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Finding the optimal reduction to meet all targets—Applying Linear Programming with a nutrient tracer model of the North Sea

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ABSTRACT

This paper describes a method to trace the origin of nutrients in marine areas and subsequently quantify the optimal reductions of nutrient loads in accordance with eutrophication water quality targets. The tracer method is incorporated in a validated Delft-3D model of the North Sea. For this model, nutrient loads are well characterized. Resulting from the tracer model, nutrient composition matrices are created for each OSPAR area of the North Sea for the year 2002. Water quality targets are also based on OSPAR agreements. The optimal reduction is obtained directly via Linear Programming, which is extremely quick and does not need scenario runs of the full model. The optimum reduction scenario obtained was validated in Delft 3D and showed a similar outcome. Results from the optimization method clearly differ from common practise (uniform reduction of all sources). They also show that some targets are inconsistent spatially or with respect to the DIN to DIP ratio. The method provides a quick and useful tool to quantify the necessary riverine reductions to achieve a healthy ecosystem state. It can be extended to include economic costs per river basin or economic sector and also be applied in combination with other eco-hydrodynamic models or for other substances.

1. Introduction

During the last decades, large amounts of nutrients particularly nitrogen and phosphorus have been discharged into aquatic ecosystems, sometimes leading to excessive growth of primary producers i.e. phytoplankton. This process, which is called eutrophication, is accompanied by several objectionable symptoms: it gives the water a green, turbid appearance; it can cause bad odours; it may harm other organisms because the minimum daily oxygen level can become extremely low during the night due to phytoplankton respiration; it can even cause the water to become completely deprived of oxygen (anaerobic) when a bloom declines rapidly, since the biological degradation processes consume large amounts of oxygen. Eutrophication in the marine environment is primarily caused not only by high riverine nutrient inputs, but also atmospheric deposition is a source of nutrients.

Thus in order to assess the eutrophication status for the OSPAR maritime areas, the so-called "Comprehensive Procedure" (CP) was implemented by the member states (OSPAR, 2005). One of the aims of the CP was to classify the maritime areas as problem areas (PA), non-problem areas (NPA), and potential problem areas (PPA) for which chlorophyll-a and secondly, oxygen are the most important indicators. To monitor and classify the state of the OSPAR regions, concentration assessment levels or thresholds were defined for each region. These thresholds include nutrients, which are categorized as causative parameters or category I variables and chlorophyll-a and phytoplankton indicator species, which are categorized as direct effect or category II variables (OSPAR, 2005).

In the past achieving targets has been attempted by formulating (uniform) reduction scenarios for loadings i.e. a 50% reduction of all loads from all rivers into the North Sea relative to a reference case such as 1985 (Parcom Recommendation: OSPAR, 1988). The actually observed reduction of nutrients and chlorophyll-a tends to be less than linearly proportional because: (1) the contribution of some sources of nutrients i.e. the Channel or the North Atlantic inflow, cannot easily be reduced by management measures, and (2) the ecological system itself tends to adapt to new conditions which often means it gets more efficient in its usage of increasingly scarce resources (see for instance De Vries et al., 1998). In view of these non-linearities, a suitable method would be a modelling approach. As a further complication substances are freely transported between various areas at sea.

By how much the actual response in a certain area deviates from proportionality, depends on many factors and therefore is not trivial. Traditionally, this is assessed by running a model for different combinations of reduction scenarios until all targets are met. In the case of the North Sea this type of analyses is carried out by a number of national modelling groups, whose activities are coordinated within OSPAR–EMO (more details in Lenhart et al., 2010). Usually, however, this method proves to be cumbersome and moreover it remains uncertain whether an adequate response of the receiving water system might have been achieved by a smaller overall reduction of the loads. In other words: after running a model many times, a valid reduction strategy might be obtained but it is unknown how efficient it is.

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Here, we propose an alternative to the traditional approach consisting of three steps: (1) application of a special tracer version of the DELFT3D-GEM model to construct what we call a composition matrix relating the present concentrations at sea to all individual sources, (2) application of an optimization technique (Linear Programming) to find the most effective reduction scenario, and (3) rerunning the model for (some) of the scenarios found under step 2 as an input to check its result.

The optimization step may be regarded as a meta-model with two major advantages: (1) every solution produced by this method is not only valid in the sense that all targets are met but can be demonstrated to be optimal and (2) scenario simulations are completed in a fraction of a second so it is possible to assess many alternative strategies in a very short period of time.

To demonstrate its validity, we apply the new method to achieve OSPAR targets of winter DIN and DIP concentrations in the Southern North Sea, and check whether the outcomes (i.e. the resulting optimal reductions) indeed result in the desired concentrations. Notice that the focus of this paper is on the methodology rather than on the precise results. So we do not propose to actually implement the reduction scenarios obtained here but rather to demonstrate how to select them.

2. Materials and methods

2.1. DELFT3D-GEM

The biogeochemical transport model DELFT3D-GEM is a generic ecological modelling instrument that can be applied to any water system (fresh, transitional or coastal water). The regular North Sea implementation of this model has a long track record of over twenty years and is among other described by Los et al. (2008), Blauw et al. (2009), Los and Blaas (2010), and Troost et al. (2012). Also, an inter-model comparison showed that the model performance is in line with that of other biogeochemical flux models, with respect to both its behaviour under default conditions and its response to changes (Lenhart et al., 2010). The model includes phytoplankton processes (BLOOM); mineralization in water and sediment; (de)nitrification; re-aeration; sedimentation, resuspension and burial of phytoplankton and particulate organic matter; and extinction of light by suspended solids, organic matter, phytoplankton, and humic substances. The most relevant processes for this study are described below.

The phytoplankton module (BLOOM) in DELFT3D-GEM simulates primary production, respiration and mortality of phytoplankton. Growth is calculated as a function of nutrients and light conditions. The BLOOM module allows for the modelling of species competition and adaptation of phytoplankton to limiting nutrients or light (Los and Brinkman, 1988). Briefly, four phytoplankton groups are defined in BLOOM: diatoms, flagellates, dinoflagellates and *Phaeocystis*, with different resource requirements and ecological properties. Within each of these groups, three phenotypes are defined to account for adaptation to changing environmental conditions: energy limited (E) types, nitrogen limited (N) types and phosphorus limited (P) types, which have different ecological characteristics and requirements. The phenotypes reflect the state of the species and can change rapidly (with each cell division) if conditions change. Using an optimization algorithm, the limiting resource is selected with the best set of phenotypes at each time under the prevailing environmental conditions and species composition. Species composition on the other hand can only change due to growth and mortality. The time steps used in BLOOM for the ecological processes (i.e. cell division) are 24 h. The characteristics of the phytoplankton species, including variable C to chlorophyll-a ratios are based on data collected over the years and can be found in Los and Wijsman (2007).

2.2. Schematization and hydrodynamics

The modelling grid used in the GEM for the North Sea is called the ZUNO-grid (Fig. 1). This grid covers the southern North Sea and, formally, also the eastern English Channel, but we refer to its domain only as the former. The model grid consists of 4350 grid cells in the horizontal and 10 vertical layers. The grid is variable, with a resolution ranging from 1×1 km at the continental coast to 20 by 20 km at the northwestern boundary. The grid covers a total area of $3.6 * 105$ km^2. In addition to the layers in the water column, a single (and relatively thin) sediment layer is taken into account.

Within the framework of OSPAR the North Sea has been subdivided into a number of areas with names such as UKC1 or NLO2. The first one or two letters indicate the responsible country, the second gives a further geographical indication (W = Wadden Sea, C = Coast and O = Offshore). Finally sequential numbers are assigned as well to account for spatial differences (i.e. UKC1, UKC2 etc.). Homogeneity with respect to physical and biological conditions varies hence for instance part of NLO2 (i.e. Oyster grounds) is deep (>40 m) and usually stratified in summer, while another part of this area remains vertically mixed all year round. Targets are expressed per area. An overview of all areas and main loadings within the domain of the DELFT3D-GEM model is shown in Fig. 2. Since the computational elements of our model are much smaller than the areas, we average the model results over the elements within an area taking the volumes into account.

2.3. Hydrodynamics, meteorology, and silt

Hydrodynamic transports underlying DELFT3D-GEM are calculated using DELFT3D-FLOW. This is a 3D hydrodynamic model, which calculates non-steady flow and transport phenomena that result from tidal and spatially and temporarily varying meteorological forcing obtained from hind cast calculations by the Royal Dutch Meteorological Institute projected on a rectangular or a curvilinear boundary fitted grid. Hydrodynamic process details are described in http://oss.deltares.nl/web/opendelft3d, its set-up for the North Sea DELFT3D-GEM is described in Los et al. (2008). Both DELFT3D-FLOW and DELFT3D-GEM (a configuration of the DELWAQ software package) are open source model codes that may be freely downloaded via the Deltares website.

In the primary production model irradiance and wind speed are included based on measurements. They vary in time, but not in space. Temperature is adopted as a 3 dimensional, time varying forcing from the simulation results of the hydrodynamic model. Similarly silt concentrations, which affect the turbidity of the water, are adopted from simulation results of an SPM model applied to the same model domain using the same hydrodynamics.

The way these forcings are imposed on the DELFT3D-GEM model is described in detail by Los et al. (2008).

2.4. Nutrient inputs

Nutrients enter the model domain via 85 rivers, 2 open boundaries (Atlantic and Channel), and via atmospheric deposition. In the model, each river discharges into one coastal grid cell in the surface layer. Discharges and nutrient concentrations for all rivers are based on a database that was set up and maintained by CEFAS. The Atlantic boundary consists of all segments located on the Northern model interface, the Channel boundary of all segments on the south-western model interface. Boundary concentrations are included as forcing functions based on measurements (Channel boundary: Bentley et al., 1999; Bot et al., 1996; Brion et al., 2004, Laane et al., 1993, 1996a; Radach et al., 1996; Atlantic boundary: Bot et al., 1996; Cadée and Hegeman, 2002; Joint and Pomroy, 1992; Laane et al., 1996b; Pätsch and Radach, 1997; Radach et al., 1996).