The Threat and Cascade Method of estuarine health assessment - a logical sequence from human impact to biological degradation *via* system physics and chemistry.

By
Victoria Stevens

Supervised by Dr Howard Waldron

MASTERS DISSERTATION: 2005

Oceanography
University of Cape Town

Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used the Harvard convention for citation and referencing. Each contribution to, and quotation in, this dissertation, from the work(s) of other people has been attributed, and has been cited and referenced.
3. This dissertation is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as his or her own work.

Signed by candidate

Victoria Stevens

LIST OF ACRONYMS

Acronym	In Full
Cd	Cadium
Ce	Coastal Exchange
Ch	Catchment Hydrology
Co	The period of time the estuary's mouth is closed to the ocean
CSIR	Council for Scientific and Industrial Research
Cu	Copper
DP	Development and Population Density
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DWAF	Department of Water Affairs and Forestry
Ed	Encroachment of surrounding development and agriculture
En	Estuary Number
Eu	Estuary Use
GDP	Gross Domestic Product
GNI	Gross National Index
LOICZ	Land Ocean Interaction and Coastal Zone

Acronym	In Full
Mi	Mixing Index
Mw	The system's mass of nitrogen
N	Nitrogen
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
O_2	Oxygen
P	Phosphorus
Pb	Lead
PPP	Purchasing Power of Parity
Q	Freshwater inflow into the estuary
Sw	Sewerage effluent flow
Sm	State of the estuary's mouth
TaCM	Threat and Cascade Method
Tp	Tidal Prism
Tr	Fresh water Residence Time
V	Estuary Volume
Vf	Freshwater volume in the estuary (Vf)
Zn	Zinc

Abstract

A methodology for the comparative assessment of estuarine health over a range of systems is presented. It is based on the assumption that anthropogenic impact is the causative variable when considering negative impacts on estuarine health. The methodology follows a logical cascade of estuarine health assessment protocols. The first step in the Threat and Cascade Method (TaCM) incorporates socio-economic to produce a scaled indicator used to identify estuarine systems that are potentially threatened by anthropogenic inputs. The socio-economic algorithm incorporates the following variables: land cover, population density, per capita wealth, state of the estuarine mouth, abstracted mean annual runoff, encroachment of development, estuary use, and sewerage input. If the Socio-Economic Threat Index identifies the estuary as being threatened, then the second stage of the TaCM is initiated. This is an assessment of the system's physics and is accomplished by considering the following variables: residence time, estuary number (freshwater inflow/ tidal prism), coastal exchange, and the proportion of the time the estuary mouth is closed to the ocean. The Threat and Cascade Method assumes that an anthropogenically threatened system with a short residence time is less likely to be impacted on than a threatened system with a long residence time. If the Physical Threat Index identifies the estuary as being threatened, then the third stage of the TaCM is initiated. This involves assessing the chemistry and then the biology of the threatened estuarine system. The TaCM was tested using both local (South African) and international case studies. The results showed that the TaCM has the potential to become a universal methodology. The results also showed that the TaCM allows estuarine researchers and managers to rapidly assess the 'health' of a number of systems, as it mainly concentrates on estuaries that are likely to be impacted upon. The TaCM assessment identifies 'what' is causing the estuary's health to deteriorate, therefore identifying the problem areas that need to be addressed in order to mitigate the impacts on the estuary. This will allow managers to assess the success of remedial action on the estuary. The results also revealed that the TaCM could be used to predict what impact 'change' in the estuary catchment would have on an estuary's health.

Acknowledgements

I would like to thank the following people who have helped me complete this dissertation.

- Post Graduate Funding Office
- Howard Waldron (supervisor)
- Geoff Brundrit
- Jenny-Lisa Harcourt-Baldwin
- Joao Ferreira
- Andrew Martens
- My Family

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Objectives, Rationale and Scope

Estuaries are the interface between the land and the sea. They are extremely dynamic systems, made up of intricate interactions symptomatic of the mixing of marine water with freshwater (Branch *et al.*, 1981; Richardson, 1997). They come in many shapes and sizes and have different geomorphological, hydrodynamic and trophic characteristics. Estuaries with similar characteristics need to be grouped together in order to manage and understand them. They have been grouped together by their tidal range (Davies, 1964); topography (Prichard, 1952), morphology (Fairbridge, 1980); and salinity structure and stratification (Prichard, 1955).

The characteristics of estuaries are also influenced by their watershed and coastline (Wepener *et al.*, unpubl.). The watersheds of estuaries are popular places for human settlement as they provide many services (for example: recreation, food, transport and nurseries for fish) (Surge *et al.*, 2002). Due to their popularity, estuaries often exhibit a wide range of human impacts (Kennish, 2002). Estuarine habitats are important as they often support large amounts of fauna and flora and through their natural functioning they mitigate the impact of human activities on the ocean. The conservation of estuarine habitats is of paramount importance because they are a valuable natural resource offering many recreational, subsistence and commercial opportunities (USA, Environmental Protection Agency, 2005). In order to conserve estuaries, managers and scientists need a method that assesses estuarine health and determines which factors are negatively impacting on their health. The identification of problem areas in the estuary's catchment will help managers mitigate the impacts on the estuary and determine the success of remedial action.

The focus of this dissertation is to provide managers and scientists with a viable methodology for the assessment of estuarine health. The assessment of estuarine health requires the terms 'estuary' and 'estuarine health' to be clearly defined. There are multiple definitions that describe the term 'estuary. Estuaries have been defined (*inter alia*) according to physiographical features (Pethick, 1993), topography (Pritchard, 1952b), morphology (Fairbridge, 1980), ecophysiological salinity (Kinne, 1971); salinity (Venice System, 1958; Prichard, 1955; Cameron and Prichard, 1963; Prichard, 1967; Day, 1980); biology (Bulger *et al.*, 1993; Laffloey, *et al.*, 1993) and in context of the entire coastal zone (Kjerfve, 1989; CSIR, 1992).

The Council for Scientific and Industrial Research's (CSIR, 1992) definition of an estuary will be used in this dissertation. "*An estuary is considered to be that portion of a river system which has or can from time to time have contact with the sea. Hence during floods an estuary can become a river mouth with no seawater entering the formerly estuarine area*" (sea-land boundary) (CSIR, 1992). This definition was chosen to describe the term 'estuary' in this dissertation because it gives a sufficiently broad definition for the purpose of this study and can be applied to most, if not all, estuaries in the Northern and Southern Hemisphere.

There are also many different interpretations of ecosystem health (Coates *et al.*, 2002). However, in this dissertation, estuarine health will be considered as analogous to marine ecosystem health. Therefore the definition given by Epstein (1999) is considered appropriate: "*to be healthy and sustainable, an ecosystem must maintain its metabolic activity level, its internal structure and organization, and must be resilient to stress over a wide range of temporal and spatial scales.*"

The assessment of estuarine health is important as it helps mangers determine whether or not the current utilisation of an estuary and its catchment is sustainable. Managers use estuarine health assessment indices as tools, in conjunction with conservation priority indices, to determine the estuary's importance. This allows managers to prioritise estuaries with a high conservation importance and deteriorating health, for remedial action.

Previous estuarine health indices have been based on the following factors: fish (Ramm 1988, 1990); trophic interactions (Rizzo *et al.*, 1996; Bricker *et al.*, 2003); benthic ecology (Hilly, 1984; Washington, 1984; Rygg, 1985; Majeed, 1987; Codling *et al.*, 1992; Weisberg *et al.*, 1992; Dauer, 1993; Engle *et al.*, 1994; Grall *et al.*, 1997; Weisberg *et al.*, 1997; Roberts *et al.*, 1998; Van dolah *et al.*, 1999; Moverly, 2000; Smith *et al.*, 2001; Eaton 2001; Paul *et al.*, 2001; Llanso *et al.*, 2002; Muxika *et al.*, 2005); plants (Coetzee *et al.*, 1996); chemical aspects; physical aspects; biological aspects, aesthetic aspects and some socio-economic aspects of estuaries (Cooper, 1992, 1994; Harrison *et al.*, 1994, 1995; CERM, 1996; Van Driel, 1998; Turpie *et al.*, 1999; Ferreira, 2000).

The initial indices that were developed to access estuarine health used one indicator to represent the quality of the sediment and water column. Examples of the single indicators used to represent estuarine health are: fish (Ramm 1988, 1990), plants (Coetzee *et al.*, 1996) and benthic organisms (Hilly 1984; Washington, 1984; Rygg, 1985; Majeed, 1987; Codling *et al.*, 1992; Weisberg *et al.*, 1992; Dauer, 1993; Engle *et al.*, 1994; Grall *et al.*, 1997; Weisberg *et al.*, 1997; Roberts *et al.*, 1998; Van dolah *et al.*, 1999; Moverly, 2000; Smith *et al.*, 2001; Eaton 2001; Paul *et al.*, 2001; Llanso *et al.*, 2002; Muxika *et al.*, 2005). The problem with this type of approach is that it is generally only applicable to estuaries that are similar to the estuary they were developed on. This type of approach is also inaccurate. This is due to the fact that no solitary indicator will accurately define the interactions between ecosystem function and structure, reaction of the estuarine system to anthropogenic stress, and stability and resilience of biological communities (Deeley *et al.*, 1999).

Scientists realised that it was necessary to develop estuarine health indices that included more than one indicator. Cooper *et al.* (1994) was on of the first scientists to develop an estuarine health index that included most of the variables that effect estuarine health. Cooper *et al.'s* (1994) methodology was based on chemical, physical, biological and aesthetic aspects of estuaries. This method was more accurate than the previous approaches as it included more than one factor in its assessment of estuarine health. The problem with the methodology is that it was only suitable for regional data sets, as the physical contrasts are only carried out on a geomorphological level.

The Estuarine Integrity Index (Turpie, *et al.*, 1999) and Equation Index (Ferreira, 2000) are other examples of integrated indices for estuarine health assessment. Both indices included physics, chemistry, biology as well as some socio-economic factors in their assessment of estuarine health.

Ferreira (2000) and Turpie *et al.* (1999) have provided the most integrated estuarine health assessment methods to date because they included system physics, chemistry, biology and some socio-economics in their methodologies. Previous estuarine health assessment indices have mainly concentrated on biological and chemical variables and it is felt that the causative factors relating to socio-economic variables mediated (or not) by system physics have largely been understated. Socio-economic impacts are very important, as they are the main cause of estuarine degradation. The physics of an estuary are also important because they determine how resilient the estuary is to anthropogenic stress.

The aim of this dissertation is to develop a health assessment method that includes the causative factors that impact estuarine health. The new method of estuarine health assessment should therefore include socio-economics, as well as physics and chemistry in its assessment of estuarine health. Another aim is to design the methodology in such a way that it can help identify the factors that are negatively affecting the estuary's health and to prioritise 'impacted' estuaries over 'non-impacted' estuaries. This will ensure that managers can concentrate their efforts on 'impacted' estuaries. The new method developed in this dissertation is called the Threat and Cascade Method (TaCM) of estuarine health assessment. The Threat and Cascade Method of estuarine health assessment is intended as a management tool that aids managers in identifying 'impacted' systems and helps them identify 'what' is impacting the estuary's health. This will allow managers to target problem areas in the estuary's catchment, therefore mitigating the impacts on the estuary. The TaCM is also intended to be a predictive tool that enables managers to predict what impact 'change' would have on an estuary's health. This will inform managers if future development has the potential to impact the estuary.

Furthermore, this dissertation uses three case studies to test whether the developed Threat and Cascade Method of estuarine health assessment is a viable estuarine health assessment tool. If the Threat and Cascade Method is proved to be viable then it can be used to help in the effective management of estuarine systems in respect of risk, impact and remedial action.

1.2 Case Studies

The three estuaries that were selected as case studies in order to test the TaCM were: the Knysna and Swartkops estuaries in South Africa and Chesapeake Bay in the U.S.A. The estuaries that were chosen are from different regions in the world, so they can test whether or not the TaCM's approach is a universally applicable method. The selection (Table 1.2.1) covers a range of likely health status, catchment area and estuary size. Another reason for the selection was the extent of previous work that provided a comprehensive data set of variables for each system.

Table 1.2.1: A table comparing the characteristics of the 3 case studies

	Knysna	Swartkops	Chesapeake Bay
Country	South Africa	South Africa	USA
Geographical location	34°04'38"S; 23°03'33"E	33°51'54"S; 25°38'00"E	37° to 39°N; 76°W
Estuary size (km^2)	48	4	11000
Depth (m)	3	3	7
Catchment area (km^2)	400	1400	160000
Tidal range	Micro-tidal	Micro-tidal	Micro-tidal
Mouth	Permanently open	Permanently open	Permanently open

1.2.1 Knysna Estuary

The Knysna Estuary (34°04'38"S; 23°03'33"E) is the largest tidal estuary (48km^2) situated on the southern coast of South Africa (Switzer *et al.*, 2002). It has been classified as a permanently open, microtidal (Grindley, 1985; Switzer, 2003), warm temperate estuarine bay (Whitfield, 2000). The Knysna River is its main supplier of freshwater (Largier *et al.*, 2000).

The Knysna Estuary is a shallow (3m), marine dominated, partially mixed estuary (Allanson *et al.*, 1999) that is influenced by the intrusion of upwelled water into the estuary (Largier *et al.*, 2000; Schumann *et al.*, 1999).

It has three distinct regions that display different hydrological characteristics. The three regions are: an embayment, lagoon and an upper estuary. The embayment is characterized by strong tidal flushing, while limited tidal and river mixing characterize the lagoon region. The upper estuary is dominated by freshwater (Largier *et al.*, 2000). An additional region of the estuary, described by Switzer (2003), is the Ashmead channel. The channel is the area bordered by the northern end of Leisure Island and Thesen Island that contains an extensive system of tidal flats (Switzer, 2003).

The Knysna Estuary has a relatively small (400km^2) catchment area (Largier *et al.*, 2000; Switzer *et al.*, 2002). The land use in the catchment is 69% natural, 28% agricultural and 3% developed (Department of Environmental Affairs and Tourism, 2001a). The agricultural areas mainly consist of commercial agriculture, commercial forestry and improved grasslands. The developed area consists of industrial, commercial and residential development (Department of Environmental Affairs and Tourism, 2001a). The town of Knysna is situated very close to the estuary and therefore it is a popular tourist destination. During the tourist season the human population in the town rises from 76 x 10^3 people to approximately 108 x 10^3 people (Switzer *et al.*, 2002). The Gross National Index per capita of Knysna is 4058 US dollars at purchasing power of parity (Knysna Municipality, 2002), which is classed as a lower-middle income (The World Bank Group, 2005).

1.2.2 Swartkops Estuary

The Swartkops Estuary (33°51'54"S; 25°38'00"E) is a shallow estuary (3m) situated on the south east coast of South Africa (Baird *et al.*, 1986). The estuary has been classified as warm-temperate (Baird *et al.*, 1986; Whitfield, 2000), well-mixed (Winter and Baird, 1991), microtidal and permanently open (Whitfield, 2000).

The catchment receives, on average, 636mm of rainfall annually (Baird et al., 1986). The impoundments in the catchment have a small storage capacity (approximately 17% of the mean annual rainfall) and therefore river flow has not been drastically altered (Reddering *et al.*, 1981).

There are approximately 1 x 10^6 people living and working in the catchment area (Binning *et al.*, 2001). The catchment area contains half of the Port Elizabeth municipal area and the majority of the municipal areas of Kwanobuhle, Uitenhage, Ibayi, and Despatch (Binning *et al.*, 2001). The catchment area's human population has a Gross National Index of 766-3035 US dollars (Statistics South Africa, 2005) at the purchasing power of parity, which is a classed as a lower-middle income (The World Bank Group, 2005).

1.2.3 Chesapeake Bay

Chesapeake Bay is a drowned river valley situated on the Atlantic Coast (37° to 39°N; 76°W) of the United States of America (Boynton *et al.*, 1998, Smith *et al.*, 1999). Chesapeake Bay is the biggest estuary (total tidal area of 11000km^2) in the United States (Boesh, 2000). The average depth of the system is approximately 7m (Boynton *et al.*, 1998, Smith *et al.*, 1999). Five major rivers deliver 90% of the freshwater received (60 x 10^6m^3) by the bay. These rivers are the Susquehanna, James, Potomac and Rappahannock rivers (Boynton *et al.*, 1998; Smith *et al.*, 1999).

The two most important features of Chesapeake Bay are its extensive catchment area (16000km^2) and its shallowness (7m). The catchment area stretches across six states: parts of Pennsylvania, New York, Virginia and West Virginia Maryland, Delaware and all of the District of Columbia (Boynton *et al.*, 1998; Smith *et al.*, 1999). The shallowness of the estuary promotes productivity, as it allows light to penetrate to the bottom (Kemp *et al.*, 1997).

The land use in the catchment area is 57.4% natural, 33.5% agriculture, 8.4% developed (Castro *et al.*, 2003). The upper part of the catchment is mainly forested. The lower parts of the catchment near the Bay and its tidal rivers include the Virginia Tidewater region (which includes the cities of Portsmouth, Newport News, Norfolk and Hampton) and the Washington and Baltimore metropolitan areas (Boynton *et al.*, 1998; Smith *et al.*, 1999).

The catchment area has a human population of over 15 x 10^6 people (Boesh, 2000) and has some of the wealthiest counties in the US. These areas are situated in the Baltimore and Washington Metropolitan Areas. The catchment area has a Gross

National Index that is greater than 9386 US dollars (US Census Bureau, 2005), which is a classed as a high income (The World Bank Group, 2005).

1.3 Background

The literature was reviewed to determine how socio-economic factors affect estuarine health and how these effects can be mitigated. The objective of the literature review was to identify all the socio-economic factors that influence the health of estuaries so they could be included in the Threat and Cascade Method of estuarine health assessment

1.3.1 Human impacts

Anthropogenic changes in an estuary and its catchment may lead to a deterioration of its health. This is because humans clear the natural landscape for agriculture, urban and industrial land use and because they exploit the estuary's resources. Increases in human population density and wealth as well as anthropogenically induced climate change can magnify the human impacts on the estuary (Kennish, 2002).

Clearing of the natural landscape

The clearing of the natural landscape in an estuary's catchment for agriculture and industrial and urban development may result in the following changes to the estuary's health:

a) Decreased water quality or eutrophication

Activities in agricultural, industrial and urban areas can cause increased amounts of nutrients and pathogens to be introduced to the estuary. Increased nutrients and pathogens in an estuary may result in water quality deterioration (Dederen, 1992; McComb, 1995; Nixon, 1995; Chapman *et al.*, 1996; Kennish 1997; National Estuary Program, 1997 a, b; Valiela *et al.*, 1997; Smith *et al.*, 1999; Eganhouse *et al.*, 2001 and Kennish, 2002). The former may cause eutrophication problems (for example: in the Jiulong River Estuary, in China, 24°27'00"N, 118°18'00"E) (Chen *et al.*, 1994 and Hong *et al.*, 1998) and increase the biological oxygen demand; and the latter may result in the spread of human diseases (for example: hepatitis and cholera) (Dederen, 1992; McComb, 1995; Nixon, 1995; Chapman *et al.*, 1996; Kennish 1997; National

Estuary Program, 1997 a, b; Valiela *et al.*, 1997; Smith *et al.*, 1999; Eganhouse *et al.*, 2001; Kennish, 2002).

Agricultural, industrial and urban areas may also introduce chemical contaminants into estuaries *via* atmospheric deposition, agricultural and urban run-off, and municipal and industrial wastewaters. If these chemical contaminants reach toxic levels they can result in bioaccumulation, diseases and death of organisms living in the estuary (Kennish, 2002).

b) *Increased sedimentation*

Increased soil erosion typically occurs due to poor farming practices, overgrazing, mining and clearing of vegetation from the landscape. If increased soil erosion occurs in an estuary's catchment it may result in increased sediment input into the estuary (Morant *et al.*, 1999). For example, the Fly River Estuary, in Papua New Guinea, (143°18'00"E, 8°18'00"S) is receiving increased sediment load due to mining activities that are currently occurring at the headwaters of the river (Opdyke *et al.*, 1997). The consequences of high sediment input into estuaries, if it is not washed out, include increased sedimentation in the estuary, changes in the benthic community living in the estuary, and shallowing of the estuary basin. A positive impact of increased sedimentation is reed encroachment and mud flat formation, as it can increase the number of birds visiting the estuary (Morant *et al.*, 1999).

c) *Decreased freshwater input*

Agricultural, urban and industrial areas in an estuary's catchment can also decrease the amount of freshwater the estuary receives. This is due to increased water abstraction from rivers, diversion of rivers and the storing of water in dams. This leads to decreased freshwater input to the estuary. Decreased freshwater supply can result in a temporarily closed estuary remaining closed for longer periods of time or a tendency towards hypersalinity (Morant *et al.*, 1999) (for example: Kromme Estuary, South Africa, 34°08'27"S; 24°50'36"E) (Baird, 2001a). Storing of water in dams can diminish the scouring potential of floods, resulting in decreased frequency of mouth openings and decreased exchange of oceanic and estuarine water (Morant *et al.*, 1999). The timing and length of time the mouth of an estuary is open is very important to the health of the biota as the period of time the mouth closes changes the salinity and hydrographic characteristics of the estuary (Morant *et al.*, 1999; Whitfield, 1994).

d) *Increased amounts of impervious cover*

Urban and industrial development results in increased areas of impervious cover (for example: concrete, tar). This leads to decreased amounts of infiltration. This means that during a rainfall event more water is transported more rapidly to rivers and estuaries resulting in flash floods (Holland *et al.*, 2004; Arnold *et al.*, 1982; Arnold *et al.*, 1996; Schueler *et al.*, 2000). These flash floods also increase the amount of sediment being transported to the estuary as they have higher erosion potential (Morant *et al.*, 1999). Urban and industrial areas also pump municipal and industrial wastewater into rivers and estuaries. This means that the estuary receives a larger volume of water more rapidly than it would naturally receive and this may result in a change in the hydrography of the estuary (Holland *et al.*, 2004; Arnold *et al.*, 1982; Arnold *et al.*, 1996; Schueler *et al.*, 2000).

Holland *et al.* (2004) found that when the amount of impervious cover in an estuary's catchment exceeds 10-20% of the ground cover, the estuary's physical and chemical attributes were negatively 'impacted'. This included alterations to salinity, hydrography and sediment characteristics and enhanced input of fecal coliforms and chemical contaminants. Schueler (1994) and Arnold *et al.* (1996) found that massive biological degradation took place when more than 30% of an estuary's catchment was changed to impervious cover.

e) *Loss of habitat and estuarine functionality*

Encroachment of urban, industrial and agricultural areas onto the banks or into the intertidal area of an estuary, may lead to a loss of reedbeds and saltmarsh areas. This can compromise the estuary's functionality as a filter, as a nursery area for fish and as a habitat for birds (Morant *et al.*, 1999).

Estuary mouths may be breached artificially in areas where urban and industrial development occurs too close to the estuary (for example: Swartvlei Estuary, South

Africa, 34°01'51"S; 22°47'49"E) (Prochazka *et al.*, 2002b). The mouths are breached to prevent flooding of urban and industrial areas. Artificial breaching can result in the functionality of the estuary collapsing. It may also have long-term impacts on the sediment dynamics and biota of an estuary by causing accumulation of sediments near the estuary mouth (for example: Bot River Estuary, South Africa, 34°18'30" - 34°22'30"S; 19°04'00"- 19°09'00"E) (van Niekerk *et al.*, 2005) and causing more frequent and longer closures of the mouth (Morant *et al.*, 1999).

Estuaries are often dredged for a number of reasons including harbour development, and creation of shipping channels. Dredging has both harmful and beneficial effects. One of the harmful effects of dredging is the removal of bottom sediments, which ruins the benthic habitat and may also result in the death of benthic organisms (Kennish, 2002). Another example is the degradation of the water quality of the estuary, due to the release of chemical contaminants and nutrients from the bottom sediment into the water column (Kennish 1997, 2001). Certain positive effects may occur including enhanced circulation in the dredged area, enhanced productivity; increased commercial and recreational usage of the estuary, and increased passive transport of juveniles into the estuary from the sea (Kennish, 2002).

Exploitation of an estuary's resources

Humans use estuarine habitats extensively. They provide food, recreation, transport, shelter and waste disposal services (Townend, 2002). The different ways estuaries are utilised and the consequences of their utilisation are discussed below.

a) Fishing

Commercial, recreational and subsistence fishing and bait collection occurs in many estuaries. These activities may result in degradation of ecologically sensitive areas, such as intertidal and marsh areas. Overfishing results in decreased numbers of fish species and reduction of fish stocks (Whitfield *et al.*, 1999), and may result in imbalances in estuarine function and overall community structure (Jennings *et al.*, 1998; Pinnegar *et al.*, 2000).

b) Mariculture

If the amount of mariculture in the estuary exceeds the estuary's carrying capacity, it can result in the accumulation of wastes and nutrients in the estuary concerned (Bailly *et al.*, 1996; Morant *et al.*, 1999). The estuary's flow characteristics may balance or mitigate these impacts, but note that the accumulation of wastes is more likely to occur in estuaries that have long residence times due to slow or infrequent flushing (Pearce *et al.*, 1997).

c) Shoreline development

The most direct physical impacts on estuaries are related to the building of shoreline structures (for example: piers and boat ramps) (Kennish, 2002). Infrastructure built in the estuary or in its catchment can also cause loss of habitat and estuarine functionality. For example when a bridge is built across an estuary the tidal regime may be reduced and therefore the flushing of the estuary, by the tides, becomes less effective (Morant *et al.*, 1999).

Population density

Human impacts in an estuary's catchment are intensified by increases in human population density. Many estuarine areas have large human population densities as they are popular places to live and because they provide multiple services (for example: recreation, food, transport and nurseries for fish) (Hodkin, 1994). Increased human population density in an estuary's catchment is often associated with increased agriculture, urban and industrial development. This results in increased pollution of the estuary and intensification of the abovementioned human impacts (Kennish, 2001). Human population expansion and changing population density in the coastal zone have been recognized as important stressors for estuaries and are generally regarded as the largest threats to the ecological performance of estuarine environments (Culliton, 1998; Beach, 2002).

Climate change

Over the past century humans have been polluting the atmosphere and this has lead to global warming. Global warming can negatively impact estuaries by causing a rise in sea level. During the past century, global warming has already caused the sea level to rise by 10-25cm (Ledley *et al.*, 1999). The sea level is expected to rise another 2.6-15.3cm, by the year 2020 (IPCC, 2001). This may result in increased flooding and erosion, decreased areas of wetland habitat, and backwards migration of estuarine shorelines (Wolanski *et al.*, 1996). It may also result in significant changes in salinity regimes and tidal prisms, which might substantially change the composition of the communities living in the estuary (Kennish, 2000).

1.3.2 Mitigation of Human Impacts

Estuarine flushing and exchange with adjacent coastal waters can naturally mitigate the abovementioned human impacts, as can human intervention (for example: restoration projects and management of estuaries).

Estuarine physics

Estuarine physics are an important factor when assessing how human impacts in the estuary's catchment will affect the estuary. This is because the physics of an estuary determine how well the estuary is mixed and how long pollutants persist in an estuary (Prichard *et al.*, 1971). The persistence of pollutants in an estuary is determined by an estuary's flushing time and residence time. The flushing time of an estuary determines its ability to flush its existing water to the sea. The residence time of an estuary determines the amount of time a water parcel or an introduced particle persists in an estuary (van de Kreeke, 1983; Prandle, 1984). The flushing time of an estuary is linked to the residence time of an estuary; the longer it takes for an estuary to flush the longer its residence time will be (Wang *et al.*, 2003).

Estuaries with short residence times (hours) can receive relatively high amounts of pollutants without deleterious effects. Similarly, in estuaries with large tidal prisms, effluents are diluted and the pollutants in the system don't persist (Alanson and Winter, 1999). Conversely, estuaries with long residence times cannot process the same amount of pollutants without deleterious effects. This is because the increase in residence time allows pollutants to persist for longer in the estuary (Ferreira, 2000). Therefore, it is more likely for the water quality in an estuary with a long residence time to become degraded.

Restoration projects

Globally, restoration projects are occurring in many degraded estuarine ecosystems. These restoration projects have concentrated on the wetlands that border estuaries. Attempts at restoration are not always successful but they nevertheless tend to slow down the rate of degradation and are therefore beneficial (Kennish, 2002).

Management

Estuaries are managed in order to minimise human impacts. An estuary's management team's main responsibilities are to ensure that use of the estuary and the development in its catchment does not become unsustainable, and to conserve biological diversity. Estuary managers should discourage development that has the potential to cause severe stress to the estuary. This only occurs if policy makers, managers and town planners communicate effectively (Morant *et al.*, 1999).

1.4 Thesis Structure

This chapter outlines the motivations, aims and objectives of the research and provides general background theory. It explains what it means to describe an estuary as healthy and the likely causes of system deterioration. It also describes previous health assessment models and provides background information on the 3 case studies that are the subject of this dissertation. It also outlines the structure of the rest of the dissertation.

Chapter 2 explains all the methodologies utilised in this dissertation and includes the TaCM's methodology.

Chapter 3 provides the results of the testing of the TaCM and the results of the TaCM's analysis of 3 case studies.

Chapter 4 places the results in context.

Chapter 5 gives a synopsis of the Threat and Cascade methodology, its results and draws conclusions in relation to its efficacy.

Chapter 2: Methods

This chapter describes the TaCM and how to perform the TaCM's analysis of estuarine health. It also describes how the TaCM's robustness and predictive ability was tested.

2.1 The Threat and Cascade Method (TaCM)

The Threat and Cascade Method has been designed to create an integrated approach to estuarine health assessment, which includes socio-economic threats, system physics, chemistry, and biology. An advantage of the Threat and Cascade Method is that it includes causative factors relating to socio-economic variables mediated (or not) by system physics and dynamics. Another advantage is that it is a rapid and a relatively cheap method to assess estuarine health, and it can be utilised by managers and conservationists to mitigate human impacts. It also permits managers to prioritise estuaries in their region with respect to remedial actions.

The TaCM is based on the assumption that human influences negatively impact on an estuary's health. This assumption is derived from the UN definition of marine pollution: "Pollution means the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of seawater, and reduction of amenities" (GESAMP, 1984).

The Threat and Cascade Method (Figure 2.1.1) of estuarine health assessment consists of 4 steps.

1. The Socio-Economic Threat Index
2. The Physical Mediation Index
3. The Chemical Impact Index
4. The Biological Impact Index

The TaCM method is a hierarchical method (Figure 2.1.1). It gives priority to human threats on the estuary, making the top of the hierarchy the Socio-Economic Threat Index, and then cascades down to physics, chemistry and biology. The Socio-Economic Threat Index measures the potential threat of the human activities impacting on the estuary. If the potential threat is low, then the estuary is 'not threatened' and the assessment is considered to be complete. If the potential of the human activities is found to be potentially threatening the estuary's health, the next step of the TaCM is completed. The next step of the assessment is the Physical Mitigation Index. This step quantifies how 'good' or 'bad' the estuary's flow characteristics are at mitigating the socio-economic threats on the estuary. If the estuary's flow characteristics are found to be able to mitigate the socio-economic threats on the estuary then the TaCM concludes that the estuary is 'not threatened' and the assessment is considered to be complete. If the estuary's flow characteristics are not able to mitigate the socio-economic threats, then the estuary is 'threatened' and the next step of the assessment is completed. The next step in the hierarchy is the Chemical Impact Index. If the assessment reaches this stage, the chemistry should be altered, as it will reflect the socio-economic and physical problems. This renders this stage of the method an effective test of the results from the physical and socio-economic assessments. If the chemistry of the estuary is 'impacted' then the Biological Impact Index is completed. At this stage the health of the biology should reflect the estuary's water quality. This is because the health of the biology living in the estuary is impacted on by the water quality of the estuary. Figure 2.1.1 provides a schematic representation of the logical flow that underpins the TaCM.

TaCM

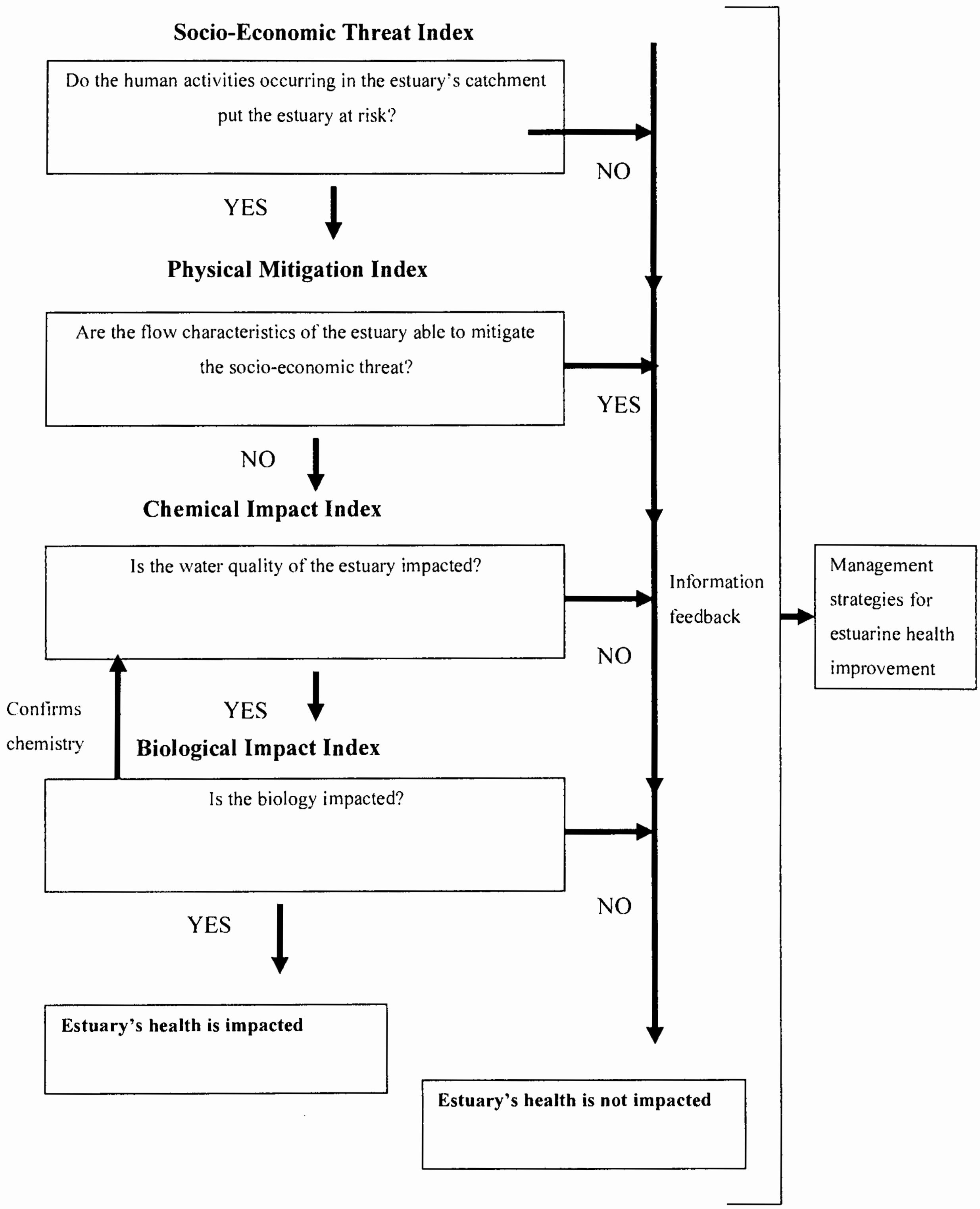


Figure 2.1.1: Basic schematic of the Threat and Cascade Method of estuarine health assessment.

Each step of the TaCM consists of a series of tables. These tables are used to grade each variable. This is achieved by choosing the box in the table that best represents the quantity of the variable being assessed. Each table is therefore used to grade the potential impact on the estuary.

2.1.1. Socio-Economic Threat Index

The Socio-Economic Threat Index is the first step of the TaCM. The aim of this component of the TaCM is to evaluate the potential threat of human activities impacting on the estuary. This index contains variables that are thought to represent the intensity of the possible human threat on the estuary. Previous indices (Edgar *et al.*, 2000; Holland *et al.*, 2004; Prochazka *et al.*, 2002b; Commonwealth of Australia, 2002; The World Bank Group, 2005) and ranking systems using these variables were adapted and used to develop the Socio-Economic Threat Index.

The Socio-Economic Threat Index adopts a hierarchal approach, starting with a primary indicator (percentage land cleared) and then moving onto secondary indicators, such as percentage developed land in the cleared land area. The Socio-Economic Threat Index consists of 4 steps. The first step uses the percentage of cleared land as a primary indicator of the potential threat of human activities impacting on the estuary's health. The second step uses the percentage of developed land, human population density, and human wealth as secondary indicators of human threats on the estuary. The third step uses the state of the estuary mouth, catchment hydrology, encroachment of development and agriculture, estuary use, and sewerage input as secondary indicators of human threat. The forth step is used to grade the total 'human threat' on the estuary. Figure 2.1.2 provides a schematic representation of the Socio-Economic Threat Index. Please note, that at this stage, a qualitative representation is given prior to the assignment of a ranking procedure.

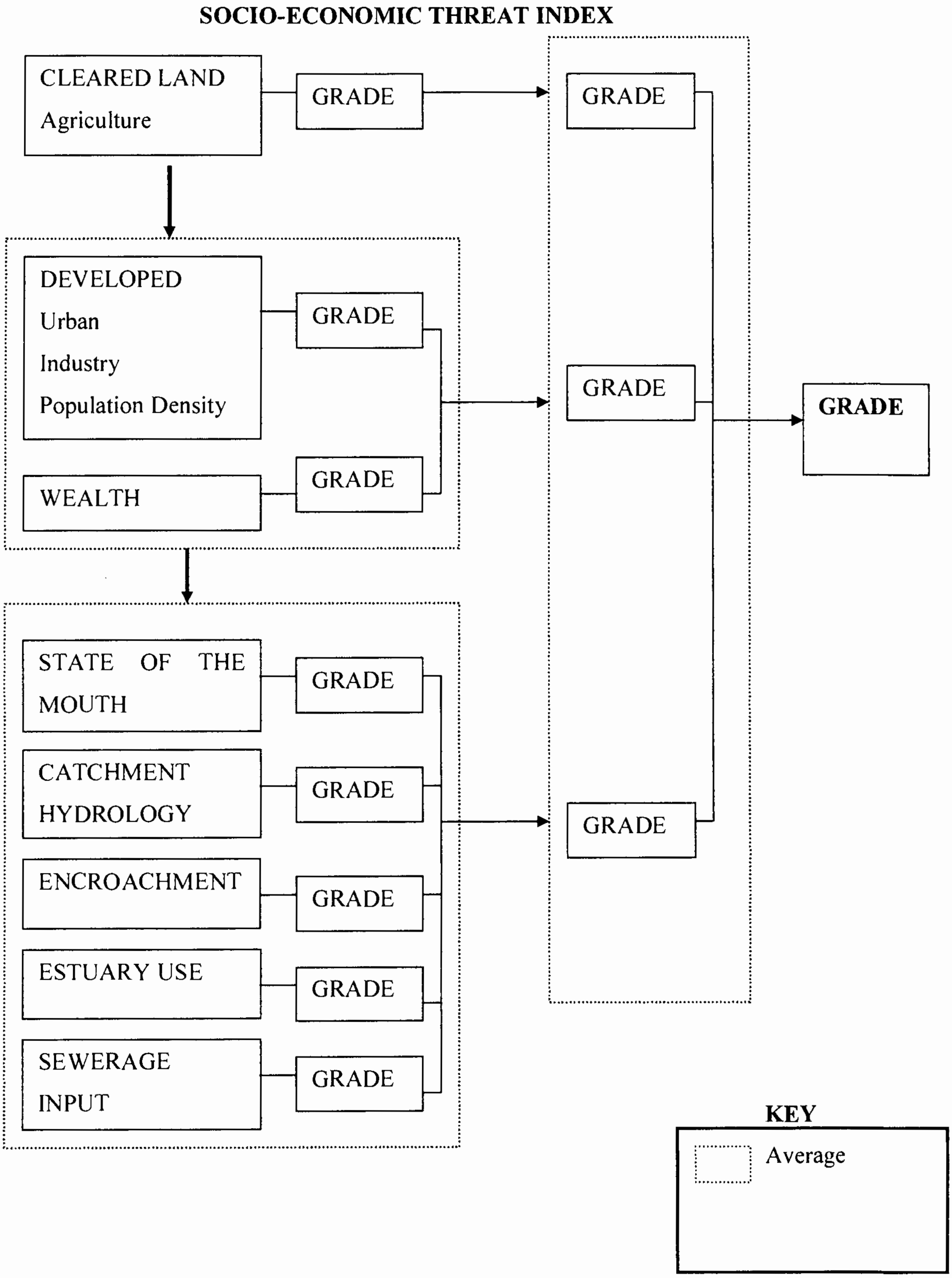


Figure 2.1.2: A schematic of the Socio-Economic Threat Index

Step 1: The percentage of cleared land in the catchment

The purpose of the first step of the Socio-Economic Threat Index is to grade the estuary in terms of how much cleared land is in the estuary catchment. In Table 2.1.1, the amount of cleared land is graded from 5 (best case scenario) to 1 (worst case scenario). Each column of Table 2.1.1 is used to give a different grade to the amount of cleared land in an estuary's catchment. Table 2.1.1's grading categories were adapted from Edgar *et al.* (2000).

Table 2.1.1: The ranking of percentage cleared land in the estuaries' catchments (Edgar, *et al.*, 2000)

Grade	5	4	3	2	1
	Pristine/ natural condition	**Low threat**	**Moderate threat**	**High threat**	**Severe threat**
Cleared Land	Only natural land types, largely untouched	>10% agricultural or cleared land	10-25% agricultural/ cleared land	25-50% cleared land	50-75% cleared land

Step 2: Grading of the percentage developed land and the human wealth

The purpose of the second step of the Socio-Economic Threat Index is to grade the potential threat of catchment-related human activities on the estuary.

The following secondary indicators are used in this step:

- percentage of developed land in the estuary catchment,
- human population density,
- and wealth

Table 2.1.2 is used to give grades to each of the indicators in this step. It is graded from 5 (best case scenario) to 1 (worst case scenario). The classification schemes of the variables, in Table 2.1.2, are adapted from Holland *et al.* (2004), Edgar *et al.* (2000) and The World Bank Group (2005).

In Table 2.1.2, the developed land use (secondary indicator) category is equal to the amount of urban and industrial land use in the estuary's catchment, expressed as a percentage. It was assumed in this dissertation that the percentage of developed land

was equal to the percentage of impervious land cover in the catchment. The human population density (secondary indicator) is used to help quantify the intensity of the developed land use's potential threat (Table 2.1.2). The acronym DP will be used to represent the score for developed land combined with population density. The human population density is equal to the number of people per square kilometer in the catchment area. The wealth (secondary indicator) of the human population living in the estuary's catchment (average Gross National Index (GNI) per capita) is also ranked in this step. It is ranked, in Table 2.1.2, using the average GNI, at the purchasing power of parity, of the catchment. In order to calculate the GNI of Knysna and Swartkops, the Big Mac Index (The Economist Newspaper Limited, 2005) was used to convert the Gross Domestic Product (GDP) in Rands to its purchasing power of parity (PPP). This was achieved by dividing the value in Rands, by 4.28 (Appendix I). The GDP value (at PPP) was divided by the number of people in the catchment, in order to get average Gross National Product per capita (GNI) (The Economist Newspaper Limited, 2005). The final part of the step averages the grades from the developed land use category and the wealth category
(I (Step2) = (DP + GNI) /2).

The airshed (source of atmospheric pollutants) of an estuary also needs to be considered when assessing socio-economic impacts on estuaries. The amount of atmospheric pollutants is determined by the percentage of agriculture, industry and urban areas in the catchment (Whithall *et al.*, 2004). Therefore the airshed is included in the Socio-Economic Threat Index.

Step 3: Grading of qualitative and semi-quantitative variables

The purpose of the third step of the Socio-Economic Threat Index is to grade the potential threat of the catchment-occurring human activities, impacting on the estuary. This was achieved by using the state of the estuary mouth; encroachment of surrounding development and agriculture, catchment hydrology, estuary use, and sewerage input as secondary indicators. The term Sw's grade is not dependent on the treatment level of the sewerage.

Table 2.1.3 is used to give grades to each of the indicators. It is graded from 5 (best case scenario) to 1 (worst case scenario). The grades for the state of the estuary mouth, encroachment of surrounding development and agriculture, catchment hydrology, estuary use, and sewerage input are then added together and divided by 5 (I (Step 3) = (Sm + Ed + Ch + Eu +Sw) / 5).

Table 2.1.2: Grading of developed land use, population density and wealth (Edgar *et al.*, 2000; Holland *et al.*, 2004 and The World Bank Group, 2005).

Grade	**5**	**4**	**3**	**2**	**1**
	Pristine/ natural condition	**Low threat**	**Moderate threat**	**High threat**	**Severe threat**
Developed	Only natural land types, largely untouched	<30% urban/ suburban and <10% impervious	> 30%, <70% urban/ suburban or >10%, <50% impervious	>70% urban/ suburban or >50% impervious	>45% urban/suburban with industrial facilities and >50% impervious
Population/ Catchment area			>0.05, <2 / km^2	>2 / km^2	
Wealth (GNI per capita (@PPP))		Low income <$765	Lower middle $766-$3035	Upper middle $3036-9385	High income ≥$9386

Table 2.1.3: The ranking of qualitative and semi-quantitative variables in the Socio-Economic Threat Index (Prochazka *et al.*, 2002; Commonwealth of Australia, 2002).

Grade	**5**	**4**	**3**	**2**	**1**
State of mouth (Sm)	Mouth opens on a completely natural cycle.		Mouth Periodically artificially breached.		Mouth altered and/or artificially controlled.
Encroachment of surrounding development and agriculture (Ed)	None	Slight (Development well set back from banks).	Moderate (Development occasionally encroaches onto banks, bank at least 90% untransformed).	High (Development often encroaches on banks, destruction of reed beds and/or salt marsh, bank 25-90% untransformed).	Very high (Widespread destruction of reedbeds and/or saltmarsh, development may extend into intertidal area, bank <25% untransformed).
Catchment Hydrology (Ch)	No dams or impoundments, virtually nil abstraction	No dams or significant impoundments, some abstraction		Dams and impoundments, moderate abstraction modifying natural flows	Dams and impoundments, significant abstraction modifying natural flows
	< 10% MAR abstracted	<25% MAR abstracted	<50% MAR abstracted	≤75% MAR abstracted	>75% MAR abstracted
Estuary use (Eu)	Extractive activities limited to indigenous or limited and sustainable commercial and recreational fishing, no aquaculture.	Extractive activities limited to sustainable commercial and recreational fishing, minor aquaculture.	Extractive activities limited to sustainable commercial and recreational fishing, moderate aquaculture.	Extractive activities include dredging, extensive aquaculture, habitat modifying fishing methods.	Extractive activities include dredging, extensive aquaculture, habitat modifying fishing methods.
Sewerage (Sw) (m^3/day)	None	Slight	Moderate (2000)	High	Very high

Step 4: Calculating the final grade

The purpose of this step is to combine the answers from steps 1 to 3, to obtain a final grade. The answers for step 1 to step 3 are therefore averaged:

[I (Step 4) = [(Step 1+Step 2+Step 3/ 3].

This value is converted, using Table 2.1.4, to get the final grade for step 5.

Table 2.1.4: Value conversion table for the Socio-Economic Threat Index

Grade	**5**	**4**	**3**	**2**	**1**
Classification	**Pristine/ natural condition**	**Low threat**	**Moderate threat**	**High threat**	**Severe threat**
Values	5	4.9-4	3.9-3	2.9-2	1.9-1

All the numbers in Table 2.1.4 are rounded down. This was done in order to weight the index towards the lower end of the range (severe threat). It is a conservative approach and tends towards a 'threat' designation.

The potential threat of human activity on the estuary is equivalent to the final grade for step 5. If the final grade is greater than 3 then it assumed that the estuary is 'not threatened'. If the estuary's health is determined to be 'not threatened' then the rest of the health assessment is ignored (Figure 2.1.2). If the final grade is less than 3, then the estuary is 'threatened' and the analysis moves onto the next stage of the TaCM: the Physical Mitigation Index.

2.1.2 Physical Mitigation Index

The Physical Mitigation Index is adapted from Ferreira's (2000) method, but excludes the heuristic matrixes. The aim of this component of the TaCM is to assess whether or not the estuary's physics will be able to mitigate the social-economic threats. If an estuary is well flushed then the pollutants and nutrients that are present in the estuary will have a short residence time. Such an estuary is less likely to be threatened than an estuary with a slow turnover (Pearce *et al.*, 1997). The Physical Mitigation Index consists of 2 steps.

Step 1:

The purpose of step 1 of the Physical Mitigation Index is to measure the estuary's ability to cope with pollution. The main assumption of this step is that anthropogenic inputs stem from the estuary's catchment. The estuary's freshwater residence time (Tr), estuary number (En), coastal exchange (Ce) and the proportion of time it is closed to the ocean (Co) are used to evaluate the estuary's mitigation potential (Ferreira, 2000). The Decision Support System, designed by Ferreira (2000), was used in this dissertation to generate these values. They can also be derived from the calculations provided below.

a) *Freshwater residence time*

The fresh water residence time (Tr) is calculated by dividing the freshwater volume in the estuary (Vf) by the freshwater inflow into the estuary (Q). The freshwater volume is derived from the mean salinity and the estuary volume. It is assumed that if the estuary has a long residence time, the pollutants will stay in the estuary for longer periods, and that they will be recycled internally. The equation for fresh water residence time is:

$$Tr = Vf / Q$$

Tr is expressed in days.

b) *Estuary number*

The estuary number (En) is an indicator of vertical stratification and is determined by dividing the freshwater inflow (Q) by the tidal prism (Tp). The tidal prism units are m^3 per unit time. Tp needs to be normalised by converting the tidal period to seconds. The equation for the estuary number is:

$$(En) = (Q / Tp) \times 100$$

En is therefore expressed as a percentage.

c) *Coastal Exchange*

The Coastal exchange (Ce) is the degree to which estuary is mixed with the adjacent coastal water. It is calculated by dividing the Tidal Prism (Tp) by the estuary volume (V). The equation for coastal exchange is:

$$Ce = Tp / V$$

Ce is expressed as a percentage.

These indicators are allocated grades of 5 (best case scenario) to 1 (worst case scenario), based on the classification scheme in Table 2.1.5 (Ferreira, 2000). In Table 2.1.5 the categories for estuary number were corrected, as they were not correct in Ferreira's (2000) paper (Ferreira, pers. com).

Table 2.1.5: Step 1 of the assessment of the estuarine system's mitigation potential (Ferreira, 2000).

Grade	**5**	**4**	**3**	**2**	**1**
Residence time (days)	<10	11-19	20-29	30-39	≥40
Estuary number (%)	≤1	2-10	11-25	25-100	>100
Coastal exchange (%)	≥70	69-36	35-11	10-2	≤ 1

<u>Step 2:</u>

The purpose of this step is to calculate an overall Mixing Index (Mi), and to include the period of time the mouth is closed to the ocean (Co), in the overall assessment of the estuary's mitigation potential. The reason for adding 'the period of time the mouth is closed' is because it verifies the mixing index's results. Mi and Co are described below.

a) *Mixing Index*

The purpose of the Mi is to provide a measure of the estuary's ability to mix the water column. Mi is the average of the residence time, estuary number and coastal exchange. The equation for Mi is therefore:

$$Mi = \frac{Tr+En+Ce}{3}$$

b) *Proportion of time closed to the ocean*

The purpose of this step is to verify the above indicators Tr, En and Ce. The period of time the mouth is open to the ocean significantly affects the values of these indicators. Therefore Co is an integral part of determining the final grade for the Physical Mitigation Index. Mi and Co are allocated grades of 5 (best case scenario) to 1 (worst case scenario), based on the classification scheme in Table 2.1.6a (Ferreira, 2000). These values are then averaged. The overall grade is classified using Table 2.1.6b. Table 2.1.6b uses integer rounding down of numbers.

Table 2.1.6a: Step 2 of the assessment of the estuarine system's vulnerability (Ferreira, 2000).

Grade	**5 (excellent)**	**4 (good)**	**3 (fair)**	**2 (low)**	**1 (bad)**
M_i	$M_i \geq 5$	$5 < M_i \geq 4$	$4 \geq M_i \geq 3$	$3 \geq M_i \geq 2$	$2 \geq M_i \geq 1$
Co	$Co = 0$	$0 < Co \leq 25$	$25 < Co \leq 50$	$50 < Co \leq 75$	$Co > 75$

Table 2.1.6b: Conversion table for the Physical Mitigation Index

Grade	**5 (excellent)**	**4 (good)**	**3 (fair)**	**2 (low)**	**1 (bad)**
Values	5	4.9-4	3.9-3	2.9-2	1.9-1

If the final value for step 2 is greater than 4, then the system is assumed to be at a medium to low risk of being threatened (Figure 2.1.3). This is because it is assumed an estuary with 'good' or 'excellent' flow characteristics is able to mitigate the socio-economic threats on the estuary. It follows that such an estuary is likely to have 'good' chemistry and biology.

If the final grade for step 3 is equal to 3, then the system is on the verge of being impacted upon, and is therefore likely to be given a high priority in terms of remediation. This is because efforts and expenditure on remediation of these human impacts are likely to 'save' the system, whereas efforts towards 'highly impacted' systems will frequently require long term commitment to achieve change.

If the final value for step 3 is less than 3, then the threatened system is at a high risk of being impacted upon and it is likely that that the chemistry and biology of the system will be impacted upon (Figure 2.1.3). If the finding at this stage of the assessment is that the system mitigates the social-economic factors then the subsequent steps in the TaCM's assessment are not deemed necessary, as it is assumed that the system is 'not threatened' (Figure 2.1.3). It should be borne in mind that the system is deemed 'not threatened' at this stage; it does not mean the system requires no further scrutiny. It does, however mean that in a list of several or many systems, it does not have a high priority in terms of immediate further work.

2.1.3 Chemical Impact Index

The aim of this step of the TaCM is to convey an image of the overall quality of the estuary (Richardson, 1997). There are numerous water quality indices (for example: Bhargava, 1983; Dinus, 1987; Dojlido *et al* 1994a, 1994b; Stambuk-Giljanovic, 1999) that have been developed for freshwater systems, but fewer have been developed for estuaries (for example: Cooper *et al.*, 1994; Engle *et al.*, 1994; Rizzo *et al.*, 1996; Richardson, 1997). The Chemical Impact Index was developed, by adapting Ferreira's (2000) method of assessing the eutrophication potential of the water. The Chemical Impact Index consists of two steps.

Step 1: Eutrophication and oxygen saturation

The purpose of the first step of the Chemical Impact Index is to access the water quality of the estuary by using the eutrophication potential and dissolved oxygen saturation as indicators.

Human pollutants can increase the phosphorus and nitrogen levels in estuaries, which may result in eutrophication (Dederen, 1992; McComb, 1995; Nixon, 1995; National Estuary Program a, b; Valiela *et al.*, 1997; Smith *et al.*, 1999). Human induced eutrophication (excessive buildup of nutrients in a water body) is becoming a serious global problem (Sweeting, 1994). One of the most serious implications of eutrophication (in terms of water use) is the increased risk of excessive algal growth (Ridge, *et al.*, 1995). Other characteristics of eutrophication include exhaustion of dissolved oxygen and fish-kills (Chen, 1970).

The Chemical Impact Index uses the nitrogen and phosphorus concentrations in the estuary as indicators of eutrophication. Nitrogen and phosphorus are the most common limiting nutrients to plant growth, in 'unimpacted' estuaries (Davies *et al*, 1998).

Nitrogen occurs in large quantities in nature. In water, nitrogen typically occurs in the form of nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) ions and as a large variety organic compounds containing nitrogen (for example: urea).

Nitrate is rarely abundant in natural waters because it is incorporated into cells and is chemically reduced by microbes and converted into atmospheric nitrogen. Nitrite is an intermediate in the interconversion of ammonia and nitrate (Davies *et al.*, 1998). Nitrite is toxic to aquatic organisms even at low concentrations (Davies *et al.*, 1998). When the nitrogen levels are assessed, the nitrite and nitrate concentrations are considered together because of the environmental conversion from one form to the other (DWAF, 1993). Nitrates are used mainly in the production of chemical fertilisers, and as oxidising agents in the chemical industry (Canadian water quality Guidelines, 1987).

In 'unimpacted' estuaries ammonia occurs in low concentrations. Ammonia occurs in water in either its free un-ionised form (NH_3) or as ammonium ions (NH_4^+). Ammonia (in its un-ionised form) is extremely toxic (Davies et al., 1998).

In the natural environment, inorganic phosphorus occurs almost entirely as the phosphate ion (PO_4^{3-}). In 'unimpacted' estuaries, immediately available Soluble Reactive Phosphorus (SRP) is seldom found in large quantities, as it is taken up by plants, or is absorbed onto suspendoids, or bonded to ions (for example: iron, aluminum and variety of organics) (Davies *et al.*, 1998). A large quantity of the total phosphorus that enters an estuary is absorbed onto sediments and a smaller fraction of the total load is dissolved in the water (Malan *et al.*, 2002). Therefore, most of the total phosphorus load is delivered to rivers and then into estuaries during storms when the discharge is high and scouring of bottom sediments and soil wash-off occurs (Verhoff *et al.*, 1982). It is important to realise that changes for example, in pH and conductivity resulting from altered discharge, may also affect the absorption/desorption equilibrium and thus the proportion of dissolved to bound phosphorus (Malan *et al.*, 2002).

In estuaries, the redox potential (N: P) is one of the most important factors affecting phosphorus exchange. This is because modifications in the redox potential result in change in the amount of phosphorus held in association with charged particles. N: P ratios were not used as a proxy for eutrophication in this dissertation, as there is still some controversy over its use (Allanson *et al.*, 1999).

The percentage saturation of dissolved oxygen is also used to determine the eutrophication potential of the estuary. This is because low oxygen events (anoxia and hypoxia) are symptoms of eutrophication, due to the loading of excess organic material. Low oxygen events may result in the death of organisms (for example: fish and oysters) living in the estuary (Diaz *et al.*, 1999), decrease the recruitment of fish stocks (Bagge *et al.*, 1990), and result in the loss of biodiversity (Baden *et al.*, 1990). The incidence of low oxygen events in estuaries seems to be increasing, due to increased human activities in estuarine catchments (NRC, 2000; Cloern, 2001).

The estuary's oxygen saturation is therefore used to indicate whether or not the estuary is experiencing anoxic conditions. The oxygen saturation value will fluctuate with modifications in temperature, salinity and height (Dunnette, 1979). The amount of oxygen available in the water determines what fauna and flora will survive in the estuary (Walski *et al.*, 1974), and is important for the preservation of aquatic ecosystems (Wepener *et al.*, unpubl.).

The eutrophication potential of the estuary's water is determined by the system's mass of nitrogen (Mw), mass of phosphorus (P) and the oxygen saturation (O_2%) of the water. The mass of nitrogen and phosphorus and the oxygen saturation value used in the case studies of this dissertation have been sourced from previous studies, such as Land Ocean Interaction and Coastal Zone (LOICZ) budgets. The oxygen saturation of the estuary's water can be deduced from the mean dissolved oxygen concentration, standardized using the mean temperature and salinity values (Ferreira, 2000). In this dissertation it was obtained from previous studies or from Ferreira's (2000) Equation Index. Mw, P and O_2 are allocated grades of 5 (best case scenario) to 1 (worst case scenario), based on the classification scheme in Table 2.1.7a (Ferreira, 2000). These values are then averaged using the following equation:

$$\text{I (eutrophication)} = \frac{(\text{Grade } M_w + \text{Grade P} + \text{Grade } O_2)}{3}$$

The overall grade is classified using Table 2.1.7b. Table 2.1.7b is rounded down using integer rounding down. The estuary has a low potential of becoming eutrophic if the grade for I (eutrophication) is greater than or equal to 3. This means that the water quality is in a 'good' state and the rest of the assessment is deemed unnecessary. If the grade for I (eutrophication) is less than or equal to 3, then the threatened system is likely to become eutrophic as it has a high nutrient content (Ferreira, 2000). If this occurs then the Biological Impact Index is completed (Figure 2.1.3).

Table 2.1.7a: Step 1 of the Chemical Impact Index (Ferreira, 2000; DWAF, 1999)

Grade	**5 (excellent)**	**4 (good)**	**3 (fair)**	**2 (low)**	**1 (bad)**
M_w (µmol/l)	$M_w \leq 10$	11-25	26-40	41-70	$M_w > 70$
Phosphate (P)(µg/l)	<5		5-25	25-250	>250
O_2 (%)	$O_2 \geq 80$	79-65	64-50	49-35	$O_2 < 35$

Table 2.1.7b: Conversion table for the Chemical Impact Index

Grade	**5 (excellent)**	**4 (good)**	**3 (fair)**	**2 (low)**	**1 (bad)**
Values	5	4.9-4	3.9-3	2.9-2	1.9-1

Step 2: Heavy metal concentrations in the sediment

The investigation of heavy metals in sediments is important as it allows the detection of pollutants that may be at undetectable concentrations in the water column (Davies *et al.*, 1991). Heavy metals, (for example cadmium, lead, copper and zinc) are typical components of marine and estuarine environments. Sewerage or industrial and municipal wastes introduce extra quantities of heavy metals into the estuary (Salomons *et al.*, 1984, and Lacerda, 1998). Increased levels of heavy metals in estuarine sediment are therefore good indicators of human induced pollution (Davies *et al.*, 1991 and Lord *et al.*, 1988). The consequence of heavy metal contaminants, on benthic organisms, may be either immediate or accumulative (Griggs *et al.*, 1977).

The purpose of this step is to examine the sediment using 4 different indicators to provide an overall measure of quality. This step does not form part of the calculation for the Chemical Impact Index. It is an extra step that considers the additional impact of Lead, Copper, Zinc and Cadmium the estuary's sediment. The reason these four heavy metals were chosen to represent sediment quality is because they are Environmental Protection Agency (EPA) priority pollutants (Guptu *et al.*, 1995).

If any of the heavy metal concentrations exceed Maximum permissible Metal and Inorganic content levels in estuarine sediment (Table 2.1.8, Table 2.1.9), they could negatively affect the health of the biota living in the estuary. Therefore the TaCM assumes that if any of the heavy metal concentrations in the estuary's sediment are above the Maximum permissible Metal and Inorganic content, the estuary's water quality is impacted upon.

Table 2.1.8: The Maximum permissible Metal and Inorganic content (mg/kg or ppm) in estuarine sediment. International guidelines (DWAF, 1995)

Heavy Metals	The Maximum permissible Metal and Inorganic content (mg/kg or ppm)
Lead	56
Copper	100
Zinc	185
Cadmium	2

Table 2.1.9: Is the concentration of X (heavy metals) above the Maximum permissible Metal and Inorganic concentration in the estuary's sediment?

Heavy Metals	YES	NO
Lead (Pb)		
Copper (Cu)		
Zinc (Zn)		
Cadmium (Cd)		

2.1.4 Biological Impact Index

The purpose of the Biological Impact Index is to determine whether or not the fauna and flora living in the estuary are healthy. The state of the biota living in the estuary will be directly related to its water and sediment quality (Davies *et al.*, 1998).

Organisms living in an estuary are adapted to the original ambient concentrations of water quality variables in the estuary. Changes in water quality are likely to impact on different organisms in different ways, as some organisms have a higher resistance to change. This means that changes in water quality may result in hardier organisms taking over the habitats of more vulnerable species. This can result in the loss of key species, therefore decreasing the biodiversity of the estuary (Davies *et al.*, 1998). Poor water quality can also lead to growth deficiencies, lowered reproduction, changes in feeding habits, changes in respiration patterns; changes in moulting patterns, shell deformation, bioaccumulation, diseases and mortality of the organisms living in the estuary (DWAF, 1995).

Due to the fact that affects on the biology are a manifestation of degraded water quality it was decided that it was unnecessary to develop a quantitative index. Therefore the Biological Impact Index is a discussion that uses birds, fish, benthic biota and vegetation as indicators of ecosystem health. If the biodiversity of the birds, fish, benthic biota and vegetation has decreased, then the estuary's health has been negatively impacted upon. If there are any other signs of ill health (for example lesions in fish), then the biota's health is impacted upon. If the biodiversity of the birds, fish and vegetation in the estuary have increased or stayed the same over time and the biota are in 'good' health, it is assumed the estuary is 'not impacted'.

The Species Richness statistic is used in this index to represent the total number of species present in the estuary. The Shannon diversity statistic is used in this index to quantify the 'evenness of species' populations (Turpie, 1995).

All the indicators in the TaCM were weighted equally. The reason for this was to 'keep it simple' based on the Ockham's Razor, or Parsimony principle.

2.2 Testing the Threat and Cascade Method

2.2.1 Pseudo Tests

The purpose of this step was to test the robustness of the Threat and Cascade Method. In order for it to be robust (over a range of systems), it should be possible to get the whole spectrum of grades (1-5) as final results in each index. The Socio-Economic Threat Index, Physical Mitigation Index and the Chemical Impact Index were tested using Matlab (Appendix II for script). The qualitative Biological Impact Index was not tested because it does not contain an algorithm. The Matlab script was used to enter every possible combination of the series 1:5 into the algorithm for the Socio-Economic Threat Index, Physical Mitigation Index and the Chemical Impact Index. The assumption made here is that each grade (1:5) has an equal chance of being an input into the TaCM. The outputs were then used to find the number of outputs equal to each grade. These values were entered into Microsoft Excel, where the number of times a grade occurred was divided by the total outputs and then multiplied by 100 to get the percentage chance of obtaining the number (Appendix II). This method of testing is known as the explanation approach (Evan et al., 2004).

The Socio-Economic Threat Index was also tested using real life scenarios. They were based on existing estuaries but some of the variables were estimated. The Humber estuary (United Kingdom), Coatzacoalcos estuary (Mexico) and Tomales Bay (California, U.S.A.) were used to simulate the scenarios (Appendix III).

2.3 Case Studies

The TaCM was applied to 3 estuarine systems.

1. Knysna Estuary, South Africa
2. Swartkops Estuary, South Africa
3. Chesapeake Bay, USA

These 3 systems were chosen because they had existing data sets available precluding the need to make field visits. The Threat and Cascade Method can be used on other systems because if need be, the data can be collected and measured. In fact, this exercise is in itself valuable since it establishes a data baseline.

Secondary data of all the variables for each estuary were collected from published literature and from databases on the Internet. This was a cost effective method for the purpose of a verification or testing exercise.

All 3 case studies were also used to test if the TaCM could be used as a predictive tool. In order to test if the TaCM could predict what impact 'change' would have on the estuary, the parameter values were changed. All 3 case studies were at risk of being impacted upon by human activities in the catchment. It was assumed that if their physics were changed to 'fair' physics they would be impacted upon by the human activities in the catchment. The physics of the 3 case studies were changed to 'fair' physics by reducing the inflow of freshwater to $0.2m^3/s$ and by changing the percentage time the estuary was open to the sea to 50%. These values were entered into Ferreira's Equation Index software (Ferreira, 2000) in order to produce the results.

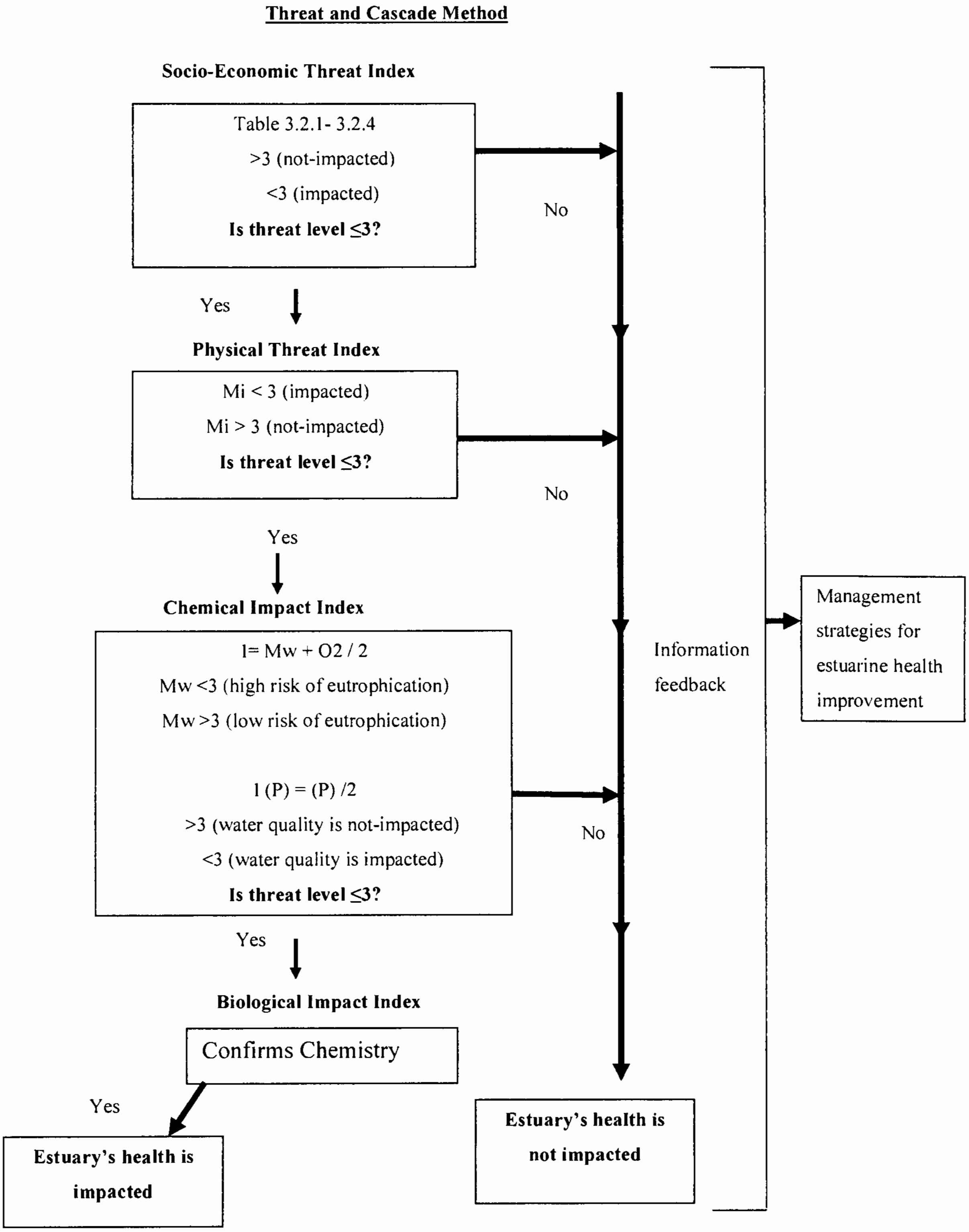


Figure 2.1.3: A flow Chart of the Threat and Cascade Method of estuarine health assessment.

Chapter 3: Results

This chapter describes the results derived from testing the TaCM and from applying it to 3 case studies.

3.1 Pseudo Tests

The results of the Matlab Script that were entered into Microsoft Excel and converted to percentages (Appendix II) are presented in Table 3.1.1.

Table 3.1.1: The percentage chance of obtaining the grades 5, 4, 3, 2, and 1 as final results in the Socio-Economic Threat Index, Physical Mitigation Index and the Chemical Impact Index when using a randomly chosen estuary from a continuum.

Grade	**5**	**4**	**3**	**2**	**1**
Socio-Economic Threat Index (%)	2.56×10^{-4}	5.49	45.42	44.20	4.79
Physical Mitigation Index (%)	20	20	20	20	20
Chemical Impact Index (%)	20	20	20	20	20

These results, presented in Table 3.1.1, are based on the assumption that there is an equal chance of each grade being input into the socio-economic, physical and chemical indices. The results show that the chance of obtaining each grade (5, 4, 3, 2, and 1) as an answer, to the Chemical Impact and Physical Mitigation indices, was equal (Table 3.1.1). They also show that the chance of obtaining each grade as an answer to the Socio-Economic Threat Index was not equal (Table 3.1.1). The implications of this are explained in the discussion. The results showed that the grade that would most likely occur as an answer to the Socio-Economic Threat Index was a grade of 3 (moderate threat) (Table 3.1.1). The second most likely result, to the Socio-Economic Threat Index, was a grade of 2 (high threat) (Table 3.1.1). The third most likely result, to Socio-Economic Threat Index, was a grade of 4 (low threat) (Table 3.1.1). The most unlikely result that would occur as an answer to the Socio-Economic Threat Index is a value of 5 (pristine) (Table 3.1.1).

3.2. Case Studies

Table 3.2.1 provides a summary of the data collected for the 3 estuaries that were used to test the TaCM. The data was collected from published literature.

Table 3.2.1: Input data for the Socio-Economic Threat Index for 3 different estuaries

Estuary	**Knysna Estuary**	**Swartkops Estuary**	**Chesapeake Bay**
Catchment area (km^2)	400	1400	160000
Mean Estuary Volume (m^3)	32.02×10^6	12×10^6	7400×10^6
Surface area (km^2)	48	4	11000
Population density per km^2	40	714.29	108.02
Natural land use (%)	69	77	57.4
Agricultural land use (%)	28	14	33.5
Developed land use (%)	3	9	8.4
Cleared land use (%)	31	23	42.6
GNI (@PPP) ($)	4058.04	766-3035	33332 -36442
% mean annual rainfall stored in impoundments		17	
Modal river inflow (m^3/s)	1.44	1.09	113.1
Mean Tidal range (m)	1.8	1.4	0.9
Mean Chlorophyll a (µg/l)	2.16	6.5	9.032
Mean Salinity	33	26.17	14.03
Mean water temperature (^{0}C)	17.80	20.08	18.24
Mean Dissolved Oxygen (mg/l)	6.76	6.25	7.87
Oxygen saturation (%)	82-97	65-80	80

The references for the Knysna Estuary's data are: Allanson, 2000; Allanson *et al.*, 2000a; Largier *et al.*, 2000; Department of Environmental Affairs and Tourism, 2001a; Knysna Municipality, 2002; Switzer *et al.*, 2002, 2003; and Switzer, 2003. The references for the Swartkops Estuary's data are: Reddering *et al.*, 1981; Baird *et al.*, 1986; Horenz, 1987; Baird, 2001b; Department of Environmental Affairs and Tourism, 2001b; Scharler *et al.*, 2003; Harrison, 2004; and Statistics South Africa, 2005. The references for Chesapeake Bay's data are Smith *et al.*, 1999; Castro *et al.*, 2003; Whitford, 1999; Jung *et al.*, 2003; and Harding *et al.*, 2005.

3.2.1 Knysna Estuary

The TaCM results for the Knysna Estuary are shown below.

Socio-Economic Threat Index

Figure 3.2.1 shows the results of a land use survey, conducted by the Council for Scientific and Industrial Research (CSIR), of the Knysna Estuary's catchment (Department of Environmental Affairs and Tourism, 2001a). These values were used to perform step 1 and step 2 of the Socio-Economic Threat Index for the Knysna Estuary.

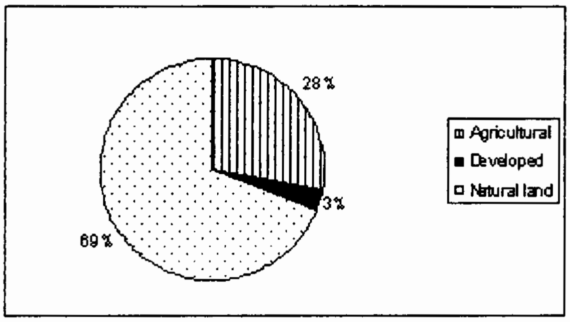


Figure 3.2.1: A pie chart of the land use in the Knysna Estuary's catchment.

The values or descriptions of all the indicators that were used to grade the Knysna Estuary's Socio-Economic Threat Index are included in Table 3.2.2. The calculations and appropriate grades for all the steps of the Knysna Estuary's Socio-Economic Threat Index are provided in Table 3.2.3.

Table 3.2.2: A table consisting of the Knysna Estuary's Socio-Economic Threat Index's variable values and their appropriate grades.

Variable	Quantity/ description	Grade
Cleared land-use (%)	31	2 (Table 2.1.1)
Developed land use, human population density (DP)	40 people per square kilometre 3 % developed land	2 (Table 2.1.2)
Wealth (GNI) ($)	4058.04	3 (Table 2.1.2)
State of mouth (Sm)	Mouth opens on a completely natural cycle	5 (Table 2.1.3)
Encroachment of surrounding development and agriculture (Ed)	Very high (<25% untransformed)	1(Table 2.1.3)
Catchment Hydrology (Ch)	<50% mean annual runoff (MAR) abstracted	3 (Table 2.1.3)
Estuary use (Eu)	Extractive activities include dredging, moderate aquaculture, habitat modifying fishing methods	2 (Table 21.3)
Sewerage or sewerage effluent flow (Sw)	Moderate (2000 m^3/day)	3 (Table 2.1.3)

The references for the data are Reddering *et al.*, 1981, Marker, 1999; and Prochazka *et al.*, 2002a.

Table 3.2.3: A table consisting of the calculations and grades for each step of Knysna's Socio-Economic Threat Index

Step	Calculation	Grade
Step 1	Cleared land	2 (Table 2.1.1)
Step 2	(DP +GNI) /2	2 (Table 2.1.2)
Step 3	(Sm + Ed + Ch + Eu +Sw) / 5)	2.8 (Table 2.1.3)
Step 4	The average of step 1, 2 and 3, rounded down using Table 2.1.5.	**2**

As can be seen in Table 3.2.3, the overall potential socio-economic threat on the Knysna Estuary was graded as 2 (High Threat).

The Physical Mitigation Index was completed because the Socio-Economic Threat Index's grade was less than 3 (Figure 2.1.3).

Physical Mitigation Index

Ferreira's Equation Index Software (Ferreira, 2000) was used to generate the data needed for the Physical Mitigation Index. The results of the assessment of the Knysna Estuary's physics are presented in Table 3.2.4. Table 2.1.5 was used to give grades to the Knysna Estuary's flow characteristics (physics).

Table 3.2.4: A table containing the appropriate grades for the physical aspects of Knysna Estuary.

Variable	Quantity	Grade
Fresh water Residence Time (Tr) (days)	14.71	4 (Table 2.1.5)
Estuary Number (En) (%)	0.04	5 (Table 2.1.5)
Coastal Exchange (Ce) (%)	269	5 (Table 2.1.5)
Mixing Index (Mi)	$Mi = \frac{Tr+En+Ce}{3}$ $= \frac{4+5+5}{3}$ $= \mathbf{4.7}$	4 (Table 2.1.6a)
Percentage of time the mouth is closed to the ocean (Co)	0 (Switzer *et al.*, 2002)	5(Table 2.1.6a)
Overall Grade	Overall grade $= \frac{(Co+ Mi)}{2}$ $= \frac{(5+4)}{2}$ $= 4.5$ $= \mathbf{4}$	**4** (rounded down by Table 2.1.6b)

As can be seen in Table 3.2.4, the overall grade for the Knysna Estuary's flow characteristics is 4. Table 2.16b classifies Knysna's flow characteristics as 'good' physics. Due to the fact that the Physical Mitigation Index was given a grade greater than 3, the TaCM assumed that the physics of the Knysna Estuary were able to mitigate the socio-economic threats on the estuary and the assessment of the estuary's health was considered complete (Figure 2.1.3). In order to test if the methodology analysis of the estuary's health was correct, the rest of the assessment was completed.

Chemical Impact Index

For step 1 of the Chemical Impact Index, the nitrogen and phosphorus concentrations (Table 3.2.5), in the Knsyna Estuary's water column, were taken from Switzer *et al.* (2002). The oxygen saturation value (Table 3.2.5) was taken from Allanson *et al.* (2000a).

Table 3.2.5: Knysna Estuary's water chemistry (Switzer *et al.*, 2002)

Variable	Whole System	Grade
Average Dissolved Inorganic Phosphorus (DIP) (mmol/m^3)	2.1	2 (Table 2.1.7a)
Average Dissolved Inorganic Nitrogen (DIN) (mmol/m^3)	8.95	5 (Table 2.1.7a)
Oxygen Saturation (%)	82-97	5 (Table 2.1.7a)
Eutrophication Potential		**4** (Table 2.1.7a)

As can be seen in Table 3.2.5, the eutrophication potential of the Knysna Estuary was graded as 4. The TaCM therefore classifies the estuary water quality as 'not impacted' (Figure 2.1.1).

For step 2 of the Chemical Impact Index, the heavy metal concentrations that were analysed were taken from Allanson *et al.* (2000a) research. They are included in Table 3.2.6. When these values were compared with Table 2.1.9 it was found that none of the heavy metal concentrations analysed were above the maximum permissible level.

Table 3.2.6: Table of concentrations of the heavy metals found in the Knysna Estuary's sediments (Allanson *et al.*, 2000a)

Heavy Metals	**Pb**	**Cu**	**Zn**	**Cd**
Mean concentration (μg/g)	8.15	2.60	19.60	0.72

Biological Impact Index

The Knysna Estuary's biology, at the time of this assessment, was generally in 'good' health and it had a high biodiversity of species living in the estuary.

Waterbirds

At the time of this assessment the Knysna Estuary had a relatively large population of birds visiting the estuary (Turpie, 1995). Turpie (1995) found that even though the estuary's waterbird population density was high, it was not as high as it should have been.

Botany

The Knysna Estuary had a relatively high abundance and biodiversity of plants (Colloty *et al.*, 2000). Marker (2003) found that the supratidal area in the estuary's catchment had decreased by 60%. Therefore the number of plants present in the estuary's catchment had decreased.

Fish

The Knysna Estuary had a relatively high abundance and biodiversity of fish living in the estuary (Maree *et al.*, 2003). The fish were established to be in 'good' health as there was no evidence of disease.

Benthic organisms

In 1997 Allanson *et al.* (2000b) compared the diversity, distribution and density of the benthic macrofauna to those of Day *et al.*'s in 1952. Allanson *et al.* (2000b) established that there was no difference between species richness of the benthic macrofauna in that time. Allanson *et al.* (2000b) also found that the species diversity of the benthic macrofauna had increased significantly in the Zostera zone sediments between 1952 and 1997 (Allanson *et al.*, 2000b).

Summary

Table 3.2.7 provides a summary of the overall results from the socio-economic, physical, chemical and biological assessment of the Knysna Estuary.

Table 3.2.7: A summary of the overall results from the socio-economic, physical, chemical and biological assessment of the Knysna Estuary

	Overall Grade	**Classification**
Socio-Economic Threat Index	2	High threat
Physical Mitigation Index	4	Good
Chemical Impact Index	4	Good
Biological Impact Index		Good

3.2.2 Swartkops Estuary

The TaCM results for the Swartkops Estuary are shown below.

Socio-Economic Threat Index

Figure 3.2.2 shows the results of a land use survey by the CSIR (2001) of the Swartkops Estuary's catchment (Department of Environmental Affairs and Tourism, 2001b). These values were used to perform step 1 and step 2 of the Socio-Economic Threat Index for the Swartkops Estuary.

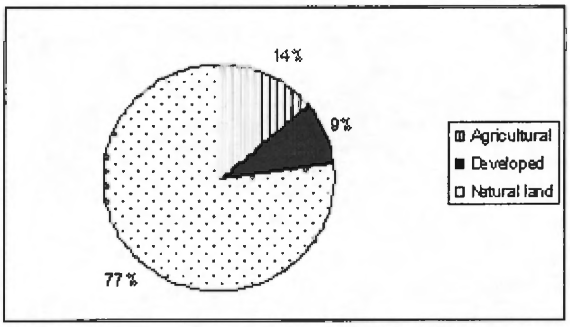


Figure 3.2.2: A pie chart of the land use in the Swartkops Estuary's catchment

The values or descriptions of all the indicators that were used to grade Swartkops Estuary's Socio-Economic Threat Index are included in Table 3.2.8. The calculations and appropriate grades for all the steps of the Swartkops Estuary's Socio-Economic Threat Index are provided in Table 3.2.9.

Table 3.2.8: A table consisting of the Swartkops Estuary's Socio-Economic Threat Index's variable values and their appropriate grades.

Variable	Quantity/ description	Grade
Cleared land-use (%)	23	3 (Table 2.1.1)
Developed land use, human population density (DP)	714 people per kilometre squared 9 % developed land	2 (Table 2.1.2)
Wealth (GNI) ($)	766-3035	3 (Table 2.1.2)
State of mouth (Sm)	Mouth opens on a completely natural cycle	5 (Table 2.1.3)
Encroachment of surrounding development and agriculture (Ed)	Very high (<25% untransformed)	1 (Table 2.1.3)
Catchment Hydrology (Ch)	No dams or significant impoundments, some abstraction <25% MAR abstracted	4 (Table 2.1.3)
Estuary use (Eu)	Extractive activities include dredging, extensive aquaculture, habitat modifying fishing methods	1 (Table 2.1.3)
Sewerage or sewerage effluent flow (Sw)	Very high (14 m^3/day)	1 (Table 2.1.3)

The references for the data are Baird *et al.*, 1988; Whitfield, 2000; Prochazka *et al.*, 2002a; and Rogers, 2005.

Table 3.2.9: A table consisting of the calculations and grades for each step of Swartkops' Socio-Economic Threat Index.

Step	Calculation	Grade
Step 1	Cleared land	3 (Table 2.1.1)
Step 2	(DP +GNI) /2	2.5 (Table 2.1.2)
Step 3	(Sm + Ed + Ch + Eu +Sw) / 5)	2.4 (Table 2.1.3)
Step 4	The average of step 1, 2 and 3, rounded down using Table 2.1.5.	**2**

As can be seen in Table 3.2.9, the potential socio-economic threat on the Swartkops Estuary was graded as 2 (High Threat).

The Physical Mitigation Index was completed because the Socio-Economic Threat Index was given a grade of less than 3 (Figure 2.1.3).

Physical Mitigation Index

Ferreira's Equation Index Software (Ferreira, 2000) was used to generate the data needed for this step. The results of assessment of Swartkops Estuary's physics are presented in Table 3.2.10. Table 2.1.5 was used to give grades to the Swartkops Estuary's flow characteristics (physics).

Table 3.2.10: A table containing the appropriate grades for the physical aspects of the Swartkops Estuary.

Variable	**Quantity**	**Grade**
Fresh water Residence Time (Tr) (days)	32	2 (Table 2.1.5)
Estuary Number (En) (%)	0.41	5 (Table 2.1.5)
Coastal Exchange (Ce) (%)	47	4 (Table 2.1.5)
Mixing Index (Mi)	$Mi = \frac{Tr+En+Ce}{3}$ $= \frac{2+5+4}{3}$ $= 3.7$	3 (Table 21.6a)
Percentage of time the mouth is closed to the ocean (Co)	0 (Whitfield, 2000)	5 (Table 2.1.6a)
Overall Grade	$\text{Overall grade} = \frac{(Co+Mi)}{2}$ $= \frac{(5+3)}{2}$ $= \mathbf{4}$	4 (Table 2.1.6b)

As can be seen in Table 3.2.10, the overall grade for the Swartkops Estuary's flow characteristics is 4. Table 2.16b classifies the Swartkops Estuary's flow characteristics as 'good'. Due to the fact that the Physical Mitigation Index was given a grade greater than 3, the TaCM assumes that the physics of the Swartkops Estuary would be able to mitigate the socio-economic threats on the estuary and the estuary's health assessment was considered complete (Figure 2.1.3). In order to test if the methodology's analysis of the estuary's health was correct, the rest of the assessment was completed.

Chemical Impact Index

For step 1 of the Chemical Impact Index, the nitrogen and phosphorus concentrations (Table 3.2.11), in the Swartkops Estuary's water column, were taken from Baird (2001b). The oxygen saturation value (Table 3.2.11) was taken from Harrison (2004).

Table 3.2.11: The Swartkops Estuary's water chemistry.

Variable	Whole System	Grade
Average Dissolved Inorganic Phosphorus (DIP) (μM)	2.4	2 (Table 2.1.7a)
Average Dissolved Inorganic Nitrogen (DIN) (μM)	21	5 (Table 2.1.7a)
Oxygen Saturation (%)	65-80	5 (Table 2.1.7a)
Eutrophication Potential		4 (Table 2.1.7b)

The references for the data are Baird, 2001b; and Harrison, 2004

As can be seen in Table 3.2.11, the eutrophication potential of the Swartkops Estuary was graded as 3. The TaCM therefore classifies the estuary water quality as 'impacted' (Figure 2.1.1).

For step 2 the heavy metal concentrations that were analysed were taken from Binning *et al.* (2001). They are included in Table 3.2.12. When these values were compared with Table 2.1.9 it was found that none of the heavy metal's concentrations, in Swartkops Estuary's sediment, were above the maximum permissible level.

Table 3.2.12: Mean heavy metal concentrations in the Swartkops Estuary's sediment (Binning *et al.*, 2001).

Heavy Metals	**Pb**	**Cu**	**Zn**	**Cd**
Mean concentration (μg/g)	32.9	6.8	35.9	

Biological Impact Index

The Swartkops Estuary's biology, at the time of this assessment, was generally in 'good' health and it had a high biodiversity of species living in the estuary.

Waterbirds

The Swartkops Estuary's waterbird population had a high species richness (33) and abundance (3131) and the Shannon diversity index (H) was high (1.02) (Turpie, 1995).

Botany

At the time of this assessment the Swartkops Estuary had a high biodiversity and abundance of plants. It had the third largest salt marsh area in South Africa (Colloty *et al.*, 2000). Colloty *et al.* (2000) found that the supratidal salt marsh area had been reduced by 88% and the intertidal salt marsh area had been reduced by 23% (Colloty *et al.*, 2000). Therefore the amount of plants present in the estuary's catchment had decreased.

Fish

Strydom *et al.* (2003) found that the Swartkops Estuary had the highest species richness and diversity of early stage fish living in the estuary (Strydom *et al.*, 2003), when it was compared to 11 warm temperate estuaries along the Eastern Cape coast, in South Africa. The fish were found to be in 'good' health as there was no evidence of disease.

Summary

Table 3.2.13 provides a summary of the overall results from the socio-economic, physical, chemical and biological assessment of the Swartkops Estuary.

Table 3.2.13: A summary of the overall results from the socio-economic, physical, chemical and biological assessment of the Swartkops Estuary.

	Overall Grade	Classification
Socio-Economic Threat Index	2	High Threat
Physical Mitigation Index	4	Good
Chemical Impact Index	3	Fair
Biological Impact Index		Good

3.2.3 Chesapeake Bay

The results of the TaCM's assessment of Chesapeake Bay are shown below.

Socio-Economic Threat Index

Figure 3.2.3 shows the percentages of natural, agricultural and urban land use in Chesapeake Bay's catchment area (Castro *et al.*, 2003). These values were used to perform step 1 and step 2 of the Socio-Economic Threat Index for Chesapeake Bay.

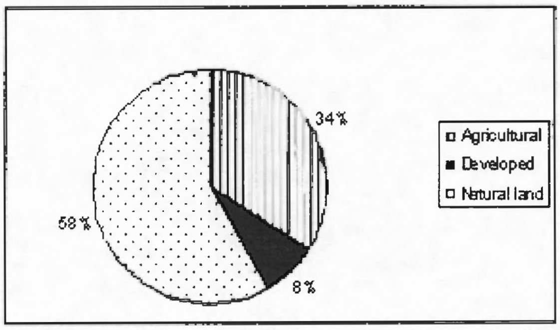


Figure 3.2.3: A pie chart of the land use in the Chesapeake Bay's catchment.

Table 3.2.14 gives the values and descriptions of all the indicators that were used to grade Chesapeake Bay's Socio-Economic Threat Index. Table 3.2.15 provides the calculations and appropriate grades for all the steps of Chesapeake Bay's Socio-Economic Threat Index.

Table 3.2.14 Variable quantities in the Chesapeake Bay's Socio-Economic Threat Index

Variable	Quantity/ description	Grade
Cleared land-use (%)	43	2 (Table 2.1.1)
Developed land use, human population density (DP)	108 people per kilometre squared 8 % developed land	2 (Table 2.1.2)
Wealth (GNI) ($)	33332 -36442	1 (Table 2.1.2)
State of mouth (Sm)	Mouth opens on a completely natural cycle	5 (Table 2.1.3,)
Encroachment of surrounding development and agriculture (Ed)	Very high (<25% untransformed)	1 (Table 2.1.3)
Catchment Hydrology (Ch)	Dams and impoundments, significant abstraction modifying natural flows >75% MAR abstracted	1(Table 2.1.3)
Estuary use (Eu)	Extractive activities include dredging, extensive aquaculture, habitat modifying fishing methods.	1 (Table 2.1.3)
Sewerage or sewerage effluent flow (Sw)	Very high	1 (Table 2.1.3)

The references for the data are Karuppiah *et al.*, 1998; Castro *et al.*, 2003; Morgan *et al.*, 2001; and US Census Bureau, 2005.

Table 3.2.15: A table consisting of the calculations and grades for each step of Chesapeake Bay's Socio-Economic Threat Index.

Step	Calculation	Grade
Step 1	Cleared land	2 (Table 2.1.1)
Step 2	(DP +GNI) /2	1.5 (Table 2.1.2)
Step 3	(Sm + Ed + Ch + Eu +Sw) / 5)	1.8 (Table 2.1.3)
Step 4	The average of step 1, 2 and 3, rounded down using Table 2.1.5	1 (Table 2.1.3)

As can be seen in Table 3.2.15, the potential socio-economic threat on Chesapeake Bay was graded as 1 (Severe Threat).

The Physical Mitigation Index was completed because the Socio-Economic Threat Index was given a grade of less than 3 (Figure 2.1.3).

Physical Mitigation Index

Ferreira's Equation Index software (Ferreira, 2000) was used to generate the data needed for this step. The results of assessment of Chesapeake Bay's physics are presented in Table 3.2.16. Table 2.1.5 was used to give grades to the Chesapeake Bay's flow characteristics (physics).

Table 3.2.16: A table containing the appropriate grades for the physical aspects of Chesapeake Bay.

	Quantity	**Grade**
Fresh water Residence Time (Tr) (days)	454	1 (Table 2.1.5)
Estuary Number (En) (%)	0.05	5 (Table 2.1.5)
Coastal Exchange (Ce) (%)	134	5 (Table 2.1.5)
Mixing Index (Mi)	$Mi = \frac{Tr+En+Ce}{3}$ $= \frac{1+5+5}{3}$ $= \mathbf{3.7}$	3 (Table 2.1.6a)
Percentage of time the mouth is closed to the ocean	0 (Chesapeake Bay Program, 2000)	5 (Table 2.1.6a)
Overall Grade	Overall grade $= \frac{(Mi+Co)}{2}$ $= \frac{(3+5)}{2}$ $= \mathbf{4}$	4 (Table 2.1.6b)

As can be seen in Table 3.2.16, the overall grade for the Chesapeake Bay's flow characteristics is 4. Table 2.16b classifies Chesapeake Bay's flow characteristics as 'good' physics. Due to the fact that the Physical Mitigation Index was given a grade greater than 3, the TaCM assumed that the physics of Chesapeake Bay were able to mitigate the socio-economic threats on the estuary and the estuary's health assessment was considered complete (Figure 2.1.3). In order to test if the methodology analysis of the estuary's health was correct, the rest of the assessment was completed.

Chemical Impact Index

For step 1 of the Chemical Impact Index the nitrogen and phosphorus concentrations (Table 3.2.17), in Chesapeake Bay's water column, were taken from Smith *et al.* (1999). The oxygen saturation value (Table 3.2.17) was taken from Jung *et al.*, 2003.

Table 3.2.17: Chesapeake Bay's DIN and DIP concentrations and oxygen saturation.

	Whole System	Grade
Average Dissolved Inorganic Phosphorus (DIP) (mmolm^{-3})	0.33	3 (Table 2.17a)
Average Dissolved Inorganic Nitrogen (DIN) (mmolm^{-3})	21.5	4 (Table 2.17a)
Oxygen Saturation (%)	80	4(Table 2.17a)
Eutrophication Potential		3 (Table 2.17b)

The references for the data are Smith *et al.*, 1999; Jung *et al.*, 2003; and Harrison, 2004.

As can be seen in Table 3.2.17, the eutrophication potential of Chesapeake Bay was graded as 3 (fair). The TaCM therefore classifies the estuary water quality as 'impacted' (Figure 2.1.1).

For step 2 the heavy metal concentrations that were analysed, were taken from Maryland Department of Natural Resources (2005). They are included in Table 3.2.18. When these values were compared with Table 3.1.9, it was found that all of the heavy metal concentrations, except cadmium, that were analysed were above the maximum permissible level.

Table 3.2.18: The heavy metal concentrations in Chesapeake Bay's sediment (Maryland Department of Natural Resources, 2005)).

	Zn	Pb	Cu	Cd
Concentration (ppm)	500	150	120	0.49

Biological Impact Index

Chesapeake Bay was extremely productive, when compared with many other estuaries, with respect to level of fishery resources and primary production (Nixon, 1988; Houde *et al.*, 1999). There were approximately 350 species of fish living in the Bay (Stone *et al.*, 1994; Murdy *et al.*, 1997; Chesapeake Bay Program, 2000). However, at the time if the assessment the biota were generally in poor health.

Waterfowl

At the time of this assessment, there was already a decline in the number of birds that usually visited or lived in the estuary's catchment. This was due to habitat loss and over harvesting of fish in the bay (Officer *et al.*, 1984; Lubbers *et al.*, 1990).

Fish

At the time of this assessment, there was already a decline in the biodiversity of fish living in the bay. Commercially valuable fish had already been lost (Officer *et al.*, 1984, Lubbers *et al.*, 1990). Some of the fish that were living in Chesapeake Bay had lesions and diseases (Morgan *et al.*, 2001; University of Maryland, 2003). Pathogenic micro-organisms had been detected in several species of shellfish such as *Crassostrea virginica* (Fayer *et al.*, 1998) and mussels (*Ischadium recurvum*) in the Chesapeake Bay (Giangaspero *et al.*, 2005).

Botany

At the time of this assessment there had already been a decline in the biodiversity of plants living in the estuary. The amount of submerged aquatic vegetation in Chesapeake Bay had also significantly decreased (Orth *et al.*, 2002; Kemp *et al.*, 1983; Dennison *et al.*, 1993; Stevenson *et al.*, 1993). There had also been an increase in phytoplankton biomass in the estuary (Malone *et al.*, 1988, Harding 1994). High phytoplankton biomass is symptomatic of eutrophication (Norton *et al.*, 2000)

Benthic organisms

The abundance of benthic macrophytes living in the estuary had already declined (Cloern, 2001).

Summary

Table 3.2.19 provides a summary of the overall results from the socio-economic, physical, chemical and biological assessment of Chesapeake Bay.

Table 3.2.19: A summary of the overall results from the socio-economic, physical, chemical and biological assessment of Chesapeake Bay

	Overall Grade	**Classification**
Socio-Economic Threat Index	1	Severe Threat
Physical Mitigation Index	4	Good
Chemical Impact Index	3	Fair
Biological Impact Index		Poor

Figure 3.2.4 is a basic schematic of the TaCM assessment of the health of the Knysna Estuary, the Swartkops Estuary and Chesapeake Bay. The schematic shows that the Knysna Estuary, the Swartkops Estuary and Chesapeake Bay are threatened by the human activities that are currently occurring in their catchments. It also shows that the physics of the systems should be able to mitigate the socio-economic threats imposed on the estuary

TaCM

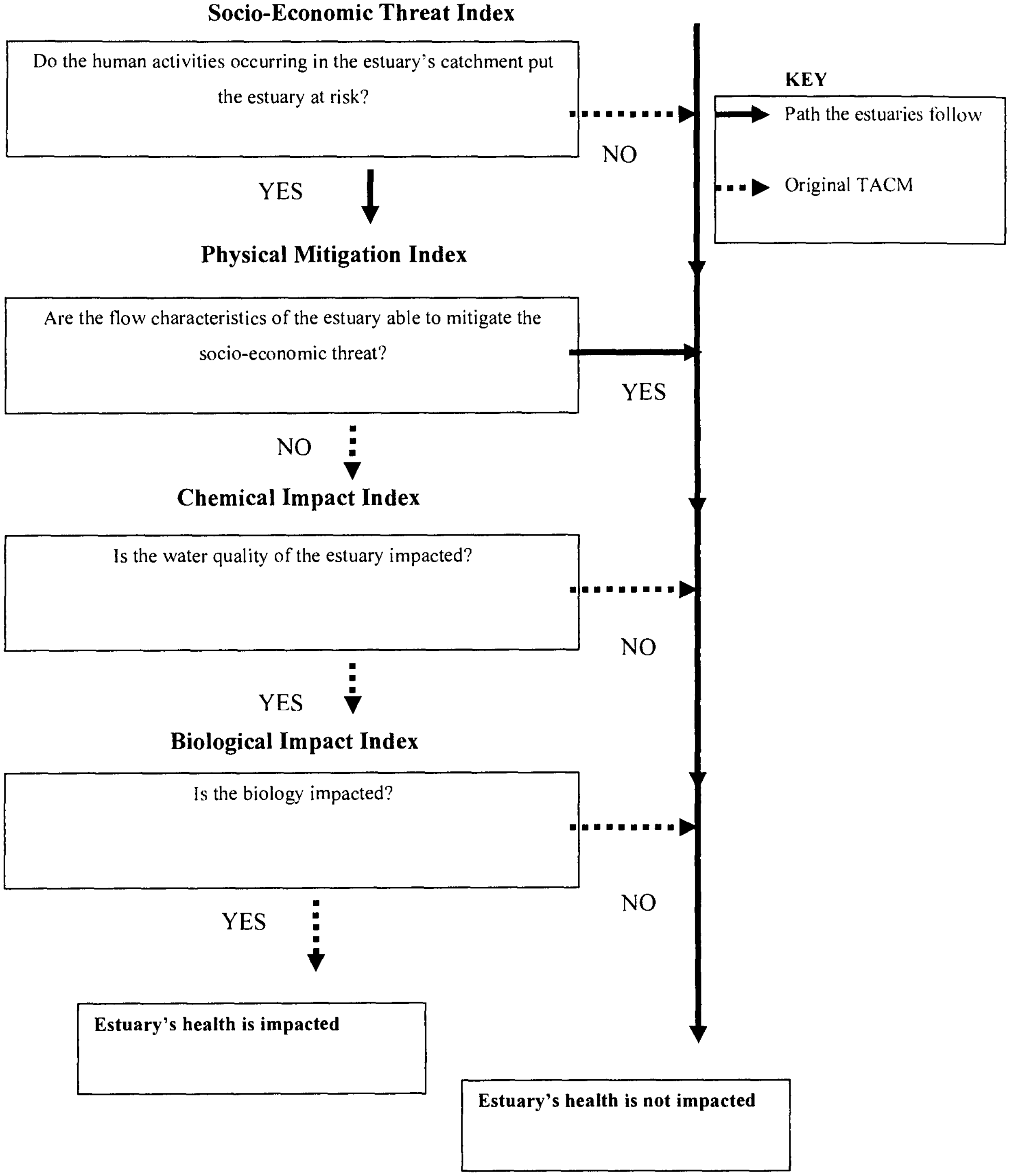
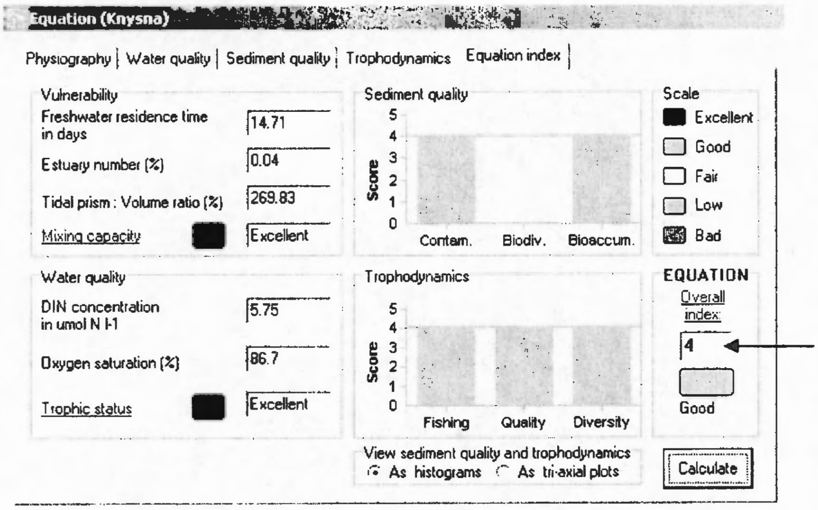


Figure 3.2.4: Basic schematic of the path the Knysna Estuary, the Swartkops Estuary and Chesapeake Bay follow, when being analysed by the Threat and Cascade Method of estuarine health assessment.

3.2.4 Predictive tool

The case studies were also used to test whether or not the TaCM can be used as a predictive tool. Ferreira's Equation Index Software was used to produce the changes that would occur if all 3 case studies' physics were changed to 'fair' physics. The results of these tests are presented in Figures 3.2.5a and b, 3.2.6a and b and 3.2.7a and b. The figures are screen shots of the Equation Index. The arrows point to the Equation Index's overall result.

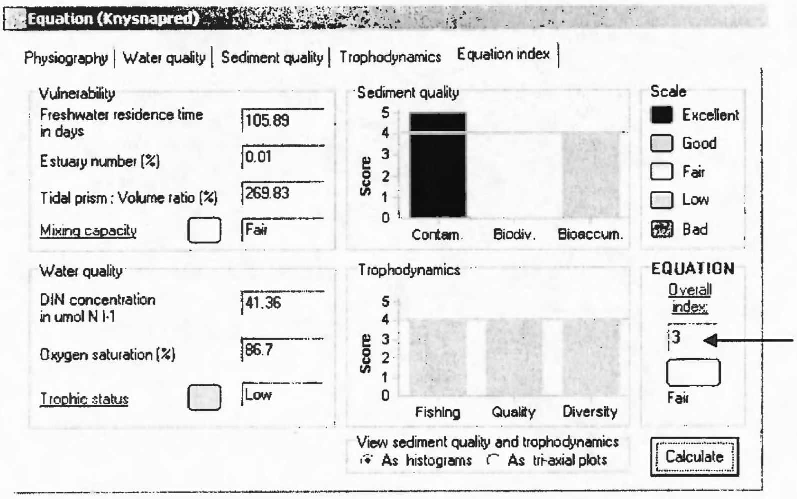

Equation (Knysna)

Vulnerability
Freshwater residence time in days: 14.71
Estuary number (%): 0.04
Tidal prism : Volume ratio (%): 269.83
Mixing capacity: Excellent

Water quality
DIN concentration in umol N l-1: 5.75
Oxygen saturation (%): 86.7
Trophic status: Excellent

EQUATION
Overall index: 4
Good

Figure 3.2.5a: The Equation Index for the Knysna Estuary, with 'excellent' physics (Ferreira, 2000)


Equation (Knysnapred)

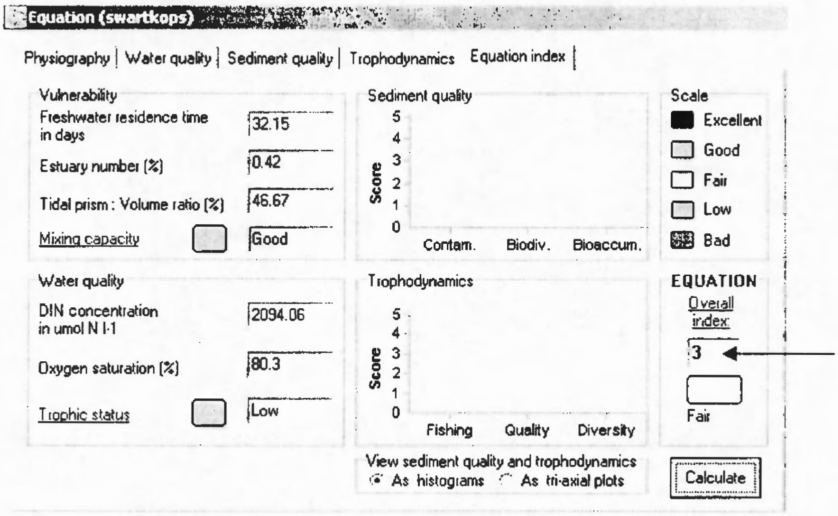
Vulnerability
Freshwater residence time in days: 105.89
Estuary number (%): 0.01
Tidal prism : Volume ratio (%): 269.83
Mixing capacity: Fair

Water quality
DIN concentration in umol N l-1: 41.36
Oxygen saturation (%): 86.7
Trophic status: Low

EQUATION
Overall index: 3
Fair

Figure 3.2.5b: The Equation Index for the Knysna Estuary, with 'fair' physics (Ferreira, 2000)

The Equation Index's results revealed that the overall index for the Knysna Estuary's health had decreased from 4 (Figure 3.2.5a) to 3 (Figure 3.2.5b).


Equation (swartkops)

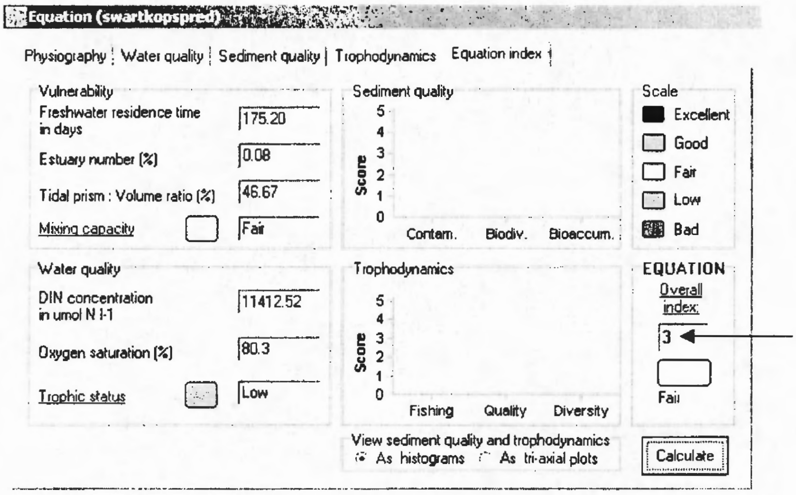
Vulnerability
Freshwater residence time in days: 32.15
Estuary number (%): 0.42
Tidal prism : Volume ratio (%): 46.67
Mixing capacity: Good

Water quality
DIN concentration in umol N l-1: 2094.06
Oxygen saturation (%): 80.3
Trophic status: Low

EQUATION
Overall index: 3
Fair

View sediment quality and trophodynamics
● As histograms ○ As tri-axial plots

Figure 3.2.6a: The Equation Index for Swartkops Estuary, with 'good' physics (Ferreira, 2000)


Equation (swartkopspred)

Vulnerability
Freshwater residence time in days: 175.20
Estuary number (%): 0.08
Tidal prism : Volume ratio (%): 46.67
Mixing capacity: Fair

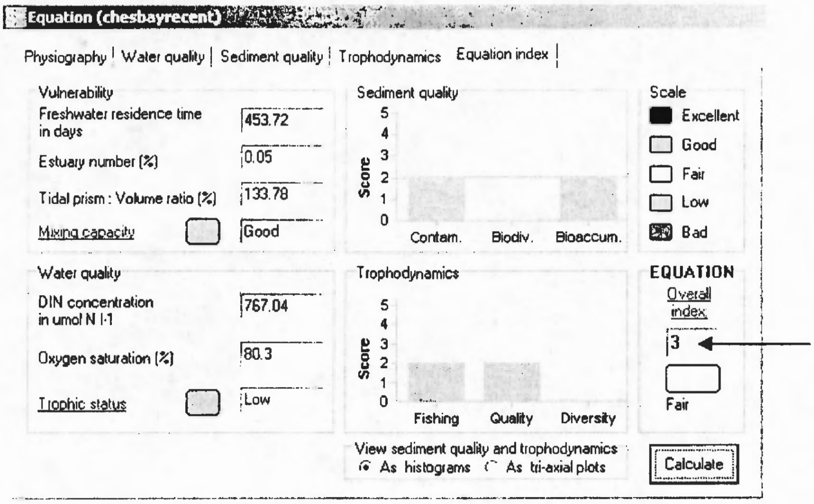
Water quality
DIN concentration in umol N l-1: 11412.52
Oxygen saturation (%): 80.3
Trophic status: Low

EQUATION
Overall index: 3
Fair

View sediment quality and trophodynamics
● As histograms ○ As tri-axial plots

Figure 3.2.6b: The Equation Index for Swartkops Estuary, with 'fair' physics (Ferreira, 2000)

The Equation Index's results revealed that the overall index for the Swartkops Estuary's health remained the same but the amount of DIN in the system had increased from 2094.06 (Figure 3.2.6a) to 11412.52 μmol N / l (Figure 3.2.6b).

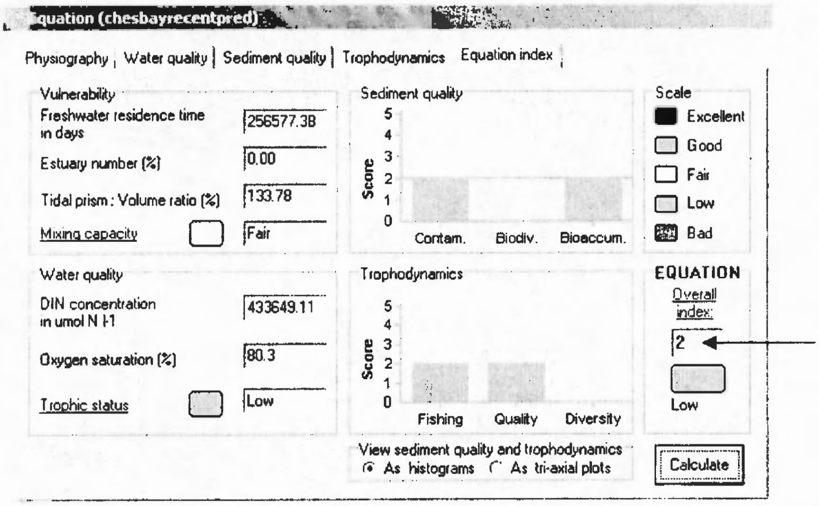

Equation (chesbayrecent)

Vulnerability
Freshwater residence time in days: 453.72
Estuary number (%): 0.05
Tidal prism : Volume ratio (%): 133.78
Mixing capacity: Good

Water quality
DIN concentration in umol N l-1: 767.04
Oxygen saturation (%): 80.3
Trophic status: Low

EQUATION
Overall index: 3
Fair

Figure 3.2.7a: The Equation Index for Chesapeake Bay, with 'good' physics (Ferreira, 2000)


Equation (chesbayrecentpred)

Vulnerability
Freshwater residence time in days: 256577.38
Estuary number (%): 0.00
Tidal prism : Volume ratio (%): 133.78
Mixing capacity: Fair

Water quality
DIN concentration in umol N l-1: 433649.11
Oxygen saturation (%): 80.3
Trophic status: Low

EQUATION
Overall index: 2
Low

Figure 3.2.7b: The Equation Index for Chesapeake Bay, with 'fair' physics (Ferreira, 2000)

The Equation Index's results revealed that the overall index for Chesapeake Bay decreased from a 3 (Figure 3.2.7a) to a 2 (Figure 3.2.7b).

The TaCM predicts that if the physics of all 3 estuaries were changed to 'fair' physics their health would become 'impacted' (Figure 3.2.8).

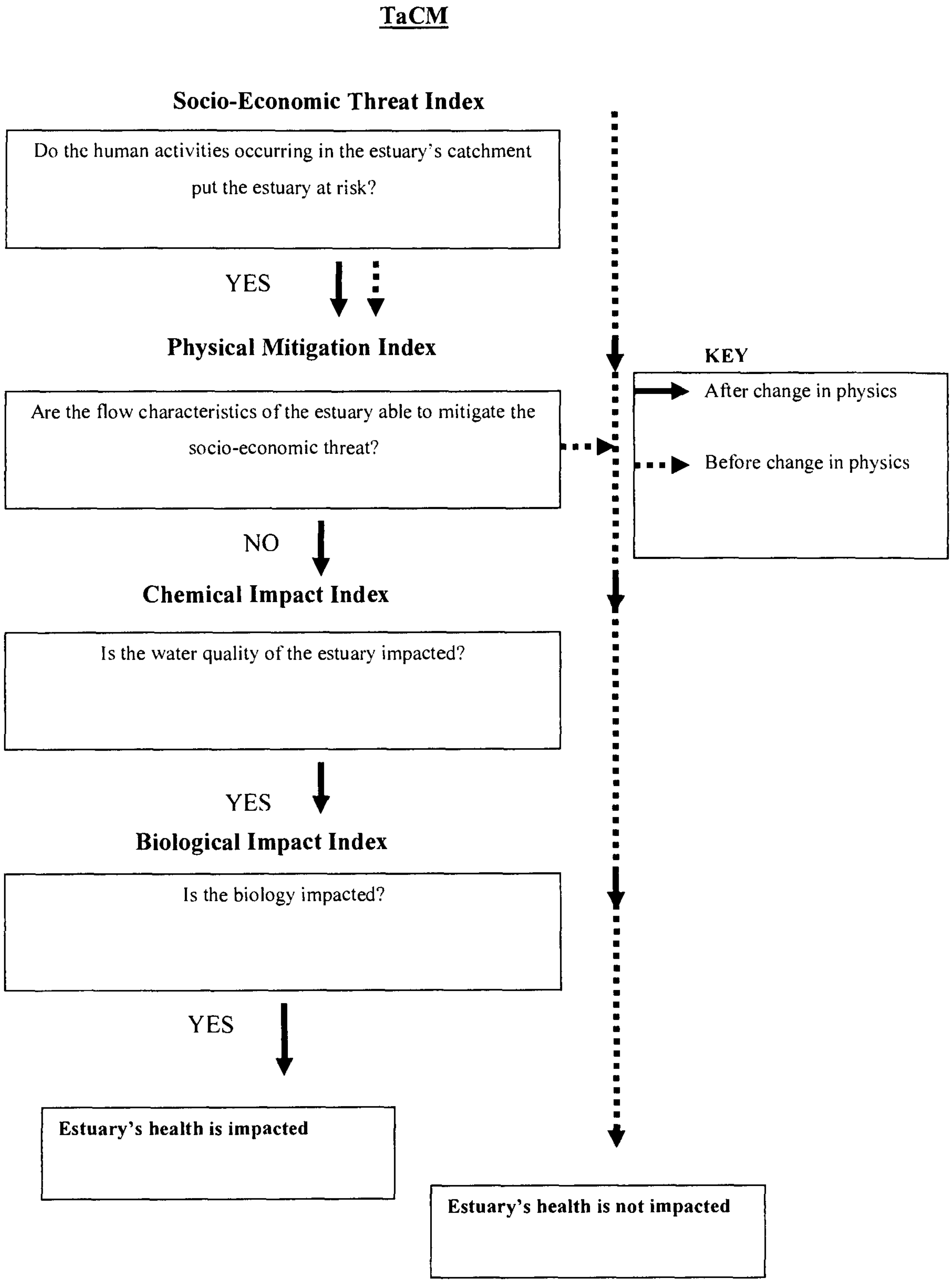


Figure 3.2.8: Basic schematic of the TaCM's path that the Knysna Estuary, the Swartkops Estuary and Chesapeake Bay follow, when their physics are changed to 'fair' physics.

Chapter 4: Discussion

This chapter discusses how the TaCM differs from previous estuarine health assessment methods. The results of the pseudo tests are then discussed. Finally, the application of the TaCM to 3 case studies is also discussed.

4.1. The Threat and Cascade Method

Previous estuarine health assessment methods (Engle *et al.*, 1994; Weisenberg *et al.*, 1992; Summers *et al.*, 1992; Cooper, 1994) have mainly concentrated on chemistry and biology at the expense of system physics and socio-economic factors. The TaCM of estuarine health assessment has addressed this gap by including socio-economic, physical, chemical and biological factors in it's assessment of estuarine health. The inclusion of human activities is important as they are the main cause of declines in estuarine health (Kennish, 2002) and the inclusion of the estuarine physics is also important as it takes into account the resilience of an estuary to stress (Ferreira, 2000).

4.2 Pseudo Tests

The purpose of the pseudo tests was to test the TaCM's viability. The pseudo tests results were based on the assumption that all possible input values are equally likely for a given estuary. The analysis of the results is therefore also based on this assumption. The results revealed that it was possible to get all the grades as answers. This proved that the method was robust.

The results also revealed that the chance of obtaining a particular grade as an answer, to the Physical Mitigation and Chemical Impact indices, was equal for all grades Table 3.1.1). This was due to Ferreira's (2000) methodological design. The percentage possibility of obtaining a particular grade as an answer to the Socio-Economic Threat Index, was not equal for all grades (Table 3.1.1). This was due to the integer rounding down of the numbers.

There are very few estuaries left in the world that have not been impacted on by human activities in their catchment (Kennish, 2000). Therefore it is very unlikely that an estuary can be classified as 'pristine'. This was reflected by the pseudo test results

(Table 3.1.1), as it was very hard to get a 5 (pristine) as a final grade when using the Socio-Economic Threat Index.

There was a relatively small chance of an estuary receiving a grade of 1 (Severe Threat) when using the Socio-Economic Threat Index (Table 3.1.1). This was due to the fact that the human activities in the catchment would have to be very intense in order for the estuary to receive this grade. The most likely grade an estuary would receive, using a randomly chosen estuary from a continuum, when assessed by the Socio-Economic Threat Index would be 3 (moderate threat). This ensures that unless an estuary's health is at a very low risk of being threatened, by the socio-economic threats in its catchment, the whole assessment will be completed. This is because the method was designed to be over cautious.

4.3 Case Studies

The TaCM was tested, in this dissertation, by applying it to 3 case studies. The case studies were used to test if the TaCM correctly identified whether or not the system was 'threatened' and to test if managers could use this method as a Decision Support System. The case studies were also used to test if the TaCM could identify what was the highest risk factor to the estuary's health.

4.3.1 Knysna Estuary

The results of the TaCM's application to the Knysna Estuary are discussed below.

Socio-Economic Threat Index

The Socio-Economic Threat Index's results (Table 3.2.1-Table 3.2.3) show that the human activities that were occurring in Knysna Estuary's catchment were likely to threaten the estuary's health. This was mainly because of the high amount of agricultural (28%) land use (Figure 3.2.1) in the catchment that resulted in increased nutrients and chemical contaminants being transported to the estuary (Switzer, 2003; Whitfield, 2000). The encroachment of development and agriculture onto the estuary banks, increased water abstraction (Prochazka *et al.*, 2002a) and the estuary's popularity with tourists was also putting the estuary at risk (Marker, 2003). The estuary's health was already threatened by these factors and the threat was likely to intensify in the future with increased development and water abstraction. This would be due to increases in the human population in the estuary's catchment and the municipality's plan to provide potable water to all of the people living in the catchment (Marker, 2003). Fresh water inflow is very important as it helps maintain the physics of the estuary, and it helps keep the estuary's mouth open, and it influences the vertical stratification and coastal exchange (Morant *et al.*, 1999).

Physical Mitigation Index

The Physical Mitigation Index's results (Table 3.2.4) showed that the Knysna Estuary's physics should be able to mitigate the socio-economic threats as it has 'good' physics. The estuary was physics were classified as 'good' as it had an 'excellent' coastal exchange and "significant dilution ability" (En) (NOAA, 1991).

Chemical Impact Index

The Chemical Impact Index's results (Table 3.2.5-3.2.6) showed that the estuary had a 'good' water quality even though it received excess nutrients. This was because the estuary was well flushed (Largier *et al.*, 2001) and had an 'excellent' coastal exchange ratio.

Biological Impact Index

The biology of the estuary was also shown to be in a 'good' state (Table 3.2.7). The estuary had a high biodiversity of birds, fish and plants and was home to some very rare species (for example: the Knysna Sea horse) (Turpie, 2000). Although the estuary was in 'good' health its biology was 'impacted' in some ways. Its bird density was not as high as it should have been. This was hypothesised, by Martin *et al.* (2000), to be a result of reasonably low populations of macrobenthic invertebrates and due to recreational disturbance. The supratidal marsh area in the estuary catchment had also decreased. This was due to recreational activities (for example: bait collection) (Day, 1981, Maree, 2000.); restriction of tidal flow (for example: sea wall around Thesen Island) (Allanson *et al.*, 1996); increased silt deposition and increased urbanisation in the catchment (Maree, 2000).

The estuary was 'not impacted' as its water quality was in a 'good' condition, it had low amounts of heavy metals in its sediments and the biology was in a healthy state.

Therefore the Physical Mitigation Index's results were confirmed by the chemical and biological assessment of the estuary.

Previous Studies

Previous health assessments of the estuary showed that even though the estuary was subjected to increased nutrient loads its 'health' was still in a 'good' condition (Switzer, 2003; Whitfield, 2000). The Threat and Cascade Method (TaCM) analysis of the estuary's health concurred with these conclusions. This means the TaCM accurately determined the Knysna Estuary's health.

Conservation Importance

The results also showed that the conservation of the Knysna Estuary would be very important as it had a very high biodiversity of species living in the estuary. This statement is confirmed by previous assessments of the estuary's conservation priority. The Knysna Estuary was given a high conservation priority in terms of its importance for waterbirds (Turpie 1995), plants (Colloty *et al.*, 2000) and fish (Maree *et al.*, 2003).

Predictive tool

The predictive results (Figure 3.2.5b) showed that if Knysna's physics were changed to 'fair' physics then the estuary would be at risk of being impacted on by the human activities in the catchment. Ferreira's (2000) Equation Index and the TaCM's assessment concluded that the estuary water quality would become 'fair' if the physics were changed to 'fair'. This change in physics could occur if the current and future development blocks off parts of the estuary to tidal flushing, the amount of abstraction increases or drought occurs, thereby decreasing the freshwater supply to the estuary.

Preventative Measures

In order to prevent further degradation of the estuary's health, managers and town planners would need to prohibit further development along the banks of the estuary and ensure that the estuary's physics are kept in a 'good' state. Other preventative measures include:

- Ensuring that the wastewater entering the estuary is adequately filtered or recycled.
- Restricting the amount of abstraction occurring in the catchment.
- Ensuring that the amount of abstraction does not prevent the estuary from getting enough water.

4.3.2 Swartkops Estuary

The TaCM was applied to the Swartkops Estuary and the results of this application are discussed below.

Socio-Economic Threat Index

The Socio-Economic Threat Index's (Table 3.2.8-3.2.9) results showed that the human activities that were currently occurring in Swartkops catchment were likely to threaten the estuary's health. This was mainly because there was a high human population density living in the catchment and because of the high amount of agricultural (14%) and urban and industrial land use (9%) in the catchment (Figure 3.2.2). These industrial and urban areas, as well as sewerage treatment works and informal settlements, pumped large quantities of wastewater into the estuary and its rivers (Baird, 2001b). This resulted in increased amounts of nutrients, chemical contaminants and heavy metals being input into the estuary (Emmerson, 1985; Baird, *et al.*, 1993).

Physical Mitigation Index

The Physical Mitigation Index's results (Table 3.2.10) showed that the Swartkops Estuary's physics should be able to mitigate the socio-economic threats that were imposed on the estuary as it had a good coastal exchange and a "significant dilution ability' (En) (NOAA, 1991).

Chemical Impact Index

The Chemical Impact Index results (Table 3.2.11-3.2.12) showed the estuary to have a 'fair' water quality, even though it received large amounts of polluted wastewaters from industrial, urban and agricultural areas (Emmerson 1985, Lord *et al.*, 1987, Baird *et al.*, 1993). The analysis of the heavy metal contamination of the estuary's sediment showed that the sediment did not contain very high levels of heavy metals.

Biological Impact Index

The biology of the estuary was shown to be in a 'good' state (Table 3.2.13), even though the water quality was 'fair'. The estuary had a very high species richness and biodiversity. Although the biology was thriving in the estuary it had been impacted on. The biological results showed that there had been large losses of supratidal and intertidal salt marsh areas in the estuary's catchment. This was due to clearing of the supratidal and intertidal salt marsh areas for development (Colloty *et al.*, 2000). Colloty *et al.* (2000) concluded that the saltmarsh that remained in the catchment would be susceptible to future development (Colloty *et al.*, 2000).

The Physical Mitigation Index's results were not confirmed by the chemical assessment of the estuary. The Physical Mitigation Index determined that the estuary's flow characteristics should have been able to mitigate the socio-economic threats on the estuary, but the Chemical Impact Index classified the estuary as 'impacted'. The estuary was classified as 'impacted' by the Chemical Impact Index, as its water quality had the potential to become eutrophic.

This means that unless the whole assessment was completed, the analysis of the estuary's health would be incorrect. This may be a potential source of error. The whole assessment was completed on all 3 case studies in this dissertation in order to test the methodology and not because of this potential error.

Previous Studies

Previous studies (Emmerson 1985, Lord *et al.*, 1987, Baird *et al.*, 1993) showed that the input of industrial effluents, storm water pollution and nutrients into the estuary from the agricultural, industrial and urban areas had resulted in a 'fair' water quality condition in the estuary. Emmerson (1985), Lord *et al.* (1987), Baird *et al.* (1993) also concluded that even though the water quality was 'fair' no eutrophication events had occurred (Lord *et al.*, 1987) and that the system still supported a large diversity of plants and animal communities (Emmerson 1985; Baird *et al.*, 1993). The previous assessment's results concurred with the TaCM's conclusion. The TaCM concluded that the estuary had a 'fair' water quality and its biology was thriving. This strengthens the case that the complete TaCM analysis could be a viable assessment tool.

Conservation Importance

The results also showed that the conservation of the Swartkops Estuary was very important as it had a very high biodiversity of species living in the estuary. This statement is confirmed by previous conservation priority analysis of the estuary. The estuary was given a high conservation priority ranking in terms of its importance for the conservation of waterbirds (Turpie, 1995), plants (Colloty *et al.*, 2000) and fish (Maree *et al.*, 2003).

Predictive Tool

The predictive tools results (Figure 3.2.6b) showed that if the physics of Swartkops Estuary were changed to 'fair' then the estuary would be at risk of being threatened by the human activities in its catchment. Ferreira's (2000) Equation Index and the TaCM assessment concluded that if the physics were 'fair', the estuary's water quality would deteriorate. The change in physics would occur due to increased abstraction, drought or parts of the estuary (or the whole estuary) being blocked off from the sea.

Preventative Measures

In order to prevent future deterioration of the health of the estuary, the physics of the estuary would need to be kept in a 'good' state and further development and agriculture near the banks of the estuary should be prevented. Managers and town planners would also need to ensure that the wastewaters from the industrial and urban areas was filtered and reduced. This is because the industrial and urban effluents being input into the estuary, at the time, were putting the estuary's health at risk (Baird, 2001b). They also would need to ensure that the sewerage treatment works, wool processing plants and tannery discharges are kept to effluent standards (Baird *et al.*, 1988). In order to conserve the remaining saltmarsh areas, development would needs to be controlled, bait digging should be reduced and the estuary mouth should be kept open to regular flushing (Colloty *et al.*, 2000).

4.3.3 Chesapeake Bay

The TaCM was applied to Chesapeake Bay and the results of this analysis are discussed below.

Socio-Economic Threat Index

The Socio-Economic Threat Index's results (Table 3.2.14-3.2.15) showed that the human activities that were occurring in Chesapeake Bay's catchment had the potential to severely threaten the estuary's health. This was mainly due to the high population density of wealthy people living in its catchment, the high percentage of agricultural land use (34%) (Figure 3.2.3) and the input of large amounts of sewerage into the estuary. Large amounts of nutrients were also put into the Bay *via* atmospheric deposition (Mason *et al.*, 1997; Grimm *et al.*, 2005). This meant that large amounts of nutrients, pathogens, chemical contaminants and heavy metals were being input into the estuary every day (Karuppiah, *et al.*, 1998). At the time of this assessment, Chesapeake Bay was also a popular tourist destination and its resources were utilised recreationally and commercially. This meant that in certain seasons the population density in the catchment increased causing increased effluent to be put into the estuary and increased fishing and boating activity in the estuary (Horton, 2005). Another factor that was increasing the human threat to the estuary was the low density 'sprawl' development patterns that had occurred in the catchment. This type of settlement pattern encouraged more roads to be built as people needed to use cars to travel as they lived a long way from where they worked or shopped. This resulted in increased habitat fragmentation and increased air pollution (Weber, 2004).

Physical Mitigation Index

The physical assessment of the estuary showed that the estuary's physics were 'good' (Table 3.2.16) and therefore the TaCM assumed that the physics would be able to mitigate the human impacts on the estuary and the estuary would be 'not threatened'. The physics were classified as 'good' even though the estuary had a very long residence time because the estuary had a "significant dilution ability" (En) (NOAA, 1991) and because of its 'excellent' coastal exchange (Table 3.2.16).

Chemical Impact Index

The Chemical Impact Index's results (Table 3.2.17-3.2.18) revealed that the water quality of the estuary was 'impacted'. The reasons for this were numerous. One of the causes of the decline of the water quality in the estuary was that more pollutants were entering the estuary due to the loss of wetlands. Wetlands act as natural filters, and without them the bay lost some of its filtering ability. Another factor that was causing the estuary's water quality to deteriorate was the input of large amounts of wastewater and sewerage effluent into the estuary. This was a result of increased development in the estuary's catchment (Bratton *et al.*, 2003).

Biological Impact Index

The biology of the estuary was shown to be in a poor state (Table 3.2.19). The fish had lesions and diseases and had declined in numbers. There had also been a significant loss of wetlands, salt marshes and submerged aquatic vegetation. The number of birds living in and visiting the estuary had also declined. This decline was thought to be due to decreased habitat and fish stocks, as well as the decline in the amount of submerged aquatic vegetation present in the estuary (Kemp *et al.*, 1983; Officer *et al.*, 1984; Lubbers *et al.*, 1990; Dennison *et al.*, 1993; Stevenson *et al.*, 1993; Cloern, 2001; Orth *et al.*, 2002).

The physical results predicted that the estuary should be able to mitigate the socio-economic threats imposed on the estuary but the chemical and biological results revealed that the estuary's water quality and biology were 'impacted' upon. Therefore the Physical Mitigation Index's results were not confirmed by the chemical and biological assessment of the estuary. This means that the TaCM assessment was not accurate for this system and that further work needs to be conducted on the method in order to improve its accuracy. The reasons it was not accurate for this system may be because of the system's complexity and size. The flow characteristics of Chesapeake Bay change a lot from the head of the estuary to the mouth because of its size and complexity and therefore the use of average physics is inadequate (Levinson *et al.*, 1997). In hindsight, the system should have been divided into sub-catchments and the health of each sub-catchment should have been assessed.

Previous Studies

Previous assessments of Chesapeake Bay's water quality had shown it to be in a poor state (Environmental Protection Agency, 1998; Boesh, 2000). The Chemical Impact Index of the TaCM categorised Chesapeake Bay's water quality as 'fair' but it did not highlight the eutrophic and anoxic events that were known to have commonly occurred in the Bay. This error was thought to be a result of the averaging of the DIN, DIP and O^2 concentrations over a year (which averages out the variations) and because of the size of the system.

The TaCM assessment of Chesapeake Bay would be more accurate if the system was broken up into sub-systems and the health of each subsystem was given an individual assessment. Therefore future work should include the re-assessment of each of the subsystems of Chesapeake Bay. In hindsight a much smaller and less complex system should have been chosen for the international case study.

Predictive Tool

The predictive tool results (Figure 3.2.7b) showed that if the physics of Chesapeake Bay were changed to 'fair' then the estuary would be at risk of being threatened by the human activities in its catchment. Ferreira's (2000) Equation Index and the TaCM assessment concluded that if the physics were 'fair', then the estuary's water quality would deteriorate. The change in physics would occur due to increased abstraction, drought or parts of the estuary (or the whole estuary) being blocked off from the sea.

Preventative Measures

In order to prevent further deterioration of the health of the estuary, the physics of the estuary would need to be kept in a 'good' state and further development and agriculture near the banks of the estuary should be prevented. Managers and town planners would also need to ensure that the wastewaters from the industrial and urban areas was filtered and reduced.

Remedial Action

The TaCM's results (Figure 3.2.4) showed that Chesapeake Bay's health could be improved by decreasing the socio-economic threats in the estuary's catchment. Socio-economic improvements would be achieved by preventing further development too close to the estuary, decreasing the storm water and industrial waste waters being put into the estuary as well as improving the treatment of the sewerage that was being input into the estuary. Another way of improving the estuary's health is to restore and replant the wetlands, salt marshes and submerged aquatic vegetation. Changing the type of settlement pattern occurring in the estuary's catchment as well as providing mass transportation (for example: busses and trains) would also improve the estuary's health (Weber, 2004).

Another suggestion is that the flushing of the estuary should be improved. This could be achieved by building another channel to the sea. This must be done in conjunction with strict regulations on the amount of phosphorus and nitrogen input into the estuary in order for it to be effective (Humphries, *et al.*, 1995). Previous examples of this type of management strategy (for e.g.: Peel-Harvey Estuary) have not always lead to an improvement in the health of the system.

4.4: Comparison of the results for all three estuaries

Table 4.4.1 summarises the results of the TaCM's assessment of the health of Chesapeake Bay, the Knysna and Swartkops Estuaries. Figure 4.4.1 summarises and compares the different types of land uses in all 3 case studies' catchments.

Table 4.4.1: A comparison of the results of the TaCM analysis of Chesapeake Bay and the Knysna and Swartkops estuaries.

	Knysna Estuary	**Swartkops Estuary**	**Chesapeake Bay**
Socio-economics	High	High	Severe
Physics	Good	Good	Good
Chemistry	Good	Fair	Fair
Biology	Good	Good	Poor

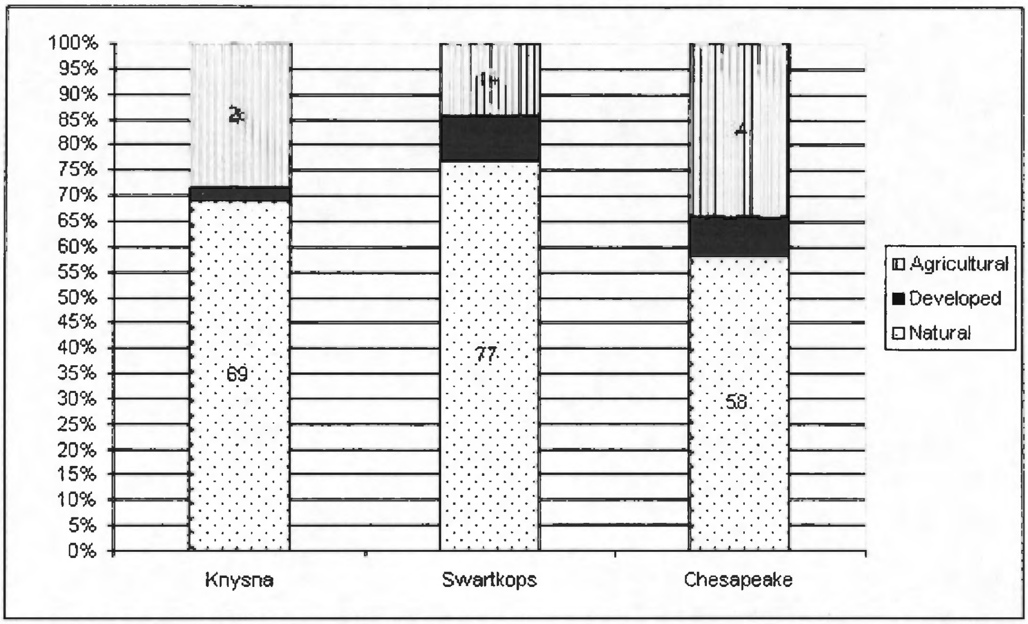


Figure 4.4.1: A bar graph comparing the land-use in Chesapeake Bay's, Swartkops and Knysna Estuaries' catchments.

The socio-economic assessment of the Knysna and Swartkops estuaries revealed similar results. This is because they have similar land-use characteristics, wealth and encroachment. Chesapeake Bay's socio-economic assessment revealed a different result. This is because Chesapeake Bay has a much higher percentage of cleared land (42%) in its catchment. It also has a higher percentage of agricultural land that input large amounts of nutrients and pollutants into the estuary via atmospheric deposition and waste water input. Chesapeake Bay also has wealthier people living in its catchment and large amounts of sewerage are input into the estuary.

The physical assessment of the estuaries revealed similar results as all 3 estuary's mouths are permanently open and they all have significant dilution abilities. The physical assessment of Chesapeake Bay is not accurate. The reason for this is that the bay is too big for Ferreira's (2000) method to accurately characterize the physics.

The chemical assessment revealed that both Chesapeake Bay and the Swartkops Estuary had 'fair' water qualities. This is because they both have very high amounts of sewerage being input into them and they both have similar percentages of developed land. The Knysna Estuary has a 'good' water quality because it receives a lot less sewerage and other effluents from its developed areas.

The biological assessment revealed that Knysna and Swartkops estuaries biology was in 'good' health and Chesapeake Bay's biology was in poor health. Chesapeake Bay's biology was in 'poor' health as it received much larger concentrations of pollutants than Knysna and Swartkops. It also had a much longer residence time.

4.5 Further Work

In this dissertation the 3 estuaries, that were used to test the TaCM, were all permanently open systems. This means that the TaCM needs to be tested further by applying it to temporarily open systems.

The TaCM could possibly be improved in the following ways. For large systems, the catchment needs to be partitioned into subwatersheds and then each subwatershed must be assessed. This will prevent the averaging out of variability in the system. It can also be improved by adding seasonal signals to the Socio-Economic Threat, Physical Mitigation, and Chemical Impact indices. This should prevent the eutrophic and low oxygen events from being averaged out and should improve the analysis of the estuary's flushing ability. Due to the fact that the method is not 100% accurate it needs to be developed and tested further. If its accuracy is improved by the changes that are suggested then it could be used to test the health of estuaries internationally.

Chapter 5: Conclusion

This chapter gives a synopsis of the Threat and Cascade methodology, its results and draws conclusions in relation to its efficacy.

Human occupation of estuarine catchments is likely to negatively impact estuarine health (Kennish, 2002). Their watersheds are popular places for human settlement due to the fact that they provide many services (for example: recreation, commercial and nursery areas for fish) (Surge *et al.*, 2002). Estuarine habitats are important as they support large amounts of fauna and flora. Conservation of estuarine habitats is important because they are a valuable natural resource offering many recreational and commercial opportunities (USA, Environmental Protection Agency, 2005). In order to conserve estuaries managers and scientists need a method that assesses estuarine health and determines the factors that negatively affect estuarine health.

The Threat and Cascade Method (TaCM) was designed for the comparative assessment of estuarine health over a large number of systems and to help managers target potentially problematic systems for detailed examination. The TaCM is based on the assumption that human impacts negatively impact estuarine health. The methodology follows a logical cascade of estuarine health assessment protocols. The first step in the TaCM incorporates socio-economic factors into an algorithm that produces a scaled indicator used to identify estuarine systems that are potentially threatened by anthropogenic inputs. The socio-economic algorithm incorporates the following variables: land cover, population density, per capita wealth, state of the estuary mouth, abstracted mean annual runoff, encroachment of development, estuary use, and sewerage input. If the Socio-Economic Threat Index identifies the estuary as being threatened, then the second stage of the TaCM is instigated. This is an assessment of the system's physics and is accomplished by considering the following variables: residence time, estuary number (freshwater inflow/ tidal prism), coastal exchange, and the proportion of the time the estuary mouth is closed to the ocean. The Threat and Cascade Method assumes that an anthropogenically threatened system with a short residence time is less likely to be impacted on than a threatened system with a long residence time. If the Physical Threat Index identifies the estuary as being threatened, then the third stage of the TaCM is initiated. This involves assessing the chemistry and then the biology of the threatened estuarine system. Applying the TaCM in reverse permits an assessment of the success of remedial action to 'impacted' systems.

The TaCM was tested using local (South African) and international case studies. The TaCM was proven to be accurate for the local case studies (Swartkops and Knysna) and that it could identify the problem areas that were likely to be impacting their health. The international case study (Chesapeake Bay) was not as accurate and it was determined that the TaCM's accuracy had to be improved in order to correctly assess this estuary's health. This was because the system was too large for the TaCM and therefore system size needs to be taken into account. The method's predictive ability was proven, as it was able to predict what impact 'change' would have on the Swartkops and Knysna estuaries. It was also proven that the method could identify the problem area that was causing Chesapeake Bay's health to deteriorate. The results proved that the method has the potential to be internationally applicable and that it concentrates mainly on those systems that are likely to be impacted on by humans. The TaCM is an improvement on previous methods as it includes socio-economics and physics in it assessment of estuarine health. It is also a relatively cheap and simple way of identifying the problem areas in an estuary's catchment. This will enable managers to use it to classify the health of multiple estuaries in a short space of time and it will enable them to prioritise estuaries that need immediate remedial action.

Further research needs to be done on aspects of the TaCM in order to improve its accuracy and its potential to be an internationally applicable method. Seasonal signals need to be added to the Socio-Economic Threat, the Physical Mitigation and the Chemical Threat Index indices. The TaCM also needs to be applied to temporarily closed estuaries. The method must also be utilised by managers and decision makers in order to ensure that it becomes a viable assessment tool.

Chapter 6: References

Allanson, B.R., 2000. The Knysna Project reviewed-research findings and implications for management. *Transactions of the Royal Society of South Africa* 55(2): 97-100

Allanson, B.R, Grange, N., and Maree, B., 1996. Specialist study on the impact of Thesen Island development on the ecology of Thesen Island. In: *Environmental impact assessment of development scenarios for Thesen Island, Knysna, Stellennbosh, CSIR.*

Allanson, B.R., Maree, B., and Grange, N., 2000a. An introduction to the chemistry of the water column of the Knysna Estuary with particular reference to nutrients and suspended solids. Knysna Basin Project. *Transactions of the Royal Society of South Africa,* 55(2):141-162

Allanson, B.R., Nettleton, J., and De Villiers, C.J., 2000b. Benthic macrofauna richness and diversity in Knysna Estuary: a 50-year Comparison. *Transactions of the Royal Society of South Africa* 55(2): 177-185

Allanson, B.R., and Winter, D., 1999. Chemistry. In: *Estuaries of South Africa. ed.* Allanson, B.R., and Baird, D. Pages 53-89. Cambridge University Press. United Kingdom.

Arnold, C.L., Boison, P.J., and Patton, P.C., 1982. Sawmill Brook: an example of rapid geomorphic change related to urbanisation. *Journal of Geo*logy **90** (2): 155-166.

Arnold, C.L., and Gibbons, C.J., 1996. Impervious Surface Coverage. *Journal of the American Planning Association* **62** (2): 243-258

Baden S.P., Loo, L.O., Pihl, L. and Rosenberg R., 1990. Effects of eutrophication on benthic communities including fish Swedish west coast. *Ambio*. Stockholm Vol. **19**, No. 3: 113–122.

Bagge, O., Nielsen, E., Mellergaard, S., Dalsgaard, I., 1990. *Hypoxia and the demersal fish stock in the Kattegat (IIIa) and Subdivision 22.* ICES Council Meeting 1990 (Collected papers), ICES, Copenhagen, Denmark, p. 52.

Bailly, D., Paquotte, P., 1996. Aquaculture and environment interactions in the perspective of renewable resource management theory. *Coastal Management*, **24**, 251-269.

Baird, D., 2001a. *Kromme River Estuary, St Francis Bay, Eastern Cape, South Africa.* http://data.ecology.su.se/mnode/Africa/S_Africa/Kromme/kromme_river_estuary_bud.htm

Baird, D., 2001b. Swartkops River Estuary, Algola bay, Eastern Cape, South Africa LOICZ budget. In: Dupra, V., Smith, S.V., Marshall Crossland, J.I., and Crossland, C.J. (Eds.). Estuarine systems of sub-Saharan Africa: carbon, nitrogen and phosphorus fluxes. *LOICZ Reports and Studies* No. **18**, i+83 pp., LOICZ, Textel,

Baird, D., Hanekom, N.M. and Grindley, J.R. 1986. Report No. 23: Swartkops (CSE 3). In: Heydorn, A.E.F. and Grindley, J.R. (eds). Estuaries of the Cape. Part 2. Synopses of available information on individual systems. *CSIR Research Report* No. **422.** 83 pp.

Baird, D., Marias, J.F.K., and Martin, A.P, 1988. Proceedings of the symposium held on the 14 and 15 September 1987 at the University of Port Elizabeth. *South African National Scientific Programmes Report* No **156.** 107 pp.

Baird, D., and Ulanowicz, R.E. 1993. Comparative study on the trophic structure, cycling and ecosystem properties of four tidal estuaries. *Marine Ecology Progress Series* **99**: 221-237.

Beach, D., 2002. *Coastal Sprawl: The Effects of Urban Design on Aquatic Ecosystems in the United States.* Pew Oceans Commission, Arlington, VA. 40 pp.

Bhargava, D.S., 1983. Use of a water quality index for river classification and zoning of Ganga River. *Environmental Pollution* (Series B), Vol. **6**: 51-67

Binning, K and Baird, D., 2001. Survey of heavy metals of the Swartkops River Estuary, Port Elizabeth South Africa. *Water SA* Vol. **27.** No 4: 461-466.

Boynton, W.R. and Swaney, D.P., 1998. *N and P budget for the Chesapeake Bay.* http://data.ecology.su.se/MNODE/North%20America/chesapeake/chbbud.htm

Branch, G., and Branch, M., 1981. *The living shores of Southern Africa.* C. Struik Publishers. Cape Town. 272 pp.

Bratton, J.F., Colman, S.M., and Seal, R.R., 2003. Eutrophication and carbon sources in Chesapeake Bay over the last 2700 yr: human impacts in context. Geochemica et Cosmochimica Acta, Vol. **67**, No. 18: 3385-3402.

Bricker, S.B, Ferreira, J.G., and Simas, T., 2003. An integrated methodology for the assessment of estuarine trophic status. *Ecological Modelling* **169**: 39-60.

Bulger A.J., Hayden, B.P., Manaco, M.E., Nelson, D.M. and McCormick-Ray, M.G., 1993. Biologically-based estuarine salinity zones derived from a multivariate analysis. *Estuaries* **16**: 311-322.

Castro, M., Driscoll, C., Jordan, T., Reay, W., and Boynton, W., 2003. Sources of nitrogen to estuaries in the United States. *Estuaries* Vol. **26**, No. 3: 803-814.

Cameron, W.M., and Prichard, D.W., 1963. Estuaries. In: *The Sea.* Vol. **II**: 306-324. (ed.) Hill, M.N. Interscience, New York.

Canadian water quality guidelines, 1987. Vol. 1. Toronto. Prepared by the Task force on Water quality Guidelines of the Canadian Council of resource and environmental ministers. Canada.

Chapman, P.M., Paine, M.D., Arthur, A.D., and Taylor, L.A., 1996. A triad study of sediment quality associated with a major, relatively untreated marine sewerage discharge. *Marine Pollution Bulletin* **32**: 47-64.

Chen, C.W., 1970. Concepts and utilities of ecological models. *Journal of Management in Engineering* **10**: 50-59

Chen, S.T, Ruan, W.Q. and Zhen, R.Z. 1994. The biogeochememical research of phosphorus in Jiulong River estuary and West Sea (1). *Acta Oceanologica Sinica* **15**(1):63-71

Chesapeake Bay Program, 2000. *Chesapeake Bay: introduction to an ecosystem*. U.S. Environmental Protection Agency. Publication No. EPA 903-R-00-001

Clark, B.C., 1989. Estuaries of the Cape: Part II: Synopses of available information on individual systems. Report No 37: Palmiet (CSW 12). Heydorn, A.E.F., and Morant, P.D., (eds.). Stellenbosh. *CSIR Research Report* 436.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series* 210: 223–253.

Coates, B., Jones, A.R. and Williams, R.J., 2002. Is "Ecosystem Health" a useful concept for coastal managers? In: *Conference proceedings from Australia's National Coastal Conference ('Coast to Coast 2002')*, 4-8 November 2002, Twin Towns Service Club, Tweed Heads, NSW, Australia. Pages 55-58.

Codling, I.D., and Ashley, S.J., 1992. Development of a biotic index for the assessment of pollution status of marine benthic communities. Final report to for WRC plc. NR 3102/1.

Coetzee, J.C., Adams, J.B., and Bate, G.C., 1997. A botanical importance rating of selected Cape estuaries. *Water SA*, **23**: 81-93

Colloty, B.M., Adams, J.B., and Bate, G.C., 2000. The botanical importance rating of the Swartkops estuary over time. *Water SA*. Vol. **26.** No.2:171-180

Commonwealth of Australia, 2002. Australian catchment, river and estuary assessment 2002.
http://audit.ea.gov.au/ANRA/coasts/docs/estuary_assessment/Est_Ass_Contents.cfm

Cooper, J.A.G., Ramm A.E.L., Harrison T.D, 1994. The Estuarine Health Index: a new approach to scientific transfer. *Ocean and Coastal Management* Vol. **25**, No.3: 103-141

CSIR, 1992. *Building the foundation for sustainable development in South Africa.* National report to the United Nations conference on Environment and Development

(UNCED) held in Rio De Janerio, June 1992. Pretoria: Department of Environmental Affairs.

Culliton, T.J., 1998. Population, distribution, density and growth. *NOAA's State of the Coast Report:* Silver Spring, Maryland, National Ocean and Atmospheric Administration (http://www.state-of-coast.noaa.gov/bulletins/html/pop01/pop.html).

Davies C.A., Tomlinson, K., and Stephenson, T., 1991. Heavy metals in River Tees Estuary sediments. *Environ, Technology* **12** 961-972.

Davies, D., and Day, J.H, 1998. *Vanishing Waters.* University of Cape Town press. Cape Town. 487pp.

Davies, J.H., 1964. A morphogenetic approach to world shorelines. *Z. Geomorphology.* **8**:127-142

Day, J.H., 1980. What is an estuary? *South African Journal of Science*, **76**, 198.

Day, J.H., 1981. (Ed) *Estuarine Ecology with Particular Reference to South Africa.* Cape Town. A.A. Balkema Publishers.

Dauer, D.M., 1993. Biological criteria, environmental health and estuarine macrobenthic community structure. *Marine Pollution Bulletin* Vol.**26,** No. 5: 249-257.

Dederen, L.H.T., 1992. Marine eutrophication in Europe: similarities and regional differences in appearance. In: *Marine and Coastal Eutrophication*, ed. Vollenweider, R.A., Marchetti, R., and Viviani, R., pages 673-682. Amsterdam, the Netherlands: Elsevier Science.

Deeley, D.M., and Paling, E.I., 1999. Assessing the ecological health of estuaries in Australia. LWRRDC occasional paper 17/99 (Urban sub-program report No. 10) land and water resources research and development corporation Australia, Canberra.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuck, R.A., 1993. Assessing water quality with submerged aquatic vegetation. *Bioscience* **43** (2):86-94.

Department of Environmental Affairs and Tourism, 2001a. *South African Estuaries Land Cover.* Knysna Catchment.
http://www.environment.gov.za/soer/estuary/catch/knysna.html

Department of Environmental Affairs and Tourism, 2001b. *South African Estuaries Land Cover.* Swartkops Catchment.
http://www.environment.gov.za/soer/estuary/catch/swartkops.html

Diaz, R.J., and Solow, A, 1999. Ecological and economic consequences of hypoxia. Topic 2 report for the integrated assessment on hypoxia in the Gulf of Mexico. *NOAA Coastal Ocean Program Decision Analysis Series* No. **16**, National Oceanic and Atmospheric Administration, Coastal Ocean Office, Silver Spring, MD. 60 pp.

Dinus, S.H., 1987. Design of an index of water quality. *Water Resources Bulletin*, **23** (5): 833-843.

Dojlido, J., Raniszewski, J., and Woyciechowska, J., 1994. Water quality index-application for rivers in Vistula River Basin in Poland. *Water Science Technology*, **30**(10): 57-64

Dunnette, D.A., 1979. A geographically variable water quality index used in Oregon. *Journal of the Water Pollution Control Federation*, **51** (1): 53-61.

DWAF (Department of Water Affairs and Forestry), 1993. *South Africa Water Quality Guidelines – Domestic Water Use.* Vol. 1. Government Printer. Pretoria.

DWAF (Department of Water Affairs and Forestry), 1995. South African guidelines for coastal marine waters. Volume 1. Natural environment. Government publications.

DWAF, (Department of Water Affairs and Forestry) 1996. *South African Water Quality Guidelines*. Volume 7 Aquatic Systems. Government publications.

Eaton, L., 2001. Development and validation of biocriteria using benthic macroinvertebrates for North Carolina estuarine waters. *Marine Pollution Bulletin* **42**, 23-30.

Edgar, J.G., Barrett, N.S., Graddon, D.J., and Last, P.R., 1998. The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical, demographic attributes as a case study. *Biological Conservation* **92**: 383-397.

Eganhouse, R.P., and Sherblom, P.M., 2001. Anthropogenic organic contaminants in the effluent of a combined sewer overflow: impact on Boston Harbour. Marine *Environmental Research* **51**: 51-74.

Emmerson, W.D., 1985. The nutrient status of the Swartkops River estuary, Eastern Cape. *Water SA* **11**:189-198.

Engle, V.D., Summers, J.K., and Gaston, G.R. 1994. A Benthic index of environmental condition of Gulf of Mexico Estuaries. *Estuaries*. Vol.**17**, No 2: 372-384

Environmental Protection Agency, 1998. *The state of Chesapeake Bay. A report to the citizens of the bay region.* www.chesapeakebay.net

Epstein, P.R., 1999. Large marine ecosystem health and human health. In: Kumpf, H., Steidinger, K., Sherman, K. (Eds.), *The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability, and Management. Blackwell Science*, MA, pages 417-438.

Fairbridge, R.W., 1980. The estuary: its definition and geodynamic cycle. In: *Chemistry and biogeochemistry in estuaries.* Olausson, E., and Cato, I., (eds.) Wiley, New York, pages1-35

Fayer R., Graczyk, T.K., Lewis, E.J., Trout, J.M., and Austin Farley, C., 1998. Survival of infectious *Cryptosporidium parvum* oocysts in seawater and eastern oysters (*Crassostrea virginica*) in the Chesapeake Bay. *Applied Environmental Microbiology* **64**: 1070-1074.

Ferreira, J.G., 2000. Development of an estuarine quality index based on key physical and biogeochemical features. *Ocean and Coastal Management* **43**: 99-122. Elsevier Science Ltd

Ferreira, J.G, 2005. Institute of Marine Research. DCEA-FCT, Qta Torre, Potugal. joao@hommi.com. Personal communication.

GESAMP (IMO/FAO/Unesco/IAEA/WHO/WMO/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution), 1984. Thermal discharges in the marine environment. Reputable Studies GESAMP, (**24**): 44 p.

Giangaspero, A., Molini, U., Iorio, R., Traversa, D., Paoletti, B., and Giansante, C., 2005. *Cryptosporidium parvum* oocysts in seawater clams (*Chamelea gallinia*) in Italy. *Preventative Veterinary Medicine* ***69**:* 203-212.

Grall, J., and Glémarec, M., 1997. Using biotic indices to estimate macrobenthic community perturbations in the Bay of Brest. *Estuarine and Coastal* Shelf Science **44**: 43-53.

Griggs, G.B., Grimanis, A.P., and Grimani, M.V., 1977. Bottom sediments in a polluted marine environment. *Limnology Oceanography*, **11**: 319-326.

Grimm, J.W., Lynch, J.A., 2005. Improved daily precipitation nitrate and ammonium concentration models for Chesapeake Bay watershed. *Environmental Pollution* **135**: 445-455.

Grindley, J.R., 1985. Report no 30: Knysna (CMS 13). In: Heydorn, A.E.F. and Grindley, J.R. (eds.). Estuaries of the Cape. Part II: Synopsis of available information on individual systems. CSIR Research Report No. **429**. 83 pp.

Harcourt-Baldwin, J.L., 2003. *Water Circulation within Tomales Bay, California, U.S.A.- a Mediterranean Climate Estuary.* Unpublished PHD Thesis. University of Cape Town. South Africa. 237pp

Harding, L.W., 1994. Long term trends in the distribution of phytoplankton in Chesapeake Bay: roles of light, nutrients and streamflow. Marine *Ecology Progress Series* **104:** 267-291.

Harding, L.W., Magnuson, A., and Mallonee, M.E., 2005. SeaWiFs retrievals of chlorophyll in Chesapeake Bay and the mid-Atlantic bight. *Estuarine Coastal and Shelf Science* **62**: 75-94

Harrison, T.D., 2004. Physico-chemical characteristics of South African estuaries in relation to the zoogeography of the region. *Estuarine Coastal and Shelf Science* **61**: 73-87

Heydorn, A.E.F., and Tinley, K.L., 1980. Estuaries of the Cape, Part I. Synopsis of the Cape Coast. Natural features, dynamics and utilization. Stellenbosh. *CSIR Research Report* 380. 96 pp.

Hilly, C., 1984. Variabilité de la macrofaune dans les milieux hypertrophiques de la Rade de Brest. Thése de Doctorat d'Etat, Univ. Bretange Occidentale, Vol.**1**, 359 pp., Vol.**2**, 337 pp.

Hodkin, E.P., 1994. Estuaries and coastal lagoons. In: Hammond, L.S., Synnot, R.N., (Eds.), *Marine Biology*. Longman Cheshire, Melbourne, pages 315-332.

Holland, A.F., Sanger, D.M., Gawle, C.P., Lerberg, S.B., Santiago, M.S., Riekerk, G.H.M., Zimmerman, L.E., and Scott, G.I., 2004. Linkages between tidal ecosystems and the landscape and demographic attributes of their watersheds. *Journal of Experimental Biology and Ecology* **298**: 151-178.

Hong, H.S. and Shang, S.L. 1998. The input fluxes of phosphorus in Xiamen Western Sea. 1. In Zhang, J. (ed) *Land-Sea Interaction in Chinese Coastal Zones,* China Ocean Press, pages 144-157.

Horenz, J.W.G., 1987. Land use planning in the greater Algola Bay metropolatian area with special reference to the Swartkops Estuary. Pages 57-63. In: Baird, D., Marais, J.F.K., and Martin, A.P., (eds.): The Swartkops Estuary. Proceedings of a symposium held on the 14 and 15 September 1987 at the University of Port Elizabeth. *South African National Scientific Programmes Report* No. 156.

Horton, T., 2005. Saving the Chesapeake. Conservationists know what wrong with the bay and how to fix it. They also know why it won't happen soon. *National Geographic.* June 2005. Pages 22-45.

Houde, E.D., Jukie-Peladic, S., Brandt, S.B., and Leach, S.D., 1999. Fisheries: trends in catches, abundances and management. In: Malone, T.C., Malej, A., Harding, L.W., Smodlaka, N., and Turner, R.E, (eds.), *Ecosystem at the land-sea margin, Coastal and Estuarine Studies* Vol. **55**: 341-366. Washington, DC: American Geophysical Union.

IPCC, 2001.*Climate Change 2001: Impacts, Adaptations, and Vulnerability*, Ed. McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S. Cambridge, UK: Cambridge University Press: 1000 pp.

Jennings, S., and Kaiser, M.J., 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology* **34**: 201-352.

Jung, S., and Houde, E.D., 2003. Spatial and temporal variabilities of pelagic fish community structure and distribution in Chesapeake Bay, USA. *Estuarine Coastal and Shelf Science* **58**: 335-351.

Karuppiah, M., Gupta, G., 1998. Chronological changes in toxicity of and heavy metals in sediments of two Chesapeake Bay tributaries. *Journal of Hazardous Materials* 59: 159-166

Kemp, W.M., Boynton, W.R., and Means, J.C., 1983. The decline of submerged vascular plants in upper Chesapeake Bay: summary of results concerning possible causes. *Marine Technology Society Journal* **17** (2): 78-79.

Kemp, W. M., Smith, E. M., Marvin-DiPasquale, M., and Boynton, W. R., 1997. Organic carbon balance and net ecosystem metabolism in Chesapeake Bay. *Marine Ecology--Progress Series* **150**: 229-248.

Kennish, M.J., 1997. *Practical Handbook of Estuarine and Marine Pollution.* Boca Raton, USA: CRC Press: 524pp.

Kennish, M.J., 2001. *Practical Handbook of Marine Science,* Third Edition. Boca Raton, USA: CRC Press: 876 pp.

Kennish, M.J., 2002. Environmental threats and environmental future of estuaries. In: *Environmental Conservation* **29** (1): 78-107.

Kinne, O., 1971. Invertebrates. In: *Marine Ecology.* Wiley Interscience, London. Pages 822-995.

Kjerfve, B., 1989. Estuarine geomorphology and physical oceanography. In: *Estuarine Ecology,* ed. Day (Jr.), J.W., Hall C.A.S., Kemo W.M., and Yanez-Aranibia, A. Pages 47-78. New York, USA: John Wiley and Sons.

Knysna Municipality. Intergrated Development Plan 2002-2005. Government Publications.

Lacerda, L.D., 1998. Biogeochemistry of trace metals and diffuse pollution in Mangrove Ecosystems. *Mangrove Ecosystems Occasional Papers* No. 2. International Society for Mangrove Ecosystems, Okinawa (Japan), p. 65

Laffloey, D. d'A and Hiscock, K., 1993. The classification of benthic estuarine communities for nature conservation assessments in Great Britain. *Netherlands Journal of Aquatic Biology* **27**: 181-187.

Largier, J.L., Attwood, C., Harcourt-Baldwin, J-L., 2000. The hydrographic character of the Knysna Estuary. *Transactions of the Royal society of South Africa.* Vol. **55** (2): 107-122

Ledley, T.S., Sundquist, E.T., Schwartz, S.E., Hall, D.K., Fellows, J.D., and Killeen, T.L., 1999. Climate change and greenhouse gases. *Eos* **80**: 453-458.

Llanso, R.J., Scott, L.C., Dauer, D.M., Hyland, J.L., and Russel, D.E., 2002. An estuarine benthic index of biotic integrity for the Mid Atlantic region of the United States. I. Classification of assessemblages and habitat definition. *Estuaries.* Vol. 25, No. 6A: 1219-1230.

Lord, D.A. and Thompson, G.A. 1987. The Swartkops Estuary: Pollution status. Pages16-24. In Baird, D., Marais, J.F.K. and Martin, A.P. (eds.): *The Swartkops estuary.* Proceedings of a symposium held on 14 and 15 September 1987 at the

University of Port Elizabeth. South African National Scientific Programmes Report No. 156.

Lubbers, L., Boynton, W.R., and Kemp, W.M., 1990. Variations in structure of estuarine fish communities in relation to abundance of submerged vascular plants. *Marine Ecology Progress Series* **65**: 1-14.

Majeed, S.A., 1987. Organic matter and biotic indices on the beaches of North Brittany. *Marine Pollution Bulletin* **18**: 490-495.

Malan, H.L., and Day, J.A., 2002. Linking discharge, water quality and biotic response in rivers: a literature review. *WRC Report No.* 956/2/02, 132pp.

Malone, T.C., Crocker, L.H., Pike, S.E., and Wendler, B.W., 1988. Influences of river flow on the dynamics of phytoplankton in a partially stratified estuary. *Marine Ecology Progress Series* **48**: 235-249.

Maree, B., 2000. Structure and status of intertidal wetlands of the Knysna Estuary *Transactions of the Royal society of South Africa.* Vol. **55** (2): 107-122

Maree, R.C., Whitfield, A.K., and Quinn N.W., 2003. Prioritisation of South African Estuaries Based on Their Potential Importance to Estuarine Associated Fish Species. *Water Research Commission.* Report No. TT203/03, Pretoria.

Marker, M.E., 2003. The Knysna Basin, South Africa: geomorphology, landscape sensitivity and sustainability. *The Geographical Journal*, Vol. **169**, No 1, March: 32-42.

Martin, P., Koff, J.V., and Watt, L., 2000. Abundance and distribution of waterbirds on the Knysna Estuary. *Transactions of the Royal Society of South Africa* **55(2)**: 215-222.

Maryland Department of Natural Resources, 2005. *Chesapeake Bay. Bay monitoring. Monitoring for Management actions.* 4. Physical and Chemical Properties http://www.dnr.state.md.us/bay/monitoring/mon_mngmt_actions/chapter4.html

Mason, R.P., Lawson, N.M., Sullivan, K.A., 1997. Atmospheric deposition to Chesapeake Bay watershed-regional and local sources. *Atmospheric Environment*, Vol. 31, No. 21: 3531-3540.

McComb, A.J., 1995. *Eutrophic Shallow Estuaries and Lagoons.* Boca Raton, USA: CRC Press: 240 pp.

Morant, P.M., and Quinn N., 1999. Influence of man and management of South African estuaries. In: *Estuaries of South Africa. ed.* Allanson, B.R., and Baird, D., Pages 27 -52. Cambridge University Press. United Kingdom.

Morgan, C., Owens, N., 2001. Benefits of water quality policies: the Chesapeake Bay. *Ecological Economics* **39**: 271-284

Moverly, J., 2000. *Estuarine health assessment using benthic macrofauna*. Museum of Victoria.

Murdy, E.O., Birdsong, R.S., and Musick, J.A. 1997. *Fishes of Chesapeake Bay*. 324 pp. Washington DC/ London: Smithsonian Institution Press.

Muxika, I., Borja, A., and Bonne, W., 2005. The suitability of a marine biotic index (AMBI) to new impact sources along the European Coasts. *Ecological Indicators* **5**: 19-31.

National Estuary Program, 1997a. Nutrient overloading. Technical report, US Environmental Protection Agency, Washington, DC, USA: 21pp.

National Estuary Program, 1997b. Management approaches being used to address critical issues. Technical report, US Environmental Protection Agency, Washington, DC, USA: 16 pp.

Nixon, S.W., 1988. Physical energy inputs and the comparative ecology of lake and marine ecosystems. *Limnology and Oceanography* **33** (Part 2): 1005-1025.

Nixon, S.W., 1995. Coastal marine eutrophication: a definition, social causes, and future consequences. *Ophelia* **41**: 199-219.

NOAA (National Oceanographic and Atmospheric Administration), 1991. *Strategic Assessment of Near Coastal waters. Susceptibility and Status of West Coast Estuaries to Nutrient Discharges: San Diego Bay to Puget Sound. Summary Report, 1991.*

Norton, M.M., and Fisher, T.R., 2000. The effects of forest on stream water quality in two coastal plains of the Chesapeake Bay. *Ecological Engineering* **14**: 337-362.

NRC (National Research Council), 2000. *Clean coastal waters understanding and reducing the effects of nutrient pollution.* National Academy Press, Washington DC USA. 405 pp.

Officer, C.B., Biggs, R.B., Taft., J.L., Cronin, L.E., Tyler, M.A., and Boynton, W.R., 1984. Chesapeake Bay anoxia: origin, development and significance. *Science* **223**: 22-27.

Opdyke, B.N., Suzuki, A., Davies, P., and Brunskill, G., 2000. *Fly River.* http://data.ecology.su.se/mnode/Pacific/NewGuinea/FlyRiver/flyrbud.htm

Orth, R.J., Batiuk, R.A., Bergstrom, P.W., and Moore, K.A., 2002. A perspective on two decades of policies and regulations influencing the protection and restoration of *submerged* aquatic vegetation in *Chesapeake* Bay, USA. *Bulletin of Marine Science*, Vol. **71**, No. 2: 1391-1403.

Paul, J.F., Scott, K.J., Campbell, D.E., Gentile, J.H., Stroble, C.S., Valentene, R.M., Weisberg, J.B., Holland, A.F., and Ranasinghe, J.A., 2001. Developing and applying a benthic index of estuarine condition for the Virginian Biogeographic Province. *Ecological Indicators* **1**: 83-99.

Pearce, M.W., and Schumann, E.H., 1997. The effect of land use on Gamtoos Estuary water quality. *Water Research Commission* Report No.503/1/97. 170 pp.

Pethick, J.S., 1993. Shoreline adjustments and coastal management: physical and biological processes under accelerated sea level rise. *The Geographical Journal* **159**: 162-168.

Pinnegar, J.K., Polunin, N.V.C., Francour, P., Badalamenti, F., Chemello, R., Harmelin-Viviien, M.-L, Hereu, B., Milazzo, M., Zabala, M., D'Anna, G. and Pipitone, C., 2000. Trophic cascades in benthic marine ecosystems: lessons for fisheries and protected-area management. *Environmental conservation* **27**: 179-200.

Prandle, D.A., 1984. A modeling study of the mixing of 137C's in the sea of the European continental shelf. *Philosophical Transaction of the Royal Society of London* **310**: 407-436

Prichard, D.W., 1952. Salinity distribution and circulation in Chesapeake Bay estuaries system. *Journal Marine Research,* **11**: 106-123

Prichard, DW 1955. Estuarine circulation Patterns. *Proceedings of the American Society of Civil. Engineering,* **81**, No. 717: 1-11.

Prichard, D.W., 1967. What is an estuary: a physical viewpoint. *American Association for the Advancement of Science* **83**: 3-5.

Prochazka, K., Allanson, B., Baird, D., Branch, G., Brown, A., Clark, B., Hanekom, N., Hecht, T., Hockey, P., Hutchings, K., Morant, P., Russell, I., Whitfield, A., and Wooldridge, T., 2002a. *Prioritising C.A.P.E estuaries for conservation.*
fred.csir.co.za/extra/**cape**/reports/ ProchazkaK_et_al_Estuarine_Report_Part1.doc

Prochazka, K., Allanson, B., Baird, D., Branch, G., Brown, A., Clark, B., Hanekom, N., Hecht, T., Hockey, P., Hutchings, K., Morant, P., Russell, I., Whitfield, A., and Wooldridge, T., 2002b. *An assessment of the threats to estuarine systems of the C.A.P.E. region and a preliminary method of prioritising estuaries for conservation of biodiversity.*
fred.csir.co.za/extra/**cape**/reports/ ProchazkaK_et_al_Estuarine_Report_Part2.doc

Ramm, A.E.L. 1988. The Community Degradation Index: a new method for assessing the deterioration of aquatic habitats *Water Research* **22**: 293-301.

Ramm, A.E.L. 1990. Application of the community degradation index to South African estuaries. *Water Research* **24**: 383-389.

Reddering, J.S.V. and Esterhuysen, K., 1981. Sedimentation in the Sundays estuary. University of Port Elizabeth. *ROSIE Report* No. **3**: 1-48.

Richardson, A.M., 1997. *Development of an estuarine quality index (eWQI) for New South Wales.,* BSc. (Honours), University of Sydney, Sydney. 148 pp

Ridge, T., Pillinger, P., and Walters, S., 1995. Alleviating the problems of excessive algal growth, Pages 211-218. In Harper, D.M., and Ferguson, A.J.D. (Eds.). *The Ecological Basis for River Management.* John Wiley and Sons. Chichester.

Rizzo, W.M., Berry, B.E., Wetzel, R.I., Dailey, S.K., Lackey, G.J., and Christian, R.R., 1996. A metabolism-based trophic index for comparing ecological values of shallow-water habitats. *Estuaries,* Vol. **19**, No 2A: 247-256

Roberts R.D., Gregory, M.R., and Foster, B.A., 1998. Developing an efficient macrofauna monitoring index from an impact study-a dredge spoil example. *Marine Pollution Bulletin.* **36**, 231-235

Rogers, G., 2005. The Herald Online. Storage plan proposed for Swartkops bait resource. http://www.epherald.co.za/herald/2003/07/15/news/n12_15072003.htm

Rosales-Hoz, L.., Cundy, A.B., and Bahena-Manjarrez, J.L., 2003. Heavy metals in sediment cores from a tropical estuary affected by anthropogenic discharges: Coatzacoalcos estuary, Mexico. *Estuarine Coastal and Shelf Science* **58**:117-126.

Rygg, B., 1985. Distribution of species along pollution- induced diversity gradients in benthic communities in Norwegian fjords. *Marine Pollution Bulletin* **16**, No.12: 469-474.

Salomons, W., and Förstner, U., 1984. In: *Metals in the hydrocycle*, Springer, Heidelberg, Germany, p. 337.

Scharler, U.M., Baird, D., 2003. The influence of catchment management on salinity, nutrient stochiometry and phytoplankton biomass of Eastern Cape estuaries, South Africa. *Estuarine, Coastal and Shelf Science* **56**:735-748.

Schumann, E.H., Largier, J.L., and Slinger, J.H., 1999. Estuarine hydrodynamics. In: *Estuaries of South Africa., ed.* Allanson, B.R., and Baird, D., pages 27 -52. Cambridge University Press. United Kingdom.

Smith, S.V., and Webb, K.L., 1999. *NP Budget of Chesapeake Bay, USA.* http://data.ecology.su.se/MNODE/North%20America/chesapeake/ches2/ches2.htm

Smith, V.H., Tilman, G.D., and Nekola, J.C., 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine and terrestrial ecosystems. *Environmental Pollution* **100**: 179-196.

Smith, D.A., and Rule, M.J., 2001. The effects of dredge-spoil dumping on shallow water soft-sediment community in the Solitary Islands Marine Park, NSW, *Australia Marine Pollution Bulletin* **42**: 1040-1048.

Stambuk-Giljanovic, N., 1999. Water quality equation index in Dalmatia. *Water Research,* **33** (16): 3423-3440.

Statistics South Africa, 2005, 1996. *Census Community Profile Data.* http://www.statssa.gov.za/

Stevenson, J.C., Staver, L.W., and Staver, K.W., 1993. Water quality associated with survival of submerged aquatic vegetation along an estuarine gradient. Estuaries **16** (2): 336-346.

Stone, S.L., Lowery, T.A., Field, J.D., Jury, S.H., Nedson, D.M., Manaco, M.E., Williams, C.D., and Andreasen, L., 1994. Distribution and abundance of fishes and invertebrates mid-Atlantic estuaries. 280 pp. *Estuarine Living Marine Resources Report* No. 12. NOAA/NOS Strategic Environmental Assessments Division, Silver Spring, MD.

Strydom, N.A., Whitfield, A.K. and Wooldridge, T.H. 2003. The role of estuarine type in characterizing early stage fish assemblages in warm temperate estuaries, South Africa. *African Zoology* **38**(1): 29-43.

Summers, J.K., Macauley, J.M., Heitmuller, P.T., Engle, V.D., Adams, A.M., and Brooks, G.T., 1992. *Annual statistical summary*: EMAP-E Louisianian Province-1991.United Sates Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Gulf Breeze, Florida EPA/600/X-92/069. 101 pp.

Surge, D.M. and Lohmann, K.C, 2002. Temporal and spatial differences in salinity and water chemistry in SW Florida estuaries: effects of human-impacted watersheds. *Estuaries*, **25**(3): 393-408.

Sweeting, R.A., 1994. River Pollution. Pages 23-32 in Calow, P., and Petts, G.E. (Eds.). *The Rivers Handbook, Vol. 2*. Blackwell Scientific Publications, Oxford.

Switzer, T., 2003. *Nitrogen and Phosphates Processes in the Knysna River Estuary.* Unpublished PHD Thesis. University of Cape Town. South Africa.

Switzer, T., and Waldron, H., 2002. Knysna Lagoon, Western Cape. In: Dupra, V., S.V., Smith, S.V., David, L.T., Waldron, H., Marshall Crossland, J.I., and C.J., Crossland (Eds.). Estuarine systems of South Africa (Regional Workshop II): Carbon Nitrogen and Phosphorus fluxes. *LOICZ Reports and Studies* No. 20: 24-30. **http://wwwold.nioz.nl/loicz/**

The Economist Newspaper Limited, 2005. *The Big Mac Index.*
http://www.economist.com/markets/bigmac/displayStory.cfm?story_id=2708584

The World Bank Group, 2005. *Country classification.*
http://www.worldbank.org/data/countryclass/countryclass.html

Townend, I., 2002. Marine science for strategic planning and management: the requirement for estuaries. *Marine Policy* **26**: 209-219

Turpie, J.K., 1995. Prioritising South African estuaries for conservation: a practical example using waterbirds. *Biological conservation* **74**:175-185.

Turpie, J.K., 2000. Classification and prioritisation of South African estuaries on the basis of health and conservation priority status for determination of the estuarine water reserve. *Report to the Department of Water Affairs and Forestry.*

Turpie, J.K., Adams, J.B., Joubert, A., Harrison, T.D., Colloty, B.M., Maree, R.C., Whitfield, A.K., Wooldridge, T.H., Lamberth, S.J., Taljaard, S., and Van Niekerk, L., 2002. Assessment of the conservation priority status of South African estuaries for use in management and water allocation. *Water SA.* Vol. **28**. No. 2: 191-206.

Turpie, J.K., Colloty, B., Joubert, A., Harrison, T., Maree, R., Taljaard, S., van Niekerk, L., Whitfield, A., Wooldridge, T., Lamberth, S., Taylor. R., Morant, P., Awad, A., Weston, B., and Mackay, H., 1999. Detailed Documentation on the Estuarine Health Index. 18 pp.

University of Maryland, 2003. *Fish health in Chesapeake Bay.*
http://www.mdsg.umd.edu/fish-health/

US Census Bureau, 2005. http://www.census.gov/

USA, Environmental Protection Agency, 2005.
http://www.epa.gov/owow/estuaries/about1.htm

Valiela, I., Kremer. J., Lajtha, K., Geist, M., Seely, B., Brawley, J., and Sham, C.H., 1997. Nitrogen loading from coastal watersheds to receiving estuaries: new method and application. *Ecological Applications* 7: 358-380.

Valle-Levinson, A., Lwiza, K.M.M., 1997. Bathymetric influences on the lower Chesapeake Bay hydrography. Journal of Marine Systems **12:** 221-236.

van de Kreeke, J., 1983. Residence time: application to small boat basins. ASCE Journal of waterway, Port, Coastal and Ocean Engineering 109 (4): 416-428.

Van dolah, R.F., Hyland, J.L., Holland, A.F., Rosen, J.S., and Snoots, T.R., 1999. A benthic index of biotic integrity for assessing habitat quality in estuaries of the southeastern USA. *Marine Environmental Resources*, **48**: 269-283.

van Niekerk, L., van der Merwe, J.H., and Huizinga, P., 2005. The hydrodynamics of the Bot River Estuary revisited. *Water SA.* Vol. **31**. No.1: 77-86

Venice System, 1958. Symposium on the classification of brackish waters, Venice April 8-14, 1958. *Archives Oceanography and Limnology* **11,** suppl., 1-248.

Verhoff, F.H., Melf, D.A., and Yaksich, S.M., 1982. An analysis of total phosphorus transport in river systems. *Hydrobiologia* **91,** 241-252.

Walski, T.M., and Parker, F.L., 1974. Consumers water quality index. *Journal of Environmental Engineering Division* **27**: 593-611.

Wang, C.F., Hsu, M.H., Kuo, A.Y., 2004. Residence time of the Dansheui River estuary, Taiwan. *Estuarine Coastal and Shelf Science* **60**: 381-393.

Washington, H.G., 1984. Diversity, biotic and similarity indices: a review with special relevance to aquatic systems. *Water Research* **18**: 653-694.

Weber, T, 2004. Landscape ecological assessment of the Chesapeake Bay watershed. *Environmental Monitoring Assessment* **94** (1-3): 39-53.

Weisberg, S.L., Fritthsen, J.B., Holland. A.F., Paul, J., Scott, K.J., Summers, J.K., Wilson, H., Valente, R., Heimbuch, D., Gerriktsen, J., Schimmel, S. and R., Latimer, 1992. *EMAP-Estuaries Virginian Province 1990 Demonstration Project Report.* United Sates Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Narragansett, Rhode Island. EPA/600/01-92/XXX.

Weisberg, S.B., Ranasinghe, J.A., Schaffner, L.C., Diaz, R.J., Dauer, D.M., and Frithsen, J.B., 1997 An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. *Estuaries* **20**: 149-158.

Wepener, V., Cyrus, D.P., Vermeulen, L.A., O'Brien, G.C., and Wade, P., unpubl. Development of an estuarine water quality index for implementation in Southern Africa. *WRC Project* K5/1163. Department of Zoology RAU University, Coastal Research University of Zululand and PhoKus Technologies. 117 pp.

Whithall, D., Castro, M., and Driscoll, C., 2004. Evaluation of management strategies for reducing nutrient loadings to four US estuaries. *Science of the Total Environment* **333**: 25-36.

Whitfield, A.K., 1994. Abundance of larval and o + juvenile marine fishes in the lower reaches of three southern African estuaries with differing freshwater inputs. *Marine Ecology Progress Series, **105**, 257-67.*

Whitfield A.K., and Marias, J.F.K., 1999. The ichthyofauna: ichthyoplankton diversity, recruitment and dynamics. In: *Estuaries of South Africa., ed.* Allanson, B., Baird, D., pages 209-233. Cambridge University Press. United Kingdom.

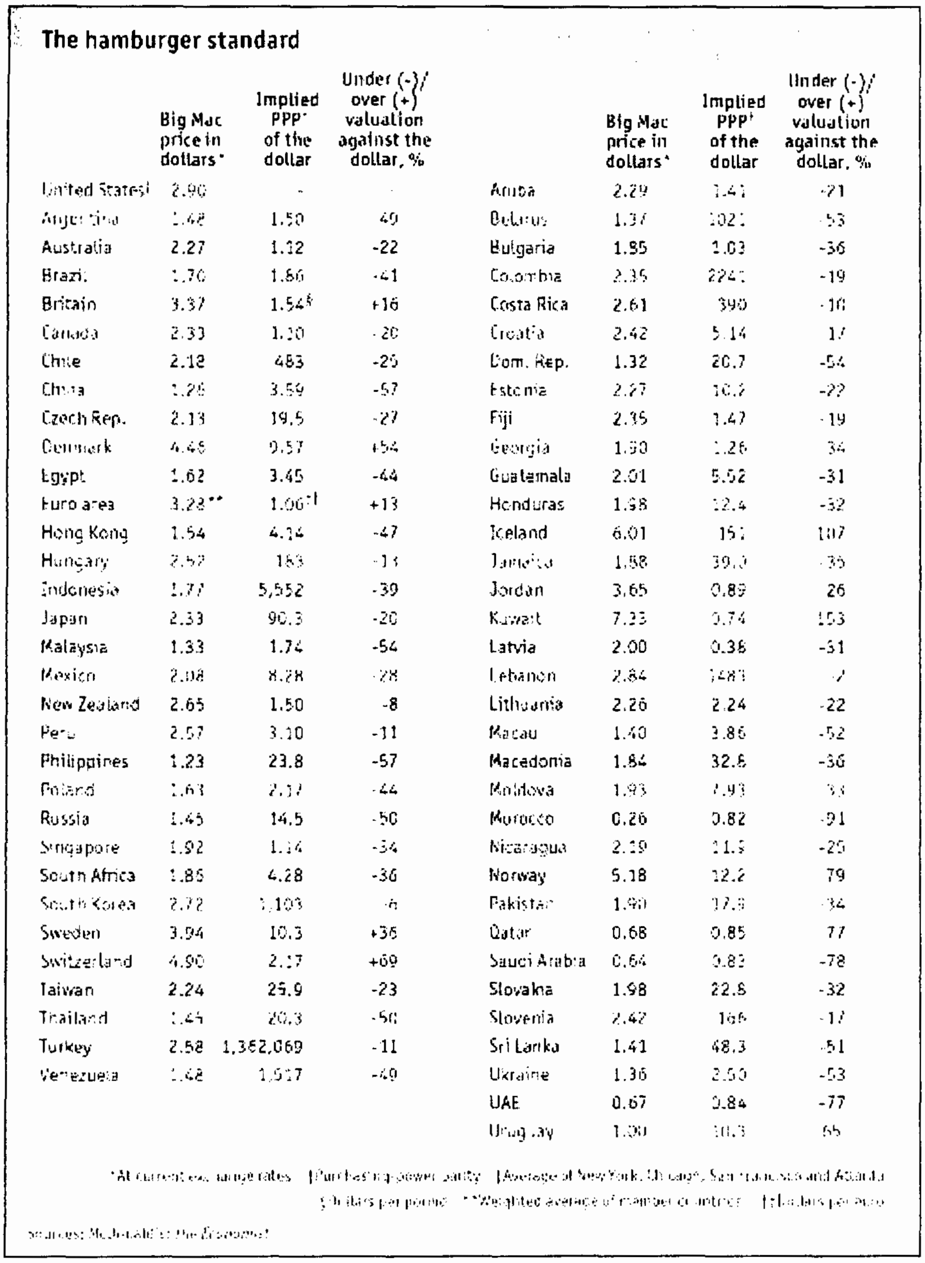
Whitfield, A.K., 2000.Available scientific information on individual South African estuarine system. *Water Research Commission.* Report Number 577/3/00. South Africa.

Whitford, D.J., 1999. Observations of current flow through the mouth of the Chesapeake Bay. *Estuarine, Coastal and Shelf Science* **49**: 209-220.

Winter, P.E.D. and Baird, D. 1991. The exchange of phosphate between the Swartkops Estuary and Algoa Bay. *South African Journal of Science.* **87**: 192-197.

Wolanski, E., and Chappell, J., 1996. The response of tropical Australian estuaries to sea level rise. *Journal of Marine Systems* 7: 267-279.

Appendix I: Big Mac Index



The hamburger standard

	Big Mac price in dollars*	Implied PPP† of the dollar	Under (-)/ over (+) valuation against the dollar, %
United States‡	2.90	-	-
Argentina	1.48	1.50	-49
Australia	2.27	1.12	-22
Brazil	1.70	1.86	-41
Britain	3.37	1.54§	+16
Canada	2.33	1.10	-20
Chile	2.18	483	-25
China	1.26	3.59	-57
Czech Rep.	2.13	19.5	-27
Denmark	4.46	9.57	+54
Egypt	1.62	3.45	-44
Euro area	3.28**	1.06††	+13
Hong Kong	1.54	4.14	-47
Hungary	2.52	183	-13
Indonesia	1.77	5,552	-39
Japan	2.33	90.3	-20
Malaysia	1.33	1.74	-54
Mexico	2.08	8.28	-28
New Zealand	2.65	1.50	-8
Peru	2.57	3.10	-11
Philippines	1.23	23.8	-57
Poland	1.63	2.17	-44
Russia	1.45	14.5	-50
Singapore	1.92	1.14	-34
South Africa	1.86	4.28	-36
South Korea	2.72	1,103	-6
Sweden	3.94	10.3	+36
Switzerland	4.90	2.17	+69
Taiwan	2.24	25.9	-23
Thailand	1.45	20.3	-50
Turkey	2.58	1,362,069	-11
Venezuela	1.48	1,517	-49

	Big Mac price in dollars*	Implied PPP† of the dollar	Under (-)/ over (+) valuation against the dollar, %
Aruba	2.29	1.41	-21
Belarus	1.37	1021	-53
Bulgaria	1.85	1.03	-36
Colombia	2.35	2241	-19
Costa Rica	2.61	390	-10
Croatia	2.42	5.14	17
Dom. Rep.	1.32	20.7	-54
Estonia	2.27	10.2	-22
Fiji	2.35	1.47	-19
Georgia	1.90	1.26	34
Guatemala	2.01	5.52	-31
Honduras	1.98	12.4	-32
Iceland	6.01	151	107
Jamaica	1.88	39.0	-35
Jordan	3.65	0.89	26
Kuwait	7.33	0.74	153
Latvia	2.00	0.36	-31
Lebanon	2.84	1483	-2
Lithuania	2.26	2.24	-22
Macau	1.40	3.86	-52
Macedonia	1.84	32.6	-36
Moldova	1.93	7.93	33
Morocco	0.26	0.82	-91
Nicaragua	2.19	11.3	-25
Norway	5.18	12.2	79
Pakistan	1.90	17.9	-34
Qatar	0.68	0.85	77
Saudi Arabia	0.64	0.83	-78
Slovakia	1.98	22.6	-32
Slovenia	2.42	166	-17
Sri Lanka	1.41	48.3	-51
Ukraine	1.36	2.50	-53
UAE	0.67	0.84	-77
Uruguay	1.00	10.3	65

*At current exchange rates †Purchasing-power parity ‡Average of New York, Chicago, San Francisco and Atlanta §Dollars per pound **Weighted average of member countries ††Dollars per euro

Sources: McDonald's; *The Economist*

The Economist Newspaper and The Economist Group, 2005. The Big Mac Index. http://www.economist.com/markets/bigmac/displayStory.cfm?story_id=2708584

Appendix II: Matlab Script

Matlab Script

a) Socio-Economic Threat Index

Script 1

```
%new TACM data generator
%working
function [input_combinations, output_combinations] = do_combinations
num_vars = 8;
num_values = 5;
num_combinations = num_values.^num_vars;
inputs = zeros( num_combinations, num_vars );

count = 1;
for land_use = 1:num_values,
    for gni= 1:num_values,
        for developed = 1:num_values,
            for sm = 1:num_values,
                for e = 1:num_values,
                    for ch = 1:num_values,
                        for eu = 1:num_values,
                            for s = 1:num_values,
                                inputs( count, :) = [land_use,developed,gni,sm,e,ch,eu,s];
                                count = count + 1;
                            end
                        end
                    end
                end
            end
        end
    end
end
output_combinations = socio_eco (inputs);
```

```
input_combinations = inputs;
```

Script 2

```
%new TACM Socio-Economic Threat Index
%working
function [outputs] = socio_eco(inputs)

[rows,cols] = size(inputs);
outputs = zeros(rows,4);

land_use = inputs(:,1);
developed = inputs(:,2);
gni = inputs(:,3);
sm = inputs (:,4);
e = inputs (:,5);
ch = inputs (:,6);
eu = inputs (:,7);
s = inputs (:,8);

outputs(:,1) = land_use;
outputs(:,2) = floor((developed+gni)/2);
outputs(:,3) = floor((sm+e+ch+eu+s)/5);
outputs(:,4) = floor((outputs(:,1)+outputs(:,2)+outputs(:,3))/3);
```

b) Physical Mitigation Index

Script 1

```
%new TACM physics data generator
%working
function [input_combinations, output_combinations] = do_combphys
num_vars = 4;
num_values = 5;
num_combinations = num_values.^num_vars;
inputs = zeros( num_combinations, num_vars );
```

```
count = 1;
for residencetime= 1:num_values,
    for estuarynumber= 1:num_values,
        for coastalexchange = 1:num_values,
            for closedocean = 1:num_values,

                                inputs( count, :) = [residencetime, estuarynumber,
coastalexchange, closedocean];
                                count = count + 1;
                            end
                        end
                    end
                end
           output_combinations = physics(inputs);
input_combinations = inputs;
```

Script 2

```
%new TACM physics
%working
function [outputs] = physics(inputs)

[rows,cols] = size(inputs);
outputs = zeros(rows,6);

residencetime = inputs(:,1);
estuarynumber = inputs(:,2);
coastalexchange = inputs(:,3);
closedocean = inputs (:,4);

outputs(:,1) = residencetime;
outputs(:,2) = estuarynumber;
outputs(:,3) = coastalexchange;
outputs(:,4) = ((outputs(:,1)+outputs(:,2)+ outputs (:, 3))/3);
outputs(:,5) = closedocean;
```

```
outputs (:,6) = floor((outputs(:,4)+outputs(:,5))/2);
```

c) Chemical Impact Index

Script 1

```
%new TACM wq data generator

function [input_combinations, output_combinations] = do_combwq
num_vars = 3;
num_values = 5;
num_combinations = num_values.^num_vars;
inputs = zeros( num_combinations, num_vars );

count = 1;
for nitrogen = 1:num_values,
   for phosphorus= 1:num_values,
      for oxygen = 1:num_values,


                  inputs( count, :) = [nitrogen, phosphorus, oxygen];
                  count = count + 1;
               end
            end
         end

        output_combinations = wq(inputs);
input_combinations = inputs;
```

Script 2

```
%new TACM water qual
%working
function [outputs] = wq(inputs)

[rows,cols] = size(inputs);
outputs = zeros(rows,4);
```

```
nitrogen = inputs(:,1);
phosphorus = inputs(:,2);
oxygen = inputs(:,3);

outputs(:,1) = nitrogen;
outputs(:,2) = phosphorus;
outputs(:,3) = oxygen;
outputs(:,4) = floor ((outputs(:,1)+outputs(:,2)+ outputs (:, 3))/3);
```

Table 1: The results of the Matlabscript, entered into Microsoft Excel and converted to percentages.

Socio-Economic Threat Index			
grade	no of times output	total	% occurred
1	18708	390625	4.79
2	172667		44.20
3	177796		45.52
4	21453		5.49
5	1		0.0002560
Physical Index			
grade	no of times output	total	% occurred
1	625	3125	20
2	625		20
3	625		20
4	625		20
5	625		20
Chemical Index			
grade	no of times output	total	% occurred
1	125	625	20
2	125		20
3	125		20
4	125		20
5	125		20

Appendix III: Extra Case Studies

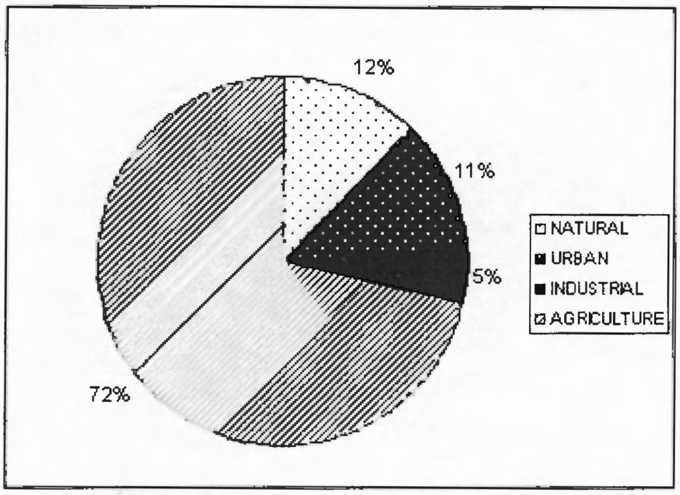


Figure 1: Approximated land use in the Humber Estuary's catchment

The Humber Estuary is located in the United Kingdom and it has a catchment area of 24240 km^2. It has a population density of 5.75 people/ha (Cave *et al.*, 2003). The wealth of the people living in the catchment was estimated to be high income as its catchment is situated in a first world country (the United Kingdom).

The mouth of the Humber Estuary is continually dredged as it is used as a shipping channel. Encroachment of agriculture onto the banks of the estuary is high (83%) (Cave *et al.*, 2003). The amount of dams and impoundments was estimated to be average (3). The estuary's fish are caught recreationally and commercially. The commercial fisheries are small and part time (Cave *et al.*, 2003). Therefore it was estimated that the extractive activities in the estuary are sustainable. The amount of sewerage or sewerage effluent flow was determined to be high. This is due to the fact that 76 sewerage treatment plants are pumping treated sewerage into the estuary (EA, 1998b). These sewerage treatment plants currently do not remove phosphorus from the sewerage before it flows into the estuary and sea (Cave *et al.*, 2003).

The TaCM’s Socio-Economic Threat Index determined that the human activities in the Humber Estuary’s catchment have the potential to severely threaten the estuary’s health.

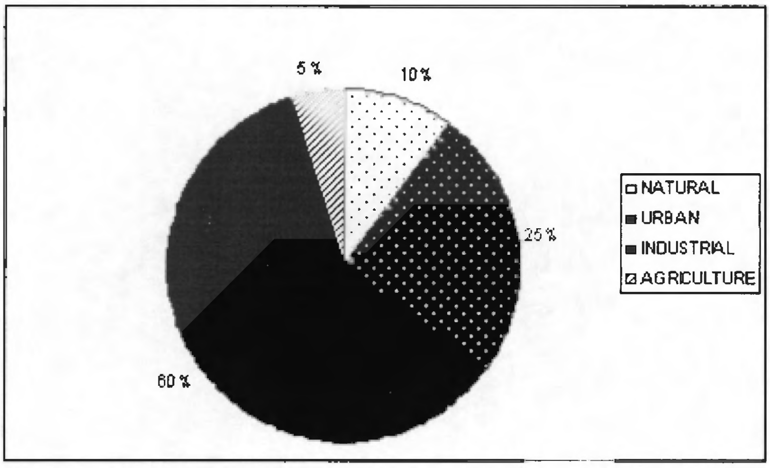


Figure 2: Approximated land use in the Coatzacoalcos Estuary’s catchment

The Coatzacoalcos Estuary is situated in the south eastern part of Mexico (17°46’N 92 ° 25’-94 °31’W) and has a highly industrialized catchment (Rosales-Hoz *et al*, 2003). It was therefore hypothesized that it would have a large population density and the wealth was estimated to be upper middle. This hypothetical estuary’s mouth is breached periodically. The encroachment of developed areas onto the intertidal banks is very high and the utilization of the estuary is high. There will be at least a moderate abstraction of water as most industries use a lot of water. The amount of sewerage or sewerage effluent input into the estuary will be high as industries usually generate a lot of wastewater.

The TaCM’s Socio-Economic Threat Index determined that the human activities in the Coatzacoalcos Estuary’s catchment have the potential to severely threaten the estuary’s health.

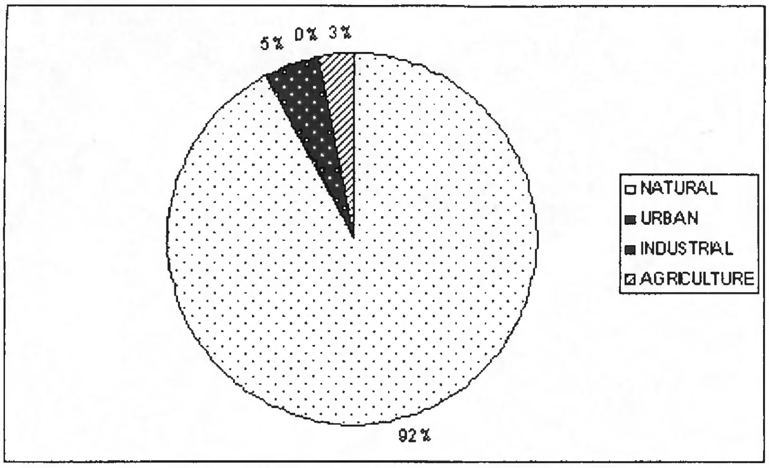


Figure 3: Approximated land use in Tomales Bay's catchment

Tomales Bay is situated on the west coast of the USA (38 ° 13'50"N, 122 ° 58' 30"W) and is a relatively pristine estuary with a small human population density living in its catchment (Harcourt-Baldwin, 2003). It will have less than 10% cleared or agricultural land. The people that live in the catchment will mainly live in rural areas and there will be hardly any urban development. Therefore the amount of impervious surfaces in the catchment will have a low percentage (<10%). The income will most probably be low as there is minimal urban development.

In a relatively pristine catchment the mouth of the estuary will be in its natural state. Encroachment will be minimal as there is minimal development or agriculture. There will also be minimal abstraction, estuary use and sewerage input due to low human population density in the catchment.

The TaCM's Socio-Economic Threat Index determined that the human activities in Tomales Bay's catchment don't threaten the estuary's health.