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Simulation-based assessment of the impact of fertiliser and herbicide application on freshwater ecosystems at the Three Gorges Reservoir in China

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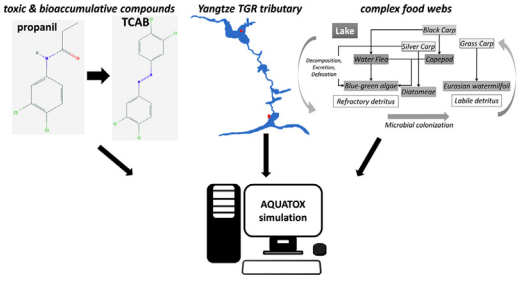
HIGHLIGHTS

- Aquatic food webs of a Three Gorges Reservoir tributary are simulated using AQUATOX.
- Impacts of high nutrient inflows from agriculture are low by dilution.
- Potential risks from propanil via edible fish consumption cannot be excluded.

GRAPHICAL ABSTRACT



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ABSTRACT

Dams have profound impacts on river ecosystems, amongst them inundation of land, altered dynamics of the water body or uprising reservoir backwaters influencing tributary or upstream river sections. Along the outstandingly ecologically important Yangtze River in China, the Three Gorges Reservoir (TGR) is the largest project, covering an area of 1080 km^2. From the beginning, the dam-project came in for criticism on increasing environmental risks due to sub-merging former industrial and urban areas.

We simulated dynamics of biotic and abiotic components of the TGR ecosystem (trophic guilds of aquatic organisms, hydrodynamics, nutrients), as well as the behaviour of the herbicidal substance propanil and its metabolites 3,4-Dichloroaniline (DCA) and 3,3′,4,4′-tetrachloroazoxybenzene (TCAB). A modelling environment, provided by the AQUATOX software, was adapted to the specific situation at a tributary reach to the Yangtze river 'Daning River'. As the simulated food web contained several interconnected trophic levels, a significant biomagnification of metabolites was demonstrated by our simulation studies. In particular, newly emerging stagnant downstream sections of tributaries exhibited high probabilities due to accumulating pesticides from upstream sources.

The common problem of algal blooms in the TGR-region was addressed by dose-response simulation experiments with essential nutrients. Impacts on structure and abundance of populations of aquatic organisms were shown. However, even high nutrient loads resulted in only slight changes of densities of organisms of all trophic levels. Nevertheless, the probabilities for large-scale algal blooms affecting drinking water quality were considered low because of high flow velocities and discharge rates towards the Yangtze River.

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We see high potential of simulation-based assessments that provide information for risk managers dealing with whole catchment areas. They are put in the position to differentiate the magnitude of impacts of various factors and decide about the most effective remediation measures.

1. Introduction

1.1. The ecosystems of the Three Gorges Reservoir after impoundment

The Yangtze River (Chang Jiang) with a length of 6300 km is the longest river in China. The middle course of 950 km in length covering a drainage area of 680,000 km^2 (Chen et al., 2010) strides across an economically prospering region in the province of Chongqing (30 million residents since the year 2015 (NBS, 2018)), with the city of Chongqing as the major fast growing economic centre and river port (Fu et al., 2010). The developing economy needs energy and safe transportation of goods throughout the whole year. For reasons of hydroelectric power production, flood prevention and navigability, numerous dams were built at the Yangtze River. Amongst them, the Three Gorges Reservoir (TGR) is the largest, covering an area of 1080 km^2. Further, the Yangtze basin has an outstanding ecological importance for China's freshwater ecosystems. It bears one of the highest diversity with 361 fish species, of which 177 are endemic and about one third is found on the list of endangered species of China (Xie, 2003). Large dams worldwide cause profound changes to the original river ecosystems. This is due to a variety of impacts, amongst them inundation of land, altered dynamics of the water body or uprising reservoir backwaters influencing tributary or upstream river sections (Dorcey, 1997). Altered land use (e.g. towards intensification of agriculture) can result in high loads of nutrients due to excess fertiliser or pesticide use on the fewer remaining cultivable areas after inundation. An intensification was foreseen for the TGR during the planning phase (Luk and Whitney, 1993) and e.g. the per capita cropland increased already during the impoundment phase (Fu et al., 2010). The use of fertilisers in the Three Gorges region increased greatly in the last decade (Sun et al., 2013). In order to analyse different patterns of nutrient loads, nitrogen (as nitrate, diversifying into the relevant nitrogen species via nitrification and denitrification processes) and phosphate as well as a combined pollution by nitrate and phosphate was simulated. In China nowadays, the excess use of water and fertilisers in rice cultures very often had led to ineffective conversion into biomass and further surface runoff into the adjacent water bodies could occur (Liang et al., 2013). Increasing use intensification should be brought into agreement with the conservation of the ecosystem services provided by the river. From the beginning, the dam-project came in for criticism on increasing environmental risks due to inundation of former industrial and urban areas. The special thing of study area was a unique hydrodynamic situation at the mouth of the Daning River where a huge eddy formation marked by long residence time of Wushan Lake water was formed.

1.2. The concept of integrated ecosystem modelling

We described the subject of our studies that we conducted at the Yangtze TGR, the problems after impounding of the new reservoir and the conceptual approach of an integrated ecosystem modelling of micropollutant impacts in several previous studies (Floehr et al., 2013; Floehr et al., 2015; Scholz-Starke et al., 2013; Fig. 1). The way forward that we describe by this contribution the final implementation of the information from all available sources of the contextual Yangtze - project, and additionally demonstrate the feasibility and ecological validity of our model calibration.

We simulated the dynamics of biotic and abiotic components of the TGR ecosystem, as well as the behaviour of propanil and closely related and highly relevant metabolites, which has been widely used in this region as herbicide. The relevance of this compound was exposed by Xiao et al. (2016) and supported by sales and marketing numbers and literature (e.g. Zhang, 2003). Specifically, the last stretch of the Daning River before the confluence with the Yangtze River at the city of Wushan, Eastern China, was analysed. The stretch was divided into ten segments of alternating flowing and stagnating waters (Scholz-Starke et al., 2013). The area belongs to the Three Gorges Reservoir and is impacted by a very large water fluctuation of 30 m within a year (winter high tide, summer low tide). Fluctuation bears many problems, amongst which we focused on the likely runoff from agricultural fields. A further focus of our work applied to the fact that after the impoundment of the reservoir, large zones of formerly fast running waters slowed down from 2 to 3 meter flow velocity per second to <0.05 to 1.5 m/s on average or became stagnant (Chen et al., 2005; Wang et al., 2009). Consequently, the residence time of the water increased and thus the probability of bioaccumulation processes to biota taking place increased. The loads of micropollutants at tributary rivers and the main stream of the Yangtze in the TGR region could be assumed as particularly high under the newly inverted water level patterns (high water levels during winter dry season, and low water levels during the rainy season) after impoundment (Floehr et al., 2013).

1.3. The AQUATOX ecosystem model

We used the complex, process-based, mechanistic ecosystem model AQUATOX in an integrative model approach. The AQUATOX model environment was originally developed to support environmental risk assessments under the responsibility of the US Environmental Protection Agency (Park and Clough, 2010). The model was used to predict fate and behaviour of chemicals or nutrients and to describe the impact of risk management options (Park et al., 2008) and successfully applied recently for the prospective risk assessment of chemicals (e.g. by Lombardo et al., 2015).

We described our conceptual approach to calibrate the model in a previous paper (Scholz-Starke et al. (2013) and Fig. 2). There was indication for the usefulness of combining predictive modelling techniques with biological assessments to support decisions on future management measures that should protect the aquatic ecosystem at the TGR (McKnight et al., 2012). The paper describes the data that was used to adapt the AQUATOX simulation environment to the situation at the Daning River from the Dachang Lake to the Wushan Lake (Fig. 3). The exposure to the herbicidal model substance propanil (*module EXM*) was estimated by analysing the land-use patterns nearby the ten tributary segments of the Daning River (global land cover map by European Space Agency, Arino et al., 2012), assuming that areas classified as irrigated croplands in this region would get overuse-rates of common pesticides. Exposure calculations taken from the European standard risk assessment for pesticides provided the predicted environmental concentrations (PEC) that the water bodies initially received ($PEC_{initial}$). Physico-chemical and morphological parameters of the water bodies were partly leant against measurements derived from the literature and Geographical Information Systems (GIS) or left to the transformations implemented in AQUATOX (e.g. organic matter cycling, *modules SDM and HDM*). Since propanil was actually registered in China and Europe for herbicidal use at that time, plenty of information on its effects on aquatic organisms was available (Ministry of Health of Italy, 2006). The parent compound showed moderate toxicity