

Chapter 2

Effect-Load-Sensitivity Analyses – Basic Concepts

The aim of this chapter is to give a brief overview of concepts related to effect-load-sensitivity analysis. In a way, this chapter may be regarded as a second introduction to the following chapters of the book.

Richard Vollenweider presented the first load models for phosphorus and nitrogen for lakes in the late 1960s (Vollenweider 1968). By means of simple mass-balance calculations and statistical regressions, he calculated critical loadings of total nitrogen (TN) and total phosphorus (TP) to avoid or reverse eutrophication. Since then, many studies have demonstrated where the Vollenweider approach can and cannot be used (Schindler 1977, 1978; Bierman 1980; Chapra 1980; Boynton et al. 1982; Boers et al. 1993; Håkanson 1999). The Vollenweider model (and later versions, such as OECD 1982), and the analysis behind this load model, constitutes a fundamental base for practically all assessments of eutrophication for lakes. The interesting part, however, is not to predict a concentration of a chemical element like a nutrient, but to predict ecological effects related to nutrients (see Fig. 2.1). It is evident that the concentration of a nutrient can be influenced by emissions from many types of sources, like point sources (domestic sewage, industries and fish farms), atmospheric deposition (to the water surface and the catchment area), internal loading (linked to resuspension, diffusion, etc.) and, in estuaries, inflow from the sea and tributary input, where the characteristics of the catchment, like bedrocks, soils, land use, etc., influence the nutrient concentration in the coastal area (see Fig. 2.2).

Differential equations are often used to quantify fluxes (g X/yr), amounts (g X) and concentrations (g X/m^3) of all types of materials (such as toxins and nutrients), but not generally for bioindicators such as the Secchi depth, chlorophyll-a concentrations, concentrations of cyanobacteria and the oxygen saturation in the deep-water zone (O_2Sat) or other types of operational effect variables (Fig. 2.3). Regressions based on empirical data on nutrient concentrations in the coastal water are often necessary to predict the target bioindicators or variables expressing ecosystem effects. In theory, both model approaches (see Fig. 2.1A and B) may be used for the effect-load-sensitivity analyses (ELS; see Håkanson 1999) provided that at least one operationally defined ecological effect variable or bioindicator relevant for the load variables(s) in question is included in the model. Step B in Fig. 2.1 illustrates

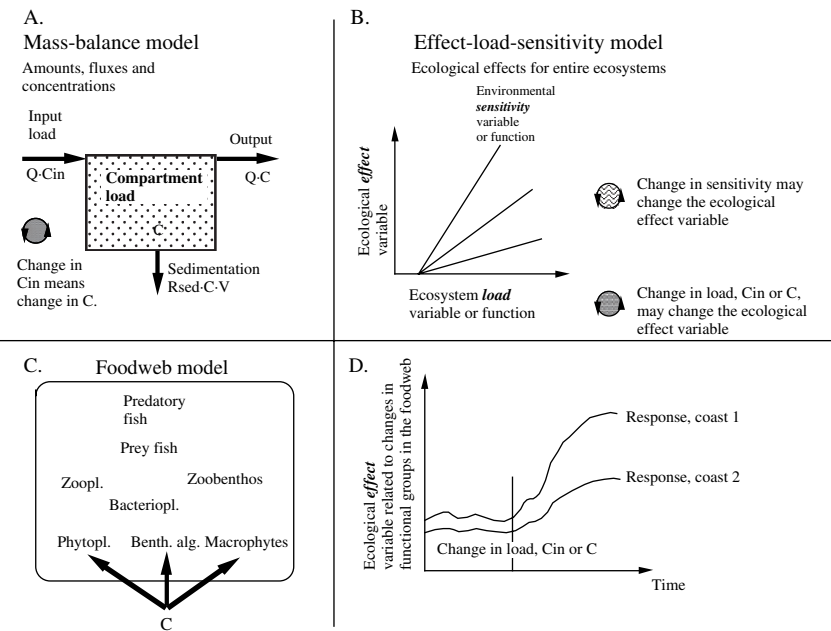


Fig. 2.1 Illustration of the fundamental difference between dynamic, mass-balance models (A) and effect-load-sensitivity models (ELS) based on regressions (B) and ELS-models related to dynamic foodweb models (C) and (D) how changes in the load at a given time may cause different responses in the aquatic foodweb in coastal systems of different size and form (coast 1 compared to coast 2). The wheels indicate that by means of remedial measures one may reduce/change the load variable in dynamic models and the load and the sensitivity variables in ELS-models. Q = Water discharge ($m^3/time$); C_{in} = concentration of substance in inflow (g/m^3); C = concentration of substance in the system (g/m^3); R_{sed} = sedimentation rate ($1/time$); V = volume (m^3)

a regression and this book will discuss many regressions of that type. Ideally, the effect variable should express the production or biomass of defined functional organisms (preferably fish at the top trophic level, see Figs. 2.1C and 2.2), which characterize a given coastal system. Figure 2.1D illustrates schematically that two coastal areas are likely to react differently to a change in the load of nutrients to the system. The classical approach (from Vollenweider 1968) to carry out ELS-analysis is to use mass-balance models to predict concentrations of nutrients and empirical models (like regressions) to link these concentrations to measured data on the operational bioindicators (see Fig. 2.2). In contexts of coastal management, one must generally for practical and economical reasons seek simpler operational bioindicators than the ideal ones related to production or biomasses of functional groups or species illustrated in Fig. 2.2. The mean concentration of a given toxic substance (or substances) in predatory fish, the Secchi depth, the oxygen saturation/concentration in the deep-water layer and chlorophyll-a concentrations are examples of simple, but relevant operational bioindicators.

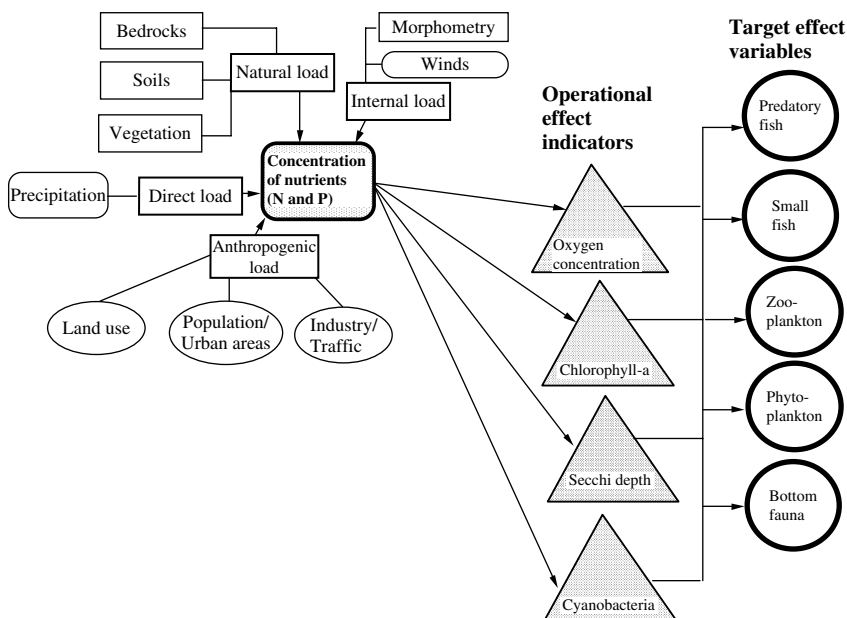


Fig. 2.2 The character of the drainage area influences the water quality in estuaries. This is a statement that is simple to make, but how can it be quantified? It is evident that the geology, hydrology, land use and precipitation influence the inputs of substances to many coastal areas, including the key nutrients, phosphorus and nitrogen. It is an important task to relate drainage area characteristics to coastal area characteristics and to predict variables of primary biological importance, like total-P concentration, which in turn may be related to operational ecological effect variables (like oxygen concentration), and to the target effect variables (like reproduction and abundance of key species)

Figure 2.4 gives the principles of an ELS-model illustrated as a ELS-diagram. Environmental goals (generally set by National Environmental Protection Agencies) should concern the ecological effect variables and not the load variables, since one and the same load may cause different effects in ecosystems of different sensitivities. From this diagram, important concepts like natural background concentration and critical load can be scientifically defined (see Håkanson 1999). When no practically useful validated ELS-models are available, there exists ample room for speculation about cause and effect, and about the best strategies to remediate aquatic systems.

In contexts of ELS-analyses, the primary interest is not on site-specific conditions (“the sampling bottle”), on the individual, organ or cell level, but at the ecosystem level. That perspective should be of main interest from a management point of view where questions are posed concerning the status of larger water bodies (ecosystems), and the remedial actions that could be used in practice to improve the conditions in such systems.

It should be stressed that ELS-analyses are of fundamental importance in water management and that ELS-models are essential tools to examine consequences of remedial measures that may influence a target effect variable. One can reduce

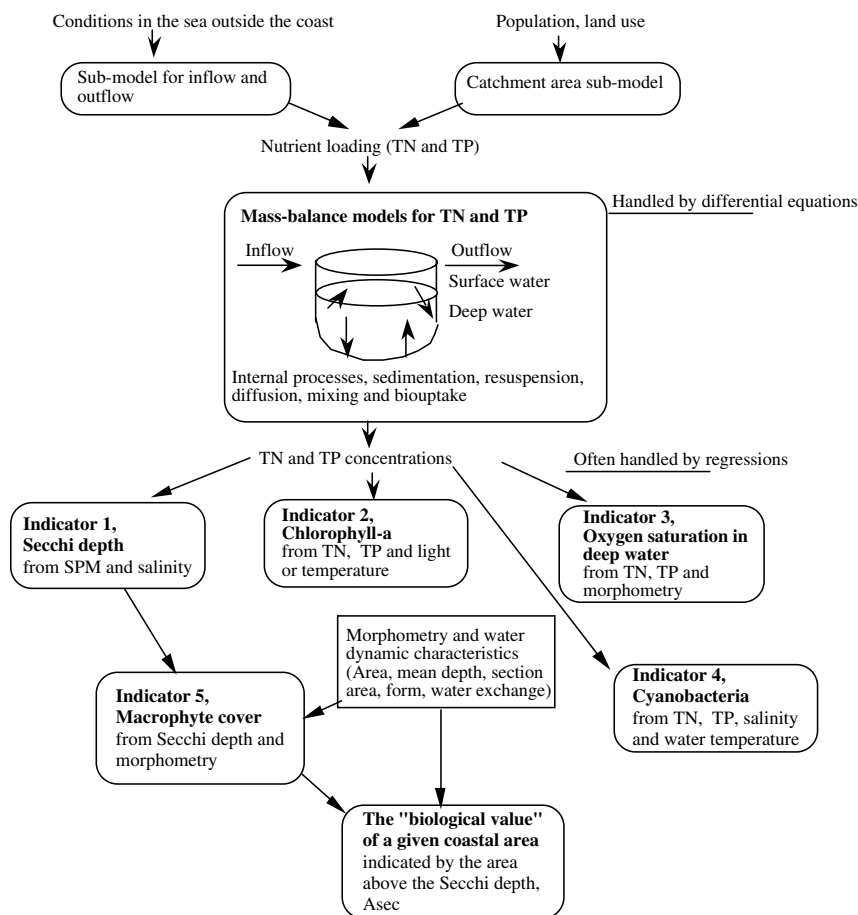


Fig. 2.3 Basic elements in Effect-Load-Sensitivity (ELS) modeling for coastal water eutrophication utilizing mass-balance modeling and regression analyses relating nutrient concentrations to operational bioindicators (Secchi depth, chlorophyll-a concentrations, concentration of cyanobacteria and oxygen saturation in the deep-water zone)

negative ecosystem effects of water pollutants by reducing the load to the system or by changing the sensitivity (for example, by changing the salinity, as in Ringkøbing Fjord, where there is a sluice regulating the fluxes of salt water from the sea to the fjord; see Håkanson et al. 2007b).

One cannot generally change the morphometry of the coastal area, but coasts of different size and form will react differently to remedial measures and it is essential to know this so that one can have realistic expectations of the remedial measures for a given coastal area.

It is generally not possible to derive ELS-models, which apply with equal success to all types of ecosystems. Therefore, the operational range, the domain, of the ELS-model must be explicitly given to avoid abuse of the model for ecosystems for which

ELS DIAGRAM

FOR NUTRIENTS IN COASTAL AREAS

EFFECT

1. Operational
bioindicators or effect
variables

- Secchi depth
- Chlorophyll
- Cyanobacteria
- Oxygen concentration
- Macrophyte cover

2. Ideal effect variables:

- Change in biomass of
key functional organisms

SENSITIVITY

- Coastal area morphometry: size and form
parameters
- Salinity and temperature regime
- Water and bottom dynamic conditions

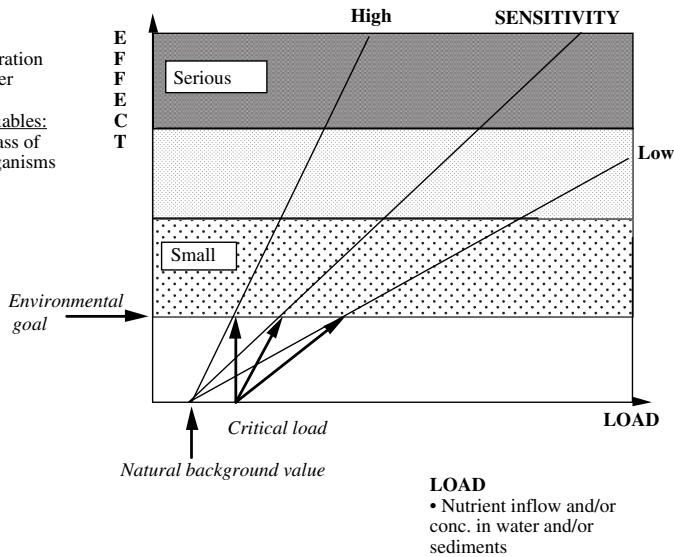


Fig. 2.4 Illustration of the ELS-diagram for coastal eutrophication

it was never intended to be used. If dynamic (time-dependent) ELS-models can meet these requirements, they would generally be preferable to statistical/empirical models because they can provide better understanding of mechanisms and processes.

This book will discuss many ELS-models based on regressions and some of those regressions are included in the more comprehensive process-based mass-balance model for phosphorus (CoastMab) to link dynamically modeled TP-concentrations to the target bioindicators (i.e., the operational effect variables). The CoastMab-model is presented in Sect. 9.1 and applied in Chap. 6.

Tools and Criteria for Sustainable Coastal Ecosystem
Management

Examples from the Baltic Sea and Other Aquatic
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