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ANALYSIS

# Cost-efficient eutrophication control in a shallow lake ecosystem subject to two steady states

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ABSTRACT

Eutrophication of water bodies is a common problem in many countries. Eutrophication processes are guided by thresholds, which must be taken into account in the formulation of optimal policies for eutrophication control. Whereas a range of general models have been developed to determine the point of optimum eutrophication control, there are few studies that determine optimum control policies for a specific lake. This paper analyses optimum eutrophication control for a Dutch shallow lake ecosystem. The shallow lake can be in either of two states, a turbid water state and a clear water state, each with specific plant and fish communities. Transitions from one state to the next are subject to a threshold related to the nutrient concentrations in the lake. The paper examines how long-term water quality data can be used to model this threshold effect and how costs and benefits of potential eutrophication control measures can be compared. The paper shows that the presence of a threshold causes there to be two points of local maximum efficiency in eutrophication control, one corresponding to the maintenance of a turbid water state and one to the transition to a clear water state. Ecological–economic modeling of eutrophication in the lake yields concrete information on the cost-effectiveness of different policy options for the lake ecosystem.



## 1. Introduction

Eutrophication of lakes is caused by the inflow of nutrients, in particular nitrogen and phosphorus, that are released in the watershed from agricultural or urban sources. Eutrophication often leads to a reduction in the supply of ecosystem services (Carpenter et al., 1999; Mäler, 2000). For instance, it may affect recreation, fisheries, or nature conservation in and around the water body. The response of a shallow lake to eutrophication is generally subject to multiple states and thresholds (Timms and Moss, 1984; Scheffer, 1998). At low nutrient levels, lakes are commonly in a clear water state with abundant water plants and a fish community dominated by piscivorous fish. At high nutrient levels, shallow lakes tend to convert to a turbid state dominated by phytoplankton and benthivorous fish (Jeppesen et al., 1990; Scheffer, 1998; Van Nes et al., 2002). The change between the clear and turbid water states is normally abrupt and proceeds at a certain threshold in nutrient concentrations. This threshold is specific for each lake (Jeppesen et al., 1990).

The identification of optimum eutrophication control strategies involves the comparison of the costs and benefits of eutrophication control measures (Carpenter et al., 1999). The costs relate to the investment, operation and mainte-

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nance of pollution control equipment, the benefits to an increased supply in ecosystem services following reduced eutrophication. A crucial factor to be considered in eutrophication control is the threshold in the ecosystem, as this has an overriding impact on the lake's response to (reductions in) nutrient loading (Mäler, 2000).

Whereas a range of theoretical models have been developed to identify optimum eutrophication control strategies (e.g. Nævdal, 2001; Brock and Starrett, 2003; Mäler et al., 2003), there are few studies that determine optimum eutrophication control strategies for specific lakes (but see e.g. Wulff et al., 2001 for a study on eutrophication control in the Baltic Sea). In order to identify an optimum eutrophication control strategy for an individual lake, it is required to analyze the supply of ecosystem services by the lake, the costs of eutrophication control measures and the response of the lake to reduced nutrient loading including the threshold involved. From a scientific perspective, the challenge lies in combining the above three issues in one ecological–economic model and to calibrate and apply the model using water quality data that is measured in a monitoring program. From a policy perspective, such studies can support local authorities with concrete advices on eutrophication management of specific ecosystems.

The aim of this study is to identify optimum eutrophication control strategies for 'De Wieden', a Dutch shallow lake ecosystem. The lake is in a eutrophic, turbid state but, because of its major importance for biodiversity conservation and recreation, local authorities are currently considering rehabilitation of the ecosystem. Ecological–economic modeling is applied in order to analyze the ecosystem's response to a reduction in nutrient loading and to compare the costs and benefits of a range of eutrophication control measures. The lake dynamics are modeled by means of a set of (differential) equations obtained through regression analysis of long-term water quality data, from Waterboard Reest and Wieden (2003). Lake dynamics have been combined with information on the supply of ecosystem services and the costs of measures in order to construct an integrated ecological–economic model for the De Wieden ecosystem. The paper presents, subsequently, a description of the model, the net present value of different eutrophication control options in 'De Wieden' and a number of recommendations for the management of De Wieden as well as shallow lake ecosystems in general.

## 2. Materials and methods

### 2.1. *The study site*

The De Wieden wetland is located in the northeastern part of the Netherlands (52°42′N, 06°03′E). The lakes and canals of the area have been created through peat extraction activities that started in the late Middle ages and continued up to the 19th century. This study considers water quality in the four biggest lakes of De Wieden—see Fig. 1. The lakes are located in close proximity to each other and there is frequent exchange of water between them. The lakes total 1640 ha and their average depth is around 1.8 m. The most important source of water is a canal entering the lakes from the north. This canal is fed by two small rivers that drain the agricultural area located to the Northeast of De Wieden, as well as by excess water released from a number of nearby polders. The main discharge of the lakes is to the downstream Lake Zwartewater (around 210 million m$^3$/year).

Up to the 1960s, the lakes were oligotrophic and the transparency was over 2 m, sufficient to see the lake bottom in most of the area. Since then, however, population pressures in the region increased and the agricultural production around the lakes intensified. This resulted in a rapid increase in the input of nutrients in the area, which caused major ecological changes in the lakes. The original burbot (*Lota lota*)–roach (*Rutilus rutilus*) fish community was replaced by a bream

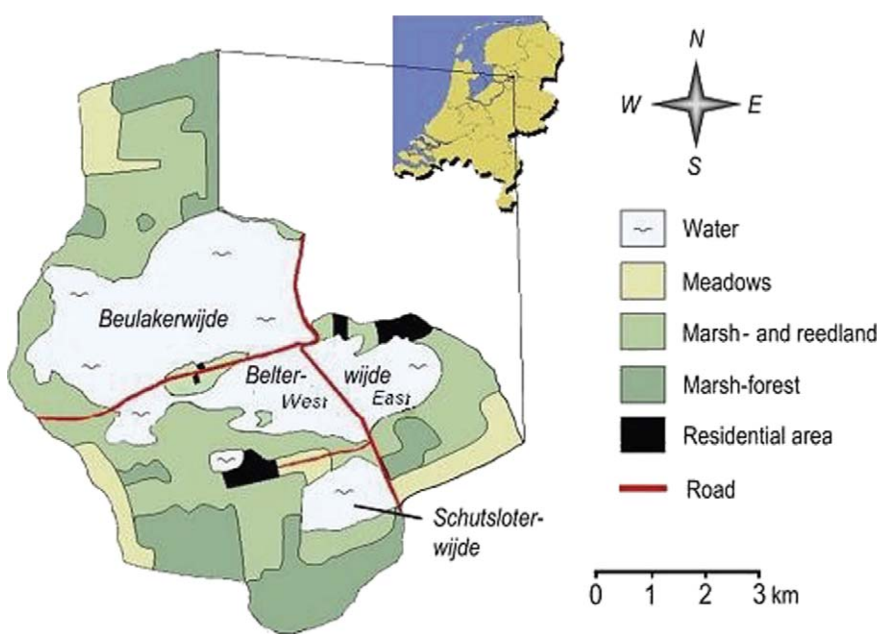


**Fig. 1 – Case study area.**