# The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles

## A management perspective

## Publication details

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**LOICZ**

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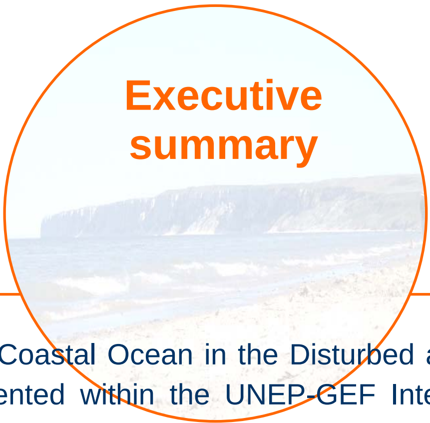
# Executive summary



The project “The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles” was implemented within the UNEP-GEF International Waters focal area, Operational Programme 10 – Global contaminants, the sub-programme: “Sustainable Management and Use of Natural Resources” by the Land-Ocean Interactions in the Coastal Zone (LOICZ) project. This publication describes the background and context for the project, illustrates some of the key science outputs and considers the wider management implications of the outcomes of the project. The principle outcomes are:

- The project funded 9 regional workshops developing 160 budget sites, provided new assessment tools and proxies for the budget models, training for more than 180 scientists and developed significant capacity building and networking.
- It describes the delivery of nutrients to the coastal zone from riverine and oceanic sources and the role of humans in eutrophication.
- The project refined existing LOICZ approaches to describe biogeochemical transformations in estuaries and coastal seas using a common methodology, generally from local-scaled data of at least phosphorus, water and salt (Budgets), and then to derive coastal fluxes at regional and global scales by consistent up-scaling methods (Typology).
- The project facilitated major progress to be made in terms of both coastal characterization itself (typology) and the development of conceptual and operational tools.
- Major outcomes elucidated were:
    - The combined controls on nutrient loads and it was shown that both population density and run-off are major anthropogenic drivers of change.
    - That coastal classifications – most notably Dissolved Inorganic Phosphorus and Dissolved Inorganic Nitrogen loads – can be used as flux predictors, and identified the additional data and tools required to fully implement up-scaling approaches.
- The project adopted a Driver-Pressure-State-Impact-Response (DPSIR) framework as a means to extend the analysis subsequent to the assimilation of the data from the budget sites and initial correlation with human factors through the typology. A goal is to develop a methodological approach for connecting the concept of Integrated Coastal Zone Management (ICZM) with that of Integrated River Basin Management (IRBM).
- The project approach has been continuously applied and updated leading to recommendations for future research needs and gaps.

# CONTENTS

1 Preface
An introduction and background of the GEF project – The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles

Context 2
Putting the project in the perspective of the coastal zone and coastal change

6 Nutrient fluxes in the coastal zone
Illustrating the budget models and typology approach developed under the project including highlights and examples

Managing nutrients and human impacts 23
Placing the science in a management context. Highlighting key impacts and the driver-pressure-state-impact-response analysis for coastal zone management

33 Looking to the future and conclusions
Key outcomes of the project and recommendations for future research needs.

37 Support materials
Further reading and references
Figure sources

# PREFACE

The Global Environment Facility (GEF), established in 1991, helps developing countries fund projects and programs that protect the global environment. GEF grants support projects related to biodiversity, climate change, international waters, land degradation, the ozone layer, and persistent organic pollutants. One aim is to contribute to a more comprehensive ecosystem-based approach in managing international waters and their drainage basins as a means to achieve global environmental benefits in order that they may sustainably support human activities. The United Nations Environment Programme (UNEP) has a key role in implementing the GEF catalyzing the development of scientific and technical analysis and advancing environmental management in GEF-financed activities. This includes executing projects of a strategic nature and importance that directly contribute to increased understanding, knowledge and awareness of critical aspects of global environmental issues addressed by the GEF.

The Land-Ocean Interactions in the Coastal Zone (LOICZ) project's goal is to provide knowledge and understanding of the interaction between global change and local pressures and its implications for the coastal zone. The science of LOICZ has been focussed on the measurement of biogeochemical fluxes into, and within, the coastal zone. These fluxes are important and relevant to global environmental change (GEC) science because they:

- describe key connections across coastal boundaries, that is, from catchment to coast, coast to ocean and coast to atmosphere;
- underpin ecosystems and renewable resources;
- determine water quality that affects habitat quality, amenity value and human use; and
- reflect important positive and negative feedbacks between land and coastal systems, determining thresholds and boundaries for system resilience.

LOICZ has established a biogeochemical budget modelling approach to provide a common methodology for delivering regionally comparable data on coastal ecosystem loads and net metabolic performance of coastal systems.

Within the GEF International Waters focal area, Operational Programme 10 – Global contaminants, the sub-programme: “Sustainable Management and Use of Natural Resources” addresses similar interests that led in 1999 to the establishment of a project: “The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles”. This project funded 9 regional workshops, which added 160 budget sites to an existing 40, and provided new assessment tools and proxies for the budget models and training for more than 180 scientists from around the world. The project helped develop a typological system to address the challenges of scaling and classification of coastal ecosystems and their characteristics (natural and human driven) to elucidate broad scale patterns and trends. The project also encompassed through staff and student exchanges, mentorship programmes and workshops a significant capacity building and networking element at a regional and global level.

This publication describes the background and context for the project, illustrates some of the science outputs from the project and considers the wider management implications of the outcomes of the project.

## What is the coastal zone and why is it important?

**The world's coastal zone denotes the area of transition between mainland, islands and adjacent seas (Figure 3 & 4, Table 1). It is an area that is shaped by natural processes that deliver materials to it from rivers, the sea and atmosphere. These, in turn, develop an extraordinary range of habitats that provide an equally diverse range of resources for human exploitation (Table 2). The coastal zone has high natural variability as it constantly responds and adapts in its physical, chemical and biological characteristics as wave and current regimes, climate, and morphological processes change.**

### Coastal change

Through geological time, the location of the land-sea interface has continued to change in response to large scale global processes that affect sea level and regional climates (Figure 1), as well as to undergo more localized short term change (Figure 4). In more recent time, particularly during the last century, human activities are exerting huge pressures accelerating rates of change and causing new changes in the structure and functioning of the coastal zone (Figure 5). Understanding the cause and effect of change in the coastal zone cannot be confined to a narrow geographic description of its boundaries, but needs to vary according to the type of issue being addressed and the objectives of management.

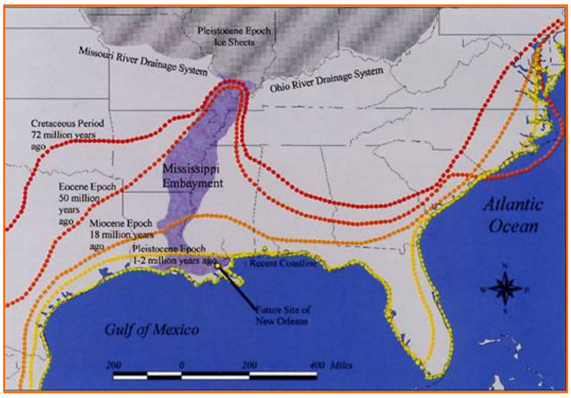


***Figure 1**. The coastline of the northern Gulf of Mexico has moved over geologic time since the cretaceous (red dotted line) through the Eocene (dark orange), Miocene (orange), Pleistocene (dark yellow) to the present (yellow).*

***Table 1**. Global characteristics of the coastal zone.*

**The coastal zone:**

- comprises <20% of the Earth's surface
- contains >40% of the human population
- is the location of 75% of cities (megacities) with >10 million inhabitants
- yields 75% of the global fisheries
- produces about 25% of global biological productivity
- is the major sink for sediments
- is a major site of nutrient-sediment biogeochemical processes
- is a heterogeneous domain, dynamic in space and time
- has high gradients, high variability, high diversity

### Humans and coastal change

Human uses and benefits obtained from the coastal zone are diverse (Table 2). Human exploitation of living and non-living resources, products and amenities within the coastal domain as well as external to it, particularly from the river catchments, is modifying the entire fabric of the coastal zone. Urbanisation and intensified land uses are resulting in degraded water and soil quality, pollution and contamination, eutrophication, overfishing, destruction of wetlands and habitat loss.

# The Coastal Zone

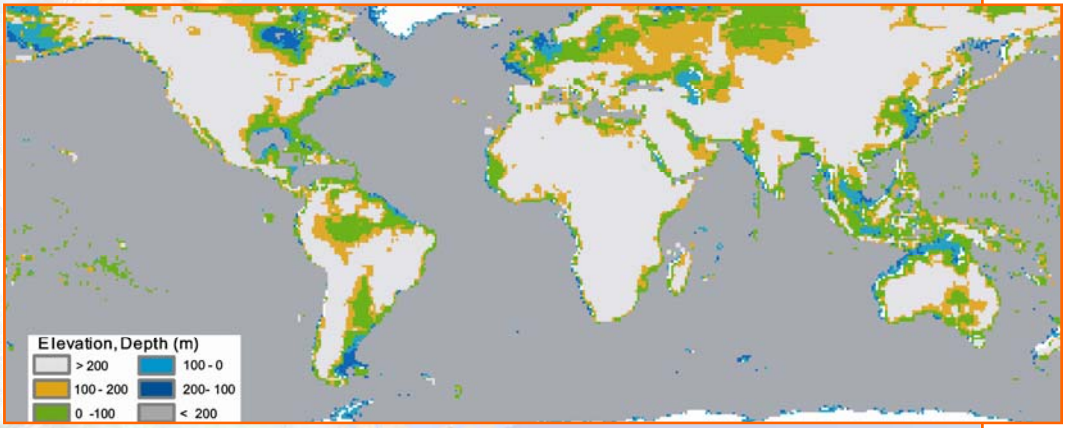


***Figure 2**. The coastal zone. The LOICZ domain (terrestrial areas: yellow 100-200 m elevation, green < 100 m elevation; marine areas: light blue 100 m depth, blue 100-200 m depth)*

The resources and amenities of the coastal zone are crucial to our societal needs. While it represents about 12% of the world's surface (<20% of the land surface area and <9% of the global marine surface area), the coastal zone presently is:

- a major food source including major crops and most of the global fisheries,
- a focus of transport and industrial development,
- a source of minerals and geological products including oil and gas,
- a location for most tourism, and
- an important repository of biodiversity and ecosystems that support the function of Earth's systems.

New commercial and socio-economic benefits and opportunities continue to be developed from use of coastal resources, while products and amenities and issues of environmental management and sustainability challenge planners, managers and policy-makers

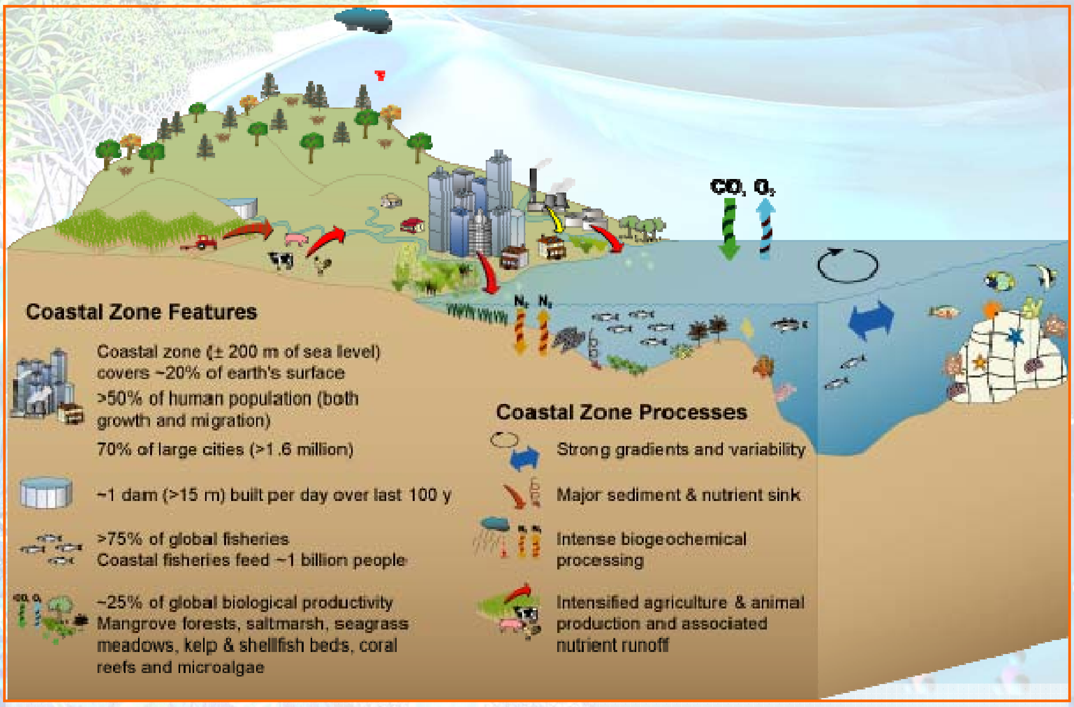


***Figure 3**. Conceptual diagram showing the key features and processes of the coastal zone.*

***Figure 4.*** *Alterations in groundwater, percolation of surface water and/or the impact of and undercutting by waves causing erosion can cause cliff slippage. Erosion can also result from altered sediment supply to the coastal zone.*

The influence of humans on changes in the coastal zone are seen both in their direct impacts on coastal processes and ecosystems and in the indirect effects of modification of natural processes. Land-based sources of pollution have been estimated to contribute approximately 80% of all marine pollution. Human activities associated with agriculture, sewage, deforestation, dam construction and urban development alter the levels of nutrients resulting in dramatic disruptions to coastal and estuarine ecosystems. Increased levels of nutrients can have profound effects on biological productivity and health of the coastal zone, including eutrophication, toxic algal blooms, anoxia, fish kills and red tides (see Nutrients and Eutrophication explanation on page 5).

***Table 2.*** *Essential resources, products and amenities provided by the coastal zone.*

| **Resource – natural materials** |
|---|
| • Water – surface, ground<br>• Forests and timber<br>• Arable land<br>• Food<br>• Geological ores and deposits<br>• Ecosystems and biodiversity |
| **Products – natural and human derived commodities** include |
| • Food<br>• Fisheries<br>• Habitation<br>• Industrial goods and processes<br>• Oil, gas and minerals |
| **Amenities – natural and human-derived services** include |
| • Transport and infrastructure<br>• Tourism<br>• Recreation and culture<br>• Biodiversity<br>• Ecosystem services |

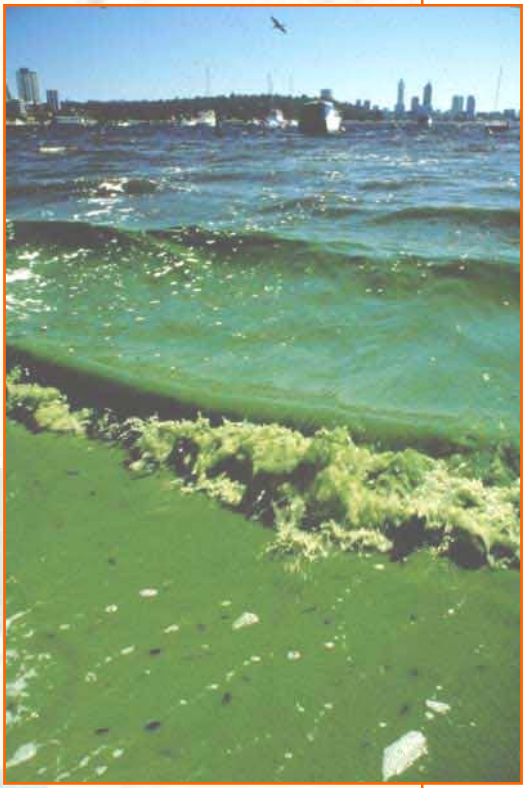
***Figure 5.*** *Human alteration of coastal processes. Dredging of the River Mersey, UK and the construction of training walls have altered sediment movement leading to erosion/accretion zones and closure of a channel in the area south west of Formby known as Taylors spit and the Formby channel between 1945 and 2002.*

# Nutrients and Eutrophication

**Nutrients** are chemical elements and compounds found in the environment that plants need to grow and survive. For water-quality investigations the various forms of nitrogen and phosphorus are the nutrients of interest. The forms include nitrate, nitrite, ammonium, organic nitrogen (in the form of plant material or other organic compounds), and phosphates (orthophosphate and others). Nitrate is the most common form of nitrogen and phosphates are the most common forms of phosphorus found in natural waters. High concentrations of nutrients in water bodies can potentially cause **eutrophication** and **hypoxia**. Excess nutrients can come from many sources, such as fertilizers (applied to agricultural fields, golf courses and suburban lawns); deposition of nitrogen from the atmosphere; erosion of soil containing nutrients; animal waste; and sewage treatment plant discharges.

**Eutrophication** is a process in which water bodies, such as lakes, estuaries, or slow-moving streams receive excess nutrients that stimulate excessive growth by algae and nuisance plants (weeds). The consequences of this enhanced growth are: reduced sunlight penetration; a decreased amount of oxygen in the water; and a loss of habitat for aquatic animals and plants. The reduction of dissolved oxygen in the water results from the decomposition of dead plant material, and can cause other organisms to die. Water with a low concentration of dissolved oxygen is called **hypoxic**.

**Hypoxia** means "low oxygen." In estuaries, lakes, and coastal waters low oxygen usually means a concentration of less than 2 parts per million. In many cases hypoxic waters do not have enough oxygen to support fish and other aquatic animals. The decrease in dissolved oxygen is caused by the decomposition of dead plant material (algal), which consumes available oxygen. Hypoxia is one of the major negative results of eutrophication. A complete absence of dissolved oxygen is termed **anoxic**.



*Microcystis* bloom in Matilda Bay, Swan-Canning Estuary during February 2000.

*Fish kill*

*Red tide*

*Algal bloom*

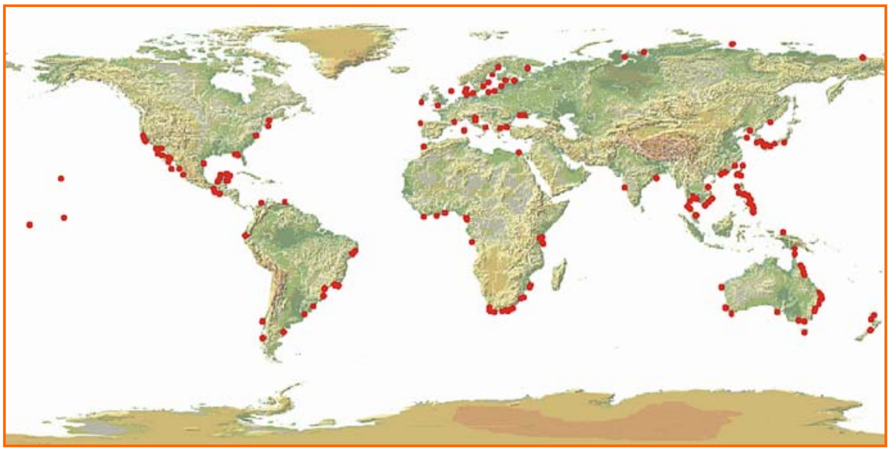
## Modelling, budgets and typology

**Natural systems such as ecosystems are usually very complex, and models are tools that help conceptualize, integrate, and generalize knowledge. Models explain and forecast how factors affect the coastal zone. Budget models are simple mass balance calculations of specific variables (such as water, salt, sediment, nutrients, etc.) within defined geographic areas and over defined periods. The LOICZ approach was refined under the GEF project and to describe biogeochemical transformations in estuaries and coastal seas using a common methodology, generally from local-scaled data (Budgets), and then to describe coastal fluxes at regional and global scales by consistent up-scaling methods (Typology).**

### Understanding nutrient change in the coastal zone

Knowledge about ecosystems, biogeochemical processes and impacts in the coastal zone has improved markedly over the last few decades. It is known that changing wave and current regimes, climate, morphological processes and fluxes of materials from the land, atmosphere and oceans all contribute to the high variability within the coastal zone, but we have limited ability to measure, model and ultimately manage their complex interactions, especially across multiple spatial and temporal scales. Budgets and inventories of the biogeochemically active elements of carbon, nitrogen and phosphorus can be used to describe the chemical transformations that occur as a result of delivery of nutrients to the coastal zone whether from river or ocean sources. These elements are critical to life, and therefore to the biological productivity of, and availability of resources, in the coastal zone. Their fluxes and budgets are profoundly altered by human activities, and these changes affect the quality of the environment for human use and indirectly affect climate change.

The dynamics of the coastal zone and its heterogeneity with regard to hydrology and geomorphology, diversity of ecosystems and climate, and the array of natural and human influences that generate change on coastal systems create major challenges for determining patterns and trends in the metabolic performance of coastal systems at all scales. Equally challenging is the



**Budget model** - A budget model is an estimate of inventories, inputs and outputs of a system over a specified period of time, based on accounting for material balances and flows.

***Figure 6**. Global distribution of LOICZ budget sites as at April 2002.*

development of proxy variables to serve as spatial or temporal predictors of functions related to ecosystem metabolic performance.

## Budget models

The budget methods adopted by LOICZ were further developed and have been applied to over 400 sites (Figure 6 & 7) and provide a steady-state snapshot of loads, sources and sinks of nutrients, and by inference carbon. They were designed to obtain and analyse basic biogeochemical data at local scales, in a way which could be upscaled to regional and global fluxes. The methods chosen were simple, in recognition of the fact that capacity to support more sophisticated models and to acquire the larger data sets required to calibrate these were not available in many places.

The budget models were not intended to support development of management scenarios, or assessment of impact. However, they have influenced the study of impacts of altered nutrient budgets such that the resulting information has greater relevance for coastal management. First, they encourage users to think quantitatively about fluxes and drivers of system state, not solely about symptoms. Second, by providing a quantitative comparison of fluxes, they help users to think about the relative importance of different sources and sinks of nutrients in the overall biogeochemical cycle. This may in itself help to set management priorities. Third, they specifically estimate average flushing or residence time of coastal water bodies, a key variable controlling their vulnerability or sensitivity to changes in nutrient loads.

**Budget** - A budget describes the rate of material delivery to the system (inputs), the rate of material removal from the system (outputs), and the rate of change of material mass within the system (storage). Many systems are approximately in *steady state*, which means that their rate of change (storage) is small compared to inputs or outputs. Even so, some materials may undergo internal transformations of state which lead to appearance or disappearance of these materials. Such changes are sometimes referred to as *internal sources* or *sinks*.

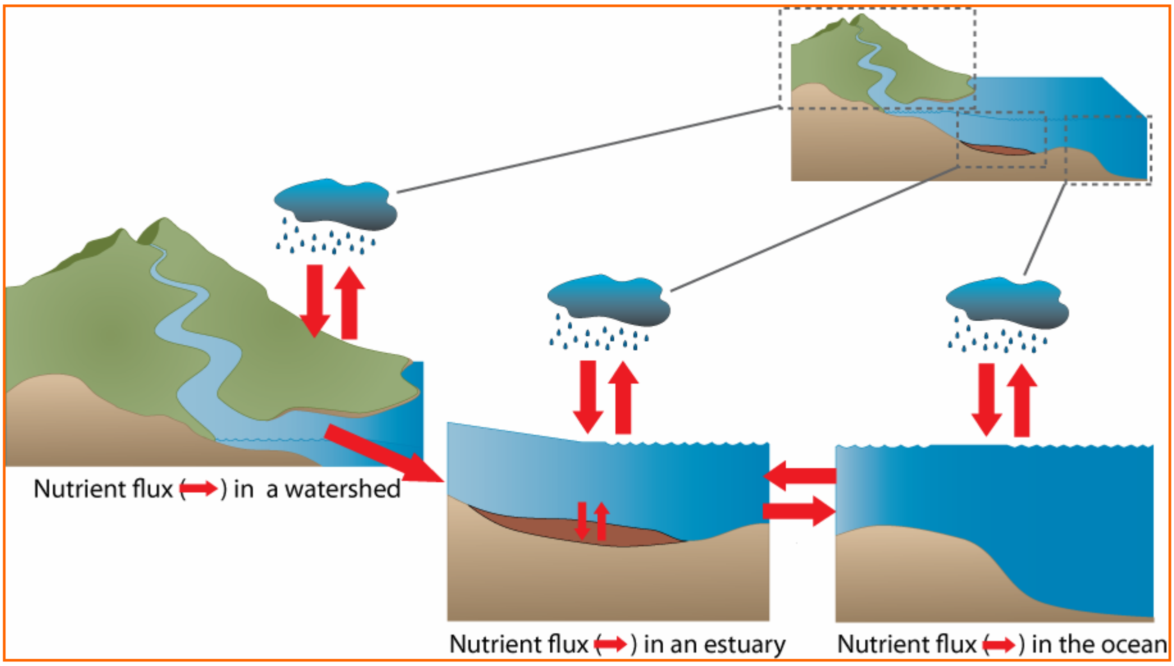


***Figure 7***. *Conceptual diagram of the biogeochemical nutrient budget methods used in LOICZ. The fluxes depicted between the various budget compartments (watershed, coastal ocean, coastal ocean sediment, open ocean and atmosphere) are quantified in the budget calculations.*

## Terminology and definitions

The terms **watershed**, **catchment** and **basin** are used interchangeably depending on geographical location.

**Groundwater** is all the water that has penetrated the earth's surface and is found in one of two soil layers. The one nearest the surface is the "zone of aeration", where gaps between soil particles are filled with both air and water. Below this layer is the "zone of saturation", where the gaps are filled with water. The water table is the boundary between these two layers. As the amount of groundwater increases or decreases, the water table rises or falls accordingly. When the entire area below the ground is saturated, flooding occurs because all subsequent precipitation is forced to remain on the surface.

**Flux -** In the study of transport phenomena (heat transfer, mass transfer, and fluid dynamics), flux is defined as the amount of a given quantity that flows through a unit area per unit time. Flux in this definition is a vector. In general, 'flux' in biology relates to movement of a substance between compartments. There are several cases where the concept of 'flux' is important. In ecology, flux is often considered input and output at the ecosystem level - for instance, accurate determination of carbon fluxes (at a regional and global level) is essential for modeling the causes and consequences of global warming.

**Nitrogen** is a chemical element which has the symbol **N** and atomic number 7 and atomic weight 14 in the periodic table. Elemental nitrogen is a colorless, odorless, tasteless and mostly inert diatomic gas ($N_2$) at standard conditions, constituting 78% percent of Earth's atmosphere. Nitrogen is a constituent element of all living organisms, principally in amino acids, the constituents of protein. Many industrially important compounds, such as ammonia, nitric acid, and cyanides, contain nitrogen.

**Carbon** is a chemical element in the periodic table that has the symbol **C** and atomic number 6 and atomic weight 12. Carbon occurs in all organic life and is the basis of organic chemistry. This nonmetal also has the interesting chemical property of being able to bond with itself and a wide variety of other elements, forming nearly ten million known compounds. When united with oxygen it forms carbon dioxide which is vital to plant growth. When united with hydrogen, it forms various compounds called hydrocarbons which are essential to industry in the form of fossil fuels. When combined with both oxygen and hydrogen it can form many groups of compounds including fatty acids, which are essential to life, and esters, which give flavor to many fruits.

**Phosphorus**, is a chemical element in the periodic table that has the symbol **P** and atomic number 15 and atomic weight 31. A multivalent nonmetal of the nitrogen group, phosphorus is commonly found in inorganic phosphate rocks and in all living cells. Due to its high reactivity, it is never found as a free element in nature. It emits a faint glow upon exposure to oxygen (hence its Greek derivation and the Latin meaning 'morning star'), occurs in several allotropic forms, and is an essential element for living organisms. The most important commercial use of phosphorus is in the production of fertilizers. It is also widely used in explosives, nerve agents, friction matches, fireworks, pesticides, toothpaste, and detergents.

**DIP-** Dissolved Inorganic Phosphorus. **DIN** - Dissolved Inorganic Nitrogen.

**Denitrification/Nitrogen fixation** - denitrification is the process of reducing nitrate, a form of nitrogen available for consumption by many groups of organisms, into gaseous nitrogen, which is far less accessible to life forms but makes up the bulk of our atmosphere. It can be thought of as the opposite of nitrogen fixation, which converts gaseous nitrogen into more biologically useful forms. This energetically demanding process is only performed by heterotrophic bacteria and cyanobacteria. Denitrification and nitrogen fixation are key parts of the nitrogen cycle. Denitrification takes place under special conditions in both terrestrial and marine ecosystems. In general, it occurs when oxygen (which is a more favourable electron acceptor) is depleted, and bacteria turn to nitrate in order to respire organic matter. Because our atmosphere is rich with oxygen, denitrification only takes place in some soils and groundwater, wetlands, poorly ventilated regions of the ocean, and in seafloor sediments.

Denitrification proceeds through some combination of the following steps:

Nitrate → nitrite → nitric oxide → nitrous oxide → nitrogen gas

**Nitrification** - The breakdown of organic matter typically releases nitrogen in the form of ammonia. Denitrification is the second step in the nitrification-denitrification process: the conventional way to remove nitrogen from sewage and municipal wastewater. Nitrification is the biological oxidation of ammonium compounds with oxygen of in dead organic material into nitrite ($NO_2$) followed with the oxidation of these nitrites into nitrates ($NO_3^-$) by bacteria (making nitrogen available to plants).The conversion of nitrogen from inorganic to organic by nitrate bacteria effectively recycles the substance so that it can be used again by plants. Nitrification is an important step in the nitrogen cycle. Coupled nitrification and denitrification is the conventional way to remove nitrogen from sewage and municipal wastewater. In hypoxic or anoxic environments, the nitrification step may be blocked indirectly preventing denitrification from removing nitrogen.

## Biogeochemical Budget Models

Understanding material **fluxes** through the coastal zone is fundamental to LOICZ and was integral to the GEF project. The development of **budget models** for **Carbon**, **Nitrogen**, and **Phosphorus** across a spread of global sites developed from the GEF project is a continuing major initiative, and can be accessed through the Biogeochemical Budget website (http://data.ecology.su.se/MNODE/). Results from the LOICZ budgets are available in database form from the global typology website.

The LOICZ budget models represent the aggregated effect of all the living components of the coastal ecosystem on nutrient fluxes and transformations as net ecosystem metabolism. It is possible to develop more complicated budget models which divide the food web into primary producers, consumers etc. and which represent exchanges and transfers among these components, or in turn divides each of these trophic levels into different functional groups. It is further possible to represent the exchanges and transformations within and between components as dynamic processes, whose magnitude is controlled by the component properties and external environmental variables. The choice among model types and levels of aggregation depends on the intended use. Typically as model complexity increases, the model looks more realistic, but it becomes more difficult to rigorously validate model predictions.

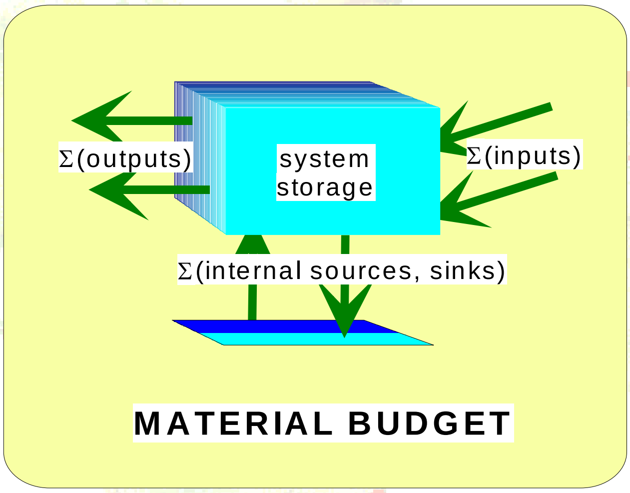


***Figure 8**. LOICZ budget modelling approach illustrating the principle of conservation of mass where by components of input, output and storage should balance.*

The LOICZ Biogeochemical budget modelling methodology provides a relatively simple assessment technique that can be rapidly applied to coastal ecosystems and is based on the fundamental concept in ecology and geochemistry, the conservation of mass (Figure 8). The budget describes the net outcome of the rate of material delivery into a system (gross inputs) and the rate material leaves a system (outputs). At any given time some of these materials also may be “stored” within the system. However, provided there are not chemical transformations (e.g., denitrification) that effectively remove from the system (sink) or produce them within the system (source), the change in the amount of material stored should always match the difference between the amount arriving into the system (input) and the amount leaving the system (output). LOICZ budgets focus primarily on the inputs, outputs and sources and sinks of dissolved inorganic nutrients, because these are widely measured and can be used to infer information about other important fluxes, as described below.

In a coastal setting, the rate that dissolved materials enter and leave a system will be determined by their concentrations and water exchanges of fresh and salt water. On average, water volume and salt content in the system remains essentially constant over time, as water flows through the system and mixes with adjacent systems. The net flow of water is described by a water budget and the mixing of water can be derived from a salt budget of non-reactive materials; together these characterise the water exchange of the system and quantify the flows of freshwater and salt water that transport nutrients from terrestrial, atmospheric and oceanic sources.

If the flux of nutrients calculated from water exchanges and nutrient concentrations balance so that nutrient inputs and outputs are the same, the system is described as “conservative”. Departure from this balance indicates that nutrients are being altered, taken-up and sequestered or released within the system, in which case the flux is described as non-conservative, and the system is a sink if input exceeds output, and a source if the reverse is the case.

Nutrient data are collected in the form of measurements of dissolved inorganic forms of phosphorus (**DIP**) and nitrogen (**DIN**). Chemical processes can contribute to changes in DIP concentration, but in most cases a non-conservative flux of DIP can be attributed to the net uptake of phosphorus into organic matter during primary production or release from organic matter by respiration. The change in phosphorus flux ($\Delta DIP$) therefore describes net ecosystem metabolism (NEM). Similarly, non-conservative flux of DIN ($\Delta DIP$) is attributed to the net balance of **nitrogen fixation** (nfix) minus **denitrification** (dinit) within a system after accounting for the flux of nitrogen associated with NEM. NEM and N-fixation/denitrification represent the most important modifications which the coastal zone imposes on the cycling of reactive materials that effect global environmental change.

Net ecosystem metabolism is the net production of an ecosystem, usually measured by the amount of inorganic carbon fixation into organic matter per year. From a practical standpoint, this represents the 'fruits of the earth' that ultimately provide food, clothing and shelter (vegetable products, meat, cloth, wood) that ecosystems generate in the course of their ecological/biogeochemical functioning, creating 'surplus' organic matter from inorganic materials. Not all net ecosystem metabolism represents material that is immediately useful to human beings, but it is fair to say that over the long run, it would be impossible for humans (and other animals) to survive without autotrophic ecosystems (i.e. those producing more organic matter than is consumed). It is also fair to say that the components of some ecosystems (microbial loops) function healthily when they are behaving heterotrophically (i.e. consuming more organic material than they are producing). Without this 'recycling' aspect of ecosystem dynamics, the world would soon contain large amounts of dead organic material. On a global scale over the long term, heterotrophy is closely balanced by autotrophy (the world is essentially a closed loop) so that net ecosystem metabolism is close to zero.

Biological nitrogen fixation is important because it is the primary way that atmospheric $N_2$ (the primary reservoir of nitrogen) is "fixed" i.e. transformed into nitrogen species that are useable by plants, and that become proteins and other biochemicals necessary for life. **Nitrification** is a biological process which transforms ammonia (a biological waste product) into nitrate ($NO_3$), which moves readily through **groundwater** and surface water, and is a primary water pollutant. Biological denitrification transforms nitrate ultimately into $N_2$, the inert and harmless form of nitrogen which constitutes most of the atmosphere. As such, the coupled nitrification/denitrification processes form the pathway from organic forms of nitrogen (those that we consume in food) back to harmless atmospheric nitrogen. On a global scale, these processes are closely balanced (discrepancies in global balances of such processes arise from accounting for long-term storage in sediments, groundwater, etc).

There follows an example of the application of the LOICZ budget modelling approach.

# Manila Bay, Luzon Island

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## Study area description

Manila Bay is situated on the western coast of Luzon Island (14.23$^{o}$-14.87$^{o}$N, 120.53$^{o}$-121.03$^{o}$E) (Figure 9). The bay is bounded by the provinces of Cavite in the south, Metro Manila and Rizal in the east, Bulacan and Pampanga in the north, and Bataan in the west and north-west. The bay has an area of approximately 1,700 km$^{2}$, a length of 60 km, and widths varying from 22 km at the mouth to 60 km at the widest section. The average depth is 17 m (volume = 30x10$^{9}$ m$^{3}$). It receives drainage from nearly 17,000 km$^{2}$ of watershed composed of 26 catchment areas.

The Pasig River Basin (9,000 km$^{2}$) and the Pampanga River Basin (3,900 km$^{2}$) make up more than 75% of the watershed of Manila Bay. The Pampanga River contributes approximately 49% of the net freshwater influx into the bay, while the Pasig River contributes about 21%. The other river systems make up 26% of the freshwater source and the remaining 4% come from precipitation onto the bay.

The population of the cities and municipalities within the catchment areas is estimated at 16 million people (approximately 27% of the population of the country), with 8 million people inhabiting the Pasig River watershed. About 70% of the organic pollution load into the Pasig River comes from domestic wastewater since the existing sewerage system in Metro Manila serves only 10% of the population. Some of the population is served by septic tanks, but it is estimated that approximately 3 million people in the area discharge their wastes directly and through sewer pipes that empty untreated sewage into Manila Bay.

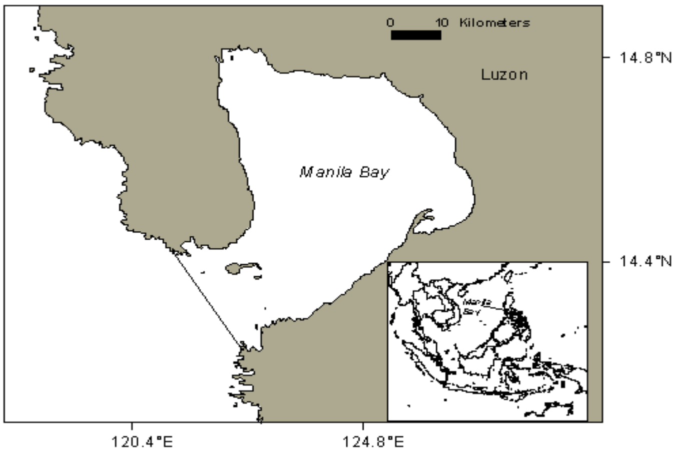


***Figure 9.*** *Map and location of Manila Bay.*

## Methodology

The LOICZ Biogeochemical Modelling Guidelines were used to calculate the stoichiometrically-linked water-salt-nutrient budgets. In these mass balance budgets, complete mixing of the water column is assumed and only dry season mean estimates are considered. Manila Bay was divided into a two-layer system, an upper and a lower box. The upper box covers the top 10 m of the water column and the lower box is from 10 m to the bottom.

## Waste loading

Particular attention is paid to the issue of waste loading into the bay because of the importance of this input to the system. In many systems, including this one, organic matter and nutrient loading from domestic, agricultural, or industrial wastes are important yet poorly-identified contributions to the biogeochemical budgets. The waste loading for Manila Bay is not known directly, so this section presents indirect estimates of organic and inorganic C, N and P loading associated with these wastes.

Effluent from human wastes is assumed to dominate discharge into this system. Thus waste loading was estimated from population size. The steps followed in doing waste load calculations from demography are given in a separate section in this LOICZ Workshop report.

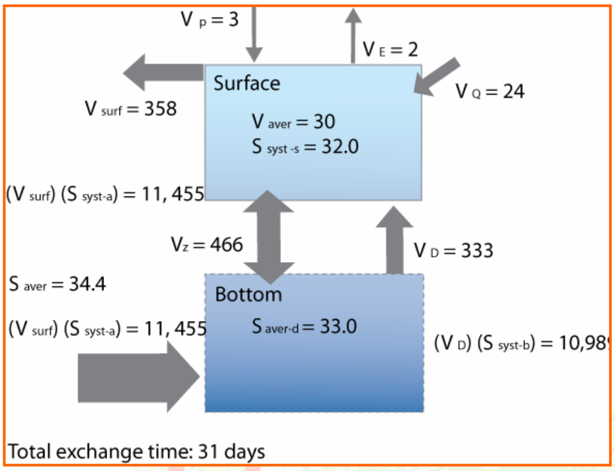


***Figure 10.*** *Water and salt budgets for Manila Bay. Volume in* $10^9$ *m*$^3$*, water fluxes in* $10^9$ *m*$^3$ *yr*$^{-1}$*, salt fluxes in* $10^9$ *psu-m*$^3$ *yr*$^{-1}$ *and salinity in psu.*

A brief explanation of how the estimates were made is given here. Effluent from human wastes has some typical characteristics. Chemical Oxygen Demand (COD, the total oxidation demand of such wastes) is typically about 2.6 times the Biological Oxygen Demand (BOD), and this can be converted from mass of oxygen consumed to mass of organic carbon by the mass ratio of carbon to oxygen, which is 12:32 (= 0.375). The product of 2.6 times 0.375 is 0.98 (close to 1), and this product represents an estimate of the conversion factor from BOD to organic C (both expressed in mass units). To estimate sewage input, an effluent load factor of 20 kg person$^{-1}$ yr$^{-1}$ of BOD is assumed (World Health Organisation 1993). From the above conversion factors, this is equivalent to a per capita organic carbon loading of 20 kg yr$^{-1}$ (about 1,700 moles C person$^{-1}$ yr$^{-1}$).

The next conversion is from organic C loading to total N and P loading. Domestic human and animal agriculture effluent has a typical TOC:TN:TP molar ratio of approximately 40:12:1. The ratios of inorganic to total N and total P in organic waste material are 0.4 and 0.5, respectively.

In Manila Bay, it is assumed that 50% of the catchment area population more or less directly inputs into the system. Some discharge directly into the river systems, and their inputs should be handled in the budget. It is estimated that about 3 million people discharge their wastes directly and through sewers that empty into the Bay; this is accounted for in the waste load approximations.

### Water and salt balance

Figure 10 illustrates the steady state water and salt budgets for Manila Bay. The water budget in the upper box of Manila Bay is influenced mainly by freshwater runoff ($V_Q$ = 24x10$^9$ m$^3$ yr$^{-1}$), precipitation ($V_P$ = 3x10$^9$ m$^3$ yr$^{-1}$) (Philippine Atmospheric, Geophysical and Astronomical Services Administration, PAGASA), evaporation ($V_E$ = 2x10$^9$ m$^3$ yr$^{-1}$) (PAGASA), the deep water input ($V_D$ = 333x10 m$^3$ yr$^{-1}$) and vertical mixing ($V_Z$ = 466x10$^9$ m$^3$ yr$^{-1}$). To balance all the inflows and outflows of water, there must be an outflow ($V_{surf}$) of 358x10$^9$ m$^3$ yr$^{-1}$ from the bay.

The salinity data outside the mouth of the bay (average of top 50 m) was obtained from a NOAA database (http:// ferret.pmel.noaa.gov/NVODS/servlets/dataset). This salinity value is 34.4 psu. The average salinity in the upper box is 32.0 psu while the lower box salinity is 33.0 psu. The salt balance is maintained by deepwater input of oceanic salinity and vertical mixing between surface and deep. This flux is estimated to be 11,455x10$^9$ psu-m$^3$ yr$^{-1}$. The total exchange time (flushing time) of bay waters, calculated from the volume of the bay divided by the sum of ($|V_R|$ + $V_D$), is 0.08 yr, or approximately 31 days.

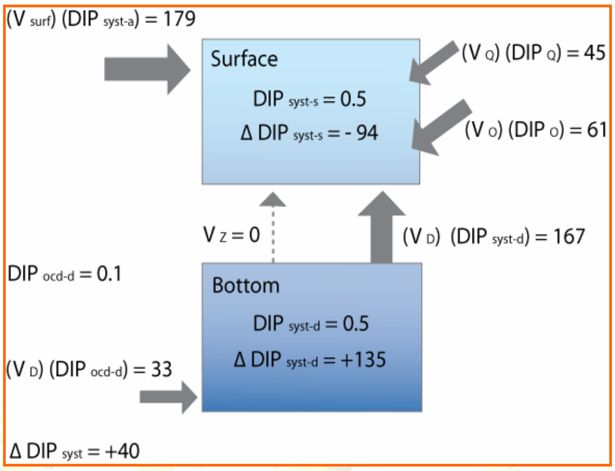


***Figure 11.** Dissolved inorganic phosphorus budget for Manila Bay. Fluxes in $10^6$ mol $yr^{-1}$ and concentrations in mmol $m^{-3}$.*

## Budgets of nonconservative materials

### DIP balance

Figure 11 summarises the steady state DIP budget for Manila Bay. The average phosphate concentration in the upper and lower boxes of Manila Bay is 0.5 µM (Velasquez *et al*. 1997), outside the Bay it is 0.1 µM (http:// ferret.pmel.noaa.gov/NVODS/servlets/dataset), and the rivers contribute 3.0 µM of $PO_4$ (EMB-DENR/UNEP 1991). In order to balance the phosphate contributed by the rivers ($V_QDIP_Q$ = 45x$10^6$ mol $yr^{-1}$), direct sewage discharge ($V_ODIP_O$ = 61x$10^6$ mol $yr^{-1}$) and vertical entrainment ($V_DDIP_{syst-d}$ = 167x$10^6$ mol $yr^{-1}$) with residual outflow ($V_{surf}DIP_{syst-s}$ =179x$10^6$ mol $yr^{-1}$), non-conservative processes must fix -94x$10^6$ mol $yr^{-1}$ of dissolved inorganic P ($\Delta DIP$) inside the upper box of the Bay. In the lower box, the balance between deep-water input and vertical mixing is satisfied when there is removal of DIP from this box. The net $\Delta DIP$ between the upper and lower boxes is a positive term implying net loss or removal of DIP from the whole system.

Figure 12 summarises the steady state DIN budget for Manila Bay. Dissolved inorganic nitrogen (DIN) is defined as $\Sigma NO_3+NO_2+NH_3$. The average DIN concentration inside the upper box of Manila Bay is 1.1 µM and in the lower box it is 4.2 µM (Velasquez *et al*. 1997). Outside the bay, DIN is 0.5 µM (http:// ferret.pmel.noaa.gov/NVODS/servlets/dataset) and DIN from the rivers is 60 µM (EMB-DENR/UNEP 1991). Structuring the DIN budget like the DIP budget yields an internal nutrient removal of about -3,950x$10^6$ mol $yr^{-1}$ ($\Delta DIN_{syst-s}$) in the upper box and internal nutrient production of +2,677x$10^6$ mol $yr^{-1}$ ($\Delta DIN_{syst-d}$) in the lower box. The net $\Delta DIN$ of -1,273x$10^6$ mol $yr^{-1}$ indicates net removal of DIN for the whole system.

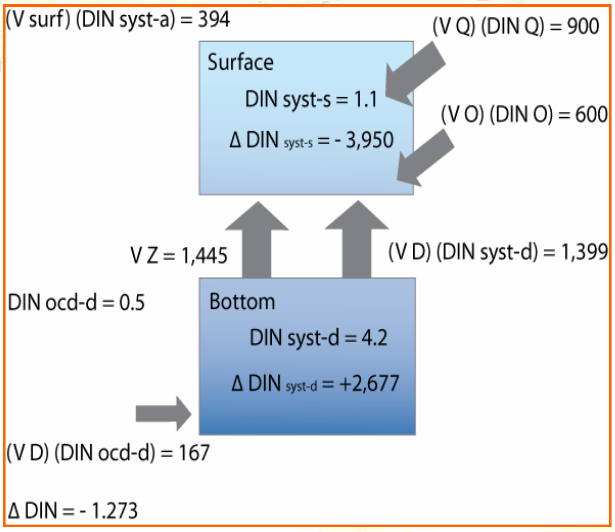


***Figure 12.** Dissolved inorganic nitrogen budget for Manila Bay. Fluxes in $10^6$ mol $yr^{-1}$ and concentrations in mmol $m^{-3}$.*

## Stoichiometric calculations of aspects of net system metabolism

The nutrient budgets can be used to estimate the difference between photosynthesis and respiration (*p-r*) and (*nfix-denit*). Net ecosystem metabolism (*p-r*) is estimated from $\Delta DIP$ and the C:P ratio of reacting particulate material, according to the relationship:

$$(p\text{-}r) = -\,\Delta DIP \cdot (C{:}P)_{part} \qquad (1)$$

In the upper box, $\Delta DIP$ is negative indicating the system is net autotrophic ($p$-$r$) = +6 mol C $m^{-2}$ $yr^{-1}$. In the lower box, $\Delta DIP$ is positive indicating net heterotrophy ($p$-$r$) = -8 mol C $m^{-2}$ $yr^{-1}$). It is most likely that the organic matter fixed in the upper box supplies the material needed to support decomposition (net heterotrophy) in the lower box. Additional material for the lower box is supplied from the sediments in the bay. The net ($p$-$r$) for the bay is -2 mol C $m^{-2}$ $yr^{-1}$.

The difference between nitrogen fixation and denitrification (*nfix-denit*) is estimated from the difference between the observed value for $\Delta DIN$ and that value expected from simple of organic matter. That is,

$$(nfix\text{-}denit) = \Delta DIN_{obs} - \Delta DIN_{exp} = \Delta DIN_{obs} - \Delta DIP \cdot (N{:}P)_{part} \qquad (2)$$

The $\Delta DIN_{obs}$ for the upper and lower boxes indicate that the upper box is a sink of DIN and that the lower box is a source of DIN. In the upper box, part of the DIN is fixed in autotrophy ($\Delta DIN_{exp}$) but the net flux still shows that this box is denitrifying (*nfix-denit* = -1.44 mol N $m^{-2}$ $yr^{-1}$). In the lower box, the amount of DIN produced by decomposition ($\Delta DIN_{exp}$) is lower than that removed within this box, hence (*nfix-denit*) is positive (0.31 mol N $m^{-2}$ $yr^{-1}$). The bay appears to be a net denitrifying system, at a rapid but believable rate: $(nfix\text{-}denit)_{syst}$ is -1.13 mol N $m^{-2}$ $yr^{-1}$. A summary of the nonconservative fluxes for nitrogen and phosphorus in Manila Bay is given in Table 3.

***Table 3.*** *Summary of nonconservative fluxes for the upper box, lower box and the whole system of Manila Bay*

| **Process** | **Upper box** | | **Lower box** | | **Whole system** | |
|---|---|---|---|---|---|---|
| | $10^3$ mol $yr^{-1}$ | mol $m^{-2}$ $yr^{-1}$ | $10^3$ mol $yr^{-1}$ | mol $m^{-2}$ $yr^{-1}$ | $10^3$ mol $yr^{-1}$ | mol $m^{-2}$ $yr^{-1}$ |
| $\Delta DIP$ | -94 | -0.06 | +134 | +0.08 | +40 | +0.02 |
| $\Delta DIN$ | -3,950 | -2.3 | +2,677 | +1.6 | -1,273 | 0.7 |
| ($p$-$r$) | +9,964 | +6 | -14,204 | -8 | -4,240 | -2 |
| (*nfix-denit*) | -2,446 | -1.44 | +533 | +0.31 | -1,913 | -1.13 |

## Typology

The word **typology** literally means the study of types. **Typology** is the classification of things according to their characteristics: The study or systematic classification of types that have characteristics or traits in common.

The typology approach combines functional data (essentially, the biogeochemical flux and budget information) and information on the environmental context of budget sites, to develop a classification of coastal systems. In this way, the information from the relatively small number of representative budget sites can be statistically summarised and extrapolated, through the use of informative environmental proxies, to other coastal systems where no concentration or flux data have been acquired. Biogeochemical performance of coastal systems at regional and global scales can be inferred. Each budget analysis was incorporated into a global environmental database[1] with emphasis on the features of the coastal zone and coastal catchments, as a basis for extrapolating from approximately 200 globally distributed budget case studies to regional and global fluxes. The global database combined a suite of available environmental variables aggregated at half-degree resolution, with high-resolution (1 km) data on drainage basin characteristics and population. This represents a first attempt to integrate biogeochemical information with socio-economic data to explore trends and scenarios of change for the coastal zone and the implications for human uses and activities. A set of sophisticated statistical tools for the analysis, identification and classification of relationships among variables and estuaries was developed, and made widely accessible and available through a user-friendly web-based package, LOICZView[2], and its successor package, DISCO[3]. These tools were used to classify the budget case studies, understand how to extrapolate from the case study estuaries and catchments to the global database, and then use the resulting relationships to develop regional and coastal flux estimates.

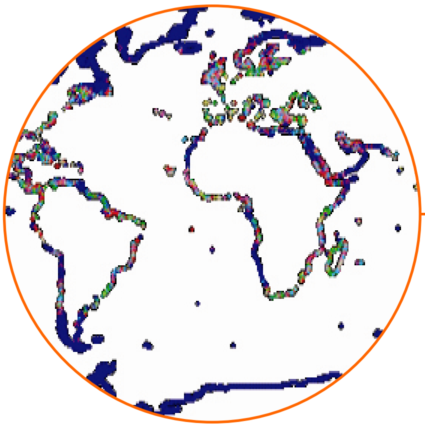
The water bodies addressed by the budget case studies ranged in surface area over 7 orders of magnitude, from small estuaries to semi-enclosed coastal seas. Both residence time and the magnitude of non-conservative fluxes were found to be related to system area. Results have shown that catchment nutrient loads play a critical role in coastal budgets. In particular, the analysis showed that small coastal water bodies are much more likely to show strongly non-conservative behaviour of nutrients, and it was suggested that these systems might be the “dominant engines of coastal metabolism”.

Web links to LOICZ resources:

[1] Global environmental database - http://hercules.kgs.ku.edu/hexacoral/envirodata/hex_modfilt_firststep3dev1.cfm

[2] LOICZView typology tool - www.palantir.swarthmore.edu/loicz

[3] DISCO typology tool - www.narya.engin.swarthmore.edu/disco



## Global typology approaches

A primary LOICZ objective is to describe the role of the coastal zone in critical biogeochemical fluxes (C, N, P). These fluxes must be understood at global spatial scales, and at temporal scales up to and including those of climate variability and change. The C-N-P biogeochemical models for estuaries and coastal seas are distinguished by their external forcings (material loads, human populations, oceanographic influences), climate regime and nature of the ecosystems that comprise the locality. These conditions form a tapestry of geographical settings that can be described across a variety of scales through a suite of variables. In our efforts to describe the biogeochemically functional state of the coastal systems, it is necessary to integrate the information across larger scales in order to determine patterns of nutrient effects and transformations and to derive information about “hot spots” and about changing conditions and drivers of ecosystem function. Currently, there are relatively few measurements of coastal zone fluxes, and their spatial and temporal coverage is limited. As a practical approach to developing and improving quantitative estimates of coastal zone fluxes at all scales, LOICZ addressed the upscaling of flux measurements by coastal zone typologies. Here, upscaling is primarily used to mean the development and application of techniques to predict, quantitatively or semi-quantitatively, the behaviour of large spatial regions based on observations made at much smaller scales. Typology (Figure 13) is the development of environmental classifications or categories of data that can be related to local and regional observations in ways that permit inferences about areas in which local observations are lacking. The typology approaches of LOICZ were an important tool within the GEF project.

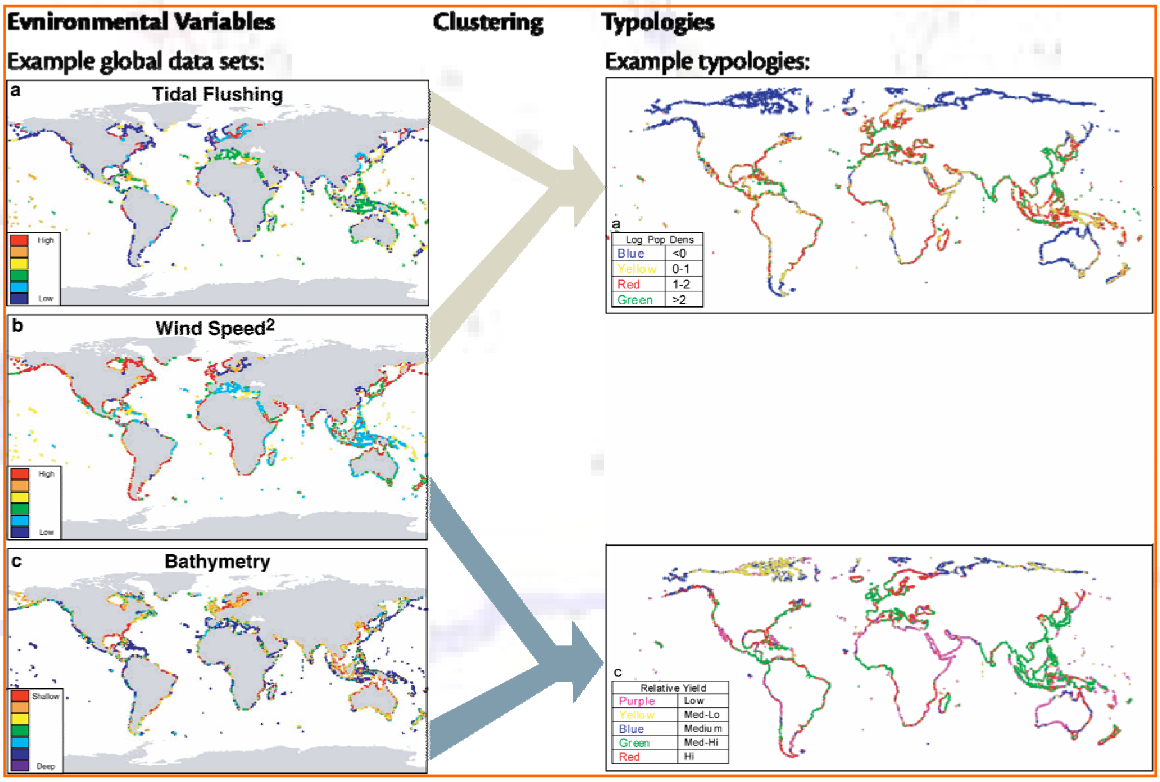


***Figure 13**. Various environmental variables can be clustered through a diversity of statistical approaches to create unique typologies in which coastal regions are compared and contrasted. LOICZ has produced on-line tools including a global environmental database to supply environmental data at 0.5 degree resolution and LOICZView and DISCO clustering tools to develop typologies.*

## Typology structure

Three typology datasets were developed for use in analysis and upscaling of the coastal zone biogeochemical flux assessments:

**1**. A global half-degree gridded environmental database (also referred to as the typology database), with the cells classified according to their relationship to the coastal zone. The objectives of the LOICZ cell structure are to provide a geographically structured basis for database design that will:

- classify coastal environments in a conceptually useful fashion;
- permit integration and consistent analysis of available global data sets dealing with land, sea, air, and human dimension variables;
- operate at a scale of resolution useful for the data and applications envisioned; and
- provide a manageable number of data points for analysis and global upscaling or extrapolation.

***Table 4****. LOICZ typology cell types and numbers.*

| Cell Class | Number of Cells |
|---|---|
| Total primary Typology cells | 47,057 |
| Oceanic-III | 143,394 |
| Oceanic-II | 2,595 |
| Oceanic-I | 19,330 |
| Coastal | 15,278 |
| Terrestrial | 12,449 |
| Inland | 66,317 |
| Non-Typology Cells | 209,517 |
| **Total number of 0.5 degree cells in the world** | **259,200** |

Half-degree resolution has been selected as the most realistically useful compromise between desired resolution and the available data and methods. Some 259,200 half-degree cells describe the Earth's surface and 47,057 of these cells have been identified as typology cells (Table 4) that describe the global coastal zone (coastal, terrestrial and ocean-I) generally extending inland 70-100 Km and offshore to the edge of the continental shelf (Text box 1). The coastal zone (Figure 14) is represented primarily by the coastal cells (containing actual shoreline), the Ocean I cells (~ one degree seaward of the coastline) and the terrestrial cells (~ one degree landward of the coastline). The remainder is classified as Ocean II (enclosed seas or basins), Ocean III, or Inland.

This database contains a wide variety of public domain, global or near-global datasets, and the variables represented are those that have relevance to either general coastal zone classification or to the factors believed likely to control or influence the fluxes of interest, including terrestrial, marine, coastal, atmospheric, human dimension, geomorphic and river-basin variables. The data for each variable has been geo-referenced and scaled to the half-degree cell array; a number of the variables

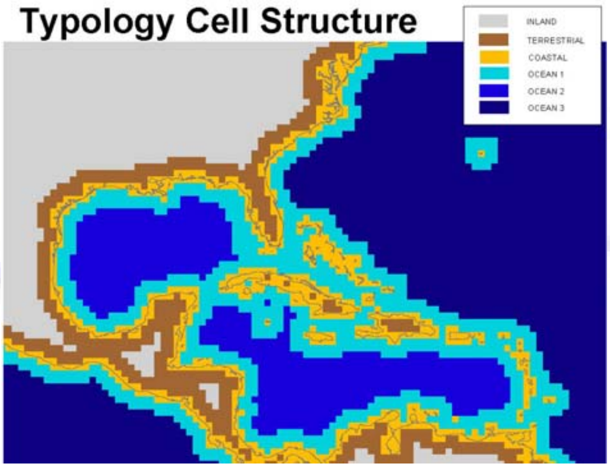


***Figure 14****. Typology – Illustration of the scale and categories of the LOICZ half-degree grid cell definitions Gulf of Mexico & Caribbean.*

***Text Box 1*** *LOICZ typology cell classification.*

**Land or Terrestrial cells (T)** are typically defined as the cells containing only land (or fresh water). Coverage typically extends two cells (one degree) inland from the most landward coastal cell, although they have been extended farther inland in a few areas (e.g., estuaries not well represented by the shoreline data set). These do not have ocean variables.

**Coastal cells (C)** are defined as those containing a significant length of the World Vector Shoreline. These cover significant areas of both land and (marine or estuarine) water, and are populated with all classes of variables.

**Oceanic I cells (O-I)** are those extending seaward from the coastal cells the greater of (a) one degree, or (b) the 50 or 100 m isobath in areas of a broad shelf, or (c) to include all of a biogeochemically budgeted area. These will have only oceanic and atmospheric variables.

**Oceanic II cells (O-II)** are those additional cells needed to complete the in-filling of relatively enclosed water bodies or coastal seas that might be the target of future up-scaled biogeochemical budgeting exercises.

**Oceanic III cells (O-III)** cover all remaining oceanic areas not included in the other classes.

**Inland Cells (I)** cover all remaining land areas not included in other classes.

have much finer resolution and all are accompanied by metadata descriptions. The native resolution of the data sets ranges from 1 km to several degrees. Where higher resolution data are aggregated into the half-degree cells, statistics on the sub-grid scale distributions are included in the database.

**2.** The biogeochemical budget database (see page 9).

**3.** Km-scale basins: A database was derived from the HYDRO1k dataset (HYDRO1k Elevation Derivative Database, (http://edcdaac.usgs.gov/gtopo30/hydro) using GIS to identify the drainage basins associated with the biogeochemical budget sites. The associated basin entries were populated with terrestrial, climatic, geomorphic and human variables by “clipping” GIS coverages of the parent datasets with the HYDRO1k basin coverage. This provided a more accurate and precise representations of those variables associated with the biogeochemical budget sites than can be obtained from the half-degree database. However, it did not address the issue of marine variables for which comparable data are not available.

The typology upscaling, for practical reasons, has evolved into two related processes. The km-scale river basin (catchment) data are used to identify relationships between terrestrial, hydrologic and human forcing functions and aspects of the biogeochemical fluxes that are or should be sensitive to those functions. This effort examined and compared relationships across a wide range of spatial scales, but did not in itself “upscale” by using measurements derived at one scale to characterise performance at another scale. The km-scale basin data were also used to compare the site-specific basin characteristics with characteristics inferred from the half-degree database alone. This comparison allowed determination of which budget characteristics, sites and environments were most amenable to upscaling with the existing datasets, and where (or whether) the additional effort involved in systematically developing coastal datasets based on km-scale budgets could be justified. The comparison also permitted assessment of the biases and uncertainties involved in upscaling.

## Outcomes

The GEF project facilitated major progress to be made in terms of both coastal characterization itself (typology) and the conceptual and operational tools available for the task.

### Combined Controls on Nutrient Loads and Anthropogenic Factors

Climatically-driven forcing functions, such as runoff, interact with land cover, land use and geomorphology to modulate inputs to the coastal zone that result from a mixture of natural processes and varying degrees and types of anthropogenic modifications.

For the km-scale budget site basins a logarithmic relationship has been observed between DIP and DIN loads, and the population density and area-normalised discharge. This robust finding substantially extends and is consistent with many studies and provides a useful starting point both for further refinement of the relationship in terms of climate and land use, and for consideration of upscaling the terrestrial inputs to the ocean on the basis of readily available terrestrial data.

Influences of human activities within river basins are encapsulated by both the population density and runoff terms. Land use modifies the potential runoff calculated from the water balance (the typology runoff variable) to produce the actual observed runoff or discharge. The use of population density as the primary human dimension forcing function glosses over the explanatory potential of various more refined variables (e.g., extent and types of agriculture, economic development levels, industrial and urban activities). Preliminary analyses have shown that agricultural land use and nutrient input variables have some potential to refine the equations, particularly for developed countries. The ubiquity of human influences and the fact that they influence both of the independent variables in the load regression equations (population density and runoff) to some degree means that estimation of the pristine or natural fluxes is particularly challenging.

### Coastal Classifications as Flux Predictors

Extrapolation of flux estimates from known sites or typical coastlines to unmeasured but similar regions is a fundamental component of the upscaling approach. The ability to associate appropriate coastal classes with flux values is an essential step. The project has had significant success in some areas, while the problems encountered in others have helped to identify the additional data and tools needed to fully implement the upscaling effort.

The most clear-cut success has come in the classification of river basins in terms of their probable DIP and DIN load based on globally available data (Figure 15).

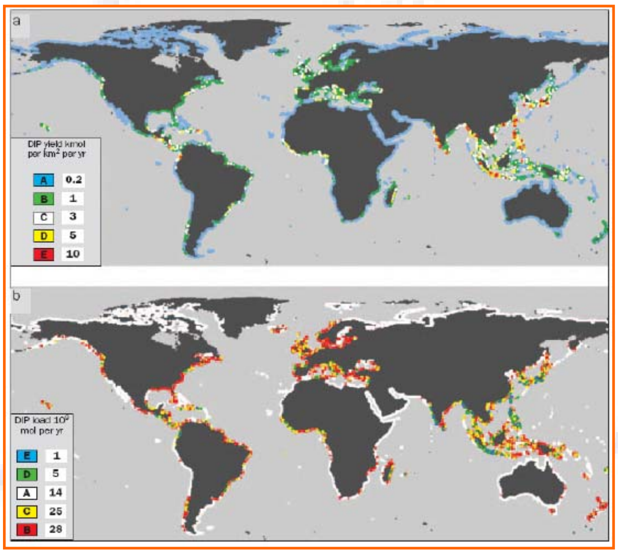


***Figure 15**. Calculated dissolved inorganic phosphorus (DIP) for the global coastline based on a population-runoff equation. Clusters are identified by the letters in the legend boxes; order is changed by the colour-coded ranking in terms of the two variables. (a) DIP yield in Kmol per km$^2$ per year. The global mean is about 600. (b) DIP load in 10$^9$ mol per year.*

This relationship, derived over a wide range of basin sizes and types, can almost certainly be extended to basins in general and to those coastal regions not identified as part of specific catchments in global-scale elevation models.

In the case of the non-conservative fluxes, the typology analysis suggests that water residence time and some of the related variables are important in explaining the sign and magnitude of $\Delta DIP$ and $\Delta DIN$, and that smaller coastal systems (as opposed to large, shelf seas) are the dominant engines of coastal zone metabolism. However, further study is necessary in order to resolve the oceanic forcing variables at a scale that can relate to small system function, and this is probably one of the major challenges to be overcome in developing a full typologic approach to global flux estimates in the coastal zone. This is because many of the budget systems are small compared with a half-degree cell, and these small systems may be disproportionately important in terms of their effects on overall non-conservative fluxes.

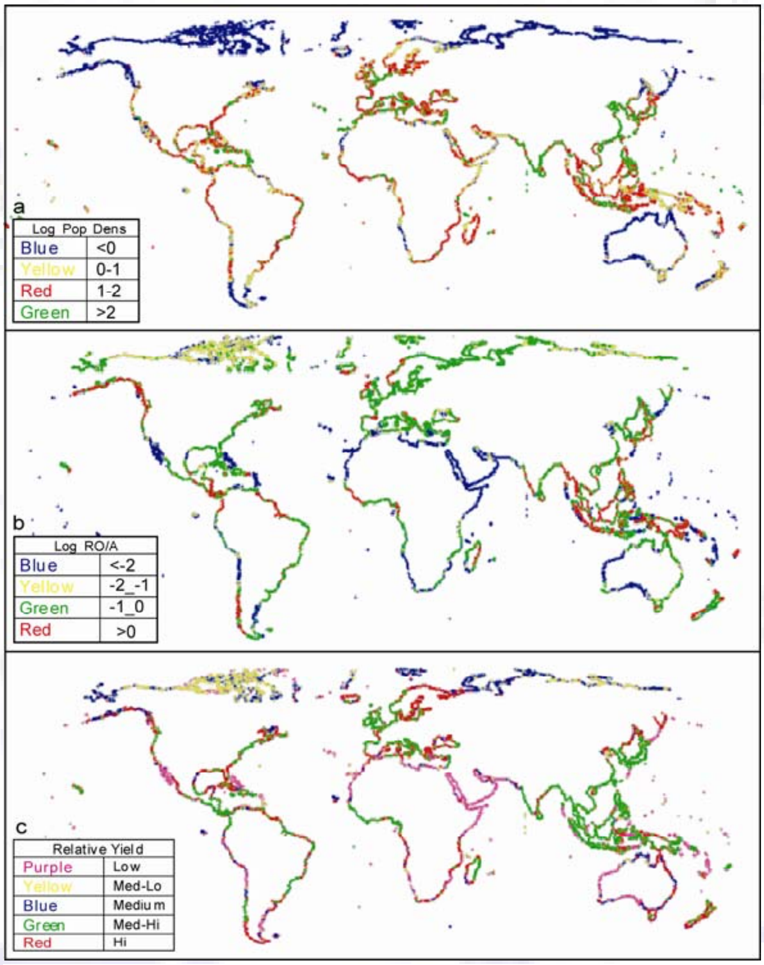


***Figure 16**. Nutrient flux. Comparisons of present population density, runoff/area, and nutrient yields in small coastal basins: (a) Four-class distribution of $log_{10}$ population density. (b) Four-class distribution of $log_{10}$ runoff/area . (c) Five clusters of DIP yield generated using the LOICZView tool. Cluster*

## Prospects for future fluxes and their assessment

### Climatic Controls and Geomorphic Evolution

Climatic controls on fluxes may be assessed for both oceanic and terrestrial changes, for changes in the input fluxes (e.g., marine and terrestrial DIP and DIN) and for changes in the conditions of the coastal biogeochemical processes that influence the nature and rates of non-conservative fluxes within the system. On the marine side, changes in upwelling and wave or current strength may occur, but predictive abilities are limited and the rates of change seem relatively slow compared with the more dynamic terrestrial inputs. Changes in the physical structure of the coastal interface (e.g., erosion, sedimentation, subsidence, inundation) may affect the nature of the coastal system in significant ways. The most confidently predictable effect is a probable sea-level rise of 0.3-0.5 m by 2050.

Coastal vulnerability and impact assessments have been carried out for human infrastructure and ecosystem function but the effects of sea-level rise on the overall biogeochemical functioning of the coastal zone have not yet been evaluated. Changes in terrestrial input can be viewed in terms of the DIP and DIN load dependence on population density and runoff, discussed above. Runoff may be influenced by climate change through both precipitation and land cover, but both land cover and the hydrologic cycle (especially runoff) are subject to greater modification by humans in areas of significant population. Results indicate that the DIP and DIN loads are relatively less sensitive to runoff than to population. Overall, the most probable short-term drivers of changes in coastal zone fluxes are human alterations of the environment.

### Human-induced change: where and how fast

Humans may change coastal zone fluxes in many ways, including land-use changes, interception of runoff for consumption, waste disposal or contamination and direct actions to modify coastlines and nearshore morphology. At local and regional scales these effects are likely to outweigh the influence of climate change, with global-scale effects that are readily predictable. At present, our best predictive tool relies on the general correlations between yields, population density, runoff and the resulting loads.

Figure 16 brings together the geographic distributions of population density and runoff classifications with a clustered map of nutrient yield for the small coastal basins that dominate most of the world coastline. Yields can be expected to change with growing population even if we assume that the natural potential runoff will be more stable. Changes in load will reflect the area-weighted changes in yield. If most of the high-population coastal areas (Figure 16a) are approaching saturation level in terms of human inputs and system responses, then the coastal systems may be relatively stable, if highly altered. On the other hand, most of these areas are experiencing continued growth and development. This is likely to be associated with still greater nutrient fluxes in the less developed countries and in areas of high to moderate runoff.

By linking expected changes in coastal zone fluxes to population projections we can identify some general geographic patterns of change now. We may also use the same approach to identifying the possible baseline or pristine areas: Figure 16 indicates that there are ample low-population, low-runoff areas to consider, but the situation is less clear for the more important moderate- to high-runoff, low-population density sites. There are relatively few low- and mid-latitude unaltered sites with runoff in the higher categories, and they tend to be close to areas that have a higher yield. This poses significant challenges to reconstructing baselines and natural mechanisms in these areas and reinforces the need for the refined analysis discussed above.

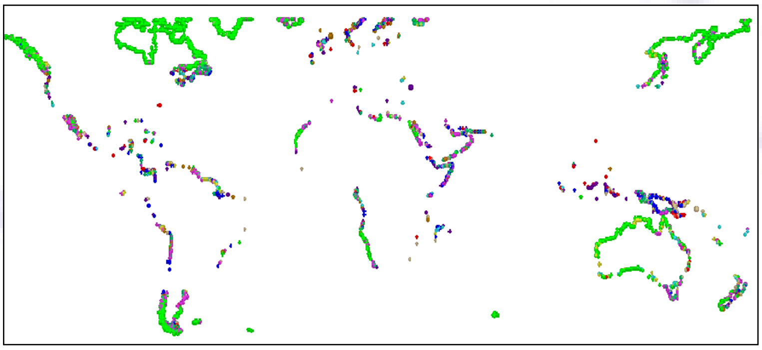


***Figure 17.*** *Global typology of low population density and low % cropland use. With polar regions cropped and data filtered for population density <10/km$^2$, land cover < 5% cropland, the clusters representing areas of probable human impact disappear.*

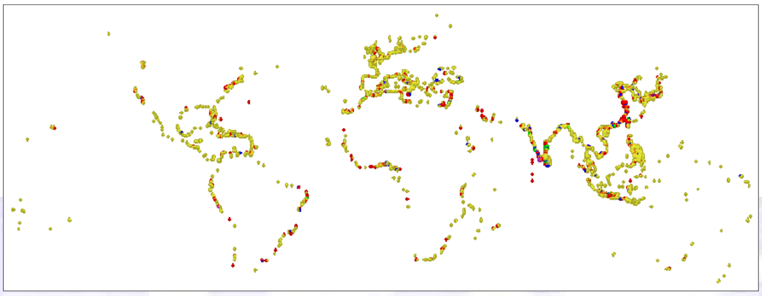


***Figure 18**. Global typology showing estimated regions of highly “disturbed” coastal systems defined as high population density [>60/km$^2$] and/or high cropland use [>10%]).*

The clear relationship between human population distribution and nutrient loads to coastal systems has led to a first geo-spatial assessment of where we can expect to find coastal ecosystems that are undisturbed, from application of the typology approach to key variables of population and cropland in the coastal zone. Using data filters (deleting the polar region and offsetting the megacities to remove their overwhelming influence on clustering), a typology of human demographic data was developed (Figure 17) representing coastal regions with a population density of <10 persons/km$^2$ and <5% cropland usage. The coastline in this graphic represents those parts of the global coastal zone where we can expect human influence to be small and thus to contain relatively “undisturbed” coastal ecosystems. This suggests that many regions of the world that can be described as containing few if any “relatively pristine” or undisturbed ecosystems. Extending this approach with population density and cropland as human pressure proxies, it can be argued that human effects predominate over landscape effects on nutrient loading to the coastal systems; population densities greater than about 30/km$^2$ may be considered to represent dominant human influences. From this assumption, we have taken a conservative value for population density (60 people/km$^2$) to make an initial estimate of coastal areas that are likely to contain systems “highly disturbed” by nutrient loading (Figure 18). Similarly, and by sub-grouping the population density data, a gradient of loading pressure can be represented (Figure 19) and, in combination with global population projections, a space-for-time interpretation could be applied to develop scenarios predicting key areas of change in coastal systems.

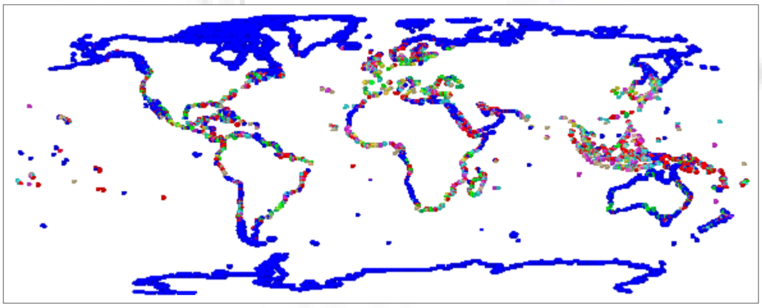


***Figure 19**. Global typology showing estimated localities and gradient of “disturbance” in coastal ecosystems, based on population density. (Blue, <10 people /km$^2$; Green, 10-20 people/km$^2$; yellow, 20-35 people/km$^2$; red, 35-60 people/km$^2$).*

## Analysis for management of coastal zones

**For management activity to be successful the analysis needs to articulate and understand the underlying reasons (drivers) and causes (pressures) for the observed changes in the environment. These are predominantly the result of societal function and human behaviour and it is by acting on these that management can alter and reverse environmental degradation. A Driver-Pressure-State-Impact-Response (DPSIR) framework has been adopted as a means to extend the analysis subsequent to the assimilation of the data from the budget sites and initial correlation with human factors through the typology. A goal is to develop a methodological approach for connecting the concept of Integrated Coastal Zone Management (ICZM) with that of Integrated River Basin Management (IRBM). The description of the interaction between the river catchment area (the source) and the coastal waters (target) in terms of nutrient mass fluxes is the critical step in this evaluation.**

### Managing Nutrient Loads and Impacts in the Coastal Zone.

Rapid increase in loads of nitrogen to the global environment as a result of industrial nitrogen fixation, has emerged as one of the major issues in global change. The coastal zone bears the brunt of much of this increasing load, as catchment applications of nitrogen fertiliser result in nitrogen runoff and transport down rivers to estuaries, and much of the nitrogen taken up by agricultural crops is released as effluent from coastal cities or livestock facilities within coastal catchments: It has been estimated that the global load of nitrogen to the coastal zone has increased three fold between the 1970s and 1990s. Human generated changes in nutrient loads to the coast, and the resultant threat of eutrophication, interact with other anthropogenic pressures in catchments and coasts (e.g. changes in land use and riparian vegetation (Figure 22), changes in water use and construction of dams, and changes in ocean exchange due to coastal engineering). Local catchment pressures also potentially interact with regional and global changes in climate, ocean circulation and ocean biogeochemical cycles.

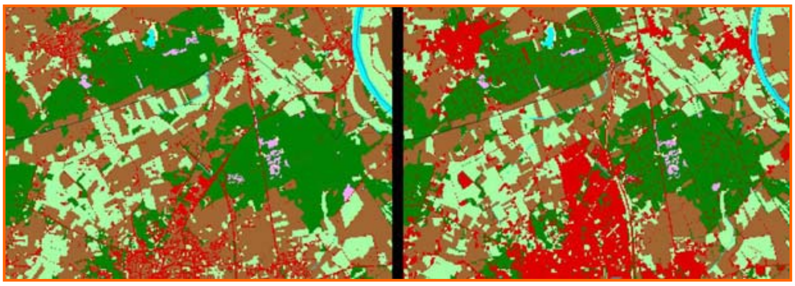


***Figure 22**. Changes can be seen from land use maps from 1984 (left) and 2002 (right) in the Netherlands; red signifies settlements, light green is grassland and dark green forests.*

Synthesis of the budgets datasets has shown the need for region, environment and process specific analyses to develop predictive understanding of budget characteristics and controls. However, common between local, regional and global scales there is a dependence of terrestrial nutrient loading to the coastal zone on human population and population density, which allows comment on the relationship between nutrient loading and human society and the implications for environmental management.

# Driver-Pressure-State-Impact-Response

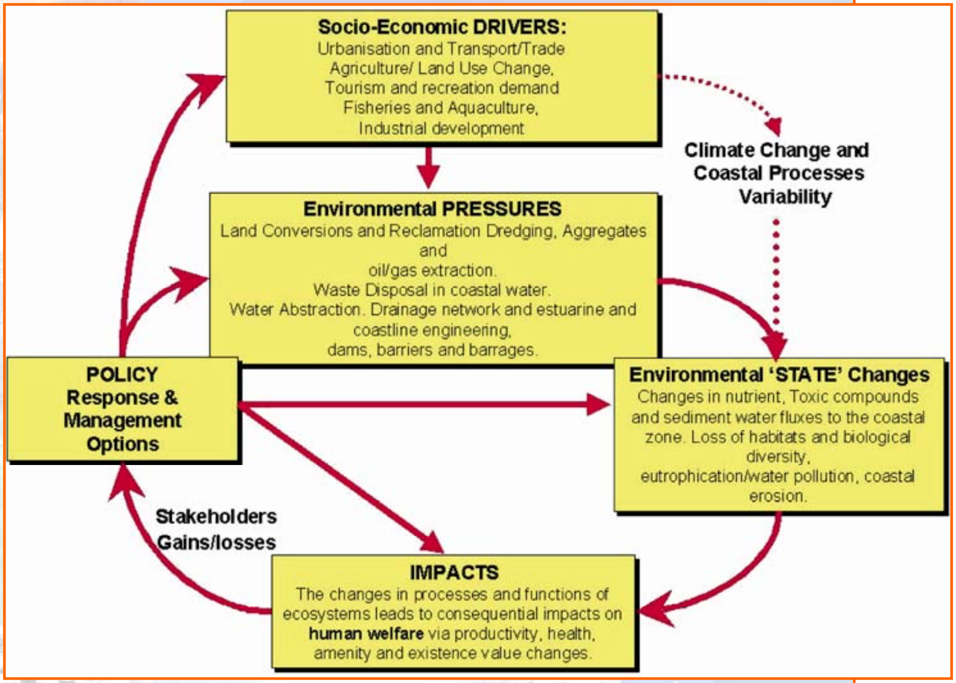


***Figure 20**. The coastal zone. Schema of DPSIR framework.*

Coastal ecosystems provide a wide range of goods and services which constitute the natural capital of the coastal zone. The global coastal zone has a high value; recent studies have estimated that the coastal zone has a total economic value of about US$17 trillion per annum and provides 53% of the total annual ecosystem service value of the world. The greatest value for a single ecosystem service was ascribed to nutrient cycling. Coastal ecosystems are vulnerable and subject to many development activities by humans. The DPSIR framework organises information about the state of the environment and highlights human components of the system, coupling socio-economics with environmental observations (Figure 20 & 21). The Drivers and Pressures on coastal systems are predominantly the result of societal function and human behaviour (Table 5) and may be amenable to management and policy decisions (Response). Most natural Drivers and Pressures are greatly modified by human activities in both extent and intensity.

***Table 5**. The DPSIR framework exemplified using population growth as a driver.*

| DRIVER | PRESSURE | STATE | IMPACT | RESPONSE |
|---|---|---|---|---|
| Population growth | • Increased water extraction (upstream)<br>• Increased wastewater release (downstream)<br>• Higher loading of pollutants | • Deterioration of water quality<br>• Changes in water level<br>• Variations in river discharge, current velocity<br>• Enhanced turbidity | • Community changes<br>• Pollution<br>• Sediment accumulation<br>• Reduced infiltration | • Water conservation management<br>• Implementation of wastewater treatment |

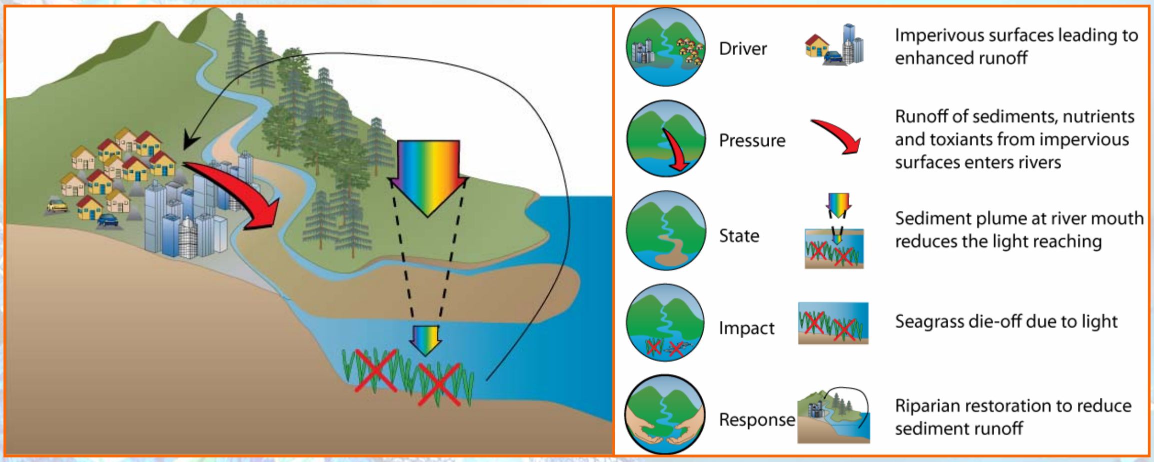


***Figure 21**. The Driver-Pressure-State-Impact-Response approach to coastal management illustrated through an example in which the issue of sediment erosion leading to seagrass loss results in riparian restoration initiatives.*

The analysis of human activities, how these interact with the environment, the changes in state that they bring about, the impact these changes have on future human uses and activities, and how management should respond are complex. Management activity and intervention to mitigate and/or ameliorate environmental perturbation often takes place once an impact that changes processes and/or functions of ecosystems, with consequential impact on human welfare, is noticed. Scientific measurement and analysis is then used to explain and quantify the changes in state of the environment that have led to the observed impact.

***Text Box 2.*** *Origins of nutrient loads to the coastal zone.*

### Land-based origins

Urbanisation and agriculture/land-use change are the socio-economic drivers of change that have the greatest impact on nutrient dynamics in the coastal zone and to which the biogeochemical budget approach of LOICZ has the greatest relevance as a means of study. These drivers are manifested in the environment as pressures on the natural system in the form of, for example, land conversion, water extraction, waste disposal, impoundments etc that lead to increased nutrient loads to coastal systems. In highly urbanised small coastal catchments, virtually all of the runoff from the non-urbanised catchment may be captured for urban use, and the remaining river discharge can consist solely of discharge from storm drains and sewage treatment plants.

As well as activities that may directly alter nutrient flows and loads to the coastal zone, there are other activities in catchments that may alter natural flows and loads. Many of the world's river systems are dammed, trapping sediments and nutrients and reducing loads to estuaries. In the case of reduced water flow, reduced flushing and increased residence times make estuaries more vulnerable to local point sources of nutrients and other pollutants. Dramatic reductions of flow due to damming, diversion or increased consumptive use can alter salinity regimes and circulation, as well as shifting the effective position of the estuary inland, thus altering the morphology of the estuary.

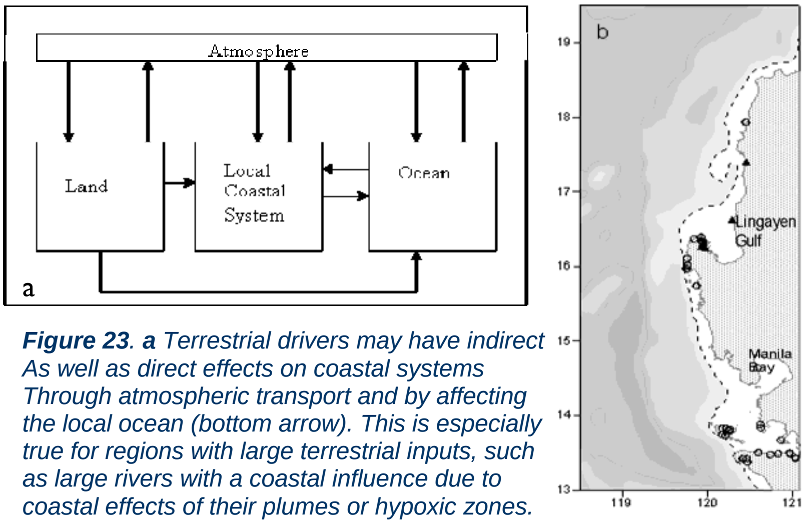


***Figure 23**. **a** Terrestrial drivers may have indirect As well as direct effects on coastal systems Through atmospheric transport and by affecting the local ocean (bottom arrow). This is especially true for regions with large terrestrial inputs, such as large rivers with a coastal influence due to coastal effects of their plumes or hypoxic zones.*
***b**. Lingayen Gulf, in the Philippines, is affected by the direct effects of its watershed, but may also be affected by indirect effects of Manila carried by longshore currents northward along the coast of Luzon from Manila Bay.*

### Atmosphere-based origins

Atmospheric deposition is now recognised to be a significant and extensive source of nitrogen load both to catchments and coastal and shelf waters. While the LOICZ case studies suggested that direct atmospheric inputs of nitrogen are generally small compared with catchment and marine inputs, they can be significant, especially in large semi-enclosed embayments and seas receiving little catchment runoff and small land-derived loads. It is also true that while direct atmospheric inputs to small coastal systems may be small, atmospheric inputs contribute indirectly where they are important contributions to catchments and oceans.

### Ocean-based origins

The importance of ocean inputs of nutrients varies widely, depending on geographical location, connectedness to the ocean, the nature of the physical and biogeochemical regime in the adjacent ocean, and the catchment size and load. At the scale of the continental shelves, nutrient budgets are typically dominated by exchange with the adjacent ocean where a variety of circulation and mixing mechanisms inject ocean nutrients onto the continental shelf.

***Text Box 3.*** *Key factors affecting the response of coastal waters to changing nutrient loads.*

**Residence Time** - Vulnerability to loads, especially point source loads with little seasonal variation, will change according to residence time. Estuarine residence time determines the capacity of internal biogeochemical processes to transform and potentially retain nutrient loads and is determined by the relative interaction of riverine flows and flushing with marine exchange. Systems with short residence times (days) tend to reflect the biogeochemical state of the dominant boundary (river or marine). If river flows dominate, most of the load is exported to the adjacent sea. For long residence times (weeks to months), internal processing can transform inorganic nutrient loads into organic matter (autotrophic), or conversely organic matter loads to inorganic nutrients and carbon (heterotrophic). With little exchange, internal sinks for nutrients and carbon, through denitrification or burial, may dominate. Such systems are more likely to be sensitive in their response to changes in nutrient load. River flows and residence times may change from days or less during floods, to months during the dry season.

**Load per unit area of receiving waters** - The capacity of a coastal system to deal with or process nutrient loads tends to scale with surface area of receiving waters. For systems with long residence times, load per unit area of receiving waters tends to determine ecological impact. Thus, small poorly flushed coastal systems with small catchments, low runoff but large point source inputs are particularly vulnerable. Coastal lagoons often fall into this category, as runoff is typically low, and exchange with the ocean is restricted or even intermittent. Urban coastal sprawl with high urban loads is likely to increase the number of systems in this category. Small systems with large catchments may be vulnerable if flow is highly seasonal or diverted. Conversely, very large systems (coastal seas and large embayments) may show little broad-scale impact, if loads per unit area are small, especially if exchange with the ocean is effective.

**Vertical Stratification** - Vertically stratified systems are more likely to show adverse symptoms of eutrophication from positive feedback processes. Stratification inhibits vertical mixing, restricting oxygen supply to bottom waters and sediments. As nutrient supply and organic matter production increase, there is increasing sediment respiration, drawing down bottom oxygen. As bottom waters become hypoxic or anoxic, changes in sediment chemistry and microbial processes lead to reduction in denitrification efficiency and desorption of phosphate bound to sediments, resulting in further increases in nutrient supply, or a reduction in nutrient sinks. There is an emerging syndrome of hypoxia, harmful algal blooms, and fish kills, apparent in eutrophic stratified estuaries worldwide.

**Tropical, macro-tidal turbid systems** - Current scientific understanding of estuarine and coastal processes and systems is largely based on studies in temperate estuaries and seas. In contrast, many tropical estuaries are characterised by high natural levels of turbidity and tidal energy. These systems may be naturally heterotrophic, with high level of DIN and DIP unutilised due to light-limitation.

**Nonlinear responses, critical thresholds and resilience** - Budgets effectively give a linearized picture of system response to changes in flows and loads. This may be used to describe how systems respond to small relative changes in load. However, systems can respond in a highly nonlinear fashion, flipping from one stable state to an entirely different one, under modest changes in load. Two possible mechanisms for system state changes in estuaries are the following:

1. In systems with long flushing times and moderate loads, denitrification can serve as an extremely efficient sink for nitrogen loads, maintaining the system in a mesotrophic or oligotrophic state. However, as organic matter loads to the sediment become sufficiently high, denitrification efficiency falls off. This potentially creates a positive feedback and hysteresis, in which the system flips over into a highly eutrophic state, which can only be reversed at very low loads.
2. Shallow lagoonal systems are often dominated by benthic macrophytes under oligotrophic conditions. The macrophytes not only consume nutrients, but also tend to trap and stabilise fine sediment, maintaining clear water. As nutrient or sediment loads increase, turbidity may increase to a point where the benthic macrophytes are lost. Once lost, wind-driven resuspension maintains high turbidity and prevents recolonisation.

The concept of critical thresholds is important for setting environmental objectives and targets. The “assimilative capacity” of a system describes the level (critical threshold) below which the system is able to absorb loads without showing catastrophic or unacceptable changes in function and properties. Systems which are deemed to be within their assimilative capacity are arguably providing a valuable ecosystem service. For example, coastal systems which denitrify most of the incoming nitrogen load are effectively providing tertiary treatment of sewage at zero economic cost. These considerations have implications for developing understanding of coastal ecosystems in order to determine the capacity of a system to absorb perturbations – its “resilience”- without switching system state in this way. Identifying which systems have the potential for such catastrophic shifts in state and determining critical thresholds that trigger such changes are difficult. It is often proposed that highly simplified systems are more vulnerable to catastrophic change, and that maintaining natural levels of ecosystem diversity and connectedness helps to maintain resilience. Regional and global databases and inter-comparisons offer an opportunity to establish empirical evidence and warning of such system shifts and thresholds.

### Drivers and Pressures for Coastal Eutrophication

Drivers of coastal change are varied and diverse. Some drivers of change originate from natural processes (e.g. storms and other extreme weather/seismic events) over which mankind has little control, if any. However, since the later 18th century mankind's activities have gradually grown to exert significant pressure at local, regional and now global scales. The term "Anthropocene", has been applied to this new geological era in which humans rival nature in their impact on the global environment. Human induced drivers of coastal change broadly are associated with urbanisation, transport and trade, agriculture and land-use change, tourism and recreational demands, fisheries and aquaculture and industrial development: many of these drivers do not act in isolation from each other but are mutually compounding in their impact Figure 24).

### Identifying the origin of drivers and pressure for changing nutrient loads

In attempting to identify drivers and pressures of change in the coastal zone resulting from altered nutrient loads, coastal managers need to be aware of the potential for catchment loads to originate from both diffuse and point sources; land, atmospheric and marine loads (natural and anthropogenic) (Text box 2). Global and regional climate change raises the possibility of changes in the pattern of supply of ocean nutrient loads to coastal systems and changes in catchment runoff and possibly in vegetation cover, leading to changes in the pattern of catchment loads. Loads may vary in time, in some cases by orders of magnitude, on time scales from event to seasonal to inter annual. This highlights the fact that many estuarine ecosystems are adapted to high natural levels of variability in nutrient loads. Moreover, while extreme anthropogenic eutrophication generally has unpleasant and undesirable consequences, some level of nutrient supply is essential to support ecosystem function.

The links between the drivers of change and the resulting pressures on the environment are complex but, as previously shown, a useful proxy has been found to be population in coastal catchments. These proxies can be used to begin exploring the relationships between terrestrial, hydrologic and human forcing functions and aspects of biogeochemical fluxes that are sensitive to those functions. This relationship is important to determining issues of human vulnerability to change that are important for management of coastal zones.

***Figure 24****. Industry and fishing activities competing for space adjacent to the coast at Chennai, India.*

### Coastal Ecosystem State and Impact

Coastal managers and communities are typically concerned with coastal ecosystem values and services (and with social and economic values), as it is alterations in these parameters that hold wider societal implications. The study of biogeochemical properties and cycles provides a means to understand many of the changes in the environment that become the subject of management effort because they play a critical role in underpinning and mediating ecosystem responses. Many environmental changes are caused by alterations to nutrient loads and flows; biogeochemical (water and sediment quality) indicators, measurements and models provide coastal management with information to inform and underpin decisions.

There are several key factors which control the vulnerability or sensitivity of estuaries and coastal water bodies to changes in nutrient loads. These are discussed further in Text box 3.

***Figure 25****. A lack of management and infrastructure can lead to unsustainable uses of coastal space – in this instance introduction of washing effluent into tidal waters.*

## Management Objectives, Strategies, Responses and Governance.

In many instances the most important impediment to coastal management is not a lack of technical knowledge or ability, but the reconciliation of competing interests and agreeing on explicit objectives, indicators and performance measures (Figure 25). This is not straightforward because of the conflict and apparent contradiction between environmental, economic and social values – the so-called triple-bottom line objectives. While different communities and cultures may place different weights on these values, an ability to compare ecological and biogeochemical states across systems, and especially across "comparable" systems, is highly useful. The LOICZ database and typology represents an initial attempt and facility to allow managers to identify and compare "comparable" systems, to understand similarities and differences in response to catchment pressures, and to compare and contrast system indicators and targets. In addition, the outcomes of the analysis make a contribution towards many current debates around issues that include:

**Determining appropriate objectives and targets for a particular system**. The wide variation in natural biogeochemical and ecological characteristics makes setting appropriate national or regional water quality standards problematic. This problem is exacerbated where there is a long history of anthropogenic impact and the "pristine" state is unknown; that often leads to a "shifting baseline", i.e. the incremental erosion in perceptions of what the desired state of nature is, based on the experience of the current generation of managers.

**Coastal management**, in common with other forms of environmental management faces high levels of both scientific uncertainty (data quantity and quality) and uncertainties in the assumptions and scenarios on which predictions of the future are based. This requires an approach of adaptive management whereby new information and understanding can become incorporated into management strategies and action. This in turn requires a monitoring strategy to measure implementation and system response, methods

for assessment and decision-making, and a long-term commitment to implementation and change. While they have not been designed specifically for this purpose, the LOICZ budget models could be modified to form the basis of assessment models in adaptive coastal management strategies.

**Management of sources** offers opportunity for proactive and planned management to avoid problems rather than reactive and defensive management of problems as they arise. There are three areas where this could be possible;

- **Management of sources on the input side.** Tracking and managing nutrient loads high in the landscape of a catchment is more efficient than attempting to manage loads leaving the catchment into coastal waters.
- **Reducing point source nutrient loads**. The budget datasets suggest that:
  - Simple reductions of water use can reduce water flows from point- and non-point sources, and associated nutrient and contaminant loads. While water re-use is emphasized in arid environments, the concept is relevant beyond these environments.
  - Conversion of diffuse sources to point sources is often an effective management tool as point sources are easier to control and regulate in principle. However, it is important to recognize the potential unintended consequences of such transformations (e.g. an effect of extending sewage networks can be to support development of higher population densities in a region, with correspondingly higher nutrient loads).
- **Management of large sources.** The relative contribution to loads and the strength of the effluent suggests that priority should be placed on managing large animal agricultural operations over small operations; establishing control over effluents from large confined feeding areas, dairies, etc, provides both greater proportional reduction of load and reduced probability of catastrophic loading events from waste lagoon failure, etc.

**Time scales** associated with system responses to management actions and natural variability in climate, catchment runoff or ocean exchanges, have important implications for management strategies. Response time scales in catchment and coastal systems can vary widely, from days to decades. Responses at longer time scales, largely associated with sediment transport and biogeochemistry in catchments, rivers and estuaries, are arguably least well understood and most critical to successful management.

As the number of budget sites increased considerably through the GEF project their similarities and differences could be used to determine their contribution for management purposes. The budgets provide the basis for simple and clear communication to community stakeholders about the system state and function, particularly if combined with conceptual models and graphical communication tools. The LOICZ database and typology could be linked with national and regional databases and typologies to provide consistent information and understanding across local, regional and global scales, and to permit managers to use experience acquired in similar systems to guide their own decisions.

## Size matters – the effect of catchment scale

An example of the links between components of LOICZ research carried out under the GEF project is the coupling of land-ocean interactions between specific types of terrestrial basins and coastal configurations. An observation emerging from the biogeochemical budget studies, supported by findings from material flux studies, is that qualitative differences exist between the functioning of large and small coastal systems and, similarly, between large and small drainage basins that discharge their fluxes to the reactive inner-shelf zone of the coast. Fluxes from large basins (i.e., Amazon, Congo and Mississippi) represent the dominant proportion of the total flux to the coast on a global scale, but directly influence only a small fraction of the length of the world coastline; most of the global coastline is fed directly by small catchments.

In addition, there is a similar socio-economic/human dimension dichotomy between large and small basins. Coastlines with catchments which are small enough for their inhabitants to interact significantly with the shore (so that the catchment is likely to be contained within the same national or sub-national political or administrative jurisdiction) present coastal management needs which are qualitatively different than those in which the coast and the hinterland are socio-economically or politically decoupled. Since the former arguably account for more of the coastline, it is important that the visibility of the larger basins not be allowed to divert attention from the quantitative coastal importance of the distinctive smaller catchments.

These studies have shown that there are fundamental issues of scale (Figure 26) that are important in understanding the biogeochemistry of the coastal zone and which relate to catchment size and catchment load versus oceanic exchange. When defined as the area shallower than 200 m, the coastal zone extends across the continental shelf, in some cases hundreds of kilometres from land. Only the plumes from major rivers exert significant influence on these scales. The spatial influence of small river systems is often confined to nearshore environments - estuaries, embayments or nearshore environments. Further offshore, and away from major rivers, shelf biogeochemistry tends to be dominated by ocean exchanges that dwarf all but the very largest riverine flows.

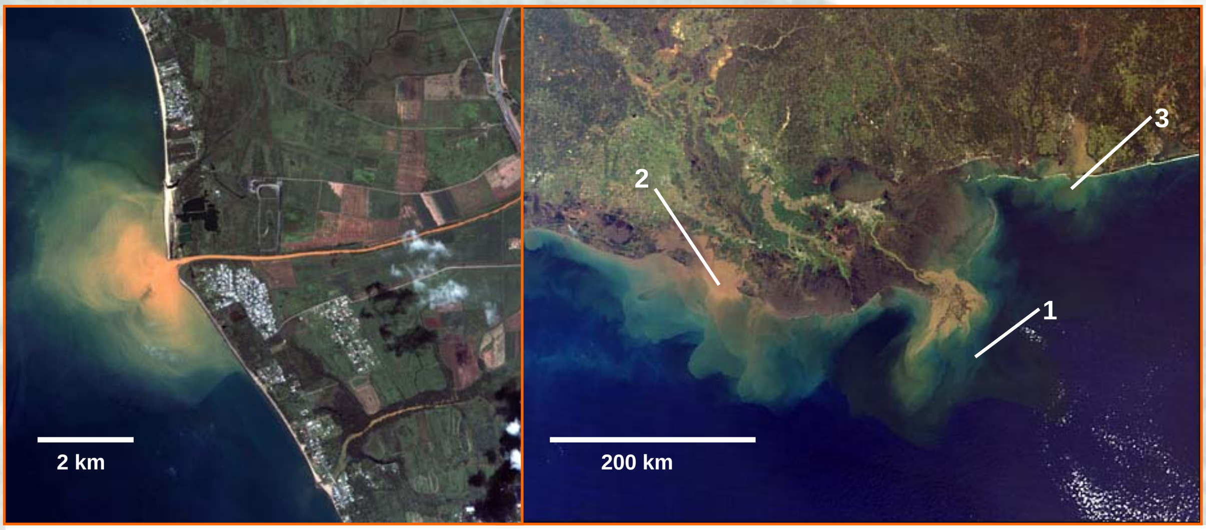


***Figure 26***. *Scale effect of small versus large river discharges. River plumes from the Anasco river, Puerto Rico (left) showing the limited extent of a small catchment river plume. Within complicated deltaic systems, such as for the Mississippi river, USA (right), there may be large extensive sediment plumes from major tributaries (1 – Mississippi river, 2 – Atchafalaya river). The Mobile bay river system plume (3) is also visible. Note the limited alongshore extent of the three major river plumes and the narrow fringes and mini-plumes that dominate the rest of the coastline and demonstrate the small basin local effects.*

Most of terrestrial nutrients reaching the ocean can be accounted for by the flows of the largest rivers; but for a small coastal lagoon far from a big river, its local environment is dominated by small inflows (partly because a lagoon is somewhat sheltered from oceanic influence); similarly, the estuary of a small river typically will be dominated by the flows from its watershed. However as boundaries further and further from shore are considered, the picture will change and oceanic exchange will become increasingly important. Although large river systems such as the Amazon and the Mississippi generate the major input of freshwater, energy and materials into the coastal and marine environment, it is the small- to medium-sized river basin systems that are more sensitive to human-induced and climatic influences on hydrology and material fluxes. For instance, the same town on a large river system/catchment has far less impact than on a small river system because of temporal and spatial scales as well as buffering capacity. The buffering capacity of large versus small systems is reflected in the time between change and when a response is found/observed, and in the magnitude of the response. In comparison to the large river systems, much less is known about these smaller rivers —

From the standpoint of fluxes, it is useful to distinguish between large and small catchments in terms of their impact on coastal ecosystems (Figure 27).

- ***Large catchments*** modulate hydrological “signals”, i.e. tend to smooth and reduce the magnitude of hydrologically driven events because there is longer “contact time” between flows and active catchment surface. There also tends to be greater temporal continuity of fluxes (persistence of hydrologically driven fluxes over dry periods) in large systems because they integrate over more contributing areas (“patches”) in space; the result is that even in persistent droughts, large watersheds may exhibit some flows due to contributions from precipitation or groundwater sources outside the range of smaller watersheds. Finally, large catchments capture large volumes of water, nutrients and other materials, and focus them into relatively small regions of the coast; this often results in a coastal plume of materials which influences areas of the sea well beyond the receiving waters of the coastal zone.

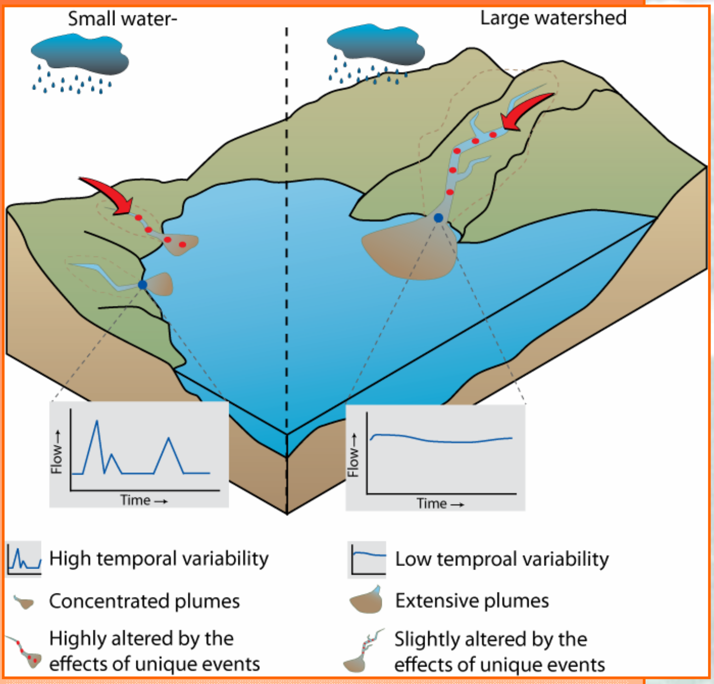


***Figure 27****. Conceptual diagram to show the relative greater impact of a given loading/change in small watersheds versus larger watersheds.*

- ***Small (coastal) catchments*** impact more of the coast directly (i.e. there are many more small coastal watersheds than large watersheds, both numerically and especially in terms of the length of coastline dominated by them). In the absence of effects of human population, fluxes from small coastal Catchments are more likely to be episodic because of the limited integrating and modulating capability of small catchments. However, in developed areas of the coast, human settlement is likely to dominate this variability by providing relatively constant and large sources of water and nutrients imported from outside catchment boundaries. The implication is that small coastal catchments and their receiving waters are disproportionately impacted by development compared to large catchments.

how they are changing, the response of associated coastal systems and their role in global change.

The analysis of the estuaries, rivers and budgets studied suggests that smaller estuaries and lagoons may also be intrinsically more vulnerable to increased loads. When adjacent to larger catchments and cities, these small systems may also be connected to the larger river system via semi-enclosed embayments and seas, and experience an additional load through increases in coastal marine nutrient concentrations.

Particulate materials tend to deposit near the sites of their delivery to the ocean, while reactive dissolved inorganic materials tend to react there. The strong negative log-log relationships seen between the absolute rates of the non-conservative fluxes and either system size or system exchange time argue that the most rapid rates of net material processing occur inshore, in small coastal systems linked to small coastal drainage basins. Since these small systems are typical of most of the length of the global coastline, integration of either the non-conservative fluxes of $\Delta DIP$ and $\Delta DIN$ or the derived fluxes of (*p*-*r*) and (*nfix-denit)* suggests that these rapid, inshore, small-system fluxes dominate global shelf fluxes, i.e., system size matters. The flux dominance by small systems suggests that the importance of terrestrial input to the shelf is largely felt at a local (inner-shelf) scale, especially in bays and estuaries. These smaller-scale features rapidly process and respond to both natural and human inputs and are thus particularly sensitive to human modification.

At global to regional scales, changed inorganic nutrient loading to the coastal zone may have little impact on the continental shelves as a whole. If we consider the loading for the ocean as a whole, we observe that cycling between the deep ocean and surface ocean (for both N and P) and between the surface ocean and the atmosphere (for N) are far larger than the nutrient load from land. Assuming that some small but significant fraction of this internal cycling exchanges with the open shelves, changes in the terrestrial load are probably not generally significant at the scale of the shelves.

This contrast – between acute local effects on systems important to and exploited by humans and greatly attenuated far-field signals at a global scale – highlights the rationale for the basic LOICZ approach and explains many of the remaining challenges. Top-down, global-scale models can neither resolve nor represent the intensity and diversity of coastal zone functions.

A major challenge in enhancing scientific knowledge and its use for informing management is the issue of spatial heterogeneity and the choice of appropriate scales to use in analysing biogeochemical processes and budgets. It is obvious that with decreasing system size comes increasing heterogeneity among systems. The ocean as a whole is a large system in which most metabolism is accomplished by plankton with relatively rapid biotic turnover rates. Smaller systems in the coastal zone are locally dominated by plankton, benthic micro- and macroalgae, seagrasses, coral reefs and mangroves. These systems differ greatly between one another, and they respond very differently to perturbations. Generalising globally therefore demands that each system type be adequately represented at an appropriate scale for data analysis.

## Looking to the future – science and management

**The "Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles" project assimilated biogeochemical datasets at a local to regional level. The project has been able to demonstrate a clear linkage between the human dimensions and coastal nutrient dynamics which provides direction for future studies and the contribution that science can make to coastal management.**

### Budgets and Coastal Models

Not all coastal systems lend themselves to the current budget modelling approaches and present challenges for the budget approach. These other types of systems include:

- Systems with highly turbid inflows (high inorganic particulate load) are problematic due to uncertainty regarding sorption/desorption of P.
- Mangroves – C:N:P ratio varies widely between different reservoirs and thus requires highly detailed information.
- Systems with significant groundwater inflows of water and/or dissolved constituents – especially when there are low or zero surface flows (e.g., flows in alluvial deposits).
- Systems subject to episodic, intermittent, and extreme events related to weather or climate extremes. In some regions, while these events are considered the norm (e.g., monsoonal weather), the effects on coastal areas may still lead to catastrophic transitions and even morphometric changes (e.g., lagoonal closures) which are very difficult to understand in quantitative terms.

Some of the issues related to the relevance of budgets to management include:

- Temporal nature of the local and regional environment (do water and nutrient flows occur episodically or evenly over time; is managing annual loads an adequate basis for management, or must seasonal variation or individual events be considered explicitly?).
- Multiple compartment systems have been considered where the physical features of the system suggest spatial complexity of the system in terms of environmental characteristics and management institutions. Future work might consider disaggregation of systems on the basis of the boundaries of management entities as well as obvious physical boundaries.

Budgets are diagnostic models, providing a snapshot analysis of the current system function. Managers frequently need to construct future scenarios of change that require prognostic models that answer "what-if" questions:

- How will the system productivity or denitrification sink change if loads are increased or decreased by X%, or if river flows are decreased by Y%?
- How might the system respond under future global change scenarios?
- What is the "assimilative capacity" of this system? Is it likely to flip over into an unacceptable state if loads are doubled? How is that risk affected by climate change scenarios?

Much coastal management is directed towards understanding the uncertainty that

surrounds *risk* associated with a hazard – whether man-made or natural – and the ensuing *vulnerability* that risk brings on human populations and their activities in the coastal zone. Current modelling capacity is limited because the available models:

- Require considerable investment in costs and time to produce.
- Are very site specific and data intensive and do not provide capacity to inform management other than at a very local scale.
- Are often not applicable to other sites or where data is not available.
- May be able to produce "plausible" management scenarios, but;
    - complex process-based models are typically unable to put rigorous quantitative probability distributions or confidence limits around these predictions, whereas
    - simple empirical models may prove illusory if pushed outside the regime for which observations are available.

There is an emerging view that some classes of models of "intermediate complexity" may be most appropriate to support management. Limnologists have long used simple load response models as management tools for lakes. Simple indices of "vulnerability" might help to direct management priorities and attention at regional scales. It may well prove that, while the complex process-based models are best used for scenarios, relatively simple assessment models will emerge to form the core of practical risk-based adaptive management strategies.

### Databases and Typologies

One of the emergent key issues for both the scientific study and management of coastal zones is the issue of spatial scales. The wide range of spatial scales implicit in coastal systems and the need to deal with interactions across them is relevant to biophysical systems, processes and interactions in catchments, estuaries and coastal seas, and equally to social, economic and governance systems. Currently, the LOICZ approaches are limited by two key constraints:

1. **Scale -** The LOICZ database currently deals with most variables at quite coarse resolution (half a degree), although it estimated population and mapped the budget-site drainage basins at 1 km resolution. This coarse resolution severely limits the capacity of the global database and typology to deal with small coastal systems, although these increasingly appear to play an important role. The need to capture a wider range of scales, and move across scales, is only likely to increase, given that many of the key coastal management decisions and issues occur at quite fine scales.
2. **Variables -** Aside from scale, the choice of variables contained in the database are critical. The LOICZ database is populated primarily with variables for catchments and coasts which were widely available and expected to provide some predictive or explanatory power (directly or as surrogates) for catchment flows and loads, marine exchanges, and internal sources and sinks. It is expected that in order to support coastal management, future databases will need to include a much broader array of data on social and

economic activities and indicators, on coastal drivers and pressures, and on ecosystem state and responses. It is also anticipated that the database will be expanded to include data on jurisdictional and governance systems, to underpin comparative analysis and evaluation of coastal management performance and outcomes.

## Conclusions

The “Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles” project assimilated biogeochemical datasets at a local to regional level and made a first attempt at global up-scaling. The up-scaling effort, through extensive international collaboration and involvement facilitated in the long term (10+ years) by the LOICZ project, led to high level policy linkages within the UNEP-GEF programme. The project has been especially effective in creating datasets with adequate global coverage to enable suitable analyses and modelling to take place. The challenges of modelling such data are extreme: however, through substantial international collaboration effort, considerable advances were made, such as the LOICZ Hexacoral database and LOICZView modelling tools. Such modelling and analyses have for the first time provided clear generic statements about the dynamics and drivers of coastal nutrient dynamics at a global and sub-global (e.g. temperate and tropical) scale. Such scientifically-derived objective statements are key to improving understanding and subsequent management of systems, the core aspect of GEF policy. The project has been able to demonstrate a clear linkage between the human dimensions and coastal nutrient dynamics. Many of the outputs of the project do have important management implications that can be used to inform managers or other local stakeholders on issues of ecosystem health. These outcomes are possible because within the constraints identified above, and often with inclusion with other ecosystem research, the project provides ‘system-level’ perspectives over processes affecting coastal systems. Some examples include inferences on:

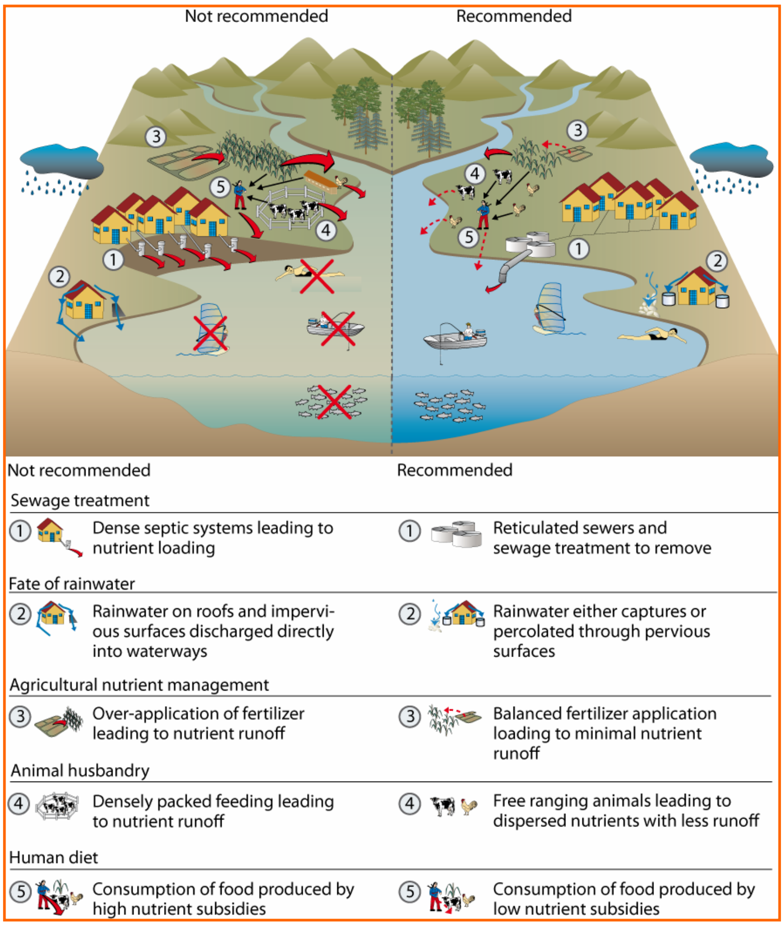
- the balance of terrestrial and oceanic forcing of nutrient flux (literally: “is the river or the open ocean most important in driving flux in my system?”),
- the absolute and relative magnitudes of dissolved and particulate C and N fluxes (“should we manage to limit dissolved or particulate fluxes from our rivers?”,
- comparing natural and anthropogenic impacts on ecosystem-level function, such as may arise from municipal loading (e.g., sewage), or the biological activity of marine farms (“is this farm important in the bigger bay-wide context?”).

Such information can be taken up by managers for transfer to the public, for example through “State of the Environment” reporting, or used to inform resource consent issues in their jurisdictions. However, there remain a number of barriers which make such science difficult to embed in management practise. These centre on the issues of making available to non-specialists complex analysis and modelling results, and on the interpretation of results in a relevant management context.

**Limited transference ability.** There is a belief, albeit rather stereotyped, that managers demonstrably fail to use science in their management and that scientists demonstrably fail to make their science

available for managers to use. Underpinning this stereotype is the fact that transference into a management context of science is extremely difficult and requires development of skills and attitudes on the part of both scientists and managers.

**Spatial scale**. The project has been effective in up-scaling from local-regional case studies into geographic region (polar, temperature, tropical) or global understanding. However, it should be noted that most management and management interventions happen at a relatively small scale (e.g. sea walls, sewage plants, pollution input quotas to rivers). In addition, the administrative boundaries of a manager's jurisdiction are typically quite sharp, and in many cases jurisdictional boundaries are at the same scale or location as the relevant environmental systems and processes. Possibilities might exist for "side-scaling" in which jurisdiction areas can be modelled so as to have much higher management relevance. Nesting of a smaller high-resolution extension within the wider LOICZ models would permit local information to be embedded and facilitate effective utilisation by managers.



| Not recommended | Recommended |
|---|---|
| Sewage treatment | |
| ① Dense septic systems leading to nutrient loading | ① Reticulated sewers and sewage treatment to remove |
| Fate of rainwater | |
| ② Rainwater on roofs and impervious surfaces discharged directly into waterways | ② Rainwater either captures or percolated through pervious surfaces |
| Agricultural nutrient management | |
| ③ Over-application of fertilizer leading to nutrient runoff | ③ Balanced fertilizer application loading to minimal nutrient runoff |
| Animal husbandry | |
| ④ Densely packed feeding leading to nutrient runoff | ④ Free ranging animals leading to dispersed nutrients with less runoff |
| Human diet | |
| ⑤ Consumption of food produced by high nutrient subsidies | ⑤ Consumption of food produced by low nutrient subsidies |

***Figure 28**. Conceptual diagram showing recommended vs. not recommended management options that can be derived from the science results and outputs of the project.*

These barriers aside, the project has demonstrated that the outputs of science research can be assimilated and synthesised effectively to outreach information and understanding of complex science issues. Further, the project has shown that these science outcomes can contribute to determining possible management responses to complex issues faced by managers of dynamic and changing coastal systems.

# Further reading and references

**“The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles” project resulted in a number of joint UNEP-GEF/LOICZ publications as part of the LOICZ Reports & Studies series. The contents of this publication used the outputs from the workshop reports as well as other published literature that provides additional detail and information; this literature is listed below and is recommended for further reading.**

## Further reading published under the LOICZ Reports and Studies series (available from the LOICZ IPO and www.loicz.org)

**Estuarine Systems of the South China Sea: Carbon, Nitrogen and Phosphorus Fluxes**
Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No. 14, 2000

**Estuarine Systems of the South American Region: Carbon, Nitrogen and Phosphorus Fluxes**
Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No.15, 2000

**Estuarine Systems of the East Asia Region: Carbon, Nitrogen and Phosphorus Fluxes**
Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No.16, 2000

**Estuarine Systems of Sub-Saharan Africa: Carbon, Nitrogen and Phosphorus Fluxes**
Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No.18, 2001

**Coastal and Estuarine Systems of the Mediterranean and Black Sea Regions: Carbon, Nitrogen and Phosphorus Fluxes**
Dupra VC, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No.19, 2001

**Estuarine Systems of Africa (Regional Workshop II): Carbon, Nitrogen and Phosphorus Fluxes**
Dupra VC, Smith SV, David LT, Waldron H, Marshall Crossland JI, Crossland CJ (eds). No.20, 2002

**LOICZ/UNEP Regional Synthesis Workshops: Australasia-Asia, the Americas, Africa-Europe. Summary report and compendium**
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**Estuarine Systems of the Latin American Region and of the Arctic Region: Carbon, Nitrogen and Phosphorus Fluxes.**
Camacho-Ibar VF, Dupra VC, Wulff F, Smith SV, Marshall Crossland JI, Crossland CJ (eds). No.23, 2002

**The Role of the Coastal Zone in the Disturbed and Undisturbed Nutrient and Carbon Cycles**
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# Figure sources

## Conceptual diagrams

Produced by William C. Dennison and Joanna L. Woerner
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Symbols courtesy of the Integration and Application Network – http://ian.umces.edu/symbols/ University of Maryland – Center for Environmental Science

## Photographs & images

Publication details and Acknowledgements: www.iczmap.com/iczmap/background/

Executive Summary: Hester A.Y. Whyte

Contents: courtesy of Natural Resource Canada

Preface & Context: Hester A.Y. Whyte

Figure 2: Integration and Application Network

Figure 3: www.americaswetlandresources.com/background_facts/detailedstory/MississippiFormed.html

Figure 4: Dr David J Jefferies Guildford Surrey UK (2000AD)

Figure 5: The 1945 photograph is from 'Cities Revealed aerial photography copyright Cities Revealed The GeoInformation Group. Imagery reproduced from M.O.D. archives'. The 2002 photograph is Copyright Liverpool Bay Coastal Group.Both supplied by Sefton Council, UK

Nutrient fluxes in the coastal zone: Martin D.A. Le Tissier

Nutrients and Euthrophication: Microcystis bloom Mathilda bay: by Dennis Sarson (University of Western Australia). Used with permission of the Waters and Rivers Commission of Western Australia; Fish kill: from US National Oceanic and Atmospheric Administration; Red tide: by M. Godfrey (www.niwa.co.nz); Algal bloom: N.J. Anderson.

Figure 15: S.V. Smith

Managing nutrients and human impacts: Martin D.A. Le Tissier

Figure 22: Data from the Kyoto-Inventory project, from the Data User Programme of the European Space Agency

Figure 24 & 25: Martin D.A. Le Tissier

Figure 26: Anasco plume: image was obtained from the Geological and Environmental Remote Sensing Laboratory of the University of Puerto Rico at Mayaguez; Mississippi river: Image courtesy Liam Gumley, Space Science and Engineering Center, University of Wisconsin-Madison and the MODIS science team.

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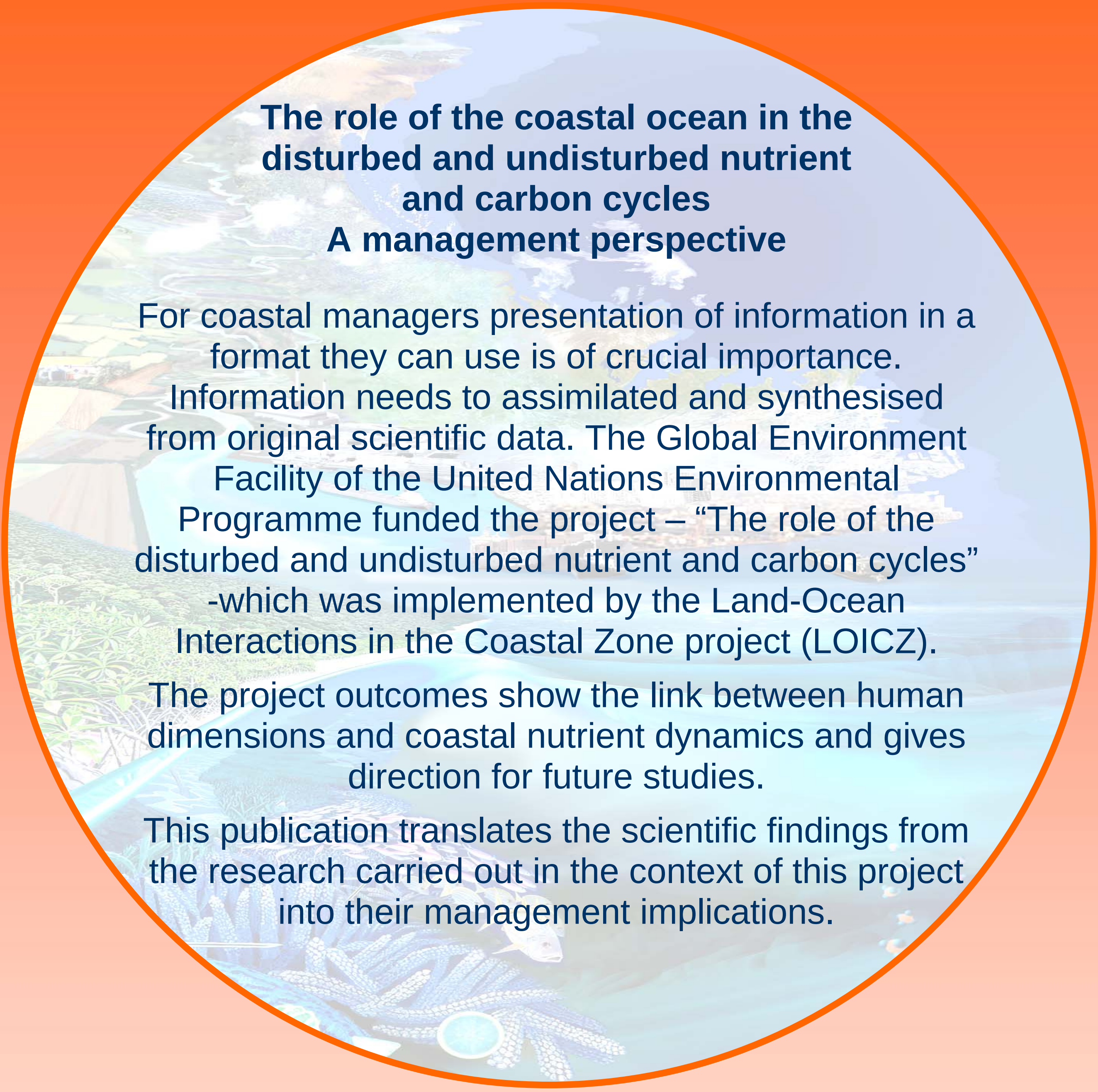

# The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles
## A management perspective

For coastal managers presentation of information in a format they can use is of crucial importance. Information needs to assimilated and synthesised from original scientific data. The Global Environment Facility of the United Nations Environmental Programme funded the project – “The role of the disturbed and undisturbed nutrient and carbon cycles” -which was implemented by the Land-Ocean Interactions in the Coastal Zone project (LOICZ).

The project outcomes show the link between human dimensions and coastal nutrient dynamics and gives direction for future studies.

This publication translates the scientific findings from the research carried out in the context of this project into their management implications.

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