# Integrated approaches to drainage basin nutrient inputs and coastal eutrophication: an introduction

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## Ingress

Eutrophication is an increase in primary production due to increased nutrient supply and its consequences. In its widest sense *eutrophication means any increase of nutrient availability that increases primary production*. Frequently, however, eutrophication is understood exclusively as the consequence of nutrient input by anthropogenic activities. The primary consequence of eutrophication in aquatic environments is an enhancement of algal productivity and accumulation of algal biomass. Secondary consequences are changes in community structure of plankton and benthos.

Man-induced eutrophication or changes in biodiversity are nothing new: they are a well-known consequence of human culture. Eutrophication phenomena accompanied all human settlements. Even in the early days of mankind human activities resulted in ecosystem changes. Several large animals such as the mammoth survived the glacial periods, but not the last one. It has been suggested that Neolithic hunters decimated this species to extinction. Similar suggestions have also been made regarding other large mammals that did not continue to exist after the last glacial. The main sewage canal in the city of Rome, 'cloaca', has given rise to a number of expression regarding sewage pathways in numerous languages. Since classical and medieval times there have been 'clean-ups' of unsanitary, plague-ridden cities. Eutrophication is thus the oldest environmental problem of human civilization and not a recent phenomenon. However, with the significant increase of human population over recent decades, eutrophication has developed from a more or less local to a global issue. Due to changes in human living conditions and the declining number of people employed in agriculture, the population in the coastal zone increases steadily. The nutrient concentration increases continually from small streams over rivers and larger lakes to the estuaries. The consequences of this, such as discoloured waters, 'rotten' bottom water, odour and reduced fishing yields are obvious to even a casual observer. The combined effect of increasing human population and movement to the coastal zone, the environmental pressure on rivers, estuaries and shelf regions results in an ever-increasing pressure on the entire coastal zone (Figure 1). Consequently, eutrophication turns into an escalating global phenomenon as long as the human population increases. *Homo sapiens* has thus a vital impact on nature that is part of its culture. As a consequence of that we have to distinguish between natural and cultural eutrophication. In most of this text the term eutrophication stands for cultural eutrophication.

## Causes of eutrophication

In general, the nutrient elements limiting the primary production in freshwater is phosphorus (mainly phosphate) while that in the marine environments is nitrogen (mainly nitrate). In the marine environment, exceptions have been reported to this general rule. Thus the eastern Mediterranean Sea and many eutrophied estuaries are P rather than N limited, while the equatorial Pacific and extensive regions around Antarctica appear to be Fe-limited. What are the sources of nutrients to aquatic ecosystems? There is nutrient supply from

- agriculture and husbandry,
- aquaculture and factories,
- sewage from towns, river run-off and erosion,
- atmospheric deposition,
- nitrogen fixation.

28% of the annual N fixation of the global biosphere is caused by nitrogen fertilizer production, which is energetically expensive and largely based on fossil fuel consumption. A three-fold increase in N utilization by agriculture in Western Europe and USA has been recorded between 1950 and 1970 on agricultural land that actually declines because increased efficiency or over-exploitation (Figure 2). Animal waste from intensive husbandry is of particular significance for nutrient point sources: considerable amounts are directly supplied to freshwater and fields. There are also significant losses by $NH_3$ emission and denitrification on fields, rivers or shallow estuaries, connecting the agricultural lands directly to the atmosphere. Agricultural run-off has given rise to significant eutrophication in most estuaries, but

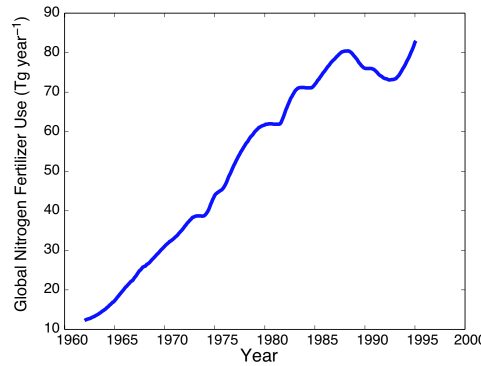


Figure 2: Annual global nitrogen fertilizer consumption for 1960–1995 (1 Tg = $10^{12}$ g; data from FAO 1999). The rate of increase was relatively steady until the late 1980s, when the collapse of the Soviet Union reduced fertilizer use in Russia and former Soviet republics. Fertilizer use is growing again, driven in large part by use in China (modified from Matson et al. 1997 and Anonymous 2000).

also in entire coastal seas such as the southern North Sea, Baltic Sea, Kattegat, northern Adriatic Sea, Chesapeake Bay and Seto Inland Sea in Japan.

Aquaculture techniques are applied to restricted areas such as straights, fjords and rias where it, in the worst case, may induce anoxia (if hydrodynamic energy supply is insufficient). C and N supply is normally regulated by environmental control, but can be detrimental in some areas. It has been reported that accumulation rates of fat- and N-rich food and faeces at the bottom below caged fish production sites could make up to 10 cm per month! As much as 30 and 40% of the annual discharge of P and N, respectively, is caused by aquaculture in some fjords. Unless an entire region is used for aquaculture, it has 'local' consequences for both plankton and benthos. However, large factories of the food industry can discharge significant amount of dissolved and particulate organic matter as well as nutrients into the recipient that can represent important point sources.

Close to cities and dense populated areas sewage is of utmost significance, but compared to run-off from agricultural drainage basins, point sources are of less significance; see also Chapter 2. The emphasis given to sewage treatment in many re-

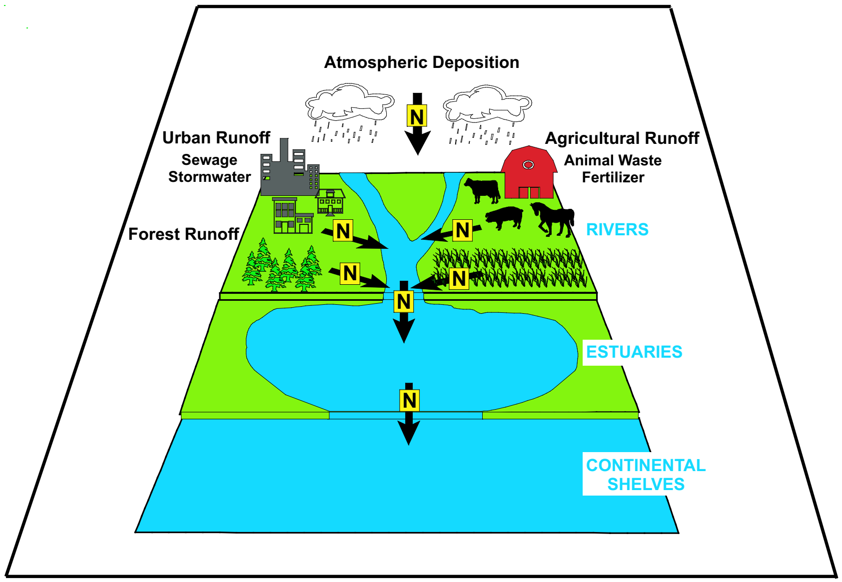


Figure 1: N and P associated with the production of food and energy enter coastal ecosystems (S. Seitzinger, pers. com.)

gions is in contrast to the inefficient and at time completely lacking emphasis on the largest nutrient source for aquatic recipients, i.e. the agriculture. Sewage discharge has 'local' consequences, although local could mean entire estuaries, river mouths and fjords. The frequent removal of P by sewage plants and the decline of utilization of P fertilizers (in contradiction to N, Figure 3) results often in an excess supply of N. Consequently, marine recipients are forced into P rather than N limitation. Far more emphasis has been given to sewage treatment than manipulations of effluents from agriculture, and this can be partly explained by the relative simplicity of removing nutrients from point sources.

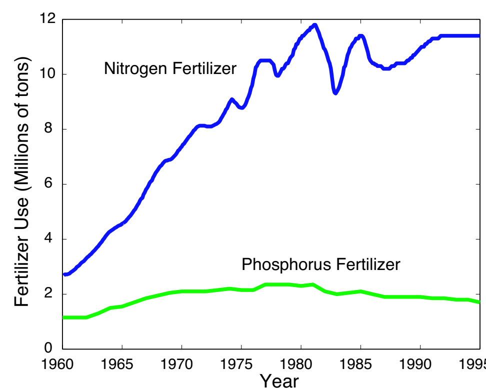


Figure 3: U.S. commercial fertilizer use (modified from Evans et al. 1996 and Anonymous 2000).

River-run off has changed significantly over the last 200 years in many region of the world. Large-scale manipulation of lower reaches of river has resulted in greater river speeds. The residence times of water in the Rhine river water shed was far greater before 1850 when it was so shallow and meandering south of the town of Strasbourg that one could walk through it even during flood times! Extensive wetlands have been removed in favour of shipping and straightforward navigation. Both agriculture and logging result in increased erosion as trees, bushes and vegetation is reduced. Removal of wetlands for agricultural purposes results in decreasing self-purification as denitrification decreases. As a consequence, we experience an increased contribution of particulate matter and nutrients to estuaries. Due to various practices, N supply to marine waters does still increase in Western Europe, while P supply decreases (Figure 3). As a consequence P limitation in eutrophicated coastal regions increases.

Lately, more focus has been given to the role of the atmosphere affecting the availability of nutrients in aquatic ecosystems (see Chapter 1). Generally, nutrient supply from the atmosphere is in the form of N. Only in case dust is deposited particulate P is deposited atmospherically. Atmospheric deposition of nutrients is partly due to fossil energy application, leading to the emission of $NO_x$ gasses to the atmosphere. Here these gasses are transformed to nutrients such as $NO_3$ that can be deposited as wet or dry deposition. However, much of the atmospheric nutrient deposition comes from the emission of $NH_4$ by intensive husbandry and meat production. The annual atmospheric supply of N to open Skagerrak is more than 30% of N the budget! It is relatively lower in the winter months when run-off from land is prominent, but can be the dominating N source during summer. Atmospheric N deposition is closely reflected to source regions, the movements of air masses and the low-pressure pathways. Atmospheric deposition of N gives rise to a wide spread eutrophication of freshwater and terrestrial environments as well as the sea. Eutrophication due to use of fossil energy depends on emission and precipitation pattern.

During nutrient limiting conditions N fixation can be an important source of N in fresh water and brackish water bodies such as the Baltic Sea. The significance of N fixation is still a matter of discussion in marine environments. However, the global $N_2$ cycle has changed greatly due to the production of fertilizers as human $N_2$ fixation is now in the same order of magnitude than the calculated global fixation.

## State of the art of research regarding river and drainage basin pollution of nutrients

The drainage basin with all ongoing human activities (such as waste production, leaching of agricultural chemicals etc.) and the coastal waters into which they drain, constitute large-scale ecosystems, that has to be protected from deterioration. Interactions between land activities, fresh water and coastal seas receive increasingly attention. International conferences, (e.g. the 'Stockholm Water Symposia' in 1997 and the 'Man and River System' conference in Paris in 1998) have been organised within the scope of these issues. The understanding of the dynamics and causes of the large-scale and long-term changes of riverine loads has been regarded as particularly important. The problems of river basin pollution of nutrients that have been addressed include:

- observed water quality changes and their relation to anthropogenic and natural variability (i.e. trend analysis)
- links between land-use, point sources and physiographic factors
- quantification of nutrient retention in rivers and lakes by empirical relationships
- modelling of biogeochemical processes
- assessment of future scenarios.

Recent research indicates that the main uncertainty is the lack of knowledge of nutrient transformation processes between the root-zone and the rivers (see Chapter 3). Attempts to integrate detailed process-oriented models with more simple large-scale approaches are in progress in Scandinavia. Another interesting topic is related to large-scale experiments in Eastern Europe with its dramatic decline in industrial and agricultural production, which has created an unique opportunity to study the river response on such changes (e.g. the Mantra-East project http://www.mantraeast.org; Chapter 3).

## State of the art of research regarding atmospheric deposition of nutrients

The processes governing the atmospheric transport, transformation and deposition of nutrients to coastal ecosystems is an important area of research within the atmospheric, marine and terrestrial sciences (see also Chapter 1). The combustion of fossil fuels and the emissions from agriculture into the atmosphere constitutes a highly significant and growing percentage of total N-loading into estuarine and coastal waters (Duce, 1986). In fact, rainfall associated deposition events are known to stimulate primary production in N-limited coastal and offshore waters (Paerl, 1995). Estimates of atmospheric inputs to the Baltic Sea (HELCOM, 1996), based on studies of the Group of Experts on Airborne Pollution of the Baltic Sea Area (EGAP), constitutes a considerable fraction of the total nutrient load, although much uncertainty surrounds these estimates (Asman & al., 1995). However, only little effort has been put into experimental investigations of the atmospheric load of nitrogen in the coastal zone.

The processes controlling the atmospheric deposition loads are not well understood. For the dry deposition of the gaseous species the horizontal gradients are of major importance. This is in particular true for $NH_3$, which can also be emitted from the water since, unlike $HNO_3$, it does not fully dissociate. Emission and deposition of $NH_3$ is influenced by chemical and biological gradients in the water and fluxes of both $HNO_3$ and $NH_3$ are influenced by the physical gradients caused by change in the wave field. Also horizontal changes due to atmospheric internal boundary layers influence the deposition of both gases. The nitrogen gases $HNO_3$ and $NH_3$ are both chemically reactive and soluble. Therefore it has been hypothesised that uptake of the gases by sea spray can influence the deposition of the gases. This has been tested in a series of field experiments and the results supported the hypothesis (Geernaert *et al.*, 1998).

In order to develop models, which can calculate the nitrogen load to the coastal waters with sufficiently high accuracy (time resolution equal to or smaller than a week and grid size capturing the horizontal inhomogeneity) the air-sea gas fluxes dependencies of the horizontal and vertical inhomogeneity have to be well known. This knowledge is rather limited to non-existent in Scandinavia for the time being.

## State of the art of research regarding marine eutrophication

The response of coastal ecosystems to nutrient loading is a central theme in estuarine research (Nixon & al., 1996), especially the role of nutrients (N, P, and Si) in limiting the growth of phytoplankton. Substantial changes in nutrient loading have occurred, especially during the last century. Large increases in nutrient loading associated with increases in population growth, changes in agricultural practices including the increased use of inorganic fertilisers, changes in collection and treatment of sewage, and increases in nitrate deposition from the atmosphere have occurred. In the last decade, major reductions in P loading through better sewage treatment, with a more or less maintained N loading have occurred. These changes in nutrient loadings and ratios have affected the productivity of coastal and marine waters and have changed the potential limiting nutrients in governing system production (Conley, 1999). These questions are also important in Scandinavia where the assessment of nutrient loadings and their effects on the Baltic Sea ecosystem are co-ordinated at high international levels (HELCOM, 1996). Scientists from the Nordic countries are at the forefront of determining the role of nutrient loading in governing ecosystem functioning (e.g. Kivi *et al.*, 1993; Borum, 1996; Elmgren & Larsson, 1997).

## Scope of the present text

This electronic book contains some of the information gathered by the Nordic network for research and education 'Integrated approaches to drainage basin nutrient inputs and coastal eutrophication'. This network attempted to co-ordinate the relevant, but scattered expertise regarding nutrient inputs and eutrophication in the Nordic and some non-Nordic countries. It was financed by the Nordic Academy of Advanced education (NorFA; http://www.norfa.no). As a continuation of the education activities during the time of the net-

What are the goals of this book? The present text attempts to improve the understanding of traditionally separated fields of science, all contributing and determining the eutrophication of rivers and coastal ecosystems: (a) atmospheric deposition, (b) agriculture and land use, (c) point source emissions, i.e. sewage discharge from urban areas and industry (Figure 4). Despite the fact that points a–c determine the state of aquatic ecosystems and have been intensively investigated *per se*, no strong endeavours have been undertaken to couple these processes in an integrated manner. Much of the details are present, but the grand view is missing. This text attempts to make a contribution to achieve this ambitious, but never-the-less crucial goal: to view the eutrophication of streams and coastal areas and human activities in the catchment areas and beyond (atmospheric deposition) in a balanced and concurrent manner.

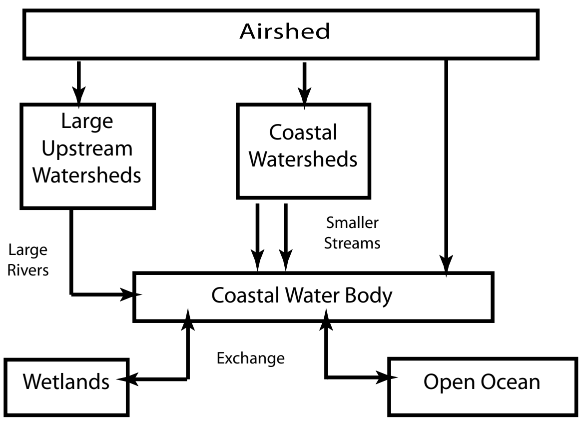


Figure 4: Schematic drawing showing general sources of nutrients and main routes of transport to coastal waters. Notice how strongly coastal waters are exposed for increases of nutrient discharge, integrating effects from the entire watershed, the atmosphere and the open ocean. From Anonymous 2000.

work, the senior scientists made an effort to make the networks joint experience and expertise available to students, young scientists, administrative personnel and interested individuals through this electronic book.

Genuine education is basically dependent on the quality of the research it is based upon and by and large most of the evidence presented here derives from recent and ongoing research projects. We believe that the basis for integrated approaches to drainage basin nutrient inputs and coastal eutrophication is still in its infancy and that far more emphasis has to be given to basic, integrated research. This research will become crucial for a forthcoming generation of scientist dealing with nutrient discharge and eutrophication. The complex questions regarding drainage basin nutrient inputs and coastal eutrophication cannot be adequately addressed at agricultural high schools, freshwater institutes, oceanographic faculties or organizations that deal with atmospheric chemistry. The problems of drainage basin nutrient inputs and coastal eutrophication are entangled and can only be tackled in concerted action. A forthcoming generation of scientists dealing with these questions need fora where they can develop their scientific specialities in an integrated context. Our educational structures separate the scientists that have to co-operate in the future to solve immanent environmental questions. This text is thus also meant to serve as a base for improved education by pointing at relevant sides of drainage basin nutrient inputs and coastal eutrophication that are not dealt with at agricultural high schools, freshwater institutes, oceanographic faculties or organizations that deal with atmospheric chemistry.

The network aimed at an improvement of the educational standard in the Nordic countries and after its completion we hope that this freely available text will continue to serve this purpose. The network became aware about the difficulty to obtain appropriate education in integrated eutrophication as the various research fields that contribute to a holistic view on eutrophication are spread over several unconnected institutions, often even over several countries. Here we attempt to summarise the expertise of the network and make it available to institutions and interested groups of scientists inside the Nordic countries and beyond. We make the Nordic expertise more comprehensive with contributions from scientists from other countries.

The text follows basically the schematic drawing in Figure 4 and is separated into 7 different parts. First, we start with an atmospheric section (Part I) that deals in detail with the transport, transformation and deposition of nutrients; (Chapter 1). A description and evaluation of the most important technique to assess nutrient deposition. i.e. numerical modelling, is a cornerstone of Part I. A run-off section (Part II) follows focusing on the impact of agriculture on freshwater run-off and water quality (Chapter 2), river supply to lakes and the coastal zone (Chapter 3), and the supply of nutrients through ground waters (Chapter 4). Part II is finalized through an extensive manuscript focussing upon nutrient supply in the Seine River drainage basin (Chapter 5). Here the linkages between human activity, water quality and consequences for nutrient discharge into the coastal zone are the focus. Chapter 5 is also a good example how numerical models can be applied in assessment of drainage basin nutrient dynamics.

After this we switch over to eutrophication processes in pelagic ecosystems (Part III) and deal with eutrophication effects on phytoplankton (Chapter 6), nutrient cycling and vertical export (Chapter 9), harmful algae (Chapter 7) and the interaction of natural perturbations and human activities on coastal ecosystems (Chapter 8). Both harmful algae chapter (Chapter 7) and human activities and natural perturbations chapter (Chapter 8) include important information about the effect of eutrophication of recipients that also could be presented in case studies (Part VI). Part III is finalized by by an evaluation of the dose-response relationship and eutrophication in European waters (Chapter 10). The chapter contains important information in the context of Part V. Part IV is dedicated the benthic environment where the basic features of marine eutrophication, as reflected by benthic nutrient release (Chapter 12), benthic metabolic pathways (Chapter 11) and benthic-pelagic coupling (Chapter 13), are presented.

Part V is dedicated to the background of mariculture (Chapter 15) and its effect on the evironments, cultural eutrophication (Chapter 17), ecological quality assessment (Chapter 16), and the cultural eutrophication (Chapter 17). Chapter 17 an attempt is made to summarise previous chapters and to put our knowledge of drainage basin nutrient inputs and eutrophication into an overbranching perspective. We finish this text by presenting a number of case studies (Part VI). The number of case studies is still limited. In order to wide the scope of the text, we hope that we can expand this section in years to come to comprise a majority of eutrophicated, coastal regions in Europe and beyond. Also an overview over eutrophication related web sites and an key-term index will be presented at the end.

Although a balanced presentation of the various aspects of drainage basin nutrient inputs and eutrophication has been the main ambition, this text is not complete. It is open for changes, amendments and additional contributions. The editors welcome comments and suggestions for improvements. Also, additional chapters are welcome (e.g. in the case study section or for an entirely missing section on the socio-economic aspects of eutrophication).

The text is kept in an electronic format, made available on a server at the University of Tartu in Estonia www.ut.ee/~olli/eutr. Each author is responsible for the particular text and the figures submitted to the web site. The editors have streamlined the text, formatted the text and compiled it. Needles to say that the editors take full responsibility for for editorial mistakes.

## Acknowledgements

The editors thank NorFA for the financial support over 5 years that made it possible to gather the various Nordic experts in drainage basin nutrient inputs and coastal eutrophication annually around one table. To the best of our knowledge, these traditionally separated fields of science were gathered for the first time in the Nordic countries. Exiting views developed that changed our opinions on the subject. Everyones perspective on eutrophication changed for good during this process. The editors wish to thank the Nordic network participants for their contributions and the steering committee of the network for enthusiasm, ideas and good leadership. In particular we wish to thank the many compassionate foreign colleagues for their contributions which significantly balanced and improved this text.

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