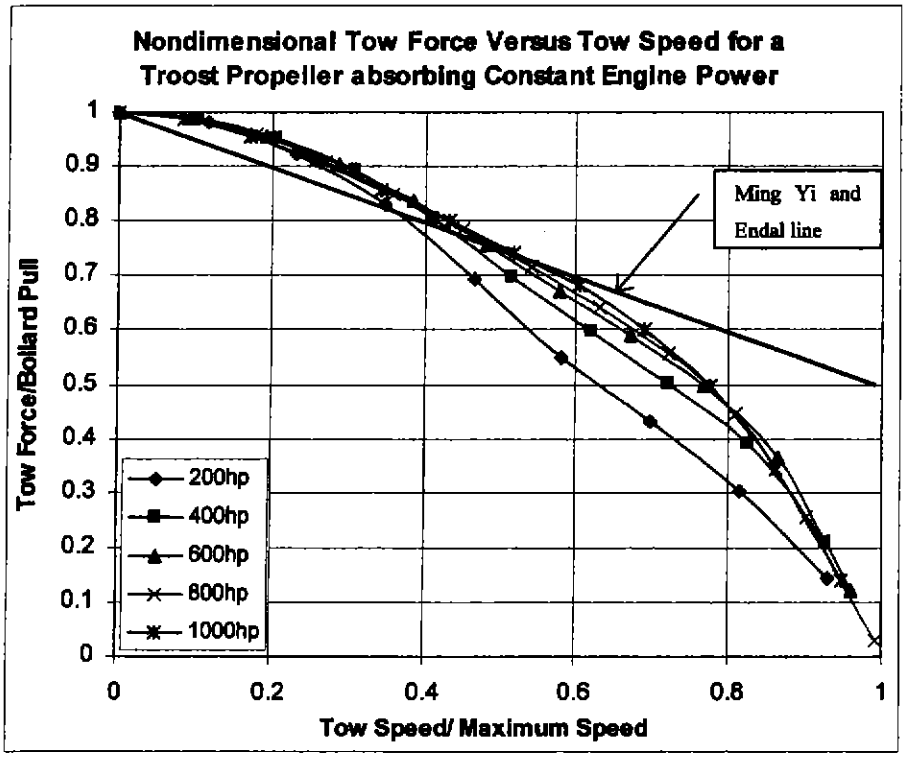


Figure 28. Tow force versus tow speed (Moor, 1963).

2.3.3.3 Results and discussion

Figure 29 shows the resulting quadratic curve fitted to the 1000hp tow force curve. Only data points for speed ratios less than 0.5 were used so that the resulting equation was forced to fit the data over the range of interest for the PTPM. The resulting expression is given in equation 13.

$$Tv/To = 1 - 0.1731\ V/Vd - 0.667\ (V/Vd)^2 \qquad (13)$$

No satisfactory solution has yet been found for the question of the effect of the Kort nozzle on the tow force/speed relationship. It might well be that it is best to retain the linear Ming Yi and Endal model for vessels fitted with a Kort nozzle because it does insist that tow force drops more rapidly from the bollard pull situation with speed than the non-linear model (see Figure 29). Given the relatively coarse nature of the estimation equations used in this part of the PTPM, errors associated with this issue are probably of the same order of magnitude as the background noise. The author believes the issue is worth noting but not worth pursuing further at this point because no additional information is available. All validation data collected so far involves vessels with open propellers so this does not give the opportunity to consider the capacity of the PTPM to deal accurately with the Kort nozzle. However given that the model proves to be valid for the open propeller case a future opportunity to compare tow force predictions with engineering data for a trawler fitted with a nozzle would be valuable for specifically testing the Kort nozzle features of the PTPM.

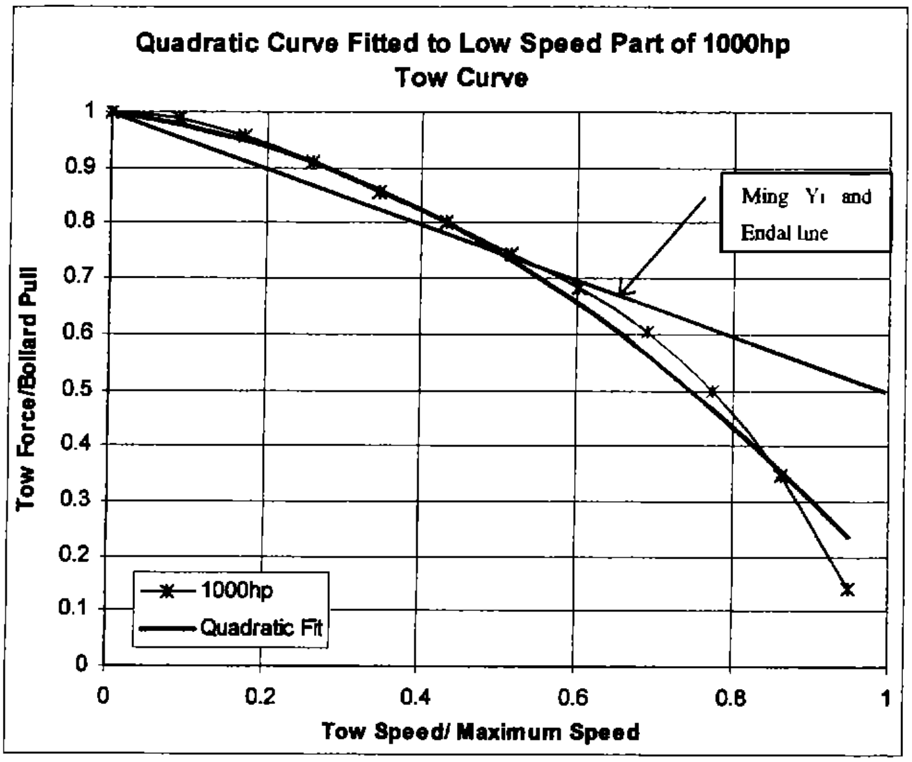


Figure 29. Quadratic relationship between two force and tow speed.

2.3.3.4 Conclusions

A new non-linear expression for the relationship between tow force and tow speed for a trawler has been derived. This is included in PTPM ver3 to improve its description of this phenomenon for open propellers. The same model is to be used for vessels fitted with a Kort nozzle subject to further information becoming available on that issue.

2.3.4 Otter board angle feedback

2.3.4.1 Introduction

In Sterling (2000b) section 2.3.3 it was established from flume tank testing that towing spider settings and also the spread ratio of the net to which the otter board is attached influence the angle of attack of an otter board. That is, as larger otter boards are used for a given net the angle of attack of the otter board increases even though the settings for the different sized boards are the same. In that section a simple single rotational degree of freedom (SRDOF) model for prediction of angle of attack was described and used to show that this empirical result made sense from the point of view of considering the steady state equilibrium of the respective force and moment systems associated with the operation of the otter board. This insight raises a significant concern regarding the accuracy of version 2 of the PTPM. In this form the PTPM does not attempt to estimate the orientation of the otter board but rather assumes that it produces forces consistent with a specific angle of attack (usually that which produces maximum spread) and it presumes that this situation is fixed irrespective of the predicted spread ratio for the system. This situation is partly justified because Sterling (2000b) section 2.3.3 indicates that the angle of attack of the otter board is relatively insensitive to its angle settings, however given that the attack angle is shown to be sensitive to spread ratio it would seem prudent to incorporate into the PTPM a feedback loop that tracks the effect of spread ratio on angle of attack and flowing from that, appropriately adjusts the forces produced by the otter board.

In Sterling (2000b) chapter 5 a three rotational degree of freedom (3RDOF) model for orientation prediction is reported. If that model was incorporated into the PTPM a fine detailed insight into the modelled systems would be available. However the 3RDOF model was developed and implemented in Basic rather than Excel and would require disproportionate effort to incorporate into the PTPM for the benefit of addressing the current issue, which essentially relates to only one rotational degree of freedom (angle of attack). Nevertheless the SRDOF model of Sterling (2000b) does not specifically deal with ground effect forces whereas the 3RDOF model does to some extent. Therefore there is a need to upgrade the SRDOF model in respect to ground effect forces before incorporating it into the PTPM.

There are also a number of other simplifying assumptions contained in the SRDOF model of Sterling (2000b) Appendix B that can be overcome by the more rigorous approaches adopted by the 3RDOF model. The improvements to the SRDOF model and its incorporation into PTPM ver3 are outlined below.

2.3.4.2 *Methodology*

Figure 30 shows conceptually how the attack angle predicting capability of the PTPM was achieved in context with new components added to the model and how they interface with existing components and process variables.

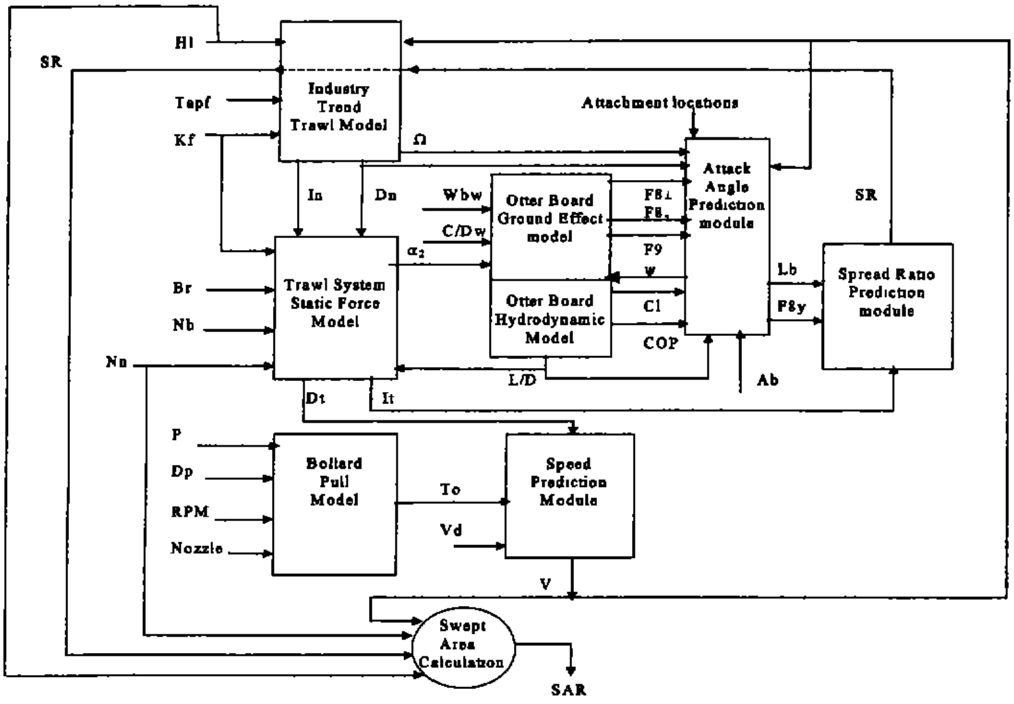


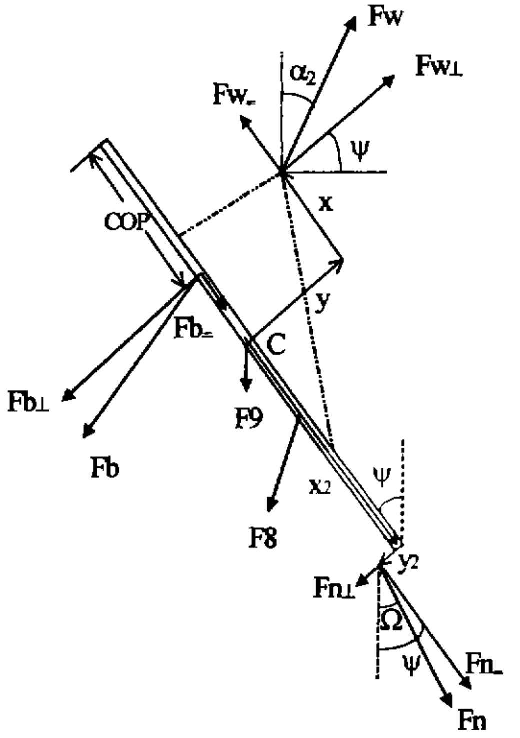
Figure 30. PTPM containing otter board angle feedback loop.

Angle of attack prediction module

The angle of attack prediction module is essentially equation 59 from Sterling (2000b) Appendix B. It drives the SRDOF model in Sterling (2000b) section 2.3.3 and expresses the condition that the sum of moments about a vertical axis through the centre of the board's length must equal zero for equilibrium. This equation can be used to find an unknown angle of attack if the applied forces and their points of application are known.

Concerns pertaining to equation 59 of Sterling (2000b) in relation to this application are that it does not include ground effect forces, assumes the location of the applied hydrodynamic force is fixed at 1/3 of the board length from the leading edge and also that the hydrodynamic force acts at right angles to the otter board face. Figure 31 shows an overhead view of the application of forces to an otter board and is more comprehensive in respect to these issues than Figure 54 in Sterling (2000b)

Appendix B. Equation 14 as used in PTPM ver3 is the upgraded version of equation 59 Sterling (2000b) and is an expression of the moment equilibrium condition pertaining to Figure 31 (clockwise positive).



Fb = hydrodynamic force
$Fb_=$ = component parallel to face
$Fb\perp$ = component perpendicular to face

Fn = wingend tension
$Fn_=$ = component parallel to face
$Fn\perp$ = component perpendicular to face

Fw = bridle tension
$Fw_=$ = component parallel to face
$Fw\perp$ = component perpendicular to face

F8 = ground ploughing force
F9 = shoe friction
α_2 = bridle divergence angle
Ω = wingend angle of net
ψ = otter board angle of attack
x,y = position of bridle connection relative to the centre (C) of the board.
x2,y2 = position of net connection relative to the centre (C) of the board.
COP = position of hydrodynamic force (centre of pressure)

Figure 31. Schematic of forces acting on an otter board.

$$\Sigma M_C=0=Fn\perp\,x2-Fn_=\,y2+1/6\,F8\perp-(0.5-COP)Fb_\perp+(Fb\perp+Fn\perp+F8\perp+F9\perp)(x-\tan(90-\psi-\alpha_2)\,y) \qquad (14)$$

It is assumed that the friction on the otter board shoe (F9) acts through C, therefore it does not generate any moment around C. It is also assumed that the ploughing force (F8) acts at a point 1/3 of the board length from the trailing edge of the otter board. In practise the position of F8 would depend on the orientation of the otter board, particularly the tilt angle[1]. No method has been developed to estimate the location of this force with respect to any influencing factors. For the 3RDOF model developed in (Sterling, 2000b) this situation also prevailed and gives rise to an essential caveat in both instances that the accuracy of angle of attack prediction relies on the tilt angle

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[1] Tilt is equivalent to pitch – elevation of front relative to back. See Figure 6.

in practise being close to zero degrees. This is the desirable attitude of the board and it can be assumed that this is generally achieved.

A plausible, but unproven argument behind estimating the location of F8 to be at 1/3 of the board length from the trailing edge is based on direct observation of the wear pattern on the keel of the otter board. Such wear patterns caused by ploughing suggests that the build-up of seabed material along the lower part of the otter board (keel) is similar to that depicted in Figure 32. One could conceptualise the build-up as an expanding conduit of seabed material that is flowing at constant speed from the leading edge towards the trailing edge. The cross-sectional area of the conduit (roughly triangular) would need to be proportional to the distance from the leading edge of the board if one assumes that the vertical contact pressure along the length of the board is constant, the amount of material dug up by the board per unit of its length is constant and the volume rate of material flowing through the imaginary conduit is proportional to the distance from the leading edge. Following these assumptions the local contact force (per unit length of the otter board) normal to the otter board keel due to the build-up of ploughed material might be assumed to be proportional to the distance from the leading edge. Under these circumstances the centre of effort of the total contact force applied normal to the otter board keel would be located 1/3 of the board length from the trailing edge. Substantial variation to this would occur depending on the hardness of the seabed and the distribution of vertical contact pressure along the length of the otter board shoe. Details regarding modelling the physics of otter board ploughing are covered in section 2.3.6.

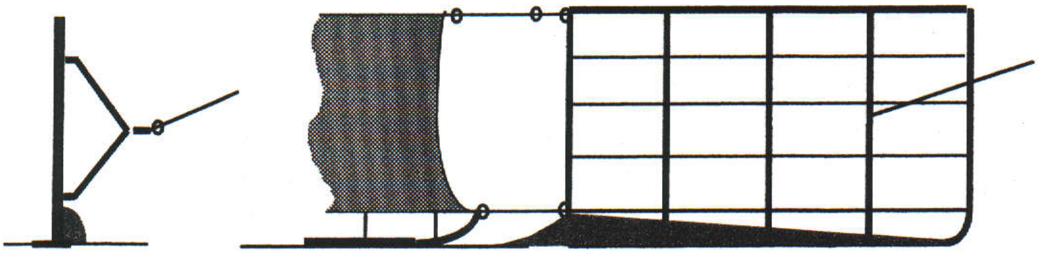

Figure 32. Ploughing action of an otter board on a soft seabed.

Otter board hydrodynamic model

The objective of incorporating an otter board orientation model into the PTPM is to allow adjustment of otter board hydrodynamic parameters (Cl, L/D) in response to the board's attack angle condition. Also, in order to predict angle of attack the relationships between attack angle and certain hydrodynamic parameters (CL, L/D, COP) are required. Therefore a detailed understanding of the hydrodynamic characteristics of the otter board is required for this aspect of the PTPM to be implemented. The problem is that the hydrodynamic characteristics of a board are a complex function of the shape of the spreading surfaces of the board and there is a large variety of different designs used in practice (see Sterling (2000b) chapter 3). Hydrodynamic models for the three most popular otter board styles used within Australian fisheries were developed. These empirical models are based on flume tank measurements taken by Edmondson (1994b). Only one specific design was tested for each style of otter board, so there remains some room for error between model predictions and actual board forces due to variations of design that exist within a design style. The three design styles covered are the Flat rectangular, Bison and Kilfoil.

Otter board ground effect model

The ground effect model used for the otter boards in PTPM ver3 is very similar to that developed in Sterling (2000b) section 5.2.2 for the 3RDOF orientation model. To increase the generality of the model a speed dependent term was included. Very little information is available to fix the parameters of the model. It is envisaged that the ground effect equations will be calibrated when the opportunity arises to compare sea trial data with PTPM predictions. More information on the ground effect model and attempts to calibrate it are covered in section 2.3.6.

2.3.4.3 Results and discussion

Flat rectangular

Figure 33 shows the hydrodynamic data collected by Edmondson (1994b) for a flat rectangular otter board of geometric aspect ratio 0.43. The model board had no longitudinal slots.

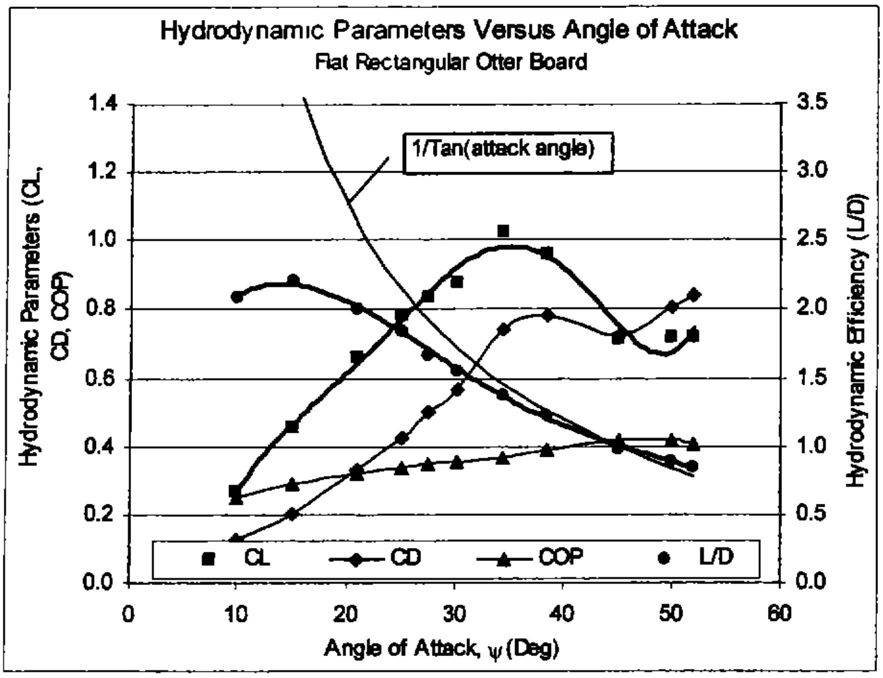

Figure 33. Hydrodynamic curves for low aspect ratio flat rectangular otter board (Edmondson, 1994b).

Polynomial trendlines have been fitted to the CL and L/D data and the resulting equations are shown below (equations 15 and 16).

$$CL = 1.564E\text{-}07\,\psi^5 - 2.199E\text{-}05\,\psi^4 + 1.137E\text{-}03\,\psi^3 - 0.02754\,\psi^2 + 0.3461\,\psi - 1.373 \qquad (15)$$

$$L/D = -1.567E\text{-}06\,\psi^4 + 2.381E\text{-}04\,\psi^3 - 0.01252\,\psi^2 + 0.2271\,\psi + 0.8699 \qquad (16)$$

The CL trendline exhibits some degree of overshoot between 45 and 55 degrees. This is not considered to be a problem because in practice no otter boards would be operating at such high angles of attack, even if the set angle of attack is that high (Sterling (2000b) section 2.3.3).

The COP data presented in Figure 33 has previously been amalgamated with COP data for flat rectangular otter boards of other aspect ratios in Sterling (2000b) section 5.2.2. In that section an empirical model was derived that predicts COP as a function of attack angle and aspect ratio (Sterling (2000b) equation 28). This equation has been used in this instance in the PTPM. Although the COP expression accounts for various aspect ratios, that in itself does not allow the PTPM to be valid for aspect ratios other than 0.43 because the CL and L/D expressions are specific only to the aspect ratio tested.

In Sterling (2000b) section 5.2.2 an alternative expression for L/D was used (L/D = 1/tan(attack angle)). This much simpler expression than equation 16 was assumed to be valid for a range of aspect ratios providing that the angle of attack specified is reasonably close to where the flat board produces maximum lift (where pressure forces dominate the hydrodynamic situation). Equation 16 gives similar answers to this expression for this range of attack angles (see Figure 33) but allows more realistic L/D predictions outside that range. 1/tan(attack angle) is the maximum possible efficiency for any flat lifting surface and therefore provides a useful reference (efficiency frontier) for Flat rectangular otter boards. This line is also shown on the performance graphs for the Bison and Kilfoil otter boards considered below, thus providing a useful visual benchmark regarding the benefits of these technologies to prawn trawling.

No expression as yet has been derived to estimate CL over a range of aspect ratios. This is not a problem for the PTPM at this stage because industry practice in terms of aspect ratio is reasonably uniform and consistent with the above expressions.

Bison

Figure 34 shows the hydrodynamic data collected by Edmondson (1994b) for a No.3 Bison otter board.

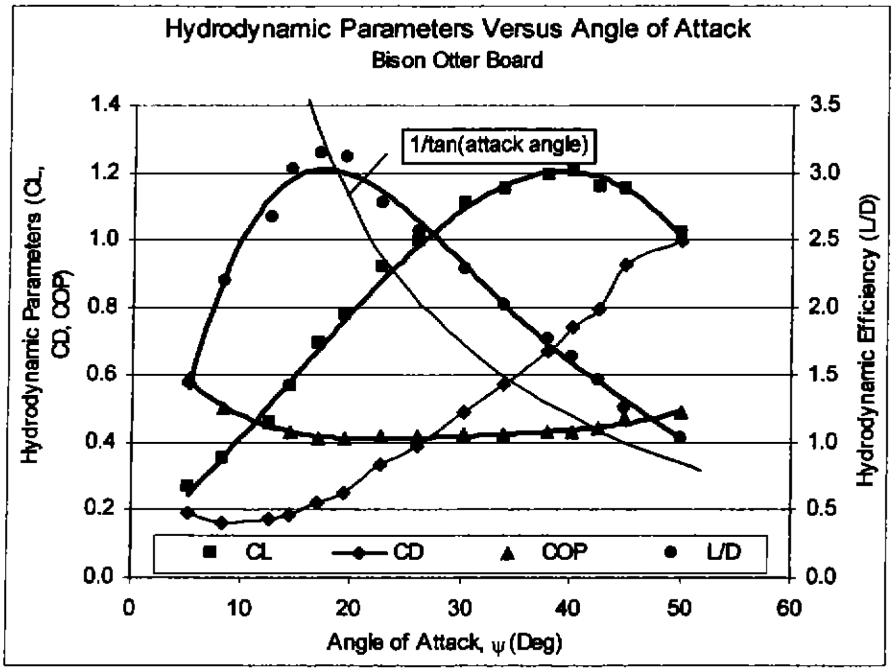

Figure 34. Hydrodynamic curves for No.3 Bison otter board (Edmondson, 1994b).

Polynomial trendlines have been fitted to the CL, L/D and COP data and the resulting equations are shown below (equations 17, 18 and 19).

$$CL = -1.955E\text{-}05\ \psi^3 + 8.070E\text{-}04\ \psi^2 + 0.02709\ \psi + 0.07876 \qquad (17)$$

$$L/D = -3.352E\text{-}06\ \psi^4 + 5.083E\text{-}04\ \psi^3 - 0.02772\ \psi^2 + 0.5731\ \psi - 0.9228 \qquad (18)$$

$$COP = 3.951E\text{-}07\ \psi^4 - 5.049E\text{-}05\ \psi^3 + 2.425E\text{-}03\ \psi^2 - 0.05029\ \psi + 0.7860 \qquad (19)$$

Design variations within the Bison style relate essentially to size. Geometric aspect ratio across the size range is fairly uniform and varies mainly between 0.67 and 0.77. The No.3 Bison tested had an aspect ratio of 0.77 and was a scale model of the Bison board tested in the six-way otter board comparison of Sterling (2000b) chapter 3.

Kilfoil

Figure 35 shows the hydrodynamic data collected by Edmondson (1994b) for a Kilfoil otter board.

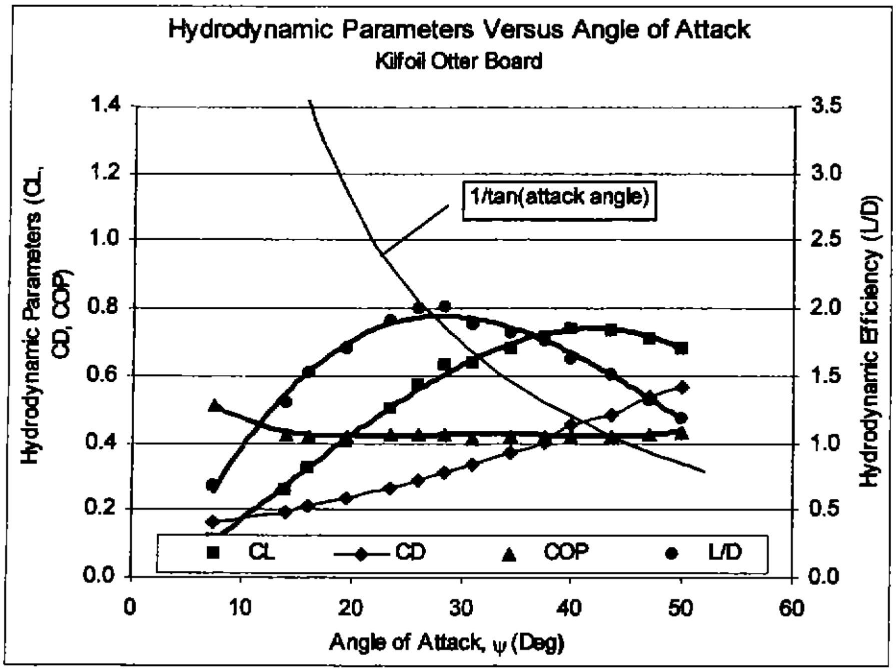

Figure 35. Hydrodynamic curves for Kilfoil otter board (Edmondson, 1994b).

Polynomial trendlines have been fitted to the CL, L/D and COP data and the resulting equations are shown below (equations 20, 21 and 22).

$$CL = -9.726E\text{-}06\ \psi^3 + 3.502E\text{-}04\ \psi^2 + 0.02178\ \psi - 0.07231 \qquad (20)$$

$$L/D = 3.406E\text{-}05\ \psi^3 - 5.226E\text{-}03\ \psi^2 + 0.2130\ \psi - 0.6736 \quad (21)$$

$$COP = 4.250E\text{-}07\ \psi^4 - 5.438E\text{-}05\ \psi^3 + 2.500E\text{-}03\ \psi^2 - 0.04862\ \psi + 0.7578 \quad (22)$$

The Kilfoil board tested was a model of the design tested in the six-way otter board comparison of Sterling (2000b) chapter 3 (see Figure 32). It was a four-foil design. Most Kilfoil boards used in practice have four foils however quite a number have only three.

2.3.5 Trawl ground effect model

2.3.5.1 Introduction

The interaction of prawn trawls with the seabed arises from the use of ground gear. Current prawn trawling practice has almost universally adopted a standard in terms of ground gear type, namely the Texas drop chain system (depicted in Figure 1). It consists of a length of chain that is virtually the same length as the fishing line of the trawl that travels along on the seabed. This "ground chain" is attached to the fishing line by dropper chains, which are generally 100mm to 200mm long and allow the fishing line to be off the bottom. Target animals that are caught are sufficiently stimulated by the chain to rise off the seabed to an extent that allows them to travel over the fishing line and into the trawl.

In terms of quantifying the forces applied to the trawl by the seabed it is required to estimate the drag on the ground chain as it travels along.

It is recognised that the interaction between the ground chain and the seabed will involve friction and ploughing and may well be sensitive to speed. The characteristics of the chain do vary a little between different boats and this will also affect the magnitude of the drag force. The magnitude of the contact pressure between the chain and the seabed may be sensitive to trawl speed and the extent that the fishing line tries to lift the chain off the seabed. This mechanism will also be influenced by the length and weight of the dropper chains.

2.3.5.2 Methodology

Very little is known about the complex mechanism which gives rise to the generation of forces on the ground gear of a prawn trawl and there will be no attempt to model the details of that mechanism here. The objective at this stage will be to capture the first order features of the ground effect situation, which entails simply trying to estimate the drag of a slack chain travelling along the seabed. Fridman (1973) reports the results of specific research aimed at quantifying the friction on a variety of cables used in Danish seine operations and is reproduced in Figure 36. The tests showed that the coefficient of friction depends on the direction of movement (angle of incidence, β[1]) and the material and thickness of the rope. In this instance the procedure will be to adopt the general form of these results and then try to build a plausible ground chain model by seeking a logical connection with the prawn trawling situation.

Figure 36 gives a fundamental start to the characteristics of the ground effect model. It is recognised that equation 23 could model the general form of the relationship.

$$\text{Friction coefficient} = a\,(1 + b\,\sin(\text{incidence}))\,(1 + c\,V^2) \tag{23}$$

Figure 36 does not indicate any speed dependence however a speed dependent term has been included in equation 23 to allow for such an effect if it is found to be significant. The parameters a, b and c in equation 23 need to be estimated but in addition to that a connection between a practical definition of ground chain configuration and incidence angle needs to be derived. A rigorous approach would be to integrate over the length of the ground chain, therefore summing the contributions to total ground chain friction by each element of the ground chain taking into account the local angle of incidence. A more expedient approach would be to estimate the average incidence angle of a ground chain as a function of the degree to which it is pulled tight[2]. In view of the level of uncertainty in the method at present it was decided to adopt the simpler approach in the first instance.

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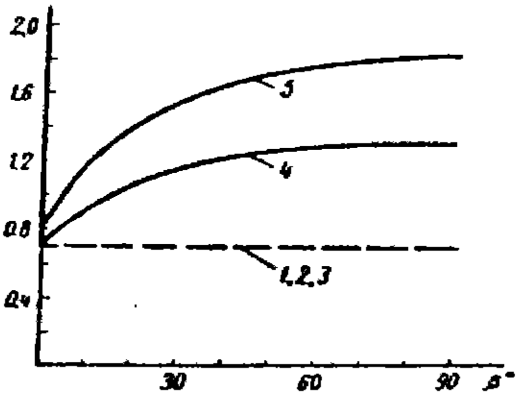
[1] Smallest angle between rope chord length and direction of travel.

[2] It is useful here to use the term spread ratio, SR, in the same way as it is used for trawl nets. In this case SR = span/chain length.



Dependence of the coefficient of friction of ropes on the direction of their movement along the bottom:

1, 2, 3 — tarred hemp ropes of diameter 3.4, 1.9 and 1.3 cm; 4 — "Hercules" cable, diameter 2.2 cm; 5 — steel-wire ropes.

Figure 36. Coefficient of friction for rope dependent on angle of incidence (Fridman, 1973).

2.3.5.3 Results and discussion

Figure 36 indicates that for zero angle of incidence the friction coefficient of all ropes is approximately the same and equal to 0.8. As the angle of incidence increases the friction coefficient of the light weight (non metal) ropes maintained this value, however for the metal ropes the friction coefficient increased by a factor of two when the angle of incidence is 90deg. How the friction on a chain responds to incidence angle is a question which needs clarification by further research.

Estimating the average incidence angle of the ground chain was achieved by concentrating on one half of the chain curve and considering that it is part of a circular arc as per Figure 37.

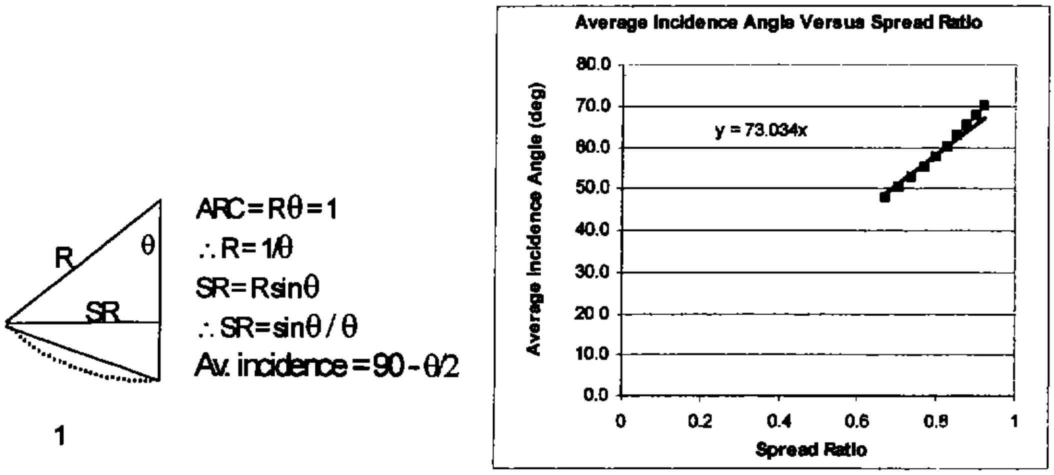


Figure 37. Deriving a relationship between average incidence angle for a ground chain and spread ratio.

Using this simple approximation of the ground chain shape the average incidence angle was estimated for a range of spread ratios and plotted in Figure 37. A proportional regression[1] fitted to these data points gave a simple linear expression for the relationship with 73deg being the proportionality constant. The final expression for the ground chain drag model is therefore:

$$\text{Chain Drag} = \text{HL wt/m } 0.8\,(1 + b\sin(73\,\text{SR}))\,(1 + c\,V^2) \qquad (24)$$

Where : wt/m = weight (N) per meter of chain length.

Inspection of Figure 36 and the result for steel-wire cable would suggest that b could take a value of 1, however it would appear quite possible due to the shape of the chain links and how well it might grip the sea bed at various angles of incidence that b could feasibly be greater than 1. Applying the model to the six-way otter board comparison of Sterling (2000b) chapter 3 in terms of trying to predict the estimated friction effects suggests that b could feasibly have a value of 4. Specific tests that measure the drag force on pieces of chain at various angles of incidence would be a valuable aim for further research. The validation work of chapter 3 addressed the issue of appropriate values for a, b and c of equations 23 and 24 in the light of comparing PTPM predictions with sea trial data, however no progress was possible with respect to establishing values with more confidence (see section 3.2.2.2). Due to

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[1] Standard least square error linear regression with intercept set to zero.

the uncertainty c is given a value of zero for all PTPM predictions calculated for this thesis.

The model at this stage contains no term that could make allowance for the type of seabed over which the chain operates. Therefore the parameters a, b and c, in equations 23 and 24, will ideally be relevant to typical trawling conditions. Since trawling occurs on seabeds that exhibit a variety of hardness it is likely that ultimately these parameters will need to be in turn some function of seabed characteristics.

2.3.6 Otter board ground effect model

The otter board ground effect model used in this instance is identical to that used for the 3RDOF orientation model. It is described in detail in Sterling (2000b) section 5.2.2. The components of the ground effect model are vertical ground reaction, sliding friction and ploughing. Sliding friction is calculated using a simple Newtonian kinetic friction model, while ploughing forces are derived in terms of components normal and tangential to the otter board's shoe.

The vertical reaction force (F7) between the otter board and the seabed is derived by subtracting from the submerged weight of the board (Wbw) the upward component of tension in the tow cable, which is dependent on the drag transferred to the cable and the ratio of cable length used to the depth of the water (C/Dw). Equation 25 is the expression used.

$$F7 = Wbw - (Db + Dn/2)\ \mathrm{Tan\ Asin}\ (1/(C/Dw)) \qquad (25)$$

The sliding friction, F9, is given by:

$F9 = \mu_k F7$ Where $\mu_k = 0.2$ (Deutschman et al., 1975).

Sliding friction does not have a first order influence on the calculation of angle of attack in the PTPM because it is assumed to act at the centre of the board length (about which moments are summed in equation 14) and therefore does not generate a turning moment. Otter board pitch is not calculated so the sliding friction force is always fixed at this point.

The normal and tangential ploughing forces ($F8_{\perp}$, $F8_{=}$) derived by the equations below from Sterling (2000b) are used by equation 14 to estimate angle of attack but they are also transformed into the directions inline and normal to the direction of tow to account for their contributions to otter board drag and spreading forces. A speed dependent factor has been added to the ploughing component to account for speed effects if it is found to be significant.

$$F8_{\perp} = \mu_{pn} F7 \,\mathrm{Sin}\ \psi \,\mathrm{GSF}\ V^{n}$$

$$F8_{=} = \mu_{k} F8n \,\mathrm{Cos}\ \psi$$ where $\mu_{pn} = 21$ and $\mu_{k} = 0.2$ (Sterling 2000b)

The validation work of chapter 3 addressed the issue of appropriate values for the unknown parameters, n and GSF in the light of comparing PTPM predictions with sea trial data, however no progress was possible with respect to establishing their values (see section 3.2.2.2). For the PTPM predictions referred to in this thesis n was given a value of zero and GSF a value of 0.05.

2.3.7 Consideration of wingend details

2.3.7.1 Introduction

The trawl drag equation used in the PTPM ver.2 (equation 1) was derived from data obtained from flume tank tests on a variety of model nets that represented trawls varying in size from 7.3m to 18.3m headline length. These nets were attached to the Trawl Evaluation Rig with a headline height typical for that sized trawl. Figure 38 shows the relationship between headline height and headline length for the series of nets tested.

It was evident from other flume tank tests that when nets were tested at some altered headline height the measured drag was substantially different from that measured for the standard value. This means that in practice for a trawler that applies a headline height to a trawl that is different from the standard the drag model will incorrectly predict net drag. Additionally operators who intend to use a high headline height would most likely design their nets to specifically cater for this by including a greater height of netting in the wings. With the objective of improving the accuracy of PTPM predictions it was decided to devise a drag prediction equation that took into account the amount of netting incorporated in the wings and the actual height of the headline.

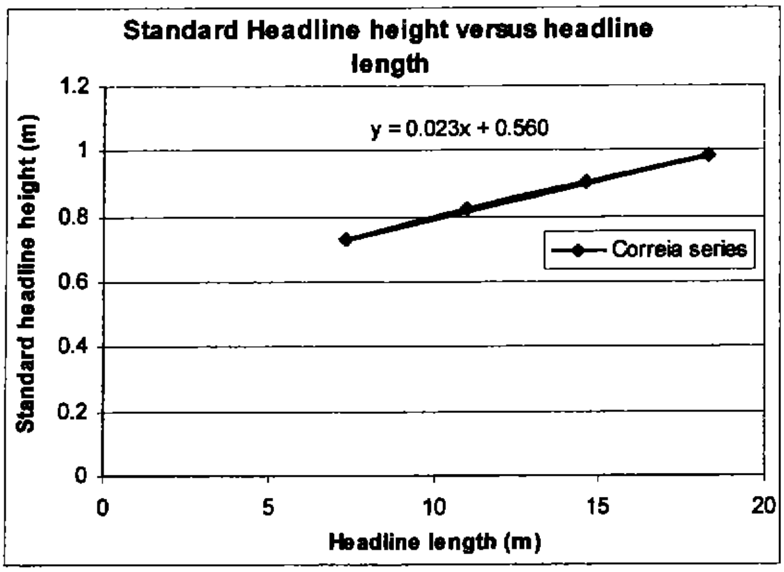

Figure 38. Assumed headline height for various sized trawls when tested for drag in the flume tank.

2.3.7.2 Methodology

It became apparent that there were two ways to approach the problem of producing a more flexible net drag model that would cater for a wider range of net specifications. Firstly it would be possible to continue to adopt the current drag expression (as part of equation 1, $Dn(HL) = 39.66\ HL^{1.473}$) and add to this by deriving a drag correction factor that would be a function of parameters defining headline height and wingend meshes. This was pursued but preliminary empirical expressions were found to be complicated and they did not appear to reflect the underlying physical relationships and processes within the data. It was felt that this approach would not give a result that could confidently extrapolate drag predictions significantly beyond the range of cases represented in the experimental data.

The alternative approach was to derive an empirical expression from first principles and use knowledge of the underlying physical processes to guide the structure of the model. It was therefore decided to rework analysis of the data used to derive the original expression and in addition to that, more data was collected from flume tank tests that explored the effect of headline height only (no change in wing end meshes) on trawl drag. The description of all tested scenarios is given in Table 5.

In relation to the two test series two parameters have been defined to classify the headline height scenarios and these are new subjects in the developed drag prediction model. Wingend mesh ratio (MR) is the ratio of the square mesh height of the netting in the wing end to the length of the headline. Wingend mesh tautness (MT) is the ratio of the headline height to the square mesh height of the wingend netting. In the development of the model these two parameters are considered to be independent variables and the two test series represent scenarios where in each case one parameter is essentially held constant while the other is varied over a range that is relevant in practice.

Table 5. Range of scenarios tested in the flume tank.

	Headline length (m)	Spread Ratio	Side Taper	Wingend Meshes	Wingend Mesh Ratio (MR)	Headline Height (m)	Wingend Mesh Tautness (MT)
Series 1							
1	7.32	0.75	1P4B	50	0.247	0.727	0.403
2	10.97	0.75	1P4B	57	0.188	0.82	0.398
3	14.63	0.75	1P4B	60	0.147	0.904	0.420
4	18.29	0.75	1P4B	60	0.118	0.983	0.456
Series 2							
1	14.63	0.75	1P4B	60	0.147	0.703	0.326
2	14.63	0.75	1P4B	60	0.147	0.801	0.372
3	14.63	0.75	1P4B	60	0.147	0.905	0.420
4	14.63	0.75	1P4B	60	0.147	1.026	0.476

The fundamental shift in the second approach for developing a drag prediction model was to adopt a general structure for the empirical model as shown by equation 26.

$$Dn = A\ HL^2 \qquad (26)$$

An exponent for HL in equation 26 was fixed at 2 rather than that which resulted from the previous analysis of series 1 only and recognises that if trawls of different size are geometrically similar (geosims) then the twine area ratio and therefore the drag ratio would be proportional to the square of headline length. This shift in thinking still produced a result as in the correction factor approach; that the effect of MR and MT needed to be incorporated into the "A" parameter in equation 26, but the resulting expression for A(MR, MT) becomes much simpler, more intuitive and more robust.

From the flume tank tests values of "A" were calculated for each scenario and an empirical expression for A(MR, MT) was fitted by regression whereby the form of the expression was guided by the style of the underlying physical process and a desire to minimise the summed square of residuals.

2.3.7.3 Results and discussion

Figure 39 and Figure 40 show the plots of "A" calculated for each scenario in series 1 and 2 respectively. For series 1 "A" is plotted against MR. The graph indicates that "A" is quite sensitive to MR. In fact "A" is somewhat more sensitive than the graph indicates because there is a slight systematic decrease in MT as MR increases (see Table 5). Figure 40 shows the effect of MT on "A". In this series MR is held constant so there is no confounding[1] in the graph.

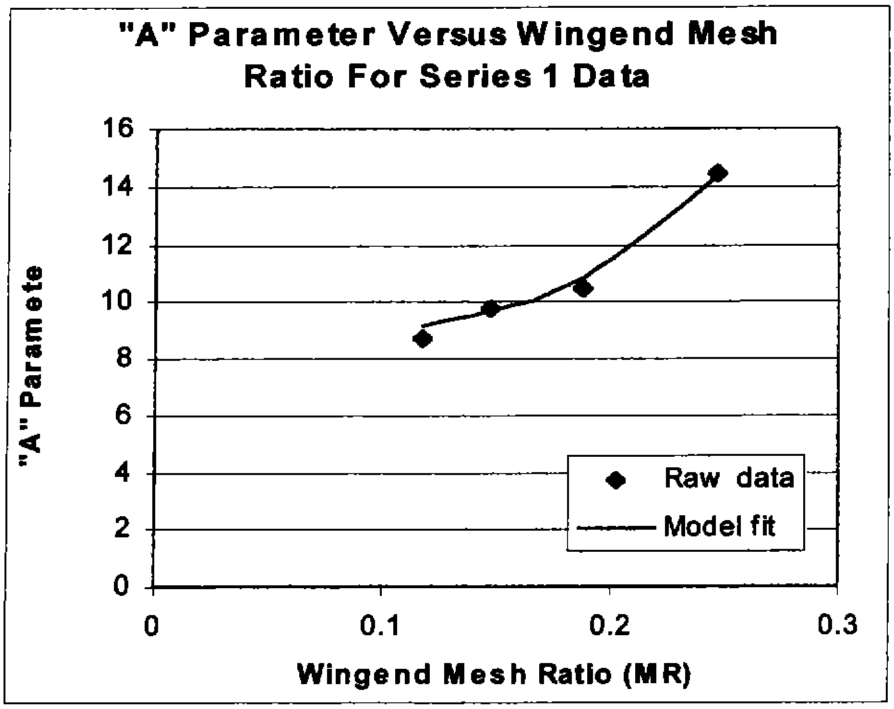

Figure 39. Drag effects dominantly caused by wingend mesh ratio.

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[1] All other variables were held constant as MT was varied.

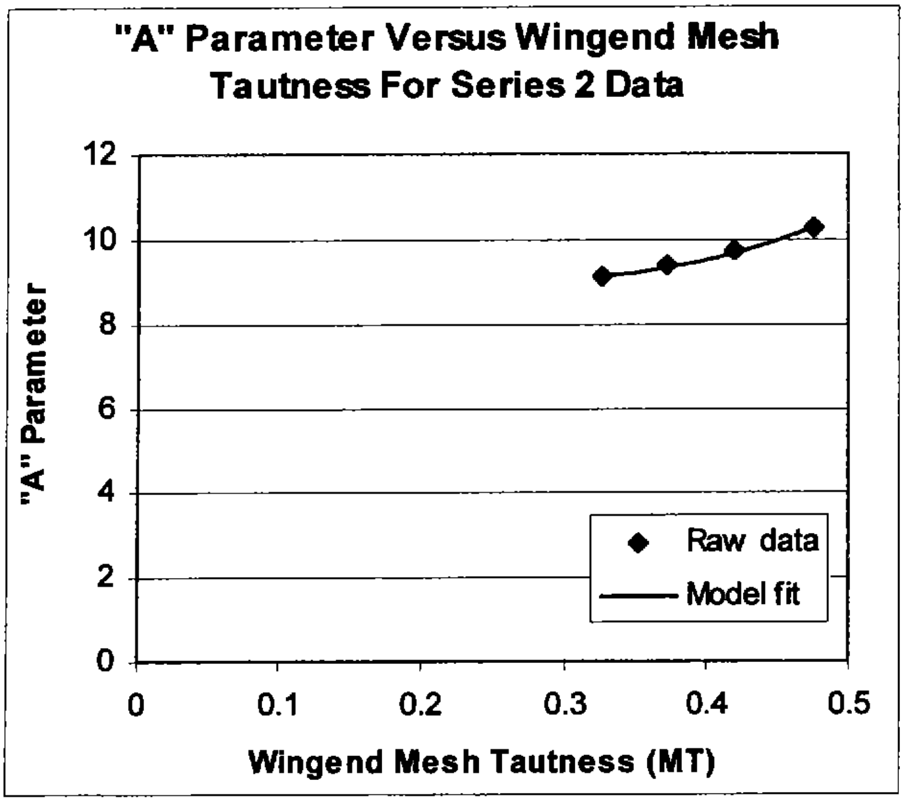

Figure 40. Drag effects caused by wingend mesh tautness.

In both of the above figures the model fit is shown. This shows that the derived empirical model closely follows the relationships indicated by the data. Equation 27 is the resulting empirical model.

$$A(MR, MT) = 3.111 + 27.012\,MR\,e^{(1.2205\,MT)} \qquad (27)$$

In Sterling (2000b) section 6.2 an issue was raised regarding the accuracy of the drag prediction formula used in Version 1 of the PTPM (essentially the same as used in Version 2 – equation 1). The main concern centred on whether the empirical model was an acceptable representation of the raw data (series 1) rather than the validity of the data itself. In particular it was apparent that 11m nets were predicted to have excessive drag (from the validation work in Sterling (2000b) section 4.4.1) and it was recognised that the empirical model did not in fact closely portray the test results for the 11m net. The new model, because of its increased complexity may well resolve this issue. This will be explored in chapter 3, where the PTPM Version 3 (Version 2 with the improvements reported here) will be subjected to validation against a range of sea trial data.

2.3.8 Headline gape parameter

2.3.8.1 Introduction

The level of drag produced by a trawl depends on the area of netting in the trawl and the orientation of the netting to the water flow. Accounting for these aspects of drag production is made difficult because information that directly relates to these features of the trawl is not easily obtained from end users and the process of analytically determining trawl forces as a function of twine area and trawl shape is complex and not generally available or fully developed. To circumvent these problems the approach in the development of the PTPM has been to derive empirical relationships between trawl forces and parameters that are readily available from industry through conducting tests in the flume tank on various systematic series of model trawls. Section 2.3.7 reported how details relating to the amount of netting that existed at the wingends of the trawl and the extent that it was vertically stretched by the applied headline height affected the drag of the trawl. In this section some fine-tuning using similar ideas is applied to the upper and lower panels of the trawl.

To this point the amount of netting in the upper and lower panels was characterised by the length of the headline and the body taper used and the arrangement of this netting in the water flow is characterised by the spread ratio of the net. If the model nets tested in the flume tank are typical of those used in practice and there is little variation in design, which would otherwise cause the amount of netting in the upper and lower panels to be variable, there would be no problem with this approach. Generally this is the case, but there is some degree of important design variation and in rare instances the disparity between the PTPM and reality can be quite large. Figure 41 shows how an extreme disparity can occur.

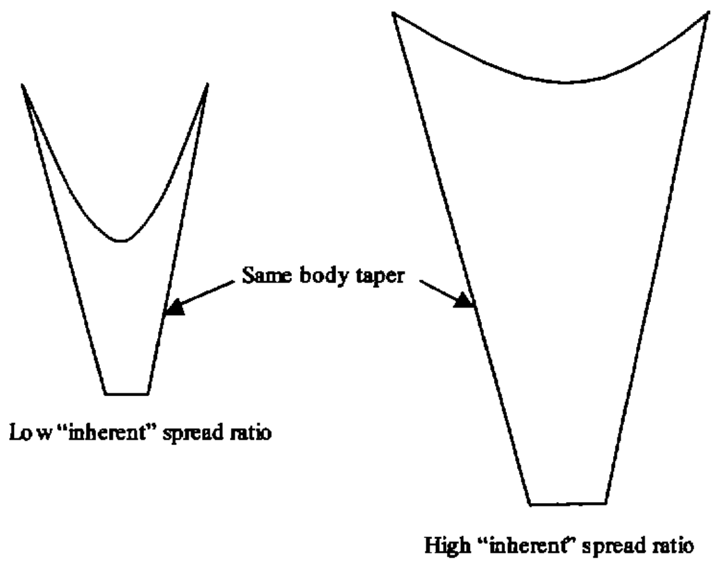

Figure 41. Two netting plans for two different trawls that have the same headline length and body taper.

Figure 41 shows the netting plan of two trawls, which have the same headline length and body taper. It can easily be seen that one trawl will contain much more netting than the other. This comes about because the two nets have different "inherent" spans or put differently, are cut from netting with different operating spread ratios in mind. It is important to note that although the plan may indicate some intended spread ratio, the actual spread ratio will depend on how big the otter boards are and how much inpull force the trawl generates while it operates. To determine the final spread ratio the PTPM must be able to predict the loading of the trawl on the otter boards and to do that accurately the PTPM must take full and appropriate account of the amount of netting used in the trawl.

2.3.8.2 Methodology

To characterise the notion of "inherent" spread ratio of the trawl as introduced above it is important to use variables that are readily available in practice and which provide a reasonably accurate result. The approach adopted in this work was to define a gape parameter to be the ratio of the lateral width of the trawl mouth to the mouth's longitudinal depth, both measured in netting meshes. These two variables are readily quantified from the net plans for trawls under consideration. To establish the actual distance values for these trawl dimensions would require a complicated determination of the average degree of stretch of the netting as it is attached to the framelines of the trawl (referred to as hanging ratio[1]). In practice the hanging ratio of netting attached to trawl framelines is reasonably consistent and the conversion of the gape parameter in terms of meshes to an equivalent determination based on distance values would involve applying a general constant that can conveniently be subsumed in the empirically determined relationship between mesh based gape and trawl drag.

The gape parameter was incorporated as a further input into the net drag prediction model, but first a series of model tests needed to be conducted to assess the affect of gape on net drag. Wakeford (1994) has measured trawl forces for a series of model nets that span the question considered here. The design of that systematic series specifically sought to produce a range of model trawls that by way of the selection of frameline tapers had an inbuilt construction that reflected specific spread ratio intentions, namely 65%, 75%, 85% and 95%. Table 6 Shows the details of the systematic series of trawls tested by Wakeford (1994). Figure 42 shows the drag results for the tested trawls.

Table 6 Systematic series of model trawls covering a range of "inherent" spread ratios as tested by Wakeford (1994).

Inherent Spread Ratio	Headline length (m)	Gape	Body Taper	Wingend Meshes	Wingend Mesh Ratio (MR)
65%	14.63	1.076	1P2B	52	0.126
75%	14.63	1.441	1P2B	52	0.126
85%	14.63	1.982	1P3B	52	0.126
95%	14.63	3.250	1P4B	52	0.126

A complication with this trawl series was that the body taper was not fixed (1P4B would have been ideal) but rather were varied by the research design so that all resulting models were approximately the same length. This was appropriate for the questions that were being considered by Wakeford, however in the current context a

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[1] Set length of mesh stretch compared to fully stretched length

fixed body taper is required so that relative trawl drag measurements are the result of changes in a single trawl parameter, that being gape. To remedy this, corrections were applied to the reported results based on the body taper drag factors presented in section 2.2.1 (see Table 1).

After standardisation of drag values to a 1P4B body taper the drag of each trawl relative to the 65% net was established by proportional regression[1] applied to plots of trawl drag versus trawl drag of the 65% net at the same spread ratio. To achieve these plots some linear interpolation of drag results was required so that data across all four nets was available for a range of consistent spread ratios. This analysis was applied to the trawl data only over the higher spread ratio regions because some of the nets had drag trends that at lower spread ratio displayed drag that was deemed to be uncharacteristically high. This particularly relates to the 85% and 95% nets (see Figure 42) and was caused by netting in the upper panel of the net becoming quite loose at low spread ratios whereby the upper panel began to vertically oscillate at low frequency during testing. This was recognised as a detrimental operational feature of these nets and considered to represent regions of tested spread ratio that would not be applicable to industry practice (Wakeford, 1997).

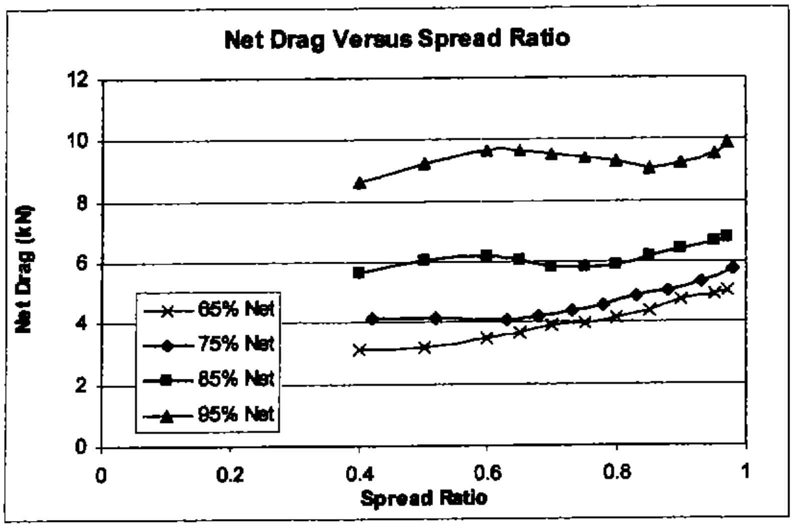

Figure 42. Drag results for Wakeford systematic series.

Once the relationship between gape and drag is found a correction formula was derived so that drag estimates based on the standard 8Fth Florida flyer which had a

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[1] Standard least square error linear regression with intercept set to zero.

gape of 1.52 could be converted to a drag estimate for a trawl of some different gape value.

2.3.8.3 Results and discussion

Figure 43 shows plots of trawl drag against the drag of the 65% net. The coefficients obtained by linear regression estimate the relative difference in drag averaged across the range of spread ratio for which data was made available. The coefficients are plotted against gape in Figure 44. From this a relationship between drag and gape is obtained, which is rearranged so that it becomes a drag correction factor given that standard drag estimated from equation 1 in the PTPM ver2 relates to a trawl that has a gape of 1.53.

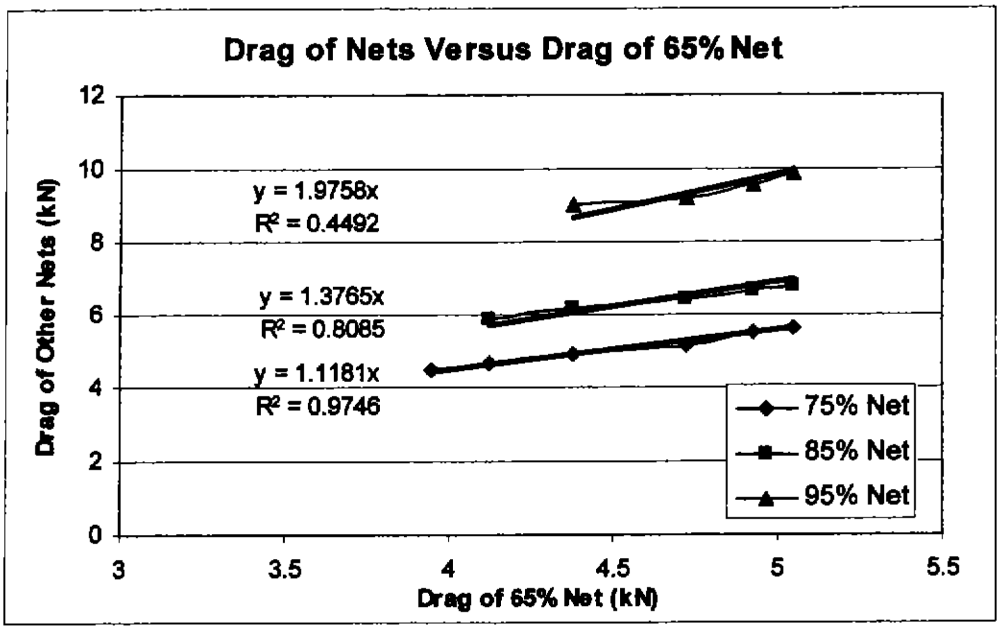


Figure 43. Plot of trawl drag versus drag of 65% net used to estimate average relative drag over a range of spread ratio.

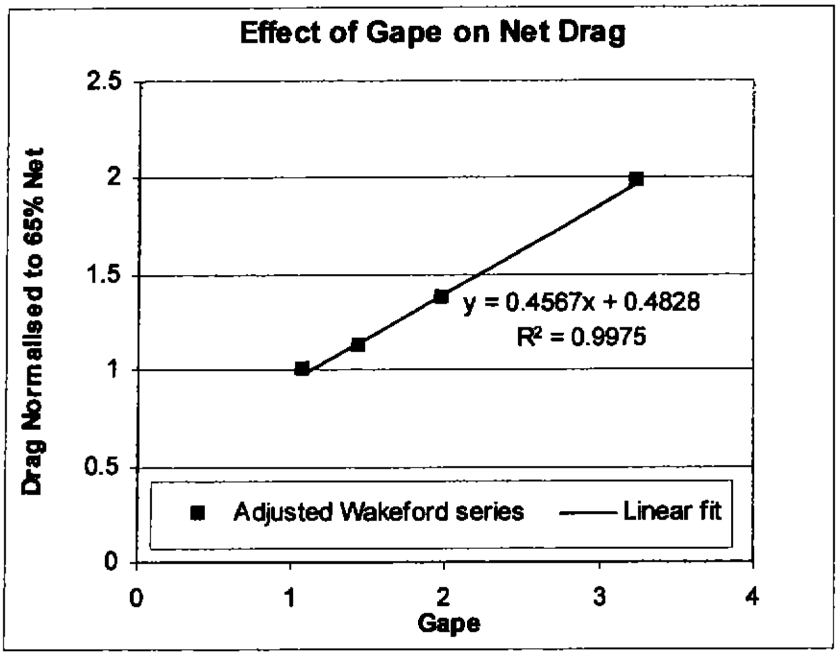


Figure 44. Effect of gape on net drag as indicated from Wakeford trawl series.

It is apparent that the drag of the standard net, which has a gape of 1.53 is 1.1815 times the drag of the 65% net. The drag correction formula derived from this information is equation 28.

Drag correction (gape) = 1 + 0.3866 (gape – 1.53) (28)

2.4 Conclusions and Recommendations

The general approach throughout the development of the model has been to try and cover the more significant features of prawn trawl systems first, in terms of factors affecting swept area performance. Originally this led to a focus on hydrodynamic forces and associated mechanisms. Over the years these more dominant aspects of the model have become refined while aspects of prawn trawling that were perceived to be less important, including ground effect forces and the hydrodynamic effect of bycatch reduction devices, have drawn more intense consideration.

In section 2.3 eight areas of improvement to the PTPM were considered. In all cases some changes were made to the PTPM including significant structural changes in the case of implementing the otter board angle feedback loop (section 2.3.4).

The resulting PTPM ver3 reflects a comprehensive revision of all operational facets of the model, which encompassed a reassessment of background data, experimental methodology and simplifying assumptions. Despite the advances made there is concern in the areas discussed below that the model does capture sufficiently well the physics of prawn trawling and doesn't produce serious prediction bias.

Within the area of hydrodynamic forces the interaction between forces developed within the trawl and the presence and characteristics of the otter boards appears to present a number of important unresolved issues. The work reported here on this subject (section 2.3.2) demonstrates that significant hydrodynamic interaction exists between a trawl net and an attached otter board. Additionally, preliminary numerical models to capture the observed features of this interaction have been developed. It is the opinion of the author that the impact of uncertainties in this area on predictions of trawl system performance by the PTPM could be high. Therefore it is important that more data is collected and further investigations are undertaken in this area.

Of similar importance to the accuracy of the PTPM are uncertainties in the magnitude of forces generated by the physical interaction of the trawl gear and the seabed as the gear moves (sections 2.3.5 and 2.3.6). More specifically there is a paucity of information on the relationship between ground effect forces on the ground gear of a trawl and the softness of the seabed, the weight of the chain and the shape of the chain. Similarly there is little information related to the ground effect forces on the shoe of an otter board in terms of magnitude and its centre of effort. Important factors that require further investigation are the orientation of the otter board, its contact pressure and the softness of the seabed.

Given the stated importance in section 2.2.1 of considering the tow vessel as part of the trawling system and its crucial role in dictating trawling performance, ongoing work is warranted on further developing methods to accurately predict the tow force produced by a trawler whilst trawling. In terms of the way the PTPM is structured, this problem can be split into three sub areas; the prediction of bollard pull for a delivered power equivalent to that used while trawling, the change in tow force produced as the speed of advance increases and the effect of the Kort nozzle on the previous issues. The work contained in this report has advanced the methodology used for tow force prediction and has identified the issue of greatest concern is the current assumption regarding how the tow force from a vessel fitted with a Kort nozzle reduces with trawl speed.

Validation of PTPM ver3 is the subject of the next chapter. Validation can occur at three important levels.

1. Verification that the code is a correct representation of the underlying theoretical and empirical models.
2. Comparison of predicted trawl performance indices with measured data for specific trawl systems.
3. Comparison of predicted swept area indices with catch rates across a fleet of trawlers.

The validation work has in fact been occurring in parallel with the model development reported here. To a significant extent feedback from the validation process has informed the direction of model development by indicating, via the formation of hypothesises, areas of the PTPM that were not performing well. This process no doubt will be ongoing as more data becomes available to compare with PTPM predictions.

CHAPTER 3 – VALIDATION/CALIBRATION OF THE PTPM

Overview

Predictions were generated from the PTPM for trawling systems that were the subject of full-scale performance measurements. The predictions were compared to the test data to assess the accuracy of the model and also fine tune components that were not confidently structured and/or parameterised. Major uncertainties relate to the effect of seabed contact on the performance of the gear, however other adjustments were also made to the model to improve the correlation between predictions and measurements.

Specifically the adjustments to the model were:

- The effectiveness (lift or shear coefficient) of Flat rectangular otter boards was reduced by 10%.
- The effectiveness of Bison otter boards was increased by 15%.

It was found that the comparison of model predictions and sea trial data had insufficient resolution to make improvements to the parameters in the ground effect components of the model.

The predictions from the model had residual errors in the following areas:

- The drag of trawl systems under commercial conditions increased more strongly (by about 7%) with trawl speed than predicted by the PTPM.
- The drag and span of 5 rig systems were overestimated by the model in contrast to underestimation of these parameters in the case of 3 rig.
- The drag and span of trawling systems containing Kilfoil otter boards was inconsistent with predictions from the model.

The correlation between catch rates and associated swept area performance as predicted by a combination of the PTPM and the fleet structure data available for trawlers that fished in the Northern Prawn Fishery was also investigated. This found that predicted swept area rate, SAR, explained up to 60% of the variation in catch. For the situation pertaining to the operation of the NPF from 1970 to 2000 it appears that the swept area rate of the trawlers was strongly linked to the size of the gear used and there was little value, in terms of explaining catch, achieved by estimating the spread ratio of the trawl gear and the trawl speed. It appears that these parameters may have been fairly uniform across the fleet at that time and attempts to estimate the parameters for each trawler in each year from the available data introduced more random error to the swept area rate predictions than valid contributions towards explaining catch.

3.1 Introduction

Chapter 2 describes the development of the latest version of the Prawn Trawling Prediction Model (PTPM ver3). This model is the culmination of applying theory and experiment to prawn trawling systems over the last decade. Theory has allowed the broad scale structure of the model to be developed such that the geometry of the towing wires and the status and performance of the system can be evaluated subject to inputs regarding the characteristics of the system's components. These inputs to the model must allow quantification of all the external forces applied to the gear as it is towed along. Because of the complexity of the forces acting on the gear theoretical approaches to prediction became difficult and the model has instead relied on experiment and empirical descriptions of various issues. Such experiments in the main were conducted on scale model gear in a flume tank. This method of investigation gives rise to ample opportunity for errors to occur between predictions extrapolated from the collected data and reality found in the field. Over and above this there is the possibility that the theories encapsulated by the model do not entirely capture the form and complexity of the mechanics of prawn trawling systems. For these reasons it is important to test the ability of the PTPM to carry out the role of describing real world factors and issues pertaining to such systems. These tests should seek to validate any claim that the PTPM is a mathematical "model" of prawn trawling systems. The following sections describe work to achieve that goal, but firstly it is necessary to further clarify the objectives of the exercise.

What should occur if statistically significant discrepancies between predictions and field measurements are found? Is this exercise to be an uncomplicated clinical process that will reject a hypothesis that the model performs to some acceptable standard and therefore reject the model or should modifications to the model be sought so that better agreement between model output and field measurement occurs.

The latter would ultimately be a more purposeful objective, given that there may be many important applications for the PTPM that could proceed to make use of its insight into trawling system performance. Such insight would have some demonstrated correlation with reality, albeit compromised by the fact that the model is no longer completely independent of the validation data.

Modification of a model based on field data may be viewed as "calibration" of the model. Loosely the work here is described as validation of the model, but ultimately irrespective of how well the model initially agrees with the validation data the prime objective is to produce a model that appears to be the best performer given all available information. If this involves a significant degree of model modification in order to force good agreement between model outputs and field measurements, the end result would still be a worthwhile and useful outcome. In the work reported here several calibrating changes were made to the model, therefore the work might more correctly be called validation/calibration of the model.

Three data sets were available for comparison with PTPM predictions. These encompass two sets of engineering data obtained from research oriented sea trials on commercial gear in Hervey Bay in Queensland, where triple rig and five rig were the subject of the measurements, and tests conducted in Tasmania on single rig. The third data set contains daily catch performance along with vessel configuration data for the commercial fleet working in the Northern Prawn Fishery (NPF) across the years 1970 to 2000.

The engineering performance data provided the opportunity to scrutinize the model's accuracy in many dimensions because data from a wide variety of trawling scenarios was available, including three different multiple net systems, a variety of net size/board size combinations, a number of different otter board types, two different sea bed conditions and a wide range of trawling speed. Depending on the quality of the data it was hoped there would be an opportunity to calibrate the model in areas where parameters have not been experimentally determined or confirmed. Ground effect is one such area where model parameters are not confidently known. Additionally the issue broadly referred to as model/full-scale correlation gives rise to the potential for various parameters, which are determined by model experiments, to be tuned to give better full-scale predictions.

The validation process begins with the Hervey Bay data because these tests were conducted in an environment typical of commercial operations and the range of gear parameters explored is quite broad. The Tasmanian data, although less fitting in those respects, has unique value in that the data covers three different otter board types that are commonly used in Australian prawn fisheries and data on otter board angle of attack was collected, thus allowing a comparison with PTPM predictions in that respect.

The NPF data provides an opportunity to check the correlation of swept area rate predictions against actual catching performance. This broadens the validation to not only the model's engineering accuracy but also the assumption that swept area rate is a reasonable proxy for catching performance in certain circumstances.

In the following sections the Hervey Bay engineering performance data is considered first, then the Tasmanian single trawl data and finally the catch and vessel configuration data from the NPF.

3.2 Hervey Bay Sea Trial Data

3.2.1 Data collection

3.2.1.1 Introduction

There was a longstanding need to generate a set of sea trial data for prawn trawl gear with the specific objective of scrutinising the accuracy of the PTPM since the development of version1 in 1994. In June 1997 a collaborative project between the Australian Maritime Engineering CRC (AMECRC), Australian Maritime College and the author was initiated to achieve this intention. Data was finally collected early in 1999 shortly before the AMECRC ceased operations and the project was closed. AMECRC researcher at that time, Tim Braund, played a significant role in physically coordinating the project and creating an electronic record of the outcomes.

Sea trials were conducted in Hervey Bay on three commercial prawn trawl systems, which included a standard East Coast triple rig (3 rig) and a recently developed five net system (5 rig). The objectives of the trials were to compare the swept area rate of the two systems and also provide data that could be used to validate the PTPM.

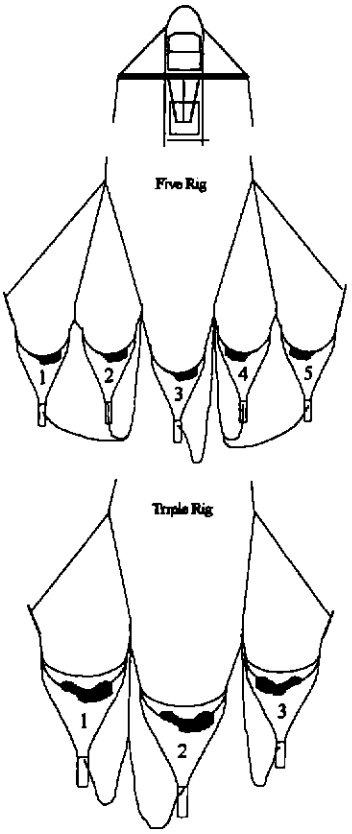
In this section of the chapter (section 3.2.1) the collection of data is described and some analysis is carried out to explore its fundamental structure. This culminates in a preliminary assessment of the relative practical benefits of using 5 rig compared to 3 rig in terms of swept area rate. In section 3.2.2 the sea trial data is compared with PTPM predictions to validate and calibrate the PTPM and further refine the comparison of 5 rig and 3 rig.

3.2.1.2 Methodology

Area of operation

The trials occurred in waters of 10 – 20 meters depth, adjacent to the western shore of Fraser Island, Queensland, Australia. Data was collected over a period of 4 days and nights from 28th February – 3rd March, 1999.

Vessel layout and rigging



Vessel Characteristics

Prop Dia (m)	Rated Power (kW)	RPM rated	RPM trawl	RPM max.	Free Run Speed (m/sec)
1.07	225	1800	1550	1550	4.6
			1400		4.3
			1250		4.0
			1100		3.7

5 Rig Characteristics

	Net 1	Net 2	Net 3	Net 4	Net 5
Headline length (m)	8.2	8.2	8.2	8.2	8.2
Mesh size (mm)	50	50	50	50	50
Twine ply	24	27	24	24	24
Body taper	1P4B	1P3B	1P4B	1P4B	1P4B
Gape	1.79	1.79	1.79	1.79	1.79
Headline height (m)	0.76	0.84	0.84	0.84	0.76
Wingend meshes	50	50	50	50	50
Total sweep (m)	3.5	4.0	11.6	4.0	3.5
Otter boards	Case 1 – Flat 2.13m X 0.914m			Case 2 – Flat 1.9m X 0.787m	
Bridles (m)	70				

3 Rig Characteristics

	Net 1	Net 2	Net 3
Headline length (m)	12.8	12.8	8.2
Mesh size (mm)	44.5	50	50
Twine ply	24	24	24
Body taper	1P4B	1P4B	1P4B
Gape	1.53	1.53	1.79
Headline height (m)	0.76	0.84	0.76
Wingend meshes	50	50	50
Total sweep (m)	4.2	8.7	3.5
Outer boards	Case 3 – Flat 2.13m X 0.914m		
Bridles (m)	70		

Figure 45. Configuration and specifications of the tested trawling systems.

The Queensland east coast prawn trawler “Cking” (15m, 300hp) was used for all trials. The vessel was rigged for commercial prawn trawling operations. The gear was deployed and hauled by port and starboard deck winches with 11 mm warps, via blocks positioned on lateral booms. Flat rectangular trawl doors were used to spread the gear and Sterling sleds linked the nets. Large doors (1.97 m^2) were used on both rigs tested (5 rig - case 1 & 3 rig – case 3) and smaller doors (1.49 m^2) were also tested on the 5 rig (case 2).

Five rig

The 5 rig used consisted of five Florida Flyer prawn trawls. Each trawl had a headline length of 8.2m and a mesh size of 50mm (see Figure 45).

Triple rig

The 3 rig used for data collection consisted of three non-uniform Florida Flyer trawls. Port side; 12.8m headline length & 44mm mesh, middle; 12.8m headline & 50mm mesh and starboard; 8.2m headline & 50mm mesh. The non-uniform configuration was tested after the original trial gear was damaged by excessive weed during its first tow (see Figure 45).

Data collection

Each rig was towed at constant depth through a range of vessel RPM settings. Every tow was reciprocated by an 180 degree change in direction so that the effects of any ocean current through the gear tend to be cancelled when the results of the two runs are averaged. An attempt was made to repeat each tow pair to improve the statistical resolution of the test results.

For each RPM setting within a tow the warp length utilised to pull the gear was set so that an approximately constant upward pull component occurred across all tests for each of the board and sleds incorporated in the trawl gear. This was designed to try and achieve a constant contact pressure between the hardware of the trawl system and the seabed because to a first order the contact pressure is the difference between the weight of the gear and the upward pull of the towing wire. As the RPM was increased and the tow force increased, more warp was used to decrease its declination angle so that the upward pull on the trawl gear remained approximately constant. The warp length schedule used was calculated after a preliminary calibration run to establish the RPM/tow force relationship for the trawler. The calculations were based on assuming straight line geometry of the towing wires and a pro rata adjustment was made between the 3 rig and 5 rig cases in consideration that 5 rig is towed by 6 wires while 3 rig is towed by only 4 (see Figure 45). This made the contact pressure on the seabed for 5 rig and 3 rig approximately the same. The assumption of constant seabed pressure is most likely to fail at the otter boards. Firstly the otter boards are usually set so that they lay out to a small extent (small amount of positive heel or clockwise roll when viewed along the direction of tow for port otter board, see Figure 6). At increasing trawl speed contact pressure will increase because a small component of the hydrodynamic force acting on the otter board is directed downwards. Due to the mechanics of the towing system at the otter board, the board is likely to lay out to a greater extent at slower speed because of the shorter warp used. This will tend to compensate for the lower contact pressure caused by the lower hydrodynamic forces, but this is likely to be only partial. As it is not certain exactly what orientation the board will take up, it was not considered practical to try and control for these 2^nd^ order issues.

Eighty-one test conditions in total were carried out. These are summarised in Appendix A.

Gear span, warp tension, declination angle, vessel speed, heading, and water depth were monitored for all test conditions. An example of the data collected for one test condition is shown in Figure 46. More information about the methodology used to collect data for each variable is given under headings below.

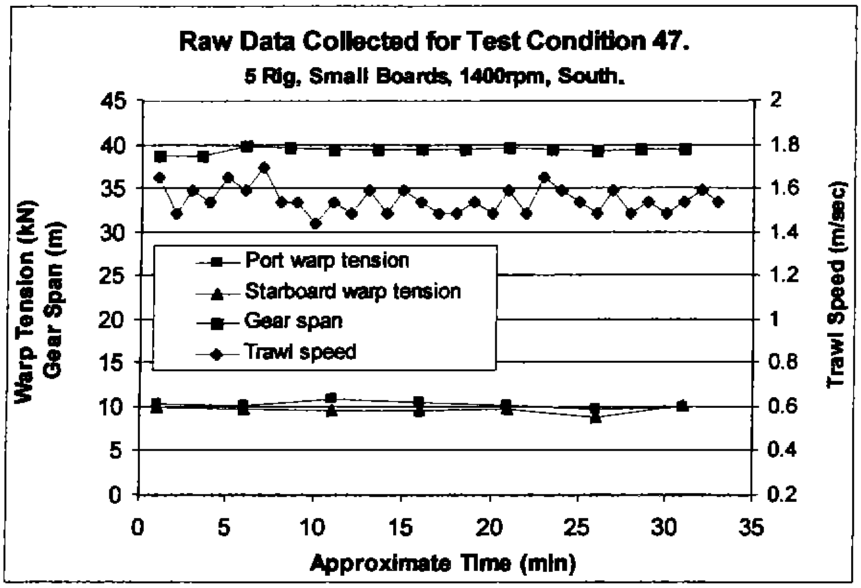


Figure 46. Plot of raw data for test condition 47 (5 rig – small otter boards, 1400rpm).

Warp tension

5 tonne capacity load cells clamped to each warp supplied tension readings for the duration of each tow. The digital display for each load cell incorporated an averaging facility such that 8 sequential samples of tension were registered, averaged and then the result was displayed. Typically 8 average tension readings were recorded during stable towing for each test condition. The cycles for determining average tension measurements, described above, were synchronised for port and starboard warps and the resulting tension measurements kept as pairs so that their sum gave the best possible indication of total gear drag in all circumstances including those where the trawler may have been crabbing due to unfavourable side winds or currents.

Declination angle

The vertical declination angles of port and starboard warps were measured aft of each block using a large protractor containing a pendulum weighted pointer. This was done concurrent to warp tension recordings. The alignment of the pendulum to the vertical direction was fairly insensitive to vessel motions as the device, which was essentially fixed to the towing wire during operation, tended only to move vertically as the vessel rolled, pitched and heaved. Irrespective of this insensitivity the conditions during tests were calm. This was a requirement of the experimental design so as not to compromise warp tension measurements, which become unsatisfactorily dynamic if the seas are other than calm to slight.

Span measurements

Two systems were used for measuring the span of the trawl gear (see Figure 47). This provided a variety of gear span data for a range of circumstances.

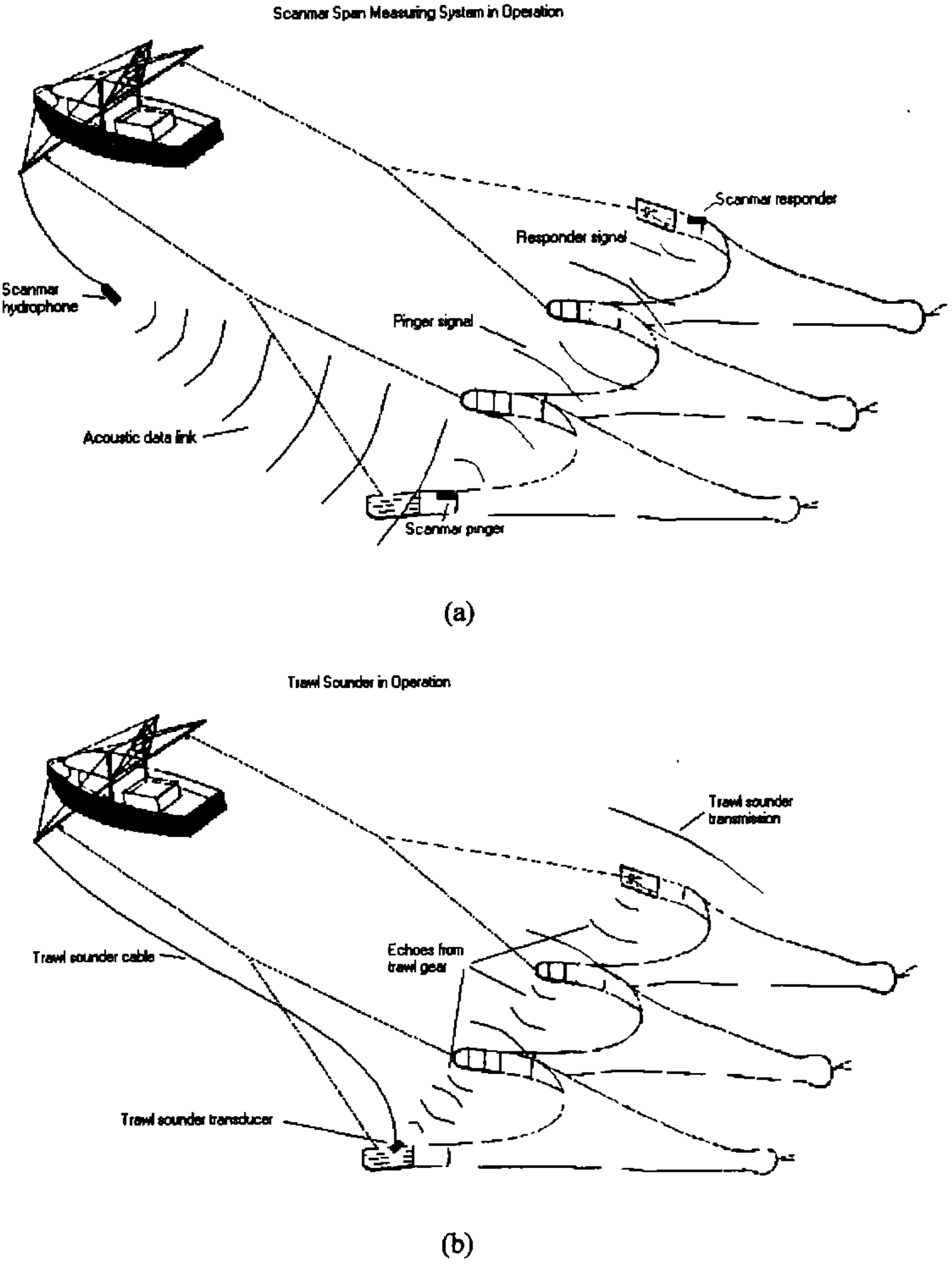


Figure 47. Diagrammatic view of the two span measuring systems used to collect sea trial data. (a) Scanmar system. (b) Trawl sounder system.

Scanmar acoustic distance sensors (pinger and responder) were attached to the gear for all runs (Figure 47(a)). A hydrophone streamed from a boom extension received distance information from the pinger to 0.1m resolution. Stable readings were recorded at irregular intervals over the period of each run as a measure of the distance between the sensor positions. The sensors were attached to the headline sweeps a known distance (generally 0.5m) laterally from the first connection of netting to the headline of the trawls. Total gear span measurements using the Scanmar system were recorded for all trawl gear cases at all speed conditions.

For each trawl gear configuration, a 200kHz echosounder transducer (connected to the vessel by a 100m signal cable) was also attached to the port door with its beam axis horizontal (Figure 47(b)) and separate reciprocal tows were conducted. Due to the short length of signal cable connected to the trawl sounder the device could not be used for the standard test runs and a separate "shallow water" run was used to gather trawl sounder data.

Echo graphs of the position of adjacent sleds and doors were recorded on a paper sounder and retained for analysis. Figure 48 is an example of the trace produced for a 5 rig test. The opening of all five trawls can be observed and measured simultaneously in real time when the scale is set so that the complete system is presented on the paper recording (as per part (2) in Figure 48). For the tows where the trawl sounder was used, the Scanmar system was also fitted simultaneously. In one instance the Scanmar was used to measure the total span and in a second instance the sensors were positioned to measure the span of the middle net only.

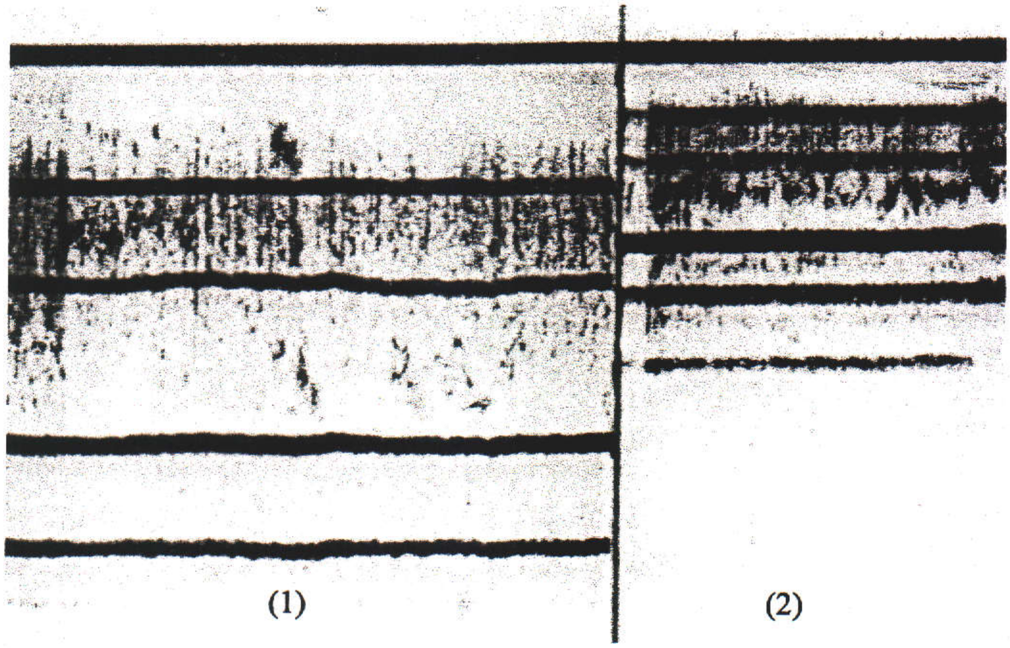


Figure 48. Echograph produced by 200kHz echosounder transducer positioned with a horizontal beam axis on the port board of a 5 rig system. (1) 36.5m full-scale. (2) 73m full-scale.

Vessel speed

Differential GPS was employed to provide all speed measurements. Typically more than 30 regular readings were recorded for each test condition. These were not always taken at precisely the same time as the tension measurements because the DGPS unit was not always receiving correction information. As much data as possible was collected while the correction information was being received. On rare occasions no correction data was available and raw GPS speed was recorded. It was considered that such data was not biased, but contained significantly more random variation over the recording period than speeds calculated from corrected positions.

Depth and bearing were maintained for all tows using conventional navigation equipment.

Analysis

The raw data was collated and the mean value along with 95% confidence intervals was calculated for warp tension, span and speed measurements at each test condition.

Further analysis of data was undertaken to develop an understanding of the general structure of the data and produce an assessment of the performance of 5 rig compared to 3 rig. To achieve that, applied thrust (= gear drag) and span versus speed relationships were determined for each test case. This ultimately provides the mathematical expressions required to estimate a range of engineering performance indicators; drag at 1.4m/sec, span at 1.4m/sec and swept area per unit time for a standard applied thrust. These three values provide the basis for a comprehensive comparison of the performance of the two systems under typical working conditions and also a comparison of observed performance to that predicted by the PTPM.

It was proposed that the swept area rate indicator, for a standard applied thrust, provides the most useful measure of performance for the different trawl systems from the fishing perspective. That is, the indicator stands as a measure of the quality of the trawl gear to the user. A standard applied thrust to a first order corresponds to a set of standard operating conditions whereby the fuel consumption rate for the trawler is constant. In exact terms this will only be true if the trawling speed is also identical because the towing efficiency of the trawler will vary with tow speed. In this analysis it is assumed that the difference in tow speed for the different trawling systems towed with a standard applied thrust is small enough that any difference in tow efficiency (tow force/fuel consumption rate) is negligible.

For each test case, linear regressions applied to the data set gave relationships for applied thrust (T_a) and span (S) as a function of speed (V). The models adopted for these relationships are of the form:

$$T_a = Df + Cd_t' . V^2 \quad (29)$$

Cd_t'= Hydrodynamic drag parameter

Df = Friction force

$$S = a_2 + b_2 . V \quad (30)$$

a_2 and b_2 are constants

The data set to be used to estimate the model parameters in each case was extracted from warp tension, span and ground speed values obtained for the range of RPM settings. Each variable value was in general the average of the two values obtained from reciprocal runs. In the case of equation 29 (which is linear with respect to velocity squared) the ground speed data used was the mean squared velocity between the two runs rather than the average velocity as used for equation 30. This is designed to further reduce the bias imposed by the effect of ocean currents through the gear and the inadvertent difference in the towing force between the tow pairs caused by wind, waves and ocean currents. The resulting warp tension and speed data point is an estimate of the applied thrust and speed response that would occur for a given RPM if no wind, waves or currents were present.

The area swept per unit time for corresponding values of V and S can be determined explicitly by using the following formula;

$$SAR = V . S \quad (31)$$

In order to determine a measure that allows comparison of the quality of the different trawl systems to the user, a representative value of SAR, SAR*, pertaining to a standard set of conditions needed to be calculated. This standardised performance index was obtained by first specifying a standard applied thrust (T_a^*) from the tow vessel and then calculating a corresponding SAR* value for each trawling system case. 18kN was adopted as the standard applied thrust. This value was selected for this situation because it produces trawl speeds corresponding to commercial operations for the gear under investigation.

For the specified T_a^*, the resulting trawl speed (V^*) can be estimated by rearranging equation 29.

$$V^* = \sqrt{\frac{T_a^* - Df}{Cd_t'}} \qquad (32)$$

The spread of the gear for this condition (S^*) can be estimated by substitution into equation 30.

$$S^* = a_2 + b_2 \,.\, V^* \qquad (33)$$

Predictions of S^* and V^* can then substituted into equation 31 to obtain an estimate of SAR^*, the area swept per unit time when the standard thrust is applied to the gear.

$$SAR^* = V^* \,.\, S^* \qquad (34)$$

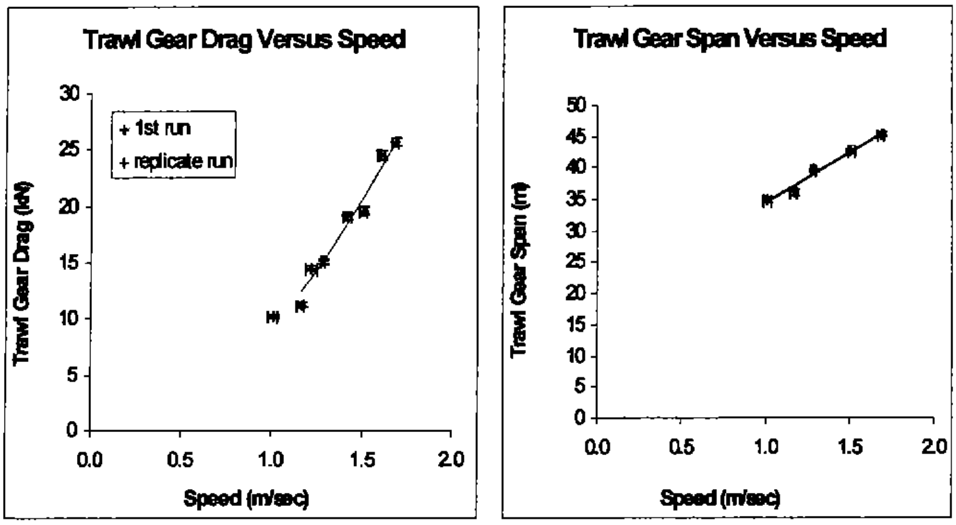
For this system of equations and the type of data collected a methodology has been developed to calculate the confidence interval for each of the estimated performance indicators. This is described in detail in Appendix E of Sterling (2000b).

3.2.1.3 Sea trial results

Figure 49 shows the raw data collected during the sea trials for the tests that were successfully completed. Only for case 1 was a replicate run achieved. For case 2 the first run was excluded because the polish on the small trawl boards indicated that their orientation was very nose up (high positive tilt). For the third case (triple rig), it was found after the first run that two of the trawls had been badly ripped by weeding up while searching for an appropriately shallow run.

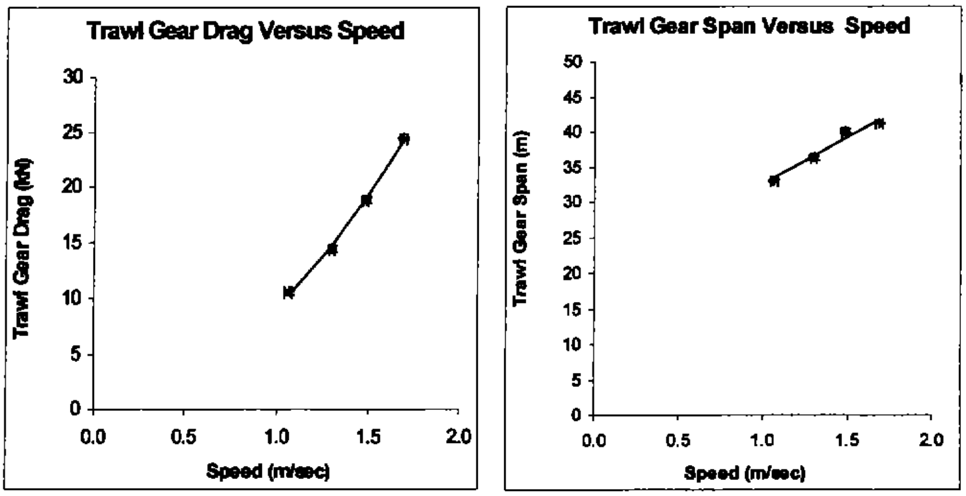
Case 1

Five rig with large boards



Case 2

Five rig with small boards



Case 3

Three rig with large boards

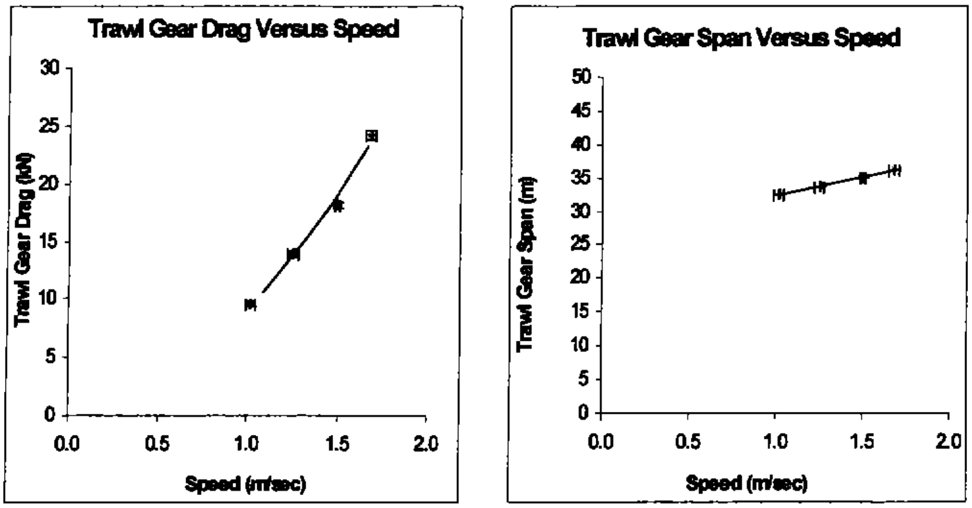


Figure 49. Graphed raw data and least square fitted models.

Table 7 contains the parameters for the models that were fitted by least square error to the raw data. A standard error for each parameter (number in brackets) is also shown.

Very high standard error values are shown for Df. This indicates the difficulty of predicting the drag of the gear at zero speed from drag data collected over a range of trawling speeds that for practical reasons cannot include values close to zero. Despite the high standard errors for this parameter in the drag model (Df), drag predictions at typical trawl speeds have low error (see Table 8) because the error is dominated by the standard error of Cd_t'.

Table 7. Parameters for models fitted to sea trial data with standard errors.

	Trawl Gear Drag Models			Trawl Gear Span Models		
Cases	Df (N)	$Cd_t'(N/(m/sec)^2)$	R^2	a_2 (m)	b_2 (m/(m/sec))	R^2
5 rig – large boards	132(1,117)	9,052(558)	0.978	17.92(1.72)	16.35(1.27)	0.982
5 rig – small boards	1,028(559)	8,084(269)	0.986	18.48(2.76)	13.82(1.96)	0.961
3 rig – large boards	1,135(1,237)	7,995(610)	0.987	26.75(0.22)	5.51(0.16)	0.998

Table 8 shows performance indices for the three trawl systems that cover drag, span and swept area/unit time for standardised operating conditions. Standard errors are also given for these indices.

Table 8. Performance indicators with standard errors calculated for the trawl gear cases based on the sea trial measurements.

	Drag @ 1.4m/sec (kN)	Span @ 1.4m/sec (m)	Speed obtained for 18kN thrust (m/sec)	Swept area/unit time for 18kN thrust (m^2/sec)
5 rig – large boards	17.87(0.33)	40.80(0.32)	1.405(0.013)	57.44(0.48)
5 rig – small boards	16.87(0.17)	37.84(0.45)	1.449(0.016)	55.80(0.58)
3 rig – large boards	16.81(0.41)	34.47(0.04)	1.452(0.016)	50.48(0.40)

3.2.1.4 Discussion of sea trial results

Total span

At 1.4m/sec the total span of the 5 rig systems was significantly higher than the 3 rig system (Table 8). However taking into account that the 5 rig systems had a greater combined headline length (41.2m compared to 33.8m) and also had a greater proportion of sweep (wires without netting attached) in the system (39% compared to 32%) it is inconclusive at this stage which system has the greater spread ratio. The 5 rig system should have a larger spread ratio given the size of the otter boards compared to the size of the nets. This will be discussed further in the "Effective span" section.

The total span of the 5 rig systems was sensitive to speed (see Figure 49). The extent of this was unexpected because past sea trial measurements on single net trawl systems produced very little change in span with speed (Sterling, 2000). The result in this case is due to the varied amount of warp used for each speed (less wire at low speed). The 3 rig system also displayed reduced span at low speed, but to a lesser degree. Unlike other common systems (ie double rig, quad rig and single rig towed on one wire) the amount of warp used affects the divergent angle of the bridles attached to the otter boards and at low speed, where the warp used is quite short, the inpull of the bridle on the otter boards (speed corrected) is significantly higher than at higher speed thus causing the span of the system to be lower. To further clarify the situation it needs to be recognised that for other systems that contain independent units towed from a single wire the divergent angle of the bridle is fixed by the length of the bridles and is not sensitive to the amount of warp used.

Friction forces

The friction force, Df (defined by equation 1), in all 3 cases is quite low and not statistically different from zero (see high standard error values in Table 7). These values can be compared to those obtained by Sterling (2000b) for the 6 way otter board evaluation. In that work it was found that Df/Cd_t' was on average 0.373 (SE = .025) for the 18 trawl configurations tested. For the 3 trawling systems considered here Df/Cd_t ' are 0.014, 0.127 and 0.143 respectively. This suggests that friction is less dominant in the Hervey Bay gear compared to the gear tested in the Tasmanian otter board trials. However, the span of the gear varied over speed for the Hervey

Bay tests and may have caused low estimates of friction force for the drag models. It is now quite apparent that the drag model (equation 1) does not mechanistically suit the circumstances of these tests. The drag model specifically relates to trawl gear that has a fixed hydrodynamic shape irrespective of trawl speed. Due to the fact that this assumption is not held true for this gear, the distortion of the hydrodynamic forces with speed very likely causes the estimate of friction force to be pushed low so that the mathematical model more successfully coincides with the measured data.

Establishing a better estimate of the friction force acting on the gear will require comparison of the sea trial data with a detailed dynamic model of the gear such that the dynamic effects of the variation in span over the speed range on the hydrodynamics drag of the system are taken into consideration, thus allowing the underlying friction/ground effect forces to be estimated from the measured data. This will be considered further in the next section where the data is compared to the PTPM.

Drag

At 1.4m/sec the measured drag of the 5 rig system with large boards is higher than the other two systems (Table 8). Statistically there is no significant difference in the drag between the 5 rig system with small boards and the 3 rig system.

Swept area

The swept area rate for each system combines the effect of gear drag and span in a way that reflects the gear's potential catching performance. The end result is that the 5 rig systems sweep the sea floor at a rate approximately 12% higher than the 3 rig system (Table 8). These are preliminary results because the spans used to calculate swept area rate have not yet been corrected for the amount of sweep that exists in the trawl systems in that the sweeps would not be expected to herd prawns into the nets and therefore are not part of the effective span of the trawl gear. Such corrections will be made when the results are amalgamated in the next section with the PTPM, which contains a detailed geometric model for the trawling systems. It is expected that the ensuing corrections will slightly reduce the gap between the performance of the 5 rig and 3 rig systems for the test conditions. This is the easiest way to make the necessary corrections because it requires calculation of the divergence angles of the sweep wires (the length of which is known) that exist between the span measuring sensors.

First order calculations regarding the performance of 5 rig compared to 3 rig (Sterling, 1997) indicate that the 5 rig system should be approximately 30% better than the 3 rig system. The calculations however are based on assuming that the small trawls used in the 5 rig system are geosims of those used in the 3 rig system. This assumption would tend to exaggerate the potential performance improvements. More realistic calculations along the same lines but not assuming the nets are geosims suggest that the swept area rate improvement should be closer to 20%. These calculations do not take into account the detrimental effect on performance caused by the use of short warps, which appears to affect 5 rig more than 3 rig (see Figure 49 – remembering that slower speed equates to shorter warps). At this stage one can only presume that the inability of the tests to show performance gains equivalent to general theory are due to the complicating effects of the relatively short warp length used during the trials because they were conducted in quite shallow water (20m as opposed to 40m for commercial operations).

A more commercially relevant comparison of 5 rig versus 3 rig may be obtained by making use of the PTPM. The PTPM expands on the general theory of trawling system performance by also capturing the effects of warp length. Therefore, although the Hervey Bay data may not realistically portray the relative practical performance differences between 5 rig and 3 rig it is quite suitable for validating performance predictions from the PTPM, which should be able to deal with all the complicating issues of this specific testing regime. Once the model is validated the PTPM could then be used to make confident predictions about the advantages of 5 rig compared to 3 rig for deeper commercial operations. This will be considered further in the next section.

There was a significant difference between the measured performances of the two 5 rig systems ($\alpha = 0.05$). The results indicate that the larger boards gave rise to a 3% improvement in swept area rate. The span of the system with small boards was 6% lower but this was partially offset by the fact that its speed was 3% faster than the system with large boards for the same applied thrust.

Effective span

In the next section attempts will be made to demonstrate agreement between the sea trial data and predictions of span and speed from the PTPM. If successful the PTPM will be able to provide useful information regarding the proportion of the span that is effectively fishing (actually pertains to nets rather than sweeps plus nets).

Introducing the information contained in the trawl sounder traces, which were recorded during the sea trials and show the span of each of the individual nets in the trawl system, will allow further validation of the PTPM in this respect. This information cannot be used directly at this point because it was collected in even shallower water than the rest of the trials because of constraints imposed by the length of the transducer cable. This data therefore represents an independent check on predictions from the PTPM with respect to variables not available from the results reported so far. These relate to the individual nets within the system.

A final view about the relative quality of 5 rig versus 3 rig will be presented as part of the conclusions of section 3.2.2.

3.2.2 Comparison of sea trial data with PTPM predictions

3.2.2.1 Methodology

Drag and span

For each test condition during the sea trials where a complete set of uncompromised data was collected, predictions of trawl gear drag and span were calculated from the associated PTPM spreadsheet at the trawl speed which was measured in the field. This makes redundant the component of the PTPM model that gives a speed prediction based on the performance of the trawler (in terms of available thrust) and the drag characteristics of the trawl gear. Validation of the available thrust part of the PTPM was carried out as a separate and independent exercise and is detailed in a following section.

Standard errors were estimated for each experimental data point based on the sample of measurements taken and 95% confidence intervals were constructed. These were two dimensional for each point because trawl speed is also subject to the errors of measurement (see Figure 49). The two dimensional (2D) confidence intervals were transformed into one dimensional (1D) confidence intervals for the dependent variables so that a more formal comparison of measured and predicted data could be made. The following formulation was the basis of converting the confidence intervals from 2D to 1D.

The crux of the problem revolves around adding the effect of the uncertainty in measured speed to the uncertainty in the measured dependent variable and to facilitate this, use was made of the relationship between the dependent variable (drag and span) and speed as estimated by the regression models.

For gear drag, D, at speeds V and $\bar{V}$ we can assume that:

$$D_{\bar{V}} = D_V + \left.\frac{\partial D}{\partial V}\right|_{\bar{V}} (\bar{V} - V) \qquad (35)$$

when $\bar{V}$ is nearly equivalent to V and

$$D(V) = Cd_t'\ V^2 + D_f \qquad \text{(as per equation 29)} \qquad (36)$$

Therefore:

$$\left.\frac{\partial D}{\partial V}\right|_{\bar{V}} = 2\ Cd_t'\ \bar{V} \qquad (37)$$

Which gives for equation 35:

$$D_{\bar{V}} = D_V + 2\ Cd_t'\ \bar{V}\ (\bar{V} - V) \qquad (38)$$

The objective of these calculations is to estimate $\sigma^2_{D_{\bar{V}}}$ given that we know $\sigma^2_{D_V}$ (estimated variance of D_v measurements) and σ^2_V the estimated variance of V measurements.

Using the following rule for variance on equation 38:

$$y = f(x_1, x_2) \qquad \sigma^2_y = \left(\frac{\delta f}{\delta x_1}\right)^2 \sigma^2_{x_1} + \left(\frac{\delta f}{\delta x_2}\right)^2 \sigma^2_{x_2} + 2\frac{\delta f}{\delta x_1}\frac{\delta f}{\delta x_2}\sigma_{x_1 x_2}$$

$$\sigma^2_{D_{\bar{V}}} = \sigma^2_{D_V} + (2\,Cd_t'\ \bar{V})^2\ \sigma^2_{(\bar{V}-V)} + (2\,\bar{V}\ (\bar{V} - V))^2\,\sigma^2_{Cd_t'} + \text{covariance terms} \quad (39)$$

Ignoring second order and covariance terms and assuming that $\sigma^2_{(\bar{V}-V)}$ is equal to σ^2_V:

$$\sigma^2_{D_{\bar{V}}} = \sigma^2_{D_V} + (2\,Cd_t'\,\bar{V})^2\;\sigma^2_V \qquad (40)$$

By ignoring second order terms we are choosing to ignore $\sigma^2_{Cd_t'}$ and covariance terms in Cd_t'. The covariance term, $\sigma^2_{D_V V}$, is assumed to be negligible in this instance because the variances of the two variables are dominated by respective measurement noises that are due to issues which are physically isolated from each other[1].

For span, S, at speeds V and $\bar{V}$ we can assume that:

$$S_{\bar{V}} = S_V + \left.\frac{\partial S}{\partial V}\right|_{\bar{V}} (\bar{V} - V) \qquad (41)$$

when $\bar{V}$ is nearly equivalent to V and

$S(V) = b_2\,V + a_2$ (as per equation 30) (42)

Therefore:

$$\left.\frac{\partial S}{\partial V}\right|_{\bar{V}} = b_2 \qquad (43)$$

Which gives for equation 41:

$$S_{\bar{V}} = S_V + b_2\,(\bar{V} - V) \qquad (44)$$

$$\sigma^2_{S_{\bar{V}}} = \sigma^2_{S_V} + b_2^{\,2}\,\sigma^2_{(\bar{V}-V)} + (\bar{V} - V)^2\,\sigma^2_{b_2} + \text{covariance terms} \qquad (45)$$

Ignoring second order and covariance terms and assuming that $\sigma^2_{(\bar{V}-V)}$ is equal to σ^2_V:

$$\sigma^2_{S_{\bar{V}}} = \sigma^2_{S_V} + b_2^{\,2}\,\sigma^2_V \qquad (46)$$

Trawl sounder data

Because of the short transducer cable (100m) the trawl sounder could not be used with any of the standard test conditions used for the varied speed tows. For tows where the trawl sounder was used in addition to the Scanmar distance sensors the

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[1] Sea surface waves in the case of drag and GPS errors in the case of speed.

engine RPM was set to 1400 but the wire length used was the same as that used for 1100rpm on the varied speed tows. The depth of the water was reduced in each case to standardise the upward pull of the towing wires (11m instead of 20m for 5 rig, 7m instead of 13m for 3 rig).

Vessel thrust

Validation of the PTPM in terms of its ability to predict available thrust (tow force) was achieved through combining all the sea trial data (5 rig and 3 rig). This was done because from the vessel's point of view the different trawl systems only represent different drag loadings and give rise to a range of trawling speeds for a given engine RPM setting. Of interest here is the ability of the PTPM to make predictions of available thrust for particular engine RPM settings while also taking into account the speed of advance (ie. trawling speed) of the vessel. The PTPM makes such predictions based on equations 6, 7, and 13 and inputs of engine RPM and trawl speed collected during the sea trials. The predictions were then directly compared with corresponding measurements of tow force taken during the sea trials.

Ground effect models

By analysing the error structure between PTPM drag predictions and sea trial measurements it could be possible to assess the accuracy of the ground effect components of the PTPM, although errors in the ground effect sub models are confounded with any error in the hydrodynamic models. Evidence that residual error is caused by the former rather than the latter might be inferred by the expectation that ground effect forces have a weaker relationship with speed than hydrodynamic forces however this presumes that the contact pressure between the gear and the seabed remains constant for the various speed settings. Although it was the objective of the experimental design to achieve this, as outlined previously it is a problematic issue and may generate errors large enough to disrupt the objective to calibrate ground effect components in the PTPM.

3.2.2.2 Results and discussion

Drag and span

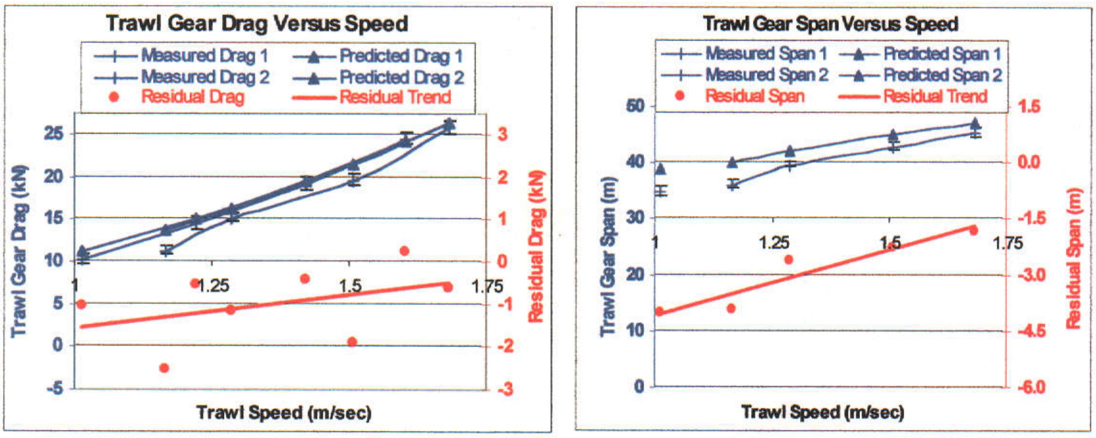
Figure 50 shows plots of measured and predicted data for trawl gear drag and trawl gear span for the three trawl systems tested. The figure also shows the residuals, which is the difference between the measured and predicted data, on an expanded scale.

In the predicted results an element of calibration has already been instituted into the PTPM. It was quite apparent on viewing the first round of predictions that the drag and span measurements for the two cases involving the large otter boards were in general less than predicted. This pointed to the strong possibility that the spreading performance of the otter board was not as good as assumed. Concerning published performance curves for Flat rectangular otter boards, many sources (Crewe 1959, FAO 1974, Patterson and Watt 1986) present data with a maximum lift coefficient typically 90% of that adopted by the PTPM. The lift curve adopted by the PTPM had the highest maximum coefficient of all available sources. The main reason why the particular curve derived from Edmondson (1994b) was adopted was to maintain the same source of information for all otter board styles. Edmondson (1994b) was the only source of performance information for the Bison and Kilfoil boards. For the predictions displayed in Figure 50 the spreading capability (lift coefficient, CL – see section 2.3.4.3) was reduced by a factor of 0.9. Because the hydrodynamic efficiency (L/D) of the otter board is unaltered there is an equivalent reduction in otter board drag as well.

The smaller otter boards used in case 2 were slotted (3 horizontal gaps). For these otter boards the PTPM already had the facility to apply a "gap correction factor", which in the first instance was set to 0.85 with respect to the standard curve sourced from Edmondson (1994b). Although a further reduction of this factor could be justified at this time based on similar arguments posed for the large otter boards, 0.85 was adopted for the predictions in Figure 50.

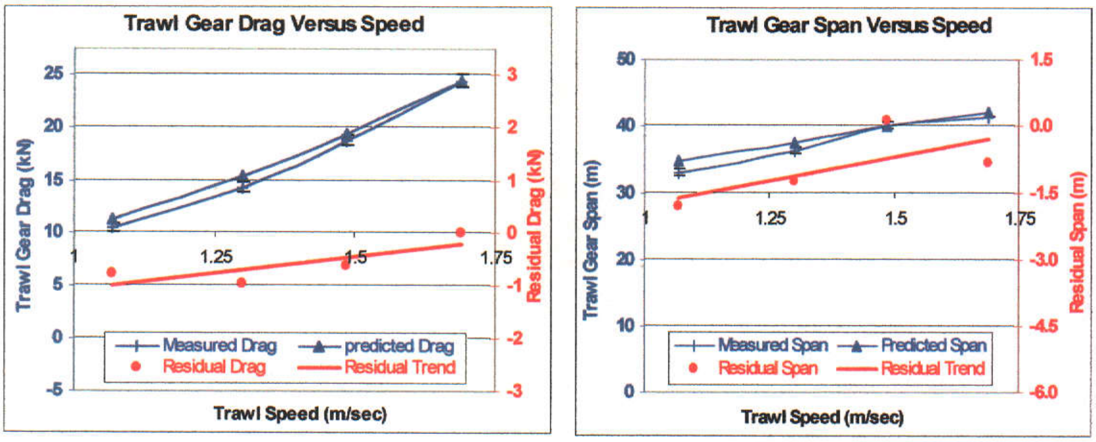
Case 1

Five rig with large boards



Case 2

Five rig with small boards



Case 3

Three rig with large boards

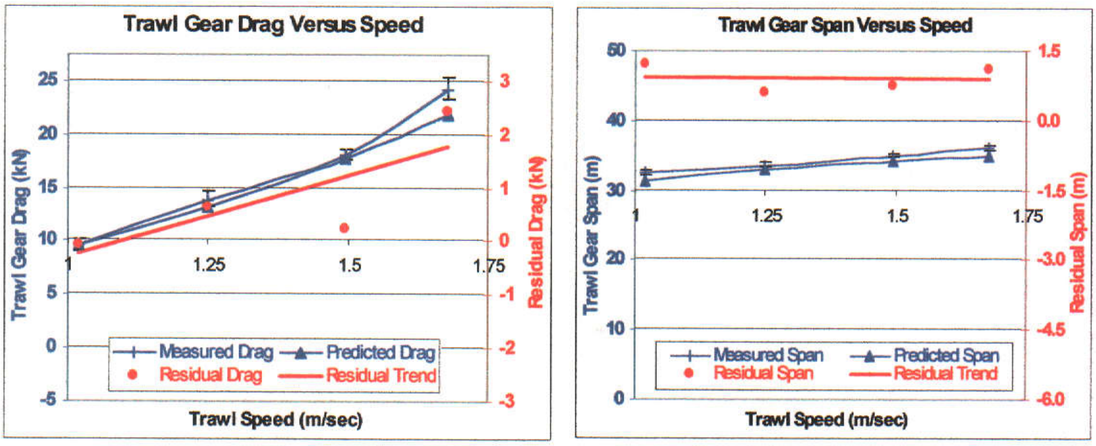


Figure 50. Comparison of sea trial data with PTPM predictions in gear drag and gear span for three trawl system cases. Residuals, being measured minus predicted, are also shown.

The results generally show that the drag of the trawl systems increases somewhat more strongly with speed than estimated by the PTPM. In general the magnitude of the residuals increases by about 1kN while the predicted drag increases with speed by about 15kN. This discrepancy could come from a number of sources, namely:

1. Ground effect forces (friction and ploughing) are a stronger function of speed than assumed by the PTPM.
2. The hydrodynamic drag parameters for the nets and/or boards might be higher than assumed by the PTPM.
3. There is a systematic error in standardising the test conditions across speed (eg. contact pressure of otter boards may be increasing with speed).

This trend in the residuals with trawl speed, although consistent, is fairly slight and probably not of concern for most applications of the model.

At the same time the predicted drags of the trawl systems are generally higher than observed, particularly at low trawl speed. This situation seems to coincide with an over prediction of span as well. If this were exactly consistent across all trawl system cases it would be logical to consider that the model was still overestimating the ability of the trawl boards to spread the gear. Unfortunately the generalisation does not hold for 3 rig, where the predicted span is less than observed and the predicted drag is generally less than observed. The most striking feature of the results is that the PTPM still seems to strongly over predict span for 5 rig, particularly for the case with large otter boards where the error is typically 9% (see Table 9 for more details). It is therefore relevant to try and find an explanation as to why the PTPM seems to considerably over predict span for 5 rig yet under predict span for 3 rig. Five physical issues related to the operation of these trawl systems have been closely scrutinized in order to try to resolve these prediction errors and inconsistencies:

1. The effect of headline height on trawl drag.
2. The manifestation of hydrodynamic forces on the towing wires.
3. The otter board angle of attack feed back loop with trawl net spread ratio.
4. The effect of incorrect sweep extensions on trawl system performance.
5. The interaction between trawl net performance and otter board size/presence.

Issue 1 does not offer a straight forward solution because increasing the sensitivity of trawl drag to headline height would indeed cause the predicted span of the 5 rig systems to go down but it would also cause the predicted drag of the systems to become higher and increase drag errors further.

Issue 2 was investigated carefully and the PTPM was expanded to allow calculation of the forces generated in the towing wires and estimate the effect on the performance of the system. The result of that exercise was that the forces on the wires and the effect on the system were an order of magnitude too small to account for the problems under consideration. Because the calculations for these forces were in themselves as intensive as the rest of the calculations combined and caused a large increase in time to run a prediction for a very small change in result, that particular expansion to the PTPM was not adopted.

Issue 3 was thought to be the most likely source of the problem to begin with, since it is likely that the lower spread ratio of 3 rig in general (large nets with small boards) would give rise to lower angles of attack for the 3 rig system (Sterling, 2000b). From the 5 rig perspective the very small nets have a larger spread ratio because they are spread by the same boards (relatively larger) and this will cause the angle of attack on the otter boards to be higher. It is envisaged that the higher attack angle could give rise to reduced otter board spread force since the boards are generally operated at or above the stall angle. This general picture could well explain the situation where the 5 rig span is somewhat less than expected and the triple rig is on target except for the fact that the 3 rig system was compromised by the forced inclusion of one small net on the starboard side. This has made the actual 3 rig system under test quite difficult to model because it has a board on one side (port) which is typical of 3 rig and a board on the other side (starboard) which is typical of 5 rig. The resulting trawl system is therefore strongly asymmetrical and it is not known whether the PTPM is coping adequately with the second order implications of this situation. The problem of trying to accurately model asymmetric trawl gear has many of the same complications as modelling gear that has incorrect sweep extensions (issue 4), because they both manifest individual nets in the system that are not towed square. The overall problem that the Hervey Bay data set presents is that all of the tested trawl systems may have been strongly compromised by the physical effects of having trawl nets that are out of square. For 3 rig this mainly arises from having one net on one side that was significantly smaller than the other two. In hindsight it would have been far better to position the smaller net in the middle rather than the side. For the 5 rig cases the trawl nets may be significantly distorted because the system was tuned to work in normal commercial water depths (about 40m), whereas the tests were conducted in water less than 20m deep. The experimental design did not consider that this issue would significantly interfere with the results. It may yet be the case that that assumption was reasonable, however in the situation where there are discrepancies in the results that assumption needs to be investigated.

A further complication is that issues 4 and 3 interact with each other. This makes it difficult to model accurately what may be happening with respect to these two complex mechanisms. The PTPM was modified to incorporate a model for issue 4 that included interaction with issue 3. This reduced marginally the size of the residuals, but as shown in Figure 50 the general problem remains. It could well be that further effort at improving the modelling of issues 4/3 might completely resolve the error, however this would involve carrying out further flume tank tests to quantify the effect of distorted nets on the tensions manifested in their framelines. Alternatively it might be equally useful to collect more sea trial data with special effort taken to remove the complications of the current data set. It would however be of some value to understand and be able to model the effects of incorrect sweep extension because it is likely that the more complex multiple net trawling systems are often operated with non-optimal tuning. Quantification of the impact on performance would be valuable if indeed it is significant.

Issue 5 (otter board/trawl interaction) is fairly independent of the other issues and is a very new area of investigation with respect to prawn trawling performance. So far only preliminary quantification of the effect has been achieved and this information has been incorporated into PTPM (see section 2.3.2). It is possible that the strength of the interaction is much stronger than the data obtained from the flume tank tests conducted so far indicate. This might have arisen through the difficulties of setting up the corresponding scale model tests in the flume tank. Issues to consider are:

1. Reynolds number effects on flow around the otter board.
2. Proximity of the flume tank wall to the otter boards (blockage effects).
3. Influences of otter board aspect ratio and headline height on the effects of hydrodynamic interaction between the otter board and the trawl.

In conclusion, investigation of the identified issues has not been able to conclusively identify the source of the problem, however it is felt that issues 4 and 5 are possible candidates and further investigation in those areas is warranted in future work.

Table 9 Percentage error between measured and predicted values of drag and span for the three trawl system cases with measurement uncertainty at 95% confidence level shown in brackets.

	Total Gear Drag Error (%)				Total Gear Span Error (%)			
Nominal speed (m/sec)	1.0	1.25	1.5	1.7	1.0	1.25	1.5	1.7
5 rig – large boards	-10.4 (5.5)	-3.9 (5.5)	-2.2 (3.9)	0.9 (3.1)	-11.6 (2.7)			
	-22.6 (4.1)	-7.8 (2.9)	-9.8 (3.7)	-2.5 (3.0)	-10.9 (2.1)	-6.6 (1.2)	-5.31 (1.7)	-4.0 (1.8)
5 rig – small boards	-7.2 (3.5)	-6.8 (3.3)	-3.2 (2.7)	0.0 (2.6)	-5.4 (1.5)	-3.5 (1.7)	0.3 (1.3)	-2.0 (1.5)
3 rig – large boards	-1.0 (5.5)	4.7 (5.0)	1.3 (2.9)	10.0 (4.1)	3.7 (1.0)	1.7 (1.0)	2.1 (0.7)	3.1 (1.0)

From Table 9 it can be seen that for 3 rig all errors were generally less than 5%. The only departure from this is for drag at the highest speed where the measured drag was 10% higher than predicted. Generally all measured values for 3 rig, both drag and span, were greater than predicted.

There is a strong contrast to this for 5 rig where very nearly all measured values were less than predicted by varying degrees. For 5 rig with small boards (case 2), errors above 5% (but <10%) occurred at the lower speeds and were less than 5% elsewhere. For 5 rig with large boards, measured values were generally less than predicted by more than 5% and by more than 10% at the lowest speed.

Numbers in brackets in Table 9 represent the uncertainty in each of the measurements for a 95% level of confidence. If prediction errors are greater than the measurement uncertainty it suggests that those predictions fall outside observations with a probability greater than of 97.5%. Most prediction errors in Table 9 are significant at that level. The only predictions that lie within the bounds of measurement error are gear drag predictions at lower speed for 3 rig and some of the drag predictions at high speed for 5 rig. Measurement uncertainty was calculated to be generally between 2.5% and 5.5% for gear drag and between 1% and 3% for span.

Table 10 shows a comparison of predictions from the PTPM for a range of performance indicators for the 3 trawling systems. These predictions are also compared to values for the same performance indicators, which were determined in section 2.1.3 from the sea trial measurements. For the observed data an uncertainty measurement is given in brackets. This uncertainty, expressed as a percentage of the observation, is calculated for a 95% level of confidence. The residual error between predictions and observations remains at a similar level to that which occurred for the direct measurements for gear drag and span.

Residual error for the swept area rate predictions are somewhat less than might be expected given the larger absolute errors generally for speed and span. This occurs because errors in speed and span for a given trawl system tend to be in opposite directions. The prediction errors for swept area rate are 1.6% for 3 rig and 0.1% and 3.1% for 5 rig with small boards and large boards respectively. In all cases the PTPM over predicted swept area rate. However, all prediction errors were not outside the bounds of measurement error.

Table 10. Comparison of performance indicators predicted from the PTPM and determined from sea trial measurements of gear drag and span over a range of trawl speed. Percentage uncertainty (for 95% confidence) is given for observed values and residual prediction error is also shown.

	Drag @ 1.4m/sec (kN)	Span @ 1.4m/sec (m)		Speed obtained for 18kN tow force (m/sec)	Swept area/unit time for 18kN tow force (m^2/sec)	
		nominal	effective		nominal	effective
5 rig - large boards observed	17.87 (3.7)	40.80 (1.6)		1.405 (1.8)	57.44 (3.2)	
PTPM prediction	18.90	44.02	32.24	1.361	59.22	43.56
% residual error	-5.7	-7.9		3.1	-3.1	
5 rig - small boards observed	16.87 (2.0)	37.84 (2.4)		1.449 (2.1)	55.80 (4.1)	
PTPM prediction	17.43	38.85	29.39	1.43	55.86	42.17
% residual error	-3.3	-2.7		1.6	-0.1	
3 rig - large boards observed	16.81 (4.9)	34.47 (0.2)		1.452 (2.5)	50.48 (3.1)	
PTPM prediction	15.87	33.66	26.47	1.51	51.30	40.30
% residual error	5.6	2.3		-4.2	-1.6	

By using the PTPM, predictions could be made of the effective span and effective swept area rate of the three trawl systems. These predictions are shown in Table 10 and can be compared with nominal values of these performance indicators. The difference between the two relates to the amount of span that is not covered by netting (ie gaps in the system) whereby the nominal value is equal to the total span and is the greater of the two because it includes lateral sections of the trawl system that do not have attached netting. Table 11 expresses the ratio of effective and nominal swept area rate as swept area efficiency. For 5 rig at the test conditions it is about 0.75 while it is 0.79 for 3 rig.

Table 11. Relative performance of the three trawling systems with 3 rig set as the reference.

	@ test conditions				@ 40m depth		
	Measured relative swept area rate	Predicted relative swept area rate		Swept area efficiency	Predicted relative swept area rate		Swept area efficiency
	nominal	nominal	effective	effective/nominal	nominal	effective	effective/nominal
5 rig - large boards	1.14	1.15	1.08	0.74	1.21	1.10	0.71
5 rig - small boards	1.11	1.09	1.05	0.75	1.14	1.07	0.73
3 rig - large boards	1.00	1.00	1.00	0.79	1.00	1.00	0.78

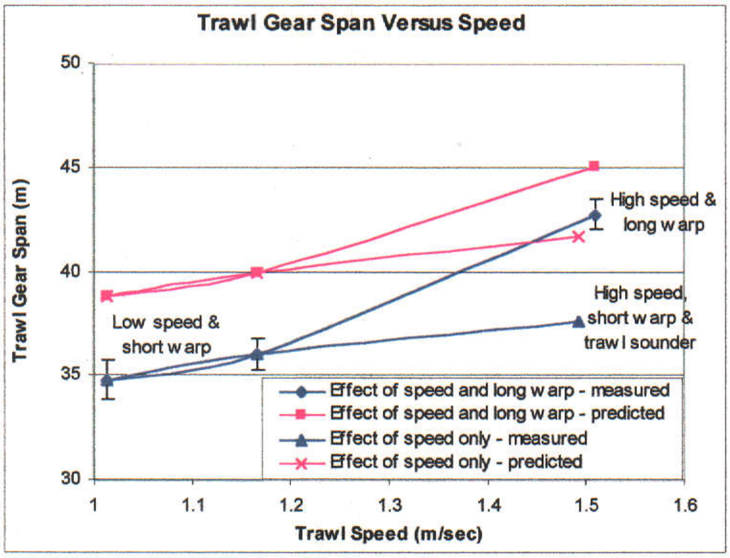
The measured and predicted swept area rate of case 2 (5 rig – small boards) was about 10% better than 3 rig (see Table 11). The performance of case 1 was 14% and 15% better than 3 rig based on measurement and PTPM predictions respectively. After correction for effective span the PTPM predicts that the benefits of 5 rig reduce to 8% and 5% for large boards and small boards respectively. The benefit of 5 rig in deeper water as predicted by the PTPM improves to 10% and 7% respectively for large board and small board cases. In nominal terms case 1 sweeps 21% more area for a given fuel consumption than 3 rig in deeper water. Therefore depending on how well target species are guided into the path of the trawls by the sweep wires catch increases of between 10% and 20% could be expected for 5rig compared to 3 rig.

Trawl sounder data

Figure 51 shows measured and predicted total span (Scanmar) for the test condition used to collect trawl sounder data, plotted in context with data obtained from the variable speed runs (no trawl sounder) that have related but not identical test conditions. This produces a diagram that shows some of the interactions between high and low trawl speed and long and short warps (the combination of low speed and long warps was not tested). Lines join points that represent pre and post conditions for each of the two treatments. The test condition pertaining to high speed and short warp may be compromised by the fact that it is the only one where the trawl sounder is fitted to the port board. The main purpose of this diagram was to illustrate whether or not the presence of the trawl sounder effected the span performance of the trawl system through observing whether the difference between measured and predicted values remain consistent within each trawl gear case. Figure 51 shows that it is likely that the trawl sounder has decreased the span of the different trawl gear. This is particularly apparent from the graph for 3 rig where for the tests that do not involve the trawl sounder the predicted span is less than the measured span (by about 2%), but for the test that had the trawl sounder connected the predicted span is higher than the measured span (by about 2%). Therefore the measured span of the test involving the trawl sounder may have decreased by about 4%. The graph for case 1 shows a similar result where the difference between predicted and measured span becomes higher for the high speed & short warp test (trawl sounder fitted) by about 5%. It appears that the trawl sounder has affected the spreading ability of the otter board to which it has been connected. In an attempt to model this effect the spreading performance of the port board was systematically decreased within the PTPM for these test situations to try and identify the extent of spread force reduction. When the effectiveness of the port board was reduced to 80% for the tests that involved the trawl sounder the distribution of errors between predicted and measured became quite consistent at high speed for each case (see Figure 52).

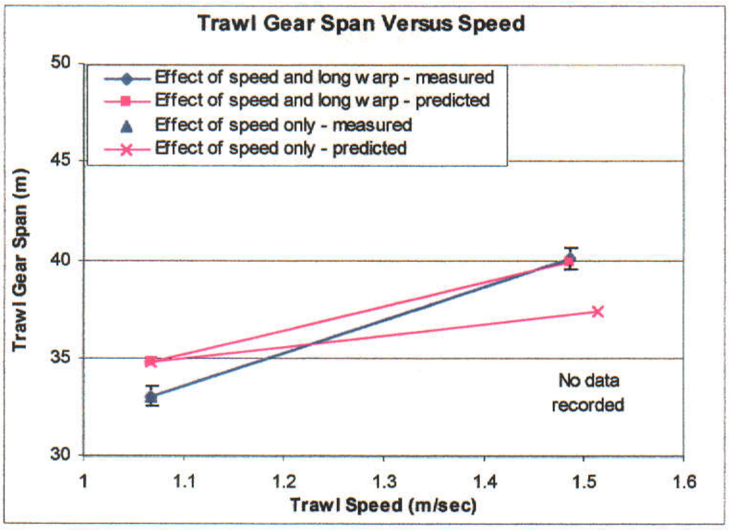
Case 1

Five rig with large boards



Case 2

Five rig with small boards



Case 3

Three rig with large boards

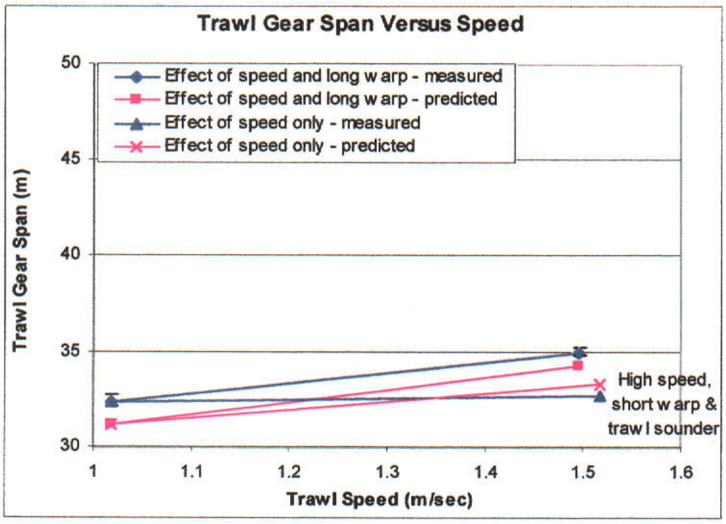
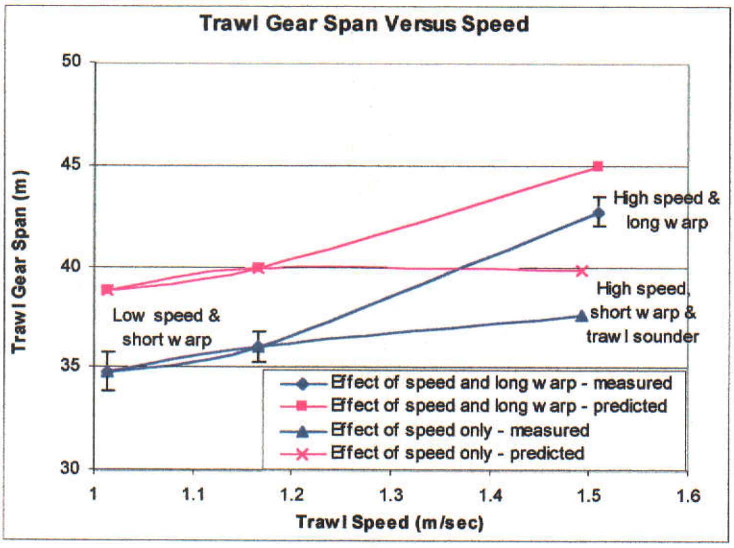


Figure 51. Measured (Scanmar) and predicted total span, with no correction for connected trawl sounder, for various combinations of speed and warp length for the three trawl system cases.

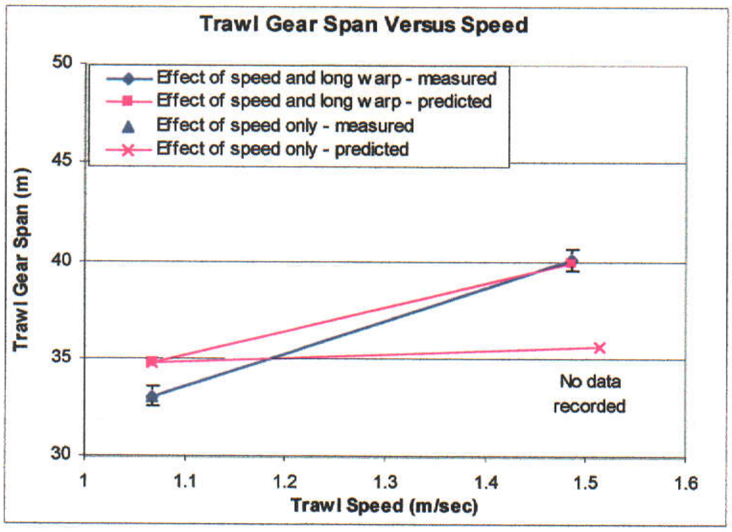
Case 1

Five rig with large boards



Case 2

Five rig with small boards



Case 3

Three rig with large boards

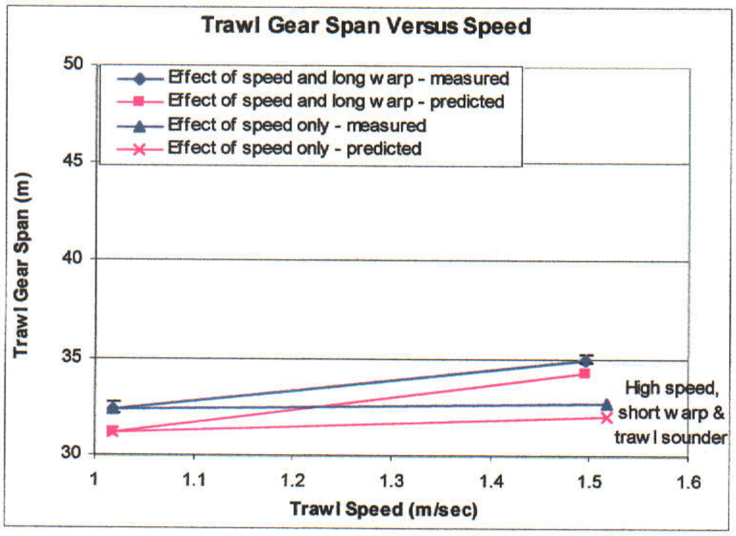


Figure 52. Measured (Scanmar) and predicted total span, with correction for connected trawl sounder, for various combinations of speed and warp length for the three trawl system cases.

It would appear logical to apply the hypothetical effect of the trawl sounder on the port board for all predictions that involve gear that incorporates that span-measuring device. This more likely would give PTPM predictions that correspond with observations made with the trawl sounder. The resulting trawling systems depicted by the prediction models become quite asymmetric. For example, for 5 rig the centre line of the middle net lies approximately 1m to starboard of the centre line of the boat. For 3 rig, where the centre line of the middle net was already 1m to starboard of the centre line of the boat due to the effect of the smaller starboard net, the middle net was predicted to track approximately 3m to starboard because of the additional influence of reduced port board spreading capacity.

Table 12 contains all measured spans for the trawl gear systems that incorporated the trawl sounder. This includes measurements of the span of all individual nets in the systems determined by both the trawl sounder and the Scanmar system where available. For each measurement a prediction of the span was obtained from the PTPM (with the port board correction applied). The reference systems for the two methods of span measurement are different and is the reason why corresponding trawl sounder and Scanmar results are different. PTPM predictions take into account the different reference systems of the two methods (see Figure 47).

Table 12. Fine scale span measurements and predictions for the three trawl gear cases

Case 1 – Five rig and large boards.

	Port side			Starboard side		
Span indicators (m)	Outer net	Inner net	Middle net	Inner net	Outer net	Total
Trawl sounder	7.93	6.14	10.31	6.74	No Data	No Data
PTPM prediction	8.09	6.62	10.62	7.54	8.68	41.55
% residual error	-2.1%	-7.7%	-3.0%	-12.0%	-	-
Scanmar			6.19			37.63
PTPM prediction			6.33			39.88
% residual error			-2.3%			-6.0%

Case 2 – Five rig and small boards.

	Port side			Starboard side		
Span indicators (m)	Outer net	Inner net	Middle net	Inner net	Outer net	Total
Trawl sounder	7.73	5.75	9.12	6.34	8.13	37.06
PTPM prediction	7.20	5.83	9.58	6.67	7.79	37.08
% residual error	6.8%	-1.5%	-5.1%	-5.2%	4.1%	-0.1%
Scanmar			5.74			No Data
PTPM prediction			5.90			35.69
% residual error			-2.8%			-

Case 3 - Three rig.

Span indicators (m)	Port net	Middle net	Starboard net	Total
Trawl sounder	10.70	13.87	9.12	33.69
PTPM Predicted	10.36	13.44	9.32	33.12
% residual error	3.2%	3.1%	-2.3%	1.7%
Scanmar		10.74		32.77
PTPM Prediction		10.49		32.03
% residual error		2.3%		2.3%

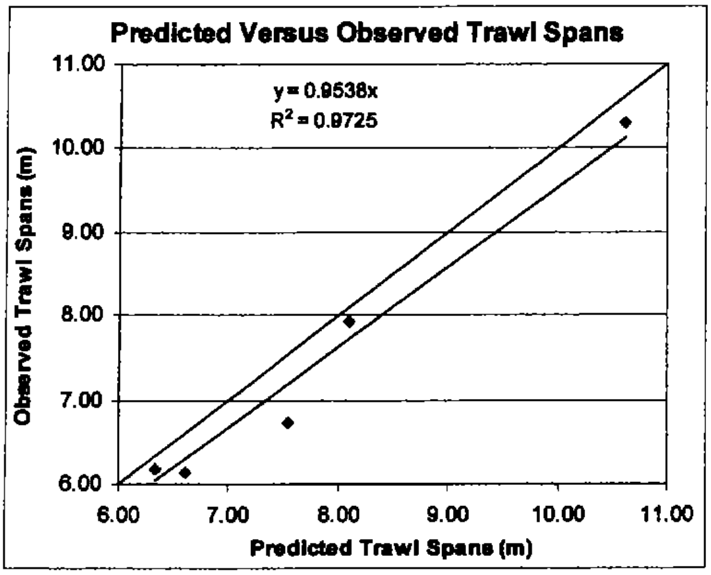
The fine scale comparison of span indicates that there are some inconsistencies between the span error for individual nets and the span error for the associated whole system. For 3 rig it appears that the PTPM over predicts the span of the small (starboard) net compared to the other larger nets. Generally though, for 3 rig all errors are quite small (<3.5%). This problem with the small net is suspiciously similar to the 5 rig cases generally and points to some unknown fundamental issue connected with the mechanics of the small nets.

For 5 rig there seems to be an indication that the PTPM under estimates the span of the outside net compared to the three middle nets. This tends to discount the possibility that the cause of the general problem of the PTPM over predicting span for 5 rig is due to otter board/trawl interaction. If it were through that mechanism that the problem occurs then the PTPM would tend to over predict the span of the outside nets. It seems that the problem of over prediction of span may involve a mechanism that focuses on the central nets. This is an important point because all the mechanisms under investigation so far tend to affect all the nets equally or have a biased impact on the outside nets.

Figure 53 shows plots of observed versus predicted trawl span for all trawls within each trawling system. This figure indicates the amount of variation explained by the PTPM[1] and the residual error in each case. Table 13 quantifies these issues based on the calculated correlation coefficient for a proportional regression between predicted and observed trawl spans and the average percentage difference for each system. In all three cases, in excess of 90% of the variation in span between the trawls in each system was predicted by the PTPM. The average PTPM error across all trawls in each system broadly reflects the results described and discussed for total span in previous sections.

Case 1

Five rig with large boards



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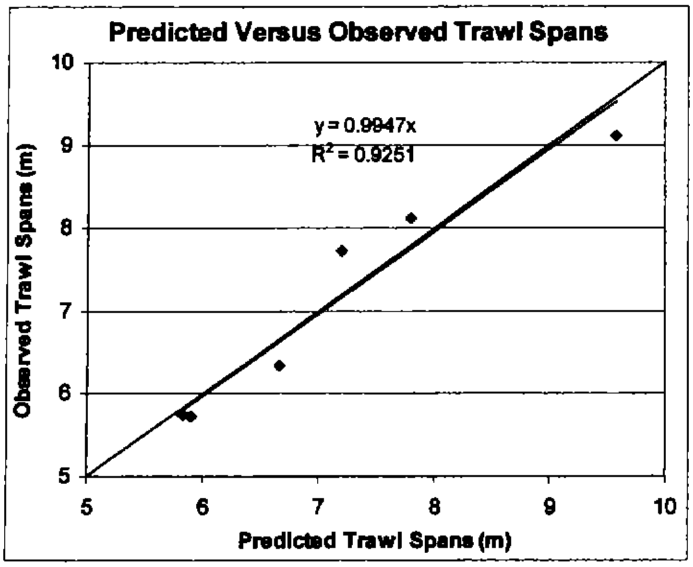
[1] A proportional regression has been applied to the data to detect the average proportional bias.

Case 2

Five rig with small boards



Case 3

Three rig with large boards

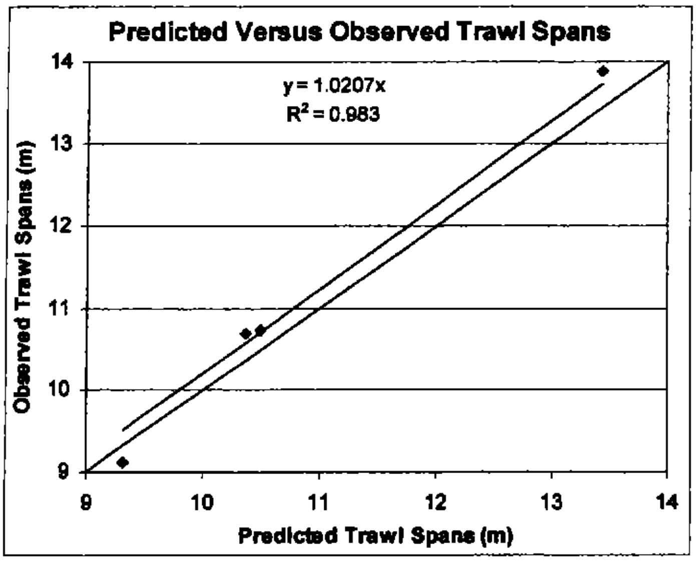


Figure 53. Predicted trawl spans (with correction for connected trawl sounder) versus observed trawl spans (trawl sounder and Scanmar) for the three trawl system cases.

Table 13. Percentage variation in trawl span within each trawling system explained by the PTPM and average percentage error.

	Variation explained by PTPM	Average PTPM error
5 rig - large boards	97.2%	5.4% (1.9)
5 rig - small boards	92.5%	0.6% (2.0)
3 rig - large boards	98.3%	-1.6% (1.6)

Vessel thrust

Figure 54 shows a plot of measured and predicted available thrust (tow force) versus engine RPM and trawl speed. The two values agree quite closely when the motor is driven near its rated output power (1550rpm), but there are considerable differences when the motor is lightly loaded. For lightly loaded situations the predicted available thrust is higher than that measured. This most likely occurs because the prediction model is tuned to make accurate predictions for semi-optimal engine power/propeller combinations. For light engine load scenarios the propeller would be far bigger than optimal and therefore will produce less thrust than is feasible from this propulsive technology.

From the point of view of the PTPM and the majority of its applications it is not an imperative to perform well for lightly loaded engine situations, however it is important to see the good results at high RPM where commercial trawling occurs.

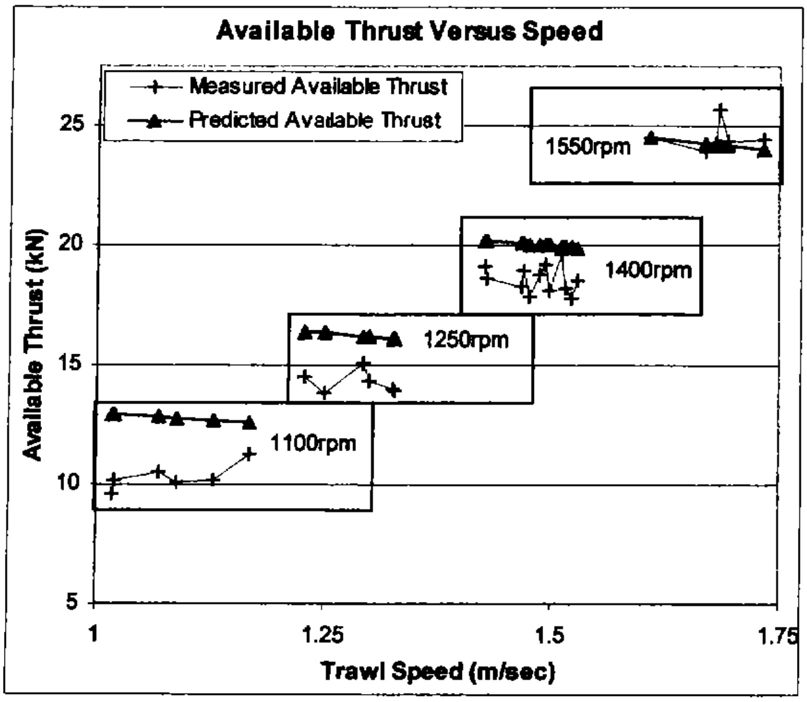


Figure 54 Comparison of measured thrust and predicted thrust versus engine RPM and trawl speed.

Ground effect models

Contrary to initial expectations it has not been possible to this point to get close enough to the issue of ground effect to make any detailed assessment of the PTPM's performance in this area. This has come about because of the problems associated with accurately modelling the trawl gear under the test conditions due to the complex peculiarities of the testing regime.

The ground effect model contributes about 20% of the total drag predicted for the trawling systems considered here. In the discussions above there has been no suggestion that errors within this component of the prediction process might give rise to some of the inconsistencies between predictions and observations. This could well be an oversight because the magnitude of the ground effect forces is sufficient to influence the prediction performance indices to an extent comparable with the prediction errors that have been identified. Additionally the model for ground effect does interact with variables that are correlated with the trend in prediction errors (eg speed, span and trawl size).

It would now appear prudent to undertake a more thorough approach to accounting for the shape and orientation of the ground chain (see section 2.3.5.3). A stronger relationship between ground chain incidence angle and spread ratio could well explain some of the disparity in predicting span for small nets compared to large nets and also the tendency for predicted drag to be relatively insensitive to speed compared to observations. There is however the problem that such change to the ground effect model would generally increase the predicted total drag of the trawl systems, which is an area where the PTPM already over predicts. Nevertheless this effect may be balanced by other issues or be resolved by interactions between ground effect forces and others (eg otter board lift and drag).

Further work in this area should begin by making more rigorous the connection between ground chain drag and trawl span.

3.2.2.3 Conclusions and recommendations

The PTPM and geometrical model for triple rig quite closely agrees with the measured data, particularly at typical trawl speeds (1.25 to 1.5m/sec) where errors in both overall drag and total spread are less than 5%.

A number of difficulties arose in trying to accurately model the trawling systems that were the subject of the sea trial tests. These difficulties came about mainly because of the peculiarities of the testing situation rather than the difficulties of modelling commercial trawling systems generally. Nevertheless, comparing PTPM predictions with the sea trial observations represented a valuable opportunity to take a close look at the strengths and weaknesses of the PTPM and the problem of collecting appropriate data for the purpose of PTPM validation/calibration.

The collection of further sea trial data that is un-compromised by asymmetry and distorted trawl nets would be valuable for further refinement of the model. A general weakness exposed in the PTPM by the existing data set was the model's capacity to deal with trawl systems that contain nets that are not towed square. Although this does not represent a scenario that is commercially desirable, a model that encompasses these issues would be a worthwhile tool for finetuning the design of prawn trawling systems and quantifying the impact of un-tuned gear that can arise from a variety of situations (eg. incorrect sweep extensions, usage of odd nets in a trawl system, unequal warp length, vessel crabbing due to side winds and currents and unequal otter board forces). To make advances in this area flume tank studies are required to establish the effect on frameline tensions caused by trawls being out of square.

Other areas of significant uncertainty within the modelling environment relate to otter board/trawl net interaction and ground effect forces. An immediate imperative is to make more sophisticated the interaction between ground chain shape and drag. This would be greatly facilitated by the availability of empirical data on the subject.

The persistent problem with the 5 rig cases was the over estimation of span and drag. Errors of about 10% occur in both these areas. The fact that both span and drag are over overestimated makes it very difficult to make adjustments to the model to resolve the inconsistencies. Mechanisms that reduce span without increasing drag, apart from reducing otter board effectiveness, are complex and relate to phenomenon where there is limited empirical information.

Despite the 10% errors in predicting span and drag, the error in predicted trawl speed is considerably smaller and because it is in the opposite direction to the error in span the resulting error in predicted swept area rate is only about 3% in the worst case.

Predictions and observations corroborate to confirm that the 5-rig system is more efficient in terms of area trawled per unit of fuel consumed than 3 rig. For commercial operations and taking into account the effective span of the system that relates to the proportion of the path actually swept by netting and not bare wires (sweeps), the swept area rate of 5 rig is about 10% higher than 3 rig for the same vessel input.

3.3 Data from Six Way Otter Board Evaluation

3.3.1 Introduction

This section of the thesis looks at the ability of the PTPM to predict the engineering performance for a number of trawling systems tested in Northern Tasmania in 1991. These tests had the objective of measuring the engineering performance of 18 different single rig systems for the purposes of evaluating the relative performance of six different otter board designs. These tests and their results are fully reported in Sterling (2000b).

The particular aspects of the PTPM that can be influenced by this data set mainly relate to the effect of otter board design. This can be pursued in reasonable detail because not only was trawl gear drag and span measured for various speeds, but attempts were made to measure otter board angle of attack. Integral to the workings of the latest version of the PTPM and the calculation of trawling performance is the model's ability to predict otter board angle of attack. The opportunity to scrutinise the model's performance in this area is therefore very important.

For each otter board type, tests were conducted on three different sized nets (see Sterling (2000b) for details). This allows an additional opportunity to check the performance of the PTPM with respect to accurately dealing with trawl net size.

The seabed conditions were very different for the Tasmanian tests compared to the Hervey Bay trials. In Tasmania the seabed was firm fine sand as would be expected on a fairly high-energy beach (north facing beach in Bass Straight). For Hervey Bay the seabed conditions were much softer and typical of southern Queensland commercial trawling areas (west facing beach on eastern side of Hervey Bay).

3.3.2 Methodology

A graphical comparison of model predictions with data measured in the field is carried out. Variables compared are trawl gear drag, trawl gear span and otter board angle of attack.

Only one half of the data available from the six way otter board analysis was used to scrutinise the PTPM. This related to tests conducted on the Flat Rectangular, Bison and Kilfoil otter boards. The PTPM currently does not contain code that allows predictions to be made for the other three otter boards tested in Tasmania. These otter boards are not commonly used commercially so there is little imperative to include those as options within the model.

No data is available to quantify the difference in seabed characteristics between the Tasmanian north coast and within Hervey Bay, however based on a the notion that the seabed in Tasmania was much firmer, ploughing forces within the model were set to zero for the Tasmanian tests. Friction however was still included and assumed to have the same Newtonian coefficient as for Hervey Bay.

In the process of comparing predicted and measured angle of attack, the measured values were re-examined with a more detailed methodology for correcting for bridle angle. The outcome of this step saw all measured values decrease by about 1.5deg because the revision took into account the effective width of the otter boards in the estimation of bridle angle for each case. For this reason the measured values of angle of attack are slightly lower than those reported in Sterling (2000b).

Only a qualitative comparison of the predicted and measured values was undertaken in this section. The objective was to explore the prospect of improving the PTPM by, in this instance, looking for unique factors that are associated with inconsistent PTPM predictions.

3.3.3 Results and Discussion

Figure 55 shows a graphical comparison of predicted and measured drag and span for the 9 trawl systems considered. Figure 56 shows a similar comparison of measured and predicted otter board angle of attack.

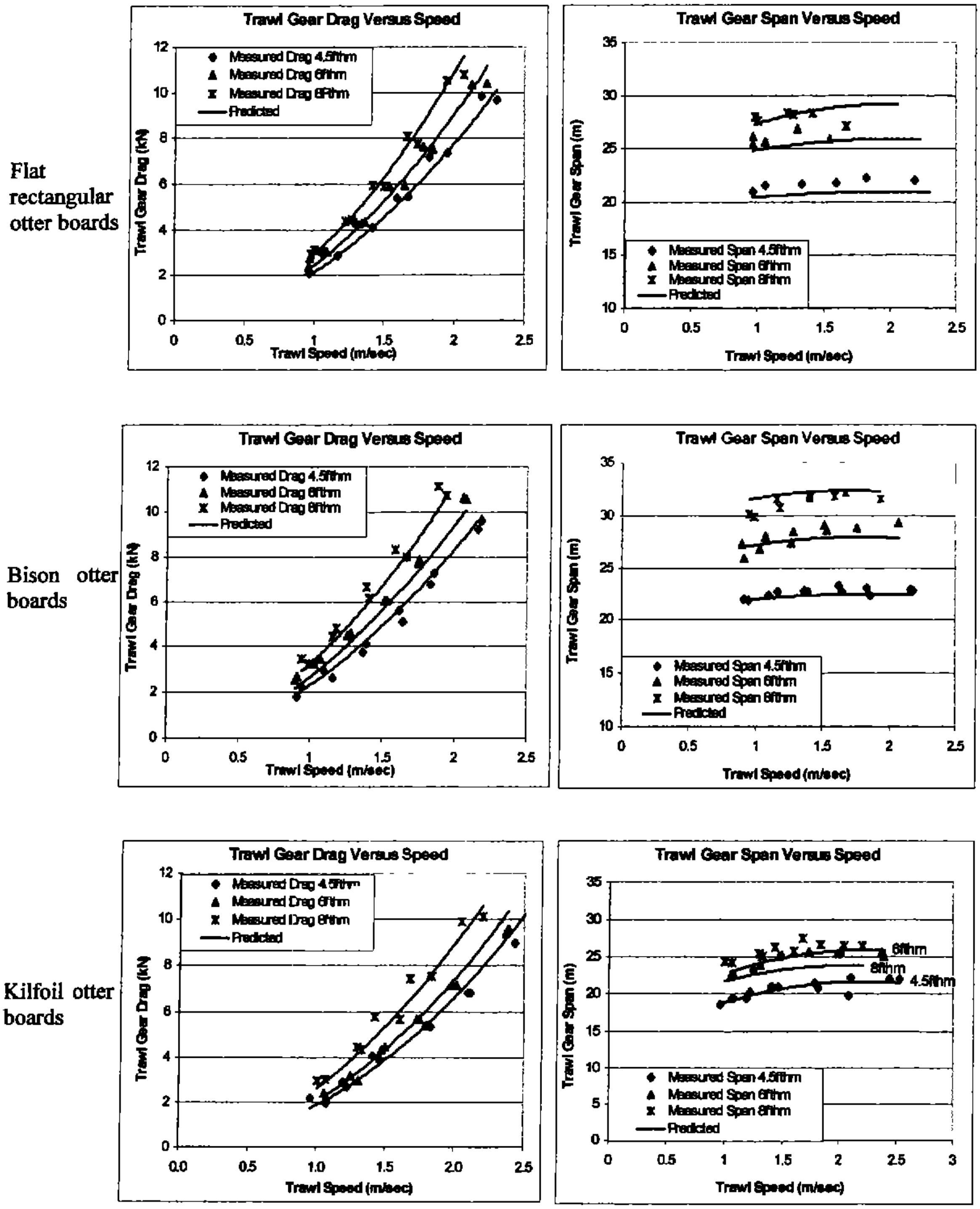
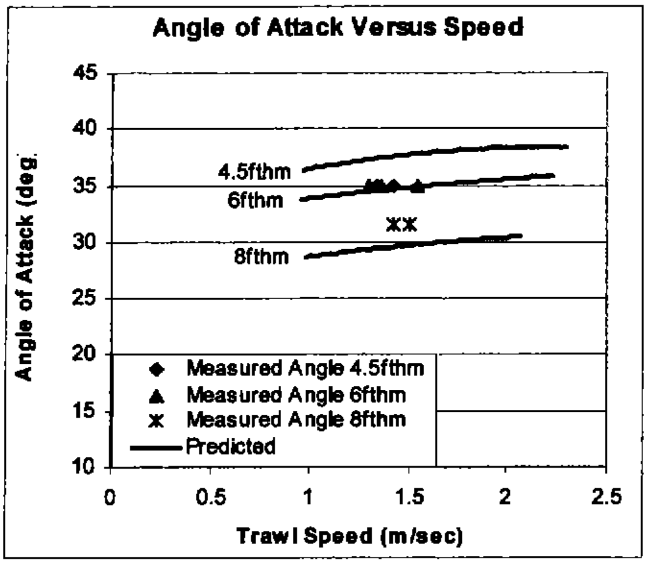
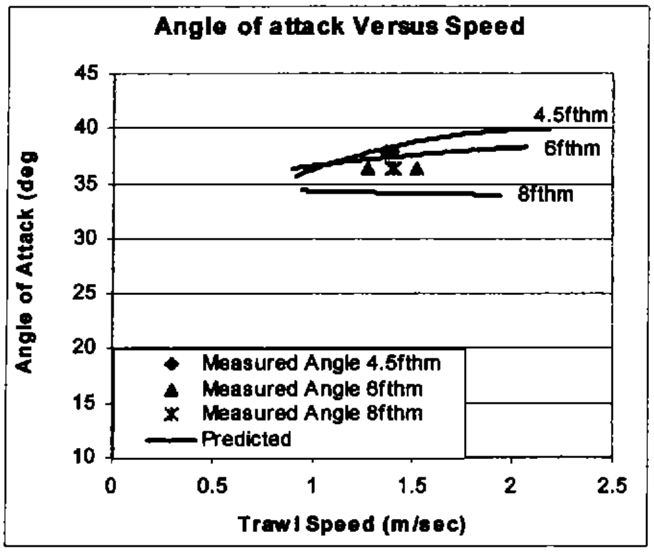


Figure 55 Measured and predicted trawl gear drag and span for single rig and three otter board designs over a range of trawl speed.

Flat rectangular otter boards



Bison otter boards



Kilfoil otter boards

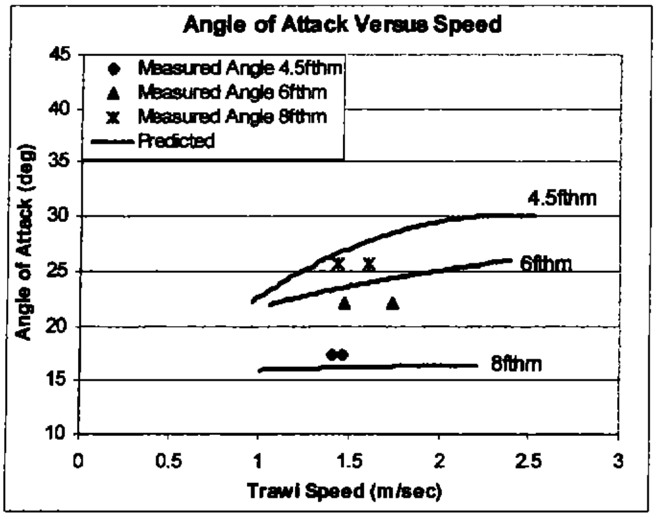


Figure 56. Measured and predicted angle of attack of otter boards for single rig and three otter board designs.

Flat rectangular otter board.

For the Flat rectangular boards, drag and span predictions agreed with measurements with less than 5% error. The otter boards in question were heavily slotted (12% of plan area). For this reason the predictions were made based on applying the 0.85 slot correction to the 0.9 flat board correction devised in the previous section. This gave an overall effectiveness correction for the flat boards of 0.765.

The biggest residual errors for drag and span associated with the Flat rectangular boards are those relating to the span of the 4.5fthm trawl. Here the predictions are consistently below observations across all speed conditions by about 4.5%.

This error in span appears to coincide with a significant prediction error in angle of attack for the 4.5fthm case. The over prediction of angle of attack by the PTPM would contribute significantly to the under prediction of span because over the angles in question the lift coefficient is falling (see Figure 33 of section 2.3.4). These prediction errors may well be the result of uncaptured interaction between otter board angle of attack and otter board tilt (pitch) caused by a varied balance of frameline tensions between the different sized nets. Such interactions are modelled by the 3RDOF otter board orientation model of Sterling (2000b), but were considered impractical for a general performance prediction model because the mechanisms involved are sensitive to the amount of lead built into the net, bias in the way that the trawl is constructed (ie how drag is transferred to the headline and the footline), the headline gape parameter and the spread ratio of the net during operation. It is perhaps premature to try and immediately implement these features into the PTPM because, apart from the complexity of the 3RDOF otter board orientation model in this respect, the strength of the interactions have not yet been fully quantified. However, it would seem that this might be an objective for future work.

It is interesting that the prediction error for the small net in this situation is the opposite of that experienced for the Hervey Bay data. For the latter there seemed to be a consistent over prediction of span. This does supply circumstantial evidence that the errors for the Hervey Bay data are connected with ploughing effects because they are considered to be non-existent in the Tasmanian trials and significant for Hervey Bay.

In view of the fact that there is some degree of uncertainty about the effectiveness of the otter board, a method was devised to explore what the optimum assumption regarding the effectiveness of the otter board would be based on minimising the errors between predicted and observed drag and span. This was achieved by using the secant method to establish a value for the otter board effectiveness parameter in the PTPM that gave the sum of errors approximately equal to zero. This method found the value where the sum of negative errors associated with predicted drag and span approximately equals the sum of positive errors. It is assumed that this gives approximately the same result as minimising the square error. Least square error was not used as the objective because Solver, the Excel based optimiser, was fully occupied with optimising individual PTPM calculations and could not be called upon to optimise the large scale optimisation that involved 32 separate Solver based PTPM calculations in each prediction update. By searching for an objective where the sum of errors was equal to zero an algorithm based on the secant method could be used to control the large-scale search for the optimal otter board effectiveness.

In the case of the Flat rectangular otter board the optimal otter board effectiveness was 0.79. This was only slightly higher than the value of the parameter specified for predictions in Figure 55.

Bison otter board

In the first instance predictions of drag and span for the Bison based trawl gear were generally low. This indicated that the effectiveness of the Bison boards was higher than that assumed by the PTPM and as indicated by Edmondson (1994b). This is a very plausible result because the physical form of the Bison board lends itself to be susceptible to Reynolds number effects. For Bison boards the hydrodynamic forces are generated on three curved plates. Flow separation on these curved plates is likely to be Reynolds number dependent and such variation in separation phenomena will likely cause variation in hydrodynamic lift and drag. The general effect that is to be expected is that at full scale where Reynolds number would be typically 6 times higher than model scale, flow separation will be delayed to higher angles of attack. Therefore at full scale and at high angle of attack it is quite likely that the effectiveness of the Bison board is higher than indicated by the forces measured on model boards in the flume tank.

The optimum correction for effectiveness was determined using the method described for the Flat board above and gave a result of 1.15. This value was used to produce the prediction results given in Figure 55 for the Bison board.

Unlike the situation for the Flat boards there is no evidence in the results that the prediction of span for the smallest trawl is low compared to the larger nets. There is however some evidence that the observed span reduces at low trawl speed to a greater extent than predicted by the PTPM. This suggests that friction may be more dominant in the gear than assumed by the model. If the assumed friction on the ground chains were increased span predictions would decrease, particularly at low speed.

There is also a clear pattern in the drag information that is worth documenting. Figure 55 indicates that the PTPM over predicts drag for the 4.5fthm net and under predicts drag for the 8fthm net. This could also be due to the interaction between angle of attack and tilt as mentioned for the Flat board. In this case variation in angle of attack may not cause changes in span because the lift coefficient is not sensitive to angle of attack over the range of angles concerned however the hydrodynamic drag curve rises steeply with angle of attack between 35 and 40 degrees. Based on the expected effects in relation to tilt, it is plausible that the angle of attack is higher than predicted for the 8fthm net and lower than predicted for the 4.5fthm net. Comparison of predicted and measured angle of attack shown in Figure 56 does not rule that out as a possibility.

Kilfoil otter board

Generally it was found that the behaviour of the Kilfoil board was very difficult to predict. The measurements taken for these boards indicated that the span was relatively low and the angle of attack was very low as well. Most peculiar was the observed result that the angle of attack for the 8fthm net was higher than for the 4.5fthm net. This is opposite to the general result for all the other otter boards tested and the associated PTPM predictions. The PTPM predictions of angle of attack for the Kilfoil boards failed to reproduce this feature of the board's behaviour (see Figure 56). It is a mystery why this phenomenon comes about, but it may be associated with the effects of tilting forces applied to the board by the nets. Much effort was applied to try and find a scenario of applied forces that can give rise to the observed results. The scenarios investigated generally relate to instituting relatively large ground effect forces on the otter board shoe to investigate whether it appears plausible that this is sufficient to manipulate the angle of attack in the desired way. So far no conclusive solution has been found and more full-scale data is sought to supplement the current data.

As a result of the very low predicted angle of attack for the 8fthm net the predicted span for that case is also much lower than measured (see Figure 55). The predicted span is so low that it is actually less than for the 6fthm net. Predicted drag for the 8fthm net is also low.

Predicted span and drag for the 4.5 and 6.0fthm nets agree well with the measured data, however the predicted angle of attack for the 4.5fthm case is too high.

Much of the problem with gaining agreement between predictions and measurements for the Kilfoil case may be due to rigging the Kilfoil boards during the tests in a way that is not typical of commercial operations. The measured angles of attack and predictions are typically less than 25 degrees. Given that normally the angle of attack desired by industry is close to that which gives maximum lift, it does not seem logical to rig the boards such that they give attack angles less than 25 degrees when flume tank data shows that maximum lift occurs at about 40 degrees angle of attack (Edmondson, 1994b) (see Figure 35). At such higher angles of attack the boards are likely to behave in a more typical and predictable fashion.

3.3.4 Conclusions

Comparison of PTPM predictions with the Tasmanian data set produced an excellent opportunity to closely investigate the performance of Flat, Bison and Kilfoil otter boards and the PTPM's ability to predict their performance.

The difference between predicted and observed measures for the Flat and Bison boards in terms of drag, span and angle of attack were generally less than 5%. A large component of the residual errors may be connected with complex interactions between the balance of forces in the framelines of the trawl and the resulting subtle effects on otter board orientation in terms of roll, pitch and angle of attack. Prediction errors were substantially higher for the Kilfoil boards, where there appears to be a significant and unknown fundamental issue with the operation of Kilfoil boards that is not captured by the PTPM for this particular case at least.

The Flat board results appeared to confirm the need to reduce the assumed effectiveness of the Flat rectangular board in line with section 3.2.2.2 while the Bison results indicated that the assumed effectiveness of the Bison board needed to be increased by 15%.

Of great significance to concerns raised from the Hervey Bay data, there did not seem to be any evidence that the PTPM over predicted span for small trawls in the Tasmanian situation. This perhaps indicates that the cause of prediction problems in the Hervey Bay context is associated with the calculation of ploughing forces.

There was some evidence that further work on ground effect forces in the Tasmanian situation is also warranted although it does only relate to prediction errors at low speed.

Discrepancies between predictions and measurements of various forms for the three otter board types seemed to fit a common hypothesis that a mechanism involving otter board tilt may contribute strongly to the residual errors.

The Kilfoil otter board as tested in Tasmania represented a very difficult subject for modelling and performance prediction. Given that this board is heavily utilised in some prawn trawling fisheries it would be valuable to collect more full-scale data associated with its commercial operation.

3.4 Northern Prawn Fishery Catch Data

3.4.1 Introduction

For prawn trawling operations a heuristic assumption may be made that the catch obtained is proportional to the area of seabed swept by the trawl gear subject to spatial variation in abundance of the target species. The rate that the seabed is swept is governed by the size of the trawl gear, how far it is stretched laterally and the speed that it travels across the bottom. Therefore it is proposed that swept area rate is a factor associated with catch and that gear size, spread ratio and trawl speed are sub factors. For each sub factor there are a number of interacting mechanisms and many trawl system variables involved in determining its magnitude for a given trawling operation. The PTPM attempts to numerically model these mechanisms and, based on known trawl system variables, predict the magnitude of those engineering factors and sub factors highlighted above as contributory to catch.

This section of chapter 3 looks at the strength of association[1] between predicted engineering factors and catch taken between 1970 and 2000 by trawlers that have operated in the tiger prawn fishery of the Northern Prawn Fishery (NPF). This work therefore investigates a general hypothesis that tiger prawn catch equates significantly with predicted swept area rate (SAR) from the PTPM and broadens the focus of validation from the model's engineering accuracy to encompass the assertion that SAR is a reasonable proxy for catching performance in certain circumstances.

Figure 57 shows a scatter plot and a line of best fit for daily catch[2] against predicted SAR for most trawlers that fished in 1998[3]. There is a measurable trend in the data whereby the proportional regression line shown in Figure 57 is highly significant at $\alpha < 0.0001$ (based on ANOVA). Each SAR measure on the x-ordinate represents a unique subject within the considered population of trawlers and the ANOVA result shows that not only is there a significant difference between subjects based on their measured daily catches, which may be inconsequential and an artefact of very high statistical power, but when the subjects are plotted on a SAR scale a proportional coefficient calculated by finding the line of best fit based on least squared error between measured and predicted catch provides a very significant explanation of average catch. The practical significance here is intensified because the relationship being scrutinized is the proportional correlation not the more typical linear

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[1] This is also called *effect size* or *treatment magnitude* TABACHNICK, B. G. & FIDELL, L. S. (2001) *Using Multivariate Statistics,* Needham Height, Allyn & Bacon.

[2] Catch is the calculated economic catch, which is the weight of tiger prawn plus ½ the weight of endeavour prawn.

[3] 1998 is used to demonstrate these affects because a technology survey of NPF trawlers occurred in that year and the predictions of SAR are the most accurate for all years of fishing in the NPF.

correlation, which leaves open the possibility that the change in measured catch across the range of measured SAR, although statistically significant may be small and of no practical importance. For the proportional relationship the change in predicted catch across the range of SAR is forced to be proportionally linked to SAR whereby the Y-axis intercept is forced to be zero.

To establish the strength of association between SAR and catch it is usual to find the proportion of variation in catch that is associated with variation in SAR. For continuous independent and dependent variables the squared correlation (R^2) is a measure of this. Figure 57 shows R^2 for the proportional regression.

Despite the very high significance of the proportional model the R^2 value is very small and indicates that only 6.7% of the catch variation is explained by the proportional relationship with SAR. This fact forces this work to recognise that the crucial question here is the strength of association between SAR and the fishing capability (or fishing power) of the trawlers and not specifically daily catch, which may be subject to immense variability due to the nature of the fishing environment and in ways that cannot be substantially mitigated through the efforts of operators. In fact such large variability occurs because of large environmental variation of prawn abundance in spatial and temporal dimensions. What is required is a measure of strength of association of SAR in terms scoped by operational factors and effects.

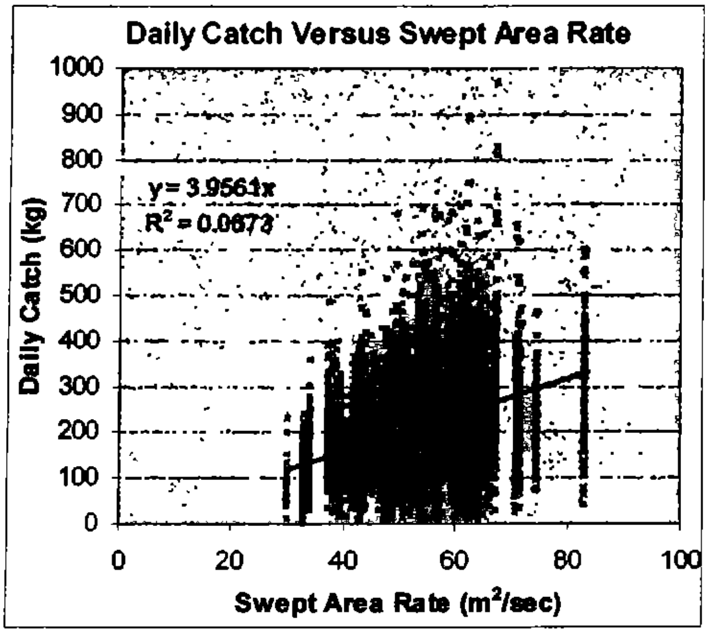

Figure 57. Regression of daily catch against swept area rate (SAR) for a variety of trawlers that fished the 1998 season (March – November).

Figure 58 helps to explain why a proportional model fitted to the swarm of scattered catch data is strongly significant despite explaining only a small extent of the catch variation. The model is significant because it reliably predicts the average catch for each level of SAR and the scatter plot in Figure 57 does not effectively portray the extent that the catch measures are concentrated on the model line. Alternatively Figure 58 presents a contour plot of the frequency of catch measures plotted on the Catch-SAR plane. This more clearly describes the structure of the raw data. To establish the strength of association indicators that are sought it is evident that some processing of the data needs to occur. It is apparent that averaging the catch for each trawler over the season would give a measure of catching performance for each subject that would inherently produce model fits with a higher and more meaningful strength of association (R^2) indicator. The process of averaging the catches over the season for each trawler would remove the effect of many nuisance variables that affect the catch taken. These nuisance variables are discussed below along with a number of issues that need to be carefully considered and which may give rise to more optimal aggregation of the data.

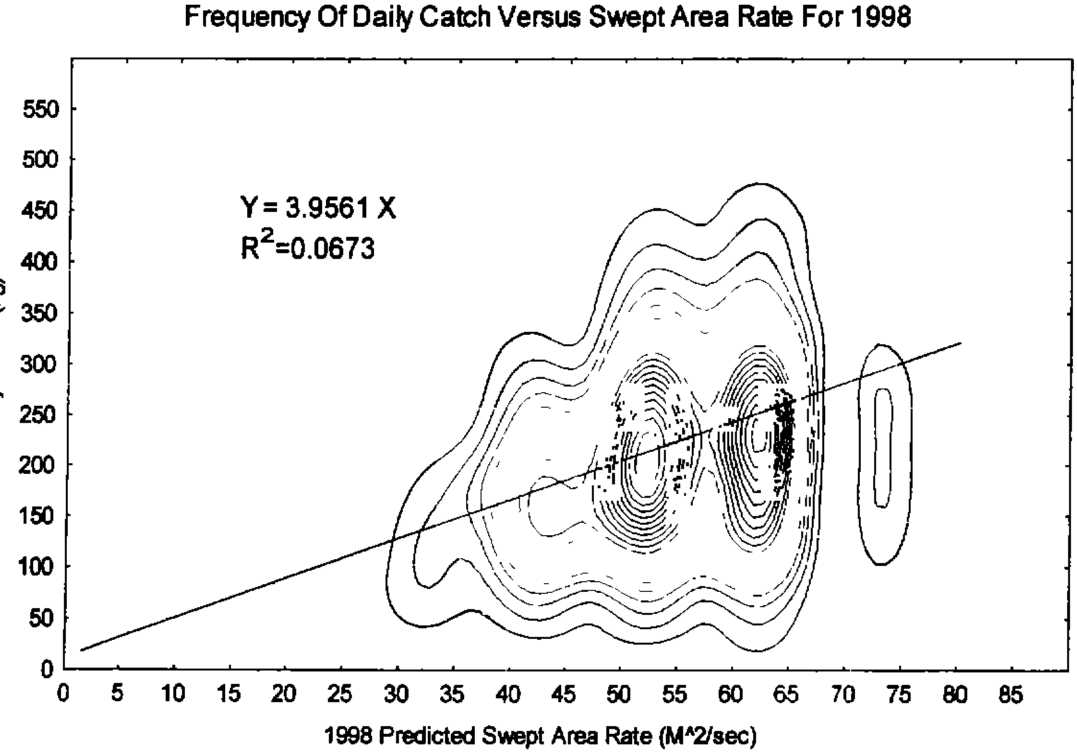

Figure 58. Distribution of daily catch with respect to swept area rate.

From the fishing perspective, forward knowledge of variation in spatial and temporal abundance is important but limited because the best place to fish at a particular time in the season varies from year to year and also depends on the history of fishing for the current season. Despite the skipper's experience of past years and information that is shared between skippers, establishing the best place to fish in the tiger prawn fishery is always heavily reliant on conducting trial trawl shots to search for the best catch rate. The ongoing experiments conducted by individual skippers, the incomplete sharing of the resulting information and the dynamic nature of prawn abundance gives rise to a large and perpetual variation in daily catches for individual boats.

Against this backdrop it is proposed as above that a boat that produces a high SAR with its trawl gear will on average catch more than boats with a lower SAR. In particular, the hypothesis to be tested is that SAR is one of the most important operational factors governing fishing performance in the tiger prawn fishery. There are many other operational factors and associated variables that also affect fishing performance. These will relate to the ability of each operator to search for good catches, process information, communicate with other operators to establish their experiential knowledge (without giving away too much of their own), maximise fishing time, achieve maximum catching efficiency and maintain peak SAR.

In order to establish the strength of association between fishing performance and the various operational factors that play a role, it is desirable to remove from the catch data the effects of nuisance variables. In this instance nuisance variables are all those that are not directly connected to the configuration and operation of any fishing activity. Nuisance variation in catch are associated with environmental factors (eg. substrate type, availability of food) that cause spatial variation in abundance; lifecycle factors peculiar to the target prawns (eg. migration, lunar effects, natural mortality) that cause both temporal and spatial variations in abundance and, paradoxically, fishing itself, which does play a role in causing temporal and spatial variation in abundance, but in a way that to a considerable extent is unknown to individual fishers. As fishing occurs abundance becomes locally depleted depending on the rate of fishing (this may be rejuvenated in short time scales by prawn migration) and there will be an associated exacerbation of abundance decline over the season.

To separate operational affects on catch at the boat scale from nuisance effects caused by environmental, prawn lifecycle and fleet wide factors a statistical model for catch was employed. The approach was to use the statistical model to convert the multitude of daily catch records covering all vessels in the fleet to a set of relative fishing power (RFP) parameters, one for each boat that fished in a given year. These parameters need to reflect the relative effectiveness of each vessel to catch prawns whilst challenged by the conditions imposed by the fishery for a specific period of time. Correlation between RFP and SAR or any other operational factor can be the basis of establishing the strength of association and determine the relative significance of operational factors. The details of this approach are covered in the next section.

Two issues drive the investigation of the relationship between predicted SAR and catch. Firstly there is the question of the utility of PTPM based predictions in context with real world problems associated with fishing power (eg. managing effort, efficiency, and equity in prawn fisheries). The extent of utility depends on the strength of association between predicted SAR and catch. If there is a low association then the SAR factor is of little interest to management. Secondly, there is the question of consistency. Accuracy and its consistency were heavily investigated in previous sections in connection with comparing PTPM predictions with direct measurements of engineering variables obtained during trials of commercial trawl gear at sea. Nevertheless the NPF dataset does present an independent opportunity to further investigate whether the relationship between catch and predicted SAR is consistent across important variable dimensions.

Catch information from a 30 year period (1970-2000) of NPF history was available for analysis. This covers time periods where a number of different scenarios were at work.

Over the period 1975 to 1983 the fleet generally moved from double rig to quad rig. In 1980 the fleet was divided almost in half in terms of those that towed double rig and those that towed quad rig. In that year there were also a small number of boats that used triple rig. These years provide an opportunity to investigate the relationship between predicted SAR and catch rate in context with an interaction with rig type.

In 1987 management measures were applied such that the entire fleet was legislated to use only double rig.

In 1990 the fleet was entirely double rig, however the fleet was split into a group that had a Global Positioning System (GPS) and a group that did not. There was also a substantial proportion of the fleet using Bison boards as opposed to the simpler Flat rectangular design.

In 1998 the Australian Fisheries Management Authority (AFMA) with the expressed objective to collect all input data that was required to run the PTPM undertook a detailed survey of vessel and gear characteristics (Bishop and Sterling, 1999). Therefore in years close to 1998 the input data to the PTPM is likely to be the most complete and accurate.

3.4.2 Methodology

3.4.2.1 SAR predictions

For this task it was ideal to have good SAR estimates for every boat in every year that it supplied logbook records of catch. Approximately 80% of all days fished for tiger prawns in the study period are covered by a logbook record. However, as many as half the fishing days in the late 1970's were missing from logbook records and it was not until the late 1980's that logbook returns approached 100%.

Based on the AFMA database of NPF vessel characteristics compiled by CSIRO Marine Research, the SAR for all boats that had logbook records was estimated. Data was processed in batches according to trawl systems type (eg. single, double, triple, quad) and three levels of missing information. For each level, SAR was estimated using a slightly different strategy that involved necessary assumptions linked to the inability to run particular blocks of the PTPM because of the missing information.

The quality of the input data is an important issue with respect to this work, but it is something that is largely beyond influence. Generally data from the end of the period was complete and was the result of the dedicated fleet survey in 1998. Prior to this the quality of the data rapidly degrades. Very quickly less crucial information like specific details related to the design of the trawl nets or the operation of the engines becomes unknown. Further back in time more crucial information like engine power, propeller diameter or trawl size becomes uncertain. It became common for records from the early part of the period to have many missing pieces of information. The overall solutions to these missing data problems involved the application of one of two approaches in each instance.

1. Missing data was imputed using cluster analysis.
2. Assumptions could be made at the point of SAR prediction regarding the process at work. For example where otter board information was missing it was assumed that the spread ratio of the trawl system was equivalent to the estimated average from all other vessels using the same rig type.

Cluster analysis and imputation within the NPF database was undertaken by CSIRO staff with the objective to produce the most "representative" database of NPF vessel configuration possible.

Although all data items were flagged with confidence ratings no attempt was made in this work to select a subgroup of the data that exceeded a defined quality standard. It was generally presumed though that the quality of configuration data for boats that produced logbook returns for catch would be higher than for those boats that didn't.

3.4.2.2 Synthesis of catch data

As outlined above in the introduction the approach adopted to synthesise catch data was to utilise a simple statistical model for daily catch that was based on having a relative fishing power (RFP) parameter for each trawler in every year. This gave a catch prediction model that depends on the fishing power of the vessel as derived from regression of the model against the logbook catch records. The difference between the predicted catch and the real catch on any day approximately includes the effect of all nuisance variables, while the RFP parameter for each boat ideally captures the total effect of all operational factors and variables that have a bearing on fishing performance and are connected with that boat. The RFP value for each boat is very similar to its average catch rate, however there are a number of important differences that ensure that bias is minimised.

Bias in the estimate of fishing power for each vessel will occur as a result of any undesigned interaction between the activity of the boat and nuisance variables that either improve average daily catch or reduce average daily catches. For example, a boat will incorrectly be given a low RFP value if through breakdown it fished for only the last part of the season when catches are generally lower. To reduce the incidence and extent of such bias, relevant correlation between the variation in catch about that explained by RFP and nuisance variables was explicitly modelled. The statistical model utilised in this exercise included a parameter for each week in the season. This standardised catches for the time within the year and reduced bias for those vessels that did not fish throughout the entire season. Moon phase was not included in the model because the parameters for week were considered to be sufficiently fine scale with respect to time that lunar effects could be expected to be adequately captured. Spatial modelling of the error term was not considered appropriate because this would remove the opportunity for RFP parameters to reflect the differing capacity of vessels to successfully establish and participate in fishing at the best location (in a broad scale sense).

A linear model estimated RFP parameters. Each record in the analysis contained daily catch information for vessel *i* during week *t* of year *k*.

The log catch of vessel i fishing in year k and week t, was estimated to be

$$\log(C_{ikt}) = \delta_0 + \sum \alpha_{ik} X_t + \sum \beta_{ik} V_t + \varepsilon \qquad (46)$$

where C_{ikt}= is the daily economic[1] catch weight in kg for boat *i* fishing in year *k* and week *t*.

Explanatory variables included terms for weekly abundance and vessel (Table 14). The logarithm transformation of catches was used because it was more normally distributed about the mean catch for any scenario defined by the independent variables (ie. a given boat in a given week) and was more homoscedastic[2]. The model was run separately in each year so there is no year term, but the k notation here refers to coefficients from separate models for each year.

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[1] Weight of Tiger prawn catch plus one-half the weight of Endeavour catch. This approximately reflects the market value of the total catch.

[2] The variability in the dependent variable is similar at all levels of the independent variable.

SAS PROC GENMOD was used to fit log(catch) and estimate the parameters. The results held a RFP series for every year of all boats that fished in that year and a series for every year of weekly abundance. These were based on prawn catches that occurred over the months August to November. The process involved approximately 460,680 daily catch records associated with 745 different vessels that fished in the NPF over the 30 year period.

Table 14. Symbols and descriptions for main effects and interaction parameters in the fishing power model.

Symbol	Definition
δ_0	The intercept: mean catch for standard vessel fishing in baseline week
X_t	X*t* are the week identifiers
α_{tk}	Coefficients for weekly prawn abundance terms in each year, to be estimated
V_i	V*i* are the vessel identifiers
β_{ik}	Coefficients for vessels in each year, to be estimated
ε	Error terms

The RFP series for each year was normalised in the SAS procedure to the arbitrary last boat in the vessel list. Each RPF series was subsequently normalised in Excel such that the average RFP in each year was 1.

3.4.2.3 Strength of association

The principle objective was to compare the variation in the RFP series with the variation in predicted swept area rate (SAR) to establish the degree of variation explained by SAR.

The overall implications due to the issues involved in the derivation of indicators for SAR and catching performance is that the investigation of strength of association has three impacting facets:

- the true strength of association between the independent and the dependent variables
- the degree to which the two variable indicators equate with their physical counterparts given the deleterious effect of process errors
- the accuracy of the two variable measures given the variable quality of the input data.

Figure 59 shows a plot of RFP versus SAR for 1998 and the results of proportional and linear regressions as determined by the standard Excel graphics software. The R^2 results indicate that approximately 55% of the RFP variation is explained by a proportional relationship with SAR. It is known that the variation in RFP is due to a combination of operational factors and chance[1]. A methodology was devised to estimate the breakdown between these two areas with respect to the variation in RFP within each year. Figure 60 shows the variance framework used to develop this method and Figure 61 shows its application for 1998.

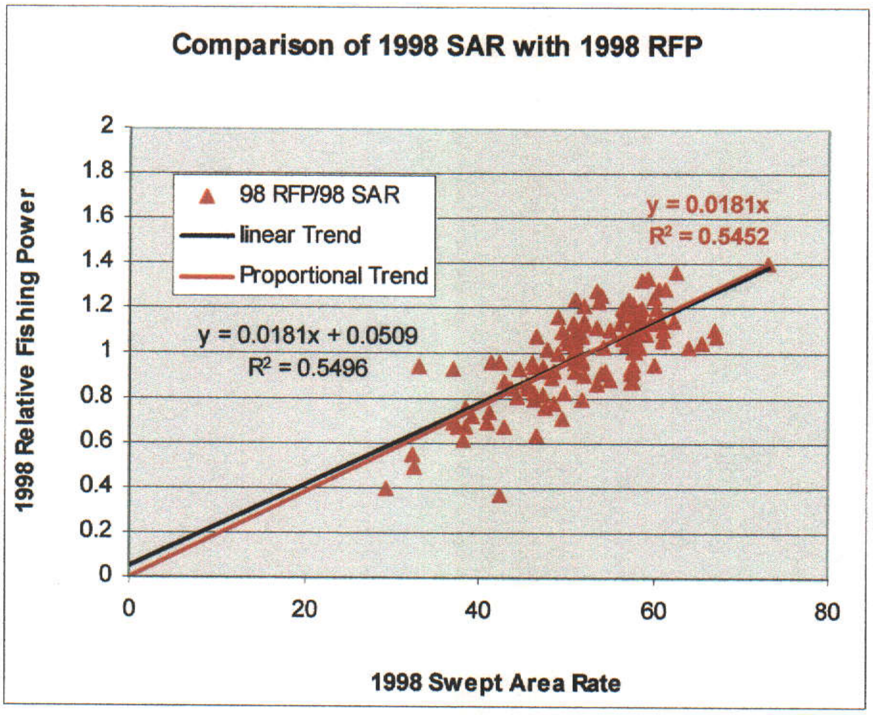

Figure 59. Comparison of Relative Fishing Power in 1998 to Swept Area Rate.

Figure 60 defines a breakdown of catch variance into useful components. Some of these relate to the objectives of the investigation and others are components that can be determined from analysis and are subsequently used to estimate the variance components of interest. The variance model therefore makes explicit definitions of terms used throughout this work and allows identification of assumptions and risks regarding the interpretation of results.

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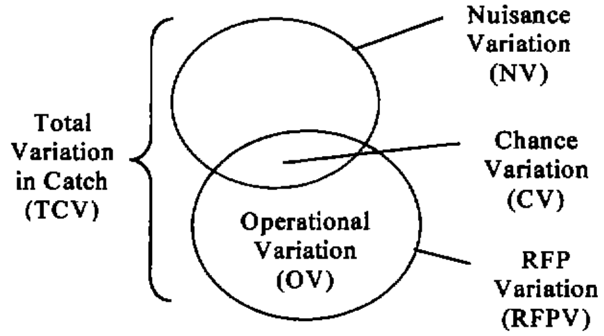
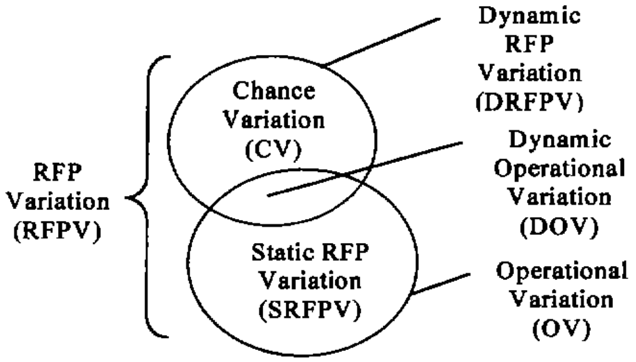
[1] Variation in RFP between vessels due to unintended correlation with nuisance variables. This is detected by the feature that it is not consistent from year to year.

VARIANCE MODEL FOR WITHIN YEAR CATCH

The statistical model for catch based on RFP was used to average out much of the variation in catch due to nuisance variables (NV). The resulting RFP parameters (RFPV) capture operational variation (OV) and chance variation (CV) in average catch.



Static RFP (SRFPV) is estimated by a 3 year average of RFP centred on the year in consideration. SRFPV is assumed to be a better estimate of the variation in operational performance (OV) than RFPV. Unfortunately the process marginally suppresses the effect of erratically applied operational factors.



The prime objective of the work was to estimate the extent to which variation in predicted SAR is correlated with (explains) operational variation (OV) in catch. There are two main issues that contribute to this strength of association. Firstly there is the true strength of association between SARV and OV and secondly there is the extent to which predicted SAR matches real SAR. The strength of association can be estimated by calculating the square correlation coefficient (R^2) for a proportional regression between RFP and predicted SAR. This raises two further issues; the extent that RFPV matches OV and the risk that there is correlation between variation in predicted SAR and the variance of other operational variables that influence catch (OOV), which would bias the results.

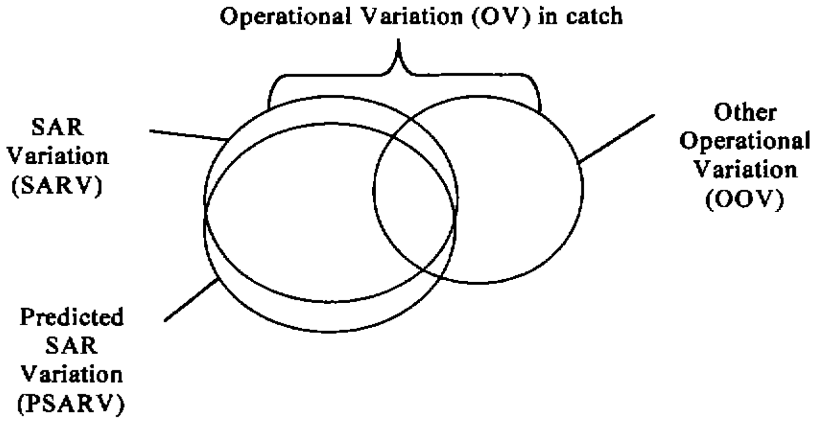
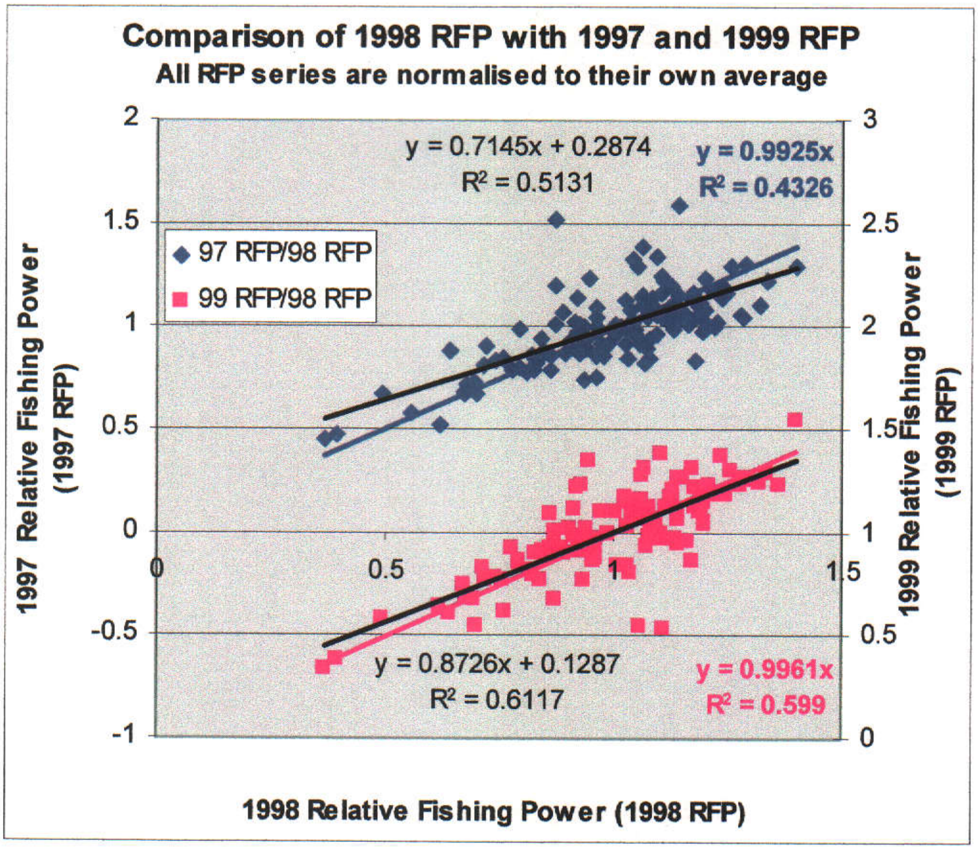
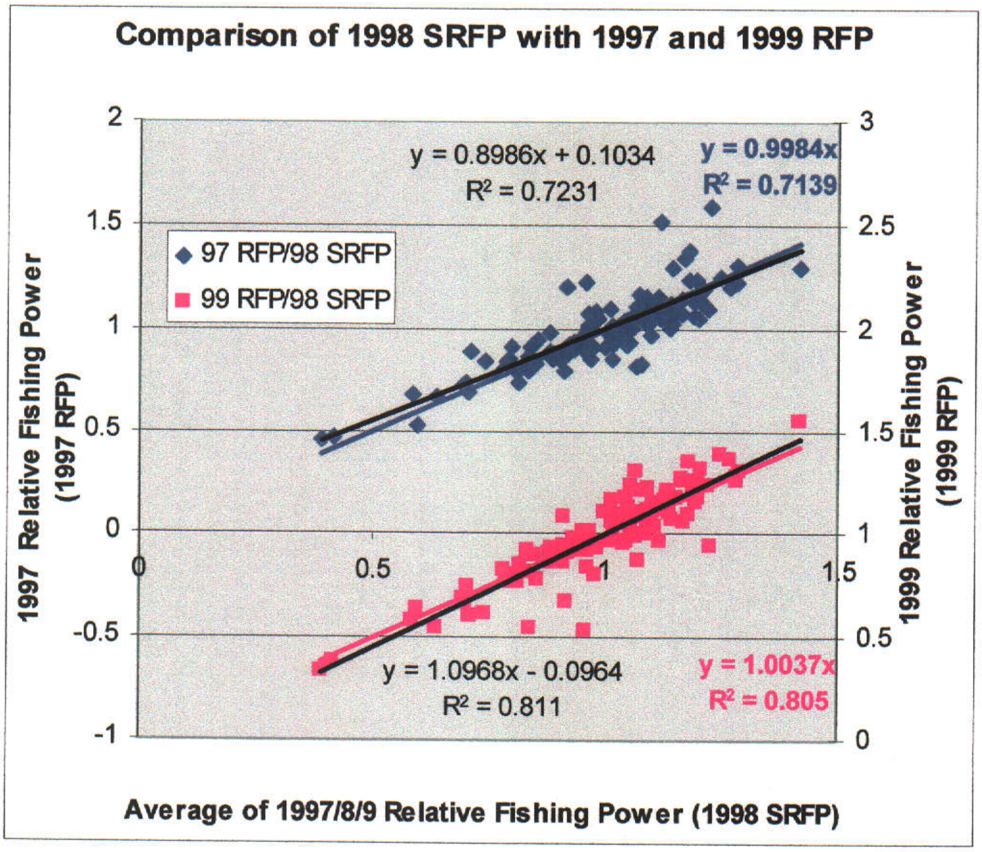


Figure 60. Variance model for within year catch in the NPF and its breakdown into useful components.

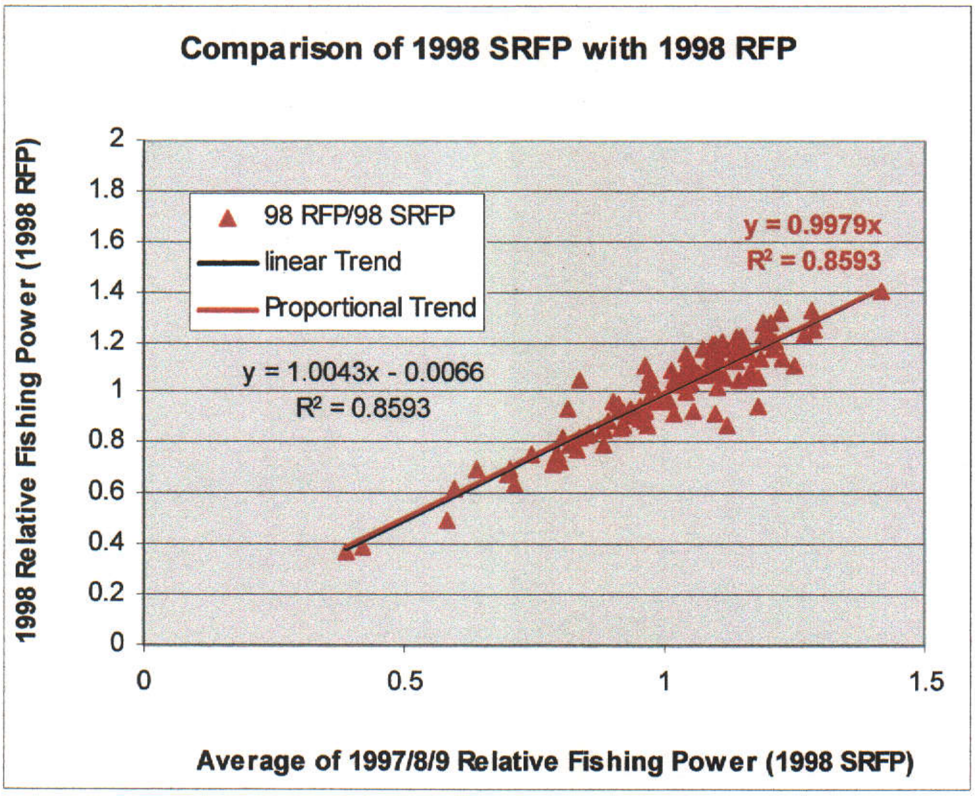
Figure 61a shows the result of a direct comparison of 1998 RFP with that of 1997 and 1999. This exercise was designed to try and indicate the average amount of variation in RFP occurring from year to year for the same boat. The amount of variation in RFP of adjoining years explained by a proportional relationship with the RFP in 1998 is only 43% and 60%. This is very similar to the strength of association between RFP and predicted SAR (R^2 in Figure 59). The result is biased low because the RFP series of 1998 is not free of random error (ie. chance variation, CV). To try and remove some of the random error contained in the 1998 RFP series it was replaced by the average of 1997, 1998 and 1999 RFP series (1998 SRFP). Figure 61b shows the result of repeating the former exercise using 1998 SRFP as the reference instead of 1998 RFP. The variation of 1997 and 1999 RFP explained by a proportional relationship with 1998 SRFP was 71% and 81% respectively. Finally it was established that the best indicator of the breakdown in chance variation in RFP and operational variation in RFP for any given year is given by the method in Figure 61c whereby the variation in 1998 RFP is compared to 1998 SRFP (the 3year average centred on 1998). The result indicates for 1998 that 86% of the variation in RFP is explained by a proportional relationship with SRFP. The remaining 14% of variation is presumed to be approximately the extent of the chance variation in RFP that occurred from year to year at that time. Note that for the first time the variation explained by the proportional relationship is the same as that explained by the linear relationship. This indicates that 1998 SRFP contains a low residual random error because random error in the independent variable tends to stretch its range and cause a negative correlation between the independent variable and residual error in the proportional regression. Such a trend in the residuals is resolved by the linear regression. When the proportional regression and the linear regression give a very similar result the amount of random error in the independent variable must be relatively small. Some of the random variation in the 1998 RFP series will in fact be due to differences between the operational performance of boats in 1998 and that indicated by 1998 SRFP. This will occur because of pseudo-random changes in operational factors, which affect fishing performance, across the fleet over the 3 year period (eg engine modifications, trawl gear changes, skipper changes, electronic changes etc.). Therefore the indication presented by SRFP in terms of the variation in RFP in a year that is due to operational factors is certainly a biased low indication. It is difficult to establish with further accuracy how much of the unexplained variation is actually due to operational factors; the assumption from this point on is that it is small enough to be disregarded for the purposes of the current objectives.


Comparison of 1998 RFP with 1997 and 1999 RFP
All RFP series are normalised to their own average
y = 0.7145x + 0.2874
R² = 0.5131
y = 0.9925x
R² = 0.4326
97 RFP/98 RFP
99 RFP/98 RFP
y = 0.8726x + 0.1287
R² = 0.6117
y = 0.9961x
R² = 0.599
1997 Relative Fishing Power (1997 RFP)
1999 Relative Fishing Power (1999 RFP)
1998 Relative Fishing Power (1998 RFP)
2
1.5
1
0.5
0
-0.5
-1
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5

(a)


Comparison of 1998 SRFP with 1997 and 1999 RFP
y = 0.8986x + 0.1034
R² = 0.7231
y = 0.9984x
R² = 0.7139
97 RFP/98 SRFP
99 RFP/98 SRFP
y = 1.0968x - 0.0964
R² = 0.811
y = 1.0037x
R² = 0.805
1997 Relative Fishing Power (1997 RFP)
1999 Relative Fishing Power (1999 RFP)
Average of 1997/8/9 Relative Fishing Power (1998 SRFP)
2
1.5
1
0.5
0
-0.5
-1
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5

(b)



(c)

Figure 61. Analysis of variation in Relative Fishing Power from one year to surrounding years for 1998.

For a 30 year period since 1970 the breakdown of chance and operational variation in RFP was estimated by the above method and compared to the amount of variation explained by a proportional relationship with 3 engineering factors; trawl gear size, trawl gear span (includes a prediction of trawl gear stretch) and SAR (additionally includes a prediction of trawl speed).

3.4.2.4 Analysis of residuals

An investigation of prediction bias for SAR was undertaken by looking at the relationship between RFP(SAR) regression residuals and system variables. Given that the relationship between RFP and SAR is assumed to be proportional the residuals investigated were calculated from the difference between the logarithms of observed RFP and predicted RFP(SAR). This gave residual plots that were more normally distributed and homoscedastic. The proportional regressions were not optimised by minimising the differences in predicted and observed log RFP because this did not allow straight forward estimates of R^2, that alternatively were conveniently available for proportional regression by least squared error from Excel's graphics routines. It is believed that using untransformed residuals in the regression process has caused minimal bias in the fitting of the models and an insignificant effect on the estimations of all R^2. The distribution of residuals of log RFP against SAR were analysed for every year in the study period to identify if there was any correlation between the residuals and factors driving or correlated with SAR.

Similarly the distribution of residuals with respect to rig type, board type and body taper were also investigated.

3.4.3 Results and Discussion

3.4.3.1 Strength of association

Figure 62 shows the result of exploring the strength of association between RFP and operational factors in prawn trawling, some of which were predicted by the PTPM. For each year, point estimates of R^2 are shown for all factors, thus indicating the degree to which the underlying factor explains RFP. For the SFRP and SAR factors 95% confidence intervals for R^2 have been constructed to indicate the degree of statistical uncertainty in R^2. For all series of results a 6th order polynomial regression was applied to indicate the general trend.

The estimated extent of chance variation in RFP from year to year is generally about 15% (ie. 85% of variation was explained by SRFP). For the first 7 years the amount of variation explained by SRFP was variable and had large 95% confidence intervals. This mainly reflects the relatively small number of boats that fished during August to November in 3 consecutive years at that time. In the early 70's the big attraction of the Gulf of Carpentaria to fisherman was banana prawns earlier in the year. It was not consistent practice to continue fishing into the latter part of the year for tiger prawn. Additionally the number of days fished over the 3 month period for tiger prawn was low for many boats and this would give rise to large variation in catch performance from year to year. This highlights that the analysis could benefit from weighting the influence of the data on the basis of how many fishing days contribute to each yearly RFP parameter.

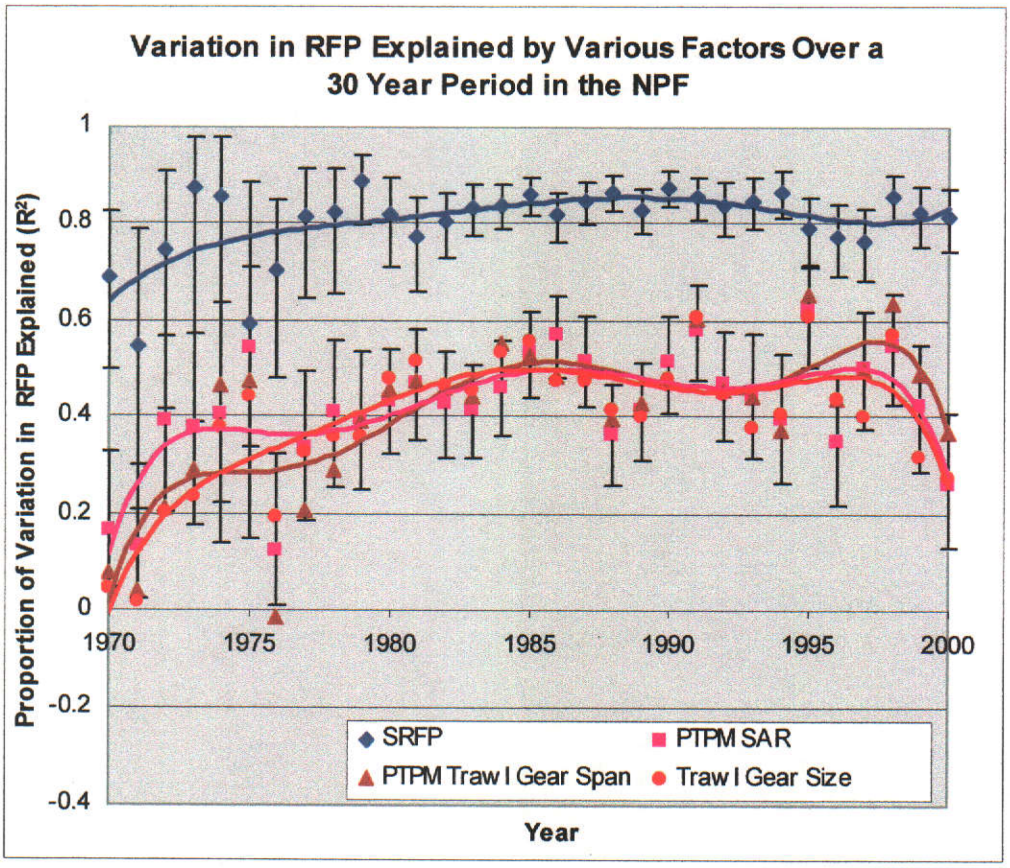


Figure 62. The strength of proportional relationship between various operational factors and catch performance over a 30 year period in the NPF.

It is surprising that there is not a strong increasing trend in the amount of variation explained by SRFP in accordance with the notion that the fleet may have become more knowledgeable about the fishery and therefore more consistent from year to year. Alternatively one could form the view that the additional knowledge has driven individual operators towards increased catch for a given amount of effort, but at this more highly tuned operating condition the risks of relative failure may actually increase. This might explain the lower explanation ability of SRFP for 1995, 1996 and 1997 or perhaps there was poor recruitment in those years, which maybe made all operations less consistent.

From Figure 62 SAR generally explains between 40% and 60% of the variation in RFP. It is also apparent that trawl gear size and trawl gear span have a similar capacity to explain RFP. This is unexpected and indicates that effort to calculate spread ratio and trawl speed from the engineering data has produced little explanation of RFP.

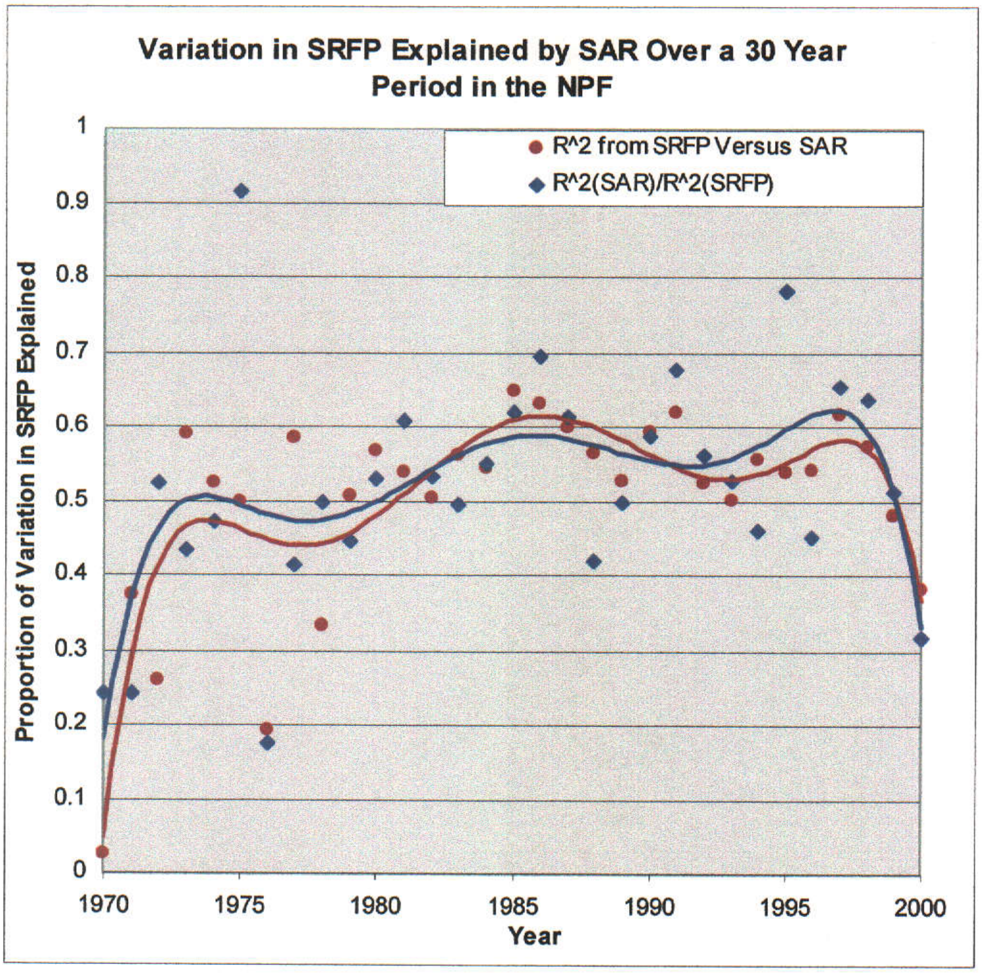


Figure 63. Estimated variation in operational RFP explained by predicted swept area rate.

In Figure 63 two methods have been used to estimate the degree to which SAR explains the portion of RFP that is assumed to be associated with operational factors. One estimate comes simply from dividing the R^2 from the proportional regression of RFP(SAR) by the R^2 from the proportional regression of RFP(SRFP). The other estimate comes from explicitly applying a proportional regression of SRFP(SAR). The two methods give similar results. Since 1980 predicted SAR was estimated to explain generally between 50% and 60% of the variation in RFP apportioned to operational factors (ie. SRFP).

The variation in utility of predicted SAR appears to be dependent on the quality of the available input data. A slight local peak in catch explanation by SAR occurs around 1998 when the technology survey was undertaken. Other years where relatively good prediction capability occurred centred on 1985. This coincides with a period where a variety of different trawl systems were used, thus giving rise to a complex variety of performance issues, which are accommodated by the PTPM in making performance predictions. Also there was an increase in management effort during the 80's that improved the quality of available data relative to the 70's. Prior to 1980 the certainty of input data was low and many unknown values in the data set were estimated using cluster analysis. During this period the variation in SRFP explained by predicted SAR dropped to as low as 10% in the early 70's when data was the least reliable (Figure 63).

Referring back to Figure 62, it appears that for the period prior to 1978 trawl gear size information is poor and has resulted in it being a bad predictor of RFP. During this period the scant information on engine power was able to provide some explanation power since it ultimately drives SAR predictions from the PTPM. Because engine power is the fundamental driver of trawl system performance due to its control over the rate at which energy is supplied to the active process, the PTPM will give a reasonable estimate for SAR from good engine power data even though there are large errors in the assumed trawl gear size. In contrast to this, the variation of RFP explained by gear size and gear span are for many years after 1978 at least as good as predicted SAR. This is particularly pointed with respect to gear size because this factor does not require any complex prediction and is a simple measurement that can be taken at any time by management authorities. Its unsurpassed explanation capacity between 1978 and 1993 indicates that during this period gear size records were reasonably accurate and that trawl system stretch and trawl speed must have been reasonably constant across most operators in any year. It is apparent that attempts to predict trawl system stretch and trawl speed for that time period based on the available data and the PTPM failed to accurately capture what may have been quite subtle variations between operators and therefore failed to explain any further variation in catch. In years subsequent to 1993, input data to the PTPM likely contained less error and allowed gear span and SAR to explain more of the variation in RFP than gear size, particularly in years close to 1998 when the technology survey was undertaken. However, it is generally the case that predictions of trawl speed, which are incorporated into predicted SAR fail to add any explanation power over and above trawl system span. This conclusion leads from the result that trawl gear span is generally the best indication of RFP for years after 1993.

To clarify the situation further, Figure 64 shows a plot of trawl speeds determined from VMS (Vessel Monitoring System[1]) data versus trawl speed predicted by the PTPM for a time period covering 1998 to 2001. Each VMS speed measure is the average determination of speed over a calendar year for a particular vessel (Bishop, 2003). Generally there is a weak correlation between VMS speed and PTPM speed, but most striking is the feature that the variance of the VMS speed is much lower than the variance of PTPM speed. This is a clear demonstration that the PTPM speed predictions contain a considerable amount of random error, which would not make any contribution towards explaining the variation in catching performance of the trawlers.

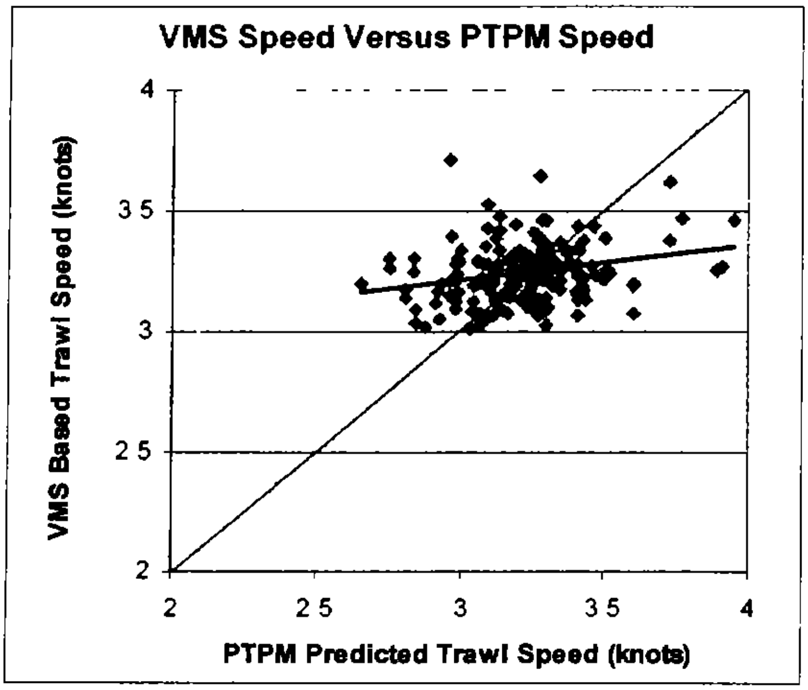


Figure 64 Plot of VMS determined trawl speed versus PTPM predicted speed based on VMS data since 1998.

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[1] A satellite based system for monitoring trawler location. GPS positions are logged onboard all trawlers and downloaded via satellite communications to fisheries management centres. In the case of the NPF, the information is collected in Canberra by AFMA.

Figure 65 shows the distribution of speed difference for the PTPM and VMS determined speeds. The average difference suggests that the PTPM under predicts trawl speed on average by 0.023knots compared to the VMS, however this value is not significantly different from zero ($\alpha < 0.025$) and in practical terms is quite small. The frequency of difference values appears symmetric and normally distributed and has a standard deviation of 0.22knots. This indicates that PTPM predicted speed for the NPF in these years might have a random error as large as 7% on average.

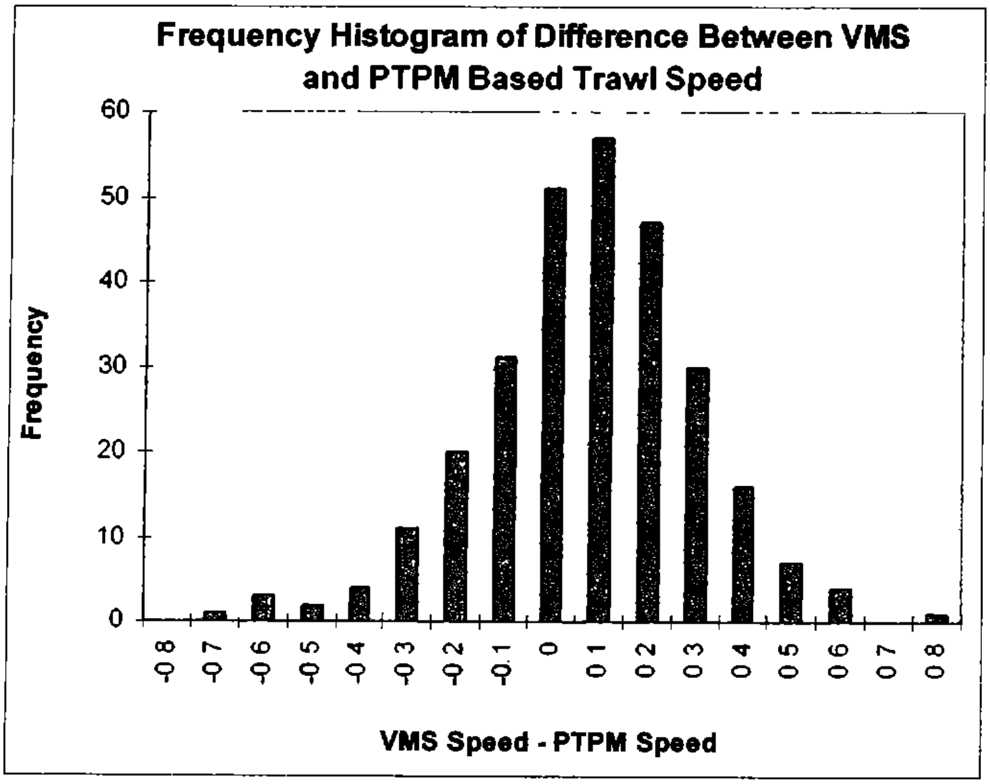

Figure 65. Histogram of speed difference between VMS speed and PTPM speed.

The basis of the problem with accurately estimating SAR, in respect to the trawl speed component, may lie with the current version of the PTPM and the approach adopted. Central to the prediction of trawl speed is an estimate of trawler tow force from a determination of developed power. Predicted trawl speed is equally sensitive to the prediction of trawl system drag, but that side of the issue, in terms of input data and prediction accuracy, is common to the prediction process for trawl system span. Given that the latter seems to be working quite well, based on its' superior ability to predict NPF catch, it may be presumed in the first instance that the calculation of trawl system drag is similarly successful. Therefore it appears that the calculation of tow force attracts the most suspicion in terms of the failure of predicted trawl speed to add any improvement to the prediction of NPF catch. It can be seen that the prediction of tow force is the result of a long chain of calculations that require a large number of inputs (see sections 2.2.2.3, 2.2.2.4, 2.3.3). The complete chain of calculations can be described by the sequence of PTPM outputs; rated power to developed power to bollard pull to tow force. The most problematic step is likely to be the calculation of developed power. Here there are a large number of inputs that define the power production characteristics of the engine, the user dependent operation of the engine and how the engine is matched to the demands of the propeller. The calculation covers a lengthy and complex range of physical issues that from the modelling perspective is not perfectly known and this is compounded by considerable uncertainty in the quality of the input data.

It might be possible to reduce the random error in PTPM trawl speed predictions by improving the quality of the fleet structure database. This would require a very stringent survey of the trawl fleet in terms of the required input data and perhaps direct observation of fishing operations would be required or electronic logging of operational parameters. Alternatively, a change of approach could be warranted. The developed power produced by any engine during trawling is closely linked to its fuel consumption rate. The efficiency of conversion between fuel consumption and mechanical power is relatively constant across engine types and operating conditions. Therefore data on fuel consumption rates while trawling would likely be a reliable indication of developed power far superior to the process adopted in the current situation where such data is not available. The best data in this respect would come from logging fuel consumption on all trawlers while they operate.

Finally, the prediction power of all 3 engineering factors in Figure 62 appears to drop away in 1999 and 2000. The results for subsequent years will be very important to establish whether some significant change in the construction of fishing power within the fleet has occurred over the later years. The introduction of Gear Units and bycatch reduction devices in 2000 has induced many changes to the makeup and dynamics of the fleet. It is possible that differential effects to the fishing performance of vessels have occurred and affected the information presented in Figure 62.

3.4.3.2 Analysis of residuals

The objective of this section is to explore the possibility that SAR predictions based on the PTPM are biased. It is desirable to detect bias and isolate the reasons for such bias and this may be achieved by using the data and the simple proportional model between RFP and predicted SAR of the previous section. The model, RFP(SAR), giving rise to the residuals under investigation is only a single factor model, however it is important to note that the SAR factor involved, is manufactured from a large number of variables by a mixed numerical model containing theoretical and empirical components (the PTPM). All the input variables to the PTPM are therefore part of the single factor statistical model and indirectly contribute to the explanation of RFP via the SAR factor.

Interpretation of residual plots for the single factor statistical model used is necessarily tentative because of the possibility of confounding between the factors that affect RFP. This is exacerbated because it is known that the model does not include all factors that significantly affect the dependent variable. The situation described does not make the analysis invalid, but does elevate the risk that correlation between variables that are explicitly included in the model and those that are important, but are not, can cause structure in residual plots that may promote misleading interpretation. Nevertheless the following work is considered to be a worthwhile step in this research area and may define important issues, which can be investigated further using more sophisticated methods.

PTPM bias correlated with SAR

Figure 66 shows the logarithmic residuals for the proportional regression between RFP and SAR plotted against SAR for the years 1974, 1980, 1990 and 2000. For none of the years is there a strong correlation between the residuals and SAR. However for 1974 the linear trend is such that for the lowest SAR boats the RFP(SAR) model over predicts RFP by about 30% on average and for the highest SAR boats the model under predicts RFP by an average of 25%. 1974 is the year with the greatest slope for the residual trend. Figure 67 shows the slope of the residual trend against SAR (with 95% confidence intervals) for all years spanning 1970 and 2000. For most years subsequent to 1974 up to 1987 there was a small positive trend in the residuals, which in some years is significantly different from zero (at $\alpha < 0.025$). After 1987 the slopes of the residual trends appear to randomly fluctuate about zero. The plots for 1990 and 1998 in Figure 66 are typical for that time period. For 2000, 1989 and 1995 the trends in the residuals are significantly different from zero.

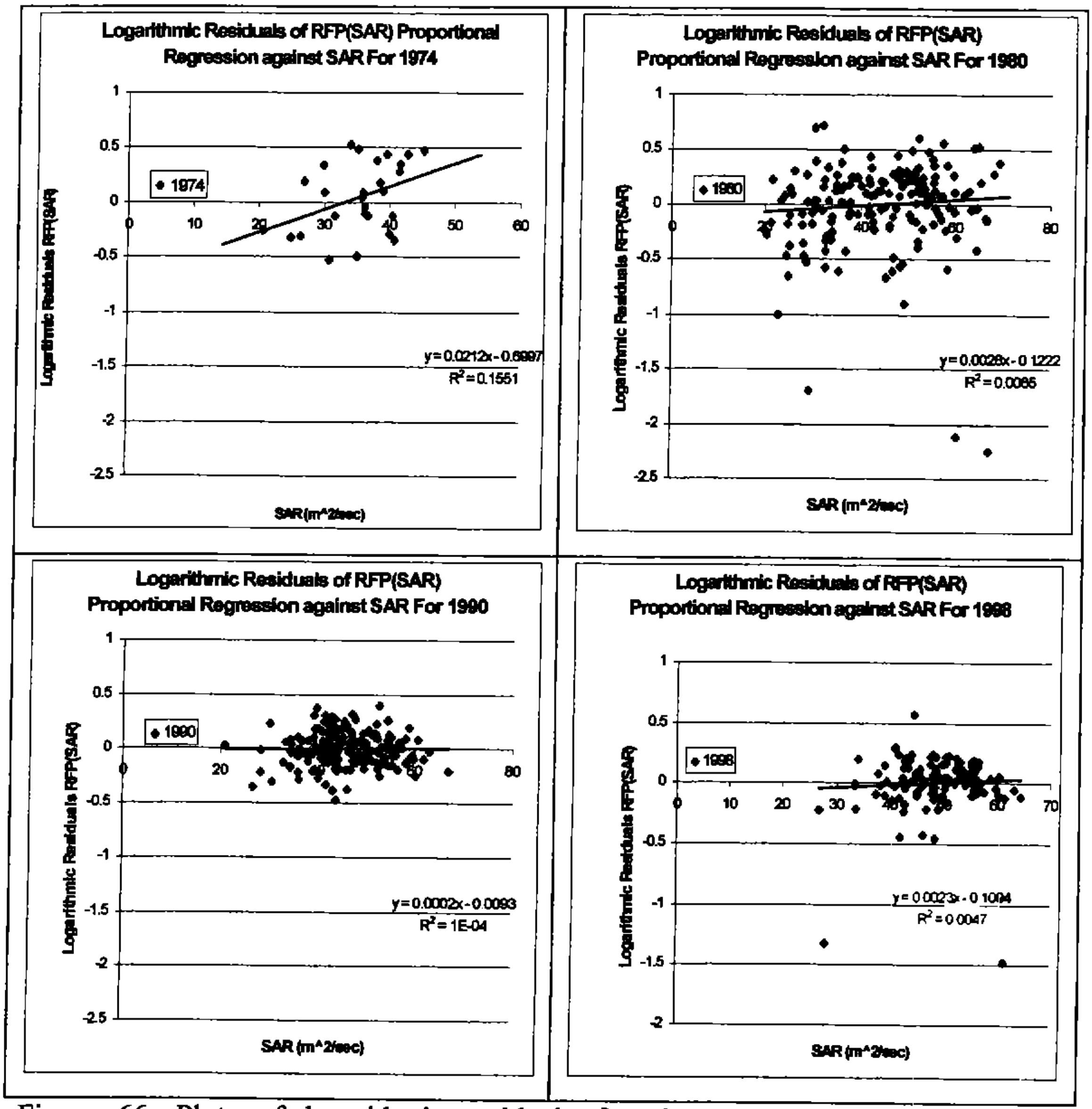

Figure 66. Plots of logarithmic residuals for the proportional regression of RFP(SAR) against SAR for 1974, 1980, 1990 and 1998.

Figure 67 shows there are few years where there is a significant linear trend in the residuals. This could be interpreted as suggesting that there are no significant issues to be raised regarding systematic bias within the PTPM that is correlated with SAR predictions. However, although the variation in RFP about the RPF(SAR) regression is generally highly scattered it is plausible that it is strongly driven by consistent systemic factors from one year to the next. Therefore the structure of the residuals is likely to be substantially consistent from one year to the next and a trend in the residuals that is found to be similar for a number of adjacent years is likely to be of practical relevance. A 4th order polynomial regression was applied to the residual trend series to try and highlight what could be a very relevant signal. A rigorous approach to improve the resolution of the analysis of residuals would be to reduce the amount of unexplained variation in the RFP model by developing a more complete prediction model that includes more of the operational factors that contribute to catch performance. This would be highly warranted, but beyond the scope of the current task and is not guaranteed to improve the situation because many of the important operational factors are likely to be intangible and not aligned with surrogate variables that are well known for the NPF fleet.

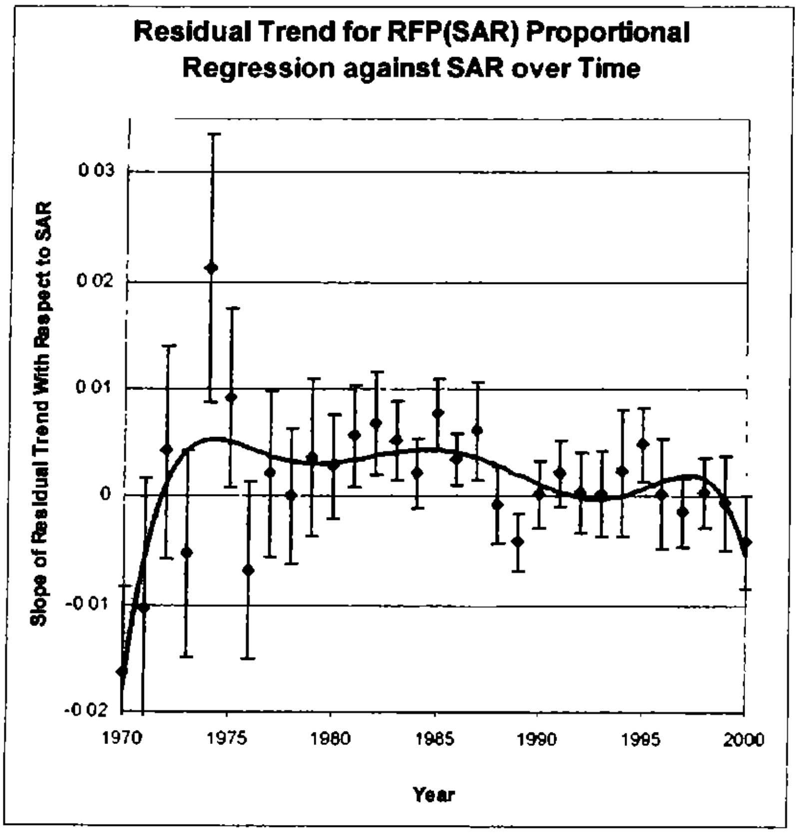

Figure 67. Residual trend slope versus year for RFP(SAR) proportional regression logarithmic residuals against SAR.

For years prior to 1987 there is a strong impression that the slope of the residual trend is positive. This suggests that for that time period the proportional relationship between predicted SAR and RFP is biased against large boat performance or equally, biased towards over predicting the RFP of small boats. This might indicate that SAR predictions are similarly biased by the PTPM. The fact that this issue exists only prior to 1987 tends to suggest that rig type is involved because during those years there were no restrictions on rig type whereas after 1987 only double rig was allowed. It is well documented that after the double rig restrictions were imposed in 1987 the performance of large boats relative to small boats declined (Robbins and Somers, 1993). Prior to 1987 it is quite likely that the uptake of quad rig was strongest for the large boats. It is apparent that prior to 1987 large boats outperformed their potential as determined by predicted SAR, however it is not possible to say whether this is because the PTPM underestimates the SAR attributable to quad rig generally or rather underestimates the SAR attributable to quad rig on large boats or whether the catch performance of large boats towing quad rig is greater than expected for reasons other than an error in predicted SAR. The magnitude of the discrepancy is approximately 20% across the extremes of the fleet. That is, the under prediction of RFP for the largest boat in the fleet is about 20% compared to perfect predictions for the smallest boat in the fleet. Bias for all other boats are prorata to this based on predicted SAR.

PTPM bias correlated with rig type

Figure 68 shows the distribution of logarithmic residuals for the proportional regression RFP(SAR) against rig type for the years 1970, 1975, 1980 and 1985. It was not important to show distribution plots for years beyond 1987 because after that year the only rig used was double. For each rig in each year the average logarithmic residual was calculated and plotted as a series over time in Figure 69. This shows quite clearly that the catching performance of single rig during the early 70's was greater than expected from their SAR measures (positive average residuals). Similarly the catching performance of triple rig boats was on average well below expectations (-35%) based on SAR measures.

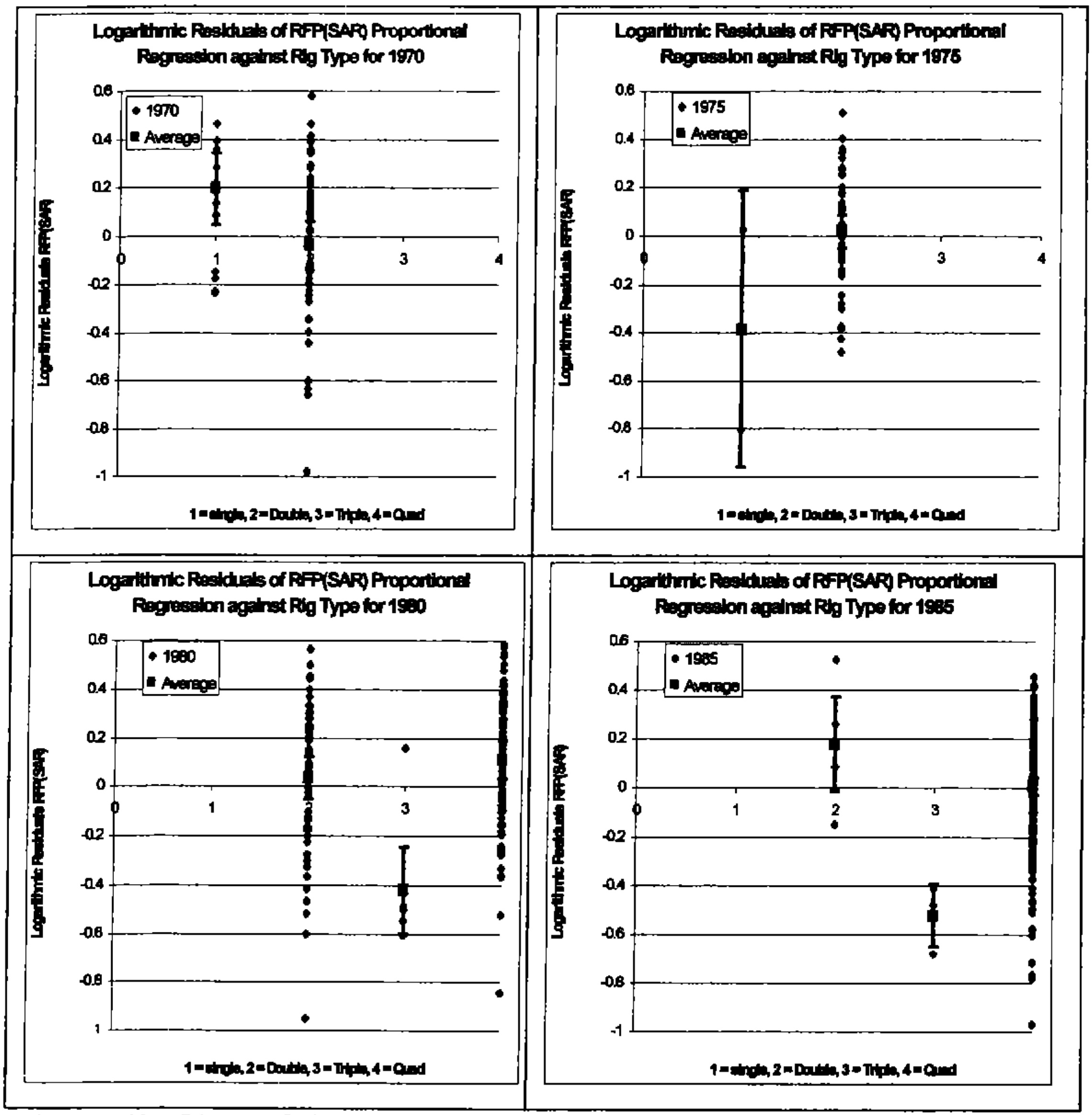

Figure 68. Plots of logarithmic residuals for the proportional regression of RFP(SAR) against rig type for 1970, 1975, 1980 and 1985.

The apparent bias for triple rig appears to be based on an over prediction of SAR. The number of triple rig boats involved is very small (maximum of 5 boats in 1980) and it is known that they are small boats in the fleet. The nature of this apparent bias would contribute strongly to the positive trend in the residuals observed in the previous section for the years before 1987. It is an important issue worthy of further investigation as to why this bias exists. One explanation is that the SAR performance of triple rig is being overestimated by the PTPM, or the triple rig boats in this instance for some unexplained reason under perform compared to their estimated potential. There could be a systematic error in the data for these boats, for example the fact that they are triple rigged might indicate that the boats have less towing performance than expected for their size. As some aspects of towing performance are often imputed from vessels of similar size it could be that this process has systematically over endowed the boats with towing capacity. Alternatively, the period of time involved here is the development period for multinet systems like triple and quad rig. It is quite possible that the full potential of these systems was still being realised at this time. This could explain the gradual increase in average residual over time for quad rig, while for triple rig there may have been some difficulties in capturing peak performance that were never overcome during the time that it was utilised in the NPF. One technical difficulty for triple rig is the operation of the two sleds that connect the middle net to the outside nets. These sleds do not tow straight (Wilson et al., 1990) because of the direction taken up by the towing wires. This problem can have serious ramifications, particularly in soft muddy bottom conditions that are typical of tiger prawn fisheries. Ramifications are loss of trawl speed, due to excessive drag, and loss of headline height as the sleds often lay over to a significant degree. These performance deficits if not corrected cause the SAR to be less than estimated and the catch efficiency of the system to be low.

It is not known whether the difficulties with the prediction of triple rig RFP is the sole cause of the positive residual trend observed in the last section for years prior to 1987. To investigate this further it would be valuable to measure the slope of the residual trend for each rig separately.

The change in average residual for quad rig is quite marked compared to the steady low values for double rig during the period where both systems are used (Figure 69). As mentioned previously this might in part be caused by the improvement in quad rig performance as operators overcame problems with the system. These were apparently quite substantial and earned the system the nickname "double trouble". By the time quad rig became the dominant system in the NPF there is evidence that it had positive residuals compared to double rig over the time where there was still a reasonable sample of double rigs for comparison (ie 1979 to 1983). Given that it is big boats that more aggressively took up quad rig this residual structure probably also contributes to the trend in the residuals observed in the last section. It is not possible to establish whether the difference in average residual between quad and double rig is due to errors in estimating SAR or other features of trawl vessels that contribute to fishing that coincidently occurred with the vessels that used quad rig to a greater extent than other vessels. Possibilities include trygear, SATNAV, Sonar or high-powered Radar or higher calibre skippers. It is also possible that the triple rigged boats might have suffered performance deficits because of slow adoptions of the beneficial factors. There is also the possibility that the small triple rig boats may have fished a different area to the other boats (more sheltered, but less productive).

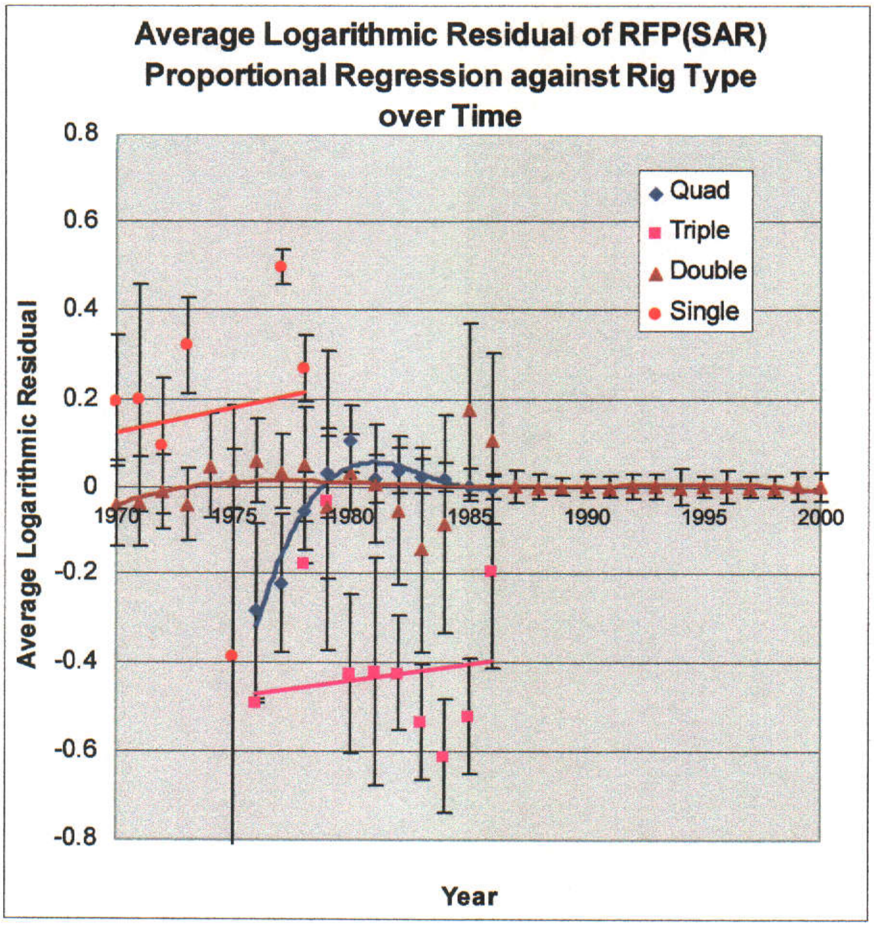

Figure 69. Average residual associated with rig type over time.

PTPM bias correlated with board type

Figure 71 indicates the distribution of residuals resulting from the proportional regression between RFP and predicted SAR against board type (examples shown in Figure 70). This information has been provided for all years between 1985 and 2000.

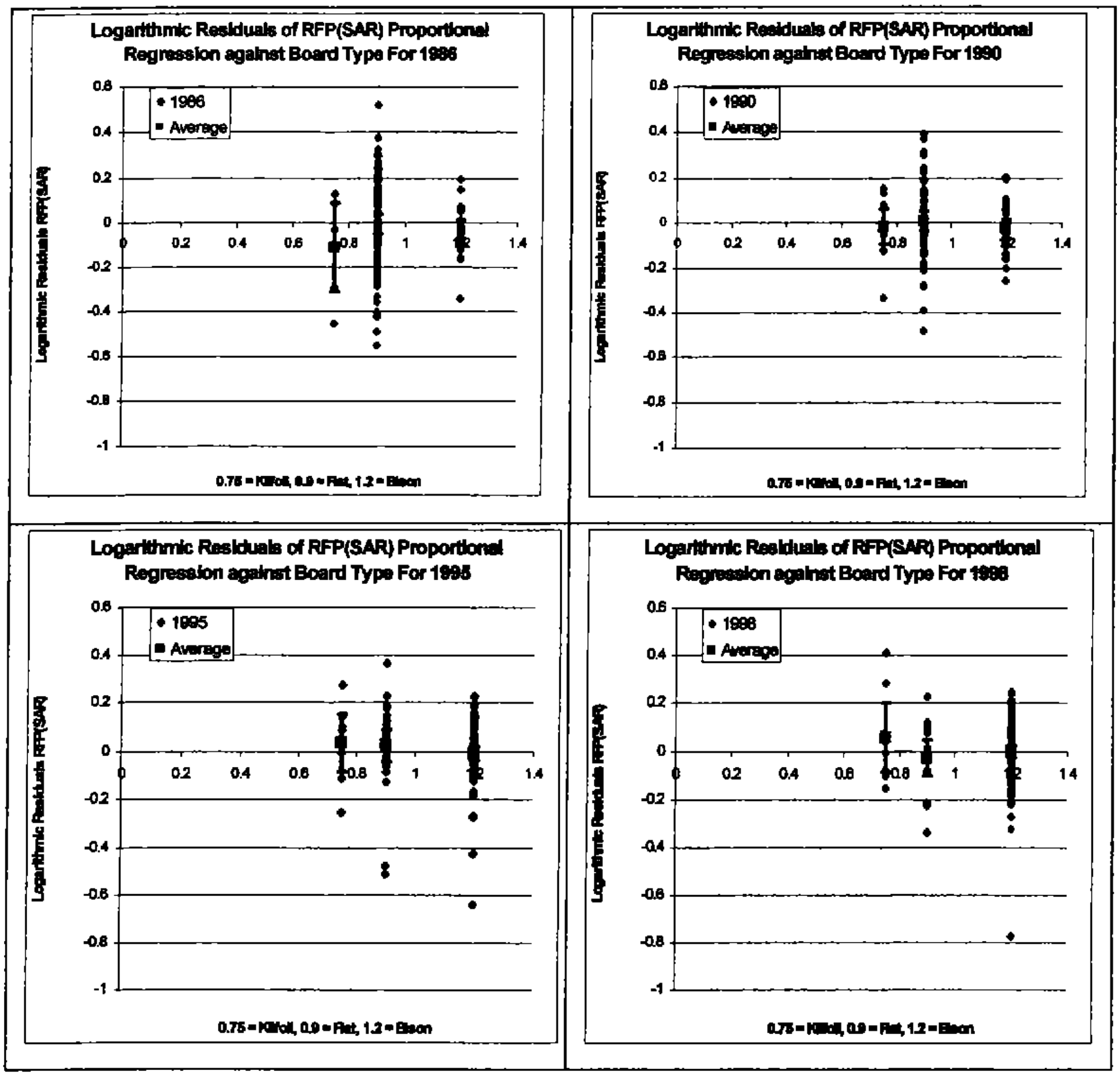

Figure 70. Plots of logarithmic residuals for the proportional regression of RFP(SAR) against otter board type[1] for 1986, 1990, 1995 and 1998.

The results indicate that for a significant period during the introduction of Bison boards (50% uptake in 1993) the predicted SAR measures suggest an RFP that is too high by about 5% for vessels using Bison boards compared to those using Flats. This situation became gradually resolved over the 4 year period leading up to 1997 and after 1997 the situation became reversed (average Bison board residuals higher than average flat board residuals).

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[1] Otter board type is presented on the X-axis by the unique Cl value each board possesses.

The catching performance of boats rigged with Flat boards was lower than expected from their predicted SAR whereas the catching performance of the Bison boats begins to be on target. Although the latter is to be expected because by the end of the 90's the Bison board was the dominantly used board in the NPF, it is apparent that the low RFP of the Flat board boats must reflect low relative performance on their behalf, which was not exhibited on average by boats rigged with Flat boards a decade earlier. This may be due to generally low performance of boats that still use Flat boards for reasons other than SAR or alternatively, it is possible that the advantages of the Bison board were not forthcoming in the early uptake period, but this may have changed over the following 15 years as experience was developed in extracting the best performance from the devices.

If the latter is true and the performance of Flat rigged trawler is not significantly different from previous years, then the catching performance of modern Bison rigged trawlers could be a further 5% better than indicated by the SAR predictions.

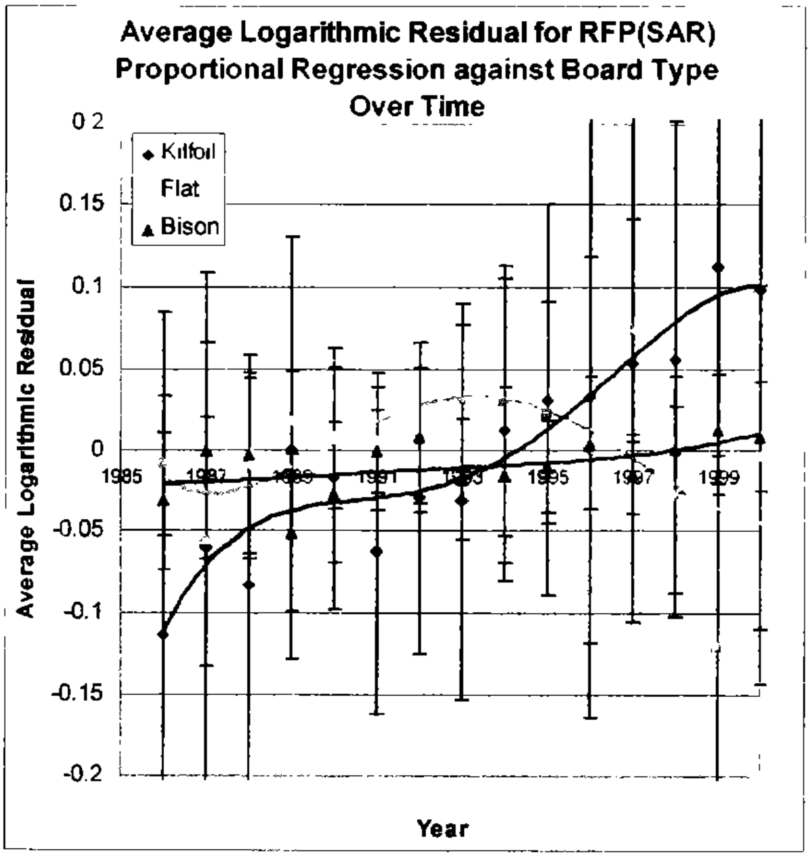

Figure 71. Average residual associated with otter board type over years since 1985.

It is possible that the effect of Bison boards on catch might be manifested by factors other than SAR. The Bison board has a significantly higher lift coefficient (Cl) and aspect ratio than the Flat board. This means that although the area of the Bison board required to produce the same trawl span as the Flat may be smaller, they could still well lead to a higher headline height being used, which may increase the catching efficiency of the gear (proportion of the prawns in the path of the gear retained). Based on the boats that used Flats and Bison boards in the NPF in 1998 it was possible to establish the average aspect ratio for both boards. After accounting for differences in aspect ratio and the size of the respective boards required to preserve the same spread force and the difference in trawl connection points it was found that there was no substantial difference in headline height between boats using Flats and boats using Bisons.

The apparent over performance of boats fitted with Bison boards in recent years could be due to a correlation between the presence of Bison boards and other technologies that significantly affect catching performance (for example DGPS or advanced plotter systems). It would be a useful endeavour to run a multifactor model with these factors included to see if this changes the trend in the residuals with respect to the presence and absence of Bison boards.

The instance of Kilfoil use is very low and the relative position of its average residual is variable. Therefore no comment is made regarding the potential for error in predicted SAR for these boards.

PTPM bias correlated with body taper

Since body taper has been shown to have a significant effect on the engineering performance of trawl gear at model scale (Sterling, 2000b) it would be valuable to establish whether or not prawn catches in the NPF corroborate that finding.

Figure 72 shows examples of residual plots for four years over the history of the NPF. Figure 73 shows the average residual for each body taper category plotted as series for all year between 1970 and 2000. For the 1P4B and 1P3/4B series a 5 term moving average was used to smooth the signal rather than a 4th order polynomial because fitted polynomials to those series were overly oscillatory.

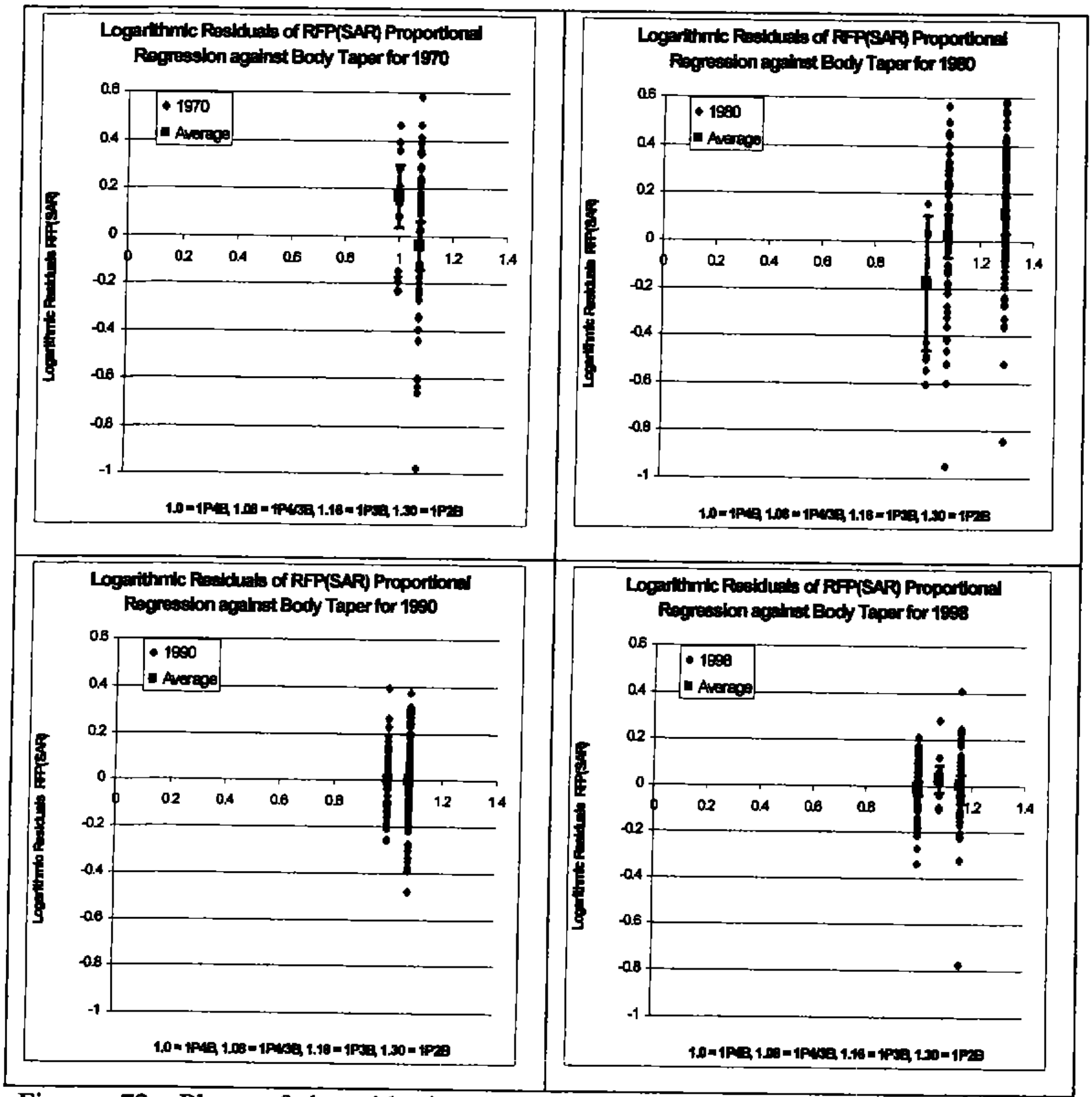

Figure 72. Plots of logarithmic residuals for the proportional regression of RFP(SAR) against body taper[1] for 1970, 1980, 1990 and 1998.

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[1] Body taper is presented on the X-axis by the unique drag factor each possesses in the PTPM. 1P4/3B was a category for double rigged boats where the body taper used was unknown. These boats were given a taper drag factor halfway between that for 1P4B and 1P3B because it was established from the known boats that each taper type was approximately equally represented in the fleet.

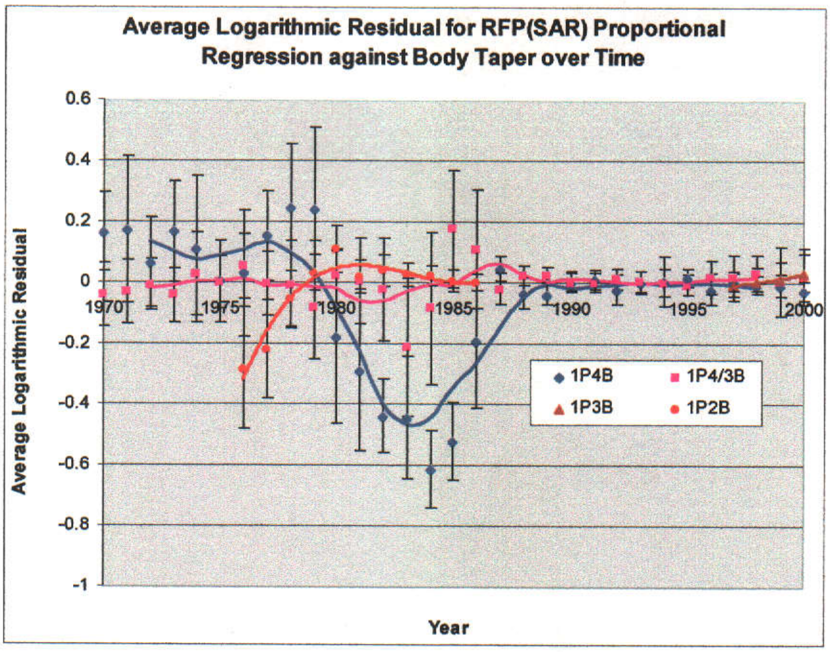


Figure 73. Average residual associated with body taper over time.

For years before 1987 the average residual for 1P4B taper was significantly or consistently different from zero . Up to 1979 the average residual was positive and between 1979 and 1987 the average residual was negative. This is explained by the fact that all single rig vessels had 1P4B taper and no other vessel during the time of single rig had that taper. Therefore the residuals for 1P4B during this period directly reflect the residual for single rig. There is a strong connection between body taper and rig type after 1979 as well where 1P4B is universally assigned to triple rig boats and therefore shows the large negative residuals associated with that rig. After 1987 all boats are double rig and the average residual for all body tapers are close to zero in all years. This suggests that body taper is not the cause of any of the large residuals. For 1998 (Figure 72) where the gear configuration data is most accurate the average residual for all body tapers represented is close to and not significantly different from zero. The only limitation to the later statement is that the body taper, 1P2B, was not represented by any vessels at that time.

3.4.4 Conclusions and recommendations

- Based on the variation in statistical RFP of vessels explained by the 3 year average of RFP centred on the year in question (SRFP), it was concluded that in general approximately 85% of variation in RFP was due to operational variables and approximately 15% was caused by chance correlation with environmental factors.

- There was no significant change in the extent of chance variation of RFP over the 30 year history of the NPF investigated.
- Generally the results suggest that predicted SAR based on the current dataset explains 50% to 60% of the variation in seasonal catching performance of trawlers in the NPF
- Across the 30 years investigated gear size, gear span and SAR were often equally good at predicting RFP, but this did apparently depend on the quality of input data, which was known to vary over the study period.
- In 1998 and surrounding years, when input data to the PTPM was the most comprehensive, gear span was indicated to be the best predictor of RFP, but this was not statistically significant at a yearly time scale.
- For years prior to 1976, SAR was the best predictor of RFP.
- It appears that SAR predictions for the NPF contains substantial random error. The main problem seems to be that the prediction process for trawl speed introduces noise because of the quality of the data currently available and the large number of input variables involved.
- Analysis of data requirements for the estimation of SAR indicated that a solution to noisy SAR predictions might be the restructure of the PTPM to accept fuel consumption data and the implementation of processes to collect such data.
- Some statistically significant systematic bias across SAR was detected for some years with respect to SAR being an indicator of RFP. This could be more widespread than indicated by the statistics and there is evidence that it is linked to rig type although further more detailed study of the bias trend within rig type is required to clarify the situation.
- There is evidence that modern boats fitted with Bison boards catch better than predicted by SAR. It is possible that this result is due to confounding between the use of Bisons and the use of other new technologies at the time.

- Critical appraisal of the possible biases within the PTPM is hampered by not having a wider inclusion of fishing power factors in the analysis. Further investigation of PTPM bias would benefit from using more complex models and a more high-powered data analysis platform.

CHAPTER 4 - APPLICATION OF THE PTPM TO ECOLOGICAL SUSTAINABLE DEVELOPMENT (ESD)

4.1 Introduction

4.1.1 Background

The PTPM relates to a particular strand of fisheries science, namely Fisheries Technology and is an attempt to coalesce and extend the current physical understanding of prawn trawling systems. Before exploring the utility of the PTPM with respect to the management of prawn trawling fisheries, as encapsulated by the principles of ESD, the role of Fisheries Technology to that same endeavour is first considered. This provides a background to the specified task and also defines a framework for the approach.

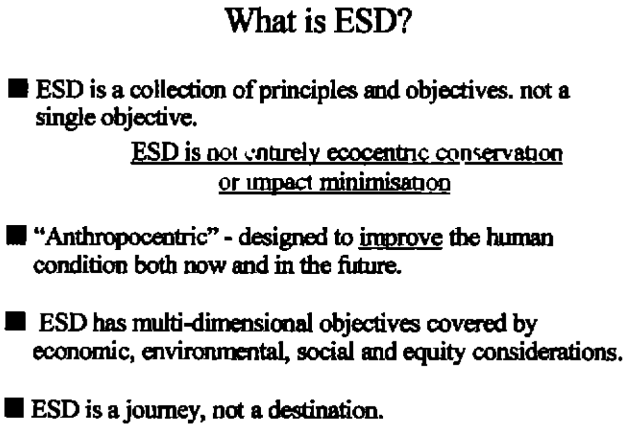
In this task it is possible to consider a complex range of ideological and sociological factors, which have prominent effects on the working environment in terms of organising dominant viewpoints and prevailing operational approaches to the task of management. The latter significantly affect the role, utility and responsibilities of functional entities in that environment. In short, the role of Fisheries Technology and the utility of the PTPM depend on how fisheries matters are viewed. This problem is evaded in this work by pursuing an idealised approach to the subject, although the complicating issues are clarified in later sections.

Despite avoiding the political complexity mentioned above there still exists a complex range of technical issues. This reflects the nature of fishing and the broad scope of ESD.

Firstly we need to develop an appreciation of ESD based on core ideas and prominent definitions.

Table 15 attempts to make a summarising description of ESD based on a mixture of notions arising from legislative documents, academic papers and practical interpretations evident in the working environment. ESD is an open-ended guide to human endeavour and has many interpretations. Despite the emphasis on ecological sustainability in its title, the main thrust of ESD is the long-term welfare of humanity, which means that the process is necessarily driven by socially derived value judgements. This in part makes it a very difficult framework for guiding management and has led to many heated debates regarding appropriate directions and approaches. Many people believe that it is unworkable in its ideal form. Based on some of these debates some of the clearest parts of the definition presented in Table 15 are what ESD is not.

Table 15. Core multi-faceted ideas behind ESD.



What is ESD?

- ESD is a collection of principles and objectives. not a single objective.

  ESD is not entirely ecocentric conservation or impact minimisation

- "Anthropocentric" - designed to improve the human condition both now and in the future.

- ESD has multi-dimensional objectives covered by economic, environmental, social and equity considerations.

- ESD is a journey, not a destination.

Environmental economists suggest that the idea behind ESD is the "Spaceship Earth" perspective of managing human affairs (see Figure 74), which brings to the fore the notions that everything about the earth is finite and that not only are goods and services produced with inputs extracted from the natural environment but some essential goods and services for society flow from the natural environment without any attached commercial costs (non-market goods). The relevance of ESD to current politics and management is that in many respects human affairs are conducted with no explicit concern for these facts.

In many instances there seems to be an assumption that the natural environment is a limitless source of inputs for economic activity and an infinite sink for wastes and impacts. This behaviour is subliminally "rational" in many instances because the limits give rise to issues that are outside the sphere of interest of the players. Simple examples of this would be where problems associated with limits occur at intergenerational time scales or occur spatially at a location remote from perpetrators of environmental impact. Additionally, non-market goods are incorrectly valued in decision-making processes, which means that they can be wasted or inadvertently harmed by interacting activities.

“Spaceship Earth” Perspective
The basis of modern environmental economics

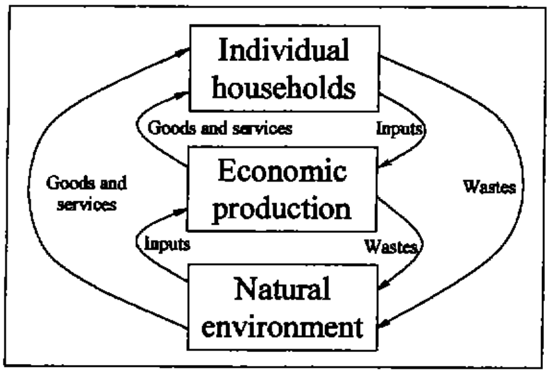


Figure 74. Spaceship earth perspective of economic production.

Over the last decade, issues such as global warming and biodiversity loss have highlighted the environment’s finite nature and economists have reacted to the strong public awakening to these issues by expanding the scope of their considerations to include environmental factors. However, economists have not become “environmentalists”, but rather consider environmental issues in context with their original professional ambition to manage economic production so that it improves the goods and services provided to people (now and in the future) in a way that best caters to the needs of humanity and makes efficient the use of scarce resources.

4.1.2 ESD in Australia

The National Strategy for ESD (NSESD) of Australia provides a comprehensive formal definition and operational guidelines for ESD (see Figure 75). These were developed over several years through extensive consultation with all levels of government, business, industry, academia, conservation organisations and the wider community. The Council of Australian Governments endorsed the NSESD in 1992 and agreed that all relevant future policies and programs should be developed within the framework of the NSESD and the Intergovernmental Agreement on the Environment (IGAE).

Goal, Core Objectives and Guiding Principles for ESD
(National Strategy for Ecological Sustainable Development, 1992)

Development that improves the total quality of life, both now and in the future, in a way that maintains the ecological process on which life depends.

The Core Objectives:

- to enhance individual and community well-being and welfare by following the path of economic development that safeguards the welfare of future generations
- to provide for equity within and between generations
- to protect biological diversity and maintain essential ecological, processes and life support systems

The Guiding Principles:

- decision making processes should effectively integrate both long and short term economic, environmental, social and equity consideration
- where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation
- the global dimension of environmental impacts of actions and policies should be recognised and considered
- the need to develop a strong, growing and diversified economy which can enhance the capacity for environmental protection should be recognised
- cost elective and flexible policy instruments should be adopted, such as improved valuation, pricing and incentive mechanisms
- decisions and actions should provide for broad community involvement on issues which effect them

These guiding principles and core objectives need to be considered as a package. NO objective or principles should predominate over the others. A balanced approach is required that takes into account all these objectives and principles to pursue the goals of ESD.

Figure 75. NSESD formal definition and operational guidelines for ESD (Anon., 1992b).

Since then all fisheries agencies in Australia have expressed commitments to implement the concept of ESD into their management of fisheries resources. With this ESD has become, either explicitly or implicitly, a major objective within Fisheries Acts in Australia and therefore management agencies are now held accountable in terms of this objective (Fletcher et al., 2002). In response to the critical need to develop a comprehensive and practical reporting system for ESD, the Fisheries Research and Development Corporation (FRDC), in 2000, funded a program to develop a nationally agreed system for ESD reporting in fisheries.

In recognising that the NSESD definition of ESD covers a very broad range of issues, so much so that it can be argued that everything could fit within these principles (Fletcher et al., 2002), there was a need to clearly scope ESD in the context of fisheries management by subdividing ESD into a number of components that cover the issues associated with target (retained) species, the ecosystem (eg. non-retained species, other species interaction and more general ecological and physical processes), social and economic issues and also management/governance arrangements.

The National ESD Reporting Framework for Australian Fisheries developed by Fletcher et al. (2002) has ESD divided into eight major components (within 3 main categories) as listed below:

Contributions of the fishery to ecological wellbeing

1. Retained species
2. Non-retained species
3. General Ecosystem

Contributions of the fishery to human wellbeing

4. Indigenous wellbeing
5. Community and regional wellbeing
6. National social and economic wellbeing

Factors affecting the ability of the fishery to contribute to ESD

7. Impact of the environment on the fishery
8. Governance

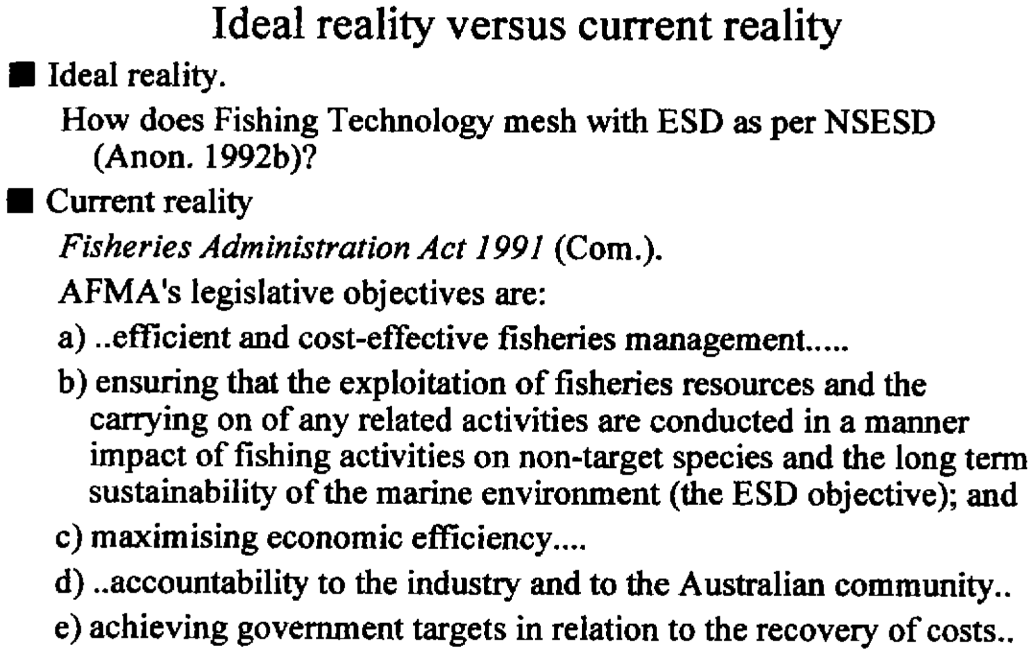
Additionally the guidelines for the National ESD reporting framework recognises the NSESD conviction in Figure 75 that; "These guiding principles and core objectives need to be considered as a package" by stating that; "It is the integrated approach of including the wider economic, social and environmental implications within decision-making processes that is the cornerstone, and major innovation, of ESD".

4.1.3 Fisheries Technology and ESD in Australian fisheries

Armed now with a formal definition of ESD, it is possible to return to the question of the role of Fisheries Technology in ESD. This can be pursued from an ideal perspective, which is simply to look for connections between the academic scope of

Fisheries Technology and the NSESD definition of ESD. However it is also a useful exercise to view the historical role of Fisheries Technology in ESD at the level of fisheries management in Australia. Table 16 outlines this challenge by stating the question in two different "realities" and for the current reality it reproduces a section of AFMA's legislated objectives. In practice the role of Fisheries Technology will be directed by the objectives of the fisheries management institutions. In the case of AFMA, their legislated objectives have ESD at their core, however the legislation goes on to make a definition of ESD that is fundamentally different from the NSESD definition. The definition of AFMA's "ESD" objective is much narrower than the NSESD definition and tends to focus management towards a prescribed ecocentric view.

Table 16. The definition of dual contexts for the role of Fisheries Technology in ESD



Ideal reality versus current reality

- Ideal reality.
  How does Fishing Technology mesh with ESD as per NSESD (Anon. 1992b)?
- Current reality
  Fisheries Administration Act 1991 (Com.).
  AFMA's legislative objectives are:
  a) ..efficient and cost-effective fisheries management.....
  b) ensuring that the exploitation of fisheries resources and the carrying on of any related activities are conducted in a manner impact of fishing activities on non-target species and the long term sustainability of the marine environment (the ESD objective); and
  c) maximising economic efficiency....
  d) ..accountability to the industry and to the Australian community..
  e) achieving government targets in relation to the recovery of costs..

The position of AFMA with respect to ESD is confusing because in addition to the "ESD" objective they have a "economic efficiency" objective. It is clear that the NSESD sees economic efficiency as part of ESD, not an additional objective, and it is additionally holistic by explicitly stating that social and equity objectives need also to be integrated into ESD in a completely balanced approach, whereby no objective or principles should predominate over the others. AFMA's contrasting position on this is stated in their submission to the Commonwealth Fisheries Review in 2000 under recommendation 3, "AFMA strongly opposes the inclusion of a specific social or regional development objective into its legislation and suggests that such an objective would undermine the pursuit of key sustainability and economic efficiency objectives" (Anon., 2000b).

Different ESD policies enshrined in legislation may not be the sole cause of AFMA's narrow view of ESD. The legislation might in part be a symptom of a broad range of sociological factors. Figure 76 attempts to picture relevant factors and the resulting narrow management attention within the ESD problem space for a prawn trawling fishery.

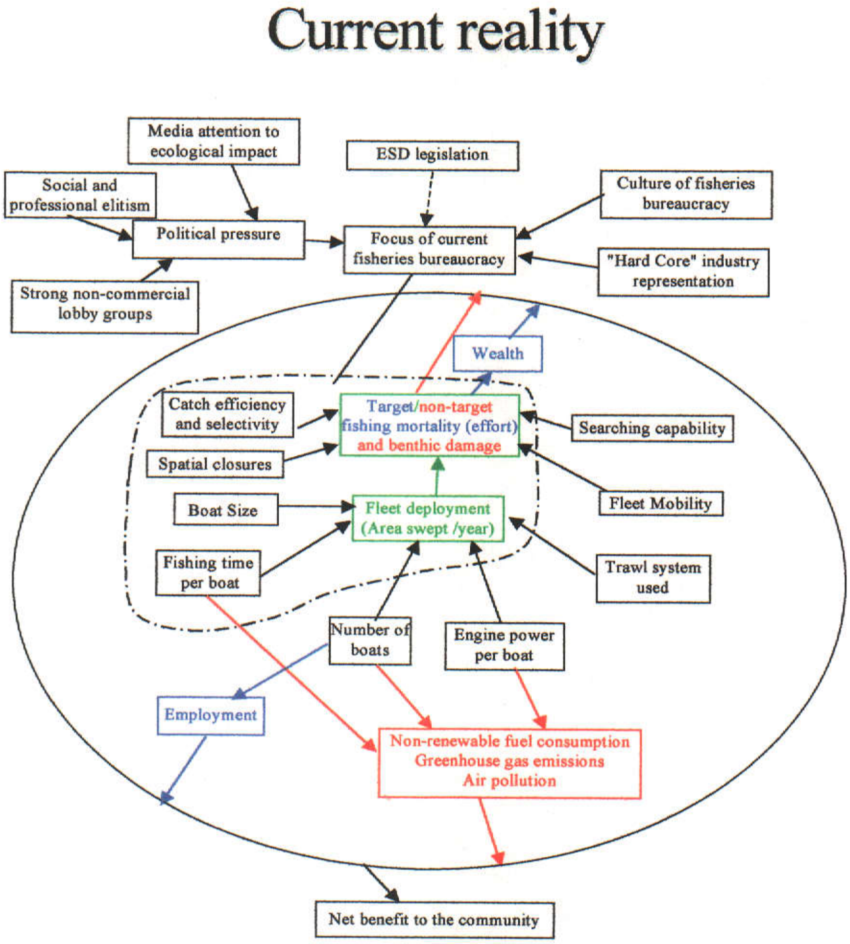


Figure 76. Outline of the ESD problem space for a prawn trawl fishery with narrowed management attention.

Figure 76 shows a broad outline of the situation and has the following features:

1. The circular space represents the entire ESD related problem space for a prawn trawling fishery and that is connected to a single outcome titled; net benefit to the

community. Here "community" captures both present and future generations and the net benefit may not be positive.

2. At the centre of the activity within the circle is the raw effort (impact) on the environment.

3. Surrounding that are the operational factors that give rise to effort and incidentally, the private cost of production.

4. Objects that directly touch the inside of the circle represent a range of benefits and costs flowing to the community from the fishery.

5. It is proposed that a focus and emphasis on a particular part of the problem space by managers comes about because of a range of sociological factors.

- Intense political pressure to deal with environmental impact as a highest priority from:
  - high media attention to "environmental" issues
  - strong lobbying by groups other than commercial fishers
    - Environmental NGOs
    - Recreational fishers
- Social and professional exclusivity produces a degree of discrimination against many fishers because of the latter's inability to participate meaningfully in sophisticated decision making processes.
- The research component of fisheries has a strong biological culture.
- Industry representation often pushes for a "hands off" approach to economic management of the fishery.

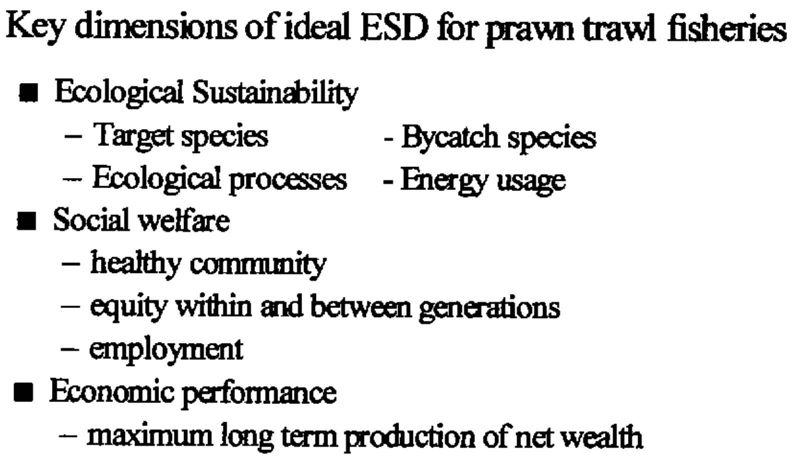
Consistent with the model of reality in Figure 76, which the author contends describes the current situation, and the narrow bureaucratic focus shown, there has been a prevalent utilisation of Fisheries Technology professionals for the development of devices to improve the selectivity of trawl gear (discard bycatch). Beyond that there have been limited opportunities for Fisheries Technology to be involved in the broader range of issues that exist.

The main point to be drawn here is that it is proposed that the approach to fisheries management depicted by Figure 76 (ie the focus) is not holistic and not ideally consistent with ESD. The potential application of Fisheries Technology is therefore much broader than currently employed, but it seems that the role of Fisheries Technology will not expand until the scope of management attention is widened to appreciate the full extent of the ESD problem space.

4.1.4 Work Plan

For the task of this thesis the perception of a full ESD problem space is considered and following this idea Table 17 is a synthesis of the key dimensions of the ESD problem space connected to the operation of prawn trawling fisheries. These key dimensions help define the goals of management and it is noted that they also fall into the framework of principles, criteria and indicators presented by Garcia (2000) for the Code of Conduct for Responsible Fisheries in order to meet a definition of sustainable development from FAO.

Table 17 Key dimensions of ESD connected with the operation of prawn trawling fisheries.



Key dimensions of ideal ESD for prawn trawl fisheries

- Ecological Sustainability
  - Target species - Bycatch species
  - Ecological processes - Energy usage
- Social welfare
  - healthy community
  - equity within and between generations
  - employment
- Economic performance
  - maximum long term production of net wealth

This gives a road map for the objective of this chapter. This might be described as a Systems Engineering approach to the ESD problem and can be undertaken because the objectives of ESD are taken to be explicitly defined by the NSESD. As Table 16 suggests this relates to an alternative possible reality, which the author has labelled "Ideal". To make the distinction between the two "realities" or contexts clearer we can refer to the ideas of Soft Systems Methodology of Checkland (1999). Checkland describes Soft System Methodology as an extension of Systems Engineering by including consideration of the "social roles of the players trying to take purposeful action". The latter is important in terms of understanding potential difficulties in implementing the results of Systems Engineering to the real world in terms of being "systematically desirable" and "culturally feasible", but it is not necessary in terms of producing ideas regarding the full range of possibilities. The "soft" component of the world, which Checkland defines to be a "stream of cultural analysis", is included in the previous section to fully describe the background to the task and is relevant to the problem of expressing the conclusions of the thesis to contemporary stakeholders.

Fisheries Technology has some bearing on all the dimensions of ideal ESD for prawn trawling fisheries shown in Table 17. However, for some dimensions the involvement is direct and significant. Such important connections will be the focus of the following sections.

In this thesis particular attention is given to the extent to which the PTPM, as an important Fisheries Technology tool in context with prawn trawling fisheries, provides useful inputs to management with ESD objectives. This is undertaken systematically by working through the key dimensions identified in Table 17.

To further clarify and ground the abstract concepts of ESD and discussion on the connections with Fisheries Technology and the PTPM, exploration of the subject will refer to the principles and sub-principles defined by Garcia (2000) for the Code of Conduct for Responsible Fisheries and also extensively use the Northern Prawn Fishery (NPF) as a case study.

To Garcia (2000) Ecological Sustainable Development indicates principles related to the need *(1)* to conserve (and sustain) the multiple resource in its environment, *(2)* to satisfy the social and economic needs for human beings and *(3)* for management to guide the required changes in institutions and technology.

4.2 Working Through The Dimensions of ESD

4.2.1 Ecological Sustainability

Ecological sustainability is obviously a key feature of ESD. Perhaps because the term exists within the title of "ESD", it may be too obvious. Some people see ecological sustainability as the only objective of ESD (Fletcher et al., 2002; Fisheries Administration Act 1991 (Com.)). Others see ESD as allowing ecological sustainability to be a counter weight to the drive for "profit motivated development" - to constrain or stop development based on legislated ecological protocols (Gorrie, 2000). However, this thesis presents the view that ecological sustainability is complementary to development and under ESD is part of an initiative for long term progress which holds as equally important, ecological sustainability and the traditional goals of development, that being economic and social advancement.

"Ecological Sustainability" in Table 17 refers to the natural environment and is limited to that in this discussion. Other discussions on ESD sometimes refer to economic sustainability and social sustainability in addition to ecological sustainability. This produces a conceptual framework that covers similar territory to Table 17, however in the present work the economic and social dimensions to ESD are given a more progressive stature by promoting the notion that ESD is about improvement in these dimensions, not simply maintenance. This means that ESD is about improving the efficiency of the process that utilises resources supplied by the natural environment to produce goods and services to people. The efficiency referred to here relates to reducing the resources used and also increasing the quality of production outcomes, measured not only in economics terms but social as well. This is referred to as eco-efficiency (Van Berkel, 2001) or resource efficiency (Hawkin et al., 1999).

One could put forward a view that the natural environment could be enhanced as well - that humanity should seek to improve rather than just sustain the natural environment. The position taken in this thesis is that improvement to the natural environment is part of ESD where it relates to environments that have been degraded to an unacceptable state by past events, however ESD is not about maintaining natural environments everywhere in "pristine" condition. ESD by practical necessity must be accepting of the fact that humanity is part of the natural environment and like all other parts has an active involvement, which unavoidably has measurable impacts through natural cause and effect. These impacts are not contrary to ESD so long as the environment can sustain the activity and impacts in the long term. Here humanity must acknowledge that there will be environmental change. The important questions are, "is that change benign to the long term prognosis for high order life on the planet?" and "are we better off as a consequence?"

The ecological sustainability dimension of ESD is sub-categorized by Table 17 into the following components:

- Target species
- Bycatch species
- Ecological processes
- Energy usage

The sense of sustainability used here corresponds with Principle 1 and its sub-principles from Garcia (2000), which are given below:

Principle 1

'The natural resource base (land, water, plants and genetic resources) should not be degraded.

1.1: The target resource characteristics should be maintained at levels capable of ensuring natural renewal and continuous exploitation of the resource under ecologically acceptable conditions.

1.2: The environment conditions should be protected, maintained and enhanced (where appropriate) to ensure the maintenance of resource productivity.'

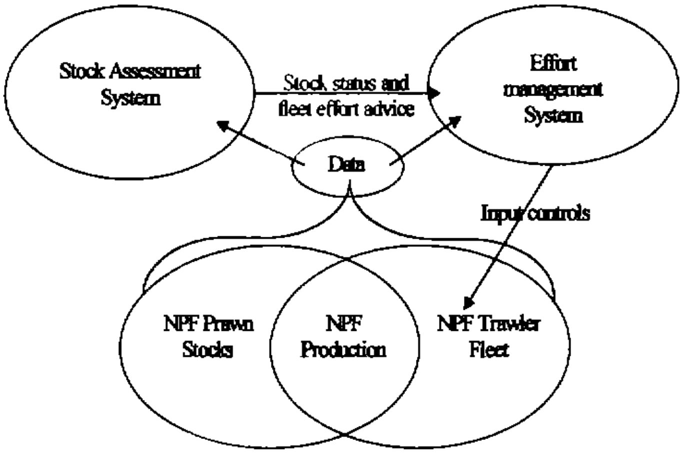
It is quite apparent that the first sub-category of sustainability, target species, is aligned with sub-principle 1.1 and the rest relate to sub-principle 1.2.

4.2.1.1 Target species

Sustainable exploitation of the target species in a prawn fishery that is managed by controls on the input fishing effort depends on the successful implementation of two subsystems: a stock assessment system that determines the level of fishing effort required to achieve a catch that is deemed to be sustainable; and a system to ensure that the applied fishing effort is no greater than the maximum allowed. The function of these subsystems in context with the sustainability of prawn stocks in the NPF is schematically presented in Figure 77.

The stated system requirements presuppose two conditions - that a stock-recruitment relationship exists for the species of prawn targeted and that the management regime is based on an input control philosophy. This is indeed the case for most of the prawn stocks in the NPF. The only exception is the banana prawn fishery where to date it is assumed that there is no stock recruitment relationship, which in practical terms is an assumption that it is not possible to overfish the stock. This assumption is currently under review.

Each of the subsystems is considered separately in sections below. Figure 77 advances key questions that these subsystems may be used to address.



- Effort management system (input control regime)
  - What are the key input variables?
  - What is the best way to control effort?
  - What level of effort do we have?
    - » EFFORT CREEP!
- Stock assessment system
  - What level of effort is appropriate to take a sustainable catch?

Figure 77. Strategic questions relating to management of target species in the NPF.

Effort management system

In the NPF controlling the total catch from the fishery and ensuring sustainability relies on directly limiting the effort applied to the prawn stocks (input controls). An alternative approach is to decide how much catch is allowed and allocate quotas to the individual fishing operations (output controls). Philosophical points connected with the question of secure property rights in fisheries proffer a view that output controls are the most economically efficient method for ensuring the sustainability of target stocks. It is argued that they produce an operating environment where there is minimal competition between operators. This in theory leads to all operators being free to search for the most economical way to take their allocated catch.

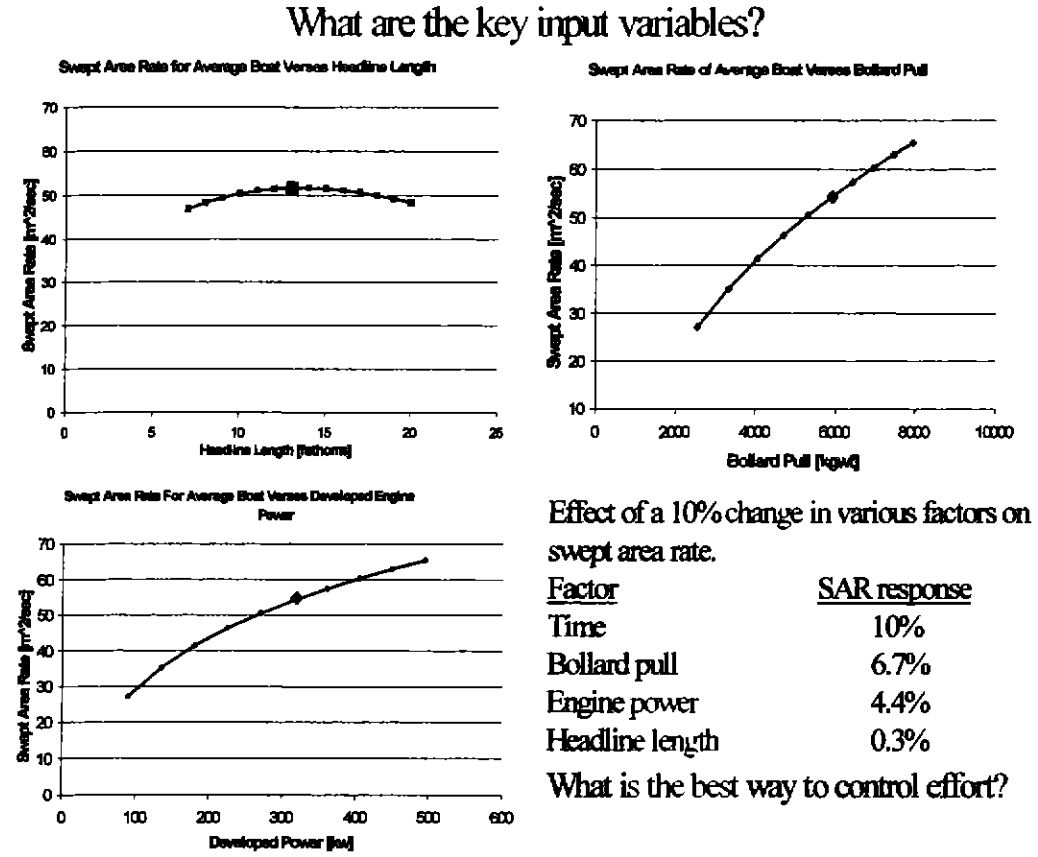
For the input control approach there is maximum competition between operators because they are still able to take as much catch as they can subject to the controls placed on the structure of their operations. In the latter environment operators invest in allowable innovations so that they might be able to increase their personal production at the expense of others. This investment and competition can in some instances increase the general efficiency of the fleet by reducing wasted trawling effort etc, but in other instances it is said to lead to resources being wasted in a war to reallocate catch towards individual operators. In the end the latter initiatives have only short-term benefits and ultimately fail as the entire fleet adopts the higher performing practices. When these initiatives give rise to increased costs of production there is a corresponding drop in production efficiency. The rise in fishing capacity of the fleet associated with this process is often referred to as Effort Creep and must continually be met with effort reductions so as to limit the total catch.

Despite the economic advantages of output controls from the perspective of wasteful competition, input control regimes are operating in all Australian prawn fisheries. This has occurred because the costs associated with managing an output controls regime are very high. Apart from the necessity to keep a running tally of the production from all operators and police against the possibility of black marketeering, there is an extra cost for prawn fisheries due to the nature of the targets species' life cycle and their strategy for survival. Prawns generally have a life span of only 1 year and their recruitment from one year to the next fluctuates wildly depending on the prevailing environmental conditions. In poor years production from the stock can be quite low, but in good years production is very high even though the stock might be small due to a run of bad years. This occurs because prawns are very fecund (each female carries many thousands of eggs). To take advantage of the potential for high catches in good years and ensure that no stock collapse occurs in bad years, the Total Allowable Catch (TAC) needs to be varied from year to year. To achieve this, costly and extensive preseason sampling of the fishery is needed each year with a fast tracked analysis of data and determination of TAC before the beginning of the season. There is also the problem of high grading, which relates to the wastage of the resource when operators maximize the value of their quota by keeping only the highest value portion of the catch. Lower value portions of the catch are returned to the sea, usually dead. The discarded catch has been removed from the stock, but it has not been recorded as catch. This then makes it impossible for the stock assessment system to accurately calculate the true fishing mortality, the status of the stocks and fine tune catch limits.

What are the key input variables?

In order to control effort in an input control regime the system must monitor effort levels, have access to a practical and sensitive control variable and be aware of a target. The target for the control system is supplied by the stock assessment system and is discussed in the next section. The most important question in designing a control system would be, "what is the best way of controlling effort?" This logically leads to the core question, "What are the key input variables?" In this respect the PTPM is very useful.

Figure 78 presents the effect of a number of key factors on effort based on PTPM predictions in context with the NPF. The focus of the performance predictions is the "average" boat in the NPF. The average boat is represented by a collection of parameters, which in each case is the average of that parameter across all vessels in the NPF during 1998. This information was obtained from Bishop and Sterling (1999).



What are the key input variables?

Effect of a 10% change in various factors on swept area rate.

Factor	SAR response
Time	10%
Bollard pull	6.7%
Engine power	4.4%
Headline length	0.3%

What is the best way to control effort?

Figure 78. Change in swept area rate of the average 1998 trawler in the NPF through changing key operating parameters – summary tables gives effect of 10% change.

The PTPM predictions allow the sensitivity of Swept Area Rate (SAR) to key characteristics of NPF trawlers to be estimated. The key variables considered in Figure 78 are time fished, bollard pull, engine power and headline length (net size).

The table within

Figure 78 shows the results of the analysis. The general form of the results is the effect on SAR caused by a 10% change in each respective factor.

The response to time is logically given a value of 10% because a boat that fishes 10% less time would sweep 10% less area. The table lists all variables in order of importance (effect on SAR) and indicates that vessel thrust and engine power have a substantial influence on fishing performance. In 1983 a system of vessel unitisation was introduced into the NPF. Each operator registered the amount of engine power used and could not legally exceed that power usage unless additional “capacity”[1]

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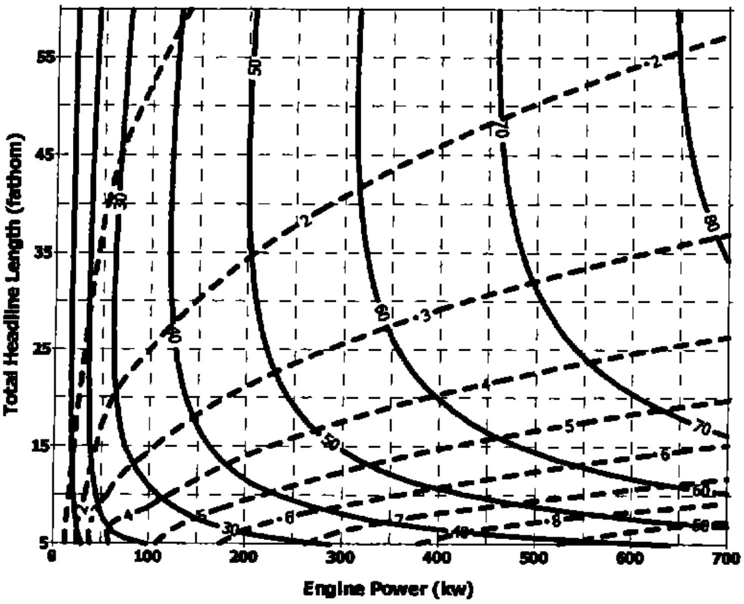
[1] These were called Aunits and was the sum of engine power in kw and the underdeck volume of the trawler hull.

units were bought from another operator. The associated market for capacity units was designed to cap and control the total capacity of the fleet while allowing a flexible allocation between operators on the basis of a free market. When reductions in effort were deemed necessary in the fishery, the length of the season could be reduced to reduce the amount of time worked or a fixed reduction in capacity units across the fleet could be applied. The latter approach occurred in 1992 and no boat was legally able to work until "top up" capacity units were procured or a smaller engine was fitted. This caused immense difficulties for many operators and the fact that the boats could not go to work until all adjustment arrangements were complete was widely seen as a discriminatory act on the part of management.

Headline length has a small effect on performance. This insensitivity can be clearly seen in the associated graph. Such a poor response suggests that headline length is a poor effort control candidate. The graph suggests that a reduction in headline length imposed on an operator will not bring about any significant reduction in effort and would engender no serious motivation to replace the lost headline from the market place if a system of tradeable headline units was created.

What is the best way to control effort?

Contrary to the above insight, NPF management moved to a new effort control regime in 2000 based on headline length units rather than engine power plus under deck volume. The main reason cited was that engine power ratings were not a reliable performance indicator for trawlers because owners (with the collusion of engine manufacturers) could falsely downgrade them in the vessel register. Another problem was that during the restructure in 1992 it was deemed too difficult for operators to reconfigure their boats in a short time frame. An effort control system based on headline length will overcome these problems, but it remains to be seen whether effective control of fishing effort is possible from the new system. Opinion on these issues based on insight from the PTPM cannot be optimistic because the key driver of engineering performance (engine power) is now unregulated (see Figure 79). Based on the acknowledged risks of input control systems generally, that the very competitive fleet will aggressively use uncontrolled inputs, it should be expected that there will be a competition driven escalation in engine power.



Swept Area Performance 10 – 80 m^2/sec ————

Trawl Speed 1 – 9 knots -------

Figure 79. Trawling performance map with respect to engine power and headline length variables.

The best way to control effort is still posing difficulties in the NPF. The preliminary engineering analysis conducted here suggests that the recent choice of control variables is unwise, however it is acknowledged that a more rigorous design exercise for the effort control system would need to incorporate other important economic features of the problem and consider further the difficult issues that existed with the previous system.

During the implementation phase of the new regime the PTPM based view was brought to the attention of the management bureaucracy. This was met with speculation that engine power would be indirectly controlled by headline restrictions through the complicating effects of catch efficiency, which was deemed to decrease rapidly with increasing trawl speed. Similarly, it was argued that these catch efficiency factors would ultimately ensure that headline length acts as a good effort control variable.

What level of effort do we have?

Monitoring the real level of fishing effort applied to a fishery is a difficult endeavour, particularly if the fleet is motivated to make continual improvements to its effectiveness. Ideally effort assessment should be approached systematically using a perfect model that can determine for each trawling operation in the fishery a fishing effectiveness rating (fishing power). This rating, which in each case is a measure of that operation's capacity to take catch, needs to encapsulate all aspects of performance that affect fishing ability. For example; searching ability, timing, catching efficiency, swept area rate and time utilisation (as per Figure 9 – more details given in section 1.4). Flowing into these aspects are a host of inputs that relate to skipper skill, technology (electronic, vessel, gear), socio-economic circumstance and fisheries legislation.

When the fishing power of each vessel is used to standardise its nominal fishing effort an accurate estimate of true fishing effort is achieved. If this is summed across the fleet and monitored for each season, the total effective effort applied to the fishery can be tracked over time.

In the NPF the nominal unit of effort used is fishing days. The crux of the effort monitoring problem from an analytical perspective is the growing difference between “nominal effort” (fishing days) and real effort (pressure on the prawn stocks). The approach of choice by fisheries scientists is to conceptualise the problem of “effort creep” using terms that allow systematic analysis and appropriate adjustment. This starts with the heuristic catch/effort relationship that forms the basis of most stock assessment models.

$$Y = q.f.B \qquad (20)$$

Where Y = yield (catch), q = catchability coefficient, f = nominal (measured) effort and B = stock biomass.

The catchability coefficient, q quantifies the proportion of the stock caught for each unit of nominal effort. Ideally q is constant and if that was the case the estimation of maximum sustainable yield and the effort limit required to avoid overexploitation would be quite straightforward using well developed stock assessment techniques. In reality q is highly variable. It is known to vary throughout the season as water temperature changes the activity level of prawns and prawns may change their range of distribution as they live-out their life cycle. q may well be dependent on the level of biomass because if the biomass is low the incentive of operators to find good catches will increase because of the imperative to operate profitably and this may be exacerbated if the prawn stock is aggregated. q may be dependent on the number of boats on the grounds because the capacity of the fleet to search the grounds for the densest concentrations of prawn may be higher when the fleet is larger. Lastly, q is also dependent on the performance of the fishing vessels, the efficiency of the trawl gear and the abilities of the skipper. It is these latter more tangible effects on q, which are related to the structure and capability of the fleet, that fisheries scientists cluster together to form the problem of "effort creep" or more properly "increasing fishing power".

To account for increases in fishing power of the fleet in the stock assessment process, q is increased yearly (NPFAG, 2004). This is achieved by applying a multiplicative factor q_{inc} to q each year. q_{inc} ideally captures the effect of all factors that contribute to changes in the fishing power. Attempts to quantify the increase in fishing power of the NPF fleet over the years stems from the work of Buckworth (1987) where consideration was given to evidence of increasing swept area performance of the fleet based on the increase in the size of the gear used. Subsequent to that the effect of position fixing equipment (GPS/plotters) was investigated (Robins et al., 1998) and also try gear and Kort nozzle (Bishop et al., 1999).

The combined effect of that work and its advice to the management process for the NPF produced a working assumption that fishing power of the NPF fleet was increasing each year by 5%. Formal stock assessments for the NPF between 1996 and 2000 used this assumption as the basis of standardising effort over the history of the fishery since 1970. The crude nature of this assumption coupled with the well-known sensitivity of the stock assessment to the value assumed made room for heavy criticism that the stock assessment results were inaccurate and misleading.

In response to criticism of the 5% assumption, AFMA in 2000 sponsored a preliminary investigation into developing a more detailed fishing power schedule for the NPF (Sterling, 2000a) based on reviewing all available information and utilising the PTPM to establish with greater certainty the component of fishing power that relates to engineering performance (swept area rate, SAR). The information and calculations were amalgamated using a scheme for summation that was informed from the catch quantity framework shown in Figure 9.

Figure 80 shows the final result of that exercise and clearly demonstrates the different picture of fishing power that was produced. The results suggest that real effort at the current time is significantly less than that estimated by using the 5% assumption. Of more significance, the PTPM based picture of fishing power has a much higher average growth in fishing power during the first half of NPF history than 5%. From 1975 to 1982 q_{inc} was estimated to be 9 – 11% per anum.

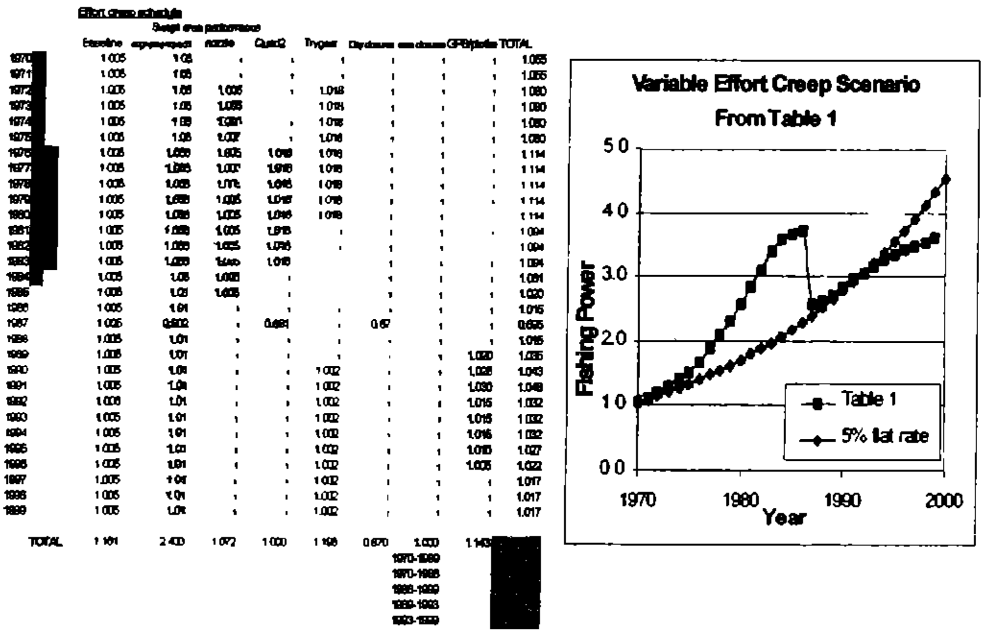


Figure 80. Preliminary usage of the PTPM to produce a more detailed picture of fishing power for the NPF fleet since 1970 (Sterling, 2000a).

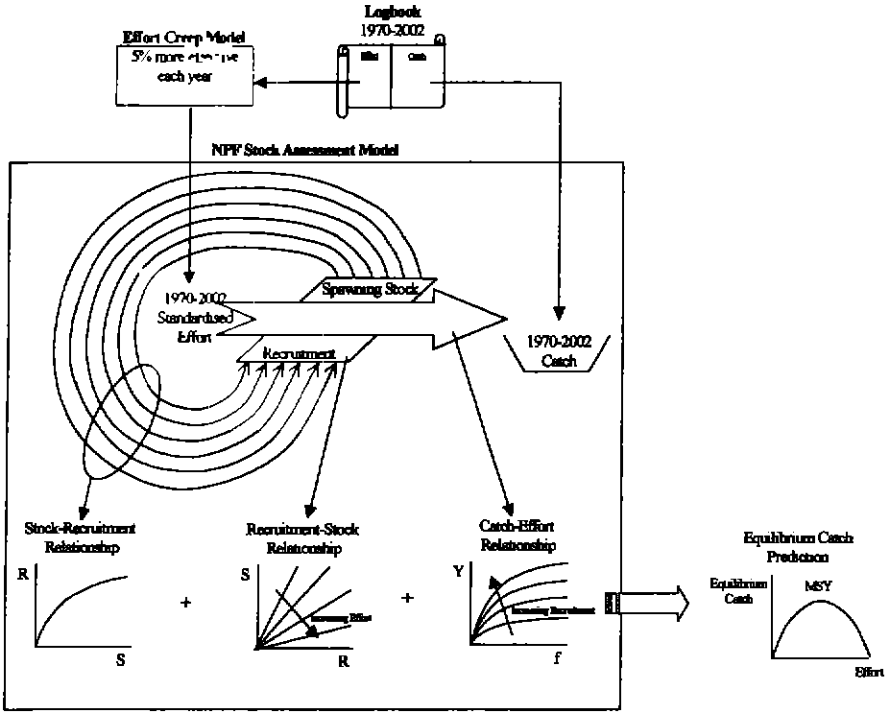
A striking feature of the new result is the sharp drop in fishing power in 1987 due to the ban on towing more than two trawl nets. No allowance was made for the effect of this management measure on the assumptions of fishing power in the past. The PTPM was able to make an estimate of that effect and for the first time it was spliced into the fishing power picture using the methodology of Sterling (2000a).

A more advanced approach to the assessment of fishing power growth in the fishery is possible by formally connecting the output of the PTPM to statistical methods used to analyse the structural details of the NPF fleet in conjunction with their historical catching performance. Work in this area was initiated after recommendations from a Senate inquiry into the amendments of the NPF management plan (Anon., 2000a) and was completed during 2003. Some details of the new approach are given in the next section.

Stock assessment system

As outlined in the last section the increase in fishing power of the trawling fleet is an important variable in the assessment of prawn stocks. Important outcomes from such an assessment are; an estimate of stock size, measurements of the stock's dynamic characteristics (capacity to reproduce) and the capacity of the stock to be fished (maximum sustainable yield, MSY and effort for MSY, E_{MSY}). In these respects uncertainty about fishing power becomes a crucial consideration.

Figure 81 shows a stylised view of the stock assessment process for the NPF Fundamental to the process is the assumption that a stock-recruitment relationship exists. This presumes that recruitment to the fishery is limited by the carrying capacity of the environment, which means that there is a diminishing return to recruitment as stock size is increased. The effect of fishing is always to reduce the average stock size from its unfished condition and also the average recruitment to the fishery in forthcoming years. The operative theory is that a sustained stable fishing effort on the stock will produce a new lower stable stock size which in turn produces a recruitment which is smaller than the past but larger than that required to replace the new stable stock size. That is, the marginal reduction in average recruitment is less than the marginal reduction in average stock size. The excess production from the stock is deemed to be the sustainable catch from the fishery. Depending on the dynamics of the stock and the environment in which it exists, the level of sustainable catch increases as the amount of effort increases and the new stable stock size is driven to lower levels.



What level of effort is appropriate to take a sustainable catch?

Figure 81. Stylised model of the stock assessment process

This occurs up to a point where the marginal reduction in stable recruitment becomes greater than the marginal reduction in stock size. At this point the larger effort is beginning to produce a catch that is smaller than if less effort was applied. In theory this smaller catch is sustainable, but the management issue of importance here is that the catch is not the maximum that can be sustained.

This approach to define criteria for maximum sustainable yield is quite a misnomer because the theory is never able to put forward any criteria that the fishery is unsustainable. The condition of maximum sustainable yield is an economic condition based on maximising the gross revenue from the fishery. A pragmatic approach to ecological sustainability would need to consider the interacting dynamics of environmental fluctuations and the minimum stock size required to avoid irreversible stock collapse for some plausible worst-case scenario of poor environmental circumstances. Additionally, the health of the ecosystem would be sensitive to the effects of reduced prawn stocks on food chains and energy flows within the system. Such ecosystem-based management has to date not reached a point where it is formally applied in the NPF.

A suitable safe minimum standard for stock size might be lower than the equilibrium stock size that produces maximum sustainable yield, but even for a fishery where the applied effort is no greater than E_{MSY}, the onset of a period of low recruitment due to environmental conditions could see the stock driven below a notional safe level. Therefore effort control based around E_{MSY} should also have carefully planned safeguards to cover adverse environmental circumstances. For the NPF the safe minimum standard for stock size is effectively that which produces MSY under average environmental conditions, S_{MSY}. This is the case because S_{MSY} is a trigger point for review of effort management and the goal is to keep all prawn stocks above S_{MSY}.

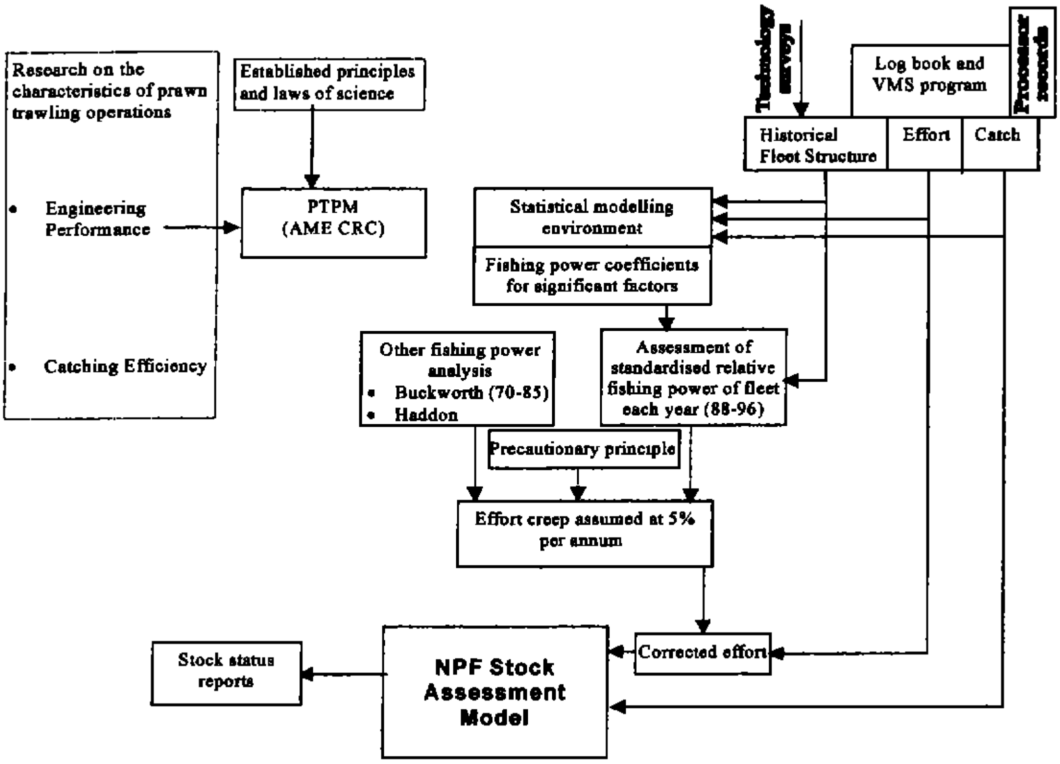
In the stock assessment process for the NPF the dynamics of the fishery are assumed to comply with the surplus yield concepts described above. The associated dynamic relationships of the stock and the catching process are expressed explicitly in the stock assessment model and the relationships are statistically calibrated in the stock assessment process through analysis of the historical catch and effort information captured by the official log books that are completed by operators. As explained above, fishing effort recorded in the logbook is nominal and is simply the number of days fished. It is clear that the effectiveness of a day fished in 1970 by the average boat in the fleet at that time was much less than the effectiveness of a contemporary fishing day using a high powered modern trawler fitted with sophisticated trawl gear and electronics and driven by a skipper who possesses the skills and knowledge passed down from the collective experience of all the vessels that worked in the fishery over the intervening period.

To achieve an accurate assessment it is essential to standardise the fishing effort in the fishery over its history, otherwise the stock dynamic and fishery production relationships in the assessment model are not realistically calibrated. This is approximately achieved in Figure 81 by applying the 5% assumption discussed in the last section, but this is a crude assumption and an improved assessment of fishing power is essential. Obvious improvements to the assumption would occur through the systematic application of the PTPM. This has already been demonstrated in the last section with the described development of the variable fishing power schedule, but that was only a preliminary study. It would seem appropriate to organise a complete integration of the engineering approach of the PTPM and the statistical methodologies of contemporary fisheries science to produce an optimal hybrid approach.

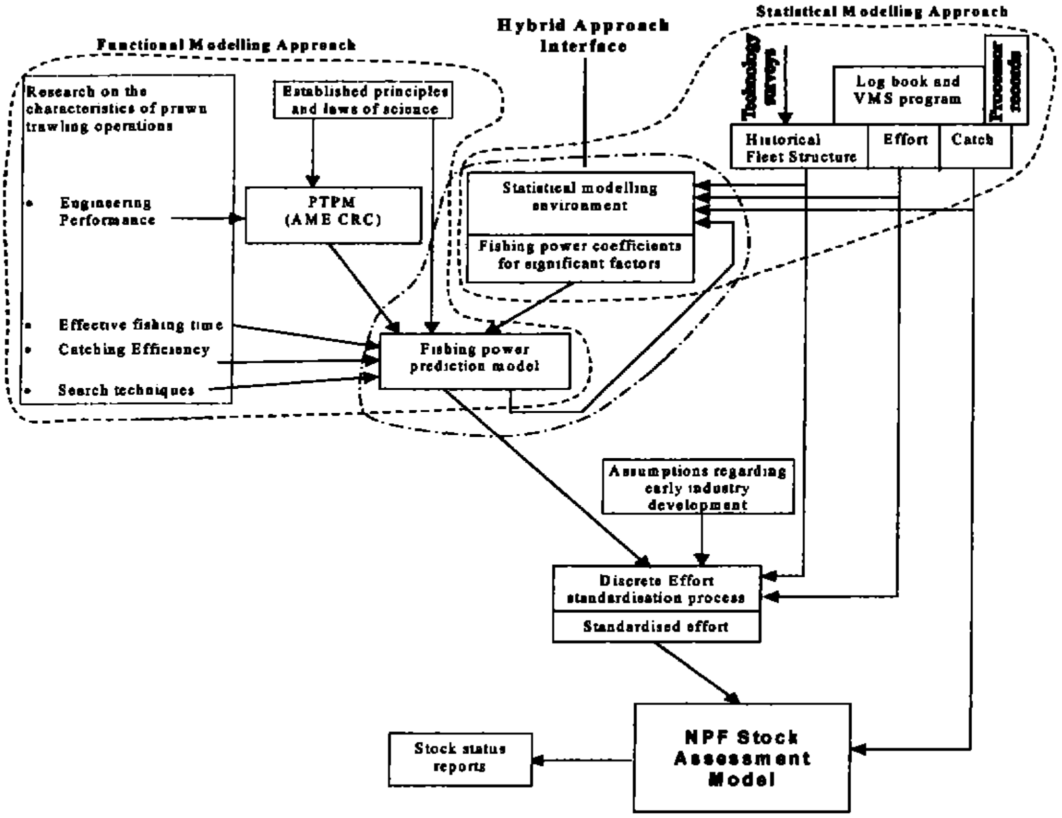
Figure 82(a) shows a schematic diagram of the situation regarding stock assessment for the NPF prawn resources up to 2003. There is only a qualitative connection between attempts to statistically measure increases in fishing power and the stock assessment process. In addition, the PTPM's capabilities have not been used.

Figure 82(b) shows a proposed methodology for stock assessment in the NPF. The key feature of this modified methodology is the development of a hybrid approach to the investigation of fishing power and culminates in the construction of a Fishing Power Prediction Model. This model incorporates the PTPM and is tuned by output from the Statistical Modelling Environment, which is connected to the three operational databases for the fishery. The Fishing Power Prediction Model also informs the Statistical Modelling Environment regarding external information (both quantitative and qualitative) related to the connection between fishing power factors and their effect on fishing performance, thus ensuring that both elements are optimally tuned to achieve their respective tasks. As alluded to above, the Fishing Power Prediction Model is open to input from other areas of investigation that might lead to useful prediction modules. Identified areas in Figure 82 are effective fishing time, catch efficiency and search techniques.

This hybrid approach is a framework that allows information from a variety of sources and approaches to be combined and should produce a more thorough investigation of fishing power. A key feature from the point of view of the stock assessment process is that the methodology can organise a discrete effort standardisation module, which can provide standardised effort over the history of the NPF at the individual boat level of detail.



(a) Current NPF Stock Assessment Methodology



(b) Proposed Stock Assessment Methodology

Figure 82. A new approach to fishing power analysis in stock assessment for the NPF.

In 2001 a collaborative project was funded by AFMA and FRRF to develop this new approach to fishing power analysis and stock assessment for the NPF. At this time that project is nearing completion and a summary report of progress has been released to the NPFAG (Dichmont et al., 2003). In respect to the PTPM it states, "The central task of assessing fishing power itself was to be accomplished using a statistical modelling approach, incorporating the swept area rate outputs from the PTPM. The central importance of the PTPM for this exercise lies in its injection of engineering knowledge into the otherwise empirical statistical models. Using the PTPM to combine vessel, engine and net characteristics in an optimal way to summarise fishing efficiency (as swept area rate) obviates the need to estimate this property in a more empirical way from the inputs to the engineering model. Thus it both improves the predictive value of the model and may also indirectly resolve some of the confounding issues. Swept area rate is clearly an important feature of vessel fishing capacity".

4.2.1.2 Bycatch species and ecological processes

From the point of view of the PTPM the issues of sustainability of bycatch species and ecological process have a similar structure to the sustainability of the target species. Sustainability in these respects relies on accurately monitoring the level of effort in the fishery and having an effective effort control mechanism. The PTPM does not make predictions regarding the relative impact of different systems in context with particular environmental issues apart from that related to their connection with swept area performance.

The features of different gears may have differential effects on impact levels with respect to bycatch or ecological processes. For example, the installation of Turtle excluder devices (TEDs) or use of lighter ground chains may reduce the incidental capture and death of non-target animals and the extent of accompanying damage to benthic structures. The PTPM in its current form does not quantify any of these differential effects.

In the case of TEDs the PTPM does not contain quantitative information on the engineering implications of towing TEDs as no data is yet available on the related drag effects. However, for ground chains there is a theory-based link, which gives a deterministic connection between the weight of ground chain used and impacts on trawl span, speed and SAR.

Despite this lack of first order relevance between the PTPM and the subject of this section, it needs to be emphasised that if the real SAR of the fleet is increasing in an uncontrolled fashion there will be a proportional increase in impact on bycatch species and ecological processes at the fleet wide scale. Thus there is an increasing importance for effort control and the PTPM with each new environmental impact issue identified.

4.2.1.3 Energy usage

Energy usage for prawn trawling fisheries evokes sustainability issues through the industry's heavy reliance on diesel fuel as its principal energy source. Trawling, being an active fishing method, is energy intensive with typically 2.5 litres of diesel fuel burnt to achieve 1kg of prawn production in night-time fisheries. Operating a trawling business according to this statistic hardly appears rational on casual inspection, but the economic justification is simple. 2.5 litres of fuel costs the operator approximately $1.50, while a kilogram of prawn is sold by the fisher for about $15.00 on average. This produces a strong economic incentive to convert diesel fuel into prawns using the trawling process.

Although the production of prawns from prawn trawling operations might be sustainable with respect to prawn stocks, natural stocks of crude oil cannot sustain the heavy use of highly refined fossil fuels indefinitely. Looming on the horizon is a likely crisis for the prawn trawling industry. The current economics and politics of fuel production and usage provide for the trawling industry a comfortable environment to continue current practices. However if fuel supplies become restricted either through depletion of natural reserves or a blockage in supply, the price will rise substantially and cause the industry to become immediately unviable. Logically, a dedicated effort should be applied to reduce this exposure to risk. Initiatives that would build long-term security to the industry would be to develop alternative energy sources and/or substantially improve the energy efficiency of the operation. In this arena the Fisheries Technologist and indeed the PTPM have a crucial and high priority role to perform, particularly in the light of continuing political conflict in many of the significant oil producing regions of the world. But under current management objectives there seems to be little drive to move forward with this initiative at this time.

Perhaps because of the intergenerational nature of the fossil fuel depletion issue and because there is no well known ecological process that relies heavily on fossil fuel reserves there is no high profile concern by fisheries management about energy usage. In the broader environment though, a clear connection is made between fossil fuel usage and the production of green house gases. This has generated initiatives and market changes with respect to large-scale energy usage, in particular the large domestic market. However for fisheries the overall level of energy consumption is relatively small, so fuel usage and efficiency is seen predominantly as an industry scale financial issue and as such it will be revisited in sections 4.2.3.

To continue viewing energy usage in fisheries from a conservation perspective and to provide a solid background to the economic implications, it is worthwhile reviewing work undertaken by Tyedmers (2000). Tyedmers has sought to establish the extent of energy usage for North Atlantic fisheries in two contexts, a worldwide fisheries context and a general food production context. This serves to gain a feel for the energy intensity of different modes of fishing in different parts of the world and also a comparison of energy efficiency between fishing and other food production industries. Of interest to this thesis is how Australian prawn fisheries fare in these respects and how the PTPM might help to inform and improve the situation.

Table 18 (Tyedmers, 2000) shows a comparison of energy intensities for a range of commercial fisheries. To equate the information in Table 18 with fuel usage it is necessary to know that 1 litre of diesel releases 36MJ of energy upon combustion. Therefore, the statistic given above that 'Australian night time prawn fisheries use approximately 2.5 litres of fuel to produce 1kg of prawn' is equivalent to '90GJ of fuel energy for 1 tonne of prawn'. This is about 2.25 times higher than the value quoted in Table 18 for Australian shrimp trawling (38GJ/tonne). This value was determined in 1976 and suggests that the energy intensity of prawn trawling in Australia may have increased dramatically over the last 25years. Another possible explanation is that the number quoted in Table 18 refers to the total Australian prawn production including, in particular, banana prawn fisheries. It is very likely that the energy intensity for banana prawns and other day time fisheries for schooling prawns is substantially less than for night-time fisheries that target widely dispersed bottom dwelling species like tiger, king and endeavour prawn.

The energy intensity for Australian prawn trawling fisheries is generally similar to the other fisheries covered by Table 18. A particularly relevant comparison is between Australian and United States prawn fisheries. Of some comfort to Australia is the observation that even the high estimate of the contemporary energy intensity (90GJ/Tonne) for night-time species appears low compared to the US figures for the late 70's (270-358GJ/Tonne).

Table 18. Comparison of commercial fishery energy intensities (Tyedmers, 2000).

Fishery (home base or location)	**Energy intensity (GJ/t)**	**Analysis includes energy inputs to**	**Source**
Purse seining for capelin (Iceland)	0.7	Fuel	Ágústsson (1978)
Purse seining for small pelagics (N. Atl.)	**1.8**	**Fuel**	**This study**
Purse seining for herring (Maine, U.S.)	2.2 to 2.4	Fuel, gear, vessels	Rawitscher (1978)
Set nets for various species (Japan)	2.9	Fuel	Nomura (1980)
Trawling for small pelagics (N. Atlantic)	**3.5**	**Fuel**	**This study**
Mobile seining for small pelagics (N. Atl.)	**5.2**	**Fuel**	**This study**
Purse seining for herring (B.C., Canada)	5.8	Fuel, vessels	Tyedmers (2000)
Trawling for pollock (Japan)	7.5	Fuel	Nomura (1980)
Trawling for perch (Maine, U.S.)	6 to 8	Fuel, gear, vessels	Rawitscher (1978)
Jigging for squid (Japan)	7.2 to 72	Fuel	Sato *et al.* (1989)
Trapping crabs (Maryland, U.S.)	8 to 10	Fuel, gear, vessels	Rawitscher (1978)
Purse seining for pelagics (Japan)	10	Fuel	Nomura (1980)
Trawling for groundfish (Wash. U.S.)	10	Fuel, vessels and other	Wiviott and Mathews (1975)
Trapping crabs (N. Atlantic)	**12**	**Fuel**	**This study**
Dredging for scallops (N. Atlantic)	**13**	**Fuel**	**This study**
Gillnetting pink salmon (Washington, U.S.)	13 to 19	Fuel, gear, vessels	Rawitscher (1978)
Mobile seine for groundfish (N. Atlantic)	**16**	**Fuel**	**This study**
Purse seining for salmon (B.C., Canada)	17	Fuel, gear, vessels	Tyedmers (2000)
Longlining for groundfish (N. Atlantic)	**18**	**Fuel**	**This study**
Trawling for cod (Massachusetts, U.S.)	18 to 20	Fuel, gear, vessels	Rawitscher (1978)
Trawling for groundfish (N. Atlantic)	**19**	**Fuel**	**This study**
Trawling for flounder (Rhode Island, U.S.)	20 to 22	Fuel, gear, vessels	Rawitscher (1978)
Jigging for squid (Japan)	20 to 44	Fuel	Nomura (1980)
Handlining for groundfish (N. Atlantic)	**21**	**Fuel**	**This study**
Trawling for pollock (Japan)	21 to 84	Fuel and other	Watanabe and Uchida (1984)
Gillnetting for groundfish (N. Atlantic)	**23**	**Fuel**	**This study**
Purse seining for tuna (California, U.S.)	31 to 62	Fuel, gear, vessels	Rawitscher (1978)
Trawling for shrimp (N. Atlantic)	**33**	**Fuel**	**This study**
Trawling for croaker (Japan)	33 to 75	Fuel and other	Watanabe and Uchida (1984)
Gillnetting for salmon (B.C., Canada)	34	Fuel, gear, vessels	Tyedmers (2000)
Trolling for salmon (B.C., Canada)	34	Fuel, gear, vessels	Tyedmers (2000)
Trawling for Norway lobster (N. Atlantic)	**37**	**Fuel**	**This study**
Trawling for shrimp (Australia)	38	Fuel, vessels	(Leach 1976)
Trawling for groundfish (Japan)	38	Fuel	Nomura (1980)
Trawling for haddock (Massachusetts, U.S.)	34 to 42	Fuel, gear, vessels	Rawitscher (1978)
Pole & line for skipjack (Japan)	42	Fuel	Nomura (1980)
Driftnetting for salmon (Japan)	44 to 68	Fuel	Nomura (1980)
Longlining for halibut (U.S.)	48 to 51	Fuel, gear, vessels	Rawitscher (1978)
Trawling for groundfish (Japan)	52	Fuel, vessels and other	Wiviott and Mathews (1975)
Longlining for swordfish/tuna (N. Atlantic)	**63**	**Fuel**	**This study**
Trolling for chinook salmon (Washington, U.S.)	82 to 87	Fuel, gear, vessels	Rawitscher (1978)
Longlining for tuna (Japan)	84 to 134	Fuel	Nomura (1980)
Trapping lobster (Maine, U.S.)	141 to 145	Fuel, gear, vessels	Rawitscher (1978)
Trawling for shrimp (Texas, U.S.)	270 to 312	Fuel, gear, vessels	Rawitscher (1978)
Trawling for shrimp (U.S.)	358	Fuel	Leach (1976)

In Table 19 (Tyedmers, 2000) edible protein Energy Return on Investment (EROI) is presented for a variety of food production systems. Such systems cover fisheries, aquaculture and agriculture. The Australian prawn trawling industry does not feature in the table, however from the methodology used by Tyedmers a comparable value for contemporary Australian night-time prawn trawling fisheries is about 0.02. This is determined by assuming that the recovery rate of edible protein from prawns is 10% and the energy content of protein is 17.6GJ/Tonne.

Table 19. Protein returns (Energy Return on Investment - EROI) for various food production systems (Tyedmers, 2000).

Food production system	**Edible Protein EROI**	**Source**
Carp farming (Indonesia)	0.70	Ackefors *et al.* (1993)[a]
Kapenta fishery (Zimbabwe)	0.25	Michélsen (1995)[b]
Groundfish trawl fishery (Washington State - 1970's)	0.17	Wiviott and Mathews (1975)
All commercial fishing (New Bedford Mass., 1968 to 1988)	0.17 declining to 0.03	Mitchell and Cleveland (1993)
Salmon purse seine fishery (British Columbia)	0.14	Tyedmers (2000)
Tilapia farming (Africa)	0.11	Ackefors *et al.* (1993)[a]
Mussel farming (Scandinavia)	0.10	Folke and Kautsky (1992)[b]
Contemporary North Atlantic groundfish fisheries	**0.095**	**This study**
Carp farming (Israel)	0.084	Ackefors *et al.* (1993)[a]
Sea ranched Atlantic salmon (Sweden)	0.083	Folke and Kautsky (1992)[b]
Turkey (USA)	0.077	Pimentel (1997)[c]
Milk (USA)	0.071	Pimentel (1997)[c]
Salmon gillnet fishery (British Columbia)	0.068	Tyedmers (2000)
Salmon troll fishery (British Columbia)	0.068	Tyedmers (2000)
Tilapia farming (Israel)	0.066	Ackefors *et al.* (1993)[a]
Tilapia semi-intensive pond culture (Zimbabwe)	0.060	Berg *et al.* (1996)
Swine (USA)	0.056	Pimentel (1997)[c]
Cod fishery (USA - 1970's)	0.050	Folke and Kautsky (1992)[b]
Contemporary North Atlantic invertebrate fisheries	**0.039**	**This study**
Egg production (USA)	0.038	Pimentel (1997)[c]
Contemporary North Atlantic longline fishery (large pelagics)	**0.034**	**This study**
Catfish - intensive pond culture (USA)	0.030	Pimentel *et al.* (1996)
Chicken (USA)	0.029	Ackefors *et al.* (1993)[a]
Tilapia - intensive cage culture (Zimbabwe)	0.025	Berg *et al.* (1996)
Atlantic salmon - intensive cage culture (British Columbia)	0.025	Tyedmers (2000)
Shrimp- semi-intensive culture (Colombia)	0.020	Larsson *et al.* (1994)
Chinook salmon - intensive cage culture (British Columbia)	0.020	Tyedmers (2000)
Lamb	0.020	Pimentel (1997)[c]
Atlantic salmon - intensive cage culture (Sweden)	0.020	Folke and Kautsky (1992)[b]
Beef (USA)	0.019	Pimentel (1997)[c]
Seabass - intensive culture (Thailand)	0.015	Pimentel *et al.* (1996)
Shrimp - intensive culture (Thailand)	0.014	Pimentel *et al.* (1996)

Note: a.) Ackefors *et al.* (1993) do not cite the original sources of these data. In addition, as they only provide energy inputs per gram of protein produced, these were converted to protein return ratios based on protein's energy density of 17.9 kJ/gram;
b.) As cited in Berg *et al.* (1996);
c.) Energy inputs to contemporary US livestock production systems as reported by Pimentel (1997) only include the energy needed to provide feed inputs (Dr. David Pimentel, pers. comm. 1999).

Compared to energy returns for food production covered in Table 19, the value for Australian prawn trawling is at the lower end of the range for fisheries but comparable to most industrial scale aquaculture and agriculture systems shown. From a conservation perspective this highlights two points:

- The energy efficiency of protein production from Australian night-time prawn fisheries is relatively low.
- Industrial scale protein production worldwide has low energy efficiency.

Following the theme of the work by (Tyedmers, 2000) and utilizing aspects of his methodology it is possible to construct a historical perspective on energy intensity for the NPF tiger fishery. Fuel consumed per unit of swept area is established each year for the NPF based on the average swept area rate (SAR) and installed engine power across the fleet. SAR estimates and engine power data are available from the work in section 3.4. Additional information used in this instance is a generic fuel efficiency for diesel engines equivalent to 0.238litres/hr/KW. For 1988 the fuel consumed per m^2 of swept area was estimated to be 3.74×10^{-4}litres on average. From the regression between daily NPF tiger fishery catch (economic) and SAR shown in Figure 57 of section 3.4, it appears that the average catch rate per unit of SAR ($1m^2/sec$) is close to 4kg/day. At this point a correction needs to be applied to account for the under representation of endeavour prawns in the regression caused by considering "economic" catch, which halves the catch of the less valuable endeavour prawn. Approximately 30% of the prawn caught in the tiger fishery for 1998 was endeavour prawn (Taylor and Die, 1999). Therefore an appropriate correction to the overall catch rate is a factor of about 1.2. Such a catch rate equates to a spatial prawn production of $1.33 \times 10^{-4} kg/m^2$ (assuming the trawlers fish for 10 hours per day). Given the fuel consumed and prawn production per unit of swept area calculated above it is straightforward to estimate the fuel consumed per kg of prawn for 1998 (2.8l/kg). This result and similar for all other years between 1970 and 2001 are plotted as a series in Figure 83. This energy intensity information is also shown with units of GJ/tonne.

From Figure 83 it is apparent that the contemporary energy intensity of the NPF night-time fishery is substantially higher than 2.5l/kg but was equivalent or less than that figure between 1978 and 1986. A sharp 20% rise in energy intensity occurred in 1987 as a result of the ban on towing trawl systems with greater than 2 nets. Therefore in part the poor energy efficiency of the NPF is due to management measures designed to reduce effort on prawn stocks. This highlights a less than ideal situation and reinforces the notion that ESD is at risk if management decisions are not optimised within a clear holistic multidimensional framework.

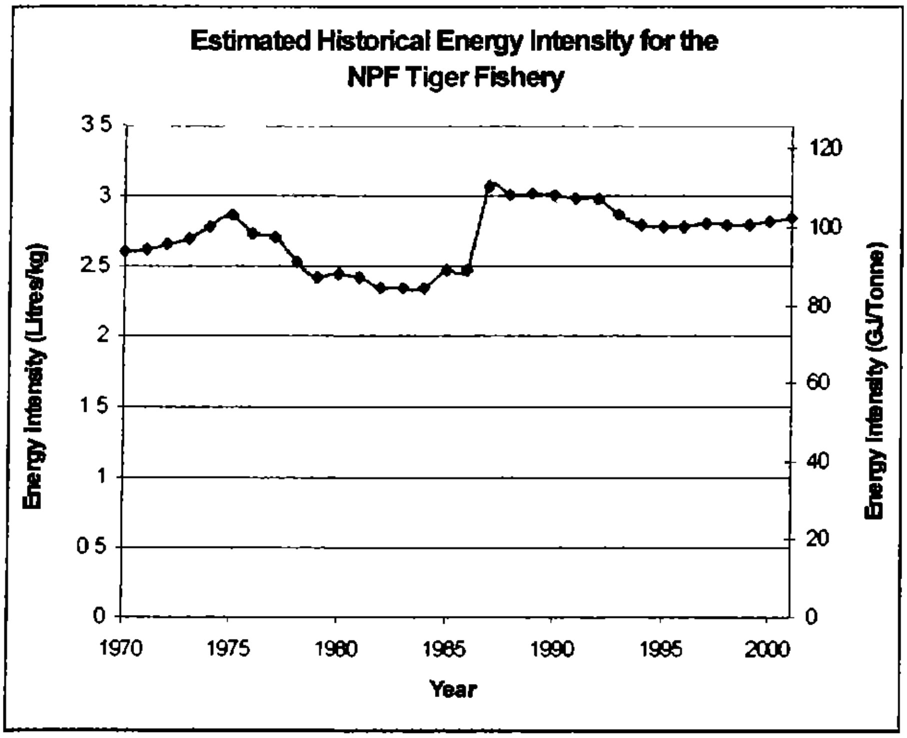


Figure 83. Estimated historical energy intensity for the tiger prawn fishery in the NPF.

Also of interest in Figure 83 is the fact that the series never gets as low as 38GJ/tonne as might be expected by the result quoted in Table 18 for 1976. This reinforces the idea that the low value in Table 18 might be due to the inclusion of fisheries for daytime schooling prawns. At that time catch from the NPF was 75% banana prawn and a relatively small effort was input into the tiger fishery compared to contemporary times. Currently the overall energy intensity for Australian prawn fisheries would be as high as depicted in Figure 83 because of three factors:

- The effort into night-time fisheries has expanded since the early 70's by an order of magnitude.
- Night-time trawling is currently the dominant activity of Australian prawn trawlers.
- In most fisheries, management have chosen to control effort partially through imposing negative impacts on the operating efficiency of trawler fleets (i.e. the banning of high order multiple net systems is common).

4.2.2 Social welfare

4.2.2.1 Introduction

The framework of ESD presented in Table 17 shows three dimensions associated with the social welfare arena:

- Healthy community.
- Equity within and between generations.
- Employment.

Social welfare is captured by Principle 2 in Garcia's (2000) translation of ESD into the Code of Conduct for Responsible Fisheries; in particular sub-principle 2.1. Principle 2 is given below:

Principle 2

'The human economic and social needs should be continuously satisfied, now and in the future.

2.1: The human needs (in terms of sustainable access to high quality and safe food, employment, income, and recreation) and societal/ethical values should be satisfied.

2.2: The economic conditions of the fishery (e.g. in terms of incentives, costs, revenues, prices) should be conducive to long term economic viability.

Many aspects of these dimensions overlap and strongly connect with other dimensions of the framework. For example, healthy communities depend on healthy economies and intergenerational equity strongly drives the sustainability imperative. That realisation does not highlight faults with the framework but accentuates acceptance of the "wicked" nature of ESD problems – that development and conservation cannot be pursued when separated from issues of community values, equity and social justice (Ludwig, 2001).

Explicitly recognising a social dimension to ESD as distinct to economic, relates to the parallel recognition that the needs/wellbeing of citizens extend beyond basic physiological needs and marketed goods available from the economy. Yet the extended part is inextricably bound up with the basic part. Maslow's hierarchy of needs (Maslow, 1970) seems appropriate to describe the entire range of human need; food and shelter, security, social belonging, self-esteem and self-realisation.

Although it is believed that needs at a higher level are put on hold until needs at lower levels are satisfied, people do not usually treat them independently (Gatewood and McCay, 1990).

The complexity of multiple needs with interactions no doubt produces the diversity of human behaviour and complex social systems observed throughout the world in the present and past. The ongoing western process of attempting to manage material scarcity in context with maximising economically tangible benefits can easily disrupt existing social structures and arguably cause more harm that good in certain instances. While taking the full breadth of social phenomena into account is near impossible, it would seem appropriate to consider major social impacts when it is necessary to apply controlling actions to human endeavour. Zoeteman (2000) also uses Maslow's pyramid of needs to help explore sustainable development using a framework approach. That framework is much more sophisticated and detailed in the characterisation of social phenomenon and development than the one pursued here.

Given that the basis of development is to provide improvements in the quality of life enjoyed by individuals, room must be allowed for individuals to search for their most comfortable place in the world and equally there needs to be protection of the rights of individuals to maintain their desired lifestyle in the face of other individuals who seek to change the environment in ways that improves theirs. Above all, it seems that a community approach needs to be pursued where these freedoms and constraints can coexist in a mutually harmonious way.

4.2.2.2 Healthy community

Focussing on the community is seen by Jentoft (2000) as an efficient way forward in managing these difficult affairs. Jentoft captures the importance of community in broad terms and in context with fisheries management. He describes the role of the community as a functional system rather than an interdependent system whereby the collection of fishers and the effect of their multiple roles in the community becomes a mutually dependent and supportive entity. "Here, communities are more than simple aggregates of individuals that are driven by self centred utilitarian motives, but well connected systems rooted in kinship, culture and history", (Jentoft, 2000).

Jentoft's view of a healthy community goes well beyond considering it as a desirable outcome of ESD, but as an essential input to sustainability. Overfishing is often seen as a typical example of market failure, that is, the costs of over fishing are not internalised in transactions but treated (ignored) as an externality. The alternative perspective held by Jentoft (2000) is that overfishing is a sign of community failure (also McCay et al., 1998). Given that fisherman are born, raised and live in local communities, they are enmeshed in cultural and social systems that give meaning to their lives and directions for their behaviour. Fishing practices are guided by values, norms and knowledge that are shared within their community. Therefore overfishing can be seen as a consequence of normative confusion, which occurs when social ties are weak and moral standards unclear. "When fisherman do not care about their resource, their community and about each other, then the ability to communicate among themselves, to agree and to cooperate is lost. Instead, their social relations are featured with opportunism, strife and conflict", (Jentoft, 2000).

Jentoft suggests that managers should look into and care for the community, rather than search for solutions to overfishing in the market. ".. moreover: managers would be careful not to damage the social structure and culture of fisheries communities .... They would avoid management designs that make communities disintegrate and become more stratified. Instead management would adopt designs that encourage cooperation, build networks and improve trust within and among local communities".

Ultimately management of fisheries affairs is faced with the problem of allocation, that is, assigning rights to scarce resources between stakeholders who collectively make claims that exceed the carrying capacity of the resource.

Also, problems can be presented in the context of a "project", whereby a development project is proposed, which plans to utilise a range of resources in a way that provides benefits to the community over a period of time. On the other hand such projects may also impact on the existing utilisation of these resources and may also have collateral effects in other environmental aspects that were not explicitly identified by the project description. Therefore there may be many costs associated with impositions, side effects and forgone opportunities caused by the project. Such projects can be closely scrutinized using benefit-cost analysis (James 1994, Dixon 1986) or extended cost/benefit analysis to calculate the net welfare benefit to the community. The net benefit is referred to as rent to the community and projects that return high rent are deemed to be economically efficient.

Such techniques are complex and represent developing analytical areas largely outside the scope of this thesis, but they do demonstrate that the current approach followed in this thesis is somewhat lacking in the way that it attempts to treat each dimension of ESD independently albeit with equal emphasis (multi-disciplinary rather than trans-disciplinary). The most useful way to approach ESD would be within an analytical framework that simultaneously comprehends all dimensions of ESD - an ideal benefit-cost analysis. This would have some chance of finding, or at least recognising progress towards optimal solutions and developments. But, the major and as yet unresolved problem with this approach is that an integrated indicator based on economic measurement is not feasible. If such an integrated approach is eventually developed it will need to be based on non-economic principles (Hundloe, 2000).

Zoeteman (2000) proposes a unifying framework based on summing performance indicators that span ecological, social and economic domains. After instituting equal weights for these dimensions they are summed to give a combined index of sustainability, which Zoeteman relates to a qualitative scale reflecting increasing eco-efficiency and more advanced social mindsets.

4.2.2.3 Equity

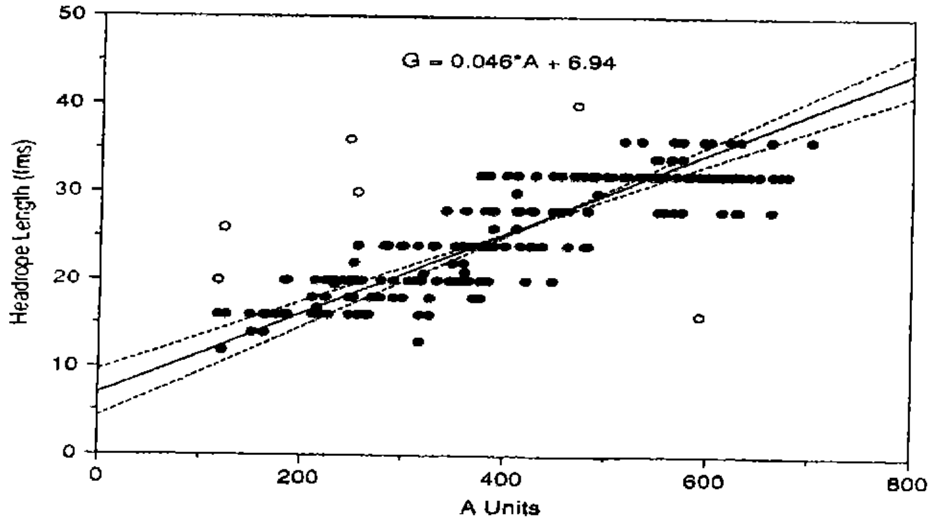
In allocation problems, achieving a peaceful outcome is likely to be facilitated by establishing agreement on a set of protocols for the equity of sharing between stakeholders and connecting the logic of the issues to the natural realities of the situation. An interesting situation developed over a period of 10 years in the lead up to the introduction of the Gear Units regime in the NPF in 2000 that exemplifies difficulties in this area.

Before the Gear Units regime could be introduced a process for fair allocation of the new fishing rights commodity between NPF operators needed to be found. Opinion on appropriate allocation formulae was fundamentally divided into two factions:

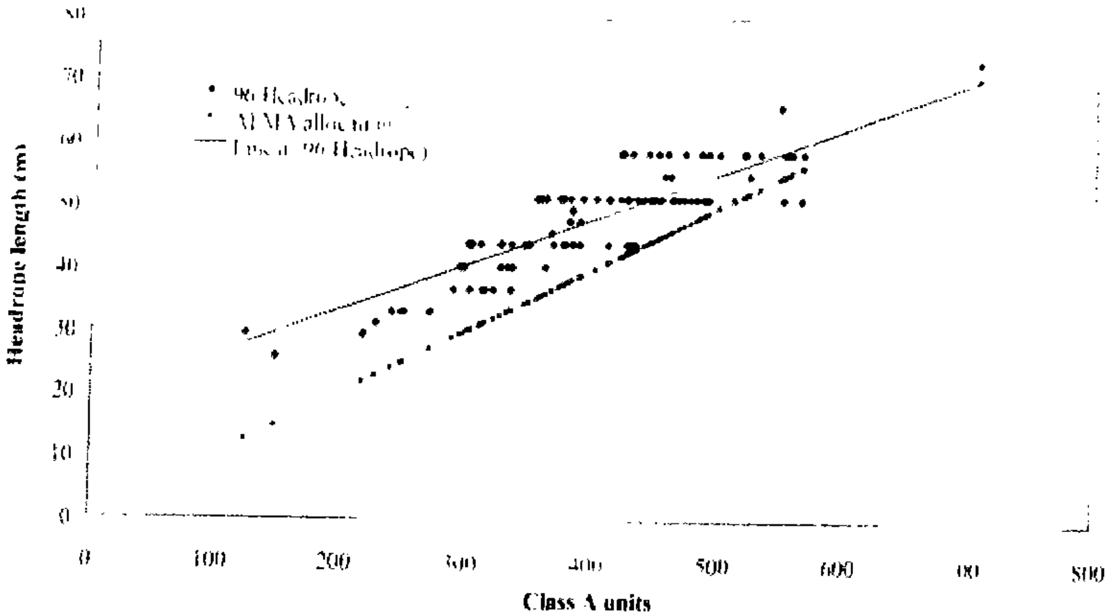
(i) Allocation based on historical use of gear size.

(ii) Allocation that matched the relative holdings of the pre-existing fishing rights commodity (Aunits).

The two options were significantly divergent because historically the size of fishing gear used was not proportional to the amount of Aunits held, as shown in Figure 84 (Somers and Robins, 1992, Eayrs and Wakeford, 2000). At the same time the balance of opinion was that historical catching performance in the fishery was proportionally correlated to gear size more so than any other single input factor (France, 2000). This lead to a logical conclusion that the pre-existing Aunits allocation in a sense produced an inappropriate allocation of fishing rights in that they did not equate accurately with the actual production capabilities of operators.



(a) Relationship between Aunits and Headline length in 1985 and 1986 (Somers and Robins, 1992).



(b) Headline length for 129 boats in the NPF in 1996 (Eayrs and Wakeford, 2000).

Figure 84. Historical headline length usage relative to Aunit holdings.

At the root of the serious conflict that developed was the reality that for each of the two options there were associated winners and losers and the situation turned into a hard pitched battle between the various groups to get a favourable final decision according to their circumstances.

Clarification of the allocation difficulty in terms of the underlying mechanics of prawn trawling.

An allocation of gear units proportionally with Aunit holdings produces a systematic inequity across the NPF fleet in terms of historical usage of headline. This systematic inequity is best understood by looking at the underlying mechanics rather than each boat on a case-by-case basis, although this does produce the same conclusion in an average sense (see Figure 84(b)). Some of the mismatch between historical usage and the AFMA allocation comes about because of technological differences between operators. For example, boats that use fine mesh netting have larger than expected nets and boats that have large hulls tow small nets for a given number of Aunits.

All things being equal though, in terms of the technology used and the ratio of engine power to hulls size, there also exists a systematic divergence between historical gear size and allocated gear size when boats are ordered by decreasing engine power. This effect is predicted by the PTPM and plotted in Figure 85.

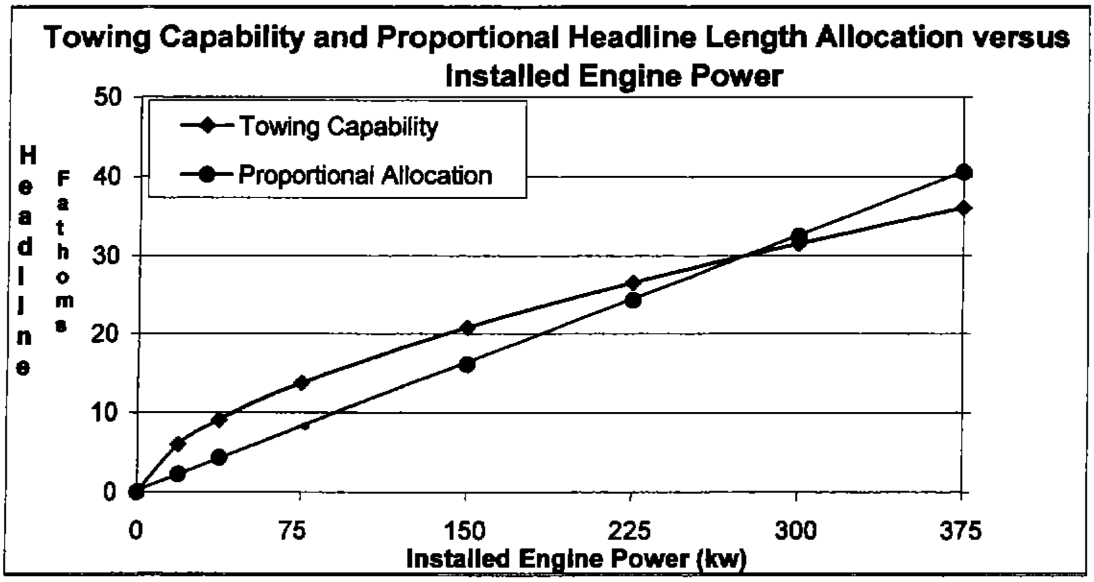


Figure 85. Allocation options for gear units in the NPF.

The physical realities of prawn trawling give rise to the situation where there is a diminishing marginal return of towing capability (in terms of gear size) as more engine power is used. This comes about not so much because the thrust produced by typical trawlers in the NPF is not proportional to engine power, but because the thrust required to tow bigger gear increases at a rate greater than the increase in headline length[1]. The final effect is that low powered boats are more fuel efficient (less fuel/kg prawn) than high-powered boats, for similar reasons that the fuel economy (fuel/km) of a car improves as it is driven slower (uses less engine power).

In terms of the debate over the allocation of gear units the important conclusion is that for trawlers using less engine power, there is a growing relative difference between the headline length allocated and that which each trawler is capable of using. That small boats tow bigger nets than many expect based on their Aunits allocation is due to fundamental physical principles, not dishonest practices or clever configuration of the gear, which was insinuated by various arguments put to the decision making process (Anon., 2000a). Alternatively, the case could be made that natural justice would be served if such boats were allocated the headline length that they were naturally capable of using similarly to the other boats in the fleet.

The potential conflict resolution role of the PTPM

In the debate that was ongoing for many years a number of powerful views emerged and became the dominant rhetoric that defined the problem and the solution. None of these views were based on a detailed understanding of the mechanics of prawn trawling.

The author believes that with a clearer understanding of the allocation issues, which necessarily needed to include technical points connected to the mechanics of prawn trawling, it would have been possible to find alternative allocation formulas and a final solution that was far more equitable than either of the considered options - provided that this was achieved early on, before the divisions became entrenched.

The PTPM was applied in the final stages of the debate. It served to clarify that both options had legitimate claims and made possible arguments to counter viewpoints that sought more to harm the character of opponents than bring relevant facts to the

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[1] According to the PTPM a 10% increase in gear size requires 15% more thrust from the trawler to maintain the same speed.

debate. Also injected into the debate was the overarching concern that headline length may not be an appropriate factor to use as an effort control variable, as outlined in section 4.2.1.1.

The interconnectedness of these issues did create greater confusion and raised the stakes of the debate. Not only was the allocation formula being contested but also there was the question of whether the idea of allocation was good at all.

In particular the problem definition as painted by the PTPM was that centrally a workable system of Statutory Fishing Rights (SFRs) must use a unit measure that directly influences the effort capacity of trawlers. It appeared that the first instance of failure in this respect was the introduction of "Units of Fishing Capacity" based on Aunits in 1983. This situation was then intensified in 1995 with the introduction of "Statutory Fishing Rights" based on Aunits.

The PTPM depiction is that Aunits are derived from operational factors that strongly correlate with and functionally influence fishing effort, that being vessel size and engine power. However the chosen Aunit measure does not accurately represent fishing capacity in a proportional way. Such a situation could be tolerated if the implications were not excessive. Unfortunately by assigning SFRs to Aunits and linking license fees, buyback costs and other industry levies to this measure, there was a significant bias in allocating industry costs relative to the real fishing capability of operators in the fishery. The bias caused large boats to be allocated costs greater than their pro rata fishing capacity and over time this generated large stresses within the fabric of the industry. This could be remedied if the system seriously sought to understand the technical processes involved and derived compensating adjustments in tune with the underlying faults of that regime. Or alternatively, it might be recognised that such bias adds needed incentive not to be wasteful of fuel by causing the industry fees and charges to be effectively a tax on fuel consumption rather than a levy on catch. This in effect tends to correct failure in this diesel fuel market by partially internalising the cost of using a non-renewable resource, polluting the atmosphere and generating green house gasses.

Instead of such considerations, replacement of Aunit SFRs by gear unit SFRs was proposed as the solution to the systems existing inequities and a number of other imperfections. This was generally supported by large boat owners who were adversely financially affected by the pre-existing system in the manner described above.

In order to relieve the situation for large boat owners, the management initiative was to introduce and allocate gear unit SFRs on a one to one basis with pre-existing Aunit holdings. This would indeed preserve the capital value of all operators' assets and give large vessels an avenue to increase their share in the fishery in real terms. However the inequity associated with this move is that it reallocates access and security within the fishery. As outlined above, small vessels would be allocated nets far smaller than they are capable of towing and large vessels are given more net than they are capable of using until they upgrade their engines. This would appear unfair because the inflated resource access assumed of large boats by NPF administration only existed on paper; an artefact of the inaccurate way that the pre-existing fisheries legislation interacted with the real world.

Alternatively, natural justice suggested that the fair way of allocating gear unit SFRs would be on the basis of true fishing capacity and compensation was due to large vessels for the way they have been unfairly paying over the years for resource access they did not in reality possess. The extent of this compensation does not overcome the problems associated with the loss of capital value that large vessel owners would incur or how to deal with Aunits that are not attached to a vessel licence.

In summary, it is apparent that a proportional translation between the two SFR systems causes a transfer of earning capacity from small vessel to large vessels and translation based on natural justice causes a transfer of capital from large boats to small boats. A compromise solution might exist somewhere in the middle ground however it doesn't lend itself easily to logical determination because of the differing natures of the inequities involved.

The final result

Despite the involvement of the PTPM, which is the most developed tool available to provide information on the dynamic components of fishing effort, it came too late to change the entrenched political certainty of the ultimate decision – that the gear units regime would be implemented and allocation would be proportional to the pre-existing allocation of Aunits (Anon., 2000a).

The proportional allocation preserved the theoretical property rights of stakeholders in relation to access to the NPF, but it changed the relative security of stakeholders and has caused a widening rift in the "community" of fishers in the NPF. This has undermined the fundamental tenet of introducing gear units, which was to allow efficient regulation of effort in the fishery in response to scientific advice regarding the status of fishing stocks and the amount of catch that can be taken. Instead, deeply divided debates have occurred surrounding further effort reduction proposals and it is generally the case that most of the effort reduction since the introduction of gear units has been achieved through reduced season length rather than gear cuts. Such is the strength of resistance from smaller operators to further cuts in gear allocation.

Working against a more comprehensive synthesis of all the relevant issues in the debate over the introduction of gear units was the plurality of cultures at work within the fisheries science community. The dominant culture had an outlook strongly connected to the status of the prawn stocks and a preference to understand all problems through statistical analysis of catch data. Alternatively the engineering or technological view focused on the extent and structure of fishing hardware in the fishery and used deterministic calculations of fishing performance to investigate issues and solutions. Amalgamation of these two distinctly different perspectives into a purposeful partnership was slow to occur because the interdisciplinary divide could not be bridged quickly.

Another factor was the questionable political independence of decision makers in the face of intense debate between industry stakeholders. The optimal solution with respect to allocation and management of fishing rights should unquestionably be based on what is best for the broad community. However, solutions from that viewpoint are likely to be less than ideal for all industry stakeholders because of the narrow perspectives of private benefit. In the confusion and turmoil of the gear units debate, the author believes that the community's perspective and best interests were never clearly appreciated by decision makers and this left them open to capture by the interests of industry stakeholders who appeared to be the most altruistic.

The effect of the late timing of the PTPM input into the institutionalised decision making process cannot be underrated. Once policy directions were set and significant steps undertaken, the ability to turn back and reappraise the situation was undoubtedly very constrained. Changes in fisheries policy necessarily need to be carefully managed so that they are clearly observed to be part of a broader process of evolution such that the past is always viewed to be "best practice". The risk of changing institutional policy is that the acknowledgement of the need for change is a corollary to a view that past and present processes and decisions were/are imperfect. From the institutional point of view it is an imperative not to allow feelings of imperfection deepen to a view that past decisions were litigiously incorrect.

4.2.2.4 Employment

In the literature, an initiative to maximise employment is viewed as a social objective, not an economic one (Hundloe, 2002a). This comes about because within an economic analysis of community benefit, market rate wages are accounted as operating costs and as such are subtracted from the business revenue. Therefore economic analyses of various fleet structure options treat negatively the situation where a fleet structure employs more people than others if the cost of wages is not at least offset by reductions in costs elsewhere. For various social reasons this could be seen as partially missing the point of economic activity.

What does seem to be important here, but is not clear in the way that we can clinically treat economic activity, is that much of the human needs of society are not satisfied by the marketable services produced by economic activity. As mentioned earlier some needs are satisfied directly from the environment without the need for economic activity (eg clean air, fresh water to dams, renewable natural food sources and waste assimilation services). Similarly, many high-order human needs are serviced by the existence of economic activity itself and is not a marketed product of it. This includes some aspects of security, social belonging, self-esteem and self-realisation – collectively referred to as job satisfaction (Pollnac and Poggie. 1988) and measured relative to the average satisfaction of unemployment.

The basic conflict here is that in standard economic analyses of community benefit, labour is treated as a scarce resource while in social contexts it is commonly the case that jobs are considered to be the scarce factor.

Both James (1994) and Hundloe (2002b) consider using "shadow prices" to reflect the true opportunity cost of inputs. In respect to unemployment in the labour market, it is stated that the opportunity cost of labour can be set much less than the going wage rate.

Unemployment in regional communities is raised as a key issue in fisheries management debates, however it is generally argued at the periphery and struggles to gain solid traction in the debate because it is rarely introduced formally into any analytical framework like resource sustainability or economic efficiency. It is of particular relevance to contemporary fisheries management because it seems that most fisheries are engaged in an endless war against overcapacity. Generally they have travelled through a common history of initially having open access and then experiencing phases of introducing limited entry and wide ranging development, characterised by competition driven technical innovation. The obvious solution to overcapacity is to reduce the number of participants but there lie a number of crucial questions:

- How many boats are appropriate?
- What size of operation is the most "efficient", given that larger boats may have a lower labour component to production?
- How much access to the resource is best for each operation?

The answer for each question is linked to the others and from the community perspective there is a difficult compromise between having healthy business profits and allowing a larger fleet of perhaps smaller boats that will increase employment.

In theory a benefit-cost analysis could be conducted for a variety of hypothetical fleet/season structures, thereby treating each scenario as an alternative project proposal to exploit prawn stocks at some given sustainable level of production. Using socially realistic shadow prices for labour the difficult profit-labour compromise could be balanced such that the appropriate number of boats and the associated number of crew and fishing days that produce maximum net benefit to the community (rent) can be identified.

The PTPM would be of particular use in pursuing this objective because one of the major operating costs is fuel and the PTPM is able to quantify the relationship between fuel costs and catch revenue (using SAR as a proxy) for a wide variety of vessel characteristics. This would allow modelling of many different fleet scenarios.

Searching for maximum rent via optimal fleet structure may have a number of difficulties. Firstly, it is possible that some of the candidate fleets identified might be unviable from a business point of view because the actual cash costs exceed the revenue, so financial viability would need to be a constraint in the analysis. Secondly, super-profits might be possible for some scenarios and this begs the question, will rent actually be collected from the fleet and distributed as benefits to the community in a way that is not wasteful? Full rent recovery is a difficult matter to achieve in Australia's fisheries. If rent is not collected it will not be used in the community in a way that returns maximum benefit and therefore it will be wasteful. This is because consumption by the industry using uncollected rent will have less social value than services having the same cash cost required elsewhere in the community by poorer people. This is due to the diminishing value of income principle (Hundloe, 2000).

Another problem with not extracting rent when it becomes available is that its capitalised value becomes attached to the market value of the property rights to fish and becomes a capital windfall for those operators who happen to be heavily involved in the fishery when the introduction of marketable fishing rights occurs.

Given that there is a national policy in Australia not to collect resource rent and this is seen as economically inefficient, it would seem appropriate to modify the financial viability constraint in the analysis to be one where cash rent (collectable) is set to zero. This ensures that the businesses are viable, but no super-profits are available. In the objective function however, where community benefit is calculated with full shadow pricing, rent is to be maximised. The end result will be that the rent calculated from the community perspective will actually be distributed in financial terms within the industry in such a way as to bias industry costs towards labour and away from underpriced natural resources.

This counters the well-described problem of labour efficiency (Weizsacker et al., 1999), which relates to the financially rational use of natural resources to concentrate profits into the smallest number of businesses (high market share) and also use cheap natural resources in place of more expensive labour wherever possible. The assessment scheme for fleet optimisation outlined above will make some way towards applying a resource efficiency paradigm rather than the existing one of labour efficiency. In short this objective function and constraints helps to minimise the ecological footprint of the industry and provides maximum employment in a way that does not cause a cost to the community.

The NPF

The issues mentioned above have impacted the NPF no less than any other fishery in Australia. The capital value of the fishing rights for each operation ($2.8mil. on average in 1999-2000) is about three quarters of the total capital (Brown et al., 2002). This forces the average return on capital to drop to 4.3% where the return to boat capital is 14.4% (Brown et al., 2002). One can see how the market value of the fishing rights has escalated to a point where the returns on capital are similar to the return for interest from term deposits.

In the NPF there are still claims of massive overcapacity in the industry. This is most strongly stated in conjunction with the situation that the length of the fishing season has been reduced substantially over the last decade to expediently deal with scientific assessments that the applied fishing effort is greater than that required to take the maximum sustainable yield.

Based on the problem of short season length there are calls to have a substantial reduction in gear units in exchange for a longer season. This will force operations out of the industry that cannot support the increased investment required to replace the gear units that are required to stay productive. Large boats are certainly more financially viable in the current climate than small boats because they use large fuel consumption to concentrate the revenue stream into systems having a low labour component to costs. With longer seasons and less competition, the larger boats will likely return super-profits. This will be reflected by a further escalation in the capital value of fishing rights and not be collected as rent for distribution where most needed in the community.

The conclusion drawn here is that the fleet with a lesser number of large super-profitable vessels is only of high economic efficiency to the community if rents are collected. If no rents are collected then almost any harvesting strategy that engages more participants is better from the communities perspective – because it will distribute benefits to those who will value them more highly.

Part of the driving force towards the natural path of progression for the NPF is the fact that fuel usage has many external costs that are not paid by the operator. The fact that the cash cost of fuel is relatively low makes the breakeven point, where the marginal benefit of more engine power becomes zero, occur at quite high engine power. This produces a strong incentive for operators to install larger engines and this is exacerbated by the situation where a large proportion of the operating costs are fixed administration costs due to the introduction of management levies, an accelerated buy back scheme and research levy (Dann et al., 1994). The author proposes that if these levies and charges were attached to fuel consumption by way of a tax on fuel usage, the financial position of fishing enterprises at the beginning of each season would be improved because of the removal of fixed costs, and the higher costs of fuel would be an incentive not to utilise large engines. This would tend to automatically contain the escalation of engine power, which has been problematic to NPF management for three decades, and also increase incentives for greater fuel efficiency by the industry in response to a greater awareness of fuel consumption.

Exploring the utility of such proposals is beyond the scope of this thesis, however such a task is facilitated by the availability of the PTPM. There appears to be a substantial need for a thorough investigation of the techno-economics of prawn trawling in conjunction with various input pricing scenarios with the goal of establishing policies to guide the optimal operation and structure of prawn trawling fleets from the perspective of the community with minimal need for direct management control.

As mentioned above the PTPM can properly establish the relationships between fuel consumption and revenue generation. This, linked to an economic welfare framework with appropriate ecological and social constraints and settings, may give rise to development options for the trawl fleet that are manifestly consistent with the ideology of ESD rather than be biased towards over-dominant sub issues or market failures.

Suggested above are search techniques for production arrangements that have a high ratio of costs for labour compared to natural resources. This actively puts "Cleaner Production" (Van Berkel, 2001) and "Resource Efficiency" (Hawkin et al., 1999) on the agenda of trawl fleet structural optimisation.

4.2.3 Economic performance

4.2.3.1 Introduction

The objective of economic performance according to the framework of ESD in Table 17 is to maximise long-term production of net wealth. This idea is also expressed by Garcia (2000) as 'the satisfaction of human needs' (Sub-principle 2.1) and 'to put in place economic conditions conducive to long term economic viability' (Sub-principle 2.2). Both these are consistent with an economist's professional charter - to make efficient use of scarce resources.

In the literature (eg. Hundloe, 2002b) there are a number of concepts that attract the attention of economists. These concepts work at various levels and all have a different but relevant connection with ESD:

(i) Economic significance – GVP.

(ii) Private Profit.

(iii) Economic efficiency – rent.

In relation to the above concepts and economic analysis Hundloe states that one has to be careful not to attach inappropriate relevance and conclusions to the data and analytical results.

Economic significance is a measure of the size of economic activity associated with an industry. This is usually measured by the gross value of production and gives an indication of the proportion of the economy that is supported by that industry. This is a direct measure of the current significance of the industry to the community, but with respect to ESD it is also necessary to establish the performance of the industry from a long-term perspective in terms of sustainability, viability and net value.

Private profit relates to the financial details of individual firms and is relevant to ESD in the sense that it shows that individual businesses are healthy and viable. However private profits of businesses express very little about the benefits of an industry to the community and it is not an objective of ESD to maximise business profits. This is where a very important conflict exists between business and ESD. Market failure is where the directions of positive development at these two levels (1. private firms and 2. the community) differ.

Public profit or rent is a common indicator of net benefit to the community. It is not simply the summation of business profits across all firms in an industry because in the calculation of public profits, production issues are valued in ways that are different from the financial analysis of business profit (Hundloe, 2002a).

In the previous section it was concluded that public profits had to be tempered with considerations of social objectives, which ultimately focussed on employment. Also there were the problems of economic inefficiency and waste associated with uncollected resource rent, which is due to systemic failure rather than market failure. In view of the later concerns and in conjunction with the quintessential objectives of ESD it was found that other closely related production concepts are more relevant. These are Resource Efficiency and Cleaner Production.

Cleaner Production is about making more efficient use of materials, energy, water and other natural resources when we conduct businesses, regardless of whether the business is in processing, manufacturing, service, transport, mining or agriculture (Prasad et al., 2004). A precise definition often used is; "the continuous application of an integrated preventive environmental strategy to processes, products and services to increase eco-efficiency and reduce risk to humans and the environment" (UNEP, 1994, ANZECC, 1998). Therefore, Cleaner Production aims at progressive reduction of the environmental impacts of processes, products and services, through preventive approaches rather than control and management of pollutants and waste once these have been created. Van Berkel (2001) states that Cleaner Production is an integrated approach, since it includes all environmental aspects and impacts, and is not confined to one impact category like most end-of-pipe (treatment and control) technologies. Moreover, it serves economic and ecological efficiency (eco-efficiency) of businesses and contributes to Environmental Risk Management objectives.

4.2.3.2 Cleaner Production

The crux of the economic problem for prawn trawling fisheries in the ESD context is to generate greater profit and community benefit from a given level of sustainable catch. As outlined in preceding sections a significant approach to that goal is to minimise the use of input resources and impacts on the environment so that a maximum amount of business revenue is available to be distributed as net benefits to the community. In all systems, both manmade and natural, it seems that resource efficiency is the result of knowledgeable (or appropriate in the case of natural selection) application of complexity, diversity and intelligence.

Given the mechanics of prawn trawling, which is characteristically active and encapsulated in the production factor flowchart of Figure 9, it can be seen that the major natural resource inputs are diesel fuel and time. Also indicated in the production flowchart is a complex array of opportunities to improve the efficiency of resource utilisation. This spans the production issues of engineering performance, catch efficiency, search power and time utilisation.

In this context the PTPM can play a role in the areas of engineering performance and catch efficiency and can generate improvements in resource efficiency (fuel and Bycatch) through a number of identifiable initiatives:

- Effective optimisation of trawl system variables.
- The development of high order multiple net systems.
- Improved component design.
- Optimisation of Bycatch reduction strategies.

Optimum component selection

Figure 86 shows an optimisation chart generated by the PTPM for a vessel towing a particular trawl system and utilising engine power of 185kw. The figure implicitly shows that the efficiency of engine power utilisation as indicated by the resulting swept area performance (SAR) does depend on correctly matching the size of the trawl, in conjunction with the size of otter boards used, with the capacity of the trawler. To date, the selection of basic trawl system parameters is made on the basis of trial and error, experience and tradition. This produces a high likelihood that much trawl effort in industry occurs with gear that is not optimal. The difficulties of selecting optimal trawl parameters for a given operation are compounded by the fact that the basic parameters interact with other variables in the system, for example, mesh size, twine diameter and otter board style. All of these variables are accounted for by the PTPM, therefore allowing it to deal with the large diversity of operating situations.

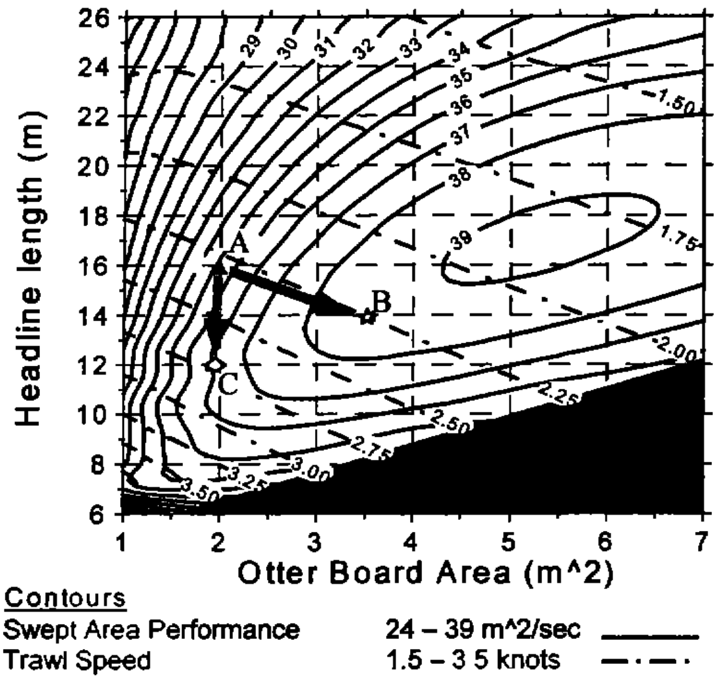


Figure 86. Optimisation chart for swept area performance.

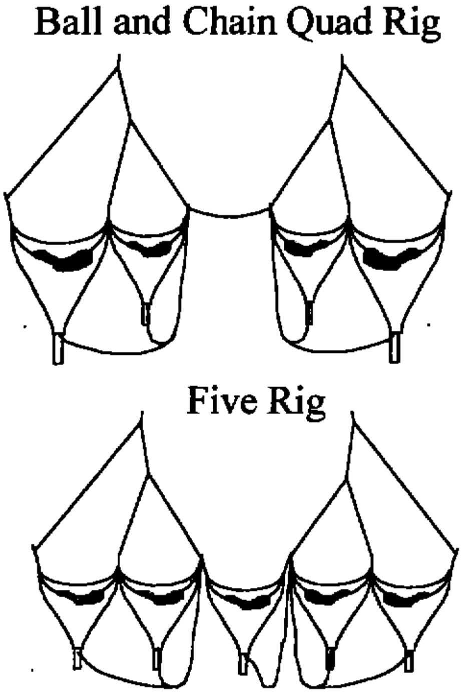
In the hypothetical situation shown in Figure 86, point A shows the current operating position for a trawler. It is clearly not where maximum performance occurs on the map. However, at the position of maximum swept area performance the trawl speed is only about 1.85knots. This could well be too slow for practical trawling, whereby the operator might specify that the minimum trawl speed allowed is 2.25knots. Under these circumstances point B would give the maximum performance available. To operate at this point the operator is required to purchase smaller nets and larger otter boards and in so doing the swept area performance would increase by 12%.

The diagram shows that this operator has made the classic mistake of trying to tow nets that are too large. If smaller nets were used in conjunction with the existing otter boards, as indicated by point C, the swept area performance would increase by 6%.

High order multiple net systems

Figure 87 shows two new high order multiple net trawl systems that have been developed; the ball and chain quad rig and the five net systems. By increasing the number of nets towed simultaneously, the total amount of netting utilised in systems of the same size is reduced. This reduces net drag and makes it easier for the otter boards to open the gear laterally.

The PTPM makes possible the design and optimisation of these systems from engineering principles rather than trial and error. Properly configured, these new trawl systems could improve swept area performance by up to 30%.


Ball and Chain Quad Rig

Five Rig

Estimated Engineering Advantage of High Order Multiple Net Prawn Trawl Systems

	Relative Drag	Swept area relative to (a) Triple	Swept area relative to (b) Quad
Triple	26%	100%	89%
Quad	21%	112%	100%
Ball and chain	19%	118%	105%
Five	15%	133%	119%

Figure 87. High order multiple net systems and their estimated advantages.

Improved components

The components of trawl gear can be developed and improved by making advances to their intrinsic structural qualities. For example the use of low drag netting in trawls or curved foils in otter boards. But the components of trawl systems need also to have extrinsic qualities that emerge in context with their function in a greater system. This is covered under the earlier topic of optimum component selection where it was outlined how the PTPM can identify the optimum size of nets and otter boards that should be used in any application.

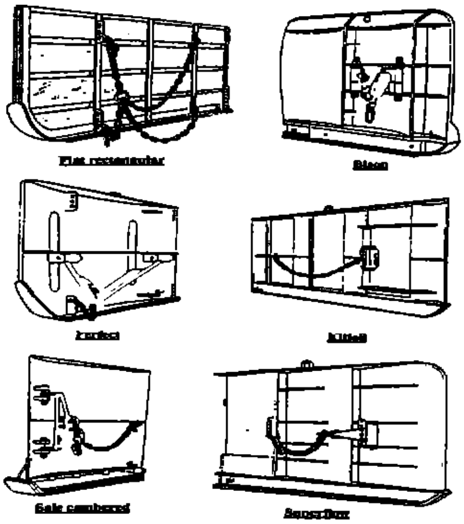
Additionally, there is yet a deeper level of complexity regarding the optimal design of components that emerges in connection with the interaction between extrinsic and intrinsic qualities. Here there is a more sophisticated role for the PTPM in terms of capturing the performance related details of these interactions in such a way that allows the structural features of components related to intrinsic qualities to be optimally designed in context with the particular circumstances that exist when all extrinsic functions are satisfied.

A good example of the need for this process and the potential efficiency improvements that may result is described by (Sterling, 2000b) in relation to the optimal design of otter boards for prawn trawling.

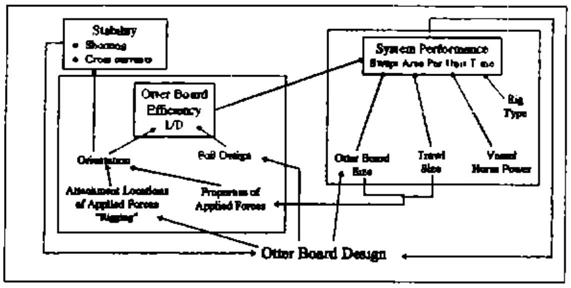
Figure 88 shows some contemporary otter boards that are used in Australian prawn trawling fisheries and a diagram that shows the structure of the design problem for otter boards. In the structure of the problem there is an interaction between intrinsic and extrinsic functionality caused by the feedback between the state of the systems as a whole and the properties of the applied forces to the otter board.

A cursory look at the problem of otter board drag very often leads people to believe that big improvements can be achieved by developing better foil shapes alone. However increased efficiency comes about by a combination of good foil design and appropriate otter board orientation.

Improved otterboards



Contemporary otterboards



- provide large degree of spread
- have low drag
- be stable at all times

It appears quite feasible that new otterboards can be developed that produce 65% less drag and allow trawling efficiency to increase by about 15%.

Figure 88. Contemporary prawn trawling otter boards with framework and vision for performance improvement.

Contemporary otter boards include many otter boards that have been developed with the narrow objective of incorporating more aerodynamic foils. From sea trial test some of these boards produce small improvements in trawling performance, but most showed no significant improvement over the traditional flat rectangular otter board (Sterling, 2000b).

By following a holistic approach to otter board development, therefore recognising all aspects of the problem (both intrinsic and extrinsic) and understanding how they interact it is very feasible that otter boards can be developed that have 65% less drag than current designs (Sterling, 2000b). This large gain is possible because the current efficiency of otter boards for prawn trawling is very low (Shear to Drag ratio about 1). Achieving an otter board with a shear to drag ratio of 3 (65% less drag) is not in itself an unrealistic expectation since that is still modest when compared to the efficiency of other common fluid-dynamic devices (eg. kites, sails, propellers, aircraft wings). The difficulties arise when one begins to deal with the peculiarities of prawn trawl systems and the extrinsic characteristics that the otter board must possess to allow the system as a whole to function in its most efficient state. Here problems associated with shooting away stability and the optimum spread ratio state of the system while fishing conspire to make it very difficult to set prawn trawling otter boards at a low and efficient angle of attack. All these issues are captured by the PTPM and allow innovative rigging strategies to be optimised and evaluated. This is a significant advance on previous efforts to develop better otter boards because the strategies in those respects were aiming in the wrong direction.

4.3 Conclusions

The Prawn Trawling Performance Model (PTPM) models the mechanics of prawn trawling to an extent that allows quantitative predictions of trawling performance and operational status. This gives rise to many applications for the PTPM that span the very broad scope of ESD. Thus, a correct understanding of the mechanics of prawn trawling can produce a wide range of immediate and long term benefits within prawn trawling fisheries and socio-economically linked communities:

1. More efficient trawling systems can be developed.
2. The effort applied by prawn trawlers can be managed;
    a. Effectively
    b. Efficiently
    c. Equitably
    d. Optimally.

3. More accurate stock assessment can occur due to better assumptions regarding fishing power.
4. Greater achievements may be made with respect to social objectives (employment, equity etc)

The range of benefits complies with the general theme of positive development promoted by (Weizsacker et al., 1999) whereby the objective of development should be resource productivity rather than labour productivity. This is also consistent with the objectives and ideology of cleaner production according to (Van Berkel, 2001).

Specific instances have occurred where the PTPM has already had an active involvement in the management of the NPF. These relate to:

- The quantification of fishing power change (Sterling, 2000a).
- Sensitivity analysis for key factors that affect engineering performance (Anon., 2000a).
- Analysis of allocation issues in relation to the translation of statutory fishing rights (Sterling, 1999).

These applications have generated mixed receptions and raised intense debates. In the end, what is important is that the application of the tool in all these instances has provided constructive input and facilitated a more comprehensive decision making process in the NPF.

REFERENCES

ANON. (1987) Our Common Future. *World Commission on Environment and Development.* New York, Oxford University Press.

ANON. (1992b) National Strategy for Ecological Sustainable Development. Canberra, Commonwealth of Australia.

ANON. (2000a) Northern Prawn Fishery Amendment Management Plan 1999. *Report of the Senate Rural and Regional Affairs and Transport Legislation Committee.* Canberra, Parliament of the Commonwealth of Australia.

ANON. (2000b) Submission by Australian Fisheries Management Authority to the Commonwealth Fisheries Policy Review. Canberra, AFMA.

ANON. (2002) Scraping The Bottom: Seafloor Trawling In The Great Barrier Reef World Heritage Area. Sydney, WWF Australia.

ANZECC (1998) Towards Sustainability: Achieving Cleaner Production in Australia. Canberra, Australia and New Zealand Environment and Conservation Council.

BISHOP, J. (2003) Objective 1.4: VMS Trawl Speed. *Final Report: A New Approach to Fishing Power Analysis and its Application in the Northern Prawn Fishery.* Brisbane, CSIRO Marine Research.

BISHOP, J., DIE, D. & WANG, Y. (1999) A Generalised Estimating Equations Approach for Analysis of the Impact of New Technology on a Trawl Fishery. *ANZ J Statistics.*

BISHOP, J. & STERLING, D. (1999) Survey of Technology Utilised in the Northern Prawn Fishery. *Final Report, Northern Prawn Fishery Management Initiated Research Fund.* Canberra, AFMA.

BROWN, D., GALEANO, D , SHAFRON, W. & BLIAS, A. (2002) Monitoring the Impact of New Management Arrangements in the Northern Prawn Fishery. Canberra, Australian Bureau of Agricultural Resource Economics.

BUCKWORTH, R. (1987) Changes in Fishing Effort and Catching Power in the DMZ Tiger Prawn Fishery. *NPF Information Notes No. 20.* Cleveland, CSIRO Marine Research.

CALDWELL, A. (1946) *Screw Tug Design,* London, Hutchinson's Scientific and Technical Press.

CHECKLAND, P. & SCHOLES, J. (1999) *Soft Systems Methodology in Action,* Chichester, John Wiley & Sons, Ltd.

CREWE, P. (Ed.) (1959) *Some of the General Engineering Principles of Trawl Gear Design,* Rome, FAO.

DANN, T., LANCASTER, A. & PASCOE, S. (1994) Dollars and Sense: Economic Assessment. IN POWNALL, P. (Ed.) *Australia's Northern Prawn Fishery: the first 25 years.* Cleveland, Australia, NPF25.

DEUTSCHMAN, A., MICHELS, W. & WILSON, C. (1975) *Machine Design,* New York, Macmillan Publishing Co.

DICHMONT, C., BISHOP, J., STERLING, D., PENROSE, J., RAWLINSON, N., EAYRS, S. & VENABLES, B. (2003) A New Approach to Fishing Power Analysis and its Application to the Northern Prawn Fishery: Summary Report for the NPFAG. Brisbane, CSIRO.

DIXON, D. (1986) The Role of Economics in Valuing Environmental Effects of Development Projects. IN DIXON, J. & HUFSCHMIDT, M. (Eds.) *Economic Valuation Techniques for the Environment.* Baltimore and London, The Johns Hopkins University Press.

EAYRS, S., BUCKWORTH, R., CARTWRIGHT, I. & BOSE, S. (1996) Headline Height Modifications to Improve Prawn Trawl Performance. IN HANCOCK, D., SMITH, D., GRANT, A. & BEUMER, J. (Eds.) *Developing and Sustaining World Fisheries Resources: The State of Science and Management: 2nd World Fisheries Congress Proceedings.* Brisbane, CSIRO Publishing.

EAYRS, S. & WAKEFORD, J. (2000) The Introduction of Gear-unit Statutory Fishing Rights in the Northern Prawn Fishery: An Independent View. *Senate Rural and Regional Affairs and Transport Commitee.* Launceston, Australian Maritime College.

EDMONDSON, I. (1994a) Frameline Tension Ratio Versus Spread Ratio. *Report 5, Project 1.4.4.* Launceston, AME CRC.

EDMONDSON, I. (1994b) Otter Board Hydrodynamic Behaviour. *Report 7, Project 1.4.4.* Launceston, AMECRC.

FAO (1974) *Otter Board Design and Performance,* Rome, FAO Fishing Manuals.

FLETCHER, W., CHESSON, J., FISHER, M., SAINSBURY, K., HUNDLOE, T., SMITH, T. & WHITWORTH, B. (2002) National ESD Reporting Framework for Australian Fisheries: The 'How To' Guide for Wild Capture Fisheries. Canberra, FRDC Project 2000/145.

FRANCE, M. (2000) Senate Inquiry into the Northern Prawn Fishery Plan Amendment. *Senate Rural and Regional Affairs and Transport Commitee.* Perth, Newfishing Australia Pty Ltd.

FRIDMAN, A. (1973) *Theory and Design of Commercial Fishing Gear,* Jerusalem, Israel Program for Scientific Translations Ltd.

GARCIA, S. (2000) The FAO Definition of Sustainable Development and the Code of Conduct for Responsible Fisheries: An Analysis of the Related Principles, Crieteria and Indicators. *Marine and Freshwater Research,* 51, 6.

GATEWOOD, J. B. & MCCAY, B. J. (1990) Comparison of Job Satisfaction in Six New Jersey Fisheries: Implications for Management. *Human Organization,* 49(1), 14-25.

GORRIE, G. (2000) What is ESD and its role in fisheries? National context. IN SMITH, D. C., HODGE, R. (Ed.) *ESD and Fisheries: What, Why, How and When.* Geelong, Seafood Industry Victoria.

HAWKIN, P., LOVINS, A. & LOVINS, L. (1999) *Natural Capitalism: The Next Industrial Revolution.,* London, Earthscan.

HILL, B. (1985) Effect of Temperature on Duration of Emergence, Speed of Movement and Catchability of the Prawn Penaeus esculentus. *Second Australian National Prawn Seminar.* Cleveland, NPS2.

HUNDLOE, T. (2000) Economic Performance Indicators For Fisheries. *Marine and Freshwater Research,* 51, 485-91.

HUNDLOE, T. (Ed.) (2002a) *Understanding Economics and Economic value,* Brisbane, University of Queensland Press.

HUNDLOE, T. (2002b) *Valueing Fisheries: An Economic Framework*, Brisbane, University of Queensland Press.

JAMES, D. (1994) *The Application of Economic Techniques in Environmental Impact Assessment*, The Netherlands, Kluwer Academic Publishers.

JENTOFT, S. (2000) The Community: A Missing Link of Fisheries Management. *Marine Policy*, 24, 53-59.

LUDWIG, D., MANGEL, M., HADDAD, B. (2001) Ecology, Conservation, and Public Policy. *Annual Review of Ecology Systems*, 32, 481-517.

MASLOW, A. (1970) *Motivation and Personality*, New York, Harper and Row.

MATHEWS, S. (1966) On the Mechanics and Economics of Trawling. *National Research Report*. Ottawa.

MCCAY, B. J. & JENTOFT, S. (1998) Market or Community failure? critical perspectives on common property research. *Human Organization*, 57(1), 21-39.

MING YI, C. & ENDAL, A. (1983) A New Determination of Available Towing Thrust at Different Trawling Speed. *International Council for the Exploration of the Sea - Engineering Working Group*. Ijmuiden.

MINNEGAL, M., KING, T.J., JUST, R., DWYER, P.D. (2003) Deep Identity, Shallow Time: Sustaining a Furure in Victorian Fishing Communities. *The Australian Journal of Anthropology*, 14:1, 53-71.

MOOR, D. (1963) An Investigation of Tug Propulsion. *Transactions of The Royal Institution of Naval Architects*, 105, 107-152.

NPFAG (2004) Status of tiger prawn stocks at the end of 2003. Cleveland, CSIRO.

PARKER, M. & DAWSON, J. (1962) Tug Propulsion Investigation. *Quarterly Transactions of The Royal Institution of Naval Architects*, 104, 237-279.

PATTERSON, R. & WATT, K. (1986) The Otter Board as a Low Aspect Ratio Wing at High Angles of Attack; An Experimental Study. *Fisheries Research*, 4, 111-130.

PENN, J. (Ed.) (1981) *The Behaviour and Catchability of Some Commercially Exploited Penaeids and Their Relationship to Stock and Recruitment,* Surrey, Fishing News Books.

POLLNAC, R. B. & POGGIE, J. J. (1988) The Structure of Job Satisfaction Among New Engaland Fisherman and its Applcation to Fisheries Management policy. *American Anthropologist,* 90, 888-901.

PRADO, J. (1990) *Fishermans Workbook,* Oxford, FAO and Fishing News Books.

PRASAD, P., PAGAN, B. & RENOUF, M. (2004) A critical analysis of Cleaner Production in Queensland's Food Industry– past efforts and future opportunities. *Asia Pacific Roundtable for Cleaner Production Conference Proceedings.* Kuala Lumpur, Malaysia.

ROBBINS, C. & SOMERS, I. (1993) Relationship Between the Fishing Power and Units of Fishing Capacity for The Northern Prawn Fishery. Cleveland, CSIRO Division of Fisheries.

ROBINS, C., WANG, Y. & DIE, D. (1998) The Impact of Global Positioning Systems and Plotters on Fishing Power in the Northern Prawn Fishery, Australia. *Can. J Fish & Aquatic Sci..*

SEDAT, R. (1984) *Part 1: Matching of Hull, Engine, Reduction Gear and Propeller,*, Webb Institute of Naval Architecture and New York Sea Grant.

SOMERS, I. (1994) Through the Crystal Ball: The Next 25 Years. IN POWNALL (EDITOR), P. (Ed.) *Australia's Northern Prawn Fishery: the first 25 years.* Cleveland, NPF25.

SOMERS, I. & ROBINS, C. (1992) Gear Unitisation for the NPF? Cleveland, CSIRO Division of Fisheries.

STERLING, D. (1999) Inequity in proportional translation of Class ASFRs to gear unit SFRs. *Submission to the NPF Independent Advisory Panel - Gear Units.* Brisbane, Sterling Trawl Gear Services.

STERLING, D. (2000a) Development of a Variable Effort Creep Schedule for the Northern Prawn Fishery. *Northern Prawn Fishery Assessment Group Working Paper.* Canberra, AFMA.

STERLING, D. (2000b) *The Physical Performance of Prawn Trawling Otter Boards and Low Opening Systems,* Brisbane, DJ Sterling Trawl Gear Services.

STERLING, D., BOLTON, S. & CARTWRIGHT, I. (1992) Trawl Gear Studies by the Australian Maritime College for the NPF. *Progress report to Fishing Development Trust Account.* Launceston, Australian Maritime College.

STERLING, D. & WATSON, R. (1989) Trawl Gear Performance Trials. *Interim report of Torres Strait Prawn Project.* Cairns, QDPI.

TABACHNICK, B. G. & FIDELL, L. S. (2001) *Using Multivariate Statistics,* Needham Height, Allyn & Bacon.

TAYLOR, B. & DIE, D. (Eds.) (1999) *Northern Prawn Fishery Assessment Report, 1997 & 1998,* Canberra, AFMA.

TYEDMERS, P. (2000) Quantifying the Energy Consumed by North Atlantic Fisheries. *Methods for Evaluating the Impacts of Fisheries on North Atlantic Ecosystems. Fisheries Centre Research Report 2000.* Halifax.

UNEP (1994) Government strategies and Policies for Cleaner Production. Paris, United Nations Environment Program: Industry and Environment.

VAN BERKEL, R. (2001) Cleaner Production for Achieving Eco-Efficiency in Australian Industry. *Sustainability 2001* Perth, Conservation Council of Western Australia.

WAKEFORD, J. (1994) The Effect of Frameline Tapers on the Engineering Performance of Prawn Trawl Systems. *Report 3, Project 1.4.4.* Launceston, AME CRC.

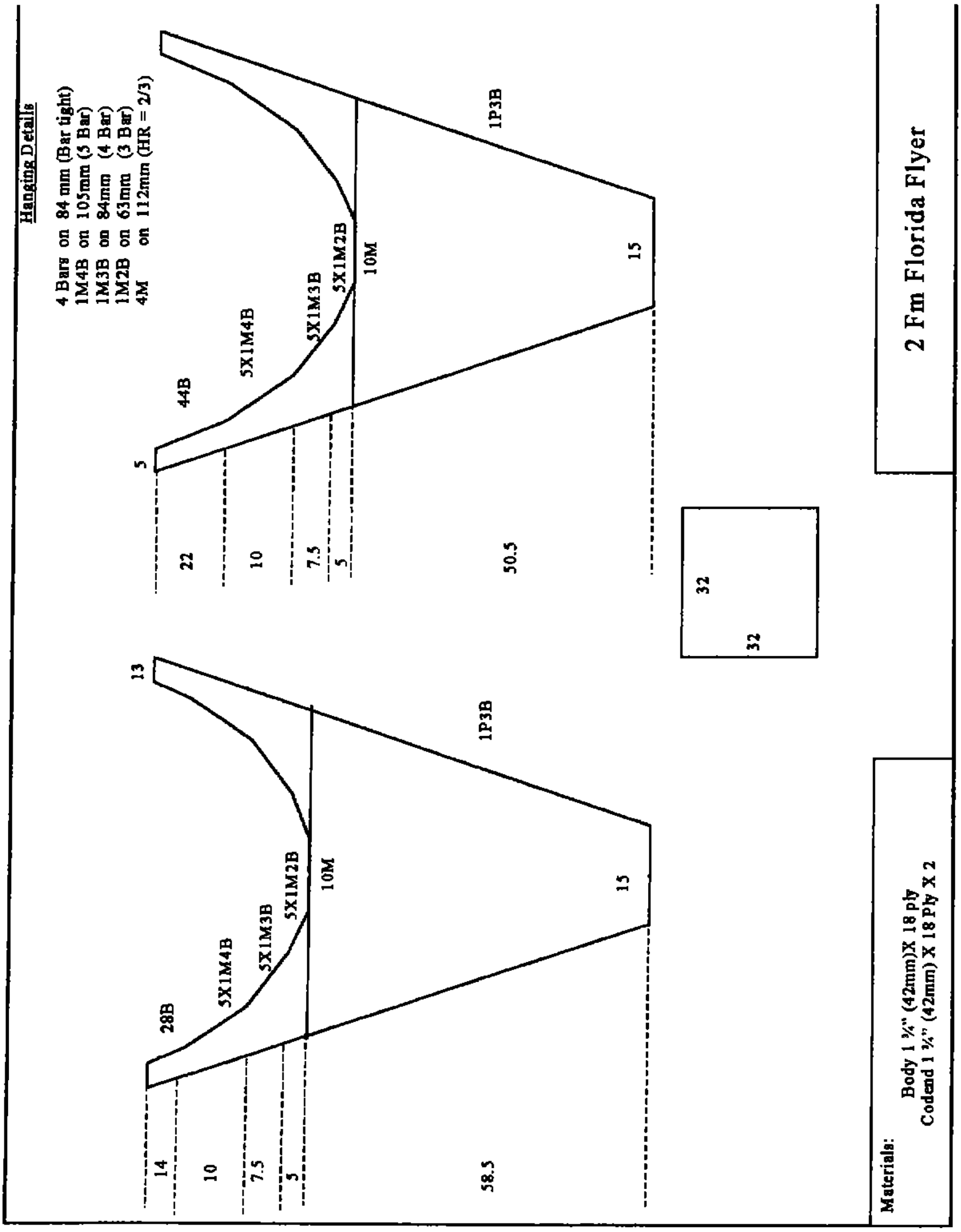
WAKEFORD, J. (1997) Prawn Trawl Research - Past Research and Future Direction. *Asia Pacific Fishing '97.* Cairns, Baird Publications.

WEIZSACKER, E., LOVINS, A. & LOVINS, L. (1999) *Factor Four: Doubling Wealth, Halving Resource Use.,* London, Earthscan.

WILSON, L., STERLING, D. & EDWARDS, C. (1990) The Sterling Sled. *Aust. Fisheries.*

ZOETEMAN, K. (2000) Sustainability of Nations. *Report of the Deputy Director-General for Environment.* The Hague, Ministry for Housing, Spatial Planning and Environment, the Netherlands.

APPENDIX A: NET PLAN AND RAW DATA FOR REFLECTED TRAWL TESTS AND SINGLE TRAWL TESTS



T.E.R. SETTINGS FOR PRAWN TRAWL TESTS

wingang parameters -58.55 274.55 -393 07 241.02

hl 3976 mm
sweep 150 mm
offset -5 mm

	wingang deg	span of net mm	span of sweep mm	beam setting (half span) m
0.55	13.6	2186.8	35.4	1133.8
0.6	16.7	2385.6	43.2	1241.0
0.65	20 0	2584.4	51 4	1348.6
0.7	23 7	2783.2	60 3	1456.9
0.75	27 9	2982.0	70 3	1566.3
0.8	32 9	3180.8	81.5	1676.9
0.85	38.8	3379.6	94.1	1788.9
0.9	45.9	3578.4	107.6	1901.8
0.95	54.2	3777.2	121.6	2015.2

Reflected nets data

	Port side				Starboard side			
Spread	headline		footline		headline		footline	
Ratio	Tension (kgf)	Angle (deg)	Tension (kgf)	Angle (deg)	Tension (kgf)	Angle (deg)	Tension (kgf)	Angle (deg)
55	3.27	14.5	3.1	13.9	2.94	13.5	3.37	12
60	3.25	17.5	3.17	14	3.17	17.5	3.36	14
65	3.63	20.5	3.17	16.5	3.41	20.5	3.45	16.5
70	3.99	27	3.16	19	3.76	27	3.44	19
75	4.42	31	3.24	19	4.18	31	3.38	21
80	4.99	38	3.19	24	4.78	35.5	3.35	25.5
85	5.93	42	3.23	29	5.77	42.5	3.34	29.5
90	7.35	50.5	3.22	31.5	7.17	50	3.35	31
95	9.89	56	3.22	40	9.77	57.5	3.39	40
	drag comp (kgf)	inpull comp (kgf)	drag comp (kgf)	inpull comp (kgf)	drag comp (kgf)	inpull comp (kgf)	drag comp (kgf)	inpull comp (kgf)
55	3.166	0.819	3.009	0.745	2.859	0.686	3.296	0.701
60	3.100	0.977	3.076	0.767	3.023	0.953	3.260	0.813

65	3.400	1.271	3.039	0.900	3.194	1.194	3.308	0.980
70	3.555	1.811	2.988	1.029	3.350	1.707	3.253	1.120
75	3.789	2.276	3.063	1.055	3.583	2.153	3.156	1.211
80	3.932	3.072	2.914	1.297	3.891	2.776	3.024	1.442
85	4.407	3.968	2.825	1.566	4.254	3.898	2.907	1.645
90	4.675	5.671	2.746	1.682	4.609	5.493	2.872	1.725
95	5.530	8.199	2.467	2.070	5.249	8.240	2.597	2.179

	drag port (kgf)	inpul port (kgf)	drag star (kgf)	inpul star (kgf)	total drag (kgf)	av wing inpul (kgf)	wing ang (deg)	drag (kgf@1m/s)
0.55	6.175	1.563	6.155	1.387	12.330	1.475	13.457	20.529
0.6	6.175	1.744	6.283	1.766	12.459	1.755	15.735	20.743
0.65	6.440	2.172	6.502	2.174	12.942	2.173	18.562	21.547
0.7	6.543	2.840	6.603	2.827	13.146	2.834	23.321	21.887
0.75	6.852	3.331	6.738	3.364	13.591	3.348	26.227	22.627
0.8	6.846	4.370	6.915	4.218	13.762	4.294	31.965	22.912
0.85	7.232	5.534	7.161	5.543	14.393	5.538	37.582	23.963
0.9	7.421	7.354	7.480	7.218	14.901	7.286	44.360	24.809
0.95	7.997	10.269	7.846	10.419	15.843	10.344	52.554	26.378

Single net Data

	Port side				Starboard side			
Spread	headline		footline		headline		footline	
Ratio	Tension (kgf)	angle	Tension (kgf)	angle	Tension (kgf)	angle	Tension (kgf)	angle
55	2.69	14.5	3.09	12	2.88	16	3	14
60	2.71	19	3.25	13.5	2.92	18	3.01	12
65	2.94	20.8	3.305	16.1	3.05	22.2	3.03	15
70	3.225	26.1	3.27	17.2	3.37	27	3.09	17.5
75	3.605	31	3.27	22.5	3.78	31	3.07	21
80	4.17	35.5	3.24	24.5	4.29	35	3.1	25
85	4.98	42	3.225	28	5.095	39.2	3.11	27
90	6.21	49	3.33	31.5	6.32	49	3.25	31
95	8.33	58	3.38	36	8.41	57	3.26	37
	drag comp (kgf)	inpull comp (kgf)	drag comp (kgf)	inpull comp (kgf)	drag comp (kgf)	inpull comp (kgf)	drag comp (kgf)	inpull comp (kgf)
55	2.604	0.674	3.022	0.642	2.768	0.794	2.911	0.726
60	2.562	0.882	3.160	0.759	2.777	0.902	2.944	0.626
65	2.748	1.044	3.175	0.917	2.824	1.152	2.927	0.784
70	2.896	1.419	3.124	0.967	3.003	1.530	2.947	0.929
75	3.090	1.857	3.021	1.251	3.240	1.947	2.866	1.100
80	3.395	2.422	2.948	1.344	3.514	2.461	2.810	1.310
85	3.701	3.332	2.848	1.514	3.948	3.220	2.771	1.412
90	4.074	4.687	2.839	1.740	4.146	4.770	2.786	1.674
95	4.414	7.064	2.734	1.987	4.580	7.053	2.604	1.962
	drag port (kgf)	inpul port (kgf)	drag star (kgf)	inpul star (kgf)	total drag (kgf)	av wing inpul (kgf)	wing ang (kgf)	drag (kgf@1m/s)
0.55	5.627	1.316	5.679	1.520	11.306	1.418	14.079	18.824

0.6	5.723	1.641	5.721	1.528	11.444	1.585	15.479	19.053
0.65	5.924	1.961	5.751	1.937	11.674	1.949	18.460	19.437
0.7	6.020	2.386	5.950	2.459	11.970	2.422	22.037	19.929
0.75	6.111	3.108	6.106	3.047	12.217	3.078	26.739	20.341
0.8	6.343	3.765	6.324	3.771	12.667	3.768	30.750	21.089
0.85	6.548	4.846	6.719	4.632	13.268	4.739	35.542	22.090
0.9	6.913	6.427	6.932	6.444	13.846	6.435	42.909	23.052
0.95	7.149	9.051	7.184	9.015	14.333	9.033	51.573	23.863

APPENDIX B: RAW DATA FOR OTTER BOARD?TRAWL INTERACTION TESTS

Small otter boards

Flow%	Flow speed (m/sec)	Hl tension (kgf)	Hl sweep angle (deg)	Fl tension (kgf)	Fl sweep angle (deg)	Net spread (mm)
30	0.602	1.66	20.25	1.77	16.75	2472.5
35	0.7165	2.285	20	2.405	17	2475
40	0.814	2.855	20.25	3.13	16.75	2477.5
45	0.9155	3.64	20.5	3.89	17.75	2490
50	1.0125	4.485	20.25	4.79	17.75	2505
55	1.1195	5.415	20.25	5.75	17.5	2500
60	1.233	6.435	21.25	6.775	17.25	2490

Large otter board

Flow%	Flow speed (m/sec)	Hl tension (kgf)	Hl sweep angle (deg)	Fl tension (kgf)	Fl sweep angle (deg)	Net spread (mm)
30	0.6025	3.0435	45.5	1.975	32.5	3360
35	0.698	4.154	46.5	2.63	33.25	3405
40	0.82	5.385	46.5	3.395	32.5	3390
45	0.9135	6.825	47	4.16	33.5	3375
50	1.0175	8.43	46	5.065	32.5	3400
55	1.1195	10.17	46.75	6.00	31.25	3385
60	1.227	12.07	45.5	7.06	30.5	3390

TER at low spread

Flow%	Flow speed (m/sec)	Hl tension (kgf)	Hl sweep angle (deg)	Fl tension (kgf)	Fl sweep angle (deg)
30	0.607	1.605	19.5	1.74	15
35	0.7115	2.135	19.25	2.35	14
40	0.8135	2.795	19.5	3.02	15.25
45	0.916	3.52	20	3.75	15
50	1.0225	4.36	19.75	4.585	14.5
55	1.1305	5.215	19.5	5.535	15.75

60	1.241	6.155	20	6.535	15.75

TER at high spread

Flow%	Flow speed (m/sec)	HI tension (kgf)	HI sweep angle (deg)	FI tension (kgf)	FI sweep angle (deg)
30	0.609	2.73	45.25	1.9	31
35	0.7165	3.72	45.75	2.515	30.75
40	0.8165	4.915	45	3.165	31
45	0.9185	6.19	44.5	3.85	29.75
50	1.0215	7.525	44	4.695	30
55	1.1265	9.025	44.5	5.605	29.75
60	1.235	10.67	44.75	6.625	29.75

APPENDIX C: SUMMARY OF TEST CONDITIONS FOR HERVEY BAY TRIALS

CALIBRATION RUN

Cond. No.	Date	Time	Tow	Hd	Revs	Depth	Wire	Notes
1	28/2/99	4.30pm	1	S	1400	20.0	100	Standard 5 trawl rig, board size 214*92 cm
2				N	1400	20.0	100	Scanmar sensors attached to outside wingends
3					1300	20.0	100	Codends closed
4					1200	20.0	100	
5					1100	20.0	100	
6					1000	20.0	100	
7					1500	20.0	100	

CASE 1

	Date	Time	Tow	Hd	Revs	Depth	Wire	Notes
8		8.40pm	2	N	1100		75	Standard 5 trawl rig, board size 214*92 cm
9		9.00pm			1250		90	Scanmar sensors attached to outside wingends
10					1400		115	Codends open
11					1550		145	
12				S	1550		145	Reciprocal
13					1400		115	
14					1250		90	
15					1100		75	

16		12.05am	3	S	1100		75	REPLICATE
17					1250		90	
18					1400		115	
19					1550		145	
20				N	1550	[25]	145	[Depth 25m from 4th spread measure]
21					1400	20.0	115	
22					1250		90	
23		2.30am			1100		75	
24	3/01/99	1.00pm	4	S	1300	12.0	75	Echosounder transducer attached to port board
25				S	1400	11.0	75	
26				N	1400	12.0	75	
27				S	1400	11.0	75	
28			5	N	1400	11.0	75	Scanmar sensors attached to middle net only
29				S	1400	12.0	75	declination angle measured

CASE 2

Cond. No.	Date	Time	Tow	Hd	Revs	Depth	Wire	Notes
30			6	S	1100	20.0	75	Standard 5 trawl rig, Smaller boards; 191*78 cm
31					1250	21.0	90	
32					1400	20.0	115	
33					[1480	24.0	145	wrong rpm for w/d
34					1550	24.0	145	
35				N	1550	20.0	145	Reciprocal
36					1400	20.0	115	

37					1250	20.0	90	
38					1100	20.0	75	
39			7	S	1100	20.0	75	Replicate, change board rig; HL to bottom hole
40					1250	21.5	90	as +ve tilt tow 6
41					1400	22.0	115	Series aborted due to load-cell breakdown
42		2.00am	8	N	1100	22.0	75	Repeat of tow 6
43					1250	18.5	90	
44					1400	17.5	115	
45					1550	18.0	145	
46				S	1550	18.0	145	Reciprocal
47					1400	18.0	115	
48					1250	23.0	90	
49		5.30am			1100	18.0	75	
50	3/02/99	Noon	9	S	1400	10.5	75	Echosounder transducer attached to port board
51				N	1400	11.0	75	
52			10	N	1400	11.0	75	Scanmar sensors attached to middle net
53				S	1400	11.5	75	Echosounder transducer attached to port board

CASE 3

Cond. No.	Date	Time	Tow	Hd	Revs	Depth	Wire	Notes
54		1.00am	11		1100	13.5	75	Triple rig, large boards, total spread.
55					1250	12.7	90	[port & stbd nets torn in hook-up at start of tow 11]
56					1400	13.0	115	
57					1550	13.0	[135]	[short wire]
58				N	1550	13.5	[135]	Reciprocal
59					1400	13.4	115	
60					1250	12.5	90	
61					1100	13.0	75	
62			12	S	1100	13.5	75	Replicate
63					1250	13.9	90	Scanmar sensors stabilised &
64					1400	12.5	115	better data-flow established
65					1550	13.0	145	
66				N	1550	12.5	145	
67					1400	13.0	115	
68					1250	13.0	[85]	[short wire]
69		5.30am			1100	13.0	75	
70	3/03/99	1.50pm	13	S	1100	13.2	75	Triple rig, large boards, total spread.
71					1250	13.2	90	tow 11 repeat due to net damage, Stb net laced up
72					1400	12.9	115	Port net replaced by 1.3/4" net
73					1550	13.2	145	15 knot wind NNW
74				N	1550	13	145	

75				1400	13	115	
76				1250	13	90	
77	3.10pm			1100	12.9	75	
78	3.45pm	14	S	1400	7	75	Transducer on port board, sounder on all tow
79			N	1400	7	75	speeds from 2D GPS only
80		15	N	1400	7	75	Scanmar sensors on middle net. 1st 26 speeds
81	5.40pm		S	1400	7	75	on 2D only, sounder on 40 fth then 20 fth scale