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# Setting critical nutrient values for ditches using the eutrophication model PCDitch

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## Abstract

Critical nutrient loads to prevent duckweed dominance loads in polder ditches were assessed using the eutrophication model PCDitch. In this article the ecological target was set at 50% duckweed coverage. This may be very high for ditches with a nature function, but is not unreasonable for ditches in agricultural areas, with upwelling nutrient rich groundwater, run-off and drainage. Since the change from a ditch with submersed vegetation to duckweed coverage is often a sudden shift, the choice of the amount of duckweed coverage does not influence the calculated loading very much. The main topic of this paper is to present a method to calculate critical loads of nutrients when ecological targets have been set. Sediment type, residence time and water depth influenced the critical loading rates. The calculated critical phosphorus load ranged from 1.8 to 10.2 g P $m^{-2}$ $year^{-1}$, while the calculated critical nitrogen load stretched from 12.1 to 43.8 g N $m^{-2}$ $year^{-1}$. The concentration ranges that were derived from the loading rate were 0.19–0.42 mg P $l^{-1}$ and 1.3–3.3 mg N $l^{-1}$. Since PCDitch does not distinguish between *Lemna* spp. and *Azolla* spp., no definite conclusions were drawn concerning the effects of nitrogen reduction. In a model situation a pristine ditch was loaded with phosphorus, which resulted into complete duckweed coverage during summer within a few years. When reducing the phosphorus load, it took 10 years before the original situation was reached again. Dredging would accelerate the process of recovery significantly, because the water depth would increase and the phosphorus release from the sediments in summer would decrease.

## Introduction

Drainage ditches are small, linear water bodies, usually less than 1.5 m depth and ranging from 1 m to several meters wide. The main task of ditches in the Netherlands is to discharge superfluous water from agricultural areas. The hydraulic residence time is days to weeks. Many ditches serve as a water transport system to agricultural areas during dry spells. Next to these hydrological functions ditches are important as a source of cattle drinking water, and they provide an important habitat for plants and animals. Because of their shallowness ditches are often dominated by macrophytes, needing periodical maintenance (mowing the waterplants) to facilitate the waterflow. The physical–chemical status of the surface water is of paramount importance for the composition of the vegetation in ditches. When nutrient concentrations are low, water is clear and both submerged plants and helophytes arise with a spring bloom of phytoplankton (De Groot et al. 1987; Veeningen 1982; Higler 1989, 2000; Nijboer 2000). Eutrophication is the greatest menace in Dutch ditches (Nijboer 2000; Arts et al. 2001). Run-off and seepage of nutrients from agricultural areas and aerobic degradation of peat are the most important sources, next to the (at present) less extensive point sources; and in some cases inlet water and upward seepage of nutrient rich groundwater (van Liere et al. 2002). Moderate increase of nutrients will result in higher growth of submerged macrophytes. This higher amount of macrophytes induces self shading and light energy limited growth, causing a shift from species with a vertical growth strategy to species with a horizontal growth strategy (Sand-Jensen and Søndergaard 1981). At still higher nutrient loading growth of filamentous and/or epiphytic algae may occur. The endpoint of the eutrophication process in ditches is a complete dominance of duckweeds (*Lemnaceae*) (Portielje and Roijackers 1995; Nijboer 2000; Arts et al. 2001). Because duckweed, as a floating plant, hampers re-aeration and releases the produced oxygen to the air compartment, while decomposition in the water phase uses the oxygen, the water underneath duckweed becomes often anoxic (Veeningen 1982). When the phosphorus load is higher in comparison with the nitrogen load nitrogen limited growth occurs, which may result in a shift to *Azolla* spp. These species grow in symbiosis with *Anabaena azollae*, a cyanobacterium which is able to fix nitrogen. At present duckweed dominance is fairly common in the Netherlands (van der Does and Klink 1991; Nijboer 2000).

It is generally assumed that phosphorus limits growth of phytoplankton and macrophytes in oligotrophic to mesotrophic freshwaters in the temperate climate zone (Corell 1998; Newton and Jarell 1999). In many eutrophic systems, such as ditches, an excess of phosphorus is present due to storage in plants and especially in the sediment. Nitrogen has a faster cycle, and a significant amount of it is lost by denitrification. It is hypothesized here that recovery from *Lemna* dominance is more efficient when phosphorus is reduced or when co-reduction of phosphorus and nitrogen occurs. As stated above, nitrogen reduction alone may result in a shift to *Azolla* spp. In shallow lakes it has been widely accepted that phosphorus is the main nutrient to be reduced. With nitrogen reduction alone the dominant cyanobacteria may be replaced by other (nitrogen fixing) ones (Zevenboom and Mur 1980).

In this paper the results are presented of simulations with the ecological eutrophication model PCDitch in order to assess critical loads and critical concentrations of phosphorus and nitrogen. Furthermore the effects of a simulated dredging experiment are shown.

## Materials and methods

### *Description of the eutrophication model PCDitch*

The eutrophication model PCDitch includes the water column and the upper sediment layer of a ditch, both assumed to be well mixed. The model may be regarded as a competition model between several functional groups of water plants, coupled to nutrient cycles (Figure 1). The model describes the cycling of dry weight (DW), phosphorus (P), nitrogen (N) and oxygen ($O_2$). All biotic components as well as detritus are modelled in these components. This is done to close the nutrient cycles within the model system, and to account for variability of the nutrient ratios of water plants depending on the loading rate. The 'target variables' are biomass of plant groups, and concentrations of nutrients and dissolved oxygen. The abiotic and biotic components and the processes relevant in calculating effects of eutrophication are depicted in Figure 1. Zooplankton, macrofauna and fish have been left out, as they are considered not to be very important for the prediction of the target components in ditches. The in- and outflow of water and the external nutrient loading to the ditch system should be given by the user or calculated by other models. The initial water depth, thickness of the sediment layer and the sediment type (defined by its density, porosity, lutum content and (initial) organic matter content) are input parameters. Many of the formulations were derived from the lake eutrophication model PCLake (Janse and Aldenberg 1990; Janse 1997), but more types of macrophytes were distinguished. Properties of the aquatic plants were extracted from literature data. In the model, the competition between plant groups is mainly determined by the factors light, temperature, nutrients and – for

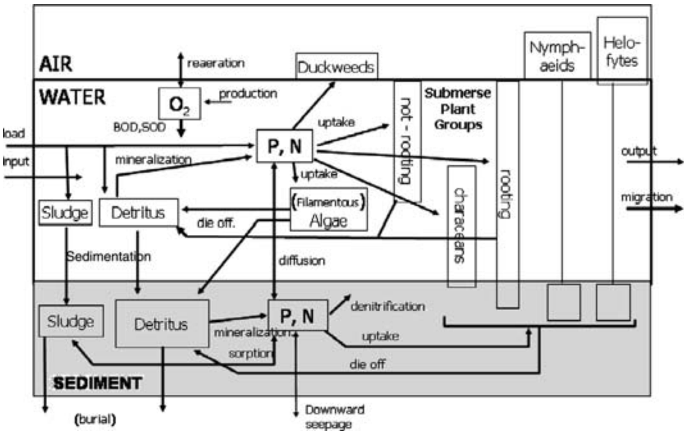

*Figure 1.* PCDitch model structure. Respiration fluxes are not shown.

algae and optionally for duckweed – outflow. The freely floating group duckweed is not limited by light, but is confined to the water column for its nutrient uptake. Duckweed hampers the growth of submerged vegetation due to light interception. The latter group is split into plants that are able to use the sediment nutrient pool and plants that are not. Both nymphaeids and helophytes may take considerable amounts of nutrients from the sediment, while the first group also is a light interceptor. In field situations, helophytes are often removed once or twice a year because of ditch management. In the model all plants can be mowed once or twice a year (default once every autumn). PCDitch was calibrated with experimental ditches with sand and clay bottom (Portielje and Roijackers 1995) that were exposed to various nutrient loads. Since phosphorus exchange in PCDitch is related with iron, aluminium, and lutum content as well as porosity and organic matter content, it is presumed that the calibration is also valid for peat ditches. Calibration and validation with field datasets are at hand.

A complete description of the model is published in Janse (1998).

## *Simulation*

The eutrophication model PCDitch version 1.22 (Janse 1998) was used to calculate the coverage of duckweed and submersed aquatic plants as a function of phosphorus and nitrogen loading. Combinations of depth (0.25–1.5 m), hydraulic loading rate ($q$, ranging from 10 to 70 mm day$^{-1}$), and type of sediment (sand, peat, and clay) were used. The sediment type was defined in terms of porosity, organic matter and lutum content. When analysing phosphorus load (0.006–0.040 g P m$^{-2}$ day$^{-1}$) nitrogen was kept in surplus to avoid nitrogen limitation of plant growth. When studying nitrogen, phosphorus was kept in surplus. An ‘average ditch’ was defined as a ditch with a depth of 0.5 m, a $q$ of 30 mm day$^{-1}$ and a clay sediment. For simplicity, the nutrient load was kept constant over the year (in field situations, the loading is often somewhat higher in winter than in summer, dependent on the local situation). The temperature and photosynthetic radiation were set sinusoidal as in an average year, vegetation was mowed every autumn, depth was kept constant and duckweed was not transported to or from the ditch. Previous simulations showed that equilibrium with the imposed nutrient load occurs normally within 10 years; to be certain that the equilibrium was reached a period of 20 years was calculated by the model.

As an indication for recovery of eutrophication 50% of duckweed coverage was assumed to be critical. This value is chosen arbitrarily. It seems high, certainly in ditches in natural areas, in which duckweed should hardly be present if external nutrient load is low. Most of the ditches are situated in agricultural areas, and in the Netherlands a large part of these ditches have been dug in areas in which nutrient rich upwelling waters are important. The differences in these situations demands for regionally differentiated settings of standards. In this paper a method is presented which can be used to set these standards. The method is applicable to any chosen relative duckweed coverage.

The various combinations gave rise to 1296 runs of PCDitch per nutrient. The simulations took about 6 h on a PC with an Intel Pentium 4 processor. It took, however, several years to construct the model.

## Results and discussion

Simulations of the summer-averaged duckweed cover as a function of phosphorus loading rate for different combinations of sediment types, hydraulic loading rate and water depth, are given in Figure 2. PCDitch simulates a rather steep S-shaped curve with a 'critical load' which, when it is exceeded, results in complete dominance of duckweed and disappearance of submerged plant growth. Since the slope of the simulated nutrient vs. duckweed coverage is often very steep it does not matter very much in critical load whether 20, 50 or 90% duckweed coverage is chosen as the critical value. This choice has still to be made. In general, a shift to duckweed dominance occurs in sand ditches at a lower rate as compared to clay or peat ditches. The critical loading generally increases with flow rate, while its relation with water depth is more complex: in some ranges the critical load increases with water depth, but in other ranges there is no effect. The depth effect shows interaction with other factors and parameters and might in some instances vanish or even be opposite. An impression of the critical values in the 'average' ditch and their range as a function of depth, *q* and sediment type is given in Table 1 (for phosphorus and nitrogen) and for phosphorus only in Figure 3. Critical nutrient loads are more reliable than critical nutrient concentrations, as in the latter case an important part of the nutrients is present in primary producers and sediment. However, a disadvantage of nutrient loads is that they can only be modelled, or measured in experimentally managed systems. Loading cannot be measured in uncontrolled field situations. Both critical loads and critical concentrations are presented in Table 1. The range of critical values for phosphorus is somewhat wider than for nitrogen; the slope of the curve of nitrogen is much less steep as compared with phosphorus (results not shown).

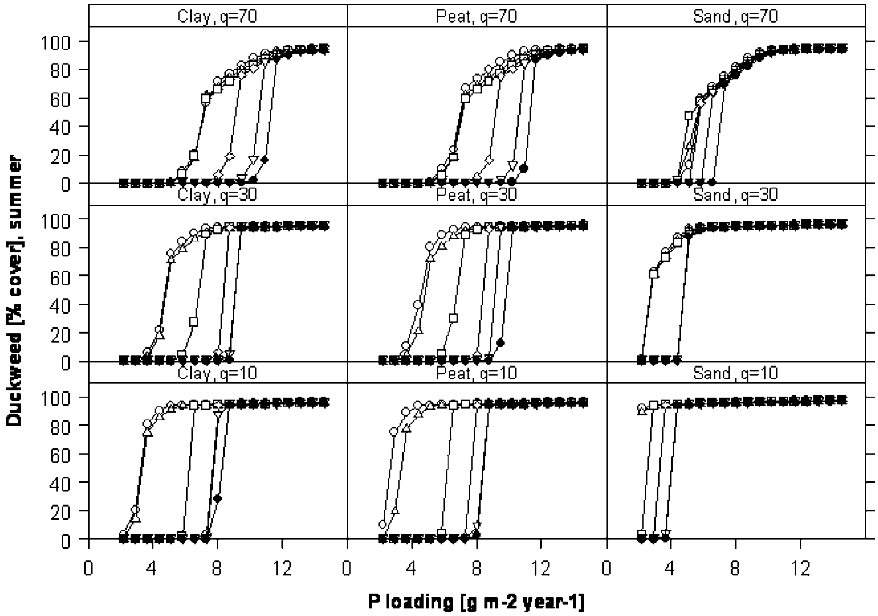

*Figure 2.* Results of PCDitch simulations for summer-averaged duckweed coverage with all combinations of P-load, sediment type, hydraulic loading rate (*q*), and water depth. Symbols depicting water-depth: ○ 0.25 m, △ 0.5 m, □ 0.75 m, ◇ 1 m, ∇ 1.25 m, and ● 1.5 m.

*Table 1.* An overview of critical values for P and N in ditches calculated with PCDitch. The average ditch in this table is defined with a depth of 0.5 m, a hydraulic loading rate $q$ of 30 mm day$^{-1}$, and clay sediment. The critical value of 50% duckweed coverage was arbitrarily chosen.

| Critical values (50% duckweed coverage) | Minimum | | Average-ditch | | Maximum | |
|---|---|---|---|---|---|---|
| | P | N | P | N | P | N |
| Load (g P m$^{-2}$ year$^{-1}$) per surface area | 1.8 | | 4.7 | | 10.2 | |
| Load (g N m$^{-2}$ year$^{-1}$) per surface area | | 12.1 | | 21.9 | | 43.8 |
| Simulated nutrient concentration (mg l$^{-1}$, summer average) | 0.19 | 1.3 | 0.23 | 1.4 | 0.42 | 3.3 |

This might be due to the larger forcing function of phosphorus in controlling duckweed. It is difficult to draw precise conclusions with respect to nitrogen reduction, since PCDitch does not distinguish between *Lemna* and *Azolla*.

In mesocosm experiments, clay sediment with a top layer of gyttja, a depth of 0.8 m, but an unknown flow rate, (Arts et al. 2002) recovery of eutrophication to a level of clear water with submerged plants and a duckweed coverage less than 5% within 2 years was simulated by reduction of the phosphorus load. It was found that the target was met at a load of 2–3 g P m$^{-2}$ year$^{-1}$. From Figure 2 it can be estimated that 5% coverage of duckweed is calculated to be reached at about 6 g P m$^{-2}$ year$^{-1}$. The difference is explicable because of different chosen targets. No data were found in the literature of ditches in which recovery from eutrophication has been studied quantitatively.

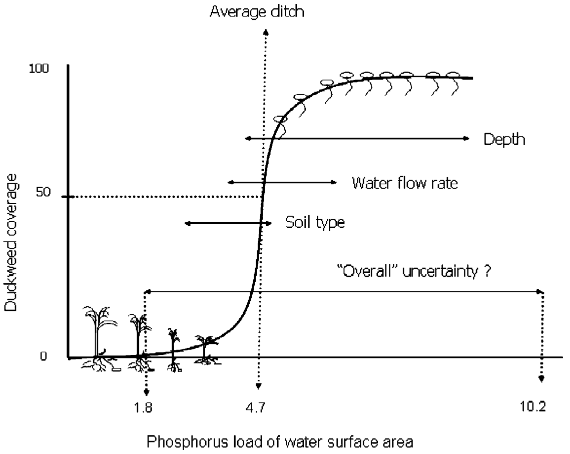

*Figure 3.* Variation of critical phosphorus loading of ditches as function of depth, flow rate and sediment type. It is assumed that 50% coverage of duckweed is accepted to be the desired ecological status. However, this choice still has to be singled out. The 'average' ditch has been defined with a depth of 0.5 m, a hydraulic loading rate $q$ of 10 mm day$^{-1}$ and clay sediment. The variation with depth and $q$ depicted in the figure are those calculated in the case of clay ditches. Sediment (described using lutum content) varies between sandy sediment on the left hand side of the arrow, and peat on the right hand side. The total bandwidth includes all depths, hydraulic loading rates and sediment types.

PCDitch predicts duckweed coverage within a few years after increasing the phosphorus load to 11 g P m$^{-2}$ year$^{-1}$ to a pristine ditch with a loading of 1.3 g P m$^{-2}$ year$^{-1}$ (Figure 4a). A loading of 9 g P m$^{-2}$ year$^{-1}$ resulted in eutrophication in experimental ditches, see Arts et al. 2001. It takes almost 15 years for the system to return to its original state after a reduction of the phosphorus load to the original low value of 1.3 g P m$^{-2}$ year$^{-1}$ (Figure 4a). The system clearly reveals resilience, among others because of adsorption to sediment and concomitant release. Dredging also influences the system: it increases water depth, such as to allow for a higher load (Figure 2), and it removes sediment rich in phosphorus, thereby accelerating restoration. Dredging of the ditch (increasing the water depth with 50 cm) without reduction of the phosphorus load (Figure 4a, first part of the curve) would have no effect on the duckweed coverage (results not shown), because the phosphorus loading (11 g P m$^{-2}$ year$^{-1}$) is too high. However, if simultaneously with dredging the phosphorus load is reduced to its original low value (1.3 g P m$^{-2}$ year$^{-1}$) the time of recovery is some 2 years instead of 15 Figure 4b compared with (Figure 4a).

There exists also a threshold phosphorus load below which dredging results in an improvement

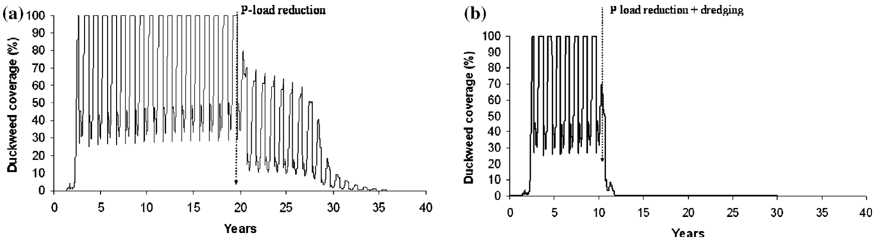

*Figure 4.* (a) Duckweed coverage as a function of phosphorus loading. Starting from a pristine ditch (1.3 g P $m^{-2}$ $year^{-1}$) the phosphorus load was increased (11 g P $m^{-2}$ $year^{-1}$) and after 20 years the loading was reduced to its original low loading rate. (b) Start as in Figure 4a. However, after 10 years the depth of the ditch was increased with 50 cm by dredging while simultaneously the high phosphorus loading was reduced to its original low rate.

of ditch quality. It is important to determine or find out this threshold loading from experiments and further modelling.

## Conclusions

In the Netherlands there are no standards set for nutrient concentrations in ditches. As a precaution critical concentrations of 0.15 mg P $l^{-1}$ and 2.2 mg N $l^{-1}$ (summer average) are used for all water in the Netherlands. These values are derived from standards in shallow lakes, and are not related to duckweed coverage in ditches.

It is evident that it is not practicable to set critical nutrient loads or concentrations in ditches on a national scale, because of the rather large bandwidth for the various ditches (Figure 3). Regionally there are better possibilities for standardization, since depth and other features of ditches are generally within narrower ranges.

According to the European Framework Directive (European Commission 2000) a Good Ecological Status has to be defined for all water bodies. Critical nutrient values should be derived from this status as precondition. The presented method for ditches in this paper is suitable for this operation. Depth, flow rate and type of sediment should be taken into account, since they too guide the ecological quality in ditches. It is also possible to attain a Good Ecological Status by performing other water management measures than nutrient reduction alone. Obviously this cannot be done above a certain threshold of nutrient loading. Therefore, reduction of nutrients still remains the most important measure in combating eutrophication.

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