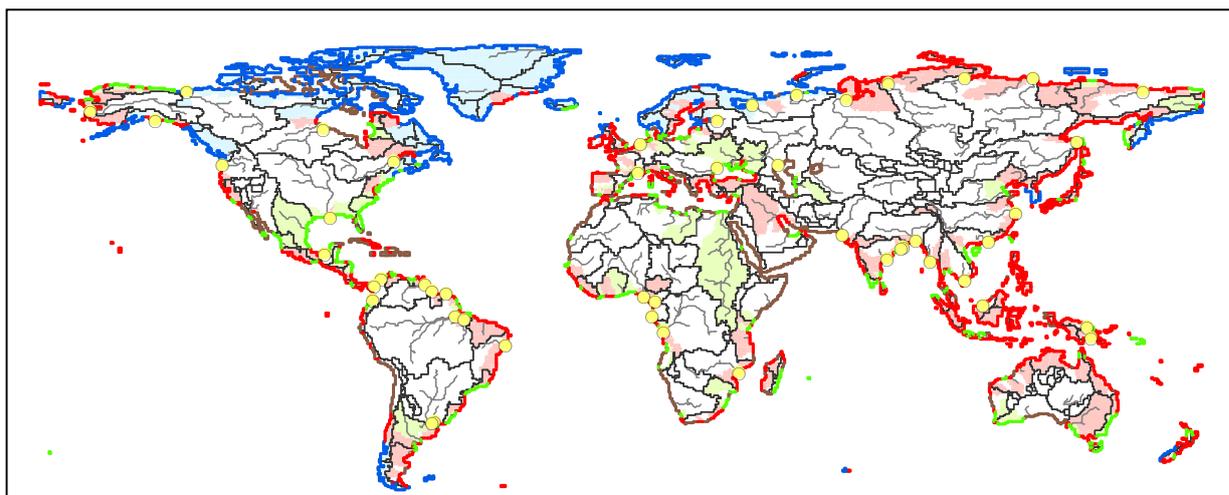


**Towards a global coastal typology for modeling nutrient fluxes at the land-ocean interface: an application to lagoons.**

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22 June 2007

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**Abstract**

The nutrients, and in particular nitrogen (N) and phosphorus (P) play important roles in both terrestrial and aquatic ecosystems, as they are essential to sustain primary production. Sudden excessive increases in nutrient availability however also have the potential to disrupt ecosystem balance, as well as the ability to provide ecosystem services. As a large proportion of the world population depends on coastal ecosystem services such as fishing and tourism for their livelihoods, there is a particular interest to understand the biogeochemical cycles and estimate nutrient levels of N and P in the coast world wide. To achieve this at the global scale, means for upscaling available data to uncovered areas are required. The development of GIS allows a spatial typologic approach to coastal biogeochemical research, as will be shown here.

In the present thesis, the first steps are made towards the development of a geochemically relevant coastal segmentation which, in future work will be coupled to generic nutrient box-models. The ensemble of segmentation and models will allow estimating nutrient levels and retention in coastal systems anywhere on earth. Here, the first preliminary steps are set, by developing a preliminary coastal typology and lagoon nutrient model.

A coastal segmentation (at  $0.5^\circ \times 0.5^\circ$  resolution) is presented here, which is biogeochemically relevant and in which all segments were classified according to a filtering typology. The classes (I, II, III and 0) represent both the magnitude and processes driving nutrient filtering in estuarine, lagoon and fjord-like coasts and finally coasts where no relevant biogeochemical activity takes place in the proximal coastal ocean, but instead in the distal coastal ocean. Each of these types makes up 40, 10, 30 and 20% of the world's coast respectively, and they receive 30, 7, 10 and 53% of the global annual runoff. The coastal segmentation was obtained by aggregating classes of a morphologic typology, also presented here. The 11 morphologic classes represent karst, fjord, fjärd, ria, macrotidal, estuarine, lagoon, big river, mangrove, arctic and glaciated sedimentary coasts.

To assess the complexity in terms of the mathematical representation of the nutrient fluxes the generic nutrient model for the type II: lagoon coasts can have, three site specific models are presented here. They are applicable to Thau, Venice and Szczecin lagoons and are simple, coupled, multi-element (N and P), multi-form (dissolved/particulate, organic/inorganic), process-based box models. All processes are represented by rate constants,

and depend only on the source reservoir. The importance of exchange of water between the lagoon and the sea is assessed, as well as a sensitivity analysis, comparison of rate constants a simulation of Szczecin lagoon for the period 1980 to 1999 and finally an assessment of the effect of the N:P ratio for consumption on lagoon biogeochemistry. The results show 1) that exchange with the sea must be included in a lagoon model; 2) primary production and remineralisation cannot be represented well by first order kinetics alone and 3) the ratio at which N and P are consumed during photosynthesis affect DIP and primary production considerably.

## Preface

Over a year ago, I stepped into Caroline Slomp's office to ask whether I could do my doctoral thesis at her research group. Having made a side trip of almost a year to the department of Sustainable Development, and with my love for programming and GIS applications, no other research project could have fitted my interests better than the G-NUX project.

The Global Nutrient Fluxes at the Land-Ocean Interface (G-NUX) research group exists of 3 phd students and a post-doc. Each of them researches nutrient fluxes in one of the earth's spheres: on the continent, in the coast, in the ocean and in groundwater. I am glad I could contribute to this grand research project and in particular the coastal part, as understanding the biogeochemical cycles and the causes of eutrophication, if translated to management practices, has the potential to benefit the millions of especially poor people, who live in coastal areas, and make a living from fishing, tourism and eco-tourism.

Apart of this humanitarian point of view, the G-NUX group has also given me a lot of opportunities in a scientific context, which I would have missed if working solo on a smaller project. The monthly G-NUX meetings allowed me to follow the research progress of the group members, as well as the process of getting papers published, visiting conferences and presenting posters.

I would therefore like to thank all the members of the G-NUX group, and in particular my supervisors Caroline Slomp, Goulven Laruelle and Hans Dürr. Sometimes your criticism made me uncertain, but on the other hand, your *immer* good moods and optimism helped me to finish it all just in time to catch my plane to Colombia. Some sort of pagan sword ritual or card trick suddenly put all the pieces of this personal Rubick's Cube in place.

Special thanks are also in place for Michel Meybeck, who received us at Sisyphe Jussieu and gave us his undivided attention. Your advise was like a secret ingredient, putting the finishing touches to our cocktail of typologies and Blue Lagoons.

Enjoy the thesis,

Cheryl van Kempen  
Utrecht, 22 June 2007

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## 1 Introduction

The coastal ocean - defined here as delimited upstream where salinity influences are first felt, and in the sea by the shelf break - occupies only about 8% of the surface area, and only about 0.5% of the volume of the world's ocean (Alongi, 1998). Despite that, it plays a considerable role in biogeochemical cycles: laying at the land-ocean interface, the coastal ocean (a) receives major inputs of terrestrial organic matter (34 Tmol TOC/y) and nutrients (2.2 Tmol TON/yr) through run-off and groundwater discharge (Rabouille *et al.*, 2001); (b) exchanges large amounts of energy and matter with the open ocean (net export of 40 Tmol OC/yr and net import of 5 Tmol ON/yr by upwelling; Rabouille *et al.*, 2001) and (c) constitutes one of the most geochemically and biologically active areas of the biosphere (Gattuso *et al.*, 1998). The biogeochemical processes taking place in the coast act as a natural regulatory mechanism for nutrient levels. Part of the nutrients entering the coast from continental discharge, are prevented from proceeding to the open ocean. The main processes which remove nutrients from the water column are burial and denitrification, which cause the nutrients to be stored in the sediment, or released to the atmosphere respectively (see §2.1.3). The coastal ocean can therefore be seen as a filter.

It was shown by Rabouille *et al.* (2001) that the nutrient filtering strength (filter capacity) of the proximal coastal ocean (PCO) differs from that of the distal coastal ocean (DCO). The PCO includes large bays, the open water part of estuaries, deltas, inland seas and salt marshes. The DCO spans the open sea in front of beaches and cliffs and includes the continental shelf up to the shelf break, which is at an average depth of 200 m (Rabouille *et al.*, 2001). The PCO is a stronger filter than the DCO because of longer water residence times, and more intensive biologic activity, i.e. it has a higher nutrient filtering capacity.

Nutrient enrichment of coastal waters is often a local problem, but it can and does occur in any climate and both by natural and anthropogenic nutrient loading. Because of this global occurrence, a global typological assessment of the nutrient cycling in morphologically different coasts is justified. In such an assessment, the geographical distribution of coasts with different filtering capacities is of interest, but also the magnitude of the nutrient concentrations and transport fluxes resulting from the different driving forces and intensities with which the biogeochemical cycles are active in these coasts.

The biogeochemical cycles of N and P are coupled to the carbon (C) cycle through photosynthesis. Apart of affecting the biomass production and thus the global CO<sub>2</sub> balance, decay of organic matter influences the release of greenhouse gases like N<sub>2</sub>O and methane (Chan *et al.*, 2006). In other words, N and P influence whether the coastal ocean acts as a C source or sink, and consequently play a role in climate change. This role may have been enhanced through anthropogenic activities which have increased the local release of nitrogen (N) and phosphorus (P) to the coast in many places as a result of changes in land-use and increasingly intensive farming, industrial, and agricultural practices in the last centuries (Crossland *et al.*, 2005; Vitousek *et al.*, 1997).

Apart of their role in climate change, N and P concentrations in the coast also directly affect the lives of millions people who rely on the coast for their livelihoods. The coastal ocean sustains 90% of the global fish catch due to its high productivity (Gössling, 2003); creates income through tourism (Added, 2001) and prevents the accumulation of pollutants from sewage sludge and industrial waste water due to its natural regulatory mechanisms.

Eutrophication, or increased nutrient inputs to the coast, have the potential to negatively affect ecosystem balance (See §2.1.4). They can lead to changes in water column nutrient ratios which can then induce shifts in species succession, reduced biodiversity, fish kills related to anoxia, and water toxicity. Whenever arising, these effects disturb the capacity of the coast to provide certain ecosystem services and has consequences for the people who rely on the coast for their livelihoods (FAO, 2005).

Nutrients in the coastal ocean have been researched at various scales and at various levels of complexity. Local problems have often driven coastal research, so that most assessments are on a local scale. These assessments often involve sampling campaigns and subsequent derivation of nutrient budgets and models. Intermediate to global scale assessments usually involve the assimilation of a consistent dataset from local studies, and the development of models to extrapolate to areas for which no data is available.

The detail in which biogeochemical processes are taken into account in budgets and models varies in accordance with the scale at which the coastal system is researched. Local studies are often more complex than regional or global scale studies. In assessments this is reflected by the number of processes taken into account, while in nutrient models also the number of variables on which processes represented depend, is higher. The reason for this higher complexity in local models and assessments is a difference in the problem definition, a

difference in the processes leading to these problems, and a difference in the feasibility of a detailed assessment at the desired scale (see § 2.2.2).

With the development of Geographic Information Systems (GIS), and the higher availability of georeferenced data sets for environmental and geochemical applications, new methods can now be developed for modeling coastal research. In the light of these developments, a GIS containing typological information on the morphology and nutrient filtering capacity of the global coastal ocean will be related to a process-based nutrient box-model in this thesis.

### **Aims and approach**

The Dutch national research program ‘Global Nutrient Fluxes at the Land-Ocean Interface’ (G-NUX) researches the biogeochemical cycles and transport of N and P on a global scale; whether on land, in the coast or in the open ocean. The present study is a contribution to the G-NUX research of the coastal ocean. The aim is (1) to assess the geographic distribution of types of proximal coastal waters that modulate their nutrient input from the continent and distal coast to different degrees, and (2) to assess whether a very simple generic nutrient box model is suitable to model the biogeochemistry of lagoons.

These aims are achieved by two separate methods: the first part is resolved by making a qualitative assessment of the relative filter capacity of 11 coastal types, which comprise a *morphologic typology*. The morphologies are karst, fjord, fjärd, ria, macrotidal, estuarine, lagoon, big river, mangrove, arctic and glaciated sedimentary coasts. The result of comparing the filtering strength of these coastal types is a *filtering typology* which differentiates between four types, namely coasts which act as ‘no filter’, an ‘estuarine filter’, a ‘lagoon filter’ or a ‘passive filter’ (types 0, I, II and III respectively). For both the morphologic and filtering typology, a segmentation scheme is established, visualizing the spatial distribution of the constituent types in a GIS.

The second aim is achieved by developing a very simple coupled, multi-element (N and P), multi-form (dissolved/particulate, organic/inorganic), and process-based box model for coasts of filtering type II: lagoons. All processes are represented by first order kinetics, and no dependency on light or temperature is assumed. Two types of the model are developed: one including exchange of water between the sea and lagoon (based on residence time) and one where this is not possible (based on flushing time). The model is calibrated to Thau, Venice and Szczecin lagoons.

A comparison of rate constants for these lagoons should show whether it is possible to make a generic nutrient model based on this simple representation alone. For this to be possible, the each of the rate constants should be close to that of the average rate constant for each of the fluxes.

Further, A sensitivity analysis is performed for these lagoons, assessing their response to changes in river nutrient load. A simulation is run for Szczecin lagoon, for the period 1980 to 1999, as well as an assessment of the effect the N:P ratio at which nutrients are fixed during photosynthesis has on the biogeochemical cycles in lagoons.

Global ocean models do not normally make an explicit distinction between the coast and open ocean, let alone between the PCO and DCO. Rabouille *et al.* (2001) showed that making this distinction in models improves their representation of nutrients in the coast. The effect is that river born nutrient fluxes in models do not enter the open ocean directly, but instead their magnitude is affected by biogeochemical processes in the proximal and distal coastal ocean. In certain coasts this may lead to retention of large portions of the original material in the coastal ocean, while other types of coast will retain less and allow more material to enter the open ocean (see §3.1.1 and §3.1.4).

In the following chapters, a literature review will first describe the background of nutrient cycling, and how they have been researched in the past. Subsequently the process for defining the typology and segmentation are presented.

The filtering typology presented here is developed in two steps. First a *morphologic typology* is developed, from which a second typology is derived by aggregating ecosystems which have comparable filtering capacities, or for which the processes driving the filtering capacity are similar: the *filtering typology*. The spatial distribution of both typologies is obtained by attributing their respective types to drainage basins in a GIS, and aggregating these to coastal segments. The GIS used here exists of a representation of the world as a grid at  $0.5^\circ \times 0.5^\circ$  resolution. Individual cells can be terrestrial, or oceanic. The basic layers of the GIS used here represent (1) river drainage basins (Vörösmarty *et al.*, 2000), (2) the COSCAT coastal segmentation (Meybeck *et al.*, 2006), (3) topography/ bathymetry (U.S. Department of Commerce, 2006) and (4) lithology (Dürr *et al.*, 2005) The segmentation arising from the typology gives an insight in the distribution of these different coastal types around the world, but also of the geographic transport path of nutrients on their way from the terrestrial sphere to the distal coastal zone. The G-NUX research aims at developing nutrient models for each of

the types constituting the filtering typology presented here, and to couple them to the information of the GIS. This will create ultimately a suite of spatially explicit, process-based nutrient models.

The framework of the present research allows the development of only a single model, and its coupling to the GIS. It was chosen to develop a model for the lagoon type based on several factors. First this is a very distinct coastal feature, which is relatively easy to recognize and delimit. Second lagoons often act as important filters, due to long residence times in shallow, quiet waters with high biologic activity. Finally many lagoons are known to be prone to temporary nutrient enrichments and their potentially adverse effects, while many lagoon systems reside in tropical areas for which not much data is available. The ability to predict lagoon response to fluctuating nutrient inputs at these locations is therefore valuable for coastal research and management.

## 2 Background

In this chapter the water fluxes and N and P cycles in estuaries are reviewed first, followed by a discussion of eutrophication and algal blooms. The negative effects which are often associated with these events lay at the basis of much research on nutrient dynamics in the coastal ocean. The exact meaning of the term eutrophication is often used wrongly, so that it needs to be clearly defined in the present assessment.

Research on nutrients in the coastal ocean has been done at various scales, and to various degrees of complexity. The scale of the area researched dictates the complexity of the model required, as different processes become relevant when looking at the same problem at different scales. Examples will be given here for local, regional and global scale assessments through sampling campaigns and modeling. The difficulty in the present research is that the work is done on a global scale, but at a resolution which corresponds better to intermediate or local scale assessments. The increased computer power and the development of databases and GIS software in the last decades now allow scientists and managers to develop new methods for coastal research which can cope with this discrepancy in scales, but new methods for upscaling still need to be developed. The first steps towards the development of such a method are set here by applying typological approaches to coastal research. Such approaches have been used in the past, but this has not yet lead to the development of a biogeochemically relevant segmentation scheme.

### 2.1 Water and nutrient fluxes in estuaries

#### 2.1.1 Water fluxes

The nutrient cycling of N and P in estuaries is closely related to the water cycle of the system. In the present paragraph, and this paragraph only, the word 'estuary' is used in its widest sense, referring to any body of brackish water surrounded for the largest part by land. Here the term estuary therefore includes lagoons and bays. The word 'sea' is used here to refer to the open ocean directly outside of the estuaries. This type of generalization was applied previously, for example by Meybeck *et al.* (2006), to be able to conveniently describe the water cycles of estuaries in the broadest sense of the word.

The water fluxes entering and leaving an estuary physically transport nutrients in- and out of the system. The net nutrient and water flux is therefore usually from the river into the estuary and then out to the sea. Some estuaries however, can also have a net influx of nutrients from the sea. This may for example be the case for tropical lagoons if they have higher

evaporation rates than the rate at which their fresh water is replenished. Because evaporation does not remove the nutrients from the water, a concentration increase of nutrients and salts is the result. Examples of such lagoons are Ghar el Melh in Tunisia (Souza *et al.*, 2003), Chiku in Taiwan (Alongi, 1998; Kjerfve, 1994), and Araruama in Brazil (Mackenzie, 1998).

Nutrients may also enter estuaries by atmospheric deposition, or when released from anthropogenic point-sources in the coastal system, such as factories and sewer outlets. The contribution of atmospheric deposition is often only minor. Anthropogenic point-sources however can have a considerable impact on nutrient levels in aquatic systems, and can be handled in similar ways as the input from river discharge.

### 2.1.2 Nitrogen and phosphorus cycling

Descriptions of the biogeochemical cycles of N and P can be found in many text books on environmental chemistry (e.g. Manahan 2000) and (Olausson and Cato, 1980; Ruttenberg, 2004). The following paragraph was compiled from different sources, among which two books which are more specific for coastal systems (Kjerfve, 1994; Mackenzie, 1998). A graphical representation of the most relevant processes for estuarine modeling of the biogeochemical cycles of N and P is given in figure 2.1. The equations corresponding to some of the processes illustrated in the figure are given in table 2.1.

#### **Bioavailable N & P species**

Nitrogen (N) and phosphorus (P) play vital roles in the photosynthesis reaction as well as in proteins, which are the principal constituents of the cellular plasma of in organisms (Manahan, 2000). P further also plays an important role in RNA, DNA, organic tissue and skeletons, (Meurer and Natland, 2001) as well as in the energy transfer within cells (as ATP).

By naming convention, the different pools of nutrient species in the water are referred to with 3-letter abbreviations. The pools used here are DIN, DIP, PON, POP, and PIP. The first letter refers to the dissolved or particulate form of the species. The second letter refers to the organic or inorganic nature (organic matter in general is also referred to as OM). The third letter finally refers to Nitrogen (N) or Phosphorus (P).

Organisms can only take up N and P from their environment if it is in a bioavailable form. The main bioavailable species are nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ) and ammonia ( $\text{NH}_3$ ), which are all DIN. The main bioavailable phosphate species is the phosphate ion itself ( $\text{PO}_4$ , or DIP). The largest reservoirs of these nutrients on earth are however not the hydrosphere, but the atmosphere

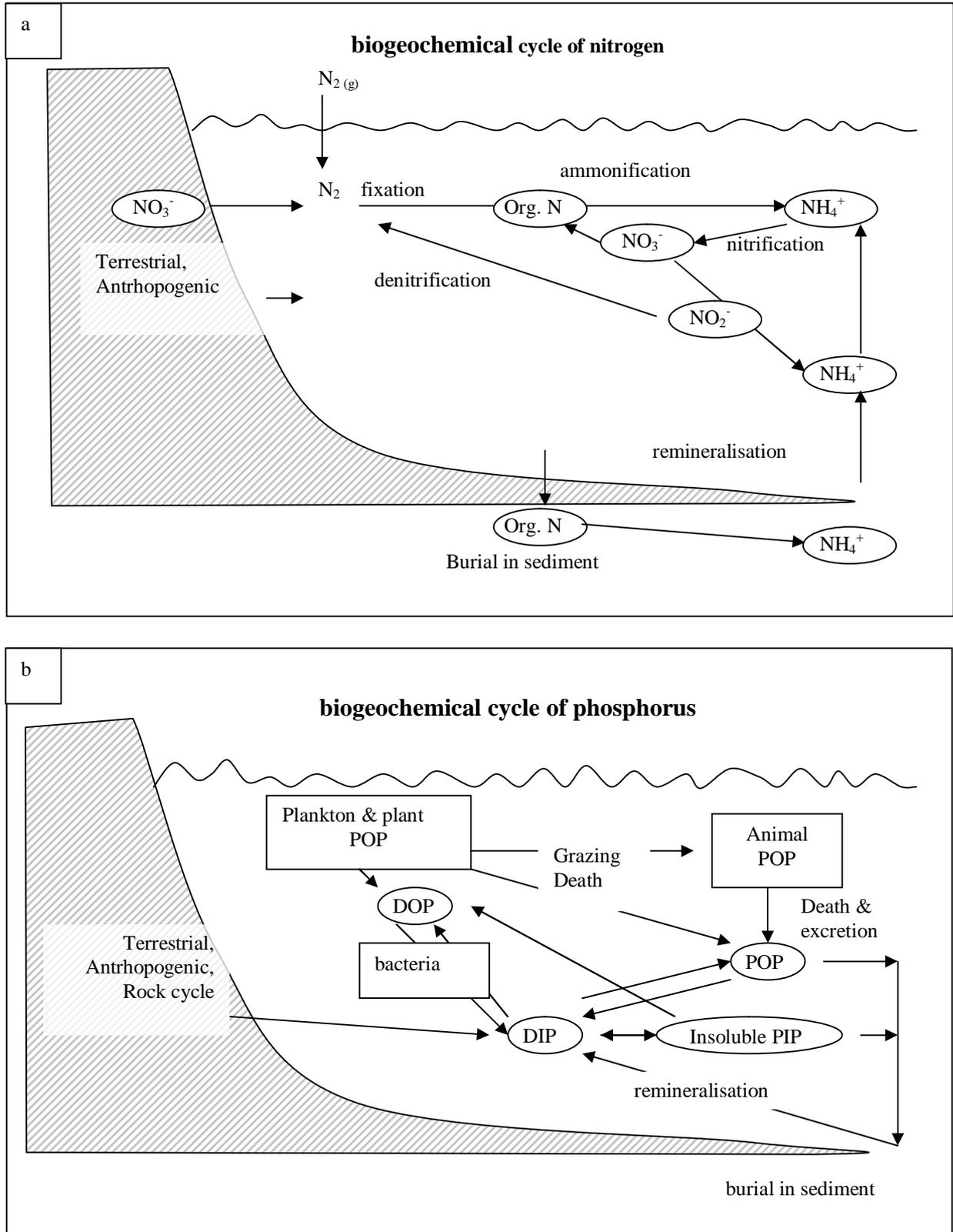
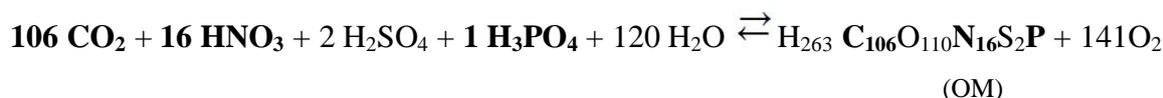


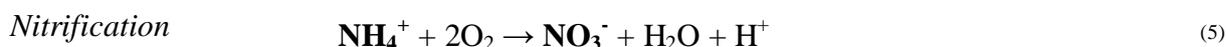
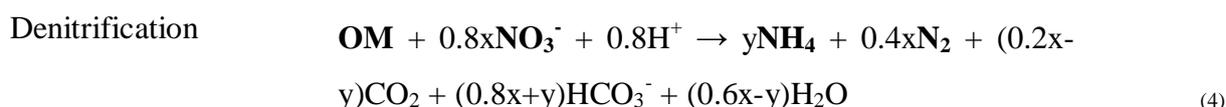
Figure 2.1 Biogeochemical cycles of a) Nitrogen and b) Phosphorus

**Table 2.1** Simplified biogeochemical reactions involving N and P

*Photosynthesis reaction for plankton*<sup>a</sup> (1)



*Reactions involving nitrogen*<sup>b</sup>



*Reactions involving phosphorus*<sup>b</sup>



a. After Lerman *et al.* (1989) in Mackenzie *et al.* (1992)

b. After Canavan (2006)

c. OM represents organic matter with a C:N:P ratio of x:y:z.

d. A generalized mineralization reaction is depicted for ammonification where  $\text{TEA}_{\text{ox}}$  and  $\text{TEA}_{\text{red}}$  represent the oxidized and reduced terminal electron acceptor.

and lithosphere respectively. To become bioavailable, the nutrients must therefore first dissolve.

78 % of our atmosphere exists of the elemental gas,  $\text{N}_2$  (Redfield *et al.*, 1963).  $\text{N}_2$  enters the biogeochemical cycle when fixed in organic matter by microbial processes. Ammonification and nitrification subsequently transform the N into the bioavailable DIN forms, ammonia, nitrate and nitrite (see figure 2.1.a).

Phosphate becomes bioavailable after being leached from phosphorus containing minerals in rocks. Examples of such minerals are Vivianite (Vitousek *et al.*, 1997) and Apatite (Crossland *et al.*, 2005) (see figure 2.1.b).

### Organic matter and nutrient ratios

Once N and P are present in the water cycle as DIN and DIP, they can be taken up by plants and incorporated in organic matter (OM) by photosynthesis. As can be seen in the photosynthesis reaction for phytoplankton depicted in table 2.1, the nutrients N and P are now coupled to each other and to the carbon cycle, in a certain ratio which varies for the different

plant species, but corresponds to the ratio in which these elements are used in the photosynthesis reaction of each plant species. The average C: N: P ratio for phytoplankton is known as the Redfield ratio, and is 106:16:1 (Jorgensen and Richardson, 1996). For marine benthos the ratios are higher, namely 550:30:1 (Atkinson and Smith 1983, cited in Mackenzie *et al.* 1992), while for land plants it varies widely, due to the large variation in plant species. A range of C:N:P ratios from 510:4:1 to 2057:17:1 was reported (Delwiche and Likens 1977 and Likens *et al.* 1981 respectively, both cited in Mackenzie *et al.* 1992).

### **Remineralisation**

When an organism dies, its tissue and bones still contain the nutrients stored in them. Organic matter degradation releases these nutrients and makes them bioavailable again. In other words, remineralisation turns the PON and POP back into DIN and DIP (see figure 2.1).

The bacteria involved in organic matter degradation get energy from reducing chemical species. The energetically most favorable electron receptor is oxygen, but in anaerobic conditions anaerobic bacteria can use other electron receptors are used, among which nitrogen.

Ammonification and denitrification are nitrogen mediated degradation processes. The result of ammonification is the release of ammonia, which subsequently can go through the biological food web once more, or it can continue its way to the ocean. The end product of denitrification is nitrogen gas, with  $N_2O_{(g)}$  and  $NO_{(g)}$  as side products. All of these gases are released to the atmosphere (see figure 2.1.a). From a nutrient transport point of view, one can say that denitrification interferes with the transport of a fraction of the N load to the distal coastal ocean, and retains this fraction in the proximal coastal ocean.

### **Burial**

Dead organic matter usually sinks to the bottom of the estuary, and decomposes for a large part there. At the same time it can get buried due to the accumulation of more OM and sediment. If the burial rate is fast enough, the material can get buried at depths where degrading bacteria are no longer active, without having lost all of the N and P it contained. These nutrients have now been removed from the estuary, and will be returned to the rock cycle. As burial prevents nutrients from flowing to the distal ocean, this too is a form of retention.

### **Particulate inorganic phosphorus**

The bioavailability of phosphorus in estuaries is strongly influenced by its presence in inorganic particulates. Phosphorus may occur in inorganic particles because (1) it was part of the bed-rock the particle was derived from; (2) it has precipitated in a mineral form; (3) it has adsorbed to a mineral surface.

Particulate Inorganic Phosphorus (PIP) is in itself not a bioavailable form of P. If the phosphorus is dissolved, however, it becomes bioavailable again. Certain PIP forms have a fraction which can become bioavailable, and a fraction which cannot. For example, phosphorus which is complexed to surface atoms in an oxidated state is potentially bioavailable. Reduction of the surface atoms will destabilize them and release them to solution, together with the complexed phosphorus. Estuaries with sediments which are rich in iron or other surface complexing elements, have been reported to remove large amounts of riverine P input. For example, Jensen *et al.* (2006) found that Danish rivers carry >50% of the phosphorus transported as particulate P (PP). >59% of this PP is iron bound, while between 2% and 13% is potentially bioavailable. It is suggested that most PP is lost during summer months due to flocculation of iron bound P, and adsorption of DIP onto particles which are subsequently transported seaward. In winter most PP is mobilized again from the bottom sediments (Jensen *et al.*, 2006).

Phosphorus is sometimes remobilized more easily in anaerobic conditions (Kisand and Nõges, 2004). Anoxia may occur after burial to a certain depth, or when the water column becomes anoxic. The latter case may happen when large amounts of organic matter die and decay at once, like after a phytoplankton bloom. The oxygen consumption during the decay may be so high that it may lead to anoxia, destabilizing the minerals and releasing the P back to the water column.

#### **2.1.3 Relative filtering capacity**

Certain coastal oceans act as a nutrient filter. Nutrients are removed from the water column by burial of organic matter, or in case of gases, they are lost to the atmosphere. In the present study only the loss of gases as a result of denitrification are taken into account. The effectiveness with which nutrients are removed from a coastal body of water, can be called the filtering capacity (FC) of the coast, measured in moles N or P per unit of time. I.e.:

$$FC_N = (PON_{\text{buried}} + DIN_{\text{denitrified}})/\text{year}$$

$$FC_P = (POP_{\text{buried}} + PIP_{\text{buried}})/\text{year}$$

To be able to intercompare the filtering capacity of different coasts, normalisation is required. Because the absolute removal of nutrients primarily depends on their input, it is logical to normalise to the absolute value of the input flux. Nutrients generally enter the coastal ocean as river load. Certain systems however can also have an input from the open ocean. Because the interest for humans is to see what the anthropogenic impact is on coastal systems, normalisation will be limited here to the total nutrient import as river load. The relative filtering capacity (RFC) is then:

$$\text{RFC}_N = \text{FC}_N / \text{TN}_{\text{river}}$$

$$\text{RFC}_P = \text{FC}_P / \text{TP}_{\text{river}}$$

The filtering capacity is a function of all processes and factors which affect the removal of nutrients by burial and denitrification. These can be divided into two groups. One group then involves the physical transport of nutrients in and out of the system, and is related to the water budget; while the other group influences the transformation of nutrients to other species, and their incorporation in particulate matter by biotic and abiotic processes. Factors which control the amount of organic matter production and degradation, as well as the amount of P stored as PIP therefore define the filtering capacity of the coastal ocean.

### **River versus ocean influence**

As was explained in §2.1.1, coastal systems have water input from rivers and groundwater on the terrestrial side, and they can exchange water with the open ocean. The filtering capacity depends on the nutrient inputs by these fluxes, and therefore also on the relative influence of river and ocean. The influence of the ocean is a function of how open the system is to the ocean (accounting for wave influence), and the influence of tides.

### **Residence time**

The removal of nutrients by biotic and abiotic processes depends on the residence time of the water. The longer the residence time, the more chance exists a nutrient will get incorporated in particulate matter, and the more likely it is to get buried or otherwise removed from the water column. The residence time depends on the volume of the system (and thus area and depth), and the rate with which river and ocean waters enter and leave it (flow velocity).

### **Growth limitation**

The effectiveness with which the biologic cycles remove nutrients also depends on the many potentially growth limiting factors. If growth is limited by a factor other than nutrient availability, then the nutrients will remain in solution and are likely to proceed to the more distal ocean with water transport. Biologically inactive coasts will therefore only act as a weak filter. Biologic activity is influenced by many factors, for example the photic depth, water temperature and stratification.

### **Degradation intensity**

The filter capacity is also influenced by the way organic matter is degraded. If much material is degraded by denitrification, more N will be lost from the system as N<sub>2</sub>, than when it is degraded by other processes. How much Organic matter is degraded by denitrification depends on the availability of dead organic matter, and the oxic state of the water column and sediments.

### **Potentially bioavailable PIP**

Finally, P ad- and desorption to particulate matter depends on the availability of a substrate and again the oxic or reduced state of the water and sediment. Relatively large amounts of P can be stored as a PIP phase. This storage is often only temporary, with part of the phosphorus being released during anoxic events. Thus, PIP is a very important component in the P household of many coasts, while its behaviour as a P source or removal term is hard to predict because of the difficulties to predict anoxic events.

#### **2.1.4 Eutrophication**

Due to the population growth in the last centuries, the release of N and P to the environment has increased in many places (Vitousek *et al.*, 1997). This is a direct consequence of a risen production in industrial waste and sewer sludge which contains N and P, as well as an enhanced application of fertilizers in agriculture. Fertilizers are used to restore the nutrient content of the soil, but they are often applied in excess. The superfluous amounts wash out of the soil, into surface and groundwater and eventually into the coast (Jorgensen and Richardson, 1996).

An increase in mineral nutrient inputs to an aquatic ecosystem is called eutrophication (Alongi, 1998). The term eutrophic is also used to give a qualitative indication that an ecosystem is nutrient rich, but no standard levels are defined above which the term is

applicable. As a result of these non-precise definitions, the term eutrophication is often only applied to situations where an increased nutrient availability has enhanced the biologic productivity of the system above normal levels, and is sometimes followed by drastic drops of dissolved oxygen in the water column. When this happens, eutrophication has the potential to disrupt the ecosystem balance and is therefore an issue of concern. It is not possible to set an exact number to which exact nutrient concentrations must be reached to call a system eutrophic in the sense that the eutrophication has adverse effects. The reason for this is that environments which are by nature nutrient poor (i.e. oligotrophic) will respond more strongly to small increases in nutrient availability than ecosystems which are normally nutrient rich (i.e. meso- to eutrophic).

In this study, the term eutrophication will therefore be used to refer to an increase in the input of N and P compared to a baseline or pristine level; whereby the increase is a temporary or permanent change, and has as effect an increase in biomass production to levels where this has adverse consequences for the ecosystem such as (temporary) shifts in species succession and fish kills.

### **Growth limiting factors**

It should be noted that an increase in the bioavailability of N or P does not always bring about a drastic increase in biomass. Only if one of these nutrients was previously growth limiting, will its addition bring about a period of flourishing growth (Alongi, 1998). If other nutrients or factors are limiting, such as potassium, calcium, sulfur, iron or light availability, then N and P additions will have no effect.

The proximal coastal ocean is often locally limited by either N or P (Howarth, 1988), because organisms need these nutrients in large amounts. As a consequence, eutrophication as defined above, may arise as a local problem almost anywhere around the world. It can come about in any climate, and both as a result of natural and anthropogenic nutrient enrichments.

### **Competition and succession**

Most of the harmful effects related to eutrophication originate in a drastic increase in phytoplankton biomass and a shift in species succession due to their (in)ability to adapt to the new circumstances, and to compete with other organisms (Jorgensen and Richardson, 1996). Often only a few successful species will account for most of the increase in biomass (Crossland *et al.*, 2005). This can be a problem if (1) the successful species has no economic relevance, while the species it replaces did; (2) if the dominating species is toxic to higher

animals and humans (Alongi, 1998) or (3) if the increase in biomass is so large that on death and decay of the material the water column becomes hypoxic (low oxygen levels) or anoxic (Added, 2001). In case of hypoxia again a shift in species succession will take place, favoring species which tolerate low oxygen availability. In the case of anoxia all aerobic life will die, further increasing the oxygen demand due to aerobic decay, and thus prolonging the duration of the anoxic event. During anoxia, phosphorus which is associated with oxidized minerals may be released as their bonding elements become reduced and go into solution (Sfriso *et al.*, 1994). If phosphorus were limiting growth in the system, this release can bring about a second cycle of eutrophication, again with the potential problems listed above.

All of these consequences have economic impacts through fisheries, aquaculture, tourism and deteriorating water quality, because the ecologic, social and aesthetic value of the coastal ocean is affected (Nakata *et al.*, 2000). It is therefore important to understand the effects of nutrient loading on the coast.

## **2.2 Coastal research**

Eutrophication and its effects lay at the basis of much local research on nutrients in the coast. The scale and depth of these researches is often related to a concern in the coastal ocean's ability to provide ecosystem services. Since these issues are often of a local character, the coastal ocean was primarily assessed on local scales. Coastal features however are usually trans-boundary, so that increasing international efforts are being made to cooperate in the improvement of coastal water management. Also the global occurrence of eutrophication problems, and the increased international collaboration in assessment and mitigation of other large scale environmental problems such as climate change and falling fish catch, increase the need for regional and global scale assessments. The methods applied in global scale research are different from those applied in local research, for several reasons. In the following chapter therefore the different methods are reviewed with which the coast is studied, and the difference between local and global scale assessments is discussed. Finally the application of typologies in coastal research is introduced, as this is a relatively new method in this research area.

## 2.2.1 Types of studies

### Sampling and experiments

The first step in researching the coast is the definition of boundaries for the coastal water masses under research. The next step is to make a nutrient budget for the system, which means that all nutrient levels in the water column and sediment are quantified, as well as all processes and fluxes, which transport nutrients in and out of the system, or transform them to other ionic species. Quantification is done during sampling campaigns, and in lab experiments. Not all fluxes and processes in which N and P are involved, can be measured during a campaign. Usually the research question does not require a complete understanding of the system, and only relevant processes and fluxes are measured. Often choices must be made of what to take into account due to time, money, physical or technical limitations, the framework of the project. It is for example impossible to sample all coasts of the world or a continent as part of a single research. Regional to global scale assessments must therefore rely on a compilation data derived from local assessments, or selectively sample locations which are considered representative for a larger area. The available data must subsequently be scaled up, or inferences must be made to cover the areas for which no data is available. The final steps in nutrient assessments of the coast involve the development of predictive models, in order to assess future nutrient concentrations and fluxes for the system.

### Budgets

Any chemical budget functions like a financial budget for a company: It is the net outcome of adding all the fluxes of money/chemical units which enter (or are generated in) the company/system, and subtracting all fluxes which remove them, or by which they are lost.

In coastal research, budgets can be made for many subjects. Based on budgets, assumptions can be made about the system. Following are a few examples of different budgets, and how information can be deduced from them: (1) the water budget of an estuary can often be assumed to be at steady state, and thus to be zero. (2) If this is the case for a tropical lagoon where the loss of water through evaporation is larger than the replenishment by ground- and river water, then it can be deduced that an influx of ocean water maintains the water level. (3) If no influx from the ocean were possible, the water budget would be negative, and the water level in the lagoon would fall. (4) In both cases the salt and nutrient budgets of the lagoon would not be at steady state (i.e. the salt and nutrient concentrations will increase).

In chapter 4 of this study budgets will be used for the water and salt cycles of lagoons, as well as for the nutrient cycles of N and P. Because the model developed differentiates between DIN, DIP, PON, POP and PIP (see §2.1.2), separate budgets need to be created for each of these nutrients as well. As was discussed in the paragraph on water fluxes in estuaries, each of these nutrients has an influx from the river and ocean, and is lost to, or exchanged with the sea. In the estuary, (bio)geochemical processes alter the concentration of the nutrients in the water column by removing or releasing them.

## Models

Numerical nutrient models usually attempt to represent the change in time of nutrient levels. They can vary in spatial scale (mm, meter or km scale), temporal scale (a tidal cycle, a day, season or year) and complexity. With complexity two types are meant: first models can vary from representing 1 to 3D bodies of water with respect to time. Second, models can vary in the number of processes they take into account, and the complexity of the equations with which these processes are represented. In other words the number of variables on which the processes depend in the model. The complexity of models is related to the scale of the research.

### 2.2.2 Scales

Compared to global models, local studies and models are generally more complex both with respect to the dimensions included, and the representation of processes. The reason for this is that local studies often focus on a local problem and research it in depth. Regional and global studies instead focus on larger scale phenomena, in which the local details are less significant. Larger scale studies also require more data, covering a larger area. If the model requires too detailed information, it becomes financially and physically hard to calibrate and validate.

Table 2.2 shows that as a result of these differences in complexity due to scales, the number of sampling campaigns performed in the coastal ocean is very large for the local scale, while on the global scale it is almost impossible to perform. Correspondingly, the more complex models become, the less they are made for the regional and global scale. For example, there is no spatially explicit global scale model for nutrients in the coast. The model sited here, LOICZ (see further on in this paragraph under the heading global scale), is a collection of budgets from which global, spatially explicit estimates of nutrient levels are derived. Such a derivation is called upscaling, and is often necessary in global scale assessments. Upscaling can be described as '*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*' (Crossland *et al.*, 2005). A method which can be used for upscaling is the application of typologies, as was done for the coastal ocean by Crossland *et al.*, as was previously applied to rivers by Green *et al.* (2004), and as will be done for nutrients in the coastal ocean in the next chapter of this thesis.

Table 2.3 lists references of assessments in local proximal coastal systems, regional seas, and the global coastal ocean. Some of these will serve as examples in the next sections to illustrate the diversity of processes and fluxes measured or taken into account during budgeting and modeling. Note that on the local scale, all assessments listed include both sampling and a budget. At the regional and global scale no budgets are derived after the sampling campaign and data is rather presented as it is. In the case of the budget made for the North Sea by Brion *et al.* (2004), no sampling campaign was performed and the budget was made based on literature values for all input and transformation fluxes. With respect to coastal nutrient models, these exist for the local and regional scale, but not for the global scale. For the global scale, estimates of continental nutrient inputs into the coast are available, or ocean models which the distal ocean rather than the proximal coastal ocean.

**Table 2.2** Effect of scales on coastal research and model complexity

Scale	Sampling campaigns for nutrient levels	1-box Budget calculations	Models		Complexity of budgets and models
			1-box models	Spatially explicit models	
<b>Local</b>	A lot	Many	Many	Many	Highly complex
<b>Regional</b>	Some	Some	Some	Some	Complex
<b>Global</b>	None <sup>1</sup>	Some	Some	LOICZ <sup>2</sup>	Simple

1) models and calculations are based on datasets compiled from local and regional studies

2) Technically LOICZ is not a model, but a compilation of budgets from which inferences were made for regions for which no information was available.

**Table 2.3** References for some budgets and models of nutrients in the coast on local and global scales.

	Sampling (S) and/ or budgets (B)	Models
Local	e.g. Ghar el Melh, Tunisia (S, B) (Added, 2001); Szczecin, Poland/ Germany (S, B) (Bangel <i>et al.</i> , 2004; Grelowski <i>et al.</i> , 2000) Thau, France (S, B) (De Casabianca <i>et al.</i> , 1997; Picot <i>et al.</i> , 1990) Venice, Italy (S, B) (Sfriso <i>et al.</i> , 1994);	e.g. Sjinji and Nakaumi, Japan (Nakata <i>et al.</i> , 2000); Cienaga de Tesca, Colombia (Lonin and Tuchkovenko, 2001); Oder, Poland/ Germany (Humborg <i>et al.</i> , 2000; Wielgat and Witek, 2004; Witek <i>et al.</i> , 2003); Thau, France (Chapelle, 1995; Chapelle <i>et al.</i> , 2000); Venice, Italy (Pastres <i>et al.</i> , 2005; Solidoro <i>et al.</i> , 2005)
Regional	e.g. Mediterranean (S) (Kress and Herut, 2001) Baltic Sea (S) (V.Sokolov <i>et al.</i> , 1997) North Sea (B) (Brion <i>et al.</i> , 2004)	e.g. Baltic Sea, 1-D model system (Vichi <i>et al.</i> , 2004) Gulf of Mexico, influence of Mississippi N load (Scavia <i>et al.</i> , 2003); NE coast US (Fennel <i>et al.</i> , 2006)
Global	LOICZ (B) (Crossland <i>et al.</i> , 2005) <sup>1</sup>	models for terrestrial input to the coast: e.g. Global-NEWS, coupled N-P models (Seitzinger <i>et al.</i> , 2005); Ocean models: (Humborg <i>et al.</i> , 2000; Rabouille <i>et al.</i> , 2001; Ragueneau <i>et al.</i> , 2002; Sherman, 2006; Slomp and Van Cappellen, 2004)

1) see <sup>2</sup> in table 2.2

### Local scales

The importance of local studies is that they research local phenomena in depth, and sometimes over large periods of time. Such assessments are of major importance for the process-based understanding of coastal systems on the molecular to ecosystem scale.

The Szczecin lagoon is a good example of a site where ongoing pollution which hampers recreation and tourism development in the area was reason for the initiation of a long-term monitoring program. As a result, a comprehensive spatially explicit data set is now available for the period 1980 to 1999 (Bangel *et al.*, 2004). This dataset includes for example river discharge and the river load of ammonia, nitrate, phosphate and total phosphorus, as well as the concentration of these elements and salinity, silicate, chlorophyll, water transparency and internal eutrophication (P-release during anoxic events) in the lagoon and in the Pomeranian Bay, in front of the lagoon. This assessment is very complete compared to many other studies, as it specifically includes PIP release, which is not always included in other monitoring efforts.

This data set has further allowed the development of sophisticated models, which are very well capable of reproducing seasonal nutrient levels and fluxes in the lagoon. One such model was developed by Wielgat and Witek (2004). Figure 2.2.a shows the model structure schematically, and allows to compare it with a global model which will be discussed later on. The model by Wielgat and Witek has as state variables N in phytoplankton, DIN, PO<sub>4</sub>, N & P in detritus, and N & P in sediment. Redfield stoichiometry is used to recalculate N in phytoplankton into phosphorus. Another constant ratio is used to recalculate nitrogen units into chlorophyll a and carbon units. The forcing functions are temperature, irradiance and loads from the Baltic Sea and drainage. The internal time scale of the model is one day, so that seasonal and annual fluctuations are reproduced well. The model shows a phosphate minimum in spring and two maximum peaks, one of which in summer and the other during a winter maximum. Also phytoplankton growth and chlorophyll measurements are well represented by the model. For the period 1980 to 1999, on average, 22% of incoming nitrogen was retained annually in the Grosses Haff, and 48% in the Kleines Haff. Phosphorus retention amounted to 17 % for the entire lagoon. Although these percentages were higher than other modeling results and sediment measurements, this discrepancy can be explained by the presence of polders which are flooded in winter and periodically when the river water level is high. During these events, it is estimated, 33 to 70% of phosphorus retention takes place, and 16% of nitrogen (Engelhard *et al.*, 1999 in Wielgat and Witek, 2004).

The model developed by Wielgat and Witek shows that relatively simple nutrient models are adequate for modeling the biogeochemical cycles of N and P in estuaries on local scales.

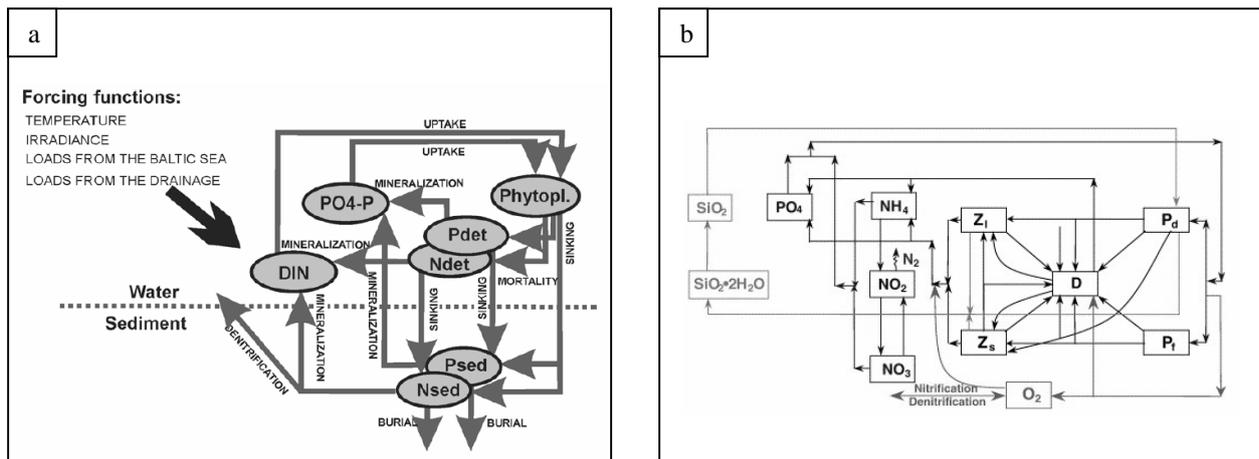
It should be noted that much of our understanding of coastal systems is based on local studies of temperate coastal systems, while the tropical systems are researched and understood to a much smaller extent (Alongi, 1998). The last few years, the number of publications of local studies on tropical coasts is increasing (Added, 2001; Labbardi et al., 2005; Lonin and Tuchkovenko, 2001; Nakata et al., 2000; Ruiz et al., 2006), but many of these focus more on ecology, rather than on the biogeochemical state of the system (Koranteng et al., 2000; Lin et al., 2006)

### **Regional scales**

An example of a regional scale nutrient assessment is the set of research cruises conducted in the Levantine basin in the Mediterranean Sea during March–April 1989, August 1990, October 1991 and April 1995. During each cruise 80 to 95 sites were sampled, except during the last cruise, when samples were taken at only 15 stations. The sampling sites were located on a regular 0.51 (latitude and longitude) grid, which covers almost the entire Southern Levantine. Continuous profiles of temperature and salinity were measured, as well as temperatures, salinity, dissolved oxygen and nutrients (N, P and Si).

An example of a regional nutrient budget is the one derived for the North Sea by Brion *et al.* (2004). This budget takes into account annual nitrogen and phosphorus budgets for the whole North Sea taking into account input and output fluxes for the marine, atmospheric, sediment and continental boundaries, and riverine inputs based on river flows and nutrient concentrations at the river–estuary interface, while taking into account retention in estuaries. The results showed that the North Sea is an extremely complex system subjected to large inter-annual variability of marine water circulation and freshwater land run-off, which is reflected in the inter-annual variation of the nutrient budgets.

In figures 2.2.a and b conceptual models of the Szczecin lagoon and the North Sea are compared. At first sight the regional model looks more complex, but this is because it represents more different organisms. The representation of the biogeochemical cycles is more sophisticated in the local model. For example, this model includes burial, and distinguishes between water and sediment compartments.



**Figure 2.2** Conceptual models for **a)** Szczecin lagoon (Wielgat and Witek, 2004) and **b)** the North Sea (Schrum *et al.*, 2006).

### Global scales

The coastal zone has been researched on a global scale, both with and without spatial explicitness. Examples of global scale approaches without spatial explicitness are assessments of the contribution of the coasts primary production compared to that of the total ocean, the continent, or certain ecosystems. It is estimated for example that the coast accounts for 25% of global biological productivity, and 90% of the global fisheries (Crossland *et al.*, 2005). Other assessments focus for example on the effect of groundwater discharge (SGD) on coastal productivity (Slomp and Van Cappellen, 2004). Two spatially explicit global scale projects are the NEWS system of nutrient models (Seitzinger *et al.*, 2005), and the LOICZ budgets (Gordon *et al.*, 1996).

The NEWS models are a system of coupled, multi-form, multi-element, spatially explicit nutrient models for continental watersheds, with a global coverage. Separate models exist for four of the pools which are also used here: DIN, DIP, PON and POP. The relevance of these terrestrial models for ocean research is that they provide the nutrient inputs from continental discharge into the coast and ocean. Seitzinger *et al.* indicate that segmentation schemes, “*in conjunction with coastal typology efforts ... will greatly enhance future efforts to use NEWS and other global nutrient export models...*”.

The Land-Ocean Interactions in the Coastal Zone (LOICZ) project is the only spatially explicit effort we know of, which focuses on nutrients in the coast on a global scale. In the framework of LOICZ, a network of scientists from all over the world was established, which allowed to bring together over 2000 sites for which budgets were made following a single

guideline (Gordon *et al.*, 1996). Three typology datasets were developed for use in analysis and upscaling of these coastal zone biogeochemical flux assessments. The typologies were obtained through clustering of sites based on relevant terrestrial, marine, coastal, atmospheric, human, geomorphic and river basin variables. The LOICZ typology is therefore of a very different nature, than the one presented in this thesis. The clusters of the LOICZ typology represent nutrient levels rather than a type of nutrient filtering.

The LOICZ budgets include some stoichiometric calculations of aspects of net system metabolism, e.g. net system production and the difference between nitrogen fixation and denitrification. These numbers were not measured however, but deduced from the difference between measured and expected DIN values.

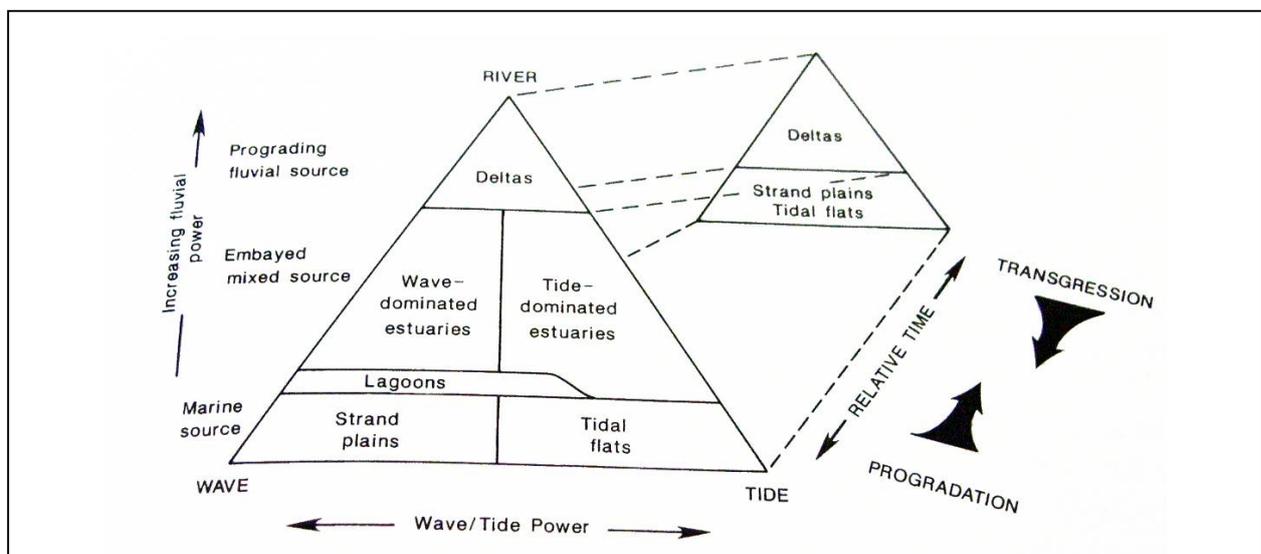
The task accomplished by LOICZ was unprecedented. They achieved bringing together a vast amount of data by relatively uniform methods, so that the resulting budgets can be inter-compared. In addition to that, by coupling and up scaling from these budgets, an insight was given in the geochemical state of the coast, based on observation and interpolation.

### 2.2.3 Typologies

Typology is the study and classification into types (Geerts and Heestermans, 1993). In this research, with a ‘coastal typology’ therefore is meant ‘*the study of coastal ecosystems and features, and their classification into types based on common attributes*’.

Coastal classifications can generally be categorised as being either genetic or descriptive (Dolan *et al.*, 1975). Genetic classifications are based on coast forming processes, while descriptive ones are based on the resultant of these processes, namely landforms. With coastal landforms are meant features such as fjords, lagoons, cliff coasts and deltas. These landforms can be seen as end-members in a spectrum of coastal morphologies.

Coastal morphology is created by an interplay of many different factors and processes. The resulting morphology depends first of all on the initial conditions. The effect of a certain wave energy on a fjord, for example, will be different than the effect of the same energy on a lagoon. Further morphology forming factors which are often used in genetic classifications, are the relative influence of rivers, waves and tides (see figure 2.3). Other factors are the energy of the system (vehemence of waves, currents and winds); the angle with which this energy works on the coast; the sediment input and removal; turbidity; biologic activity; relative sea level changes due to tectonic movements and isostatic adjustments (progradation/transgression due to submergence/ emergence) (Kelleat, 1995). These factors physically alter the coast through morphodynamic processes, such as sedimentation, swamp encroachment, building up of barriers and dunes, undercutting of cliffs, mixing of saline and fresh water etc.



**Figure 2.3** Coastal classification by river, wave and tidal factors (Carter and Woodroffe, 1994).

Coastal evolution, as a transition between different morphologies, depends on the starting-morphology and the prevailing conditions, or factors, which physically alter the coast. Due to feedback-mechanisms these processes are self-forcing. Coastal morphology can be seen as a state of the coast, which is constantly tested for whether it is in equilibrium with the prevailing conditions. If not, the morphodynamic processes will alter it, and move it towards equilibrium. This feed-back mechanism is called self-regulation, and leads to self-organisation of the coast into several morphologies (Carter and Woodroffe, 1994).

Because the coast is a very dynamic place, the conditions and intensity with which processes work constantly change, and because a finite amount of time is required for the coast to reach a new equilibrium after conditions have changed, a smooth transition exists between coastal morphologies which follow each other up; both in space and in time. As a consequence an existing coastal morphology does not necessarily reflect the present state of the morphodynamic processes, but instead can reflect those from the past.

Different typologies have been used in the past with the purpose of discussing or mapping coastal morphology and coastal processes. Text books use classifications to discuss the different processes, landforms or ecosystems in an organised fashion. They usually use a mixture of descriptive and genetic classifications (Davis and Fitzgerald, 2004), but purely genetic approaches exist as well (Kellestet, 1995). A much appreciated typology was developed by Davies (1973), and is often taken as a basis to discuss coastal processes and ecosystems.

Books often contain very rough maps of the global geographic distribution of a coastal type, but they rarely bring the different maps together in a single figure. This is only done, if the purpose is to develop a regional or global map of coastal types or processes. Examples are the maps by Dolan *et al.* (1975) and McGill (1958).

As was explained in the previous paragraph, the coastal ocean has been researched more extensively on the local scale than on the regional or global scale. Due to globalization, an increased world population and higher pressure on natural resources, the trans-boundary nature of watersheds and the coastal ocean has now become more evident. This was triggered by pollution problems, which have grown to such extent, that coastal managers have come to realize that they can only be addressed adequately through international cooperation.

As was also explained in the previous paragraph, working on a larger scale often requires a different approach, because there is often less data coverage. The way to overcome this is to work at a coarser resolution, and by using upscaling techniques. The coastal ocean is

very diverse and constantly changing, but because of its self-organising character, it is particularly suitable to be addressed with typological approaches. Typology could therefore also be used as an up scaling technique in coastal issues. This was for example applied in the fisheries industry, where Large Marine Ecosystems (LME's) have been defined in order to monitor fish populations, and prevent overexploitation (Sherman, 2006). These LME's are now also used in the Global International Waters Assessment (GIWA), a program of the United Nations Environmental Program (UNEP).

The LME's also show how the use of typology has changed with the adoption of GIS. The term 'coastal typology' now not only includes the definition of types, but also the spatial distribution of these types (referred to as the segmentation). The use of typology in this sense is relatively new in coastal research, so that not many coastal segmentation schemes exist yet.

### **Coastal segmentation**

The 'coastal segmentation' by which the coast was assessed until now was usually delimited by political boundaries, and thus had no physical meaning. This issue was addressed when a global coastal segmentation was developed by Meybeck *et al.* (2006), which delineates Coastal segments and identifies their corresponding river Catchments (COSCATs). The COSCATs are based on natural limits (continents, oceans, regional seas, major capes and bays), continental shelf topography (sills, basins, island chains) and geophysical dynamics (climate, ocean currents and tectonics) and are intended as a first step towards a coastal segmentation suitable for coastal research. The COSCATs are relevant for physical purposes, but for geochemical purposes a process-based segmentation is more appropriate. The first step towards the development of such a geochemical typology is therefore set in the present study. The filtering typology, developed here, is not meant as a replacement or modification of the COSCATs, but as an additional typology which can be used for geochemical assessments of the proximal coastal zone, while the COSCATs can be used for more physical purposes. The COSCATs will be used in the present study for example, to represent the spatial transport of water and nutrients from land to the distal coastal ocean (see Ch4). The magnitude of these fluxes will be assessed by relating box-models to the geochemical filtering typology developed in the next chapter (Ch 3).

Relating the filtering capacity of the coast to a typologic assessment was already done in the EUROCAT project (Meybeck *et al.*, 2000), which researched the impact of European river catchments on the ocean. During this project, a typology for Europe was used to discuss the relative filtering capacity of drainage basins and the proximal coastal ocean for nutrients and particulate matter. The typology distinguishes between karstic, fjord, fjärd, ria, delta, macrotidal estuary and 'delta with lagoon' coasts. In the present thesis the segmentation scheme for a similar typology will be established on the global scale, and used as a proxy for a biogeochemically relevant segmentation which finally will be coupled to nutrient box models.

### 3 Part 1: A global coastal typology and segmentation

#### 3.1 Approach

The aim of this chapter is (1) to develop a typology for the nutrient filtering capacity of the proximal coastal ocean, and (2) to document its geographic distribution by defining a corresponding coastal segmentation in a GIS. With the nutrient filtering capacity is meant here the coast her ability to remove N and P from the water column by denitrification or burial. In short, this capacity depends on the residence time of the water and on the intensity of biologic activity in the system (see §2.1.3).

Figure 3.1 shows the workflow for the development of the typology and segmentation. The bracketed letters in the text correspond to those in the figure, and represent steps taken. First an inventory was made of previously used coastal morphology classifications found in literature and on maps. A set of 11 morphological types for the proximal coastal ocean was compiled from this, hereafter referred to as the morphologic typology (a) (see table 3.1). Next, an inventory of the processes which are expected to control the filtering capacity of the coast was made (b). An assessment of the levels in which these driving forces work in the defined morphologic coastal types, allowed to regroup them by filtering strength. This yielded the filtering typology (c), which distinguishes between coasts which act as ‘*no filter*’, an ‘*estuarine*’, ‘*lagoon*’ or ‘*passive filter*’ type (types 0, I, II or III respectively).

Subsequently the coastal segmentation corresponding to the typology had to be established. This was done by using a Geographic Information System (GIS), which allows instant mapping of georeferenced information contained by a database. The term ‘georeferenced’ indicates that the information is coupled to known geographic coordinates. The GIS exists of a representation of the world as a grid at  $0.5^\circ \times 0.5^\circ$  resolution (i.e. 30 minutes, or 50 x 50 km at the equator). For each coastal cell (>6000) the filtering typology it belonged to had to be determined. This was obtained by aggregation of a morphologic segmentation (d), in accordance with the previously defined filtering typology (c), yielding the new *filtering segmentation* (e).

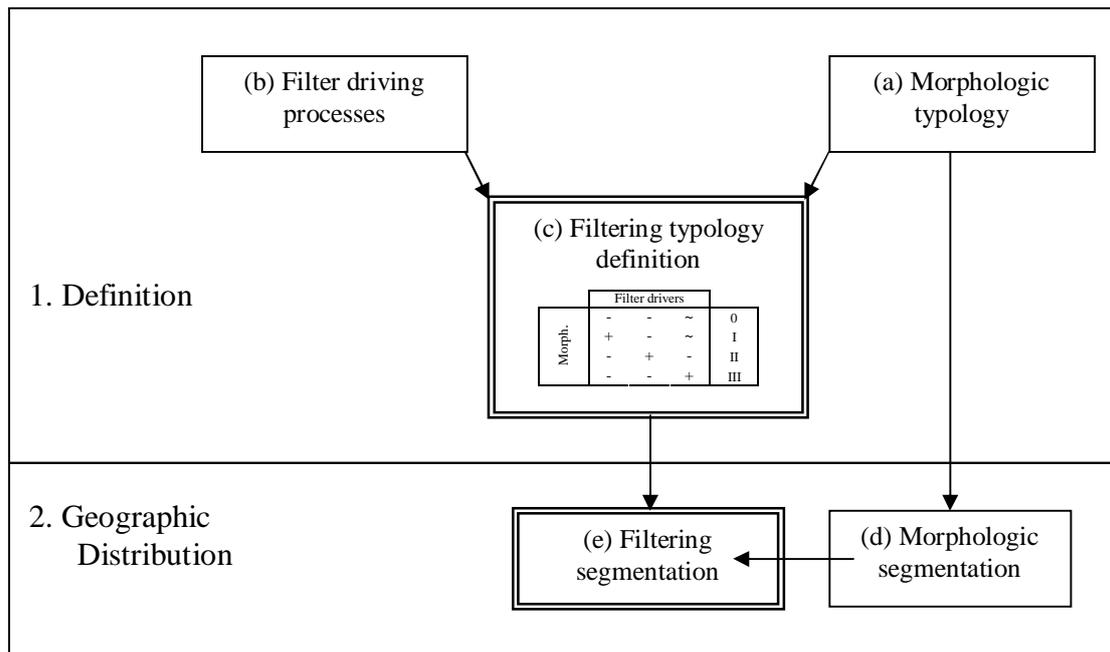


Figure 3.1 Work flow for typology definition

### 3.1.1 Typology definition

#### Morphologic typology

The morphologic typology developed here, was based on a typology presented in the EUROCAT project (see §2.2.3; Meybeck *et al.* 2000). This typology differentiates between karst, ria, fjord, fjärd, glaciated sedimentary coasts, deltas, big rivers and deltas with lagoons (see table 3.1 for definitions). It was chosen to take this typology as a starting point, because the aim of the present study partially coincides with the aim of the EUROCAT project. There, the typology was used to assess the filtering capacity of both the terrestrial and estuarine parts of European watersheds for nutrients and particulate matter. Here, it will be used to assess the filtering capacity of the proximal coastal ocean, as in the EUROCAT project, but this time for the whole world. In addition to that, the morphologic typology has the potential to be used in other geochemical applications, a.o. as a tool for upscaling.

Because the typology is to be applied here to the whole world, the typology is expanded with non-European morphologies, such as mangrove. Expansion is done simultaneously with the development of the segmentation scheme, to ensure that a minimum of types is defined.

**Table 3.1** Morphologic typology for the proximal coastal ocean.

Type	definition
Estuary	A semi-enclosed coastal body of water which has a free connection with the open sea and where fresh water, derived from land drainage, is mixed with sea water
Delta	An outward building river mouth due to sediment deposition; included here in the estuarine morphology
Lagoon	A coastal water bodies, separated from the ocean by a barrier
Ria	A drowned river valley, not glacierised during the last ice age
Fjord	A steep walled inlet of the sea, created by glacial gauging during the last ice age
Fjärd	Similar to fjords, but wider and less steep. Characterised by islands, as near Stockholm
Glacierised sedimentary coasts	A sedimentary coast which was glacierised during the last ice age
Mangroves	Tropical trees or forests in brackish water
Macrotidal estuaries	Estuaries with a tidal range > 4m. (officially >5m)
Big rivers	Rivers of which the load bypasses the coastal zone, so that nutrients are directly deposited on the shelf, often in RiOMar environments (river dominated ocean margins)
Karsts	Karst forms by dissolution of lime-stone, can be ancient, characterised by sinkholes and limited surface runoff
Arheic	Region where surface runoff is <3 mm/y

Two tropical types were considered, namely mangrove and coral reefs. Coral reefs were discarded, because they are rather a feature of the distal coastal ocean than of the proximal coastal ocean. Mangrove was kept as a type, because it has a widespread distribution in the tropics, and has a very distinct biologic cycle compared to other types of coast. Mangrove ecosystems are very different form other coastal types, because they have a large above-water, woody biomass which directly influences the water quality (Alongi, 1998).

Initially a ‘beach/cliff’ morphology was considered as well, because many coasts exist of a stretch of cliffs, rocks or beach. These straight coasts are completely open to the ocean and are therefore dominated by it. Because of that, coastal stretches are expected not to have a coastal filter. It was felt that they should be considered explicitly however, because many coasts are of this type. Later this type was deprecated and a general estuarine type was defined, which stands for all coasts which are not part of any of the other morphologic types. The morphology ‘estuary’ therefore includes delta, beach, cliff and rocky coasts, as well as estuaries which are not rias or macrotidal and not colonized by mangrove.

The morphologic typology used here then exists of ‘plain estuaries’, rias, macrotidal estuaries, mangrove, lagoons, fjords, fjärds, glaciated sedimentary coasts, big rivers, karst and

arheic coasts. They are listed in table 3.1 with a definition. For completeness deltas are also defined in this table, although they are not a separate morphologic type in this typology.

### **Filtering typology**

After having reviewed which factors determine the filtering capacity of the coast, the following factors are considered as the most important: relative influence of river and ocean; depth; closed or openness to the ocean, residence time, stratification and biologic activity.

Comparison of the strength and variability of these processes in each of the defined morphologies yields a division in 4 groups (see Table 3.2): the typology for filtering capacity. Generalisation of the filter determining factors to only residence time and biologic activity allows the most simplified characterisation of each of the types in the filter typology, and shows their main differences (see table. 3.3).

The filtering capacity of each of the morphological types will be discussed in detail later this chapter. In this paragraph only the philosophy of their distribution over the filtering typology is presented. A somewhat deeper discussion of the morphologies which act as *no filter* (type 0) is appropriate here, because larger internal differences exist between the morphologies of this type, compared to those of the other types.

### **Types I and II**

Two of the types in the filtering typology represent coasts which are dominated by a single coastal feature like an *estuary* (type I) or *lagoon* (type II). The basins formed by these morphologies protect their inner waters from the open ocean. These obstacles reduce water flow and thus prolong the water residence time, and allow the development of a more heterogeneous distribution of ecologic niches. This and the often relatively shallow depth of lagoons and in some parts of estuaries, allows the photic zone to extend to the sediment, enhancing biodiversity and biologic productivity there. The high biologic activity increases burial and denitrification. Thus, estuarine and lagoon type coasts act as a filter for nutrients which are transported along the land-ocean continuum.

**Table 3.2** Correlation between the morphologic typology and some filter defining factors. Based on this, the morphologic typology can be aggregated to a filtering typology.

Coastal type	River influence <sup>a</sup>	Tidal influence	Depth	enclosed	Residence time	Stratification	Biol. Act.	RFC <sup>b</sup>	Proximal filter Type
Big rivers <sup>c</sup>	++	~	-	--	--	~	~	-	0
Karst + Field delta	+	-	~	-	-	-	~	-	0
Arheic	-	~	~	~	-	~	-	--	0
Ria	~	+	-	-	-	-	~	~	I
Macrotidal estuary	~	++	-	-	+	-	+	+	I
mangrove	~	+	-	-	~	-	+	+	I
estuaries	~	+	-	-	~	-	+	+	I
(Delta	~	~	-	-	~	+	+	~	I)
Lagoon	+	-	-	++	+	~	++	+	II
Delta with lagoons	+	-	-	+	~	~	++	+	II
Glacierized sed. coast	?	-	-	~	~	~	-	~	III
Fjord	-	+	++	+	++	++	-	~	III
Fjaerd	~	-	-	+	+	+	~	++	III

a) if present

b) relative filter capacity

c) if connected to RiOMar environments (River dominated Ocean Margins)

**Table 3.3** Filtering typology for the proximal coastal ocean.

Type	Name	Biologic activity	Residence time	Coastal morphologies
0	No filter	Occurs	Very short	arheic and karst regions, rocky coasts, beaches and big rivers which are associated with RiOMar environments
I	Estuarine filter	Occurs	Short to medium	classical estuarine types such as macrotidal estuaries and rias. Further deltas, mangrove, beach and rocky coasts.
II	Lagoon filter	High	Long	Lagoons and features which behave as such, like deltas with lagoons
III	Passive filter	Low	Variable: short to very long	Fjords, Fjårds and glaciated sedimentary coasts

Estuarine types of coast include macrotidal estuaries, rias, mangrove and deltas. These coasts are often more open to the ocean than lagoon-type coasts and thus overall act as a weaker filter. Lagoon coasts often form in deltas, as their emergence depends on a sediment supply to form barriers. A large difference between lagoons and estuaries is that estuaries only have a water and nutrient input flux from the continent, while lagoons often exchange water with the open ocean. As a result a significant part of the nutrient supply to lagoons may

originate in the distal coastal ocean. This is especially true for lagoons in arid climates like Ghar el Melh (Added, 2001).

### **Type III**

The third coastal type (III) is characterised by very low biologic activity due to the colder temperatures prevailing at higher latitudes. Because of the low biologic activity, one would expect that in these systems, a large part of the nutrient load is transported to the open ocean. In fact however, many of these coasts are part of Fjord and fjärd water basins, which have relatively large volumes and sometimes stagnant water. Especially fjords can develop stratification (Gregory, 1913). Because of the combination of long residence times, and a low through flow, some of type III coasts may act as a considerable nutrient filter. The processes active in this type of coast may be different however than the processes active in coasts of types I and II. Because the biologic activity is low, more nutrient removal can be expected to be due to particle formation in the water column (coagulation) and subsequent burial (Meybeck *et al.*, 2000). These coasts could be described as a '*passive filter*', to reflect that filtering takes place as a result of passive physical processes as opposed to biologic processes which actively incorporate nutrients in their tissue, or release them during organic matter degradation.

### **Type 0**

There may be different reasons why a coast barely has a filtering function. First there may be a very restricted water flow, and thus a low nutrient input. This is the case for arctic regions. Second there may be no estuarine-like coastal feature in which the water stays for a time. This is the case for karst coasts.

In karst environments there is limited surface runoff, because leaching of the limestone bedrock results in the development of a network of interconnected tunnels. Surface runoff quickly disappears into these tunnels and flows directly into the ocean. Karst is therefore considered as not having a proximal coastal zone, and no proximal coastal filter capacity.

Finally, the type 0 comprises coasts through which a 'big river' flows. Big rivers usually have a very large drainage basin, and consequently have a relatively high discharge and a large particulate load. Some of these big rivers are recently being referred to as 'RiOMar', which stands for a River dominated Ocean Margin. In coastal research, big rivers have often been considered with special interest. If a continental input of nutrients or

particulate load to coast or ocean was considered, this was often based on a number of the largest rivers in the world. Continental inputs through the rest of the coast were usually neglected and no filter effect was taken into account. This approach was justified until recently, because it used to be difficult to obtain data on discharge and water composition for most discharge basins, while for big rivers it was easy to measure and readily available. With the development of internet and GIS. Local and regional environmental organisations increasingly make their observational data available through databases accessible via the internet. Despite that, there are still many parts of the world where not many of such organisations exist, notably in South-America, Africa and some parts of Asia.

The assumption that big rivers are the largest contributors to the discharge, nutrient and particular load of the coast and open ocean, is not necessarily incorrect. However, it is probably an oversimplification for regions where no big rivers occur. The importance of big rivers in oceanic biogeochemistry is illustrated by the fact that the world's 25 largest rivers in terms of sediment and water discharge, account for approximately 40% of the fluvial sediments and 50% of the freshwater entering the ocean. However, it is estimated that only 5% of the river sediments delivered to the proximal and distal coastal ocean eventually reach the deep sea (McKee, 2003). Because of the importance of the big rivers in the biogeochemistry of ocean margins, special attention is given to these systems in our results.

In the present study it is assumed that large rivers have such a high discharge that they bypass the proximal coastal zone, and that they deliver their load directly to the continental shelf and shelf slope, i.o.w. the distal coastal ocean. There, and in regional seas, the river load is filtered so that only part of the original load will eventually reach the open ocean. Not all rivers with a high discharge are associated with a RiOMar. A river basin might consist of a successive set of filters, considerably reducing even large material loads before reaching the coastal zone (Meybeck and Vorosmarty, 2005). Some rivers for example have dams in their course, where virtually all nutrients and particulates are retained. The distinction between big rivers which are not connected to a RiOMar, and rivers which are, can be made by taking into account discharge, sediment load, the extent of the river plume on the coastal shelf and the occurrence of obstacles in front of the river mouth, which shelter the water flow from the open ocean.

### **3.1.2 Segmentation definition**

With the filtering typology defined, the geographical distribution of its constituent types can be assessed. In parallel with the method applied while defining the filtering typology, the segmentation scheme is obtained by first developing a morphologic segmentation which is aggregated to a filtering segmentation.

To do this, a means is needed to collect and visualise georeferenced information, as well as to establish relationships between, and identify trends in the information. This means is provided by the use of a Geographic Information System (GIS). A GIS exists of a map with areas, lines or points, each of which has a record in a database. Information can be assigned to each of these elements via the database and can be typologic or quantitative in nature. The information can subsequently be displayed in the GIS as different layers. From the relationships between elements of different layers (topology), new layers can be created. The morphologic and filtering typology are thus established by looking at relations, such as overlap, nearest neighbour, intersection, line length, and other topologic relationships between layers representing various data sources. §3.3.1 explains which elements the GIS contains, while §3.3.2 gives an overview of the main sources used to identify the spatial distribution of the separate morphologic coastal types. The morphologic types are discussed one by one, in §3.3.3.

The GIS developed here has two functions. First it is a tool with which the coastal segmentations for morphology and filtering capacity are developed. Second it is a tool with which the spatial transport path of nutrients over the earth surface can be represented.

The first function is fulfilled by allowing the organisation and aggregation of information to a new coastal segmentation. The second function is fulfilled by the connections between the different elements of the GIS. The network of connected segments represents a potential transport path of water and nutrients over the earth surface, and is relevant for spatially explicit modelling as is done by the G-NUX group and for which an example model is given in the second part of this thesis.

#### **The GIS**

The GIS used here is based on a representation of the world as a grid at a  $0.5^\circ \times 0.5^\circ$  resolution. Information can be assigned to the individual cells in the grid.

Each cell is part of one out of four modules: the continent, coast, regional seas or ocean. The continental module represents all terrestrial surface and groundwater. The coastal module represents the distal coastal zone as described in the introduction chapter. The

proximal coastal zone is not displayed in the GIS, because it is too thin. The last continental cell is used as a placeholder for information about the proximal coastal ocean. These cells will therefore be referred to as 'coastal cells'. Their ocean-side boundary represents the coastline and the proximal coastal zone.

The remaining cells are either part of regional seas like the Gulf of Mexico and the Baltic sea, or they are part of the open ocean. The distinction between the regional seas and open ocean is made because it is part of the filtering/transport philosophy which the G-NUX group uses to model nutrient transport over the earth's surface.

### **Drainage basins**

All terrestrial cells in the GIS are part of a drainage basin (DB). 14% of the continental surface is endorheic (Vörösmarty *et al.*, 2000), which means that they are part of drainage basins which do not ultimately drain their water to the ocean, but to a continental cell, which is surrounded by other continental cells. All other drainage basins are connected to the ocean by a coastal cell. The drainage basin segmentation as used here was developed by Vörösmarty *et al.* (2000a, b), who obtained it from a Simulated Topological Network for potential river flow pathways (STN-30p), which is also used in this GIS.

### **COSCAT**

The COSCAT segmentation as developed by Meybeck *et al.* (2006) forms another basic layer of the GIS. It delineates Coastal segments and identifies their corresponding river Catchments. What this segmentation effectively does, is grouping together several drainage basins, of which the waters all potentially flow into one coastal segment. As was explained in the literature review, the COSCATs are relevant for physical purposes, but are less appropriate for geochemical purposes. The COSCATs are therefore regarded here as useful to identify which coastal cells will contribute their water to a segment of the distal coastal ocean (distal box), but they are inappropriate as a filtering segmentation. For the proximal coastal ocean a new coastal segmentation appropriate to represent different filtering capacities of the coast is therefore developed here, and will function much like the COSCATs. The filtering segmentation can be regarded as nested in the COSCATs, while the drainage basins again are nested in the filtering segments.

**Table 3.4** Segments in the G-NUX GIS

	<b>Description</b>	<b>Module</b>	
<b>Cell</b>	Continental cells in the GIS grid at 0.5 x 0.5° resolution	Continent	
<b>Proximal segment</b>	Delimits a proximal coastal zone.	Coast	
<b>Distal segment</b>	Delimits a distal coastal zone	Coast	
<b>Regional sea</b>	Delimits a regional sea	Regional sea	
		<b>Exists of</b>	<b>Input for</b>
<b>Drainage basin</b>	Ensemble of cells which are all part of one potential river flow network (Vorosmarty <i>et al.</i> 2000)	Continental cells	A proximal coastal segment
<b>RiOMar drainage basin</b>	Drainage basin belonging to a 'big river' whos output dominates the coastal margin and bypasses the proximal coastal zone.	Continental cells	A distal coastal segment
<b>Coastal segment</b>	Catchment area of a proximal segment of the coast	Drainage basins	A proximal coastal segment
<b>COSCAT</b>	Catchment area of a distal segment of the coast (Meybeck <i>et al.</i> , 2006)	Drainage basins and proximal segments	A distal coastal segment or ocean segment

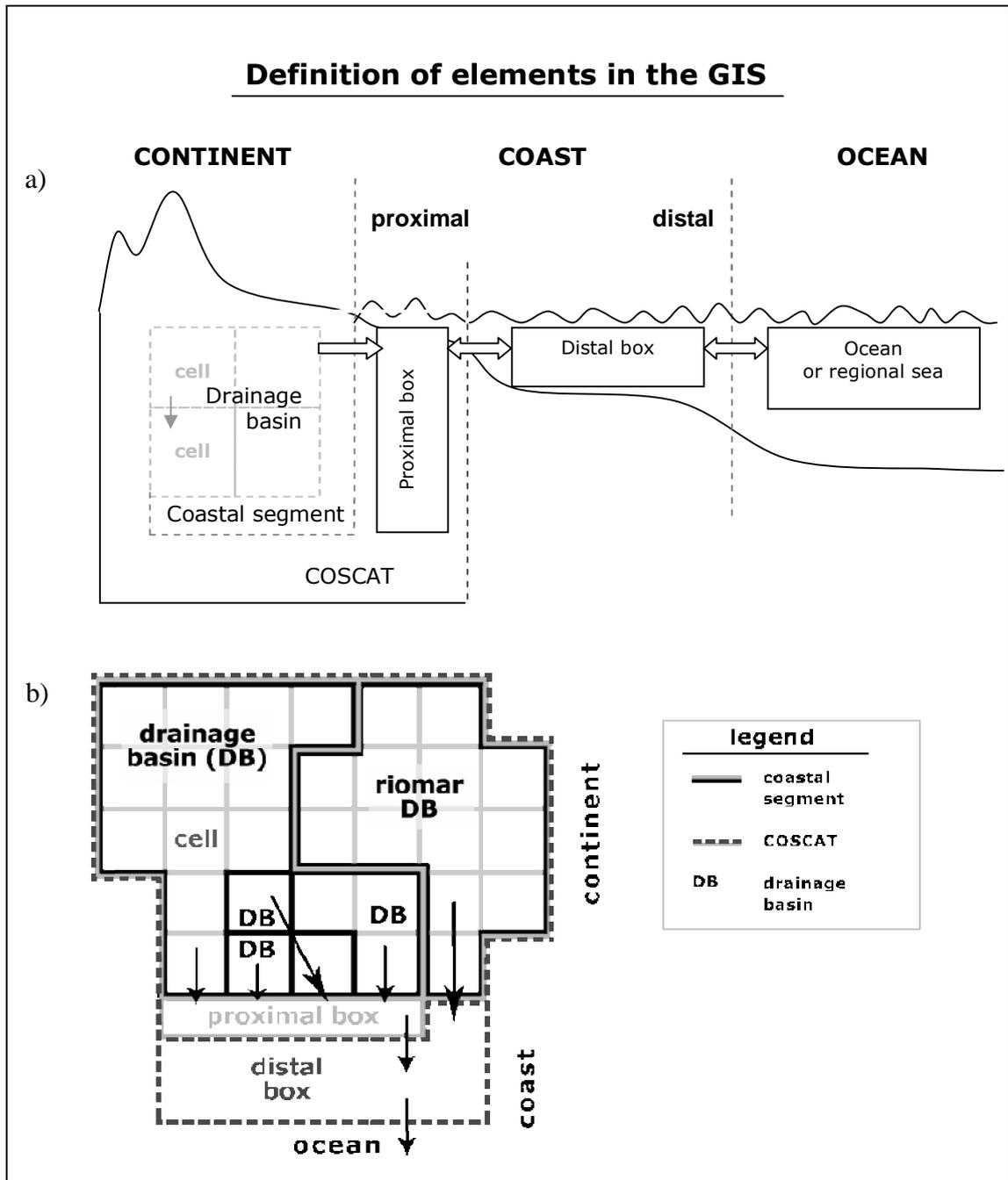
## Transport

Using the terminology introduced in the previous paragraphs, the transport of water, nutrients and particulates in the GIS can now be described as follows:

The net transport of water and nutrients is from the continent, via the coast to the ocean (see figure 3.2). On the continent the transport of water is from cell to cell. The river discharge Network by which this flow is represented, delimits drainage basins. Several drainage basins are part of one coastal segment, which means they all discharge into one proximal box of the coastal ocean. In this proximal box filtering takes place, according to the filtering typology the box belongs to. The magnitude of this filtering is the focus of attention of the G-NUX research group, and will be established with process-based nutrient box-models, one of which is presented in Ch 4 of this thesis, namely for the lagoon type (II).

Several coastal segments are nested in one COSCAT. This means that several proximal boxes of different filtering type are all connected to one distal box with which they may exchange water. In the distal boxes more filtering takes place and several distal boxes are again connected to either a regional sea, or the open ocean.

Drainage basins belonging to type 0, like RiOMar DB, are a special case, because these drainage basins do not have a proximal box. Instead they are connected directly to a distal box.



**figure 3.2** Definition of elements in the GIS. Transport of water takes place between *cells*. All the cells which drain into a proximal segment through a single coastal cell are part of a single *drainage basin*. All drainage basins which empty in the same proximal segment are part of the same *coastal segment*, and the ensemble of drainage basins and proximal segments which exchange water with a distal segment are part of a *COSCAT*. a) cross-section of the land-ocean interface, b) plan view.

### 3.1.3 Accuracy, precision, problems and statistics

The geographic distribution of each of the morphological coastal types is assessed based on different sources of information which are added to the GIS database. Table 3.5 shows the source material used. Because most of the sources are only useful for determining a single morphology or filtering type, they will be discussed per type in the next paragraph. The present paragraph will be limited to some general remarks.

**Table 3.5** Listing of the source material for geographic identification of the morphologic typology.

	Coastal type	Tides <sup>a</sup>	River discharge <sup>b</sup>	Satellite images <sup>c</sup>	lithology <sup>d</sup>	Max. ice extent <sup>f</sup>	Emerging/ submerging <sup>e</sup>	Slope <sup>g</sup>	Rock/ sediment <sup>h</sup>	Coastline smoothness <sup>i</sup>	Maps	
II	Delta with lagoons	.	.	X	.	.	.	.	.	X	(Davis and Fitzgerald, 2004)	-
II	Lagoon	.	.	X	.	.	.	.	.	X		
III	Fjord	.	.	X	.	X	Emerging	High	Rocky	X		
III	Fjärd	.	.	.	.	X	Emerging	Med.	Rocky	X		
III	Sedimentary coast glac.	.	.	.	.	X	Emerging	Low	Sed	.	(Gregory, 1913)	-
I	Ria	.	.	.	.	.	Submerging	.	.	.		
I	Mangrove	.	.	.	.	.	.	.	.	.	(WCMC, 1997)	+
I	Macrotidal estuary	X	.	.	.	.	.	.	.	.	(Kelletat, 1995)	-
0	Big River	.	X	X	.	.	.	.	.	.	(McKee, 2003) (Ericson <i>et al.</i> , 2006) (Davis and Fitzgerald, 2004)	+
0	Karst + field delta	.	.	.	X	.	.	.	.	.	(Dürr <i>et al.</i> , 2005) (Herak and Stringfield, 1972) (Sweeting, 1972)	+
0	Arheic	.	.	.	.	.	.	.	.	.	arheic in the COSCATS (Fekete <i>et al.</i> , 2002)	+

	Reference	Remarks	Integrity
a.	LOICZ database	Tidal range field	+
b.	GTN-R database	Rivers selected with discharge > Rhône discharge	+
c.	Sea Wiffs, Google Earth	Visual identification in Google Earth and images of Sea Wiffs, features must be clearly visible from a height of 40 miles	-
d.	(Dürr <i>et al.</i> , 2005)	Carbonate lithologies	+
e.	(Kelletat, 1995)	map of emergence/ submergence	-
f.	(Dürr <i>et al.</i> , 2005)	ice extent during las glacial maximum	+
g.	(GEBCO, 2007)	Slope was calculated from bathymetry	-
h.	(Kelletat, 1995)	Rocky coast map; rest is consequently sedimentary	-
i.	Google Earth		+

### **Accuracy**

Each of the used maps and databases has a different accuracy and precision, related to the scale of the map as hardcopy, or the resolution of the digital data. Accuracy and precision of the source material can be reduced during the process of transferring the information from a paper map into the GIS, for example when the map is in a different projection than the GIS used here, and georeferencing does not give a 100% fit. To give an indication of the integrity of the material, a qualitative measure was added to table 3.5 (the + and – signs).

The material which has the integrity ‘ – ’ generally consists of very coarse-scale maps from books, which were digitized using a photo camera, after which the image is georeferenced in the GIS. When a sufficiently good fit is obtained, the information is transferred to the drainage basins.

### **Problems**

Because the coastal types were determined separately it is possible for one basin to fall within several morphological types. A basin may for example be a big river, a delta and a lagoon at the same time; or karst with lagoons; or mangrove with lagoons etc. This was resolved by defining an order of priority for the types (see table 3.6). The priority was based on the integrity of source material, and the certainty that a type occurred at that location. Because the integrity of the source material is not the same for the entire world, the decision was made per basin in some cases.

The available maps do not cover all of the basins in the GIS, so that for some coasts the morphology has to be determined in a different way. This is the case for some islands around Indonesia, and in the Pacific, as well as some drainage basins in Asia, Russia and South America. Additional literature on local studies and aerial photographs can help to overcome this ( i.e. SeaWifs, Google Earth).

A third problem is formed by coasts which seem to be of one filtering type based on morphology, but based on the local conditions can be expected to belong to a different type. In this case, more weight was given to the filtering driving forces than to the morphology, as morphology is only a proxy for the filtering capacity. These basins were therefore adjusted manually and on a per basin basis.

**Table 3.6:** order in which the types were identified geographically, based on the certainty of their distribution.

			certainty
1.	Type 0	RiOMar	+++
2.	Type 2	Lagoon	+++
3.	Type 0	Karst	+-
4.		Arheic	++
5.	Type 3	Fjord	++
6.		Fjard	--
7.		Glac. Sed.	--
8.	Type 1	Macrotidal	+
9.		Ria	-
10.		Mangrove	++
11.		Estuary	Rest

### Statistics

After having assigned all basins in the GIS a single filtering and morphological type, they are aggregated so that neighbouring basins of the same type become part of one zone. Thus, the filtering and morphological segmentation scheme arise. Some geographic statistics were determined for the segmentation schemes, notably the coastline length, drainage basin area belonging to each type, and the runoff received by each type.

**The number of basins** in the database which belong to one type was counted, and will be used here as an approximation for coastline length. Not all basins are actually part of the coastline, so that the absolute coastline length is slightly overestimated. Further, because of the projection used here, cells at the equator do not represent the same area as cells at the pole. As a result the cells at higher latitudes are overestimated. This effect is especially seen in type III and type I, because many arctic coasts fall in these types.

**The continental area** draining through each of the types was approximated by counting the cells which belong to each of the types. This again gives the problem related to the cell size which is different at the equator than at higher latitudes. Secondly Antarctica is not represented in the maps used here, so that a slight discrepancy exists when comparing with other sources. Our approximation of area gives a slight overestimation.

**The runoff** each of the types receive annually was determined with data from the Composite Runoff Fields V 1.0 (Fekete *et al.*, 2000). The simulated runoff of the Water Balance Model (WBM) was used here, which is based on the STN-30p network and has been compared by Fekete *et al.* (2000) with data from gauging stations. The sum, mean, minimum and maximum runoff were calculated with the zonal statistics function of ARCMAP, using the filtering and morphologic segmentations as zone delimiters.

In the following paragraphs the different filtering and morphological types are discussed more closely. For each a definition is given, as well as a more detailed description of how its geographic distribution was obtained, and the problems arising during the process.

### 3.1.4 Definitions and method per filtering type and morphology

#### **Type I: estuarine filters**

An **estuary** is defined by the oxford dictionary of earth sciences (Allaby and Allaby, 1990) as "*a semi-enclosed coastal body of water which has a free connection with the open sea and where fresh water, derived from land drainage, is mixed with sea water*".

Estuaries normally form as the result of the post- glacial rise in sea level which drowned many valleys (Allaby and Allaby, 1990).

In areas of high relief the estuary is called a '**ria**'. Classic examples of ria coasts are found in Brittany, Cornwall and Galicia. They were qualified by Meybeck *et al.* (2000) as having a medium filtering capacity, mostly due to tidal wetlands and deposition of particulates. The geographic distribution of rias can be found on the map by Gregory (1913) and by taking into account that rias form along coasts which are submerging.

Estuaries are often subject to tidal action. If the tidal range exceeds 5 meter, one speaks of a **macrotidal estuary**. Meybeck *et al.* (2000) concluded that the macrotidal estuaries of western Europe have a high filtering capacity, particularly at low and medium river flow velocities. Their geographic distribution was derived from the tidal information as available in the LOICZ database. In this database a classification is made, discriminating between the ranges 0-2, 2-4 and >4 m. As a consequence the macrotidal estuaries identified here do not only represent estuaries where the tidal range is larger than 5 m, as in its official definition, but also includes estuaries which have a tidal range of 4 to 5 meter. It was chosen to use the LOICZ database, because it has a global coverage and is at the same resolution as the GIS used here. Other data is available, but often at a much finer resolution, and not with a world coverage.

**Deltas** form due to sedimentation processes at river mouths in subsiding areas. When the river enters an open body of water, the velocity of the current is reduced and rapid deposition of sediment takes place. The shape and nature of the delta is controlled by a variety

of factors including climate, water discharge, sediment load, rate of subsidence of the area, and the nature of the river-mouth processes, particularly tidal and wave energy.

A classic typologic classification of deltas distinguishes between river-dominated, wave-dominated and tide-dominated deltas. River dominated deltas take the form of a bird-foot. Examples are the Mississippi and Po. Wave-dominated deltas usually have one main channel through which most of the runoff takes place. Examples of wave-dominated deltas are the Rhône and Nile. Finally the Ganges and Mekong are tide-dominated deltas. Because ebb and flood tides tend to flow through different channels, tide-dominated deltas are characterised by a braiding network of streams, and many islands.

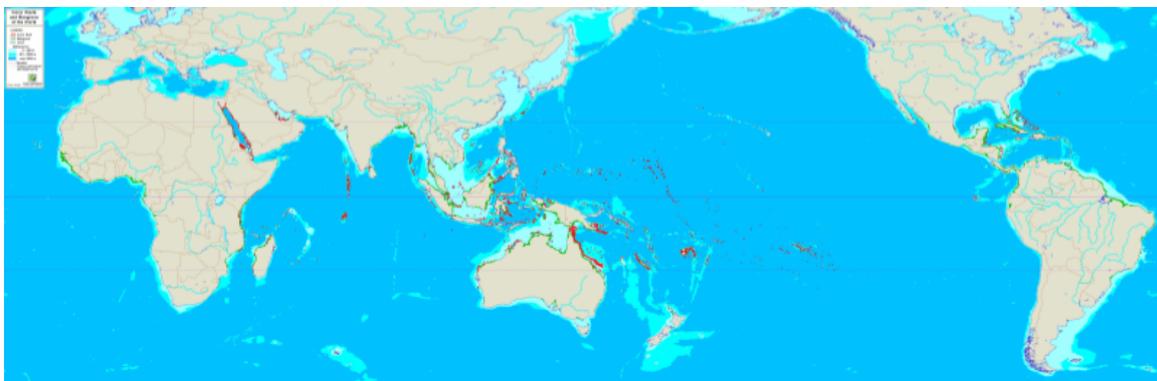
Meybeck *et al.* (2000) found that deltas generated by high runoff and high erosion rivers are very limited filters. i.e. the filtering capacity is mostly effective during low flows and is very reduced at high flows.

The geographic distribution of deltas was first assessed using available literature (Davis and Fitzgerald, 2004; Ericson *et al.*, 2006). But most of these deltas later turned out to be large rivers associated to RiOMars. No information of coasts characterised by smaller deltas was found, so that in the end the delta typology was deprecated, and the delta coasts are now included in the estuarine morphology.

### **Mangrove**

The mangrove type correctly speaking does not represent a coastal morphology, but a coastal ecosystem type. Mangrove forests consist of salt-tolerant woody vegetation, which may vary in size from bushes to trees, depending on the climate they grow in.

The geographic distribution of mangrove was based on a map by the World Conservation Monitoring Centre (WCMC, 1997), see figure 3.3.



**Figure 3.3** Distribution of mangrove and coral in the coast and ocean (WCMC, 1997).

Mangrove forests attain peak biomass near the equator, with a decline towards temperate latitudes where the mangrove is replaced by seagrass species. Seagrass becomes the dominating coastal plant from roughly 28° latitude, although the two species may co-exist until 38° latitude.

The mangrove habitat is a brackish-water environment, with low wave energy and where soft sediments accrete because of the quiet waters. Mangrove forests are important for economic and ecological reasons: They are the source of edible finfish and shellfish, and also provide shelter, wood, fuel and other natural products. Although low in biodiversity, mangrove forests are believed to be highly productive. This is a generalisation, which does not hold for the arid tropics, and for mangrove forests, which reside in more temperate climates.

### Type II: lagoon filter

Coastal lagoons are water bodies, which are separated from the open ocean by a barrier. Water exchange with the open ocean is possible through inlets. Sometimes this is only possible during part of the year due to the seasonally changing water levels and the coastal processes opening and closing the inlets. Lagoons are often less than 5 meters deep, very elongated but narrow, and often lay parallel to the coast (for example Ebrie lagoon in Western Africa, is over 120 km long while less than 20 km wide (see figure 3.4).

Many coastal lagoons seem to fit the definition of an estuary given earlier: they are semi-enclosed coastal bodies of water. However, their connection to the open sea is often restricted, as will be shown in the next paragraph. Further, lagoons do not always have a fresh water input derived from land drainage. Some lagoons form because along-shore currents deposit sediments in front of a bay, eventually sealing it off from the sea. Whereas an estuary requires a fluvial feature to be present, lagoons do not.

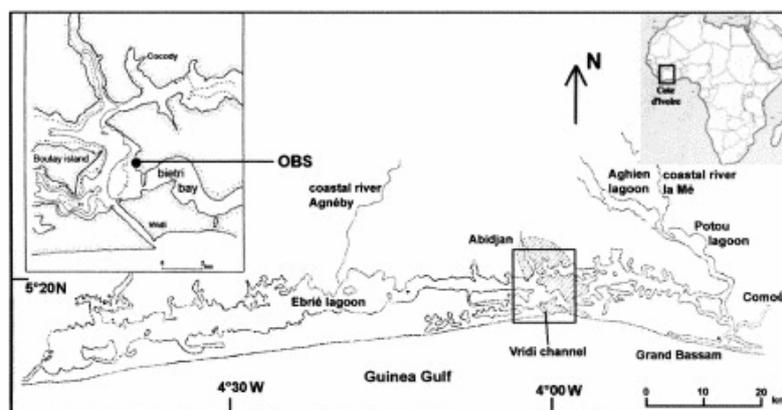


Figure 3.4 Location of the choked Ebrie Lagoon in Ivory Coast (Brenon *et al.*, 2004).

### **Choked, restricted and leaky lagoons**

Lagoons can be classified as choked, restricted or leaky, reflecting their openness to the sea. Choked lagoons may lay a bit more inland than the other two types, and are connected to the ocean by channels. This type of lagoon experiences the least influence from the open ocean, because only limited amounts of sea water achieve at entering the lagoon (except possibly in tropical settings where lagoons may have a negative water budget). As a consequence the residence time of the continent-derived water is longest in these types of coast, because it is restricted from leaving the lagoon. This combination allows a high nutrient availability and promotes biologic activity and allows a high coastal filter capacity (Kjerfve, 1994). Ebrie is an example of a choked lagoon.

Restricted lagoons exchange more water with the sea than choked lagoons, because they lay closer to the sea, only divided from it by a dune barrier. Permanent inlets may exist in the barrier, or they may only be open part of the year. The location of the inlets may constantly change due to the coastal processes. New inlets can form due to storm waves breaching the barrier, and sedimentation can seal existing inlets. Due to more turbulent waters and shorter resident times, these types of lagoon can be expected to be slightly less good filters than choked lagoons, but still stronger filters than leaky lagoons.

Leaky lagoons have many and broad inlets, so that they are relatively open to the ocean. Leaky lagoons are characterised by barrier islands, as the Wadden Islands in the Netherlands, which protect the Wadden Sea from the open North Sea. As they are very open to the ocean, the water residence time is shorter, and biologic processes are of an ocean type. However, because of shallow depths in most of the lagoon, the photic zone may extend to the sediment and the waters may be relatively quiet compared to the open ocean. This allows high biologic activity. Leaky lagoons are therefore still regarded here as a proximal coastal filter.

### **Deltas with lagoons**

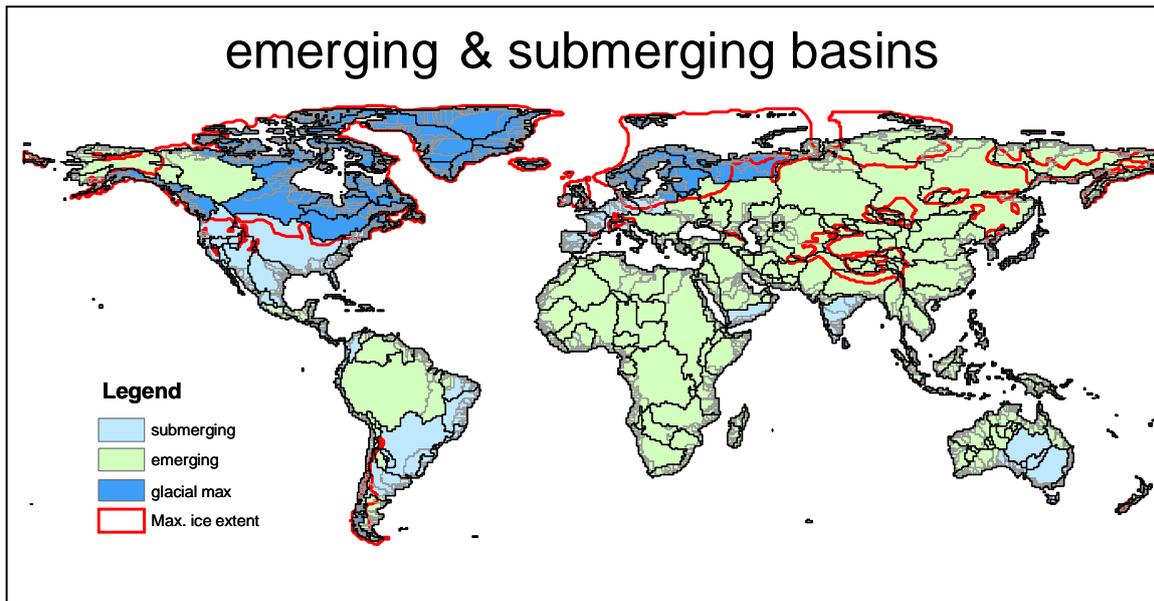
Lagoons often form in deltas, because these systems have enough sediment supply to form barriers which can seal off bays. These lagoons however often form on the sides of the delta and not in the main channel's path. Because of that, deltas with lagoons are not automatically regarded here as 'lagoon' coasts (type II), but are assessed one by one to see whether the lagoon is likely to play a dominating role in the coastal processes. Most of the deltas with lagoons assessed here turned out to be big rivers associated with RiOMars.

The global geographic distribution of lagoons was first determined by using maps depicting lagoon and barrier coasts (Davis and Fitzgerald, 2004). Later the selected basins were validated by visually scanning all the earth's coasts in Google Earth and on aerial photographs of SeaWiFS (NASA, 2006). The criterion was used that a lagoon was only noted when easily visible from a height larger than 40 miles. This criterion still brought some questionable sites, as some lagoons are extremely narrow, but extend over a very large stretch of coast, e.g. the 500km of lagoon coast along the South-Eastern shores of Madagascar

In lowland area as in the Baltic, Black Sea and parts of the Mediterranean basin, deltas and associated enclosed or semi enclosed lagoons are more efficient filters depending on their connexion with the open coast, their possibility of being flooded, the flooding occurrence and other factors.

### **Type III: passive filter**

During the ice ages, glaciers covered large parts of Europe and North America, and small parts of New Zealand and South America. Further some continental ice sheets occurred in the Alps and Tibet. Moraine, erratic blocks and other glacial features are the remaining evidence of the extent of the ice sheets, allowing us to now reconstruct the maximum ice extent during the last glacial maximum (Dürr *et al.*, 2005) (see figure 3.5). The rapid melt of the ice has left many of these previously glaciated terrains away of isostatic equilibrium. The removal of the extra weight of the ice brought these terrains in an emerging movement. The scouring glaciers of the ice age, and the rapidly incising rivers because of the emergence of the continents, have resulted in some very specific coastal forms. All the coasts which fall inside the maximum ice extent are considered here as type III coasts. A distinction is further made between fjords, fjärds and glaciated sedimentary coasts based on slope and coastline smoothness.



**Figure 3.5** Emerging and submerging basins, as well as maximum ice extent. Drainage basins were selected based on Kelletat (1995), while contours of the maximum ice extent are from Dürr *et al.* (2005)

**Fjords** were created by glacial scouring and are drowned glacial valleys. As a result, fjords are characterised by very steep topographies. Fjords can be several hundred meters deep, which compared to their width is very deep, and they have a very wiggly coastline.

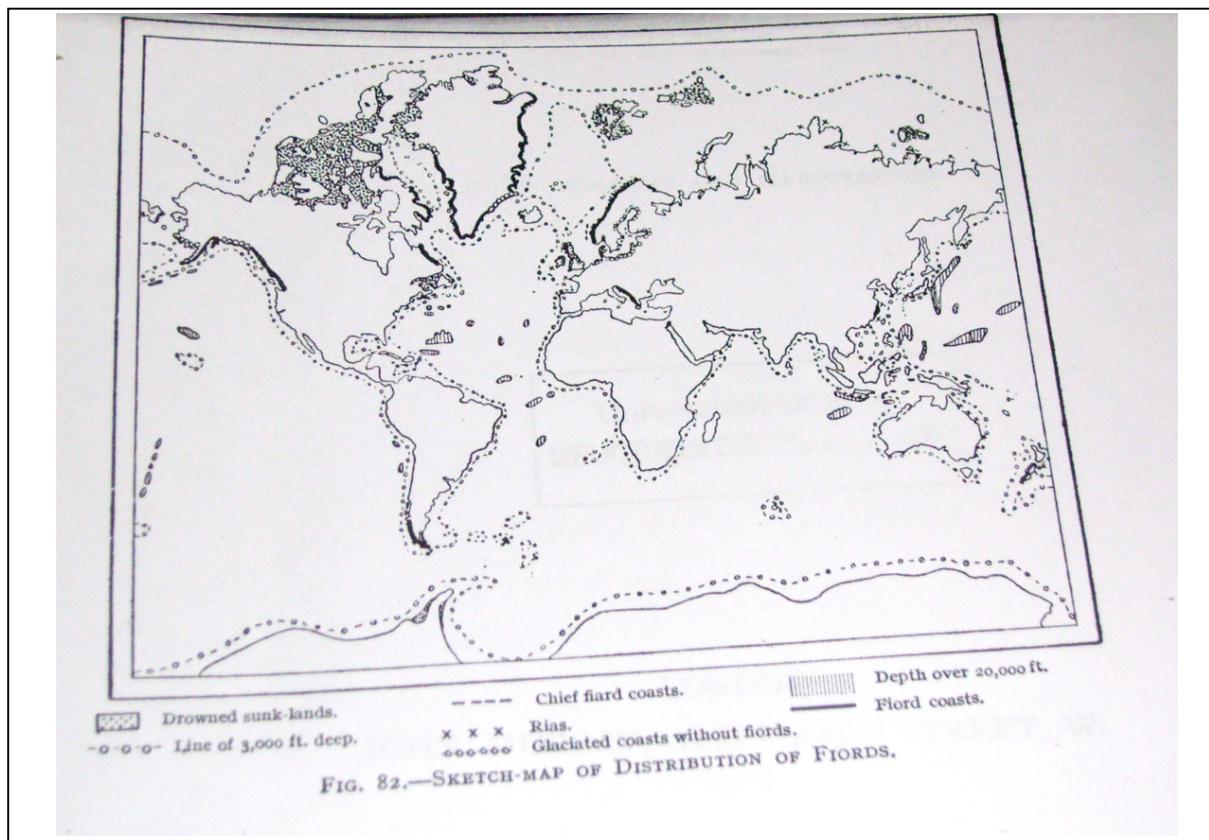
**Fjärds** are like the sweet niece of Fjords. Less edgy, they are wider and shallower, and thus have lower slopes. Although related from a biogeochemical point of view, they have a different genetic history. Fjärds are characterized by islands, as at the coast of Stockholm.

**Glaciated sedimentary coasts** finally have almost no slope and can be identified with a lithology map (Dürr *et al.*, 2005).

According to the EURCOAT findings, the filtering capacity of fjords and fjärds is mainly related to the settling of river particulates. In deep fjords the longer water retention may favour biogeochemical processes, hence increasing the filtering capacity for carbon and nutrients.

A map by Gregory (1913) shows the extent of fjords, fjärds, rias and other glaciated coasts (see figure 3.6). It was the only map found to show the geographic distribution of these morphological types.

An attempt was also made to make a distinction between fjords and fjärds, based on slope. This gave almost the same results as the map from Gregory. The **slope** was calculated from the bathymetry in the GEBCO database. This is however known to be not very good in coastal environments. The fjords are in fact represented in this coverage as being only a few metres deep. The slope calculated from this data however still shows a very high slope in the fjord areas, and less steep slopes in areas which are known to be flat (i.e. in deltas). Because for our purposes only a relative indication of the slope is necessary, and the slope as calculated from GEBCO was considered as representative, even though it is not representative for absolute bathymetry in the coastal zone.



**Figure 3.6** Fjords, fjärds, rias and glaciated coasts without fjords (Gregory, 1913).

## Type 0: no filter

### Karst

Karst forms by dissolution of lime-stone, in (semi) arid areas. The result of this dissolution is a network of caves or hollows which captures surface water, which further flows sub-surface. Karst landscape is therefore characterised by sinkholes and no surface runoff, or only over short distances. The direct underground inputs by karstic springs cannot be qualified as filters, because effectively the cavities are natural pipes which transfer continental waters directly to the open coastal zone (Meybeck *et al.*, 2000).

From the lithology map by (Dürr *et al.*, 2005), all the coastal stretches were selected where carbonates occur. Next, the drainage basins were selected, which drain through these coasts (see figure 3.7). Our selection was compared with maps in books about karst (Herak and Stringfield 1972; Sweeting 1972). Based on the occurrence of Karst and the lithologic map it was concluded in this research that the time scale in which karst forms is relatively short in geologic terms, so that the formation of karst morphology depends on sea level changes rather than on the age of rocks or their geologic structures.

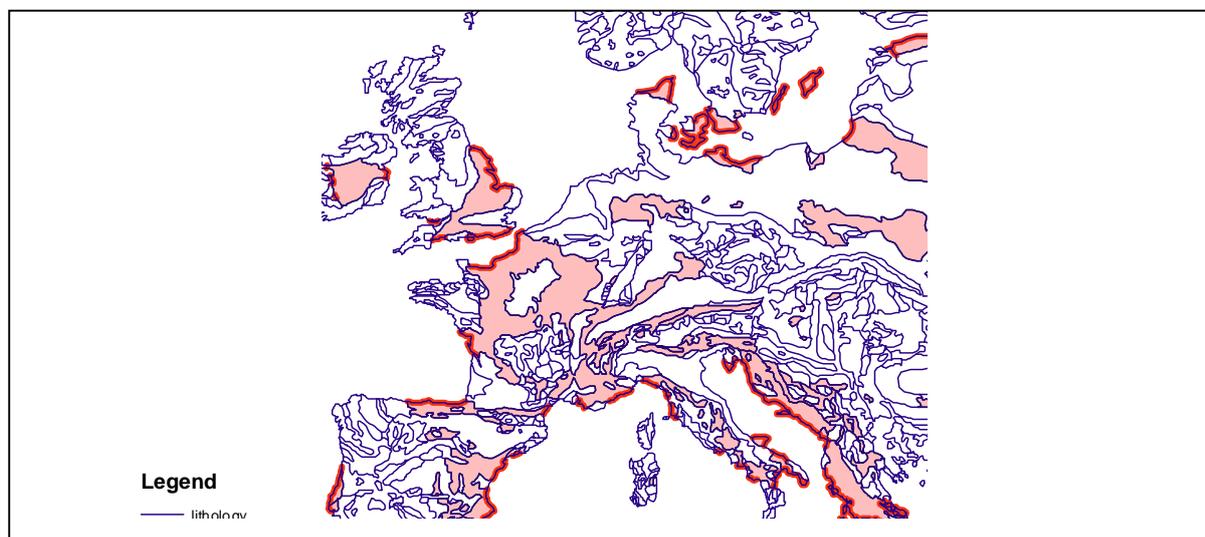


Figure 3.7 Potential coastal karst locations in Europe (adjusted from Dürr *et al.*, 2005)

### Arheic and endorheic

Most drainage basins are exorheic, meaning that they drain to the sea. Endorheic basins do not drain to the sea, but to a continental drainage basin, which sometimes leads to the formation of a continental sea. Many endorheic basins however occur in deserts, as in the Sahara and in Australia.

Arheic lands do not have any surface runoff because of high evaporation. An ecosystem is called Arheic when its annual runoff is  $< 3$  mm. Because many of the endorheic basins are Arheic they were put together in a morphology, although in the results section a distinction will again be made between these two types.

Which basins are endorheic was predefined in the drainage basins database. Figure 3.8 shows these basins, as well as the exo-arheic basins (Vörösmarty *et al.*, 2000).

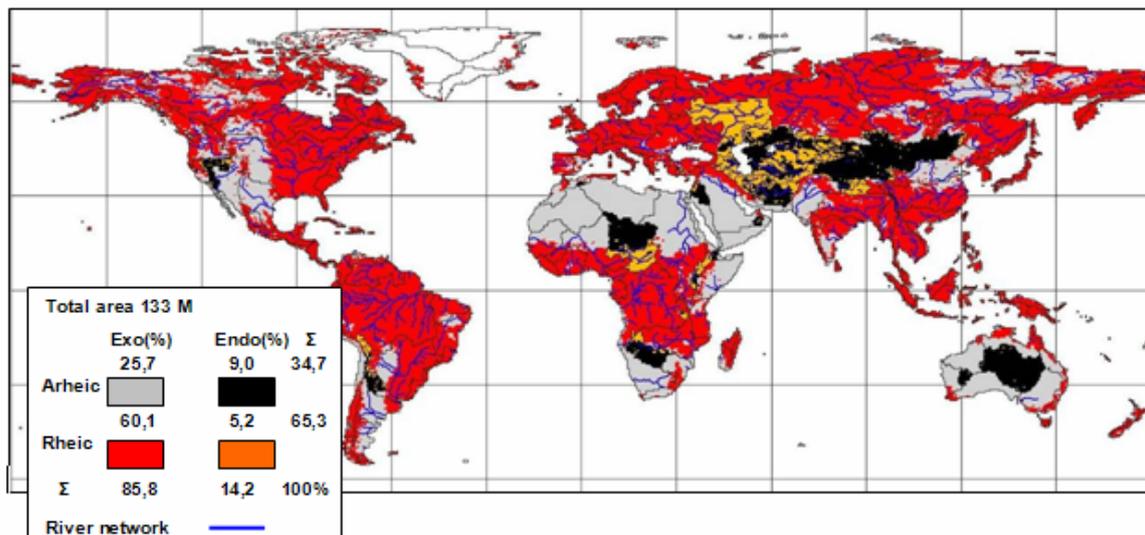


Figure 3.8 Potential River network (Vörösmarty *et al.*, 2000) and runoff (Fekete *et al.*, 2002)

### Big rivers and RiOMars

In 2001 and 2003 conferences were held about River Dominated Coastal Margins (RiOMars). These conferences unfortunately did not result in a geographical identification of such systems. Instead a list of major rivers of the world was made by looking at high water and sediment discharge. Here similarly, first a selection was made of big rivers based on the discharge of rivers, available through the GTN-R-database.

The GTN-R database contains discharge measurements of about 150 rivers worldwide. Taking the rivers with a discharge higher than the Rhone, 66 rivers were selected. The Rhône was used as a limiting point, because it is the smallest for which it was known to be a RiOMar. Having a large discharge, or sediment input does not yet mean that a river's load

will bypass the proximal coastal zone. For each river it was therefore determined visually from Google Earth's aerial photographs whether these rivers had a visible river plume extending into the open ocean, or whether filtering in a lagoon, marsh or estuary was likely. Because the Rhône itself also drains via a lagoon, most of the rivers however had to be concluded to be a RiOMar as well.

Exceptions are the Copper river, which empties in a leaky lagoon and the Churchill which empties in a Fjord. In both cases it is likely that filtering takes place. As was discussed previously, all of the most famous deltas of the world are likely to be RiOMars.

Because big rivers were long the only discharge features taken into account when assessing the supply of continental discharge to the world's oceans, a paragraph in the result sections will be especially dedicated to the runoff of RiOMars.

### **3.2 Results**

Figure 3.9 shows the distribution of drainage basins, continental cells and runoff over the different filtering types. Here, only relative numbers are given, normalized to the total number of basins (6781 basins in total), the total number of continental cells in a 30 minute resolution grid (57500 in total), and the sum of the annual runoff over all the continents respectively (~1500 m/y). The absolute values can be found in appendix A.

The number of drainage basins or continental cells can be seen as an approximation of coastline length and drainage basin area respectively. One should however bear in mind that the assignment of a coastal typology to the drainage basins only reflects the coastal morphology of the coastal cell, through which the basin is connected to the sea, and that cells at the equator have a different size than those at higher latitudes.

The geographical distribution of the filtering and morphologic coastal typologies will be discussed in the next paragraph, and is given in figures 3.10 and 3.11. In these paragraphs, the number of basins, cells and discharge per type were normalized to their respective values for the continents, and not for the global total.

Finally the integrity of our assigned typologies will be discussed, as well as the runoff via RiOMars.

### 3.2.1 General statistics

#### **type 0**

type 0 stands out from the other types, because it receives 53 % of the global runoff . This runoff is collected in 63% of the continental cells, and flows through 21% of all coastal cells, into the ocean. In the G-NUX philosophy this runoff is not filtered in the proximal coastal ocean, but is transported to the distal coastal ocean immediately. The reason why this happens is generally because no coastal morphology has developed. In the case of arheic coasts the lack of water and sediment supply has hindered this development. In the case of karst, the subsurface discharge through tubes hinders it. The karst and arheic types have much the same statistics. Both types receive only 3% of the global runoff, which flows through 10% of the worlds` drainage basins (see figure 3.9).

It should be noted that the morphology only shows the coastal distribution of karst. Karst occurring inside the continents is not represented here.

The results in figure 3.8 make a distinction between arheic and endorheic basins. The endorheic basins represent the shores of the continental Black Sea, Caspian Sea and Aral Sea.

The big rivers which are connected to RiOMars on the other hand have such an energetic hydrology, that it bypasses any coastal morphology. Only 1% of all drainage basins is of the riomar type, but as these are associated to the largest rivers in the world, 47% of the global runoff flows directly into RiOMar systems.

#### **Type I**

The estuarine coasts are the most frequently occurring types of coast, as might be expected. Estuaries make up the coastline of 40% of the drainage basins in our GIS. They receive 30% of the global runoff, from 20% of all continental cells. In both these respects the estuarine types are second to type 0. Within the estuarine type, one can distinguish plain estuaries, macrotidal estuaries, mangrove encroached estuaries and rias. The ‘plain estuary’ type includes coasts with small deltas.

Of all the subtypes, the plain estuaries make up the longest coastline length (most estuarine drainage basins are of the ‘plain estuary’ type. The associated continental cells however are slightly fewer then for the other types. This is because the ‘plain estuary type’ includes coasts with small deltas. These coasts are often connected to small drainage basins,

which is why they do not deliver much sediment or water, and which is why no protective coastal morphology forms (Meybeck 2007, personal communication).

The rias receive relatively less runoff than the other estuarine types. In the section with geographic results will be shown that most rias occur in arctic climates, which are generally relatively arid. The distinction between macrotidal, mangrove, ria and other estuaries is still relevant however, because they comprise clear sub-groups within the estuarine type, with distinctly different ecosystem habitats (i.e. the macrotidal and mangrove ecosystems). Therefore this distinction is relevant for geochemical assessments of the natural environment.

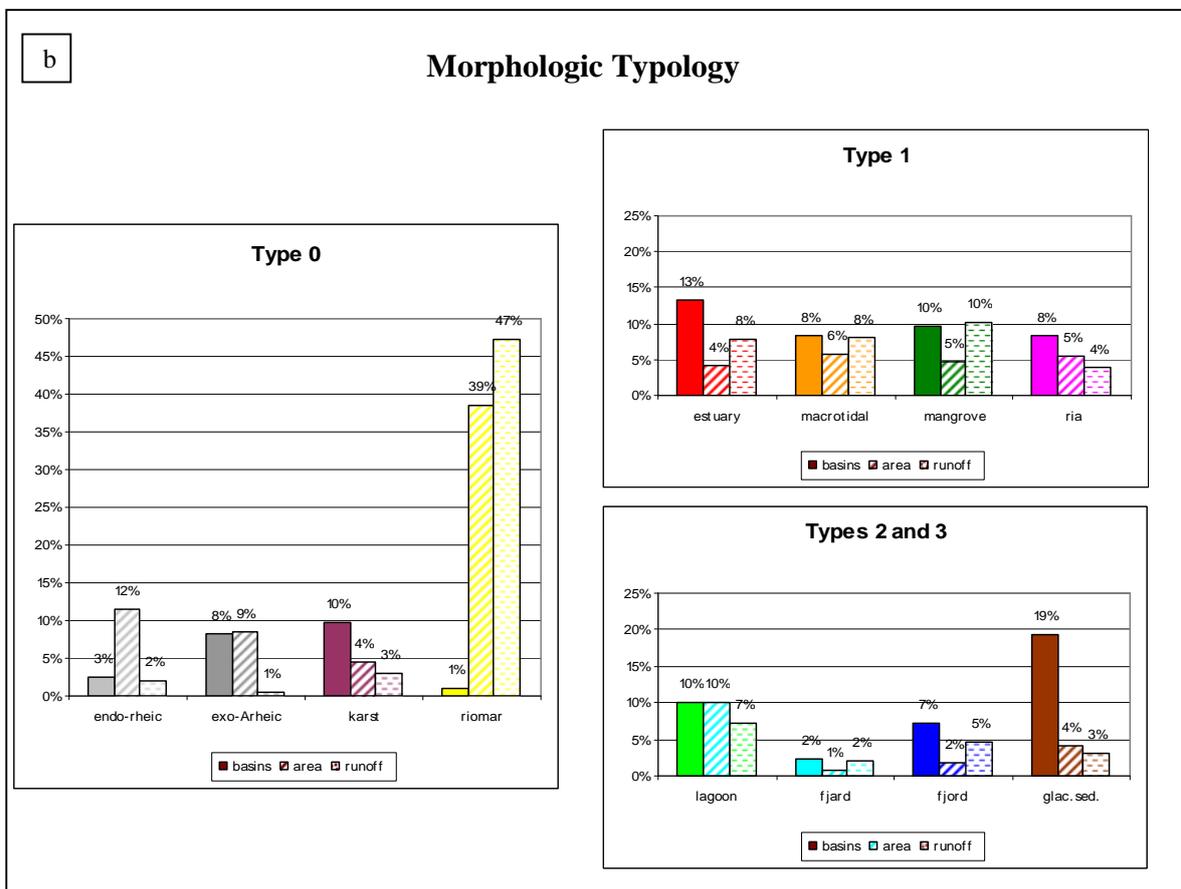
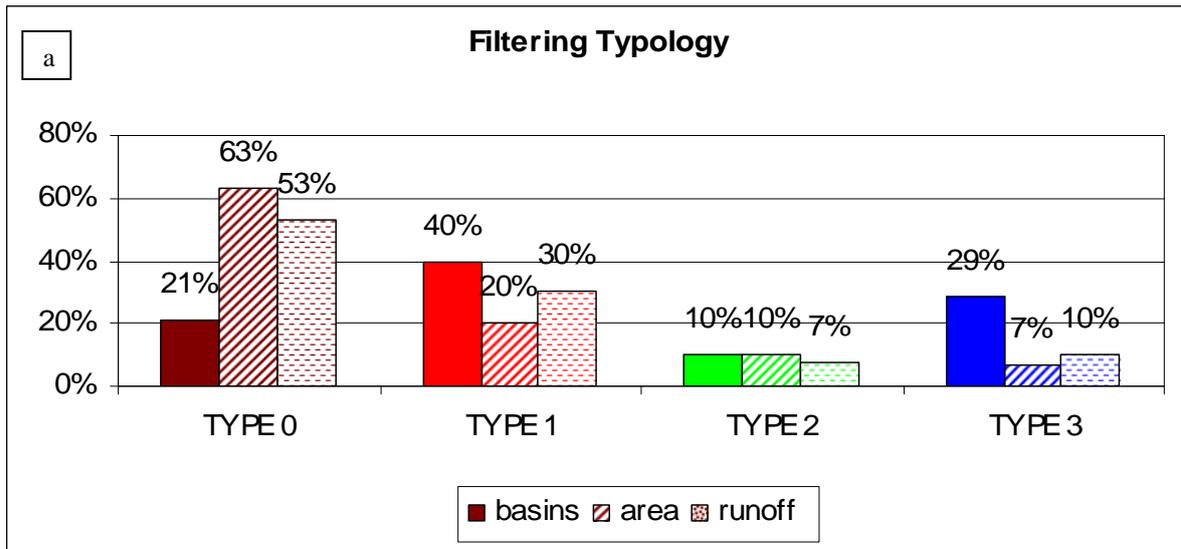
Mangrove occurs in estuaries, but also in lagoons. The statistics given here for Mangrove are therefore a lower limit. One could extract from the database where lagoons and mangrove overlap for a total overview of the mangrove type. This however was outside the scope and purpose of the present research.

## **Type II**

The lagoon type coasts make up 10% of the coastline, and receive 7% of the global runoff annually even though they have 10% of the continental area. This means that lagoons, with a total drainage area slightly bigger than that of type III coasts, annually receive less runoff. Possibly this is because lagoons occur in more arid climates, as will be shown later with the geographic distribution of the types.

## **Type III**

After the non-filtering type, the cold type III coasts stand out from the other types, because with 30% of the coastline, they surprisingly have only 7% of the continental area, and accordingly receive 10% of the global runoff. As for the rias, the geographic distribution of these coasts will show that they occur at high latitudes, which are expected to be relatively dry.



**Figure 3.9** Drainage basins (solid), continental cells (striped) and runoff (dotted) for the filtering (a) and morphologic typology (b)

### Preliminary Global Coastal Filtering Typology

Utrecht, 14 June 2007

Cheryl M. Van Kempen<sup>(1)</sup>, Goulven G. Laruelle<sup>(1)</sup>, Hans H. Dürr<sup>(2)</sup>, Caroline P. Slomp<sup>(1)</sup>, Hans Middelkoop<sup>(2)</sup>, Michel Meybeck<sup>(3)</sup>

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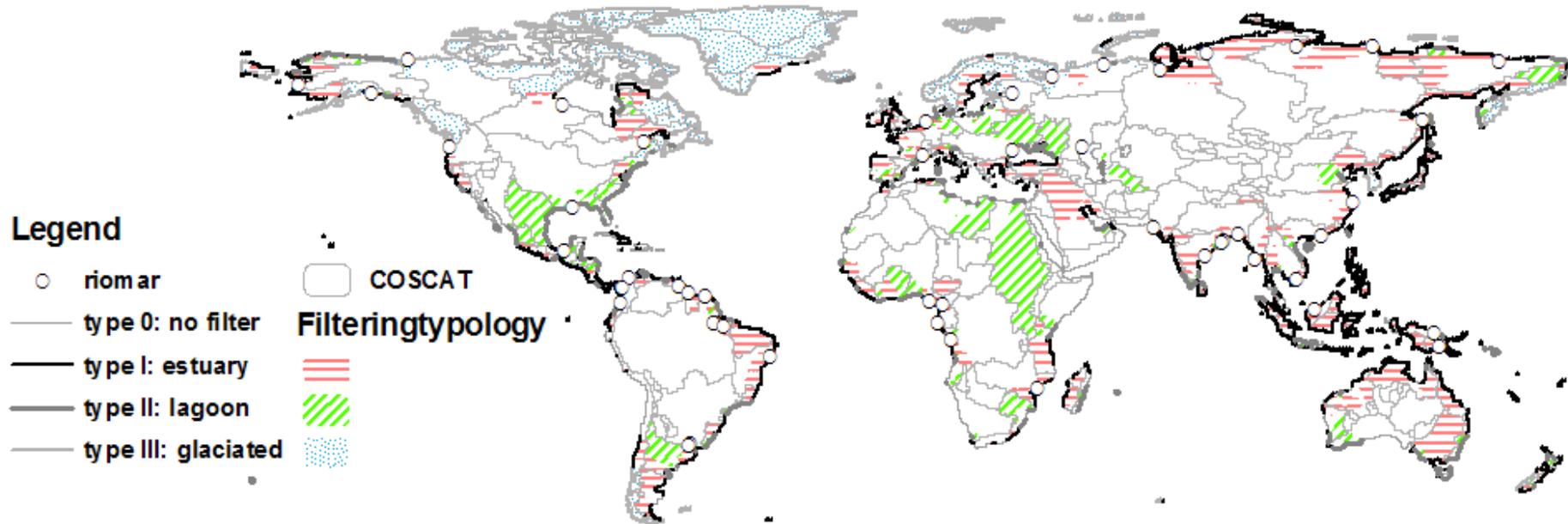


Figure 3.10 Preliminary Global Coastal Filtering Typology, classifying the world's coasts by biogeochemical factors

### Preliminary Global Coastal Morphologic Typology

Utrecht, 14 June 2007

Cheryl M. Van Kempen<sup>(1)</sup>, Goulven G. Laruelle<sup>(1)</sup>, Hans H. Dürr<sup>(2)</sup>, Caroline P. Slomp<sup>(1)</sup>, Hans Middelkoop<sup>(2)</sup>, Michel Meybeck<sup>(3)</sup>

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- (3) UMR Sisyphe, Université Paris VI, France

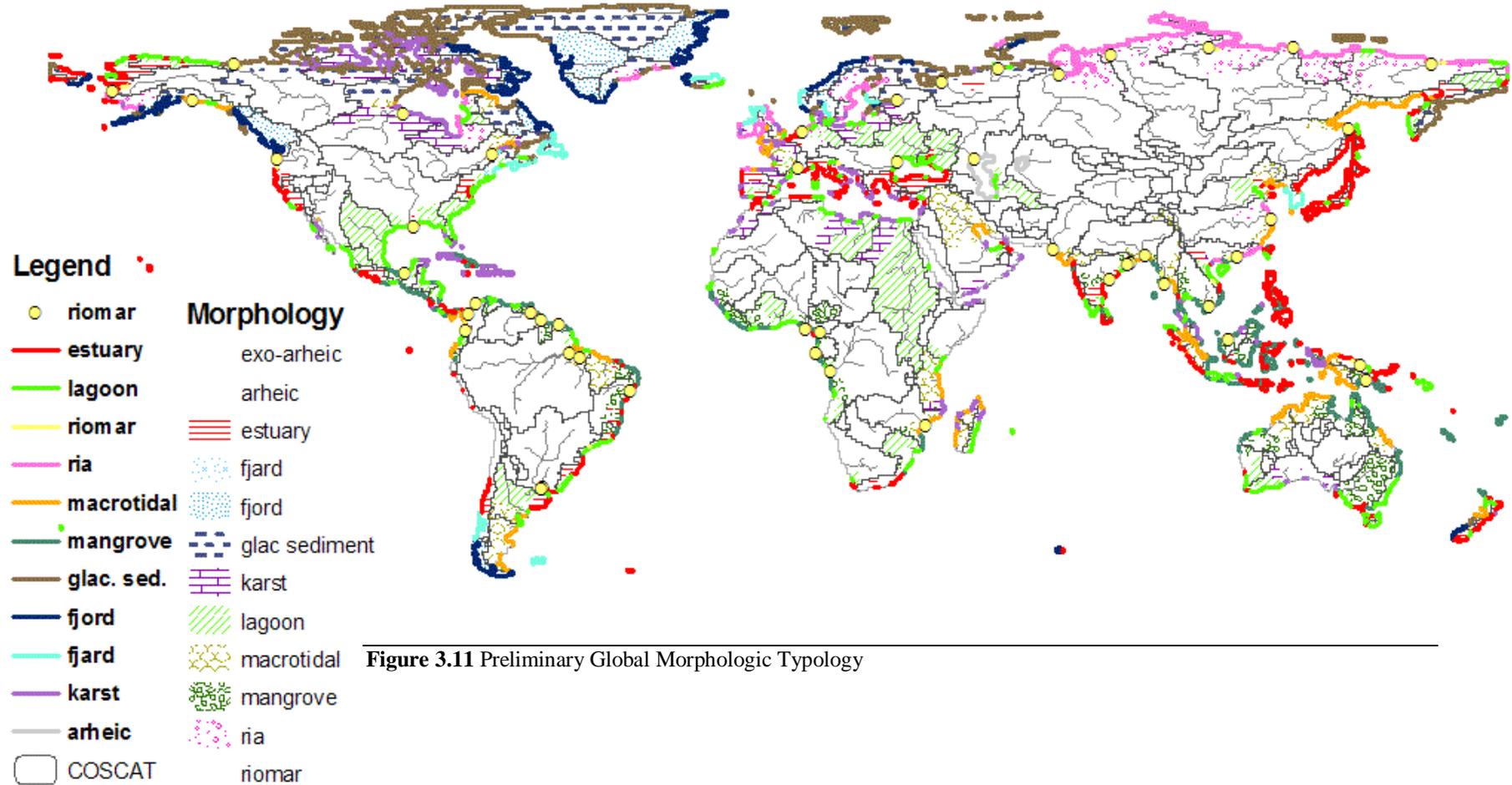


Figure 3.11 Preliminary Global Morphologic Typology

### 3.2.2 Geographic results

Before looking at the global geographic distribution of the filtering and morphologic types, some statistics are presented about the coastline length, area and runoff of each of the continents. Figure 3.12 shows the continent limits applied here. The distinction between the continents was based on the UP6 typology as defined by Meybeck *et al.* (2004) in the COSCAT database. Indonesia is mentioned separately in this continental segmentation. In this division some ‘remote Islands’ occur, which were added to the results of Indonesia. Figure 3.13 shows the statistics corresponding to each of the continents.

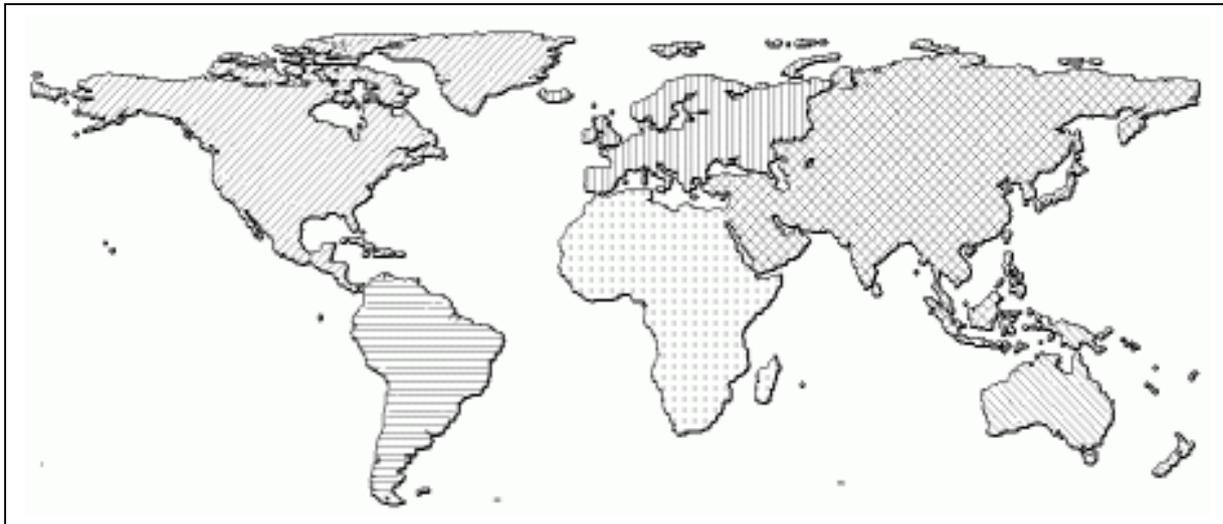


Figure 3.12 Continent boundaries. Note that Indonesia is a separate continent.

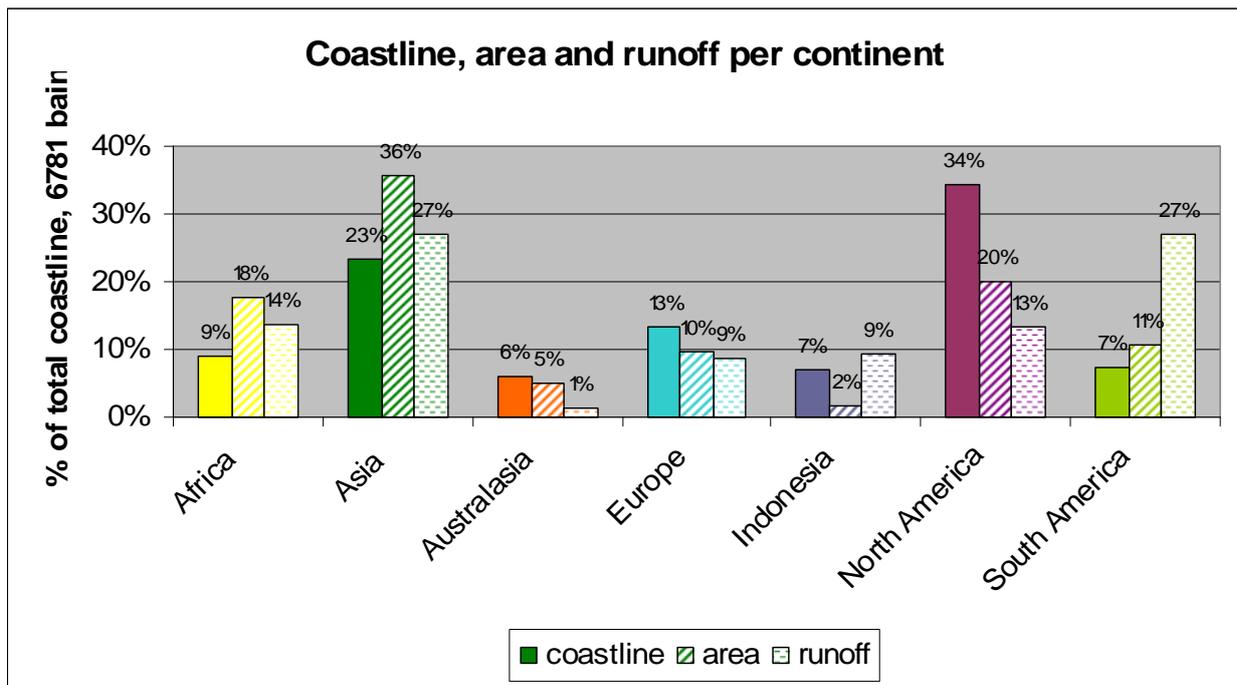


Figure 3.13 Drainage basins, continental cells, and runoff associated to each continent.

### **Coastline, area and runoff per continent**

In terms of the number of drainage basins, continental cells and the annual runoff per continent, the most obvious peaks are those of North America, which has most drainage basins, and therefore most coastal cells and presumably the longest coastline (34% of the world, see figure 3.14), Asia which has most continental cells, and therefore the largest draining area (36% of the world) and South America, which has the largest runoff compared to its coastline length and drainage area (27% of the total global annual runoff against 7% and 11% of the global coastline and drainage area respectively).

North America and Asia make an interesting couple because together they have the most coastal cells (NA: 34%, Asia: 23%) and the most continental cells (Na: 20%, Asia: 36%), closely followed by Africa (18%). The runoff of Africa is in the order of North-America. This could be seen as remarkable, because large parts of Africa are arid, and so Africa overall could be expected to have less runoff than North America. There are two reasons why Africa has a higher runoff than North America. First large parts of the North American continent are in the dry Arctic regions. Second, large parts of the African continent are in the rainforest regions and receive very high runoff, like in South America.

Because of its rainforests, South America has a runoff which is equal to that of all Asia, despite being smaller than Africa. As will be shown with the results for big rivers, this is for the largest part due to the Amazon. Indonesia, which is also famous for its rainforests, also receives very high runoff compared to its draining area, while Australia is again arid. Australia has an area half that of Europe, and more than double that of Indonesia, but receives only 1% of the global runoff, compared to 10% by Europe and Indonesia each.

### **Filtering typology per continent**

When looking at the division of the filtering typology over the continents, again North America and Asia stand out. 20% of the global coast comprises North-American fjord-like coasts, and 14% of the global coast comprises Asian estuaries. The other types make up less than 7% of each of the continents coastline.

Like North-America, Europe and Indonesia too are dominated by estuaries (6 and 85% of all drainage basins on these continents respectively). Australasia and South America are also dominated by estuaries, but less expressive than Europe and Indonesia.

Africa is the only continent dominated by type 0, but Asia and North-america have type 0 as second most prevalent type.

None of the continent's coasts are dominated by lagoons. They are most common in North-America, and are surprisingly less common in Indonesia and Asia than would be expected. Normalized to the total number of basins per continent, lagoons make up 10 % of the European, North- and South-American coast, 15% of the African, 20% of the Australian, and only 5 and 7 % of the Indonesian and Asian coasts.

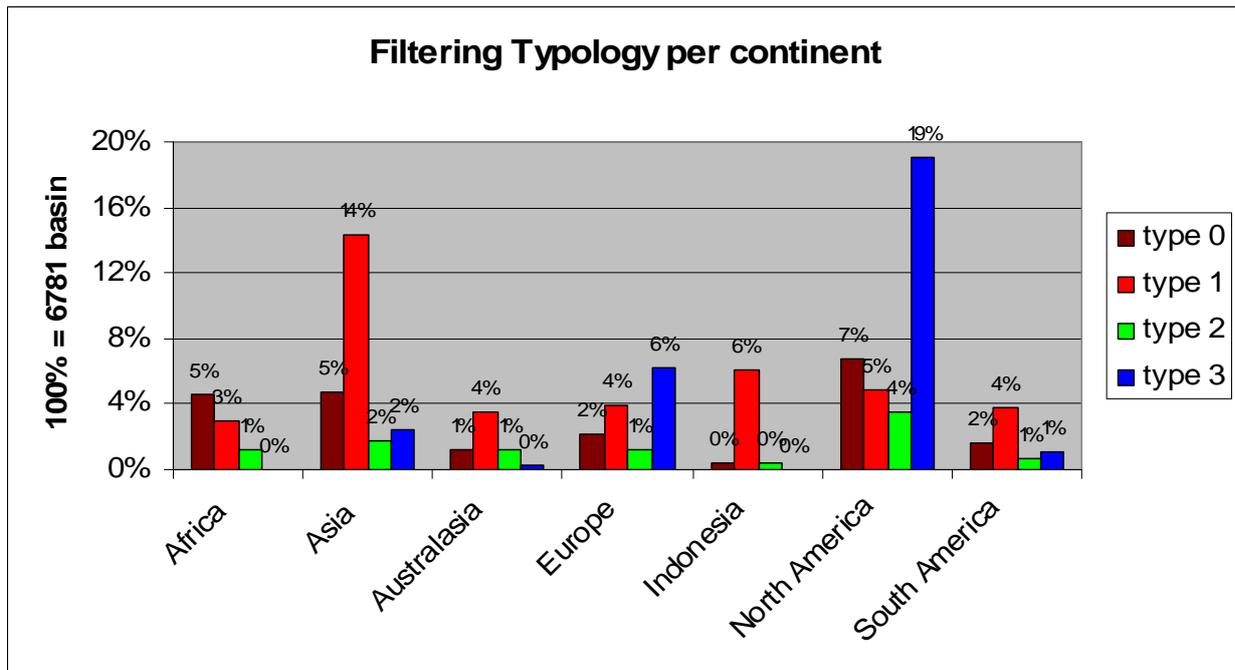


Figure 3.14 Statistics for the distribution of the filtering typologies over the continents.

In the following paragraphs the geographic results will be discussed per continent, each time followed by a result sheet. These sheets show 2 maps: one for the filtering typology and one for the morphologic typology of the continent. In addition to that, 4 graphs are presented. In the upper left corner a basin-count is given for the filtering typology, and in the upper right corner for morphology. Beneath that, on the lower left the runoff results are given for the filtering typology and for the morphologic typology on the right.

The columns of the filtering typology represent from left to right the types 0, I, II and III. The columns of the morphologic typology represent from left to right arheic (e), exo-arheic (a), karst (k), big river (b), estuary (e), macrotidal (t), mangrove (m), ria (r), lagoon (l), fjärd (fa), fjord (fo) and the glaciated sedimentary morphologies (s).

## Europe

Almost 50 percent of the European coasts consists of Type III coasts, while only receiving 25% of the Runoff. 30% of the European coast is of type 1, 16% of type 0 and 9% of the lagoon type II. These types receive 19, 12 and 44% of the European runoff respectively.

The Mediterranean is surrounded by karst, lagoons and estuaries as well as some arheic places in Spain and North-Africa. Lagoons also occur in patches on the coast from the Netherlands to Poland, alternated with karst and rias. The English channel is surrounded by macrotidal channels and karst. The British Isles further have ria and fjard coasts. Fjards also occur in Norway at the sea-side of the large fjords: Sognefjord and Hardanger fjord, on the Swedish coast which borders to Skagerrak, and in Finland, west of Helsinki. The Coast of Norway further consists of Fjords, changing into glaciated sedimentary coast in Russia. Sweden has rias bordering the Baltic Sea and Gulf of Bothnia. The Black sea, which strictly speaking is surrounded by endo-rheic basins, has lagoons on its northern shores and estuaries to its South. These were given priority over the arheic type, because the little water that flows here will go through these lagoons. These lagoons are however likely to be negative, meaning that they evaporate more water than they receive via runoff, so that to maintain the water level, water from the sea must flow into the lagoon. The result is a very saline lagoon. The caspian sea too is surrounded by arheic basins, with some lagoons.

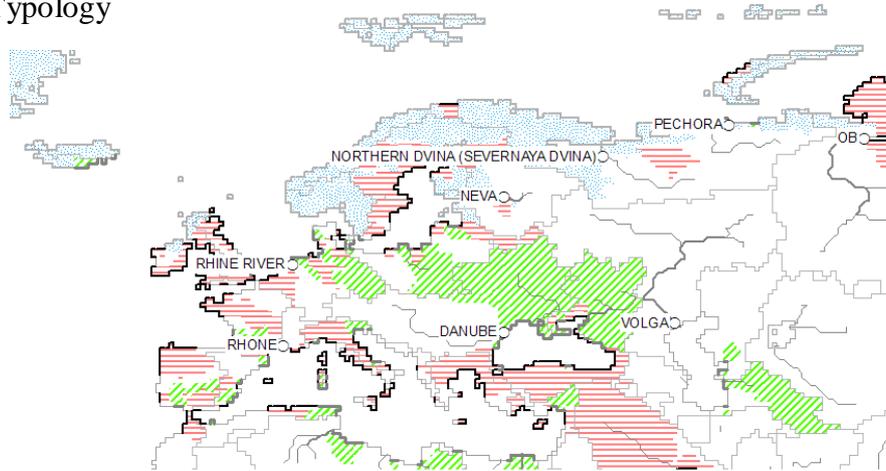
RiOMars in Europe are the Rhine, the Rhône, Neva, the Danube, the Volga and Dvina. They account for 35 % of the runoff in Europe.

The other morphologic types each receive about 10% of the annual European runoff, or less. Rias only receive 2% of the annual runoff. (Arheic basins by definition receive very low runoff, and therefore will not further be mentioned while discussing runoff.)

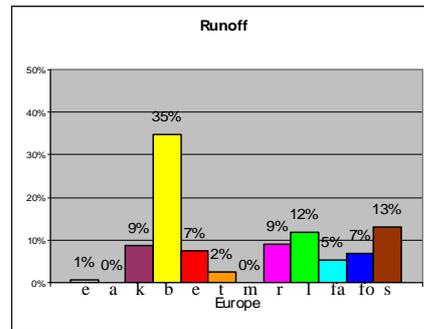
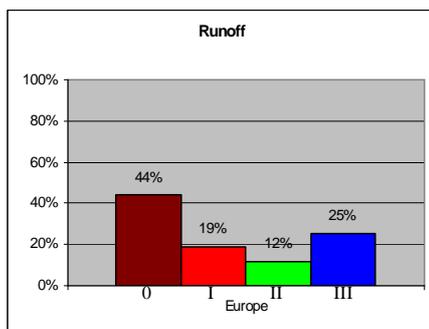
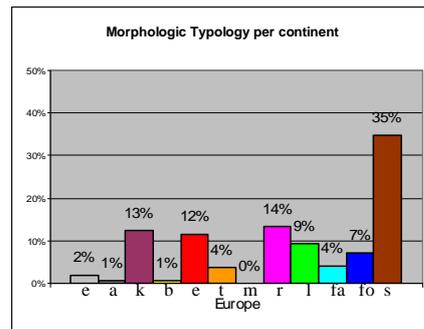
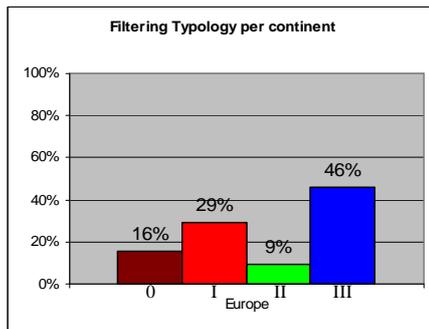
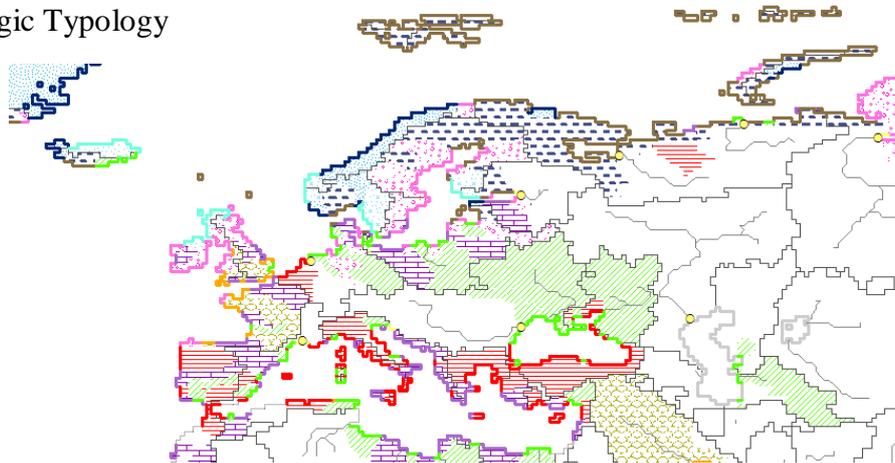
Mangrove does not occur in Europe according to this typology.

## Result Sheet: Europe

### Filtering Typology



### Morphologic Typology



## North America

Most of the North American coast is of filtering type III (56% of the DBs). The Runoff it receives however is of the magnitude of type 0 (20% of the DBs). If we look at the morphologic differentiation, then the runoff through type III is as much as that of the big rivers: 30% of the annual runoff in North America.

37% of the North American coast has a glaciated Sedimentary morphology. Fjords and Fjards make up another 15% and 3% respectively. The glaciated sedimentary coast occurs mainly on the northern coast of Greenland and together with karst they constitute the coast of the Queen Elizabeth Islands, Victoria Island, Baffin and the Northwest Territories. The Hudson bay is further dominated by Karst, and on its eastern shores by rias and lagoons.

On the East-Coast, Fjords occur in Greenland, along the northern shores of Baffin and along Labrador. On the west-coast they occur along the Coast Range of the Rocky Mountains and along the Alaska Peninsula and Alaska Range. Between these two Ranges macrotidal estuaries occur. The rest of Alaska constitutes some rias, but is dominated by estuaries on its Western, and by lagoons along its Northern coast.

Newfoundland, Nova Scotia and the Northern end of the Appalachian Mountains were identified here as Fjards.

South of these Fjards the American East-Coast is characterized by lagoon coasts, up until the coast of Costa Rica. The Gulf of Mexico and Yucatan are very good examples of lagoon coasts, with the famous lagoons Laguna Madre and Laguna de Términos respectively. In these more tropical settings many lagoons coexist with mangrove, i.e. in Florida. Lagoons make up 10% of the coast of North-America, which is almost 2/3 of all estuarine types together, or of the fjord coasts. Despite that, lagoons receive half the runoff the type 1 coasts receive: 11% vs 22% of the annual North-American runoff.

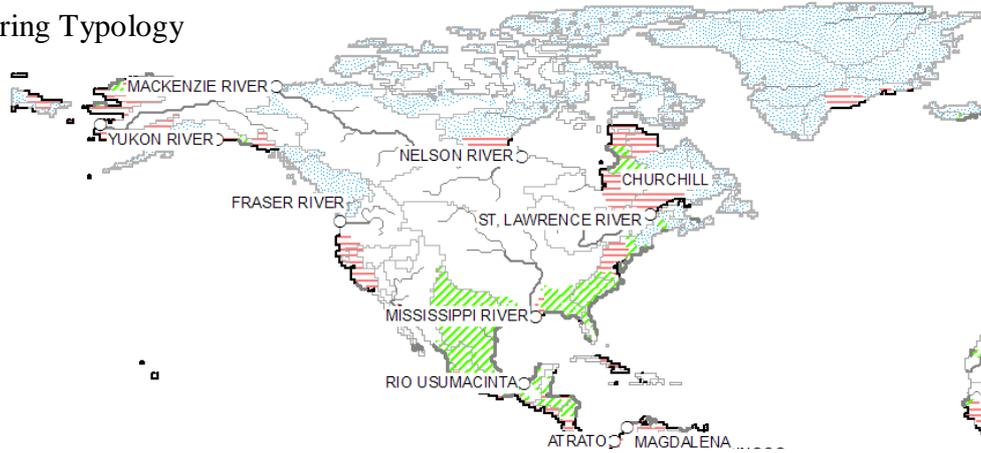
Cuba and Haiti are dominated by karst, and mangrove. On the East-Coast of North-America mangrove, estuaries and lagoon coasts alternate, with arctic coasts along the Gulf of California.

Big rivers in North-America are the Mackenzie, Yukon, Nelson, Copper, Mississippi, and Usumacinta. Together these rivers account for 30% of the runoff in North-America. Karst accounts for the other 7% of the runoff in the type 0 group. The Churchill is usually also

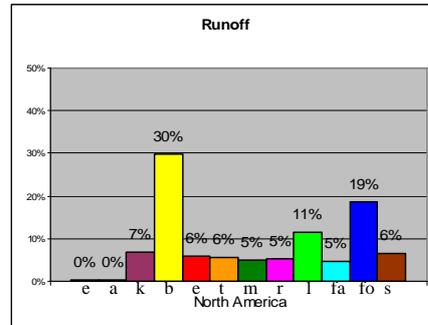
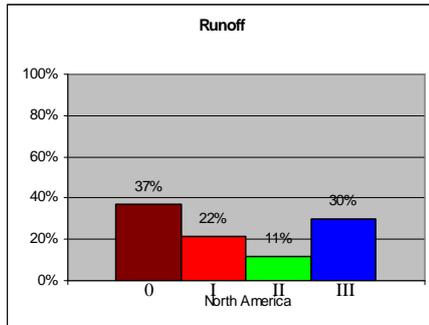
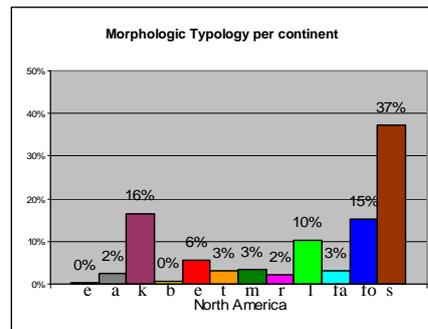
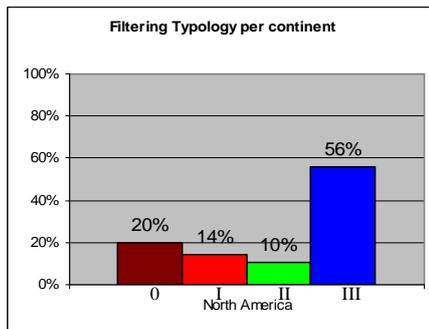
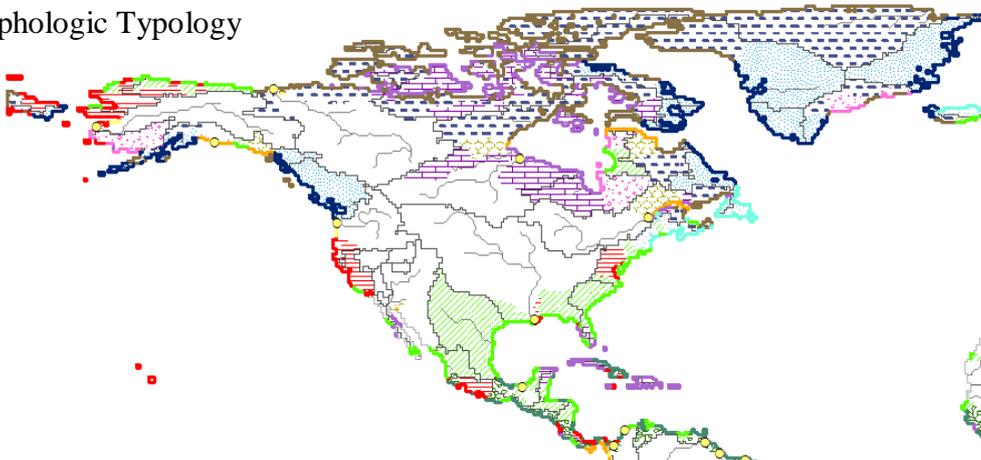
listed as a big river by other authors (Dagg *et al.*, 2004; McKee, 2003), but because it drains into a fjord, which is likely to modulate the particulate and nutrient load of the water, it is treated here as a fjord. The same holds for Fraser river, which was discarded here because it ends in a very leaky lagoon, which itself is sheltered from the open ocean by Vancouver island.

**Result sheet: North America**

**Filtering Typology**



**Morphologic Typology**



## **South America**

The coast of South-America is dominated by estuaries and deltas. Lagoons occur in Colombia South of Buenaventura and on the East-Bank of the big river Río Magdalena. In Venezuela Lago de Maracaibo was treated as a lagoon, and a lagoon coast exists east of Caracas. Brazil has a few more patches of lagoon coast north and South of the Amazon. Further, a long lagoon coast stretches south from Rio de Janeiro. Two famous lagoons lay on the border between Brazil and Uruguay: Lagoa dos Patos and Lagoa Mirim respectively. In Argentina, lagoons occur around the Golfo San Matías and South of Buenos Aires.

The largest part of the West-Coast of South-America is of type 0. This Arheic coast makes up 17% of the total South-American coastline. Another characteristic of South-America is the extremely high runoff which type 0 receives: 78% of all the runoff on the continent per year. This runoff is entirely accredited to the RiOMars, as almost no karst occurs along the coast, and the arheic basins barely have any runoff.

The big rivers of South-America are Magdalena, Orinoco, Mároni, Essequibbo, Toantins, Sao Francisco, Paraná, Uruguay, Atrato and the Amazon.

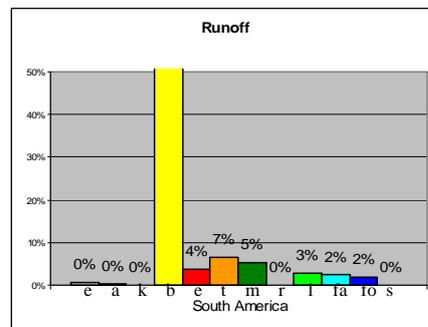
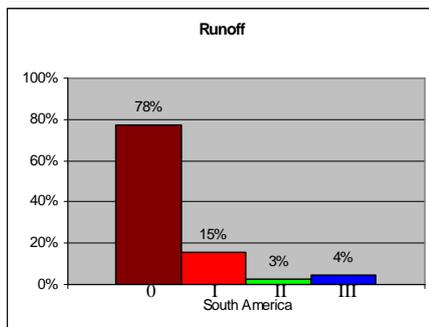
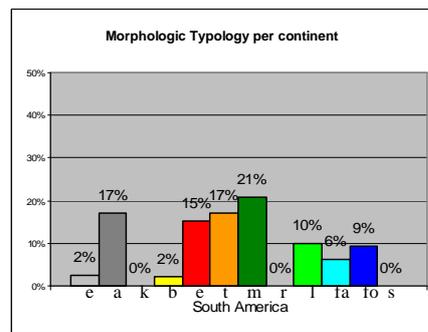
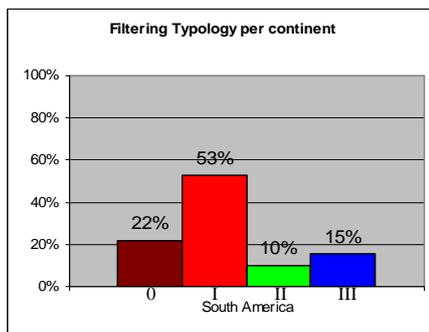
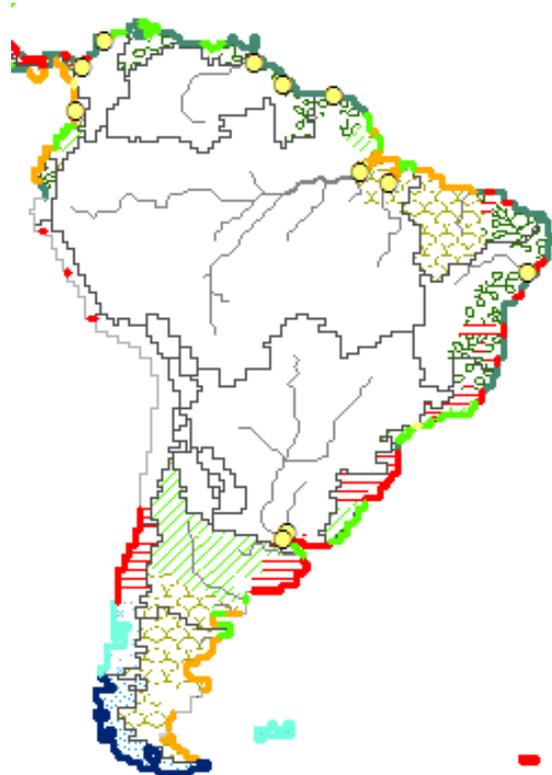
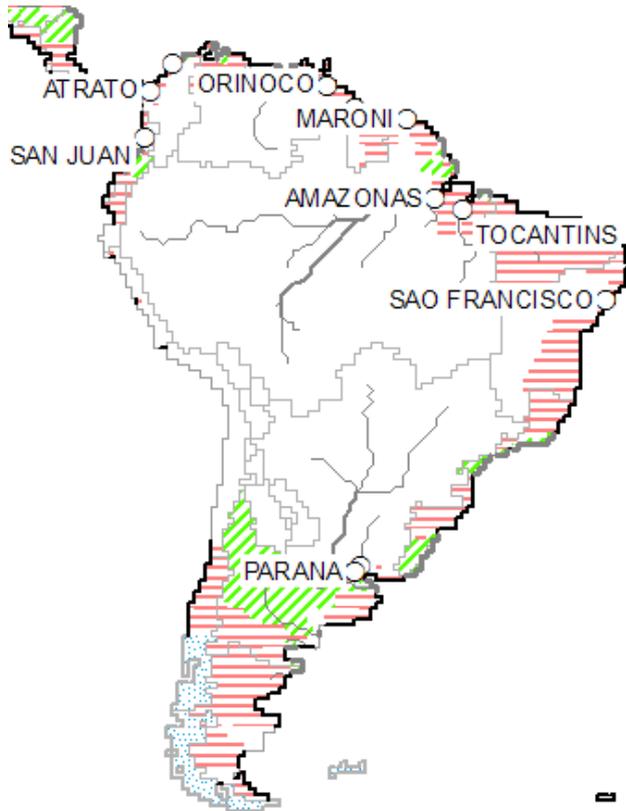
The South-American coast has more mangrove and macrotidal estuaries than plain estuaries. The macrotidal estuaries occur along the Amazon Shelf, along the East-coast of Colombia and Ecuador, and along the coast of Argentina at the Patagonian Shelf

The Falkland Islands, Isla de Chiloé and the Archipiélago de los Chonos are fjärds, while more South the Magellan coast are fjords (so all type III).

**Result sheet: South America**

Filtering Typology

Morphologic Typology



## **Africa**

Africa is dominated by type 0 coasts (53%) and has no type III coasts. 14% of the African coastline consist of lagoons. This is a high percentage compared to the other continents.

Remarkable is that 35% of the African coast is exo-arheic, while another 13% is karst. This percentage of karst is quite high, but is also for the largest part of the Arheic type. The West-African coast is exo-arheic from Mauritania until Morocco, with some lagoons and karst. Lagoons and especially karst dominate the (for a large part still arheic) Mediterranean coast until the Nile, which is treated here as a lagoon/deltaic coast of type 2.

The Red Sea and Arabia are entirely arheic, just as the African coast down to Somalia.

The coasts of Tanzania, Mozambique, and the West-Coast of Madagascar are macrotidal. The East-coast of Madagascar has a lagoon coast, which is very narrow, but very elongated. Madagascar further has some karst in the north, and some arheic basins in the south.

South-Africa has some estuaries, but is also for a large part Arheic, which continues North on the West-coast until halfway Angola. From there on, the Angola basin and the gulf of Guinea is bordered by mangrove estuaries and lagoons with mangrove, which continue until Senegal.

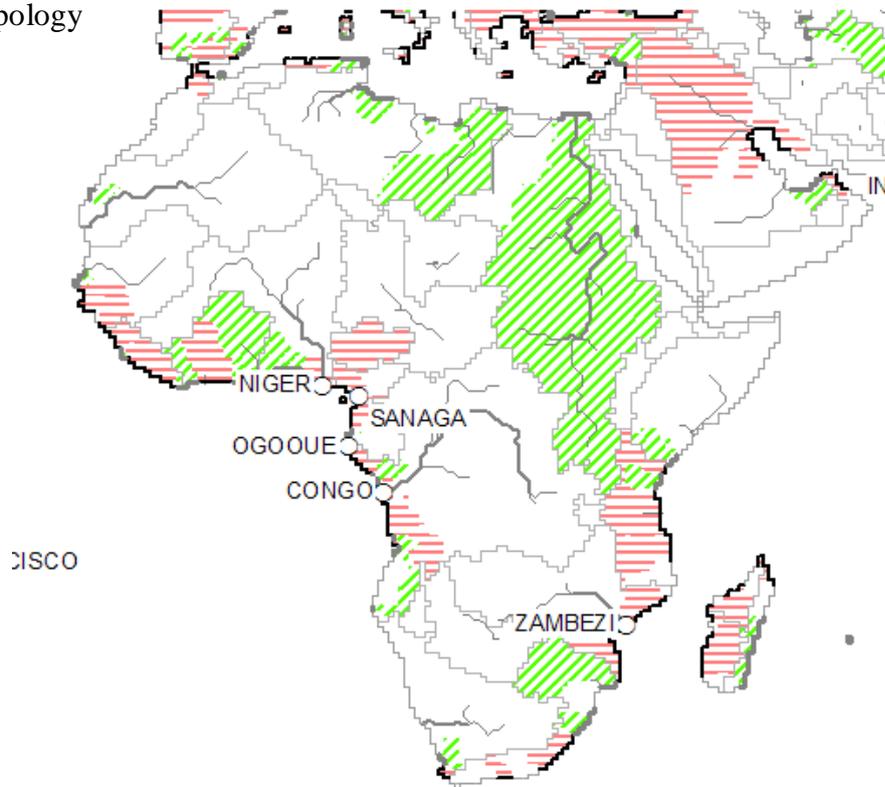
5 big rivers are present in Africa: the Niger, Sanaga, Ogouoé and Zaire (Congo) in the Gulf of Guinea and Angola Basin, and the Zambezi on the East-Coast.

RiOMars account for 46% of the runoff in Africa. Further most runoff goes through mangrove and macrotidal estuaries. African lagoons receive half the runoff the estuaries receive together.

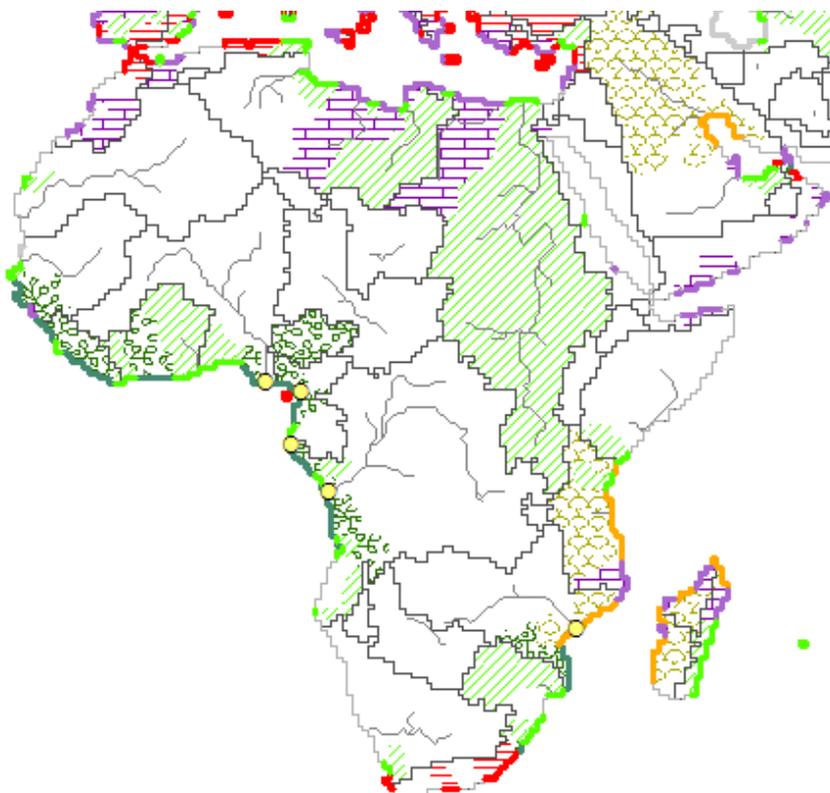
Typical lagoon coasts span from Kwazulu in South-Africa to North of Maputo in Mozambique, and from Lagos in Nigeria to Abidjan in Ivory Coast.

**Result sheet: Africa**

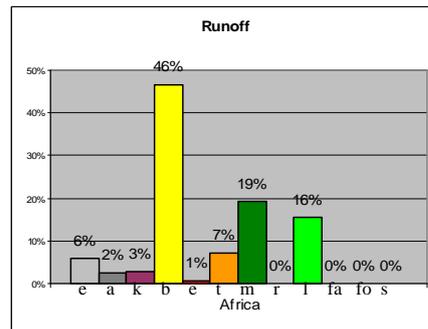
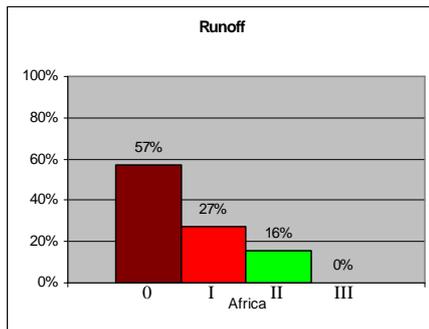
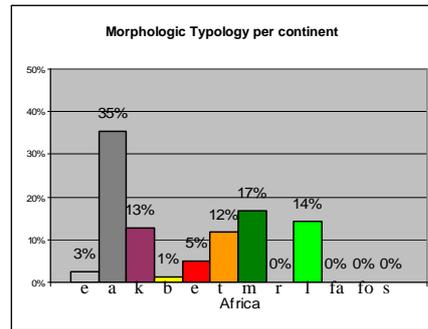
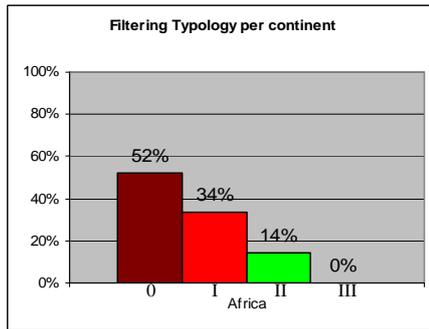
Filtering Typology



Morphologic Typology



**Result sheet: Africa (continued)**



## Asia

Asia is dominated by estuaries (62% of the DBs), and has relatively less lagoons than other continents. Also the length of type 3 coast is only 10%, which is surprising because Asia has a very long coastline in the arctic climate zone. This coastline was however almost entirely assigned the ria type, based on a map by Gregory (1913). Rias make up 25% of the Asian coast, with plain estuaries accounting for another 21% and macrotidal streams for another 10%. The runoff of the arctic coasts is dominated by 6 big rivers.

The type 3 coasts which occur at the European side of Russia and along the Bering Sea are primarily glaciated sedimentary coasts. The West-coast of Kacatka is dominated by lagoons while the rest of the sea of Okhotsk is dominated by macrotidal streams. Japan and the continental coasts bordering the Japan sea are all dominated by estuaries, with some lagoons, as are Taiwan and the Philippines.

South Korea was assigned a fjärd type, again based on Gergory (1913).

The Chinese coast is characterised by rias and macrotidal estuaries. South of this latitude mangrove becomes the dominating ecosystem in Asia, except in India where plain estuaries and lagoons alternate. Macrotidal streams further occur along the coast of Myanmar (check!), along the Mouths of the Ganga in Bangladesh, near Karachi in Pakistan and on the coast of Kuwait in the Persian Gulf.

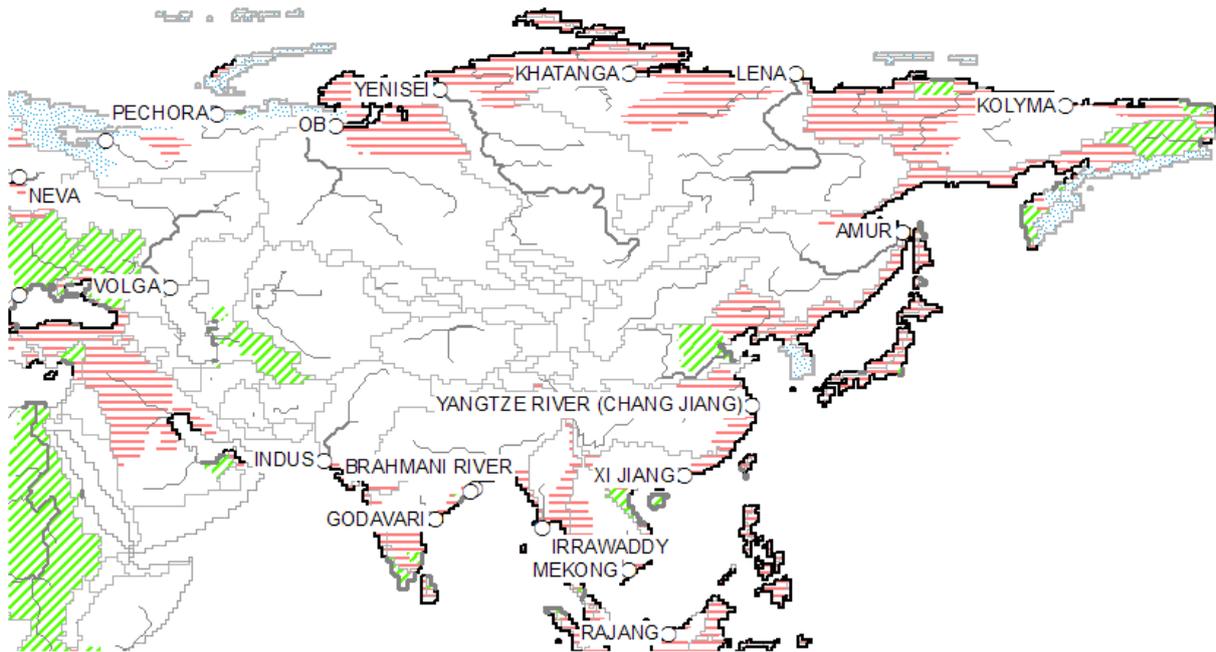
The big rivers in the arctic regions of Asia are (from West to East): Dvina, Ob, Pechora, Yenisei, Khatanga, Lena and Kolyma. North of Japan is the amur. China has Ghang Jiang and Zhujiang. Indonesia has Sepik and Rajang. Along the Southern shores are the Mekong, Irrawaddy, Godavari, Ganges, Mahanadi and Indus. The Volga drains into the Caspian Sea.

All these big rivers together are good for 50% of the annual runoff in Asia which is not even that much considering that 19 of the world's biggest rivers are in Asia.

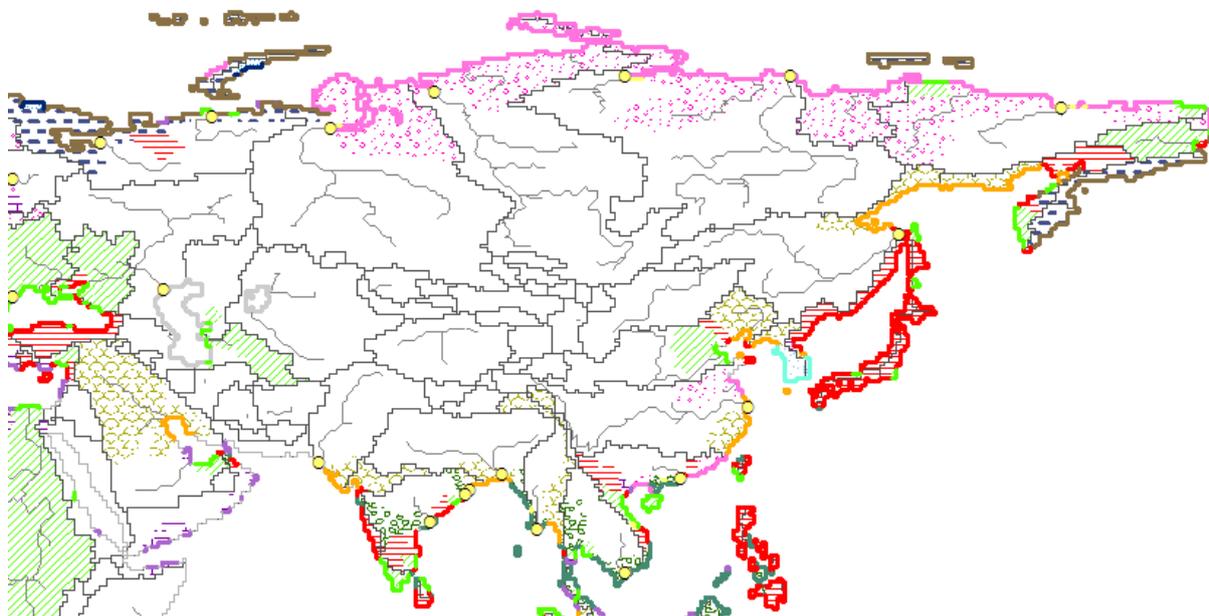
China is famous for its karst regions. However, these do not extend to the coast. Therefore China does not have much karst in the typology presented here. Other Asian karst regions are the coasts of Vietnam, Indonesia and Malaysia.

### Result sheet: Asia

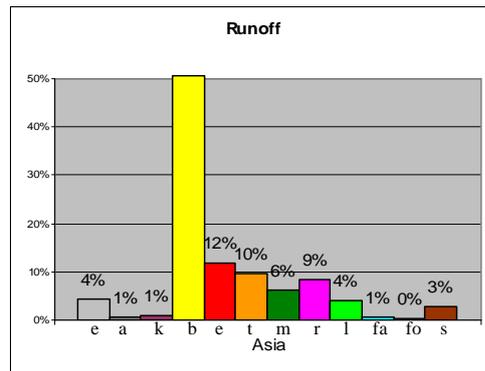
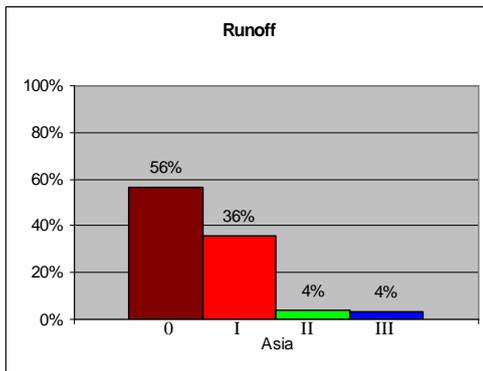
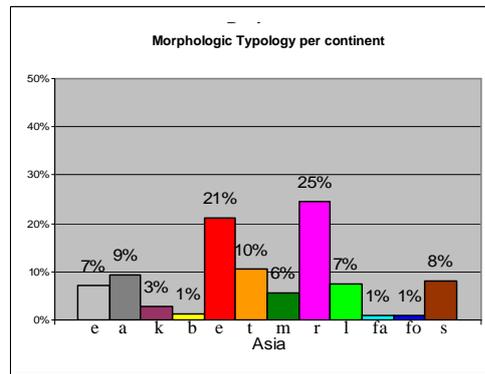
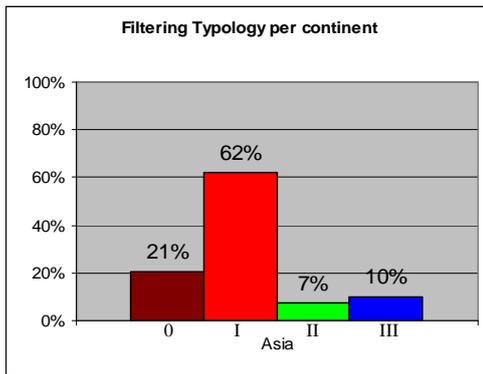
#### Filtering Typology



#### Morphologic Typology



**Result sheet: Asia (continued)**



## **Oceania**

The Philippines, Indonesia and the islands of Melanesia are dominated by plain estuaries and estuaries with mangrove. Some karst occurs in Malaysia and along the coast of New Guinea. Lagoons can be found on the Northern tip of Sumatra, and on the northern coast of Java. The Solomon islands are surrounded by coral atolls, which were counted here as lagoons.

Despite that New Guinea has 2 big rivers, this region experiences only 8% runoff via these big rivers. Most of the Indonesian runoff goes through estuaries with mangrove (44%), macrotidal estuaries (21%) and estuaries (20%).

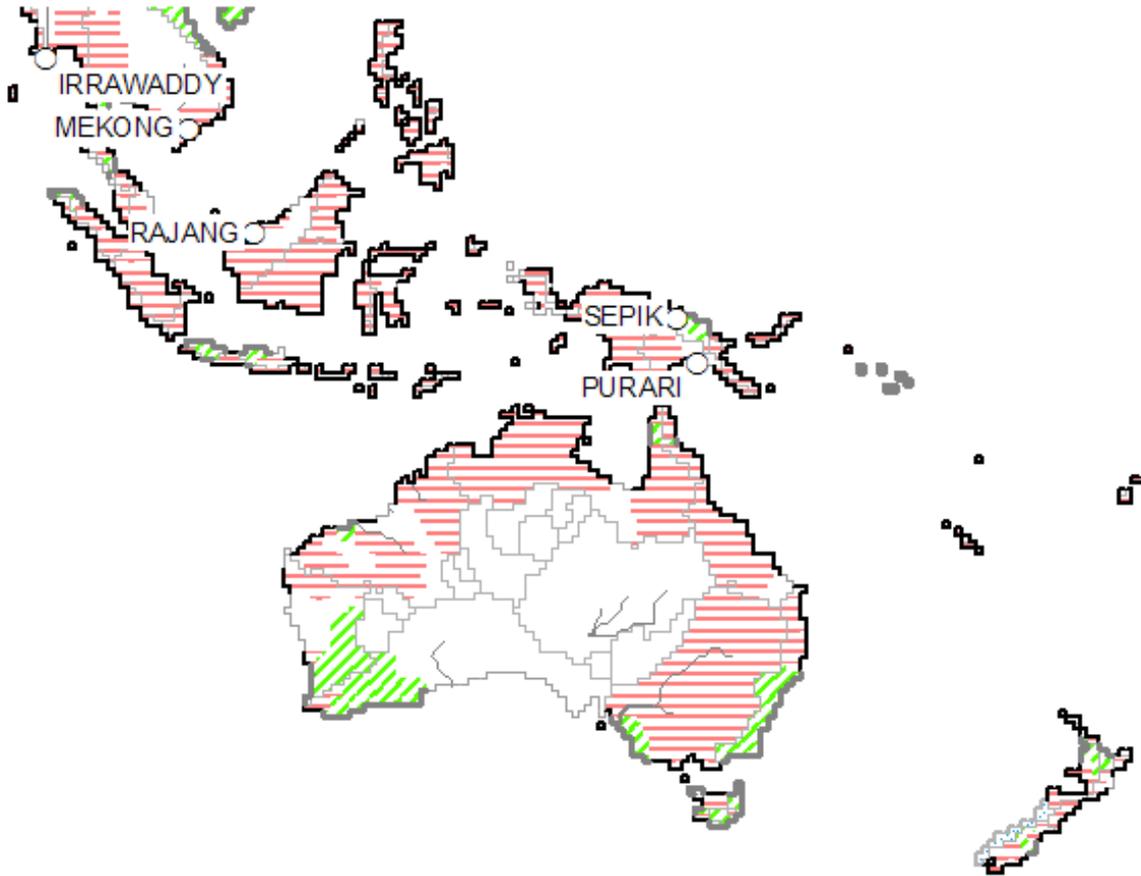
Australia has no big rivers, but 16% of exo-arheic coastline which is partially karstic. Australia, like Indonesia and the Melanesian islands is dominated by mangrove estuaries, but it has slightly more lagoons than macrotidal estuaries and plain estuaries. However, these lagoons receive a bit less runoff than the estuaries.

The arheic districts of Australia are along its South and west coasts. Macrotidal estuaries are found in the North along Tasman Land and Arnhem land and in the west, South of the Great Barrier Reef. Lagoons are found along the South-Eastern and South-Western coast, and on Tasmania.

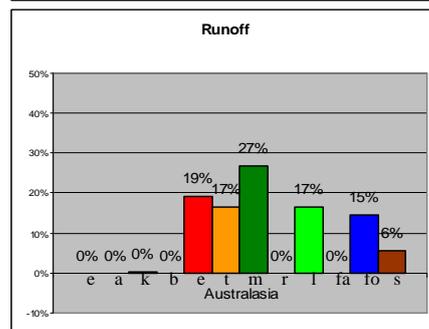
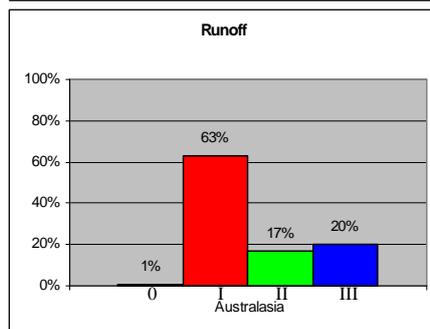
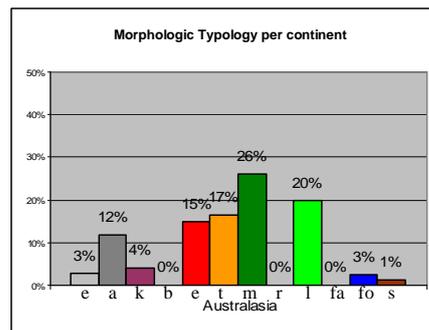
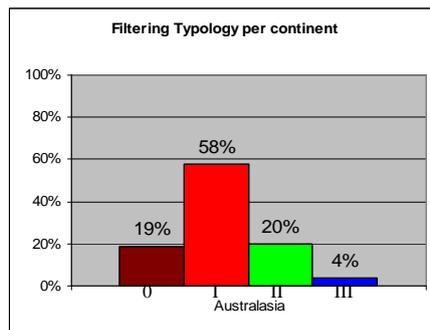
New Zealand has a variety of morphologies, but is dominated by estuaries on its Eastern coast, and has some macrotidal estuaries on its Western coast. Some lagoons occur near Auckland on the Northern Island, while fjords and glaciated sedimentary coast occurs on the Southern Island. These are good for 4 % of the Australian coastline, and receive 20% of the Australian runoff.

**Result sheet: Oceania**

Filtering Typology

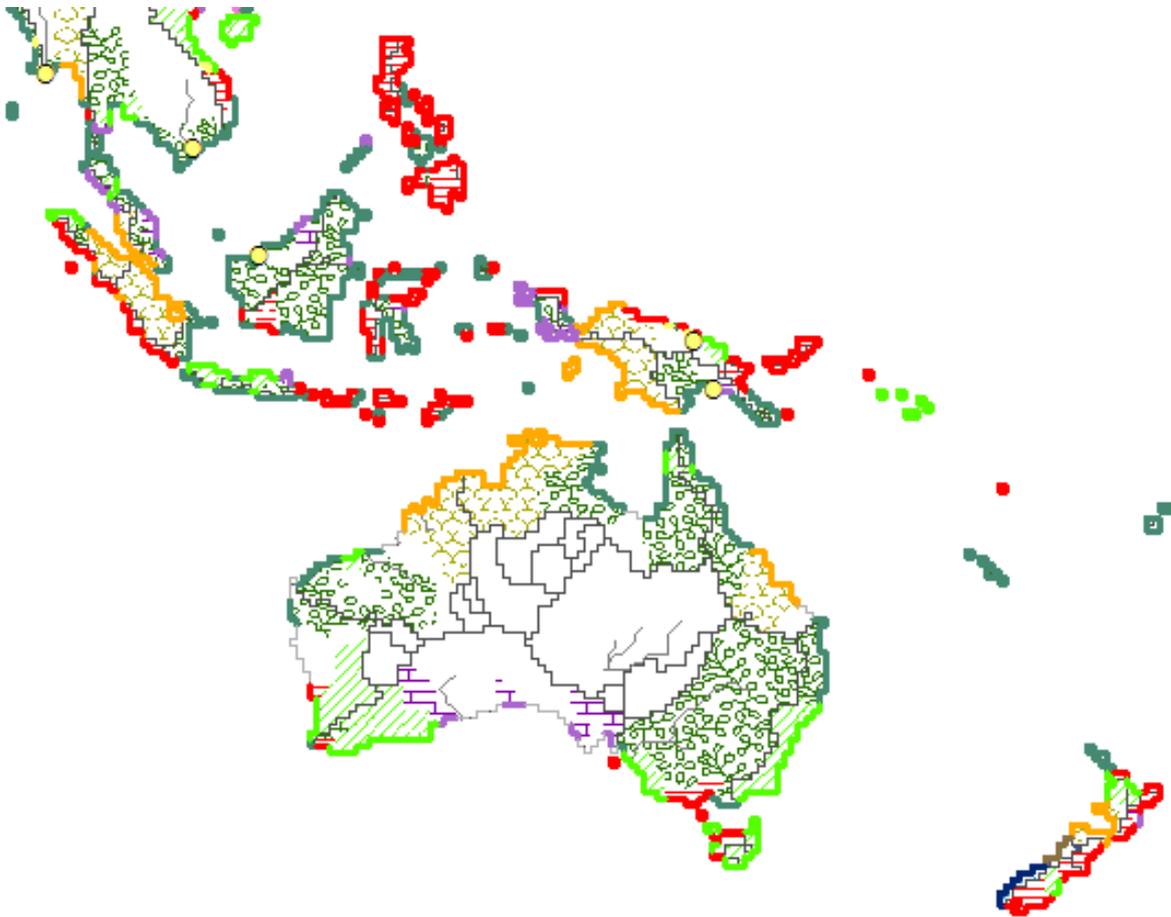


Australia

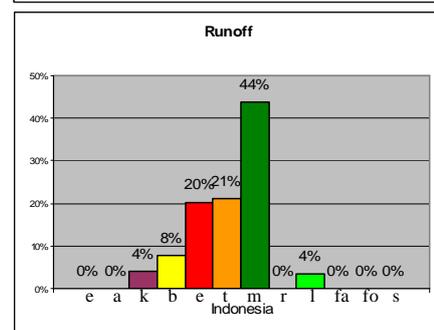
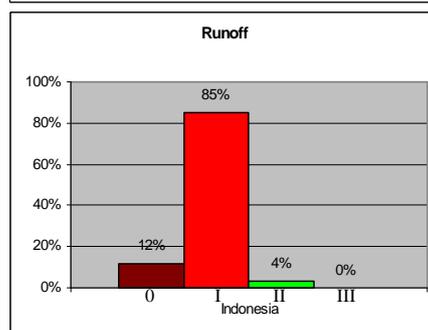
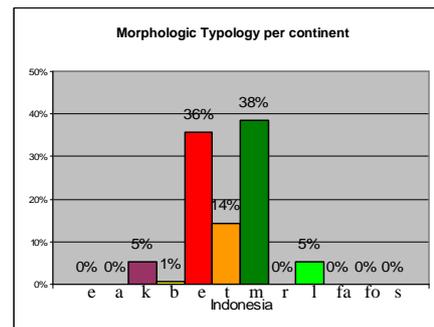
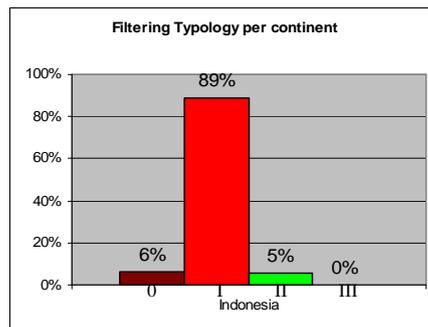


**Result sheet: Oceania (continued)**

Morphologic Typology



Indonesia



## Big rivers

66 of the drainage basins in the GIS belong to one of the 48 big rivers, which potentially drain into a RiOMar environment. Together these drainage basins are responsible for 47% of the global runoff.

11,7% of the global runoff flows through a single drainage basin: that of the Amazon. The Amazon river alone is therefore responsible for 25% of the runoff by all big rivers together (see figure 3.15).

The 25 rivers with the largest runoff selected by our method - having a discharge large than that of the Rhône, which is known to be a RiOMar – are largely the same as those listed by McKee (2003) and Ericson *et al.* (2006), but in a slightly different order.

Table 3.7 lists the rivers selected by this method, and gives an indication of the type of morphologic feature each river has at its mouth. These features can be seen on satellite images like from seaWifs or Google Earth. An inventarisation of these features was made to be able to make a distinction between big rivers and big rivers which are connected to RiOMar environments. Rivers which do not drain into lagoon-like structures, or ‘sheltered seas’ are potentially RiOMars. Rivers which have a large area with marshes in their drainage basins are unlikely to have a large particulate load, and are therefore likely to belong in the estuarine type (I).

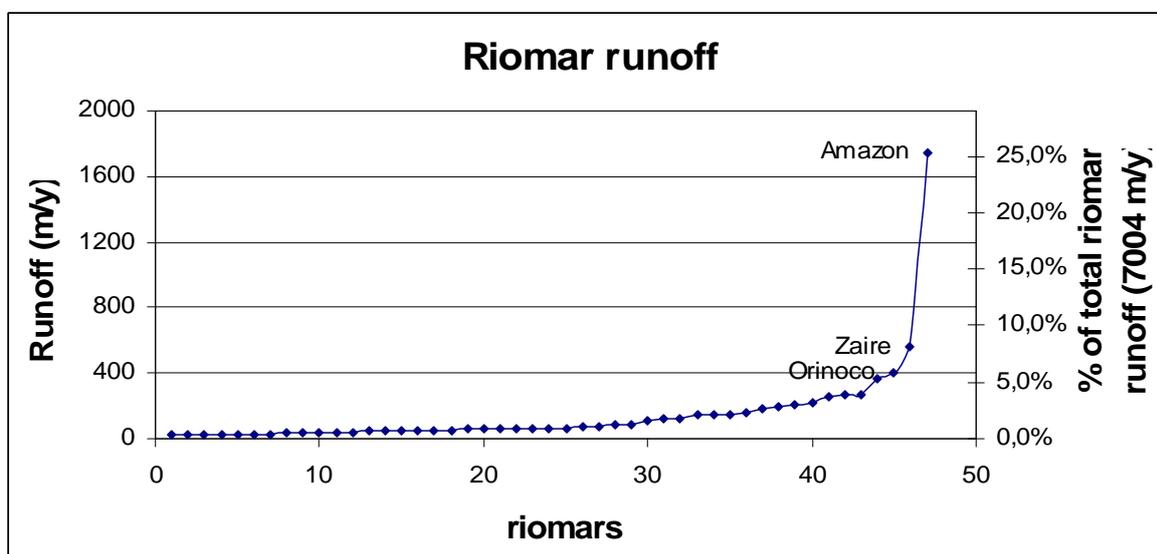


Figure 3.15 Runoff for the 48 drainage basins with the largest discharge on earth.

**Table 3.7:** RiOMar basins, ordered by decreasing annual runoff (Fekete *et al.*, 2000). Percentage is normalized to the global annual runoff (14897 m/y).

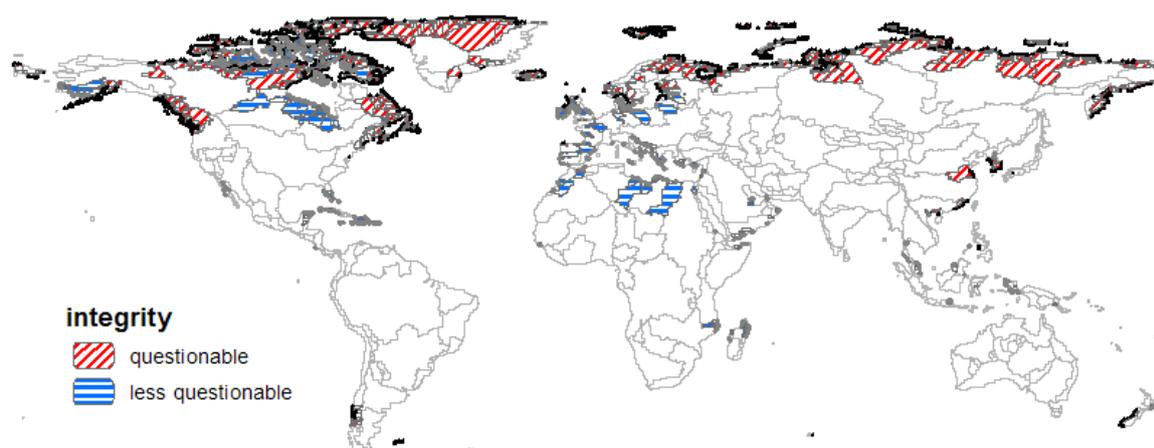
<b>River</b>	<b>Runoff Sum m/y</b>		<b>coastal feature</b>
1. Amazon	1739	11,7%	braiding river
2. Zaire	562	3,8%	cusate wave delta
3. Orinoco	407	2,7%	wave/ tidal delta
4. Ganges	368	2,5%	estuary
5. Ob	273	1,8%	sheltered sea, marshes
6. Mississippi	265	1,8%	birdfoot delta
7. Parana	253	1,7%	sheltered sea, marshes
8. St Lawrence	217	1,5%	sheltered sea
9. Chang Jiang	213	1,4%	river delta
10. Yenisei	200	1,3%	large lagoonlike sea
11. Tocantins	182	1,2%	braiding river
12. Volga	164	1,1%	tidal delta, sheltered sea
13. Mekong	149	1,0%	tidal delta
14. Lena	145	1,0%	large lagoonlike sea
15. Amur	143	1,0%	large lagoonlike sea
16. Zambezi	127	0,9%	delta
17. Irrawaddy	125	0,8%	delta
18. Danube	113	0,8%	fluvial delta, sheltered sea
19. Niger	81	0,5%	all equal delta
20. Uruguay	80	0,5%	sheltered sea
21. Pechora	76	0,5%	large lagoonlike sea
22. Columbia	72	0,5%	lagoon
23. Magdalena	67	0,4%	lagoons/ delta, inland marshes
24. Zhujiang	66	0,4%	sheltered sea
25. Sao Francisco	65	0,4%	cusate wave delta
26. Neva	61	0,4%	lagoonlike structure, inland water, sheltered sea
27. Mackenzie	61	0,4%	tidal delta
28. Indus	61	0,4%	sheltered sea
29. Khatanga	56	0,4%	estuary
30. Yukon	51	0,3%	fluvial delta all equal delta
31. Dvina	50	0,3%	lagoon, sheltered sea
32. Ogooue	47	0,3%	cusate wave delta
33. Rajang	44	0,3%	braiding river
34. Nelson	43	0,3%	estuary
35. Essequibo	43	0,3%	cusate wave delta
36. Rhine	41	0,3%	large lagoonlike sea
37. Kolyma	40	0,3%	estuary
38. Sepik	35	0,2%	cusate wave delta
39. Sanaga	33	0,2%	cusate wave delta
40. Godavari	31	0,2%	delta
41. Usumacinta	26	0,2%	cusate wave delta
42. St Juan	25	0,2%	cusate wave delta
43. Rhone	23	0,2%	lobate delta
44. Maroni	23	0,2%	cusate wave delta
45. Bramani/ Mahanadi	20	0,1%	river delta
46. Atrato	20	0,1%	birdfoot delta, sheltered sea
47. Purari	19	0,1%	braiding river
48. Copper			wave/ tide delta

### 3.2.3 Integrity

As stated in the method, the correctness of the segmentation presented here depends on several factors: choice and availability of source material, correct transfer of information from the source material to the GIS and the decision to give one morphology priority over another in cases of overlap. An indication of integrity was already given in the method, but the overall integrity and problem areas will be discussed here.

As can be seen in figure 3.16 the most questionable parts of the map are those in Arctic climates. We overall feel confident about the rest of the segmentation and geographical distribution of the filtering and morphologic typologies. The questionable basins make up 30% of the total, with another 10% being less questionable, but of which we still feel less certain. The integrity was assigned per morphology, and per continent. Thus, the rias of Asia are being questioned, while those of Europe are seen as less questionable. Table 3.8 shows the integrity per morphological type, and how many basins are involved. As can be seen, the most questionable morphologies are those of type 0, the rias and the karst.

All karst morphology was indicated here as questionable, because it was difficult to determine where karst regions occur. With the method used here, all basins with a carbonate lithology dominating the coast were initially selection. The selection was later adjusted based on literature. However, for some regions no further literature was available and karst does not necessarily form in all carbonate regions. On the other hand karst may also form in other lithologies. Therefore the distribution of the coastal karst morphology should be handled with care.



**Figure 3.16** Integrity of the morphologic and filtering typologies. Especially in type III coasts, and the rias of Asia lies uncertainty. Further the indicated karstic regions should be used with caution.

The distribution of the Fjärd, ria and glaciated sedimentary morphologies are questionable, because the main source material consisted of a map with coarse resolution. For fjärds further corrections were made based on visual judgement in Google Earth. The definition of Fjärd environments was relatively unclear because it is not a commonly used word, and therefore the visual identification was very difficult and is subject to scrutiny. The question with the ria morphology is whether all the rias identified should be in Type I, or whether some of them belong to Type III. Although rias genuinely are estuaries, those occurring in the Arctic zones perhaps should have been included in the 'passive filter' type. The glaciated sedimentary morphology was a 'rest'-morphology like the estuaries of type I. All basins which were covered by glaciers during the last glacial maximum, but were no fjords, fjärds or rias, were added to this group. Because there was no real criterium for this morphology, and because the difference between this morphology and rias is relatively thin, it is difficult to say whether its geographic distribution is correct.

Although not indicated on the map, two regions of less uncertainty can further be identified: The Mediterranean coast of Europe, and the coasts of Japan, China and Indonesia.

The European Mediterranean coast is very heterogenic, meaning that quite a few different morphologies occur side by side. The exact boundary where one morphology changes into another is therefore more difficult to establish, and there was more overlap of different morphologies in this region. The large karstic basins identified in Europe and North America will probably have to be revised, because if the drainage basin of a karstic region is large, it is probable that the waters will contain enough sediment to develop a coastal morphology belonging to one of the other morphological types. Only karstic regions with drainage basins of 1 or 2 cells are likely to act as type 0 coasts, because the waters are truly injected into the deeper ocean by tunnels in the limestone (Meybeck 2007, personal communication).

The Coasts of Japan, China and Indonesia were largely assigned the estuarine morphology, but this was generally because these basins were left over when all other morphologies were already assigned.

Similarly, type I includes many delta coasts which are so small that no clear delta can be distinguished from aerial photographs. Many of these coasts were 'left over' when all other morphologies were assigned. Because a considerable amount of runoff takes place through these coasts, they had to be included in a coastal typology where filtering takes place. As

these small delta coasts are not fjord-like, nor lagoon-like, they had to be included with type I, the estuaries. Reconsideration however lead to the suspicion that these small delta coasts physically and biogeochemically different from estuaries, and that less filtering takes place in these coasts than in the other estuarine types. It is therefore advised for future revision of the typology, to define a separate filtering typology for 'small delta' coasts, which would have a relatively weak filter capacity.

Finally it should be reminded that the macrotidal coasts identified here, represent estuaries with a tidal regime larger than 4 metres, while in the official definition it is 5 metres.

**Table 3.8** Integrity of the different morphologies and the number of basins involved.

Integrity	morphology	number of basins	
0	fjard	157	2%
0	fjord	238	4%
0	glac sediment	1316	19%
0	ria	391	6%
		2102	31%
1	karst	645	10%
1	ria	41	1%
		686	11%
2	arheic	175	3%
2	estuary	900	13%
2	Exo-Arheic	554	8%
2	fjord	253	4%
2	karst	15	0%
2	lagoon	684	10%
2	macrotidal	564	8%
2	mangrove	658	10%
2	ria	129	2%
2	RiOMar	61	1%
		3993	59%
		6781	100%

### 3.3 Conclusions

In the present chapter a coastal filtering typology was defined, which differentiates between coasts which do not act as a coastal filter (type 0) coasts which act as an estuarine filter (type I), a lagoon filter (type II) or as a fjord-like filter (type III). A coastal segmentation scheme was established, showing the geographic distribution of these types. The filtering typology differentiates between coasts in which the importance of various biogeochemical processes is different, resulting in different amounts of retention of nutrients by burial and denitrification in these coasts. The filtering typology and segmentation were found by first defining a morphologic typology and segmentation, and then aggregating this to the filtering typology.

#### **A global coastal segmentation**

The geographic distribution of the filtering typology shows that 21% of the world coastline is of type 0, meaning that there is no filtering of nitrogen and phosphorus in these proximal coastal oceans. The reason for this is that either there is no water, as for arheic basins, or there are no reservoirs which can facilitate biologic and abiotic filtering processes, as for karst and big rivers. 63% of the cells in our GIS eventually drains through a type 0 coast, delivering 53% of the global runoff, of which roughly 90% is delivered by big rivers. 12% of the global runoff is delivered by a single drainage basin, that of the Amazon. Africa is the only continent which has a coastline dominated by type 0 coasts, although the type 0 coastline length of Africa is equal to that of South America, and slightly less than that of North America.

At the remaining 80% of the world's coast, removal of nitrogen and phosphorus takes place in the proximal coastal ocean, by burial and denitrification. Together, the filtering types receive 47% of the global runoff from 37% of all continental cells. Roughly 50% of the drainage basins and coastline where filtering takes place is of type I. These basins deliver 60% of the runoff which will be filtered in the proximal coastal ocean (30% of the global runoff).

Type I coasts can be subdivided in plain estuaries, macrotidal, mangrove and ria coasts. 30% of the type I coastline can be depicted as an estuary without further specification. Mangrove estuaries make up 25% of this type's coastline while macrotidal and ria coasts each

make up 20% of it. The runoff each of these types receive is roughly equally distributed over the estuarine, macrotidal and mangrove estuaries (each 30%), while the rias receive only 10%. The reason why rias receive less runoff is because they occur in arctic climates, which are dryer. Most estuarine coasts occur in Asia and Indonesia (20% of the global coastline, and 50% of all estuaries worldwide).

Only 10% of the global coastal cells consist of lagoon type coasts, which receive 7% of the global runoff, from 10% of the continental surface. Most lagoons occur on the East-coast of the American continent, along the shores of the Gulf of Mexico. On the other continents they occur in roughly equal amounts, but they are underrepresented in Indonesia.

The type III coasts, which represent 'passive filter' type coasts finally make up 30% of the global coastline and receive 10% of the global runoff from only 7% of the continental area. Roughly 70% of the coasts of this type are glaciated sedimentary coasts. They receive however only 30% of the runoff received by type III coasts. Fjords, which make up 25% of the type III coastline, receive half of the runoff which is filtered in type III coasts. Fjårds finally make up only 7% of the coastline, but receive 20% of the type III runoff.

Type III coasts occur primarily in North America (20%) and Europe (6%), and in smaller amounts in Asia (2%) and South America (1% of the global coastline).

### **Geographic distribution**

The distribution of the filtering typology over the continents, shows that Africa is the only continent dominated by type 0 (51% of its basins), but Asia and North-america have type 0 as second most prevalent type. North America and Europe are dominated by glaciated sedimentary coasts and other type III coasts (55 and 46% of their basins respectively). Asia, Australasia, Indonesia and South America are all dominated by estuaries (62, 58, 88 and 53% respectively).

None of the continent's coasts are dominated by lagoons. However, they are most common in North-America, and are surprisingly less common in Indonesia and Asia than would be expected. Normalized to the total number of basins per continent, lagoons make up 10 % of the European, North- and South-American coast, 15% of the African, 20% of the Australian, and only 5 and 7% of the Indonesian and Asian coasts.

The distribution of runoff over the continents shows a division in 4 groups: 1) Australasia receives only 1% of the global runoff; 2) Europe and Indonesia 9%; 3) Africa and North-America 14%; and 4) Asia and South-America each 27 %. On all continents, except for Australia and Indonesia, between 37 and 77% of the runoff flows into type 0

coasts. The amounts of runoff received by type one coasts varies between 16 and 37%. Australia and Indonesia have 63 and 87% of their runoff flowing into type I coasts. Type II coasts receive between 3 and 17% of the runoff on each of the continents. Type III coasts of receive 4% of the continental runoff of South America and Asia, and between 21 and 30% of Australasia, Europe and North America.

### **Integrity**

Overall we feel confident about the segmentation and geographical distribution of the filtering and morphologic typologies. Some regions for which uncertainty exists however can be defined. These regions include especially the Arctic climates, the Mediterranean coast of Europe, and the coasts of Japan, China and Indonesia. The questionable basins make up 30% of the total number of basins, with another 10% being a bit less uncertain. The most questionable is the geographic distribution of fjärds and glaciated sedimentary coasts, as well as the distribution of ria and karst morphologies.

Finally it is suggested that perhaps a distinction should be made between small deltas and estuaries, as small deltas can be expected to have a smaller filtering capacity than the other estuarine types (Meybeck, personal communication, 2007).

## 4 Part 2: A general nutrient box model for lagoons

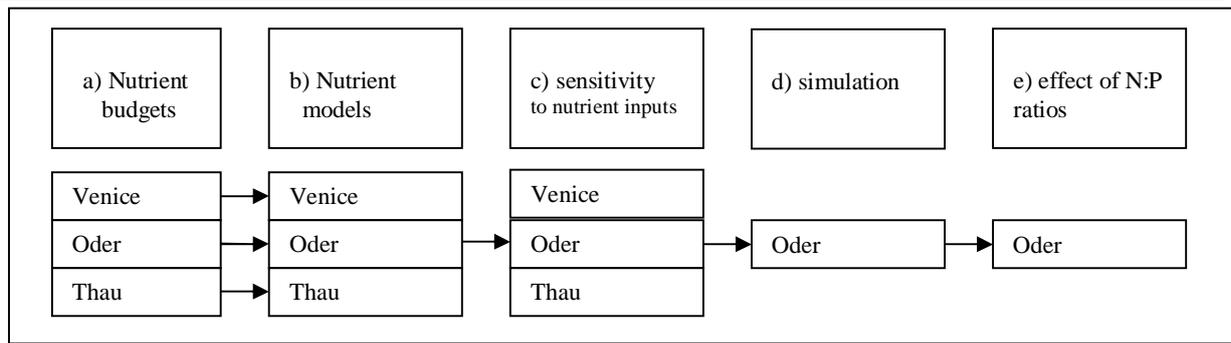
### 4.1 Approach

The filtering typology presented in chapter 3 shows the geographic distribution of 4 types of coast which are assumed here to have different biogeochemical dynamics, and therefore different effects on the fate of nutrients in the proximal part of the ocean. For each type, a generic nutrient model will be developed in the G-NUX framework. The 4 generic models together with the filtering typology would then allow an approximation of the nutrient fluxes and levels in any proximal coastal ocean on earth. In the present chapter, an attempt is made to develop one of these generic models, namely the one for lagoons. The other models and a better version of the lagoon model will be published by Laruelle *et al.* (in preparation).

The aim of this chapter is to assess whether a simple representation of processes with only first order kinetics is appropriate to develop a generic lagoon box model, as well as to assess whether any typical characteristics of lagoons, which differentiate them from estuaries, should be included in the model.

Figure 4.1 shows the workflow for the development of the box model. The bracketed letters in the text correspond to those in the figure, and represent steps taken. First nutrient budgets were calculated from information available in literature for 3 sites: Oder, Venice and Thau lagoon (a). Box models are derived from these budgets by assuming first order kinetics for all fluxes, and by basing the kinetic constant on the observed fluxes and concentrations at these sites (b). For each site 2 types of models were made: one with a very simple hydrologic representation, consisting merely of the river input and sea efflux. The second model also takes into account evaporation, precipitation and water inflow from the sea. This yields 6 site-specific models, 2 for each site (c). The only difference between each of the models are the rate constants, which are obtained from the previously obtained steady state nutrient budgets.

The performance of the site-specific Oder box-model was tested over a time span of 1980 to 2000 (d). The observation that in this simulation the model underestimates the lagoon DIP, while overestimating lagoon DIN lead to the assumption that this is correlated with the limitation of growth by either N or P in the model. This limitation is prescribed by the ratio at which primary producers consume N and P. The influence of a wide range N:P ratios at which photosynthesis can take place was therefore tested (e).



**Figure 4.1** Work flow for the modelling part

## 4.2 Method

### 4.2.1 Budgets

In a nutrient budget for a lagoon all relevant pathways by which nutrients can enter and leave the lagoon, as well as the internal processes by which nutrients are transformed from one form to another are identified and quantified.

The present model focuses on the nutrients N and P and distinguishes between 5 pools of nutrients which can be found in the water column of lagoons: By naming convention, these pools are organised as dissolved inorganic N and P (DIN, DIP), particulate organic N and P (PON, POP) and particulate inorganic P (PIP). DIN includes nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ) and ammonia ( $\text{NH}_3$ ), while DIP represents the phosphate ion ( $\text{PO}_4$ ). These are the state variables of our model, and are listed in table 4.1

The main pathways by which the nutrient pools are replenished and depleted from outside the lagoon system are 1) transport with the water cycle (see the thick arrows in figure 4.3); 2) exchange of nitrogen gas with the atmosphere as a loss of DIN due to denitrification; and 3) burial of the particulate matter pools PON, POP and PIP. Inside the lagoon the nutrients can be transferred from one pool to another by 1) ad- and desorption of DIP to surfaces, forming PIP or releasing DIP from PIP; 2) incorporation of DIN and DIP into organic matter during production; and 3) transformation of PON and POP to DIN and DIP during remineralisation.

**Table 4.1** State variables

Symbol	State variable	Unit
DIN	dissolved inorganic N	$10^6$ mol N
PON	particulate organic N	$10^6$ mol N
DIP	dissolved inorganic P	$10^6$ mol P
PIP	particulate inorganic P	$10^6$ mol P
POP	particulate organic P	$10^6$ mol P

The dissolved and suspended nutrients in the water column are transported by advection. The amount of nutrients transported ( $T$ ) can therefore be estimated if their concentration in the water column ( $C$ ) and the transported volume of water ( $V$ ) are known:

$$T = C \cdot V \quad [10^6 \text{ moles / km}^3] \cdot [\text{km}^3 / \text{y}] = [10^6 \text{ moles / y}] \quad (1)$$

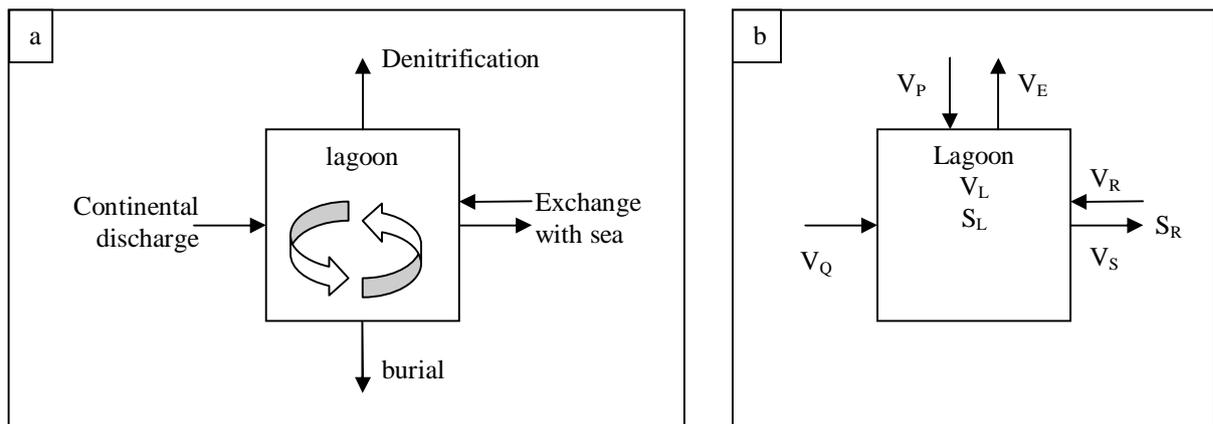
To calculate the nutrient budget of a lagoon, a water budget is therefore required.

### Flushing time

The simplest representation of the water cycle in lagoons would only involve river discharge ( $V_Q$ ) and export of water to the sea ( $V_S$ ) (see figure 4.2). The residence time (referred to here as flushing time  $\tau_{\text{flush}}$ ) of nutrients in this simple system would correspond to the volume of the lagoon ( $V_L$ ), divided by the river discharge.

Because the volume of water in the lagoon can be assumed constant,

$$\tau_{\text{flush}} = V_L / V_Q \quad (2)$$



**Figure 4.2** a) Schematic representation of fluxes entering and leaving lagoons.

b) Water budget for lagoons,  $V_P$  = precipitation,  $V_E$  = evaporation,  $V_Q$  = continental discharge,  $V_R$  = sea import and  $V_S$  = lagoon export.  $S_L$  and  $S_R$  are lagoon and sea salinity respectively

### Residence time

A better representation of the physics of lagoons would however also include water inputs from precipitation ( $V_P$ ), and through inlets, which connect the lagoon to the ocean ( $V_R$ ). Water removal would then still take place by outflow ( $V_S$ ) to the ocean, but also by evaporation ( $V_E$ ). The Volume of water in the lagoon can be assumed constant in time, so that:

$$dV_L/dt = V_E + V_P + V_Q + V_R + V_S = 0 \quad (3)$$

Precipitation, evaporation and continental discharge are usually measured directly. The exchange with the ocean however is not.  $V_R$  can still be estimated from a salt-budget, as is applied by Witek *et al.* (2003) and a modified version of which is prescribed in the LOICZ budget methodology (Gordon *et al.*, 1996). Because salinity data is usually readily available, this method can easily be applied to many coastal systems. Assuming that the salinity of river, rain and evaporated water are all zero, and that the lagoon's volume is constant over time, the salt budget reads:

$$V_R \cdot S_R = V_S \cdot S_L \quad (4)$$

This means that the amount of salt imported from the sea must equal the amount of salt exported from the lagoon. Because the sea and lagoon have different salinities, the volume of water imported is not equal to the volume of water exported.

From equation (2) an expression for  $V_S$  can be found, which subsequently can be substituted in equation (3), allowing to calculate  $V_R$ : the volume of water imported from the sea.

$$V_S = (V_E + V_P + V_Q + V_R) \quad (5)$$

$$V_R = S_L \cdot (V_Q + V_P + V_E) / (S_R - S_L) \quad (6)$$

Finally, when  $V_R$  is known,  $V_S$  can be calculated with equation (4), so that all fluxes of the water budget are now determined.

The residence time of nutrients in this water budget is slightly different then that in the simple model. The residence time is now the volume of the lagoon divided over the amount of water exported from the lagoon to the sea.

$$\tau_{res} = V_L / V_S \quad (7)$$

It depends on the climate and morphology of the lagoon whether this flux is positive or negative. Many lagoons in arid climates may experience an net influx of water, while lagoons in more temperate regions will have a residence time which is close to their flushing time. The openness of the system to the sea also determines whether the residence and flushing time are much alike, or much different. Choked lagoons are connected to the sea by river-like channels, while restricted and leaky lagoons are progressively more open to the sea. The relative importance of the river and sea in the lagoon then also affects the residence time. River-dominated systems will have less inflow from the sea, than lagoons where continental discharge is low.

Once the water budget is complete, the nutrient budgets can be derived for each of the nutrient pools. This is done by multiplying the transported volumes of water with the

concentration of the different pools in the lagoon. The concentrations of the pools in the lagoon, river and sea are obtained from literature, as are all other fluxes representing transformations from one pool to another, and removal of nutrients from the system by denitrification and burial.

#### 4.2.2 Nutrient models

Simple nutrient box-models can be derived from nutrient budgets relatively easily by finding a mathematical expression for all of the fluxes in the budget. In the following paragraphs the derivation of the mathematical expressions will be explained. Figure 4.3 shows in black, all the fluxes and state variables taken into account. The state variables are DIN, PON, DIP, POP and PIP. The fluxes are denitrification, production, remineralisation, PIP ad- and desorption and burial of PON, POP and PIP. Water fluxes taken into account are those from river discharge and the water exchanged with the sea.

##### Nutrient imports and exports

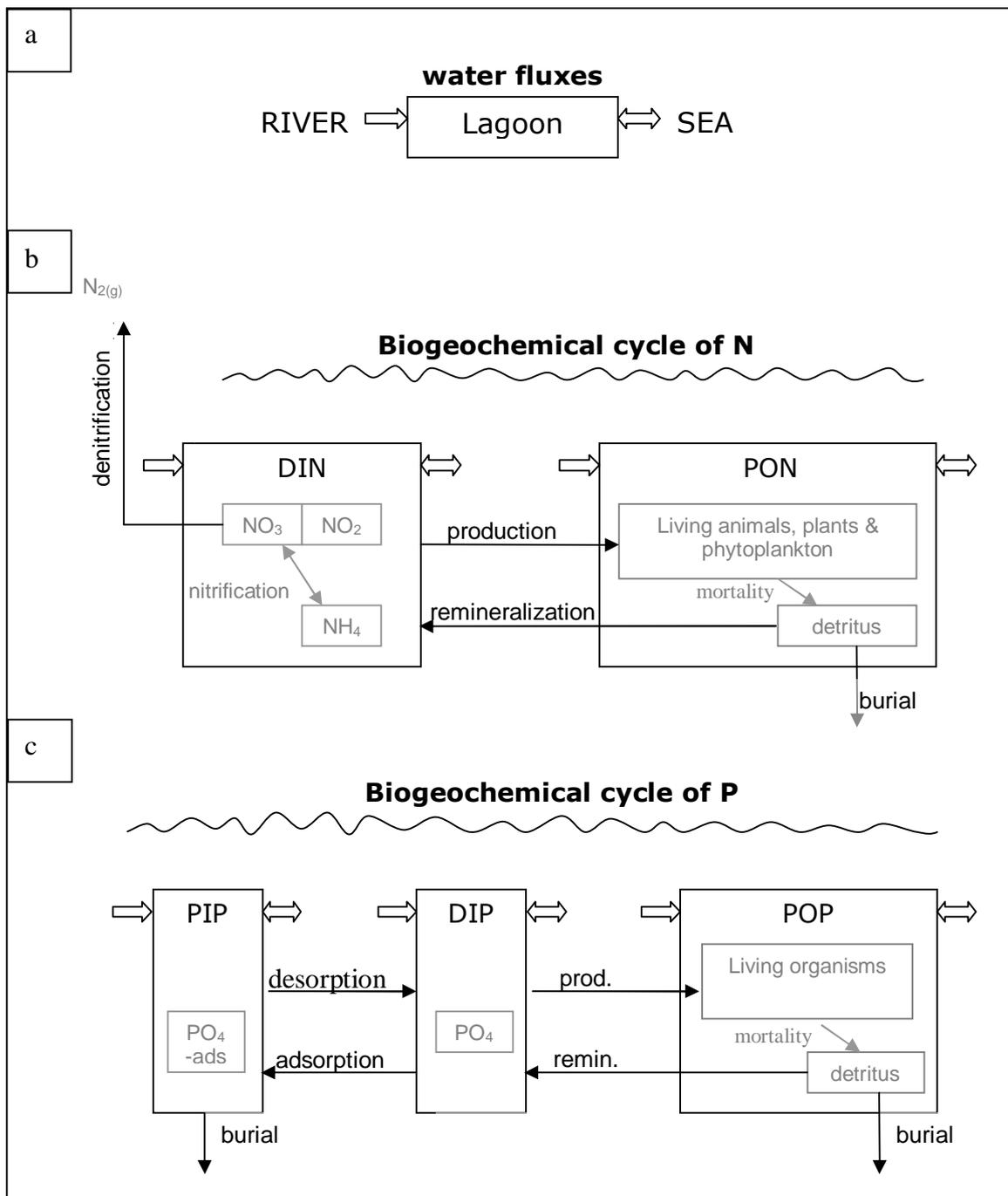
The input of nutrients by river discharge and from sea inflow on a yearly basis, are either obtained from literature, or by multiplying the river discharge and sea inflow with an average nutrient concentration in the river and sea respectively:

$$T = C \cdot V \quad (8)$$

The export of nutrients from the lagoon can be obtained from the flushing time or the residence time, according to the physics of the model used. If the flushing time is used, only river inputs and lagoon exports are taken into account. If the residence time is used, precipitation, evaporation and inputs from the sea must be considered as well.

##### Transformations

It was assumed here that all of the fluxes follow first order kinetics and that the magnitude of a flux is proportional to the source reservoir. Assuming first order kinetics is the simplest representation possible for the biogeochemical cycle. Although often dependencies on temperature and luminosity are used to represent primary production and remineralisation (i.e. in Witek *et al.*, 2004), mineralization was also successfully represented by first order kinetics in other models (Rabouille *et al.*, 2001)



**Figure 4.3** a) Water cycle and biogeochemical cycles of b) N and c) P in lagoons The nutrient pools and processes which are included in our model are depicted in black boxes and by black arrows respectively.

A first order rate constant is obtained for each of the fluxes by dividing the flux (production, remineralisation, denitrification, PIP ad-/desorption or burial) by the reservoir it originates in ( $R_Q$ ). For production for example, the source reservoirs are DIN and DIP, while for P release it is the PIP reservoir.

$$k = Q / R_Q \quad (9)$$

The rate constants thus obtained are listed in table 4.2, together with the state variable which represents their source reservoir.

Transformation of DIN to PON and DIP to POP are complex processes, whose representation is somewhat simplified by the 1<sup>st</sup> order kinetic approach. Organisms take up N and P in certain ratios, which corresponds to the ratio with which N and P are required by the photosynthesis reaction (see §2.1.2). Light and nutrient availability can limit phytoplankton growth, according to van Liebig's law of the minimum. Growth limitation is taken into account in this model, by only allowing N and P production at the ratio of 16:1 (in moles). This is the Redfield ratio, and is the average N:P ratio at which phytoplankton uses nutrients during photosynthesis

**Table 4.2** List of rate constants and the state variables they should be multiplied with.

$k_{PPN}$	× DIN	rc for N assimilation
$k_{PPP}$	× DIP	rc for P assimilation
$k_{remN}$	× PON	rc for N remineralisation
$k_{remP}$	× POP	rc for P remineralisation
$k_{denit}$	× DIN	rc for N denitrification
$k_{burN}$	× PON	rc for N burial
$k_{burPOP}$	× POP	rc for P burial
$k_{burPIP}$	× PIP	rc for PIP burial
$k_{Prel}$	× PIP	rc for P release from PIP

Phosphorus sorption and desorption processes play important roles in many lagoons, because P release in previously P-limited systems may enhance primary production. In the model presented here only net ad- or desorption is represented. Generally this flux consists of a net adsorption of DIP to surfaces, forming PIP. This flux is therefore driven by the DIP pool. In cases where a net desorption of P takes place, the process would be driven by the PIP pool.

The system of differential equations which describes the change in each of the nutrient pools in our model, is given in table 4.3. The models were written in Matlab 6.5. Some sample models can be found in appendix B.

**Table 4.3** System of differential equations

---

$\frac{dDIN}{dt}$	$= In_{DIN} + In_{seaDIN} - \min(k_{PPN} \times DIN, k_{PPP} \times DIP \times NP) + k_{remN} \times DIN - k_{denit} \times DIN - DIN / r_t$
$\frac{dPON}{dt}$	$= In_{PON} + In_{seaPON} + \min(k_{PPN} \times DIN, k_{PPP} \times DIP \times NP) - k_{remN} \times PON - k_{burN} \times PON - PON / r_t$
$\frac{dDIP}{dt}$	$= In_{DIP} + In_{seaDIP} - \min(k_{PPN} \times DIN / NP, k_{PPP} \times DIP) + k_{remP} \times POP + k_{PreI} - DIP / r_t$
$\frac{dPIP}{dt}$	$= In_{PIP} + In_{seaPIP} - k_{PreI} \times PIP - k_{burPIP} \times PIP - PIP / r_t$
$\frac{dPOP}{dt}$	$= In_{POP} + In_{seaPOP} + \min(k_{PPN} \times DIN / NP, k_{PPP} \times DIP) - k_{remP} \times POP - k_{burPOP} - POP / r_t$

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### 4.2.3 Research sites and data

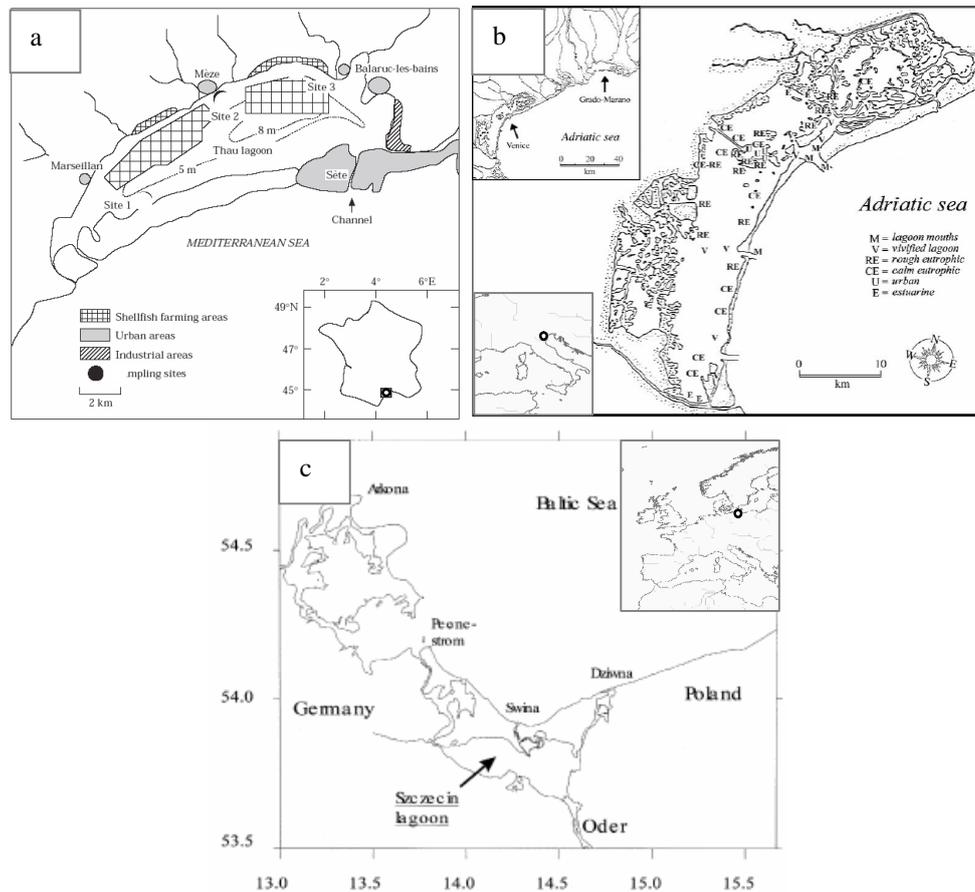
Nutrient budgets were created for 3 sites in Europe: Thau, Venice and Szczecin lagoon, at the mouth of the Oder. These sites represent the end-members of morphologically different types of lagoon. The main characteristics of the lagoons are listed in table 4.4. Their location and regional environment are given in figure 4.4, as well as the references from which the data for the budgets and models were obtained.

#### **Szczecin lagoon**

The Szczecin lagoon is a choked lagoon. It is connected to the sea via several channels which are narrow compared to the size of the lagoon. The lagoon is very large, but undep: it has an area of 687 km<sup>2</sup>, and is on average 3.8 m deep. The lagoon consists of two parts, one of which lies in Poland and the other in Germany. The Oder river discharges in what the Polish call the Wielki Zalew, and what the Germans refer to as Grosses Haff. This half comprises 60% of both the lagoon area and volume. It has two outlets at Dziwna and Swina, through which 80% of the Oder river water leaves the lagoon. 20% of the Oder river water reaches the Kleines Haff on the German side. From the Kleines Haff a third outlet, the Peenestrom, meanders through several smaller lagoons before reaching the Baltic Sea.

**Table 4.4** Characteristics of Thau, Venice and Szczecin lagoons

	Szczecin	Venice	Thau	
<b>area</b>	687	54	75	km <sup>2</sup>
<b>volume</b>	2,60	0,54	0,30	km <sup>3</sup>
<b>discharge</b>	17,59	0,95	0,07	km <sup>3</sup>
<b>Depth</b>	3,80	1,00	4,00	m
<b>Type</b>	Choked	leaky	restricted	
<b>Character.</b>	2 halves, dredging	Shallow, dredging	shellfish	
<b>References</b>	(Grelowski <i>et al.</i> , 2000;	(Flindt <i>et al.</i> , 1997;	(De Casabianca <i>et</i>	
<b>Used to constrain the</b>	Pastuszak <i>et al.</i> , 2005;	Sfriso and	<i>al.</i> , 1997; Picot <i>et</i>	
<b>nutrient budgets and</b>	Wielgat and Witek,	Marcomini, 1994;	<i>al.</i> , 1990; Plus <i>et</i>	
<b>models</b>	2004)	Sfriso <i>et al.</i> , 1994;	<i>al.</i> , 2006; Souchu <i>et</i>	
		Sfriso <i>et al.</i> , 1995;	<i>al.</i> , 1997; Souchu <i>et</i>	
		Sfriso <i>et al.</i> , 1988;	<i>al.</i> , 2001)	
		Solidoro <i>et al.</i> , 2005)		



**Figure 4.4:** location of a) Thau, b) Venice and c) Szczecin lagoon (adjusted from De Casabianca *et al.*, 1997, Humborg *et al.*, 2000; and Marchini and Marchini, 2006)

The Szczecin lagoon is extensively researched and monitored by Polish and German authorities. The lagoon is of economic interest for both countries, because of its biologic richness, and relatively warm waters, making it attractive for tourism. Schernewski (2004) published an extensive report with discharge and water quality parameters of the Oder river, both halves of the lagoon and the Pomeranian bay from 1980 to 1999.

### **Venice**

Venice is a leaky lagoon, meaning that it is quite open to the sea. Despite that, Venice resembles more to Szczecin lagoon than to the Thau, because of its volume and residence time. The lagoon covers an area of about 500 km<sup>2</sup>. Its average depth is less than 2 m, but deeper channels cut through the tidal plains. Three narrow inlets connect the lagoon to the Adriatic Sea: Lido, Malamocco and Chioggia inlet. The lagoon of Venice receives approximately 4.6 x 10<sup>6</sup> kg of nitrogen and 0.21 x 10<sup>6</sup> kg of phosphorus per year from its inhabitants, as well as inputs of port and industrial activities. The lagoon provides for fisheries, recreational and touristic activities (Solidoro, 2005).

### **Thau**

Thau lagoon is the smallest lagoon investigated here. It is a restricted lagoon, meaning that it is separated from the sea by a barrier, and connected by a few inlets. The Thau coastal lagoon covers 75 km<sup>2</sup> and has a mean depth of 4 m, with a maximum of 11m. Its volume approximates 300 Mm<sup>3</sup>. Fresh water inputs are provided by many small and mostly non-permanent streams. The lagoon has an exceptionally high nutritional potential, supporting the main industrial activity of the area: shellfish-farming and fisheries. Shell-fish farms cover one fifth of the lagoon area. There is not much industrial activity in the area, the two main factories produce fertilizers for the vine yards which occupy 40% of the catchment area

## **4.3 Results**

### **4.3.1 Nutrient budgets**

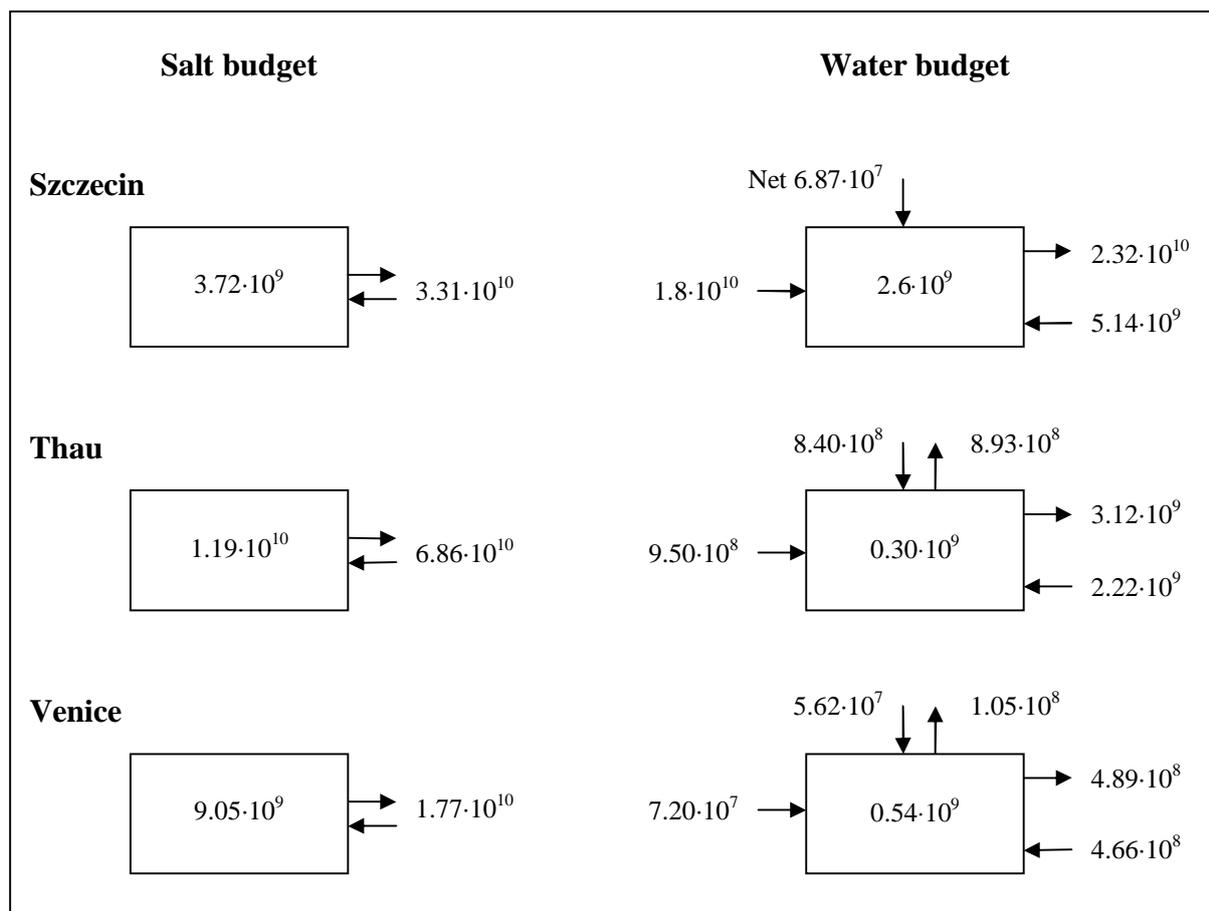
The salt and water budgets belonging to the three lagoons are given in figure 4.5. The salt budget is used to calculate the water exchanged between the lagoon and the sea. The Oder receives the largest river discharge and the largest net precipitation.

From the water budgets, flushing and residence times can be derived (see table 4.5). The flushing time and residence time hardly differ for the Oder, where it varies from 1.6 to

1.3 months respectively (0.14 and 0.11 years in the table). For Venice lagoon the difference is somewhat larger, having a flushing time of 7 months and a residence time of 2 months (0.57 and 0.17 years). Thau lagoon experiences the largest influence from the ocean, which is why its flushing and residence time differ most. Thau lagoon has a flushing time of 3.5 years, while its genuine residence time is only 6 months. This shows that the difference between flushing and residence time is significant for systems which are influenced by the ocean, while it is negligible for systems where ocean influence is small.

**Table 4.5** flushing time and residence time in years

	Venice	Thau	Szczecin
Flush $\tau$	0.57	3.47	0.14
Residence $\tau$	0.17	0.51	0.11



**Figure 4.6** Salt and water budgets for Szczecin, Thau and Venice lagoons, based on values reported in the literature.

When making a nutrient budget based on literature data, one depends on the available literature to obtain values for each of the processes and reservoirs. Often some of these values are not available, or it is unclear what numbers in literature genuinely represent. For example, PIP ad- and desorption are not always estimated. Also, reported values may differ widely in literature. This is because of seasonality and daily to annual variations. Sampling is often only performed during a few days or weeks each season, while it is used to represent the entire season or year. As a result, reported seasonal and annual values may differ from one campaign to the other. Finally, lagoons and estuaries are not homogeneous bodies of water. By definition, they show gradients as the river water mixes with sea water. This forms a limitation for box models, as they have to approach these systems as homogeneous.

The end result of all these uncertainties is that when making a nutrient budget, the constraints for some of the processes will be worse than for others. When compiling a budget from different data sources, for example because one assessment did not include PIP burial while the other did not include the N cycle, discrepancies may exist between the obtained values so that the resulting budget is not at steady state.

The fluxes which are considered the least reliable can be adjusted to the other values, because it can be assumed that the water and nutrient budgets of a lagoon are at steady state. Often the fluxes which are deduced by mass balance are burial, remineralisation, PIP ad- and desorption and export to the sea. This was the case for the budgets of Thau and Szczecin presented here. For Venice lagoon however, all processes were well constrained, and it was chosen to adjust the river input fluxes, because there were large seasonal fluctuations.

For most estuaries, a budget based on flushing time will suffice to represent the nutrient levels well. For lagoons however, this is not necessarily the case, because many lagoons are known to exchange water with the sea. To assess the influence of this exchange, and the importance of these fluxes, budgets were made both based on flushing time (no exchange with the sea) and residence time (allowing exchange with the sea). When making these two different budgets, the constraints from literature remain the same, while the steady state differs, because an extra nutrient input flux is introduced. Because the system can be assumed at steady state, the least reliable fluxes can be deduced from all other fluxes. As was said before, this was done differently for Venice then for Thau and Szczecin lagoons. The result is that for Venice, the amount of nutrients retained in the budget based on flushing time differs from those retained in the budget based on residence time, while the absolute amount

of nutrients does not change (see table 4.6). The retention of nutrients predicted here for Venice should therefore be taken with care. It should be noted that the amount of retention does not change significantly for the other sites, and because denitrification was considered as well restrained the difference in retention is entirely due to differences in PON burial. This also explains why the N retention predicted by budgets based on flushing and residence time differ more from each other than the P retention.

For Venice, nitrogen retention increases from 74% to 82% based on residence time (see table 4.6). For the Thau, it decreases from 89% to 70%. For Szczecin, it decreases from 46% to 38%. P retention decreases from 65% to 36% for Venice, but only from 91% to 89% for Thau, and remains constant for Szczecin lagoon.

Finally, note that Thau lagoon shows a net adsorption of P, by the negative value for PIP-release, both with flushing and residence time. Also, no denitrification takes place in Thau lagoon (Picot *et al.*, 1990; Plus *et al.*, 2006).

**Table 4.6** Steady state nutrient budgets for Venice, Thau and Szczecin lagoon. Compiled from various data sources (see table 4.4) and adjusted for steady state. Unless stated otherwise, units are  $10^6$  moles

	Venice flush	Venice res	Thau flush	Thau Res	Szczecin flush	Szczecin res	units
flushing time	0,57		3,47		0,14		y
residence time		0,17		0,51		0,11	y
<b>Lagoon</b>							
DIN	19,27	19,27	1,74	1,74	249,76	249,76	$10^6$ moles
PON	3,85	3,85	1,50	1,50	140,76	140,76	
DIP	5,23	5,23	0,15	0,15	7,69	7,69	
POP	0,24	0,24	0,07	0,07	8,80	8,80	
PIP	1,50	1,50	0,28	0,28	17,60	17,60	
<b>Sea input (<math>V_R</math>)</b>							
DIN	0	71,08	0	1,95	0	182,95	
PON	0	3,33	0	1,86	0	194,21	
DIP	0	0,62	0	0,09	0	7,18	
POP	0	0,22	0	0,19	0	12,14	
PIP	0	0,87	0	0,52	0	48,55	
<b>River input (<math>V_Q</math>)</b>							
DIN	239,00	314,00	4,03	4,03	3211,99	3211,99	
PON	70,00	13,00	4,31	4,31	1784,44	1784,44	
DIP	6,50	0,87	0,48	0,48	80,72	80,72	
POP	4,38	6,46	0,28	0,28	111,53	111,53	
PIP	23,13	53,00	0,78	0,78	513,03	513,03	
TN	364,00	327,00	8,34	8,34	4996,43	4996,43	
TP	34,00	60,33	1,55	1,55	705,28	705,28	
<b>Sea export (<math>V_S</math>)</b>							
DIN	33,90	111,31	0,50	3,40	1724,28	2224,92	
PON	6,78	22,26	0,43	2,93	971,81	1253,98	
DIP	9,20	30,21	0,04	0,29	53,10	68,51	
POP	0,42	1,39	0,02	0,14	60,74	78,37	
PIP	2,64	8,68	0,08	0,55	121,48	156,75	
<b>Transformations</b>							
PPN	331,00	331,00	343,11	343,11	5292,83	5292,83	
PPP	21,00	21,00	21,44	21,44	330,80	330,80	
Nrem	240,00	171,23	339,58	340,52	4306,63	4624,33	
Prem	18,30	19,76	21,43	21,50	287,60	282,19	
PONbur	154,00	153,84	7,41	5,83	1798,83	1393,18	
POPbur	6,60	6,53	0,28	0,27	93,99	93,90	
PIPbur	15,40	15,23	1,12	1,10	375,97	375,61	
TPbur	22,00	21,76	1,41	1,37	469,97	469,51	
Ndenit	114,00	114,00	0,00	0,00	501,51	501,51	
PIPrelease	5,10	29,96	-0,42	-0,34	15,58	29,22	
<b>Retention</b>							
N	268,00	267,84	7,41	5,83	2300,34	1894,69	
P	22,00	21,76	1,41	1,37	469,97	469,51	
N	74	82	89	70	46	38	%
P	65	36	91	89	67	67	%

### 4.3.2 Nutrient models

#### Towards a generic nutrient box model for lagoons

From each steady state nutrient budget a nutrient box-model can be derived. Each of these nutrient models has different rate constants. Table 4.7 lists these constants.

The aim of making nutrient box models in this thesis, is to find a generic model which coupled to the filtering typology would allow to predict nutrient levels, fluxes and retention in any lagoon coast in the world. It was assumed that the rate constants of different lagoons would be relatively alike, allowing to easily base a generic model on these constants.

Comparison of the rate constants however shows that this is not possible. The last two columns in table 4.7 list the standard deviation (SD) and a normalized standard deviation (Nor. SD) for each group of rate constants. Normalisation was done to the mean rate constant of each group. A normalized SD which is greater than 1, indicates that the SD of that group is larger than the group's average. In other words, the k-value could be anything from zero to more than 2 times the average.

The representation of primary production and remineralisation as a first order rate equation is therefore too primitive to represent these fluxes in a generic model for lagoons. Dependency of these fluxes on other factors such as temperature or light attenuation, as was done by Wielgat *et al.* (2004), might allow the development of a generic model for lagoons. However, as the generic models is intended to be used coupled with the filtering typology, the extra required information will have to be collected or inferred for every (lagoon) coast in the world.

**Table 4.7** Rate constants for the models derived from the steady state flushing time and residence time- budgets.

	Venice flush	Venice res	Thau flush	Thau res	Szczecin flush	Szczecin res	SD	Nor. SD
flushing time	0,57		3,47		0,14	y		
residence time		0,17		0,51		0,11	y	
k-values								
kPPN	17,18	17,18	197,47	197,47	21,19	21,19	84,06	1,07
kPPP	4,01	4,01	142,96	142,96	43,01	43,01	58,52	0,74
kNrem	62,27	44,42	226,39	227,01	30,59	32,85	87,42	1,11
kPrem	75,97	82,04	306,1	307,19	32,69	32,08	119,83	1,52
kPONbur	39,95	39,91	4,94	3,89	12,78	9,9	15,40	0,20
kPOPbur	27,4	27,09	4,02	3,92	10,68	10,67	9,78	0,12
kPIPbur	10,25	10,13	4,02	3,92	21,37	21,35	7,19	0,09
kNdenit	5,92	5,92	0	0	2,01	2,01	2,46	0,03
kPIPrel	3,39	19,94	-1,51	-1,23	0,89	1,66	7,38	0,09

The other processes, burial, PIP release and denitrification, have a normalized SD varying between 3% and 20 % of the standard deviation. Considering the uncertainty in this kind of assessments, this range of variation seems acceptable.

### 4.3.3 Sensitivity analysis

A sensitivity analysis was performed, which shows the response of Thau, Venice and Szczecin lagoons to changes in river nutrient inputs. The analysis was done for both the model based on flushing time and the model based on residence time, so that the difference between the results of these models can be compared.

Anthropogenic activities have lead to increases in nutrient inputs to the coast in many places in the past. In many places the anthropogenic load of nutrients to the coast continues to rise, in other places it is decreasing again since the effect of nutrients on ecosystems is better understood, and measures are being taken.

The nutrient inputs were varied from 0% to 200% of the present, steady state values. A nutrient input of 0% is not realistically possible, but low nutrient inputs represent a situation where an extensive area with marshes or a dam occur in the river course, and many nutrients are retained in these reservoirs. The results for a river input of 100%, represent the original steady state of the model and corresponds to the present state of the lagoons. An increase of 200% represents a situation where anthropogenic activities increase the nutrient load on the coast due to increases in sewer sludge from population growth, or increases in fertilizer use.

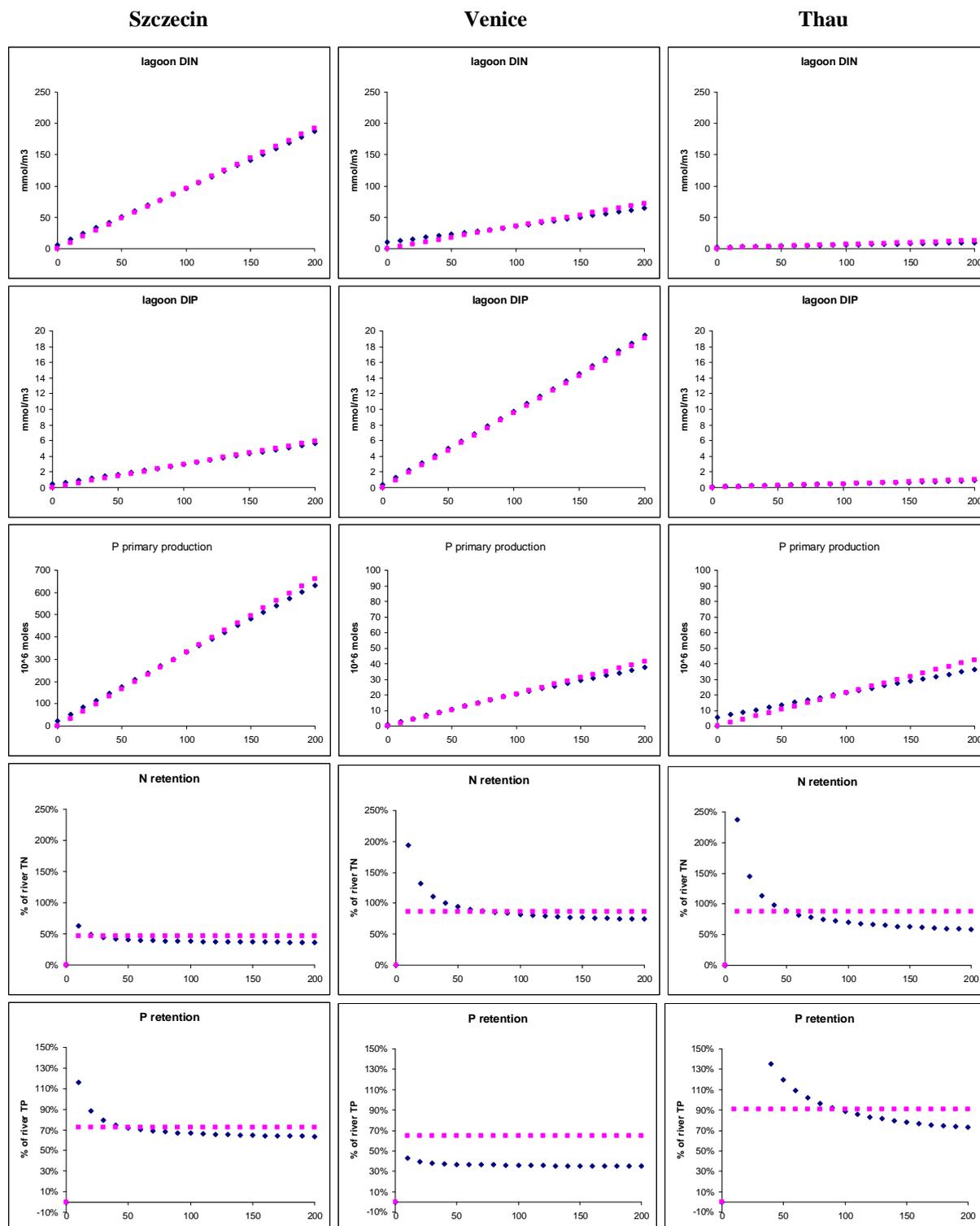
The results of the sensitivity analysis are given in figures 4.9 to 11. Each figure shows the response of Szczecin, Venice and Thau lagoon according to both the model based on residence time and flushing time to a variation of nutrient inputs (light squares and dark diamonds respectively). For each lagoon are given the modeled lagoon DIN and DIP, primary production and N and P retention. Primary production is given in moles of P, because from these values it is easier to recalculate productivity in terms of carbon or nitrogen with Redfield stoichiometry, C:N:P = 106:16:1.

### **Sensitivity to simultaneous changes in river N and P inputs**

Figure 4.9 shows the response of the lagoons when the river input of both N and P is increased, or decreased. First of all it can be observed that the models based on residence time and flushing time do not yield very different results, except for the retention of nutrients. In the model based on flushing time, the percentage of nutrients retained remains constant, while the model based on residence time shows a very high percentage of retention at low river nutrient inputs, which rapidly decreases to a retention which is lower than that of the model based on flushing time. The high percentage of retention is caused by an import of nutrient from the sea, while little nutrients are imported from the river and normalization is done versus the river load. At high river nutrient inputs, a larger amount of the nutrients is flushed from the lagoon, so that relatively less of the river load is retained in the lagoon.

Lagoon DIN, DIP and primary production all respond linearly to a linear increase in river nutrient inputs. DIN and primary production are most sensitive to river nutrient inputs in Szczecin lagoon, probably because this choked lagoon experiences the least influence of the sea. For DIP concentrations, Venice is the most sensitive lagoon.

### Sensitivity to variations in both N and P



**Figure 4.9** Sensitivity to variations in river nutrient inputs, if both N and P increase or decrease. Light squares correspond to results of the model based on flushing time, dark diamonds correspond to results of the model based on residence time. Each diamond and square represent a separate simulation in which steady state can be arrived at in 12 years.

### **Sensitivity to changes in river N inputs**

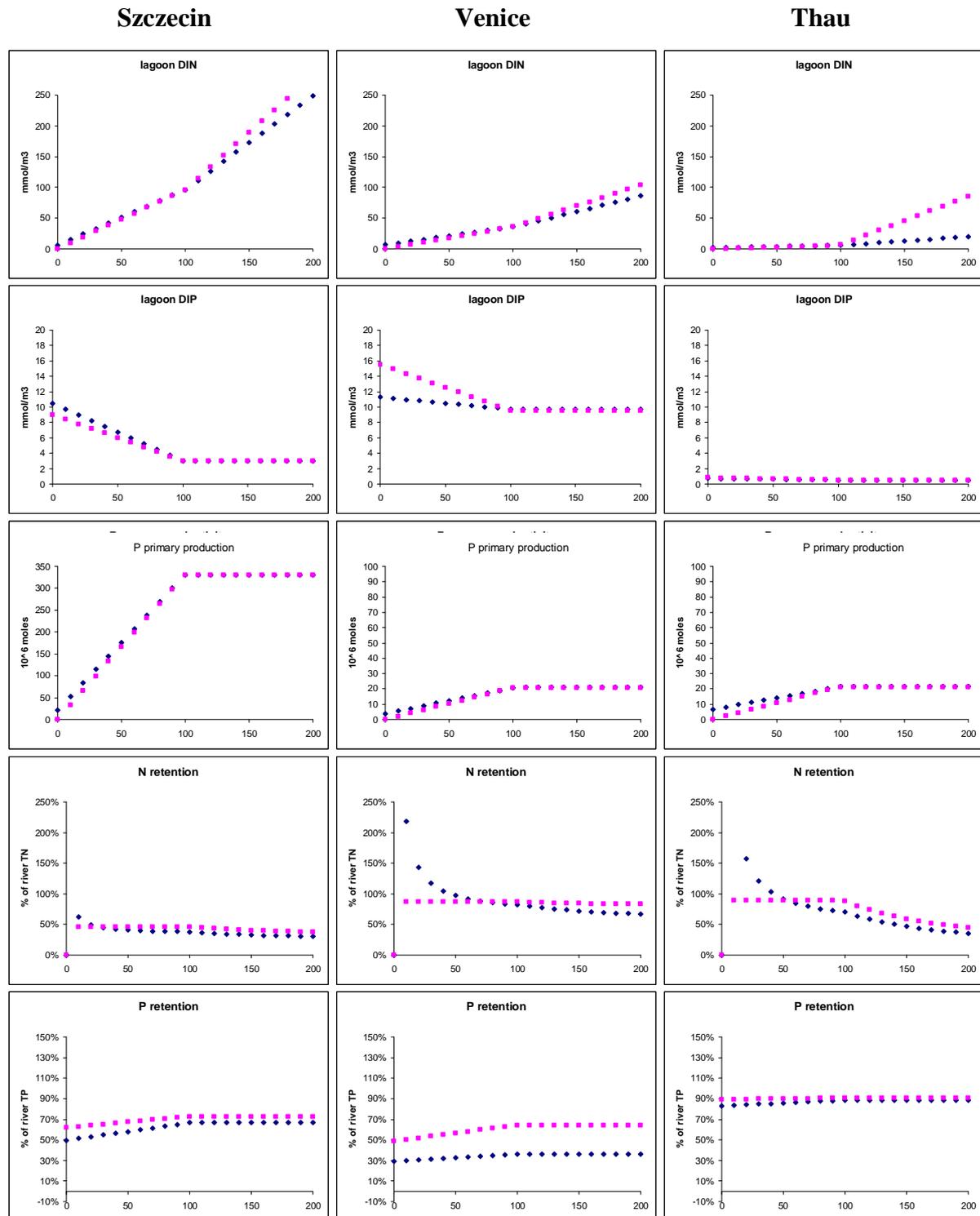
Figure 4.10 shows the response of the lagoons when the river input of N is increased or decreased, while P load is kept constant. The result is that N is the limiting nutrient if its river load is low, while P becomes the limiting nutrient when the river N input is high. The differences between the model based on flushing time, and the model based on residence time arise because of this change in limitation. The model based on residence time allows the sea to import nutrients, and thus partially meet the nutrient demand, or to export superfluous nutrients, and thus reduce lagoon concentrations.

As can be seen from the graphs, the switch from N-limitation to P limitation takes place at or close to the present, steady state situation. This is true for the Szczecin lagoon, which has a DIN:DIP ratio of 15:1, close to the Redfield ratio (Bangel *et al.*, 2004).

With increasing river nitrogen load, from zero to 100% the steady state value, lagoon DIN, primary production and retention increase while lagoon DIP decreases. When P becomes limiting, lagoon DIN increases even faster, while lagoon DIP, P retention and primary production remain constant. N retention is slightly reduced in the model based on residence time, because some of the superfluous amounts of N are flushed to the ocean.

Again, the most sensitive system is Szczecin lagoon, with the largest primary production and the fastest increase in DIN in the lagoon. Venice again shows the largest change in lagoon DIP, at least for the model based on flushing time. The model based on residence time gives a much more stable response. Thau lagoon too shows a relatively stable response in the model based on residence time, while the model based on flushing time shows an increase in DIN from almost zero to nearly 100 mmol/m<sup>3</sup> once P becomes limited.

Sensitivity to variations in N



**Figure 4.10** Sensitivity to variations in river nutrient inputs of N, with P remaining constant. See the caption of figure 4.9 for a legend.

### **Sensitivity to changes in river P inputs**

When only the river P inputs are adjusted, an opposite response can be seen than when only N inputs are changing. Again this is due to a shift in the growth limiting nutrient, this time from P to N. With increasing P availability, lagoon DIN increases and becomes constant when N becomes limiting. DIP increases, and increases even faster at the shift in limiting nutrient. Primary production increases until growth becomes limited by N availability. N retention builds up, until growth is limited by N, while P retention is almost constant for the model based on flushing time, and first drastically decreases in the model based on residence time. This decrease again is due to import of P from the sea, which allows a retention of P larger than 100% of the river inputs.

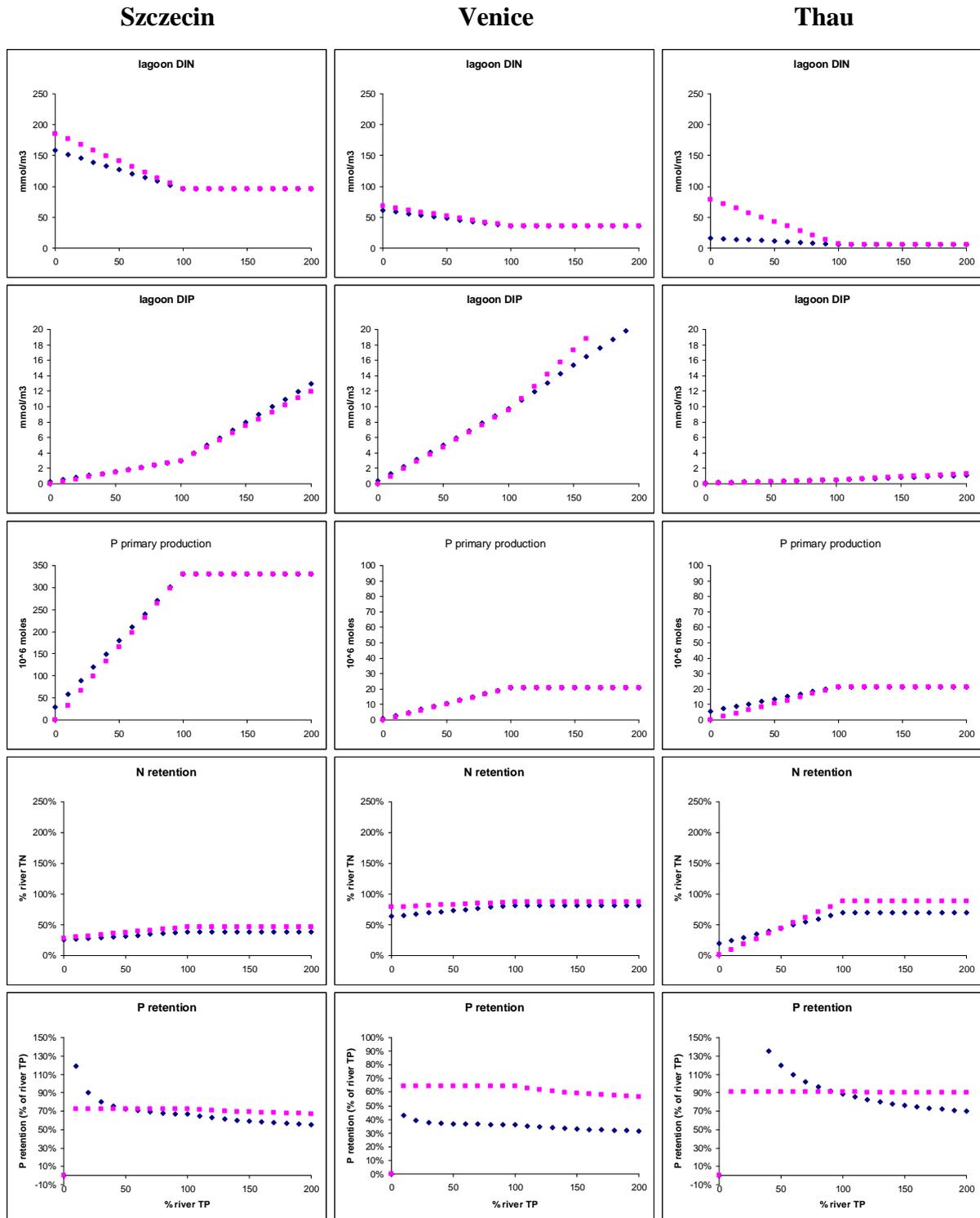
Further, from these results, the same conclusions can be drawn as from the sensitivity analysis to changes in river N inputs.

### **Conclusions**

From the sensitivity analysis it can be concluded that the models based on residence time and flushing time do not yield very different results for primary production or for DIN and DIP concentrations as long as the nutrient observed is limiting. If the other nutrient is limiting, a difference in the response of the models can be observed, because exchange of nutrients with the sea will 1) import the limiting nutrient, increasing primary production and retention and 2) remove superfluous amounts of the non-limiting nutrient from the water column. When the nutrient load of the river is very low for either N or P, and an influx of nutrients from the sea is possible, lagoons can retain more nutrients than the river input provides. When the DIN:DIP ratio of nutrients in the river input does not change, while the magnitude of the input does, the lagoon will show a linear response, and no change in nutrient limitation will take place.

The most sensitive lagoon to changes in nutrient inputs is Szczecin lagoon, because it relatively experiences the least influence from the sea. The models based on flushing time and residence time show that water exchange with the sea has a regulating effect on nutrient levels. It can sustain primary production when nutrient inputs from the river are lower than normal, and it prevents the buildup of a nutrient by flushing it out of the system.

### Sensitivity to variations in P



**Figure 4.11** Sensitivity to variations in river nutrient inputs of P, with N remaining constant. See the caption of figure 4.9 for a legend.

#### 4.3.4 Simulation: Szczecin nutrient levels in the period 1980 – 1999

Having concluded that no generic model can be created from the different site-specific models, and having compared the three site specific models at steady state and their response to changes in river nutrient loads, it still needs to be determined whether the models in themselves are capable of reproducing past variations or predict future variations in nutrient levels for the site they were designed for. Because of the amount of data required, only a simulation for Szczecin lagoon is performed for past variations.

Normally a model is calibrated to data which precedes the period for which a forecast is desired. In this way, the model starts at steady state when the simulation is made. In this case, the calibration was done based on data from 1990 to 1995. The period for which a simulation is done however is from 1980 to 1999, because of restraints in data availability.

An extensive dataset with river, lagoon and seawater concentrations of nutrients, salinities and discharge are available from Schernewsky (2004, and see §2.2.2 in the section on local scales). The river and sea values are used as input values (see figure 4.11a and b) for the site specific model for Szczecin lagoon, based on residence time. The dataset allows comparison of model results with observed lagoon concentrations (see figure 4.11c and d).

The modeled lagoon DIN largely follows the river N inputs. The Oder is generally P-limited, so that lagoon DIP does not follow the same trend. DIP is depleted except in the periods when N-limitation occurs, then the DIP increases slightly. The DIP peak in 1991 is an example of such a period with N-limitation.

The lagoon DIN and DIP are of the correct order of magnitude, but compared to the literature data they consequently over- and underestimate DIN and DIP respectively. Because the model used here has a very simple representation of the physics and nutrient fluxes, these results are still of sufficient quality. N and P retention through the years follows the river input of the nutrients (see figures 4.12e and f). Figures 4.12g and h show that N-retention in Szczecin lagoon is on average 40%. In 1982, 1984 and in the period of 1989 to 1993 the retention increases to 50 - 58%. In the other periods it is around the 35%.

Our results can be compared to the results of Wielgat and Witek (2004), who simulated the biogeochemistry in Szczecin lagoon for the same period. Their model was slightly more complex than the one developed here, including temperature and light dependency, as well as separate boxes for the two halves of the lagoon. The average retention for the period 1980 to 1999 was on average 22% in the Grosses Haff, and 48% in the Kleines Haff. The Grosses Haff makes up 60% of both the area and volume of the lagoon. A weighted

average of the estimates of Wielgat and Witek then yields a retention 32%. This estimate is lower than the results obtained here.

Phosphorus retention in the model by Wielgat and Witek amounted to 17 % for the entire lagoon. The model presented here however predicts P retention between 60 and 80% of the river input. Although our results are very different from those of Wielgat and Witek, they can still be explained by the presence of polders which are flooded in winter and periodically when the river water level is high. During these events, it is estimated, 33 to 70% of phosphorus retention takes place, and 16% of nitrogen (Engelhard *et al.*, 1999 in Wielgat and Witek, 2004). In addition to that, there is a channel crossing the Szczecin lagoon, which is dredged annually. The removed material is deposited on land, and should therefore be included in the retention. Many estimates of organic matter burial however are based on the amount of organic matter in the sediment of the lagoon, and the sedimentation rate in the lagoon. Removal of part of the sediments yields then wrong estimates for sedimentation and burial. Minning *et al.* (in Wielgat and Witek) estimate that annually between 7,500 and 10,000 ton N is retained or dredged in Szczecin lagoon, and on average 2500 ton P. Recalculated to moles this gives between  $536 \cdot 10^6$  and  $714 \cdot 10^6$  mol N and  $83 \cdot 10^6$  mol P, which is 4 to 5 times smaller than our estimates.

In the period 1990 to 1998, a trend of increasing DIN concentrations can be observed, while N retention initially increases, but later decreases (see figure 4.12c). This is counter intuitive, since one would expect N retention to increase when more DIN is available. This is not the case however, partially because of nutrient limitation. In the period from 1990 to 1991, N is the limiting nutrient. From 1991 on, P again becomes limiting .

Figure 4.12i shows another reason why retention does not necessarily increase with higher nutrient availability. There is a linear relation between nutrient retention and residence time. As a consequence, the longer the residence time, the more retention of nutrients will take place. The variation in retention observed in the period 1980 to 1999 is governed by the residence time rather than the changes in nutrient discharge. A similar relation was found by Nixon *et al.* (1996).

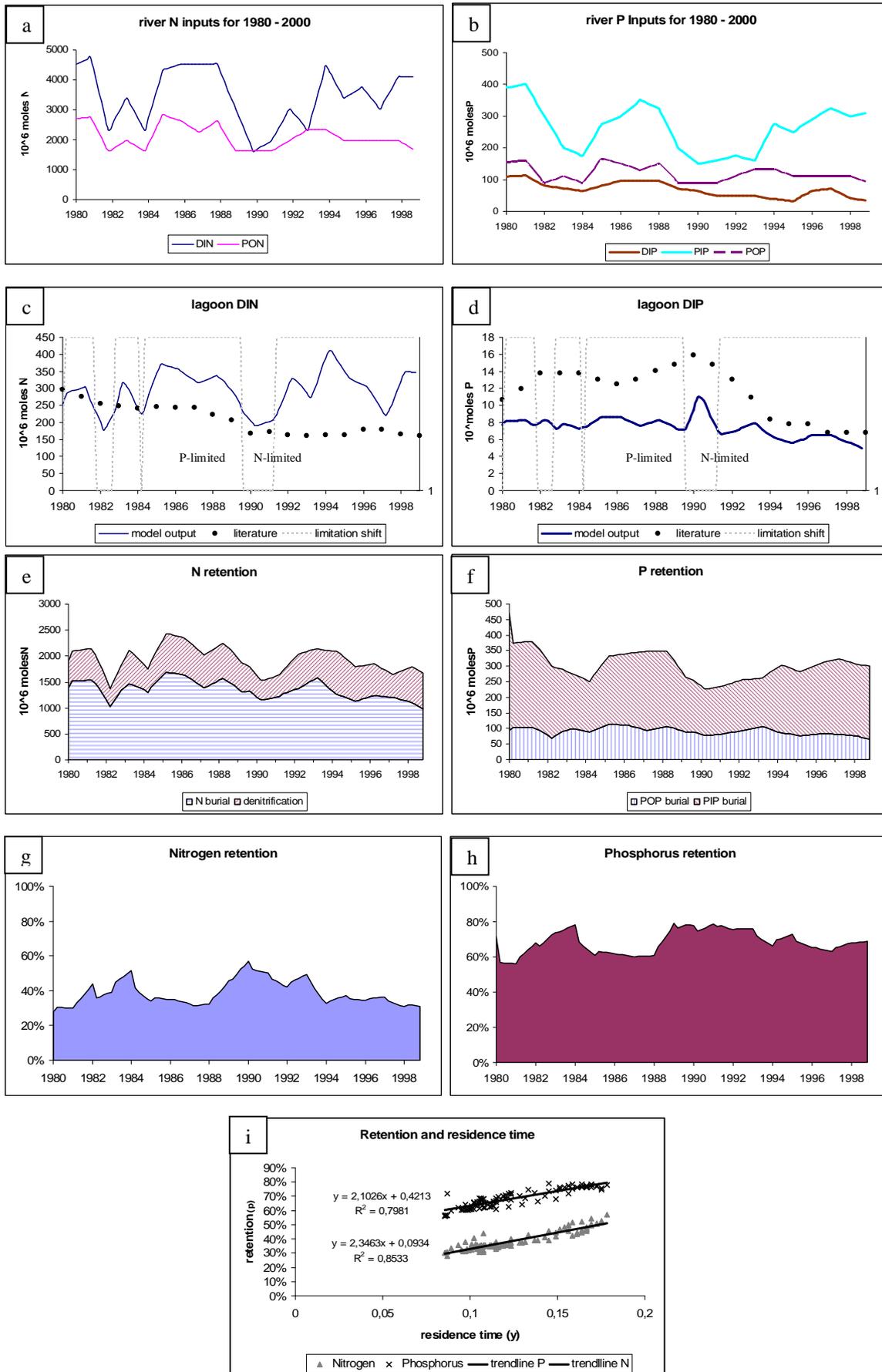


Figure 4.12 Results for the simulation of the Szczecin model based on residence time for 1980 to 1999.

#### 4.3.5 Influence of N:P ratios

The observation that our model consequently over- and underestimates lagoon DIN and DIP lead to the assumption that this could be due to the dominating condition of P-limitation. This limitation is a result of the model, controlled by the restriction that production is only possible at a N:P molar ratio of 16:1.

Apparently the DIP concentrations in the water column are lower than this ratio, so that growth is generally P-limited. A relaxation of the N:P ratio for consumption would increase the events where the lagoon is N-limited, reducing lagoon DIN and increasing lagoon DIP. A change of the N:P ratio would represent a situation where the Szczecin lagoon is not dominated by phytoplankton with the average N:P ratio of 16:1, but by an other type of organism, with a different nutrient ratio in its tissue. For sea grass, for example this ratio would be 30:1 (Kjerfve, 1994) while for land plants it can be as high as 600.

The effect of different N:P ratios was tested by running simulations for 1980 to 1999 with N:P ratios varying from 10 to 600. Between 10 and 30, increments of 2 were applied. Between 30 and 100, increments of 20; and from 100 on, increments of 100.

The effect of the N:P ratio on P limitation, P primary production and lagoon DIN and DIP are given in figure 4.13.

First of all, Figure 4.13a shows that for N:P ratios of 15 and smaller, the Szczecin lagoon would have been N-limited for the entire period of 1980 to 1999. For N:P ratios greater than 28 the lagoon would have been P-limited for the same entire period. Between these ratios, years which are P-limited and N-limited alternate.

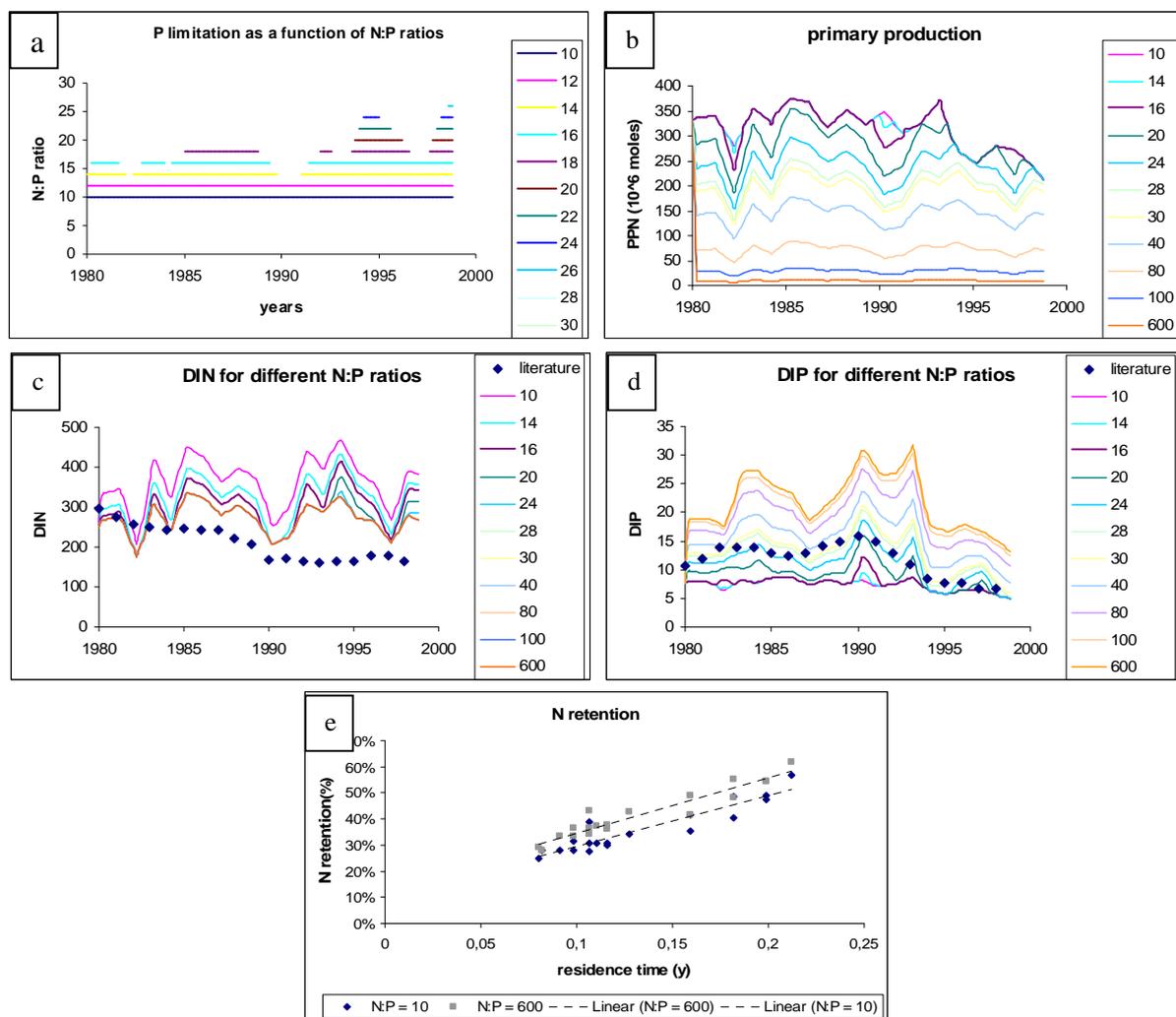
Figure 4.13b shows that primary production is highest for low N:P ratios.

Figure 4.13c shows that the trends observed in the lagoon DIN do not significantly change for different N:P ratios. The DIN at an N:P ratio of 16 is in fact close to that obtained for an N:P ratio of 600. The assumption that a higher N demand for photosynthesis would bring the DIN down to the literature values, therefore does not hold. The reason that this does not happen, is because N becomes the limiting nutrient in the entire period from 1980 to 1999 as soon as the N:P ratio is above 26.

Figure 4.13d shows however, that the literature values for DIP do fall inside of the range of DIP values obtained with the different N:P ratios tested. In fact, a DIN of 26 fits the literature data best. This lays close to the N:P ratio of sea grass, but is still slightly under it. Neglecting the bad results for the DIN representation, this would mean that the Oder might be dominated by sea grass and to a lesser extent by phytoplankton. Unfortunately no literature

was found stating this explicitly, as most biogeochemical studies only take into account phytoplankton. A list of lagoons in which is stated whether they are dominated by sea grass or phytoplankton, is available from Kjerfve (1994). Unfortunately the Oder was not accounted for.

In figure 4.13e finally is plotted the relation between residence time and retention for the N:P ratios 10 and 600. The figure shows that the relation between residence time and retention is not very much different. An N:P ratio corresponding to land plants would increase retention by 5%. Perhaps this situation applies to mangrove ecosystems, as these consist of woody vegetation.



**Figure 4.13** Influence of different N:P ratios on the simulation nutrient levels, primary production and retention in Szczecin lagoon.

## **4.4 Conclusions**

In the present chapter, steady state nutrient budgets were calculated based on literature data for Venice, Thau and Szczecin lagoons. Two types of budgets were made, one with a simple representation of physics of the lagoon, and one with a better representation of the water cycle. The budget with the simple representation only has an input of nutrient fluxes from river drainage, while the other budget also includes precipitation, evaporation and exchange with the ocean. Classically, residence time for nutrients in estuaries is calculated by dividing the volume of the estuary by the river inputs. In many cases this is a correct approach, because most estuaries do not have significant exchange of water with the ocean. Lagoons however sometimes do exchange a lot of water with the ocean, and thus a distinction should be made between flushing time (residence time based on river discharge) and genuine residence time (based on the more complete water cycle).

### **Generic box model**

From all steady state budgets, box models were derived by assuming first order kinetics for all fluxes and acquiring corresponding rate constants from the budgets. It was expected that the different lagoons would have rate constants of comparable magnitude, so that a generic lagoon model could be derived from the rate constants. It turned out that this was not the case. The rate constants for N production and N and P remineralisation had a standard deviation which was larger than their average, meaning that the generic rate constant could be anything from zero to two times the average value. It must therefore be concluded that first order kinetics are inappropriate to represent primary production and remineralisation in nutrient models. The rate constants for N and P burial varied between 12% and 20% of their average value. A Sensitivity analysis of these values could determine whether these variations in rate constants would yield acceptable results, or that these fluxes too should be represented differently. Improvements of the model could be done by including temperature and light dependency of the fluxes.

### **Sensitivity analysis**

From the sensitivity analysis it can be concluded that the models based on residence time and flushing time do not yield very different results for primary production or for DIN and DIP concentrations as long as the nutrient observed is limiting. The models based on residence and flushing time respond differently however when the nutrient observed is not limiting. From the sensitivity analysis, it can be concluded that exchange of water and

nutrients with the sea will 1) import the limiting nutrient, increasing primary production and retention and 2) remove superfluous amounts of the non-limiting nutrient from the water column. When the nutrient load of the river is very low for either N or P, and an influx of nutrients from the sea is possible, lagoons can retain more nutrients than the river input provides. When the DIN:DIP ratio of nutrients in the river input does not change, while the magnitude of the input does, the lagoon will show a linear response, and no change in nutrient limitation will take place.

The most sensitive lagoon to changes in nutrient inputs is Szczecin lagoon, because it relatively experiences the least influence from the sea. The models based on flushing time and residence time show that water exchange with the sea has a regulating effect on nutrient levels. It can sustain primary production when nutrient inputs from the river are lower than normal, and it prevents the buildup of nutrients by flushing them out of the system.

### **Simulation**

Simulation of the nutrient levels and biogeochemical fluxes in Szczecin lagoon for the period 1980 to 1999 showed that overall the lagoon is P limited. As a result the DIN concentrations from the model result follow the DIN from river inputs, while DIP concentrations remain at a baseline. DIN concentrations predicted by the model are overestimated, while DIP concentrations are underestimated compared to literature data. Despite that, the discrepancies between simulated and observed concentrations fall within the range of spatial variability inside the lagoon itself.

The retention of N by our model is on average 40% of the river input, with periods where it increases to 58%. The model predicts phosphorus retention to vary between 60% and 80% of the river P load. These results are much higher than the estimates by other authors, but are not necessarily incorrect. Correct estimation of the amount of nutrients retained in the Oder estuary is difficult due to increased retention in polders which are flooded annually during high river water levels. Further, a large amount of nutrients is dredged from a channel in Szczecin lagoon. It is estimated the amount of nutrients dredged is sometimes equal to the amount which is estimated to be retained (Minning *et al.*, 2003).

### **Influence of N:P ratios**

Because DIN and DIP are consequently over- and underestimated by our model, the influence of the N:P ratio of consumption during photosynthesis was assessed. The N:P ratio was varied to represent a range of organisms varying from phytoplankton (N:P=16) and sea grass (N:P=30) to terrestrial vegetation (N:P=600). These simulations showed that the lagoon DIN is barely affected by the N:P ratio of photosynthesis, because it becomes the limiting nutrient when the N:P ratio is higher than 28. The DIP ratio however is affected, and the literature DIP lays close to a N:P ratio of 26, which again lies between the ratio for phytoplankton and sea grass. Such a ratio however can also still represent phytoplankton species. Relatively large differences between the N:P ratio of photosynthesis for example exist between pelagic and benthic phytoplankton species (Heipe *et al.*, 1996).

The amount of nutrients retained did not differ much for an N:P ratio of 10 or 600. The primary production however was affected considerably. At the N:P ratio of phytoplankton primary production is almost maximized, while at the ratio for terrestrial plants it is close to zero. Nutrient limitation in the Szczecin lagoon only changes if the N:P ratio of photosynthesis in the lagoon lays between 12 and 28. Below this range the lagoon is P limited during the entire period of 1980 to 1999, and above this range it is always N limited.

### **Budget constraints**

Comparison of the residence time and flushing time of Venice Thau and Szczecin lagoons showed that the Szczecin lagoon is least influenced by the sea, and the Thau the most. This corresponds with the morphology of these lagoons, since Szczecin is a choked lagoon, and Thau a restricted lagoon. Venice, which is a leaky lagoon would have been expected to have a larger difference between its flushing and residence time than Thau, but perhaps the influence of the sea is reduced due to the shallowness of the lagoon, and a larger influence of the river on the lagoon.

The amount of nutrients retained in the lagoons based on the residence time and flushing time differs. Venice retains 8% more N and 30% less P based on residence time, while Thau and Szczecin retain up to 20% less N and only a fraction less P. The difference in retention between Venice and Thau and Szczecin lagoons, might arise from how the steady state nutrient budget for Venice was restrained. In the case of Venice, the river input fluxes were adjusted to all other fluxes, while for the other two lagoons PIP release and remineralisation fluxes were adjusted.

From these comparisons it can be concluded that the physical representation of the system plays an important role in the retentions derived from a conceptual nutrient model. Because lagoon systems can be assumed to be at steady state, a change in their water and nutrient budget will also change the fluxes of biogeochemical transformations.

## 5 General discussion

In the present thesis a biogeochemically relevant global coastal typology was developed, as well as 2 types of nutrient box-models for each of the sites Venice, Thau and Szczecin lagoon.

The coastal typology distinguishes coasts based on their filter capacity as well as on the processes governing the strength of the proximal coastal filter. Its constituent types represent an '*estuarine*', '*lagoon*' and '*fjord*' type (I, II and III respectively), as well as a type where no retention of nutrients is possible in the proximal coastal ocean. Each of the filter types constitute several morphologic types. These are estuaries, mangrove and macrotidal streams for type I; lagoons for type II; fjords, fjärds and glaciated sedimentary coasts for type III; and karst, arctic and big rivers for type 0.

The coastal segmentation shows the geographic distribution of its constituent types, as well as the path followed by nutrients during their transport from continental drainage basins into the proximal coastal zone. According to the G-NUX philosophy, the coastal segmentation delimits which drainage basins together provide the nutrient input to one coastal segment, as well as what type of filtering takes place in that segment. Application of a filter-specific model to each of the segments therefore allows to combine site-specific information with general nutrient models. The site-specific information is for example the type of filtering taking place, and the amount of nutrients provided by continental discharge. The same philosophy can be extended for segments and models on the continent (i.e. for drainage basins), in the distal coastal ocean (i.e. with COSCATS), and in the open ocean. In the G-NUX framework, a set of such geographically coupled models is in development, and as far as we know of, this has never been done before. We will refer to this coupled system of models as the typology-model system.

### **Further improvements to the coastal typology**

In the present thesis, the typology was developed by which the continental drainage basins will be coupled to the proximal coastal ocean. Although much effort was put in correct identification of the morphologic and filtering types, some adjustments can still be made. These were already discussed in the paragraph on integrity (§3.2.3), and are recapitulated here.

These adjustments include a re-evaluation of the big rivers, to distinguish between rivers connected to RiOMar environments and big rivers which either have only a small

fraction of particulate and nutrient load, or which flow into seas or basins which are sheltered from the open ocean, and where filtering is likely to take place. This is for example the case for Ob, Lena, Dvina and Pechora (Meybeck 2007, personal communication)

Further, karst drainage basins which constitute more than two continental cells can be expected to have too much runoff and to large a nutrient load to flow into the distal coastal ocean directly. In other words, rivers in these drainage basins may carry sufficient load to allow the development of morphology.

The distribution of Fjärds and sedimentary coasts could be re-evaluated if better restraints for their identification can be found.

Finally a fourth filtering type should be established, representing small delta coasts, since it can be expected that these coasts have a different biogeochemical behaviour than other estuaries.

### **Comparison with existing typologies**

For a long time, coastal research was usually delimited by political boundaries rather than physical boundaries. The most relevant coastal segmentation available until now were the COSCATs, which were developed by Meybeck *et al.* only as recently as 2006. The coastal segmentation developed here is not an improvement of the available coastal segmentation schemes for the coast, rather it is developed for a different purpose and therefore is better suited for application to that purpose than any other existing scheme. The COSCAT segmentation is relevant for physical purposes and was developed for general applications in coastal research. The coastal segmentation developed here is the first coastal segmentation scheme available with biogeochemical relevance for the proximal coastal ocean. Apart of that, the segmentation could be used for upscaling and indicates a potential transport path for nutrients at the land-ocean interface. The segmentation was developed specifically for application of typologic approaches to the global assessment of nutrients in the proximal coastal ocean by mathematical biogeochemical models.

It should be emphasized that this coastal segmentation is only relevant for the proximal coastal ocean, so for large bays, the open water part of estuaries, deltas, inland seas, salt marshes and other such inland water bodies at the land-ocean interface.

### **Nutrient box-model**

A nutrient box-model for lagoons was developed here as an example of the types of models the typology is going to be connected to. Because of the global application of the

typology-model system, a simple model is desired. Therefore, the model developed here represents all fluxes by first order kinetics, and by assuming that the fluxes are only a function of the source reservoir. A comparison of rate constants however showed that no generic model can be created from the site specific models presented here, and that a more complex relation should be sought to represent primary production and remineralisation (§4.3.2) in particular. Literature shows that dependencies on temperature and light availability already allow to represent estuarine biogeochemistry to a sufficient extent (i.e. in Wielgat and Witek, 2004).

A drawback for making the generic models more complex is that if site-specific information is required, this must be obtained for all coasts in the world. Although this might be overcome since surface sea water temperature is readily available, and solar radiation could be derived from the solar radiation analysis tools, in the ArcGIS Spatial Analyst extension. This tool is based on methods from the hemispherical viewshed algorithm developed by Rich and Fu (2000). It enables to map and analyze the effects of the sun over a geographic area for specific time periods. It accounts for atmospheric effects, site latitude and elevation, steepness (slope) and compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography. The resultant outputs can easily be integrated with other GIS data and is intended to model physical and biological processes as they are affected by the sun (Rich and Fu, 2000).

### **Coupled typology-model system**

In the present thesis two of the building blocks have been presented with which a coupled typology-model system can be made. Each of the blocks - the typology and the lagoon model - however need further development before they can be assimilated to the coupled typology-model system.

As separate products, the typology and lagoon model still have intrinsic value. Especially the coastal typologies, both the filtering and the morphologic typology, can be applied to different purposes as they are at present.

The lagoon model presented here is not well qualified to represent the biogeochemical cycles of lagoons, however it has shown that in a generic box model for lagoons, primary production and remineralisation cannot be represented by first order kinetics, and that the generic box models for the other filtering types should not be based on comparison of rate constants, but on relations between the processes to be represented and temperature, or insolation. Thus the model has given direction for the further development of the generic models for each of the filtering types.

## 6 Conclusions

In this conclusion the main findings of both the typology and modeling part are recapitulated, as well as those of the general discussion.

### Coastal typology

The coastal typology developed here shows that 47% of the global runoff is supplied to the distal coastal ocean directly by big rivers. The Amazon alone, one of these big rivers, already accounts for 12% of the global runoff. At approximately 20% of the world's coastline no filtering takes place because of karst morphology or arheic circumstances (each 3% of global runoff). At the remaining 80% of the world's coast, removal of nitrogen and phosphorus takes place in the proximal coastal ocean, by burial and denitrification. Together, the filtering types receive 47% of the global runoff. Estuaries (I) make up 40% of the global coast, lagoons (II) 10% and the fjord-type (III) 30%. They receive 30, 7 and 10% of the global runoff respectively, while type 0 receives 53%.

In terms of geographic distribution, North America and Europe are dominated by type III coasts, Africa by type 0 coasts, and the other continents by estuaries. Lagoons are most common in North-America, and less common in Indonesia and Asia than could be expected. Lagoons make up 5 and 7% of the Indonesian and Asian coasts respectively. 10 % of the European, North- and South-American coast, 15% of the African and 20% of the Australian coastline are also lagoons.

The distribution of runoff over the continents shows a division in 4 groups: 1) Australasia receives only 1% of the global runoff; 2) Europe and Indonesia 9%; 3) Africa and North-America 14%; and 4) Asia and South-America each 27 %. On all continents, except for Australia and Indonesia, between 37 and 77% of the runoff flows into type 0 coasts. The amounts of runoff received by type I coasts varies between 16 and 37%. For Australia and Indonesia it is 63 and 87%. Type II coasts receive between 3 and 17% of the runoff on each of the continents. Type III coasts of receive 4% of the continental runoff of South America and Asia, and between 21 and 30% in Australasia, Europe and North America.

### **Lagoon box model**

Comparison of the residence time and flushing time of Venice Thau and Szczecin lagoons showed that the Szczecin lagoon is least influenced by the Sea, and the Thau the most. The amount of nutrients retained in the lagoons based on steady state residence time and flushing time differs. Venice retains 8% more N and 30% less P based on residence time, while Thau and Szczecin retain up to 20% less N and only a fraction less P. In correspondence with these results, a sensitivity analysis showed that the models based on residence time and flushing time do not yield very different results for primary production, DIN and DIP concentrations, but they do show a difference for nutrient retention. Choked lagoons, like the Szczecin lagoon here, are more sensitive to fluctuations in river nutrient inputs, as they lack regulating mechanism which water exchange with the sea provides. Exchange fluxes with the sea 1) import the limiting nutrient, increasing primary production and retention and 2) remove superfluous amounts of the non-limiting nutrient from the water column. A generic nutrient model for lagoons must therefore be based on residence time.

Simulation of the nutrient levels and biogeochemical fluxes in Szczecin lagoon for the period 1980 to 1999 showed that overall the lagoon is P limited. The DIN and DIP concentrations predicted by the model are of the right order of magnitude, but are consequently under- and overestimated. Seen the simplicity of the model used here (only first order rate constants, no dependency on temperature or light availability), these results are acceptable however.

The influence of the N:P ratio of nutrient consumption during photosynthesis on model results was assessed for ratios ranging from 10 to 600 (terrestrial vegetation). These simulations show that lagoon DIN is barely affected by the N:P ratio of photosynthesis. The DIP ratio and primary production however are affected, and the literature DIP lays close to a N:P ratio of 26, which again lies between the ratio for phytoplankton and sea grass. Primary production of the system decreased with increasing ratios, while the amount of nutrients retained did not differ much for an N:P ratio of 10 or 600.

### **Coupled typology-model system**

In the present thesis two of the building blocks have been presented with which a coupled typology-model system can be made. For each of the blocks - the typology and the lagoon model - further development should be considered, before they are assimilated to the coupled typology-model system.

For the typology, these adjustments include a re-evaluation of the big rivers, to distinguish between rivers connected to RiOMar environments and big rivers which either have only a small fraction of particulate and nutrient load, or which flow into seas or basins which are sheltered from the open ocean, and where filtering is likely to take place. Further, the distribution of karst Fjårds and sedimentary coasts could be re-evaluated. Finally, it can be expected that small delta coasts show a different biogeochemical behaviour than other estuaries and therefore require their own, a separate filtering class. A type IV should therefore be defined and identified geographically.

Although no generic model could be obtained from the site specific models presented here, the models developed here have given indications on what the complexity of the generic models for each of the filtering types should be. First order kinetics are appropriate to represent all fluxes except primary production and remineralisation. Relations between these processes and temperature, or insolation should therefore be included. Further, the generic lagoon model should include exchange with sea water in the water budget, since this is an important flux in lagoons and results in different a biogeochemical response between choked and leaky lagoons. Finally, if information about the dominating primary producer is available (i.e. being phytoplankton or sea grass) it would be advisable to include this information in the model, as the N:P ratio by which primary production takes place influences DIP concentrations and primary production, but not retention. Thus, the model has given direction for the further development of the generic models for each of the filtering types.

The filter typology presented here is of key importance to the G-NUX research, as it provides the means to geographically relate continental nutrient fluxes to coastal bodies of water and identifies which type of nutrient filtering takes place in each of the proximal coastal ocean segments. By coupling generic nutrient models to each of the filtering types, spatially explicit process-based forecasts can be obtained of nutrient fluxes and levels in the global coastal ocean. The generic models are in preparation with Laruelle *et al.* (2007). The lagoon models presented in here have given indication of the complexity these models can have, to remain as general and simple as possible while still representing the nutrient levels and fluxes to an acceptable degree.

## 7 References

- Added, A. (2001) Biogeochemical cycles of Org-C, Tot-N and Tot-S in the sediment of the Ghar El Melh Lagoon (north of Tunisia). *Journal of Marine Systems*, 30 (1-2): p. 139-154.
- Allaby, A. and Allaby, M. (1990) Oxford Dictionary of Earth Sciences. (ed.), Oxford: Oxford University Press. 920 p. (used was p. 192).
- Alongi, D. M. (1998) Coastal Ecosystem Processes. *Marine Science Series*, Kennish, M. J. and Lutz, P. L. (ed.): CRC Press LLC. 419 p. (used were p. 4-11 and 183-247).
- Bangel, H., Schernewski, G., Bachor, A. and Malgorzata, L.-U. (2004) Spatial pattern and long-term development of water quality in the Oder Estuary, in *The Oder Estuary - against the background of the European Water Framework Directive.*, Schernewski, G. and Dolch, T. (ed.).
- Brenon, I., Mondé, S., Pouvreau, N. and Maurin, J. C. (2004) Modeling hydrodynamics in the Ebrié Lagoon (Côte d'Ivoire). *Journal of African Earth Sciences*, 39 (3-5): 535 - 540.
- Brion, N., Baeyens, W., Galan, S. d., Elskens, M. and Laane, R. W. P. M. (2004) The North Sea: source or sink for nitrogen and phosphorus to the Atlantic Ocean? *Biogeochemistry*, 68: 277 - 296.
- Carter, R. W. G. and Woodroffe, C. D. (1994) Coastal evolution. Edited by Carter, R. W. G. and Woodroffe, C. D. (ed.), Cambridge: Cambridge University Press. 517 p. (used were p. 25, 42 - 64, 219 - 231).
- Chan, K. M. A., Shaw, M. R., Cameron, D. R., Underwood, E. C. and Daily, G. C. (2006) Conservation planning for ecosystem services. *PLoS Biology*, 4 (11): e379 p. 2138 - 2152.
- Chapelle, A. (1995) A preliminary model of nutrient cycling in sediments of a Mediterranean lagoon. *Ecological Modelling*, 80 (2-3): p. 131-147.
- Chapelle, A., Menesguen, A., Deslous-Paoli, J.-M., Souchu, P., Mazouni, N., Vaquer, A. and Millet, B. (2000) Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oysters farming and inputs from the watershed. *Ecological Modelling*, 127 (2-3): p. 161-181.
- Crossland, C. J. C., Kremer, H. H., Lindeboom, H. J., Marshall crossland, J. I. and Le Tissier, M. D. A. (2005) Coastal Fluxes in the Anthropocene. *IGBP Global Change*, Crossland, C. J. C., Kremer, H. H., Lindeboom, H. J., Marshall crossland, J. I. and Le Tissier, M. D. A. (ed.), germany: Springer-verlag. 231 p. (used were 96 - 105, 145 - 165).
- Dagg, M., Benner, R., Lohrenz, S. and Lawrence, D. (2004) Transformation of dissolved and particulate materials on continental shelves influenced by large rivers: plume processes. *Continental Shelf Research*, 24 (7-8): p. 833-858.
- Davies, J. L. (1973) Geographical variation in coastal development. *Geomorphology texts*, Clayton, K. M. (ed.), 4, New York: Hafner.
- Davis, R. A. J. and Fitzgerald, D. M. (2004) Beaches and Coasts. (ed.), Oxford: Blackwell Publishing. 419 p. (used were p. 130 - 187, 200, 289 - 293).

- De Casabianca, M. L., Laugier, T. and Marinho-Soriano, E. (1997) Seasonal changes of nutrients in water and sediment in a Mediterranean lagoon with shellfish farming activity (Thau Lagoon, France). *ICES Journal of Marine Science*, 54 (5): p. 905-916.
- Dolan, R., Hayden, B. and Vincent, M. (1975) Classification of coastal landform of the Americas. *Zeitschrift für Geomorphologie, Supp. Bull.*, 22: p. 72-88.
- Dürr, H., Meybeck, M. and Dürr, S. H. (2005) Lithologic composition of the Earth's continental surfaces derived from a new digital map emphasizing riverine material transfer. *Global Biogeochemical cycles*, 19, GB4S10: p. 1-22.
- Ericson, J. P., Vorosmarty, C. J., Dingman, S. L., Ward, L. G. and Meybeck, M. (2006) Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change*, 50 (1-2): p. 63-82.
- FAO (2005) The state of food and agriculture 2005. *FAO Agriculture Series*, (ed.), 36: Publishin Management Service FAO. p. 1-211.
- Fekete, B. M., Vörösmarty, C. J. and Grabs, W. (2000) Global, Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances. GRDC and WMO, (22) p. 1 - 109
- Fekete, B. M., Vörösmarty, C. J. and Grabs, W. (2002) High-resolution fields of global runoff combining observed river discharge and simulated water balances. *Global Biogeochemical Cycles*, 15 (3): p. 15-1.
- Fennel, K., Wilkin, J., Levin, J., Moisan, J., O'reilly, J. and Haidvogel, D. (2006) Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget. *Global Biogeochemical cycles*, 20, GB3007: p. 1 - 14.
- Flindt, M. R., Kamp-Nielsen, L., Marques, J. C., Pardal, M. A., Bocci, M., Bendoricchio, G., Salomonsen, J., Nielsen, S. N. and Jorgensen, S. E. (1997) Description of the three shallow estuaries: Mondego River (Portugal), Roskilde Fjord (Denmark) and the Lagoon of Venice (Italy). *Ecological Modelling*, 102 (1): 17-31.
- Gattuso, J.-P., Frankignoulle, M. and Wollast, R. (1998) Carbon and Carbonate Metabolism in Coastal Aquatic Ecosystems. *Annual Review of Ecology and Systematics*, 29: p. 405-434.
- GEBCO (2007) General Bathymetric Chart of the Oceans. last updated: december 2006; Available from: <http://www.ngdc.noaa.gov/mgg/gebco/>.
- Geerts, G. and Heestermans, H. (1993) Van Dale groot woordenboek der Nederlandse taal. 12. Geerts, G. and Heestermans, H. (ed.), Utrecht: van Dale Lexicografie.
- Gordon, J. D. C., Boudreau, P. R., Mann, K. H., Ong, J. E., Silvert, W. L., Smith, S. V., Wattayakorn, G., Wulff, F. and Yanagi, T. (1996) LOICZ Biogeochemical Modelling Guidelines. *LOICZ Reports & Studies*, (ed.), 5, Texel, The Netherlands: LOICZ. p. 1 - 96.
- Gössling, S. (2003) Market integration and ecosystem degradation: is sustainable tourism development in rural communities a contradiction in terms? *Environment, Development and Sustainability*, 5: p. 383 - 400.
- Green, P. A., Vörosmary, C. J., Meybeck, M., Galloway, J. N., Peterson, B. J. and Boyer, E. W. (2004) Pre-industrial and contemporary fluxes of nitrogen through rivers: a global assessment based on typology. *Biogeochemistry*, 68: 71-105.

- Gregory, J. W. (1913) The nature and origin of fiords. (ed.), london: John Murray.
- Grelowski, A., Pastuszak, M., Sitek, S. and Witek, Z. (2000) Budget calculations of nitrogen, phosphorus and BOD5 passing through the Oder estuary. *Journal of Marine Systems*, 25 (3-4): 221-237.
- Herak, M. and Stringfield, V. T. (1972) Karst - Important Karst Regions of the Northern Hemisphere. in, (ed.). Elsevier Publishing Company: Amsterdam. 551 p. (used were p. 25, 94, 132, 343, 418, 446, 470).
- Howarth, R. W. (1988) Nutrient Limitation of Net Primary Production in Marine Ecosystems. *Annual Review of Ecology and Systematics*, 19: p. 89 - 110.
- Humborg, C., Fennel, K., Pastuszak, M. and Fennel, W. (2000) A box model approach for a long-term assessment of estuarine eutrophication, Szczecin Lagoon, southern Baltic. *Journal of Marine Systems*, 25: p. 387 - 403.
- Jensen, H. S., Bendixen, T. and Andersen, F. O. (2006) Transformation of Particle-Bound Phosphorus at the Land-Sea Interface in a Danish Estuary. *water, Air, & Soil Pollution: Focus*, 6 (5-6): p. 547 - 555.
- Jorgensen, B. B. and Richardson, K. (1996) Eutrophication in Coastal Marine Ecosystems, in *Coastal and Estuarine Studies*, Jorgensen, B. B. and Richardson, K. (ed.), American Geophysical Union: Washington, DC.
- Kelletat, D. H. (1995) Atlas of coastal geomorphology and zonality. *journal of coastal research*, (special issue no 13): 286 p. (used were p. 11, 21, 22, 102, 132, 176, 197).
- Kisand, A. and Nõges, P. (2004) Sediment phosphorus release in phytoplankton dominated versus macrophyte dominated shallow lakes: importance of oxygen conditions. *Hydrobiologia*, 506 - 509 (1-3): p. 129 - 133.
- Kjerfve, B. (1994) Coastal lagoon processes. in *Elsevier Oceanography Series*, (ed.). 60. Elsevier Science B.V. 577 p. (used were p. 9 - 36, 85 - 91, 133 - 153, 243 - 275).
- Koranteng, K. A., Ofori-Danson, P. K. and Entsua-Mensah, M. (2000) Fish and fisheries of the Muni lagoon in Ghana, West Africa. *Biodiversity and Conservation*: p. 487-499.
- Kress, N. and Herut, B. (2001) Spatial and seasonal evolution of dissolved oxygen and nutrients in the Southern Levantine Basin (Eastern Mediterranean Sea): chemical characterization of the water masses and inferences on the N:P ratios. *Deep Sea Research I*, 48: p. 2347 - 2372.
- Labbardi, H., Ettahiri, O., Lazar, S., Massik, Z. and El Antri, S. (2005) Etude de la variation spatio-temporelle des parametres physico-chimiques caracterisant la qualite des eaux d'une lagune cotiere et ses zonations ecologiques: cas de Moulay Bousselham, Maroc. *Comptes Rendus Geosciences*, 337 (5): 505.
- Lin, H.-J., Dai, X.-X., Shao, K.-T., Su, H.-M., Lo, W.-T., Hsieh, H.-L., Fang, L.-S. and Hung, J.-J. (2006) Trophic structure and functioning in a eutrophic and poorly flushed lagoon in southwestern Taiwan. *Marine Environmental Research*, 62 (1): 61.
- Lonin, S. A. and Tuchkovenko, Y. S. (2001) Water quality modelling for the ecosystem of the Cienaga de Tesca coastal lagoon. *Ecological Modelling*, 144 (2-3): p. 279 - 293.
- Mackenzie, F. T. (1998) Our changing Planet. (ed.), Upper Saddle River, New Jersey: Prentice Hall.

- Manahan, S. E. (2000) Environmental Chemistry. 7 th edition. (ed.), Florida: CRC Press LLC. 898p. (used were p. 16, 18, 168 - 173 and 198-199).
- Marchini, A. and Marchini, C. (2006) A fuzzy logic model to recognise ecological sectors in the lagoon of Venice based on the benthic community. *Ecological Modelling*, 193: 105 - 118.
- McKee, B. A. (2003) RiOMar: The Transport, transformation and fate of carbon in river-dominated ocean margins, in *the riomar workshop*: Tulane university, new Orleans, LA, 54 p.
- Meurer, W. P. and Natland, J. H. (2001) Apatite compositions from oceanic cumulates with implications for the evolution of mid-ocean ridge magmatic systems. *Journal of Volcanology and Geothermal Research*, 110 (3): p. 281-298.
- Meybeck, M., Dürr, H., Vogler, J., Lachartre, L. and Guéguen, Y. (2000) Space analysis of catchment/ coast relationship. European Commission, DG Research,
- Meybeck, M., Dürr, H. and Vörosmary, C. J. (2006) Global coastal segmentation and its river catchment contributors: A new look at land-ocean linkage. 20, GB1S90, doi:10.1029/2005GB002540: p. 1 - 15.
- Meybeck, M. and Vorosmary, C. (2005) Fluvial filtering of land-to-ocean fluxes: from natural Holocene variations to Anthropocene. *Comptes Rendus Geosciences*, 337 (1-2): p. 107 - 123.
- Minning, M., Leipe, T. and Schernewski, G. (2003) Auswirkungen der regelmässigen Kanal-Ausbaggerungen auf the Trophie des Stettines (Oder) Haffs. *Deutschen Gesellschaft für Limnologie*, Tagungsbericht 2002, Tutzing 2003 (submitted).
- Nakata, K., Horiguchi, F. and Yamamuro, M. (2000) Model study of Lakes Shinji and Nakaumi -- a coupled coastal lagoon system. *Journal of Marine Systems*, 26 (2): p. 145 - 169.
- NASA (2006) SeaWiFS. Available from:  
<http://oceancolor.gsfc.nasa.gov/SeaWiFS/BACKGROUND/>.
- Olausson, E. and Cato, I. (1980) Chemistry and biogeochemistry of Estuaries. (ed.), Chichester: a Wiley-Interscience publication.
- Pastres, R., Ciavatta, S., Cossarini, G. and Solidoro, C. (2005) The seasonal distribution of dissolved inorganic nitrogen and phosphorous in the lagoon of Venice: A numerical analysis. *Environment International*, 31 (7): 1031.
- Pastuszak, M., Witek, Z., Nagel, K., Wielgat, M. and Grelowski, A. (2005) Role of the Oder estuary (southern Baltic) in transformation of the riverine nutrient loads. *Journal of Marine Systems*, 57 (1-2): 30.
- Picot, B., Péna, G., Casellas, C., Bondon, D. and Bontoux, J. (1990) Interpretation of the seasonal variations of nutrients in a mediterranean lagoon: étang de Thau. *Hydrobiologia*, 207: 105-114.
- Plus, M., Jeunesse, I. L., Bouraoui, F., Zaldivar, J.-M., Chapelle, A. and Lazure, P. (2006) Modelling water discharges and nitrogen inputs into a Mediterranean lagoon: Impact on the primary production. *Ecological Modelling*, 193 (1-2): 69.
- Rabouille, C., Mackenzie, F. T. and Ver, L. M. (2001) Influence of the human perturbation on carbon, nitrogen, and oxygen biogeochemical cycles in the global coastal ocean. *Geochimica et Cosmochimica Acta*, 65 (21): p. 3615 - 3641.

- Rabouille, C., Witbaard, R. and Duineveld, G. C. A. (2001) Annual and interannual variability of sedimentary recycling studied with a non-steady-state model: application to the North Atlantic Ocean (BENGAL site). *Progress In Oceanography*, 50 (1-4): 147.
- Ragueneau, O., Lancelot, C., Egorov, V., Vervlimmeren, J., Cociasu, A., Deliat, G., Krastev, A., Daoud, N., Rousseau, V. and Popovitchev, V. (2002) Biogeochemical Transformations of Inorganic Nutrients in the Mixing Zone between the Danube River and the North-western Black Sea. *Estuarine, Coastal and Shelf Science*, 54 (3): 321.
- Redfield, A. C., Ketchum, B. H. and Richards, F. A. (1963) The influence of organisms on the composition of sea water. *the Sea*, Hill, M. N. (ed.): Interscience. p. 26 - 77.
- Rich, P. M. and Fu, P. (2000) Topoclimatic habitat models. in *Proceedings of the Fourth International Conference on Integrating GIS and Environmental Modeling*.
- Ruiz, F., Abad, M., Olias, M., Galan, E., Gonzalez, I., Aguila, E., Hamoumi, N., Pulido, I. and Cantano, M. (2006) The present environmental scenario of the Nador Lagoon (Morocco). *Environmental Research*, 102 (2): 215.
- Ruttenberg, K. C. (2004) The Global Phosphorus Cycle, in *Treatise on Geochemistry*, Holland, H. D. and Turekian, K. K. (ed.), Elsevier: Amsterdam. p. 585 - 643.
- Scavia, D., Rabalais, N. N., Turner, R. E., Justic, D. and JR, W. J. W. (2003) Predicting the Response of Gulf of Mexico Hypoxia to Variations in Mississippi River Nitrogen Load. *Limnology and Oceanography*, 48 (3): p. 951 - 956.
- Schrum, C., Alekseeva, I. and John, M. S. (2006) Development of a coupled physical-biological ecosystem model ECOSMO; Part I: Model description and validation for the North Sea. *journal of Marine Systems*, 61 (1-2): 79 - 99.
- Seitzinger, S. P., Harrison, J. A., Dumont, E., Beusen, A. H. W. and F., B. A. (2005) Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of Global Nutrient Export from Watersheds (NEWS) models and their application. *global Biogeochemical cycles*, 19, GB4S01, doi: 10.2029/2005GB002606: p. 1-11.
- Sfriso, A. and Marcomini, A. (1994) Gross primary production and nutrient behaviour in a shallow coastal environment. *Bioresource Technology*, 47 (1): 59.
- Sfriso, A., Marcomini, A. and Pavoni, B. (1994) Annual nutrient exchanges between the central lagoon of Venice and the northern Adriatic Sea. *The Science of The Total Environment*, 156 (1): p. 77- 92.
- Sfriso, A., Pavoni, B. and Marcomini, A. (1995) Nutrient distributions in the surface sediment of the central lagoon of Venice. *Science of The Total Environment*, 172 (1): 21.
- Sfriso, A., Pavoni, B., Marcomini, A. and Orio, A. A. (1988) Annual variations of nutrients in the Lagoon of Venice. *Marine Pollution Bulletin*, 19 (2): 54.
- Sherman, K. (2006) The Large Marine Ecosystem network approach to WSSD targets. *Ocean & Coastal Management*, 49 (9-10): p. 640 - 648.
- Slomp, C. P. and Van Cappellen, P. (2004) Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *Journal of Hydrology*, 295 (1-4): p. 64 - 86.
- Solidoro, C., Pastres, R. and Cossarini, G. (2005) Nitrogen and plankton dynamics in the lagoon of Venice. *Ecological Modelling*, 184 (1): p. 103 - 124.

- Souchu, P., Gasc, A., Cahet, G., Vaquer, A., Collos, Y. and Deslous-Paoli, J. M. (1997) Biogeochemical Composition of Mediterranean Waters Outside Thau Lagoon. *Estuarine, Coastal and Shelf Science*, 44 (3): p. 275 - 284.
- Souchu, P., Vaquer, A., Collos, Y., Landrein, S., Deslous-Paoli, J.-M. and Bibent, B. (2001) Influence of shellfish farming activities on the biogeochemical composition of the water column in Thau lagoon. *Marine ecology progress series*, 218: 141-152.
- Souza, M. F. L., Kjerfve, B., Knoppers, B., Landim de Souza, W. F. and Damasceno, R. N. (2003) Nutrient budgets and trophic state in a hypersaline coastal lagoon: Lagoa de Araruama, Brazil. *Estuarine, Coastal and Shelf Science*, 57 (5-6): p. 843 - 858.
- Sweeting, M. M. (1972) Karst Landforms. (ed.): The Macmillan Press LTD. 362 p. (used was p. 7).
- U.S. Department of Commerce, N. O. a. A. A., National Geophysical Data Center (2006) 2-minute Gridded Global Relief Data (ETOPO2v2). *Journal*, Volume, Pages,
- V.Sokolov, A., Andrejev, O. A., Wulff, F. and Rodriguez-Medina, M. (1997) The Data Assimilation System for Data Analysis in the Baltic Sea. *Ecology Contributions*, 3: 66 p.
- Vichi, M., Ruadij, P. and Baretta, J. W. (2004) Link or sink: a modelling interpretation of the open Baltic biogeochemistry. *Biogeosciences*, 1 (1): p. 79 - 100.
- Vitousek, P. M., Mooney, H. A., Lubchenco, J. and Melillo, J. M. (1997) Human Domination of Earth's Ecosystems. *Science*, 277 (5325): p. 494 - 499.
- Vörösmarty, C. J., Fekete, B. M., Meybeck, M. and Lammers, R. B. (2000) Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution. *Journal of Hydrology*, 237 (1-2): p. 17-39.
- WCMC (1997) Coral Reefs and Mangrove of the World, in, World Conservation Monitoring Centre. map.
- Wielgat, M. and Witek, Z. (2004) A dynamic box model of the Szczecin Lagoon nutrient cycling and its first application to the calculation of the nutrient budget. in *The Oder Estuary - against the background of the European Water Framework Directive*, Schernewski, G. and Dolch, T. (ed.). 57. p. 99 - 125.
- Witek, Z., Humborg, C., Savchuk, O., Grelowski, A. and Lysiak-Pastuszek, E. (2003) Nitrogen and phosphorus budgets of the Gulf of Gdansk (Baltic Sea). *Estuarine, Coastal and Shelf Science*, 57 (1-2): 239.

**Appendix A: typology statistics**

**Table A.1: statistics for the filtering and morphologic typology**

Basins			area		runoff (m/y)			(mm/y)				
								mean	min	max		
<b>FILTERING TYPOLOGY</b>												
TYPE 0	1450	21%	36375	63%	7857	53%	159	0	10093			
TYPE 1	2683	40%	11481	20%	4474	30%	630	0	5822			
TYPE 2	684	10%	5839	10%	1090	7%	378	0	4589			
TYPE 3	1964	29%	3827	7%	1475	10%	438	0	5805			
TOTAL	6781	100%	57522	100%	14897	100%	401	0	10093			
<b>MORPHOLOGIC TYPOLOGY</b>												
endo-rheic	175	3%	12%	6656	12%	18%	301	2%	4%	82	0	2360
exo-Arheic	554	8%	38%	4946	9%	14%	87	1%	1%	16	0	964
karst	660	10%	46%	2557	4%	7%	441	3%	6%	269	0	2845
Big river	61	1%	4%	22216	39%	61%	7029	47%	89%	551	0	10093
TYPE 0			100%			100%			100%			
estuary	900	13%	34%	2406	4%	21%	1151	8%	26%	688	0	3612
macrotidal	564	8%	21%	3309	6%	29%	1220	8%	27%	587	0	5822
mangrove	658	10%	25%	2689	5%	23%	1510	10%	34%	912	0	4608
ria	561	8%	21%	3077	5%	27%	594	4%	13%	235	0	1389
TYPE 1			100%			100%			100%			
lagoon	684	10%	100%	5839	10%	100%	1090	7%	100%	378	0	4589
TYPE 2		10%			10%			7%				
fjard	157	2%	8%	382	1%	10%	315	2%	21%	933	0	3194
fjord	491	7%	25%	1021	2%	27%	687	5%	47%	832	0	5805
glac. sed.	1316	19%	67%	2424	4%	63%	473	3%	32%	199	0	4486
TYPE 3			100%			100%			100%			
TOTAL	6781	100%		57522	100%		14897	100%		5682	0	49769

**Table A.2: absolute number of Basins and total runoff per continent and morphology.**

type	morphology	Basins							TOTAL
		Africa	Asia	Australasia	Europe	Indonesia	North America	South America	
0	arheic	16	113	12	16	0	6	12	175
0	Exo-Arheic	215	145	49	6	0	55	84	554
0	karst	77	45	17	114	25	382	0	660
0	Big river	8	21	0	7	3	11	11	61
1	estuary	30	333	62	106	166	128	75	900
1	macrotidal	72	164	69	35	67	73	84	564
1	mangrove	102	89	109	0	178	78	102	658
1	ria	0	385	0	123	0	53	0	561
2	lagoon	87	115	83	84	25	241	49	684
3	fjard	0	17	0	37	0	73	30	157
3	fjord	0	16	11	66	0	352	46	491
3	glac sediment	0	128	5	317	0	866	0	1316
TOTAL		607	1571	417	911	464	2318	493	6781

type	morphology	Runoff (m/y)							TOTAL
		Africa	Asia	Australasia	Europe	Indonesia	North America	South America	
0	arheic	106	162	0	10	0	5	18	301
0	Exo-Arheic	45	24	0	0	0	6	10	87
0	karst	49	34	1	134	49	175	0	441
0	Big river	851	1890	0	528	98	759	2903	7029
1	estuary	13	442	44	113	252	150	137	1151
1	macrotidal	131	359	38	37	264	140	252	1220
1	mangrove	351	229	62	0	548	123	194	1506
1	ria	0	319	0	139	0	136	0	594
2	lagoon	285	153	38	181	45	289	100	1090
3	fjard	0	24	0	81	0	116	94	315
3	fjord	0	8	33	104	0	472	70	687
3	glac sediment	0	102	13	196	0	162	0	473
TOTAL		1830	3745	229	1523	1255	2531	3779	14893

**Table A.3: Basins and total runoff per continent and morphology, as a percentage of the total amount per continent**

		Basins						
type	morphology	Africa	Asia	Australasia	Europe	Indonesia	North America	South America
0	arheic	3%	7%	3%	2%	0%	0%	2%
0	Exo-Arheic	35%	9%	12%	1%	0%	2%	17%
0	karst	13%	3%	4%	13%	5%	16%	0%
0	Big river	1%	1%	0%	1%	1%	0%	2%
1	estuary	5%	21%	15%	12%	36%	6%	15%
1	macrotidal	12%	10%	17%	4%	14%	3%	17%
1	mangrove	17%	6%	26%	0%	38%	3%	21%
1	ria	0%	25%	0%	14%	0%	2%	0%
2	lagoon	14%	7%	20%	9%	5%	10%	10%
3	fjard	0%	1%	0%	4%	0%	3%	6%
3	fjord	0%	1%	3%	7%	0%	15%	9%
3	glac sediment	0%	8%	1%	35%	0%	37%	0%
		100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%
		Runoff (m/y)						
type	morphology	Africa	Asia	Australasia	Europe	Indonesia	North America	South America
0	arheic	6%	4%	0%	1%	0%	0%	0%
0	Exo-Arheic	2%	1%	0%	0%	0%	0%	0%
0	karst	3%	1%	0%	9%	4%	7%	0%
0	Big river	46%	50%	0%	35%	8%	30%	77%
1	estuary	1%	12%	19%	7%	20%	6%	4%
1	macrotidal	7%	10%	17%	2%	21%	6%	7%
1	mangrove	19%	6%	27%	0%	44%	5%	5%
1	ria	0%	9%	0%	9%	0%	5%	0%
2	lagoon	16%	4%	17%	12%	4%	11%	3%
3	fjard	0%	1%	0%	5%	0%	5%	2%
3	fjord	0%	0%	15%	7%	0%	19%	2%
3	glac sediment	0%	3%	6%	13%	0%	6%	0%
		100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%

## Appendix B: Matlab models

In this appendix all developed Matlab models are listed. They are organized as given in table A.1, and as described hereunder:

- 6 input files were created, 2 for each of the sites: Venice, Thau and Szczecin. 1 serves as input file for the model based on flushing time, and the other for the model based on residence time.
- Each of the input files calls the model it requires: salt.m or river.m.
- Thau lagoon requires its own model, because it has net PIP adsorption instead of release. The changed differential equations are:
 
$$dSV2(3)=ln(3)+ln(8)-PPP2+remP2-Prel-expDIP2;$$

$$dSV2(4)=ln(4)+ln(9)+Prel-expOxP-burOP2;$$
- The simulation for the Oder requires a separate input model and running models, which loop through the years and use annually changing residence times and nutrient inputs. The annual values are recalculated to the internal clock of the model, so that smooth transitions take place.
- Optionally, results can be represented on screen in matlab by calling the appropriate plotting script:
- Results can also be obtained by calling the array Results in matlab, or by writing this array to a text file. The columns then represent variables in the following orders:

Because large parts of the files are the same, only Venice\_r\_1.m, Venice\_s\_1.m, river.m, salt.m, Oder\_s\_range\_4d.m and saltfw\_range.m are given here. Input data and k-values for the other models can be obtained from tables 4.6 and 4.7 respectively.

Input file	description	Calls Model file	Optional Plotting file
Venice_r_1.m	Flushing time	River.m	Plot_r
Venice_s_1.m	Residence time	Salt.m	Plot_s.m
Thau_r_c.m	Flushing time	Riverprel.m	Plot_r
Thau_s_c.m	Residence time	Saltprel.m	Plot_s.m
Oder_r_c.m	Flushing time	River.m	Plot_r
Oder_s_c.m	Residence time	Salt.m	plot_s.m
Oder_r_range_4d.m	Flushing time	Riverfw_range.m	
Oder_s_range_4d.m	Residence time	Saltfw_range.m	

---

---

Venice\_r\_1.m

---

---

```
SV2=[ 19.2719      3.8544 5.2309 1.5027 0.2409 ]
aerin=[ 239.0000      70.0000      6.5000 23.1250      4.3750 ]

Start=[ 331.0000      21.0000      240.0000      154.0000      18.3000
        6.6000 114.0000      5.1000 15.4000      ]

kexp= 1.7593

oldexp=[      33.9044      6.7809 9.2025 2.6437 0.4238 ]

Input=[]
for dar=1:1:15
    Input=[Input;aerin];
end
Input

dt=0.002;
tstart=1990;
tmax=2003;

river
plot_r
```

---

---

---

Venice\_s\_1.m

---

---

```
SV2=[ 19.2719      3.8544 5.2309 1.5027 0.2409 ]

aerin=[ 314.0000      13.0000      0.8700 53.0000      6.4600 71.0826
        3.3320 0.6220 0.8663 0.2221 ]

Start=[ 331.0000      21.0000      171.2290      153.8410      19.7640
        6.5271 114.0000      29.9570      15.2299      ]

kexp= 5.7758

exp=[ 111.3116      22.2623      30.2126      8.6795 1.3914 ]

Input=[]
for dar=1:1:100
    Input=[Input;aerin];
end
Input

dt=0.002;
tstart=1990;
tmax=2003;

salt
```

```

plot_s
river.m
=====

%load: SV2 Start Input and kexp

NP=0.0625;
count=0;
y=1;
first=0;

Inputs=Input;
In=Inputs(1,:);

dSV2=[];
oldRes2=[];
oldResFluxN2=[];
oldResFluxP2=[];
limiting=[];

kPPN=Start(1)/SV2(1);
kPPP=Start(2)/SV2(3);
kremN2=Start(3)/SV2(2);
kburN2=Start(4)/SV2(2);
kremP2=Start(5)/SV2(5);
kburP2=Start(6)/SV2(5);
kdenit2=Start(7)/SV2(1);
kPrel=Start(8)/SV2(4);
kburOP2=Start(9)/SV2(4);

oldforplot=[SV2 Input(1,:) Start];
oldd=size(oldforplot);

for ex=1:1:oldd(2)
for why=1:1:7
oldarie(why,ex)=oldforplot(ex);
end
end
oldarie(:,20)=oldexp(1); %DIN output
oldarie(:,21)=oldexp(2); %PON output
oldarie(:,22)=oldexp(3); %DIP output
oldarie(:,23)=oldexp(4); %PIP output
oldarie(:,24)=oldexp(5); %POP output
oldarie;

for t=tstart:dt:tmax
count=count+1;
first=first+1;

which = 0;
why = kPPN*SV2(1);
zed = kPPP*SV2(3)/NP;
if why<zed
% disp ('N limiting!')
which = 1;
end
if why>zed
% disp ('P limiting!')
which = 2;
end
end

```

```

    if first==1
        In=Inputs(y,:);
        limiting=[limiting;which];
        oldRes2=[oldRes2;SV2];
        oldResFluxN2=[oldResFluxN2;ln(1) ln(2) Start(1) Start(3) Start(4) Start(7) oldarie(1,20)
oldarie(1,21)];
        oldResFluxP2=[oldResFluxP2;ln(3) ln(4) ln(5) Start(2) Start(5) Start(6) Start(8)
oldarie(1,22) oldarie(1,23) oldarie(1,24) Start(9)];
        end

        PPN2=min(kPPN*SV2(1),kPPP*SV2(3)/NP); %P- or N-limiting
        PPP2=min(kPPN*SV2(1)*NP,kPPP*SV2(3));

        remN2=kremN2*SV2(2);
        burN2=kburN2*SV2(2);
        remP2=kremP2*SV2(5);
        burP2=kburP2*SV2(5);
        denit2=kdenit2*SV2(1);
        Prel=kPrel*SV2(4);
        burOP2=kburOP2*SV2(4);

        expDIN2=kexp*SV2(1);
        expTON2=kexp*SV2(2);
        expDIP2=kexp*SV2(3);
        expOxP=kexp*SV2(4);
        expPOP=kexp*SV2(5);

        dSV2(1)=ln(1)-PPN2+remN2-denit2-expDIN2;
        dSV2(2)=ln(2)+PPN2-remN2-burN2-expTON2;
        dSV2(3)=ln(3)-PPP2+remP2+Prel-expDIP2;
        dSV2(4)=ln(4)-Prel-expOxP-burOP2;
        dSV2(5)=ln(5)+PPP2-remP2-burP2-expPOP;

        SV2=SV2+dSV2*dt;

    if count==500
        y=y+1;
        In=Inputs(y,:);
        limiting=[limiting;which];
        count=0;
        oldRes2=[oldRes2;SV2];
        oldResFluxN2=[oldResFluxN2;ln(1) ln(2) PPN2 remN2 burN2 denit2 expDIN2 expTON2];
        oldResFluxP2=[oldResFluxP2;ln(3) ln(4) ln(5) PPP2 remP2 burP2 Prel expDIP2 expOxP
expPOP burOP2];
        end
    end

    %disp ('model run successfull, results:')
    oldprint=[oldRes2 oldResFluxN2 oldResFluxP2 limiting];
    %disp ('choose a plot routine: plot_r.m plot_s.m plot_both.m')

```

## Salt.m

---

```

%load: SV2 Start Input and kexp

NP=0.0625;

dt=0.002;
tmax=2003;
count=0;
y=1;
first=0;

Inputs=Input;
In=Inputs(1,:);

dSV2=[];
Res2=[];
ResFluxN2=[];
ResFluxP2=[];
limiting=[];

kPPN=Start(1)/SV2(1);
kPPP=Start(2)/SV2(3);
kremN2=Start(3)/SV2(2);
kburN2=Start(4)/SV2(2);
kremP2=Start(5)/SV2(5);
kburP2=Start(6)/SV2(5);
kdenit2=Start(7)/SV2(1);
kPrel=Start(8)/SV2(4);
kburOP2=Start(9)/SV2(4);

forplot=[SV2 Input(1,:) Start];
d=size(forplot);

for ex=1:1:d(2)
for why=1:1:14
arie(why,ex)=forplot(ex);
end
end
arie(:,25)=exp(1); %DIN output
arie(:,26)=exp(2); %PON output
arie(:,27)=exp(3); %DIP output
arie(:,28)=exp(4); %PIP output
arie(:,29)=exp(5); %POP output
arie;

for t=1990:dt:tmax
count=count+1;
first=first+1;

which = 0;
why = kPPN*SV2(1);
zed = kPPP*SV2(3)/NP;
if why<zed
% disp ('N limiting!')
which = 1;
end
if why>zed
% disp ('P limiting!')
which = 2;

```

```

end

if first==1
In=Inputs(y,:);
limiting=[limiting;which];
Res2=[Res2;SV2];
ResFluxN2=[ResFluxN2;ln(1) ln(2) Start(1) Start(3) Start(4) Start(7) arie(1,25) arie(1,26)
ln(6) ln(7)];
ResFluxP2=[ResFluxP2;ln(3) ln(4) ln(5) Start(2) Start(5) Start(6) Start(8) arie(1,27)
arie(1,28) arie(1,29) Start(9) ln(8) ln(9) ln(10)];
end

% PPN2=kPPN*SV2(1);
% PPP2=kPPP*SV2(3);

PPN2=min(kPPN*SV2(1),kPPP*SV2(3)/NP); %P- or N-limiting
PPP2=min(kPPN*SV2(1)*NP,kPPP*SV2(3));

remN2=kremN2*SV2(2);
burN2=kburN2*SV2(2);
remP2=kremP2*SV2(5);
burP2=kburP2*SV2(5);
denit2=kdenit2*SV2(1);
Prel=kPrel*SV2(4);
burOP2=kburOP2*SV2(4);

expDIN2=kexp*SV2(1);
expTON2=kexp*SV2(2);
expDIP2=kexp*SV2(3);
expOxP=kexp*SV2(4);
expPOP=kexp*SV2(5);

dSV2(1)=ln(1)+ln(6)-PPN2+remN2-denit2-expDIN2;
dSV2(2)=ln(2)+ln(7)+PPN2-remN2-burN2-expTON2;
dSV2(3)=ln(3)+ln(8)-PPP2+remP2+Prel-expDIP2;
dSV2(4)=ln(4)+ln(9)-Prel-expOxP-burOP2;
dSV2(5)=ln(5)+ln(10)+PPP2-remP2-burP2-expPOP;
SV2=SV2+dSV2*dt;

if count==500
y=y+1;
In=Inputs(y,:);
count=0;
limiting=[limiting;which];
Res2=[Res2;SV2];
ResFluxN2=[ResFluxN2;ln(1) ln(2) PPN2 remN2 burN2 denit2 expDIN2 expTON2 ln(6)
ln(7)];
ResFluxP2=[ResFluxP2;ln(3) ln(4) ln(5) PPP2 remP2 burP2 Prel expDIP2 expOxP
expPOP burOP2 ln(8) ln(9) ln(10)];
end
end

% disp ('model run successfull, results:');
print=[Res2 ResFluxN2 ResFluxP2 limiting];
% disp ('choose a plot routine: plot_r.m plot_s.m plot_both.m');

```

---



---

 Oder\_s\_range\_4d.m

```

SV2=[ 249.7560      140.7640      7.6908 17.5955      8.7978 ]

aerin=[ 182.9461      194.2118      7.1758 48.5530      12.1382      ]

Start=[ 5292.8346      330.8022      4624.5000      1393.0000      282.0000
        94.0000      501.5100      29.0000

376.0000      ]

kinner= [11.47
11.71
9.28
6.86
6.25
8.68
9.28
10.49
9.89
6.86
5.64
5.89
6.25
5.89
8.68
8.07
9.04
9.89
9.28
9.52
]

%exp=[ 2224.9189      1253.9778      68.5125      156.7472      78.3736      ]

Input=[4282.655246      2498.21556      109.7836616      156.1384725      34.36846968      ;
4568.165596      2569.593148      113.0125928      160.5995717      26.67843924      ;
2141.327623      1427.551749      80.72328059      89.2219843      39.93526465      ;
3211.991435      1784.439686      72.65095253      111.5274804      16.01530297      ;
2141.327623      1427.551749      64.57862448      89.2219843      23.79060853      ;
4139.900071      2640.970735      80.72328059      165.0606709      -19.75876588      ;
4354.032834      2426.837973      96.86793671      151.6773733      9.769187883      ;
4354.032834      2069.950036      96.86793671      129.3718772      15.93002784      ;
4354.032834      2426.837973      96.86793671      151.6773733      42.05850012      ;
2855.103498      1427.551749      71.03648692      89.2219843      98.05602668      ;
1427.551749      1427.551749      64.57862448      89.2219843      23.79060853      ;
1784.439686      1427.551749      48.43396836      89.2219843      23.79060853      ;
2855.103498      1784.439686      48.43396836      111.5274804      -14.65954366      ;
2141.327623      2141.327623      48.43396836      133.8329764      -36.96503973      ;
4282.655246      2141.327623      38.74717469      133.8329764      -11.13358994      ;
3211.991435      1784.439686      32.28931224      111.5274804      1.485112461      ;
3568.879372      1784.439686      64.57862448      111.5274804      17.62976858      ;
2855.103498      1784.439686      71.03648692      111.5274804      43.46121837      ;
3925.767309      1784.439686      41.97610591      111.5274804      7.942974908      ;
3925.767309      1427.551749      32.28931224      89.2219843      7.645952416      ];

first=[]

```

```
for dar=1:1:20
    first=[first; aerin];
end

Inputer=[Input first]

Discharger=[
2.46
2.52
1.89
1.26
1.10
1.73
1.89
2.21
2.05
1.26
0.95
1.01
1.10
1.01
1.73
1.58
1.83
2.05
1.89
1.96
];

Input=[];
kexpin=[];
Discharge=[];
sam = 5;
grootte = size(kinner);
for een = 2:1:(grootte(1))
for twee = 0:1:sam-1
    kexpin = [kexpin; ((kinner(een)-kinner(een-1))/(sam)*twee)+kinner(een-1)];
    Input = [Input; ((Inputer(een,:)-Inputer(een-1,:))/(sam)*twee)+Inputer(een-1,:)];
    Discharge = [Discharge; ((Discharger(een,:)-Discharger(een-1,:))/(sam)*twee)+Discharger(een-1,:)];
end
end

% kexpin = [kexpin; kinner(20)];
% Input = [Input; Inputer(20,:)];
% Discharge = [Discharge; Discharger(20)];

figure (1)
subplot (2,1,1)
plot (kexpin)
subplot (2,1,2)
plot (Input)

pause
    saltfw_range
    plot_s
```

---

```

Saltfw_range.m
NP=1/16;

dt=0.002;
tstart=1980;
tmax=1998.8;
count=0;
y=1;
first=0;
num=1;
usedkexp=[];
limiting=[];

Inputs=Input;
In=Inputs(1,:);

dSV2=[];
Res2=[];
ResFluxN2=[];
ResFluxP2=[];

kPPN=Start(1)/SV2(1);
kPPP=Start(2)/SV2(3);
kremN2=Start(3)/SV2(2);
kburN2=Start(4)/SV2(2);
kremP2=Start(5)/SV2(5);
kburP2=Start(6)/SV2(5);
kdenit2=Start(7)/SV2(1);
kPrel=Start(8)/SV2(4);
kburOP2=Start(9)/SV2(4);

forplot=[SV2 Input(1,:) Start];
d=size(forplot);

for ex=1:1:d(2)
for why=1:1:14
arie(why,ex)=forplot(ex);
end
end
arie(:,25)=exp(1); %DIN output
arie(:,26)=exp(2); %PON output
arie(:,27)=exp(3); %DIP output
arie(:,28)=exp(4); %PIP output
arie(:,29)=exp(5); %POP output
arie;

for t=tstart:dt:tmax
count=count+1;
first=first+1;
kexp=kexpin(num);
usedkexp=[usedkexp; kexp];

which = 0;
why = kPPN*SV2(1);
zed = kPPP*SV2(3)/NP;
if why<zed
% disp ('N limiting!')
which = 1;
end

```

```

        if why>zed
% disp ('P limiting!')
        which = 2;
        end

        if first==1
        limiting=[limiting;which];
        In=Inputs(y,:);
        Res2=[Res2;SV2];
        ResFluxN2=[ResFluxN2;ln(1) ln(2) Start(1) Start(3) Start(4) Start(7) arie(1,25) arie(1,26)
ln(6) ln(7)];
        ResFluxP2=[ResFluxP2;ln(3) ln(4) ln(5) Start(2) Start(5) Start(6) Start(8) arie(1,27)
arie(1,28) arie(1,29) Start(9) ln
(8) ln(9) ln(10)];
        end

        PPN2=min(kPPN*SV2(1),kPPP*SV2(3)/NP); %P- or N-limiting
        PPP2=min(kPPN*SV2(1)*NP,kPPP*SV2(3));

        remN2=kremN2*SV2(2);
        burN2=kburN2*SV2(2);
        remP2=kremP2*SV2(5);
        burP2=kburP2*SV2(5);
        denit2=kdenit2*SV2(1);
        Prel=kPrel*SV2(4);
        burOP2=kburOP2*SV2(4);

        expDIN2=kexp*SV2(1);
        expTON2=kexp*SV2(2);
        expDIP2=kexp*SV2(3);
        expOxP=kexp*SV2(4);
        expPOP=kexp*SV2(5);

        dSV2(1)=ln(1)+ln(6)-PPN2+remN2-denit2-expDIN2;
        dSV2(2)=ln(2)+ln(7)+PPN2-remN2-burN2-expTON2;
        dSV2(3)=ln(3)+ln(8)-PPP2+remP2+Prel-expDIP2;
        dSV2(4)=ln(4)+ln(9)-Prel-expOxP-burOP2;
        dSV2(5)=ln(5)+ln(10)+PPP2-remP2-burP2-expPOP;
        SV2=SV2+dSV2*dt;

        if count==100
        y=y+1;
        num=num+1;
        In=Inputs(y,:);
        count=0;
        limiting=[limiting;which];
        Res2=[Res2;SV2];
        ResFluxN2=[ResFluxN2;ln(1) ln(2) PPN2 remN2 burN2 denit2 expDIN2 expTON2 ln(6)
ln(7)];
        ResFluxP2=[ResFluxP2;ln(3) ln(4) ln(5) PPP2 remP2 burP2 Prel expDIP2 expOxP
expPOP burOP2 ln(8) ln(9) ln(10)];
        end
        end

disp ('model run successful, results:')
oldprint=[Discharge kexpin Input Res2 ResFluxN2 ResFluxP2 limiting ];

```

```
%disp ('choose a plot routine: plot_r.m   plot_s.m   plot_both.m')  
  
% oldprint(1:50,1:12)  
% pause  
% oldprint(1:50,13:24)  
% pause  
% oldprint(1:50,25:42)  
% pause  
% oldprint(51:95,1:12)  
% pause  
% oldprint(51:95,13:24)  
% pause  
% oldprint(51:95,25:42)  
% pause  
  
save NP16.txt oldprint -ASCII
```

---