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Global modelling of surface water quality: a multi-pollutant approach

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In many world regions the availability of clean water is at risk. Pollution of rivers and coastal seas poses a threat to aquatic ecosystems and society. Here, we review representative examples of mathematical models that simulate pollutant flows from land to sea at global and continental scales. We argue that a multi-pollutant modelling approach would help to better understand and manage water quality issues. Pollutants often have common sources and multiple impacts. Most existing spatially explicit models, however, focus on one type of pollution only. A new generation of models is needed to explicitly address the combined exposure of surface waters to multiple pollutants. Such models could serve as a basis for integrated water quantity and water quality assessments.

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Introduction

The availability of clean water is essential for nature as well as for people. Water systems are polluted in many different ways. For people, clean drinking water is essential. It is a key issue in meeting the Sustainable Development Goals [1]. In many world regions the availability of clean water is at risk as a result of population growth and economic developments [2••]. Changes in water quantity and water quality threaten the availability of clean water. In this article, we focus on the quality of surface waters including rivers and coastal waters.

Surface water pollution is often caused by nutrients, pathogens, plastics and chemicals such as antibiotics, heavy metals and pesticides. These pollutants have different environmental effects. Excess nutrients, for instance, may result in harmful algal blooms and hypoxia both in rivers and in coastal seas [3,4]. Pathogens in rivers pose a threat to human health [5]. Chemical pollution can have toxic effects [6]. Surface waters often suffer from the combined impact of multiple pollutants [7].

Human activities on land are the main reason why rivers are polluted. Once in a river, pollutants can be transported over long distances to end up in coastal seas. Pollutants in rivers often have common sources [8••]. For instance, agriculture is a source of nutrients, pathogens, pesticides and heavy metals. And sewage is a source of plastic, chemicals, pathogens and nutrients. This implies that measures to reduce a certain pollutant likely affect other pollutants as well. For instance, in waste water treatment, levels of most pollutants are reduced during the recovery of nutrients and water. Effective pollution management needs to account for these side-effects and co-benefits. Moreover, regional differences in the causes of surface water pollution exist. For instance, open defecation is a source of pollution in India [9] but not in all other world regions. Likewise, direct discharges of animal manure are typical for China [10]).

River and coastal water pollution is a worldwide issue [11]. Worldwide, rivers transport pollutants from land to sea. In Europe, North America and similarly well-studied world regions the causes of river pollution are relatively well understood. In many other world regions, however, the causes of observed water pollution are often not well known. In such cases, models can help to better understand the problem and support decision making on pollution control and environmental management [12]. Global river pollution models exist for, for instance, nutrients [13–15,16•] and pathogens [5,17,18•] and thermal pollution

[19], but hardly for chemicals [20] and not for plastics, although first modelling exercises are starting [21–23]. Continental-scale models exist for chemicals [20], faecal indicators, salinity, and biological oxygen demand [8••]. In addition there are many models for individual river basins [e.g., 24]. So far, only a few modelling studies tried to model multiple pollutions simultaneously, but mainly for continental analyses [8••]. A global multi-pollutant analysis that accounts for all of the abovementioned pollutants does not exist.

In this article, we focus on modelling of pollutant flows from land to sea from a multi-pollutant perspective. We focus on common sources of pollutants and multiple impacts. First, we present some typical examples of global, spatially explicit models to assess surface water quality variables (Section 'Examples of global and continental-scale models for surface water quality variables'). We cover the following water quality variables: nutrients, pathogens, some chemicals, plastics and river temperature. We also discuss representative examples of continental-scale models. Next, we compare the selected models (Section 'Model comparison'). In our model overview we compare models that have been developed for more than twenty years (nutrients) to more recent models (for pathogens, chemicals and microplastics). Our model comparison does not intend to be complete, but it gives a representative overview of models that are available today for global-oriented or continental-oriented water pollution assessments. Finally, we discuss the need for a multi-pollutant approach (Section 'The need for a multi-pollutant approach').

Examples of global and continental-scale models for surface water quality variables

Nutrients

Nutrient pollution in surface waters is a problem when harmful algal blooms develop. This can occur both in river systems and coastal seas. The Global *NEWS* (Nutrient Export from WaterSheds) model [14,15], and the IMAGE-GNM (Global Nutrient Model) are currently the only comprehensive river export models for nutrients (nitrogen and phosphorus) with a global coverage [16•,25]. Both models calculate river export to sea as a function of human activities on land (Table 1). The models include both diffuse and point sources of nutrients in rivers. Diffuse sources are, for instance, the use of synthetic fertilizers or animal manure in agriculture. Also nutrient inputs to rivers associated with land use change can be considered diffuse sources. Both models use gridded datasets (at 0.5×0.5 degree longitude by latitude) as model input. Both models include more than 6000 rivers.

Global *NEWS* predicts steady-state annual exports at the mouth of rivers for dissolved inorganic forms, dissolved organic forms and particulate forms of nitrogen (N), phosphorus (P) and carbon (C) using mostly empirical, mainly linear, relationships for sinks or retention in land and water systems. IMAGE-GNM is a physically based model, and calculates river export using a nutrient spiralling approach for in-stream retention of N and P. IMAGE-GNM is part of the IMAGE framework, and is used in many assessments to feed GLOBIO-aquatic, the IMAGE biodiversity model. An important difference between IMAGE-GNM and Global *NEWS* is that Global *NEWS* includes a few parameters that are calibrated using nutrient export data at the river mouth, while IMAGE-GNM is not calibrated. Moreover, Global NEWS calculates river export as annual totals for river basins. IMAGE-GNM, calculates nutrient flows on a 0.5×0.5 degree grid using a nutrient spiralling approach for in-stream retention of N and P. IMAGE-GNM has been implemented for the period 1900–2000 only. Global NEWS has been used to analyse the period 1970–2000 and future trends, for specific world regions such as Africa [26], South America [27], Bay of Bengal [28,29], and the Black Sea [30,31]. Moreover, a sub-basin version of Global NEWS has been developed for China [32,33]. Other than IMAGE-GNM, the Global NEWS model can be used to calculate an indicator for coastal eutrophication that can be used to analyse the impact of nutrient inputs for coastal seas [3].

Model results and scenario analyses indicate that nutrient export by world rivers increased considerably during the past decades, and may continue to increase in the future. This increase is associated with an increase in food production for a growing population, and increasing point source inputs of nutrients to rivers from sewage. As a result of increased nutrient loads, harmful algal blooms may continue to develop in the future. Similar results have been obtained with continental-scale models that have mainly been developed for Europe [e.g., 34–36] and America [e.g., 37].

Pathogens

Waterborne pathogens, such as the protozoan parasite Cryptosporidium, are a major cause of diarrhea worldwide. GloWPa (Global Waterborne Pathogen model) [18•] is the only available global model for waterborne pathogens (Table 1). The focus is on enteric pathogens that cause diarrhea and spread via the faecal-oral route. GloWPa has been implemented for Cryptosporidium (GloWPa-Crypto [38], and rotavirus (GloWPa-Rota [39•]), and it is divided in a human and livestock module. Human feces enter the water via sanitation systems or after runoff from land. Manure from 11 livestock species is, often after storage where pathogens can decay, also transported with runoff to the surface water. GloWPa inputs (e.g., for population and agriculture) are 0.5×0.5 degree grid and country data, outputs are pathogen loads to surface waters on a 0.5×0.5 degree grid. The model has been implemented for the year 2010. The current model calculates inputs of pathogens to rivers,