Eutrophication assessment and nutrient criteria development: Atlas of global assessments and scenario forecasting on nutrient cycling and environmental impacts

Prepared by: GRID-Arendal

Component C: Doc: B7-1

Partners:

December 2018
About the GEF-Global Nutrient Cycle Project

**Project objective:** to provide the foundations (including partnerships, information, tools and policy mechanisms) for governments and other stakeholders to initiate comprehensive, effective and sustained programmes addressing nutrient over-enrichment and oxygen depletion from land based pollution of coastal waters in Large Marine Ecosystems.

**Core project outcomes and outputs:**
- the development and application of quantitative modeling approaches: to estimate and map present day contributions of different watershed based nutrient sources to coastal nutrient loading and their effects; to indicate when nutrient over-enrichment problem areas are likely to occur; and to estimate the magnitude of expected effects of further nutrient loading on coastal systems under a range of scenarios
- the systematic analysis of available scientific, technological and policy options for managing nutrient over-enrichment impacts in the coastal zone from key nutrient source sectors such as agriculture, wastewater and aquaculture, and their bringing together an overall Policy Tool Box
- the application of the modeling analysis to assess the likely impact and overall cost effectiveness of the various policy options etc brought together in the Tool Box, so that resource managers have a means to determine which investments and decisions they can better make in addressing root causes of coastal over-enrichment through nutrient reduction strategies
- the application of this approach in the Manila Bay watershed with a view to helping deliver the key tangible outcome of the project – the development of stakeholder owned, cost-effective and policy relevant nutrient reduction strategies (containing relevant stress reduction and environmental quality indicators), which can be mainstreamed into broader planning
- a fully established global partnership on nutrient management to provide a necessary stimulus and framework for the effective development, replication, up-scaling and sharing of these key outcomes.

**Project partners:**
- Chilika Development Authority
- Energy Centre of the Netherlands
- Global Environment Technology Foundation
- Government of India - Lake Chilika Development Authority
- Government of the Netherlands
- Government of the Philippines
- Government of the United States
- Intergovernmental Oceanographic Commission of UNESCO
- International Nitrogen Initiative
- Laguna Lake Development Authority
- Partnerships in Environmental Management for the Seas of East Asia
- Scientific Committee on Problems of the Environment
- University of Maryland
- University of the Philippines
- University of Utrecht
- Washington State University
- World Resources Institute

**Implementing Agency:** United Nations Environment Programme

**Executing Agency:** UNEP- Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA)
The Index for Coastal Eutrophication Potential (ICEP) is an indicator for the potential of riverine nutrient export to sustain new production of non-diatoms phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatoms growth.

A negative value of the ICEP indicates that Si is present in excess over the other nutrients and would thus indicate a low likelihood of HAB development. Positive values of ICEP indicate an excess of N or P over Si, which may lead to blooms of non-diatom, possibly harmful algae species. The ICEP represents the potential impact of the riverine delivery to the coastal zone.

Here the ICEP value is presented with the MODIS satellite derived chlorophyll-a measurements. Areas with high chlorophyll-a measurements often correspond to high ICEP values, including the Bay of Bengal, parts of south-east Asia and the Baltic Sea.
About the GEF-Global Nutrient Cycle Project

**Project objective:** to provide the foundations (including partnerships, information, tools and policy mechanisms) for governments and other stakeholders to initiate comprehensive, effective and sustained programmes addressing nutrient over-enrichment and oxygen depletion from land based pollution of coastal waters in Large Marine Ecosystems.

**Core project outcomes and outputs:**

- the development and application of quantitative modeling approaches: to estimate and map present day contributions of different watershed based nutrient sources to coastal nutrient loading and their effects; to indicate when nutrient over-enrichment problem areas are likely to occur; and to estimate the magnitude of expected effects of further nutrient loading on coastal systems under a range of scenarios

- the systematic analysis of available scientific, technological and policy options for managing nutrient over-enrichment impacts in the coastal zone from key nutrient source sectors such as agriculture, wastewater and aquaculture, and their bringing together an overall Policy Tool Box

- the application of the modeling analysis to assess the likely impact and overall cost effectiveness of the various policy options etc brought together in the Tool Box, so that resource managers have a means to determine which investments and decisions they can better make in addressing root causes of coastal over-enrichment through nutrient reduction strategies

- the application of this approach in the Manila Bay watershed with a view to helping deliver the key tangible outcome of the project – the development of stakeholder owned, cost-effective and policy relevant nutrient reduction strategies (containing relevant stress reduction and environmental quality indicators), which can be mainstreamed into broader planning

- a fully established global partnership on nutrient management to provide a necessary stimulus and framework for the effective development, replication, up-scaling and sharing of these key outcomes.

**Project partners:**

- Chilika Development Authority
- Energy Centre of the Netherlands
- Global Environment Technology Foundation
- Government of India - Lake Chilika Development Authority
- Government of the Netherlands
- Government of the Philippines
- Government of the United States
- Intergovernmental Oceanographic Commission of UNESCO
- International Nitrogen Initiative
- Laguna Lake Development Authority
- Partnerships in Environmental Management for the Seas of East Asia
- Scientific Committee on Problems of the Environment
- University of Maryland
- University of the Philippines
- University of Utrecht
- Washington State University
- World Resources Institute

**Implementing Agency:** United Nations Environment Programme

**Executing Agency:** UNEP- Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA)
Foreword

(to come)
Human activities such as agriculture, domestic and industrial wastewater as well as natural processes may cause excessive nutrient loads, known as eutrophication. Increased nutrient loads can lead to many adverse effects including harmful algal blooms, and in extreme cases hypoxia. Hypoxia, or oxygen depletion, is an environmental phenomenon where the concentration of dissolved oxygen in the water column decreases to a level that can no longer support living aquatic organisms. Mitigation of the negative effects of eutrophication requires reduction of nutrient inputs and an ecosystem-based management strategy.

The map shows the location of water bodies impacted by eutrophication and reported hypoxia and impacts (fish reduction) between 1985 and 2000. The data is sourced from the World Resource Institute (https://www.wri.org/resource/interactive-map-eutrophication-hypoxia). The pattern of eutrophic sites reflects the availability of data, with more research available in places like the US and Europe than many other parts of the world.
The Eutrophication Process

Eutrophication leads to degradation and loss of aquatic habitats and depletion of oxygen in the water. Imbalanced nutrient load favours plant growth in water bodies - phytoplankton thrives. Algae blooms cover the water surface and prevent sunlight to reach bottom plants - oxygen in water are depleted. Decomposition of plant material further depletes oxygen and releases more nutrient.

The Phosphorus Cascade

Estimated Phosphorus fluxes
Years 2000 to 2010

The Nutrient Cascade

Estimated Nitrogen fluxes
Years 2000 to 2010

Forms of nitrogen
- $\text{N}_2$ – molecular nitrogen
- $\text{NO}_x$ – various nitrogen oxides
- $\text{NH}_x$ – nitrogen oxide
- $\text{NH}_3$ – ammonia

Denitrification: process of conversion of nitrate to molecular nitrogen
Fixation: conversion of molecular nitrogen from the air into ammonia or other nitrogenous compounds
Leaching: movement of soluble nutrients from the soil

Natural N fluxes
- fixation
- ocean to coast

Human related N fluxes
- waste water
- nitrogen emissions
- human excreta

Coastal waters
- Inputs from the sea
- Inputs from river
- Inputs from terrestrial ecosystems
- Inputs from agriculture
- Inputs from industry
- Inputs from domestic wastewater

Ocean
- Outputs from the sea
- Outputs from rivers
- Outputs from terrestrial ecosystems
- Outputs from agriculture
- Outputs from industry
- Outputs from domestic wastewater

Freshwater bodies
- Inputs from the sea
- Inputs from rivers
- Inputs from terrestrial ecosystems
- Inputs from agriculture
- Inputs from industry
- Inputs from domestic wastewater

Flux from land to sea
- Flux from land to sea
- Flux from land to sea
- Flux from land to sea
Hypoxic events in coastal regions have been increasing over the last several decades across the globe. These events have been documented along the east and gulf coasts of the United States, in the Baltic region, and off the coast of Japan. The low occurrence of these events in the tropics is likely due to lack of consistent monitoring results in these regions. Hypoxic events have been classified as either persistent (occurring all year round), periodic (occurring at different times) or seasonal (occurring at a certain time of year).

The pattern of dissolved oxygen in bottom water shows many areas with low oxygen concentrations, particularly in Southern and Eastern Asia, the Pacific coast of Central America, the red sea and the Baltic Sea. There is no clear correlation between the location of observed hypoxic events and global bottom water oxygen concentration, reflecting a difference in spatial and temporal scale between the two data sources.

In the above map Sensitivity of COSCATs to changes in nutrient loading according to COOLBEANS model. Red denotes high sensitivity, whereas blue represents low sensitivity. The primary purpose of the COOLBEANS model is to quantitatively link changes in bottom water oxygen concentrations to shifts in terrestrial nutrient loading and vertical exchange. COOLBEANS suggests that O2 conditions in these regions are likely to be sensitive to additional N inputs. In particular, the west coast of Central America and northern South America, the east coast of the South eastern Asian peninsula and the east coast of India are indicated as moderately to strongly sensitive to increasing nutrient inputs.
Harmful algal blooms can have direct impacts on aquatic life, for example fish kills, and on human health, for example paralytic shellfish poisoning. Harmful algal blooms are often a result of excessive nutrient loads in a water body allowing certain species of algae to increase rapidly in number. Therefore efforts to reduce nutrient loads in waterways can have direct impacts on improved human health.

The map shows the number of reported harmful algae blooms for the period 1980 to 2015. The data are based on the harmful algae event database (HAEDAT, http://haedat.ioe.org) and are displayed by Coastal Segmentation and related CATCHments (COSCAT).
Globally reported Harmful Algal Blooms (HABs)
Number reported between 1980 and 2017

Source: HAEDAT database, 2018
The Index for Coastal Eutrophication Potential (ICEP) is an indicator for the potential of riverine nutrient export to sustain new production of non-diatoms phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatoms growth.

A negative value of the ICEP indicates that Si is present in excess over the other nutrients and would thus indicate a low likelihood of harmful algal bloom development. Positive values of ICEP indicate an excess of N or P over Si, which may lead to blooms of non-diatom, possibly harmful algae species. The ICEP represents the potential impact of the riverine delivery to the coastal zone.

ICEP of water draining into coastal seas presented on the scale of river basins, and observed algal blooms collected from HAEDAT.
Concentrated manure from factory farms

Negative ICEP
A negative value of the ICEP indicates that silicon is present in excess over the other nutrients and would thus indicate a low likelihood of Harmful Algal Blooms development.

Positive ICEP
Positive values of ICEP indicate an excess of nitrogen or phosphorus over silicon, which may lead to blooms of non-diatom, possibly harmful algae species.

Average C:N:P:Si of all ocean: 106:16:1:20

Fertilizer runoff
Untreated urban sewage and waste water

Aquaculture

Local physical and weather conditions on a coast influence how ecosystems deal with changes in nutrient loads

An Indicator of Coastal Eutrophication Potential

ICEP is an indicator for the potential of riverine nutrient export to sustain new production of non-siliceous phytoplankton biomass; it is calculated by comparing the Nitrogen (N), Phosphorus (P) and Silicon (Si) loading to the Redfield ratios expressing the requirements of marine diatoms growth.

How to calculate the ICEP:
The ICEP number can be calculated by the following relationships (based on the Redfield molar C:N:P:Si ratios 106:16:1:20):

\[
\text{ICEP} = \left( \frac{N \text{ River}}{14 \times 16} - \frac{Si \text{ River}}{28 \times 20} \right) \times 10^6 \times \frac{12}{365}
\]
if N/P < 16 (N limiting)

\[
\text{ICEP} = \left( \frac{P \text{ River}}{31} - \frac{Si \text{ River}}{28 \times 20} \right) \times 10^6 \times \frac{12}{365}
\]
if N/P > 16 (P limiting)

N=nitrogen (14 molar mass) P=phosphorus (31 molar mass) Si=silicon (28 molar mass)

Unit: concentration (mean annual concentration g m⁻³) or total loads (kg yr⁻¹)

Selection of human activities that are known to contribute to nitrogen and phosphorus, and silicon content of water bodies
Predicted changes in per-area nutrient fluxes by large river basin and nutrient form globally between years 2000 and 2050. Note especially large anticipated changes in DIN and DIP loading in South Asia and parts of Central and South America.

There are substantial differences in the relative contributions of various nutrient sources and human drivers causing the scenario trends between developing countries and industrialized countries. Global NEWS scenarios for 2030 and 2050 indicate that substantial changes in coastal nutrient loading may occur due to changing nutrient management in agriculture.

DIN: Dissolved Inorganic Nutrients
DON: Dissolved Organic Nutrients
PN: Particulate Nitrogen
DIP: Dissolved Inorganic Phosphorus
PP: Particulate Phosphorus
DOP: Dissolved Organic Phosphorus
Main drivers of ecosystem change for Millennium Ecosystem Assessment (MEA) scenarios

### Urban wastewater drivers

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Global Orchestration</th>
<th>Order from Strength</th>
<th>Technogarden</th>
<th>Adapting Mosaic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urbanization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downscaling to country scale is from Grübler et al. (2006)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Detergent use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorus (P)-free detergent connected to GDP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry detergent use, fraction of P-free laundry detergent use and fraction P-free dishwasher detergent use are entirely based on GDP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry detergent use, fraction of P-free laundry detergent use and fraction P-free dishwasher detergent use are entirely based on GDP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry detergent use, fraction of P-free laundry detergent use and fraction P-free dishwasher detergent use are entirely based on GDP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry detergent use, fraction of P-free laundry detergent use and fraction P-free dishwasher detergent use are entirely based on GDP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal of N and P through wastewater treatment plants:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Four treatment classes:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. No treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Primary or mechanical treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Secondary or biological treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Advanced treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Source:
Modified from Alcamo et al. (2006)
The Index for Coastal Eutrophication Potential (ICEP) is an indicator for the potential of riverine nutrient export to sustain new production of non-diatoms phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatoms growth.

A negative value of the ICEP indicates that Si is present in excess over the other nutrients and would thus indicate a low likelihood of HAB development. Positive values of ICEP indicate an excess of N or P over Si, which may lead to blooms of non-diatom, possibly harmful algae species. The ICEP represents the potential impact of the riverine delivery to the coastal zone.

Here the ICEP value is presented with the MODIS satellite derived chlorophyll-a measurements. Areas with high chlorophyll-a measurements often correspond to high ICEP values, including the Bay of Bengal, parts of south-east Asia and the Baltic Sea.
Estimated annual volume of Dissolved Inorganic Nitrogen load to coasts by major world region

Values calculated using the Global Nutrient Export from Watersheds (NEWS) Model for years 1970 and 2000 and projected to year 2030 based on global development scenarios.

Estimated annual volume of Dissolved Inorganic Phosphorus contributed to rivers by Source

Values calculated using the Global Nutrient Export from Watersheds (NEWS) Model for years 1970 and 2000 and projected to year 2030 based on Millennium Assessment scenarios.

Chlorophyll-a, the index for coastal eutrophication potential & harmful algal blooms’

Assessment of Chlorophyll-a and its link to the ICP and HABs mapping

The index for coastal eutrophication potential (ICP)

- The possibility of a coastal environment becoming eutrophic based on the balance between nutrient loads in coastal waters

ICP reflects the rivers ratio between nitrogen, phosphorus and silicon.

Chlorophyll-a is typically measured in milligrams of chlorophyll per cubic meter of seawater in a time period.

Chlorophyll-a - A measure of phytoplankton in the ocean.

Chlorophyll-a concentration in the ocean are derived from satellite imagery.

From chlorophyll-a knowledge, Net Primary Production maps can be calculated. These are used to estimate a coastal systems sensitivity to changes in nutrient load.

Chlorophyll measurements give scientists valuable insights into the health of the ocean’s environment.

Most phytoplankton blooms are a sign of good health, such as the large blooms occurring every spring in the North Atlantic Ocean. Other blooms can point to problems developing in the ocean - such as harmful algal blooms (HABs).

Even if the blooming plant itself is not harmful, as billions of phytoplankton die and decay over a span of days, they can rob the water of oxygen, creating “dead zones” where fish and other marine organisms cannot survive.

With higher projected estimates of nitrogen and phosphorus, the potential for eutrophication and resultant harmful algal blooms will increase. This is reflected by higher positive ICP values.

The link to harmful algal blooms & dead zones

Chlorophyll-a measurements give scientists valuable insights into the health of the ocean’s environment. Most phytoplankton blooms are a sign of good health, such as the large blooms occurring every spring in the North Atlantic Ocean. Other blooms can point to problems developing in the ocean - such as harmful algal blooms (HABs).

Even if the blooming plant itself is not harmful, as billions of phytoplankton die and decay over a span of days, they can rob the water of oxygen, creating "dead zones" where fish and other marine organisms cannot survive.

From chlorophyll-a knowledge, Net Primary Production maps can be calculated. These are used to estimate a coastal systems sensitivity to changes in nutrient load.

Nutrient sources are both natural processes, for example weathering of rocks for silicon and human activity like fertilizer use in agriculture and urban sewage water providing nitrogen and phosphorus.

There is an agreement between rivers with positive ICP values and observed harmful algal blooms.

Local physical and environmental conditions will determine the tendency of a coastal marine ecosystem for developing high biomass algal blooms, harmful algal blooms or hypoxia.

Risk of future harmful algal blooms

With higher projected estimates of nitrogen and phosphorus (over silica) lost from watersheds, the potential for eutrophication and resultant harmful algal blooms will increase. This is reflected by higher positive ICP values.

The index for coastal eutrophication potential (ICP)

- The possibility of a coastal environment becoming eutrophic based on the balance between nutrient loads in coastal waters

ICP reflects the rivers ratio between nitrogen, phosphorus and silicon.

Chlorophyll-a is typically measured in milligrams of chlorophyll per cubic meter of seawater in a time period.

Chlorophyll measurements give scientists valuable insights into the health of the ocean’s environment. Most phytoplankton blooms are a sign of good health, such as the large blooms occurring every spring in the North Atlantic Ocean. Other blooms can point to problems developing in the ocean - such as harmful algal blooms (HABs).

Even if the blooming plant itself is not harmful, as billions of phytoplankton die and decay over a span of days, they can rob the water of oxygen, creating "dead zones" where fish and other marine organisms cannot survive.

From chlorophyll-a knowledge, Net Primary Production maps can be calculated. These are used to estimate a coastal systems sensitivity to changes in nutrient load.

Nutrient sources are both natural processes, for example weathering of rocks for silicon and human activity like fertilizer use in agriculture and urban sewage water providing nitrogen and phosphorus.

There is an agreement between rivers with positive ICP values and observed harmful algal blooms.

Local physical and environmental conditions will determine the tendency of a coastal marine ecosystem for developing high biomass algal blooms, harmful algal blooms or hypoxia.

Risk of future harmful algal blooms

With higher projected estimates of nitrogen and phosphorus (over silica) lost from watersheds, the potential for eutrophication and resultant harmful algal blooms will increase. This is reflected by higher positive ICP values.

Nutrient sources are both natural processes, for example weathering of rocks for silicon and human activity like fertilizer use in agriculture and urban sewage water providing nitrogen and phosphorus.

There is an agreement between rivers with positive ICP values and observed harmful algal blooms.

Local physical and environmental conditions will determine the tendency of a coastal marine ecosystem for developing high biomass algal blooms, harmful algal blooms or hypoxia.

Risk of future harmful algal blooms

With higher projected estimates of nitrogen and phosphorus (over silica) lost from watersheds, the potential for eutrophication and resultant harmful algal blooms will increase. This is reflected by higher positive ICP values.
The index of coastal eutrophication potential (ICEP) concept [Billen and Garnier, 2007], we can now use the scenarios for river nutrient export to assess the potential risk that non-diatom algal growth may lead to harmful algal blooms in coastal marine ecosystems. ICEP is an indicator for the potential of riverine nutrients to sustain new production of non-diatom phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatom growth. Positive values of ICEP indicate an excess of N or P over Si, which may lead to blooms of non-diatom, possibly harmful species.

The historical data suggest that harmful algal blooms risk increased considerably between 1970 and 2000. Scenario results for 2050 indicate that this risk will further spread (South America, Africa) and increase in areas with current high risk (Eastern Asia) (Figure 7.10). There are also large parts of the world where HAB risk is expected to decrease as a result of higher efficiency of nutrient use in agriculture and improved wastewater treatment. This is particularly so in the Adapting Mosaic scenario, which is a scenario with an orientation towards environmental issues and local simple
Ten Key Action Areas to Address the Nutrient Challenge

1. Implement a ‘five-element strategy’
   a. nutrient management;
   b. selecting appropriate crop cultivars;
   c. precision irrigation whenever needed;
   d. integrated weed, pest and disease management;
   e. site-specific mitigation measures.

2. Improve fertilizer value by:
   a. manure processing;
   b. animal housing;
   c. animal health;
   d. dietary management to avoid over-feeding of nutrients;
   e. nutrient management planning.

3. Reduce and improve:
   a. technology for extracting N from waste streams.

4. Innovation capture with utilization:
   a. technology for extracting N from waste streams.

5. Optimization of:
   a. nutrient pollution sources placing them farther away from sensitive receptors (spatial planning, buffer zones, etc.);
   b. integration of different nutrient flows to foster more effective use;
   c. nutrient production to being closer to consumers.

6. Reduce:
   a. intake of animal protein where its above dietary needs.
   Replace:
   b. animal protein with plant-based protein.

7. Reduce and improve:
   a. sewage system and treatment;
   b. agriculture point source waste treatment;
   c. industrial effluent treatment.

8. Improve:
   a. transport activities by advanced telematics;
   b. transport planning;
   c. mass public transportation;
   d. development of highly fuel efficient cars.

9. Implement and improve treatment of:
   a. sewage system and treatment;
   b. agriculture point source waste treatment;
   c. industrial effluent treatment.

10. Spatial and temporal optimization of nutrient flows
    a. reducing waste from phosphorous mining and processing;
    b. improving food supply efficiency and reducing food waste.

The Nutrient pool
The Index for Coastal Eutrophication Potential (ICEP) is an indicator for the potential of riverine nutrient export to sustain new production of non-diatoms phytoplankton biomass; it is calculated by comparing the N, P and Si loading to the Redfield ratios expressing the requirements of marine diatoms growth. A negative value of the ICEP indicates that Si is present in excess over the other nutrients and would thus indicate a low likelihood of harmful algal bloom development. Positive values of ICEP indicate an excess of N or P over Si, which may lead to blooms of non-diatom, possibly harmful algae species. The ICEP represents the potential impact of the riverine delivery to the coastal zone.