Integrated modelling for nutrient loading of polder lakes

P.J.T.M. Van Puijenbroek

J. M. Knoop

Integrated modelling for nutrient loading of polder lakes

P.J.T.M. van Puijenbroek and J.M. Knoop

National Institute of Public Health and Environment, Bilthoven, The Netherlands
(peter.van.puijenbroek@rivm.nl, j.knoop@rivm.nl)

Abstract: Many shallow lakes in the lower parts of the Netherlands are hypertrophic and dominated by algae blooms. The present ecological situation reflects the result of past and the present nutrient loading – a combination of point and diffuse loading from different sources. The difference in catchment and hydrology between lakes leads to a difference in nutrient loading and water residence time. Management options to reduce the trophic state have to be analysed.

A model is presented that calculates the load of nutrients for 35 polder lakes in the Netherlands separated for different years and emission routes. Detailed hydrological information on the complex water system of the polders is used to determine the lake catchment. The loading of a lake is the result of runoff and leaching in the catchment, atmospheric deposition, point source emissions and the inlet of water from outside the polder. These input fluxes are modelled separately and the input is retrieved from other models and databases. The output of this model is input to the ecological model PCLake, which calculates the growth of algae, fish and plants in the lake. Using these models it is possible to calculate the sequence from agricultural practice and reduction in point source up to ecological effects in the lake. The effect of water management options, such as phosphorus removing from inlet water or reducing inlet water by allowing flexible water levels, can also be modelled.

Estimated input concentrations for the nineties are compared with in lake measurements. They are with a few exceptions in line with the assumption that they have to be higher because of the in lake retention of nutrients. Comparison with a few available observations of input concentrations shows a good agreement for nitrogen. For phosphorus estimates agree with more recent observations and lie below observations made in the eighties when point sources were more important.

Keywords: shallow lakes; eutrophication; nutrients; nitrogen; phosphorus; hydrology; catchment

1. INTRODUCTION

In the lower parts of the Netherlands many shallow lakes are situated. Mostly the quality of these lakes is poor: algae dominated systems with chlorophyl-a levels of more then 100 $\mu g\ l^{-1}$ in summer, where they used to be clear lakes, rich of plant and fish species with pike as the most appealing in the early days. Main cause is the diffuse loading of nutrients in the vicinity of the lakes. All lakes are situated in polder systems. A polder consists of a number of areas with similar water level (sub polder systems). Since most water levels are below sea level dwelling ground water has to be drained out off the polder with the use of a complex system of surface water bodies varying from small ditches to larger canals. The main water system of a polder is called the boezem. It has the highest water level in the polder. Water is pumped from the smaller and lower lying sub polder systems into the boezem system and from there eventually pumped into the main Dutch water system. In dry warm summer periods however the whole system is used the other way around. Water from the main Dutch water system is pumped into the polder to maintain constant ground water levels in order to prevent growth reduction of grass and crops. The lakes are situated both in the smaller polder systems as well as in the boezem systems. Especially the last ones are to a rather high extent influenced by the quality of water from outside the polder. Yet the use of manure and fertilisers in the polder itself is the dominant source of nutrients in the lakes. Minor important sources are direct atmospheric deposition of nitrogen into the lake and the effluents of sewage systems inside the polder. The management of all lakes is focused on reduction of eutrophication. Local direct emissions from households have been removed and point sources reduced. The water management of some lakes nowadays aims at reducing the inlet of water. Also the phosphorus concentration of inlet water of some lakes is reduced to 0.03 mg P l^{-1} with a phosphorus-removal installation.

Catchment modelling with GIS is a common practice nowadays. Water movement is mostly driven by differences in elevation so elevation maps are used to determine the catchment and the direction of water movement. The water movement in a polder however is almost completely determined by water level management. Hence, other methods must be developed to determine the loading of polder lakes. This paper presents a polder lake catchment model that calculates the total loading of the lake system with nutrients and the amount and origin of water flowing through the lake based upon mapped information on the complex hydrological relations of the Dutch polder systems. With this generic approach, the input of water and nutrients into 35 Dutch shallow lakes is calculated. Input into the model is the diffuse load of nutrients in the polder system itself, the atmospheric deposition onto the lake and the emission of local point sources. In dry summer periods water is led into the system to maintain constant water levels. The quality and amount of this inlet water is also input to the model. A simple model is used to account for the retention of nutrients in the feeding water system.

The results of the model give information about the water balance and the nutrient load of the lake. The output will be used as input for the ecological model PCLake [Janse, 1997]. This model calculates the growth of algae, fish and plants in the lake. Mobilisation of phosphorus from the sediments, resulting in an internal load, is a process of the PCLake model itself.

The quality of the model is difficult to judge. Extensive data basis on lake water quality are available but the state of a lake with residence times ranging from a month up to 1.5 year depends to an increasing extent to in lake processes itself. Hence lake water quality can better be seen as a lower boundary condition for the quality of the inlet water. Yet estimation of the nutrient balances of a few lakes are available. They will be compared with our model estimations but since no complete set of data on the quality of drainage water exist the quality of the estimations of the loading of a lake are the result of the performance of at least two models. Especially the model for the estimation of the local diffuse sources plays a crucial role.

2. MODEL CONCEPT

The polder lake catchment model calculates the load with nutrients and the water balance of 35 Dutch lakes. With this model it is possible to calculate the effect of changes in land use and agricultural practices in the catchment, reduction of point emissions, atmospheric deposition and water management changes. The model provides input to lake water quality models.

The model uses rather simple concepts for the calculation of the water flux and nutrient load:

$$\text{Water flux} = Q_{\text{discharge catchment}} + Q_{\text{water demand catchment}} + Q_{\text{deposition on lake}} + Q_{\text{lake water demand to replenish evaporation and leaching}}$$

$$\text{Nutrient load} = L_{\text{nutrient discharge catchment}} + L_{\text{nitrogen deposition on lake}} + L_{\text{point source emissions}} + (Q_{\text{water demand catchment}} + Q_{\text{lake water demand}}) * C_{\text{concentration of inlet water}}$$

Q = waterflux [mm day^{-1}]

L = nutrient load [g m^{-2} day^{-1}]

C = concentration of nutrients [mg l^{-1}]

Nutrient fractions: NH_4, NO_3, organic nitrogen, PO_4 and organic phosphorus

Time step: summer (April 1 to October 1) and winter half year.

The catchment of a lake is determined using the Waterstaatkundig Informatie Systeem [WIS, Meetkundige Dienst, 1990]. The WIS contains information on the location of surface waters, polders and sub polders and all hydrological relations between them. First the catchment is set as the (sub) polder in which the lake is situated and all upstream polder areas. Yet some lakes are not directly situated in the main water bodies of the polder system. Only part of the drainage water of the catchment will flow through these lakes and the residence time will be overestimated if it is calculated as the ratio of lake volume and all drainage fluxes of the catchment. We then made a spatially proportional reduction of the lake catchment area using the ratio of measured and calculated residence time. The measured residence time is the 1990–1996 average value [RIZA, 1998] whereas the calculated residence time represents the 1986-2000 period.

The STONE model [RIZA, 2001] calculates the water flux and the emissions of nitrogen and phosphorus from agricultural land and distinguishes between meadows, maize, other agriculture and extensive grassland. Extensive grassland is assumed to represent all other non-agricultural and non-urban land use types. The aim of STONE is to calculate the emissions of nutrients as a function of different parameters: application of manure, type of land use and number of cattle. The minimum spatial scale of STONE are plots uniform with respect to land use, hydrological state and soil, with a minimum size of 25 hectare. The STONE model calculates the runoff and leaching of water from agricultural area's and the inlet water flux needed to maintain constant water levels with a time step of 10 days. This information is aggregated to 1986 – 2000 summer and winter averages. The spatial units are aggregated into the catchment of a lake with an overlay.

The drain water from the catchment flows trough a system of ditches and canals before it enters the lake. During this transport retention of nutrients will take place due to sedimentation and uptake by plants. This retention is estimated as a function of the residence time τ in the feeding surface water system : $1 / (1 + \sqrt{\tau})$, [OECD, 1979]. This residence time is estimated as the ratio of the volume of water in the catchment, based on WIS information, to the discharge from the catchment. Hence differences between catchments, as for example between clay areas with relatively few ditches and a short residence time and peat areas with many ditches and a long residence time, are included in the model.

Lakes lose water due to leaching and evaporation. In dry summer periods these losses have to be compensated by inlet water. The quantity of inlet water needed for the lake to maintain a constant water level is calculated as the sum of evaporation and leaching minus the precipitation. The STONE model calculates the water demand of the catchment. The concentration of nutrients in the inlet water is provided by the PAWN model [RIZA/WL, 1990], which calculates the concentration in the main Dutch surface waters, including estimations of future developments on a half-yearly basis. In case a lake receives water passing through a phosphorus-removal installation, a lower phosphorus concentration 0.03 mg P/l. is assumed [Ecotest, 1990].

The atmospheric deposition of nitrogen is taken from the OPS model [Erisman, 1998]. Major point sources for the lakes are the effluents of wastewater treatment plants, mostly on the boezem. The point emissions are retrieved from the Emission Registration Collective Database [CCDM, 1999]. Yearly emission data are available at the catchment scale.

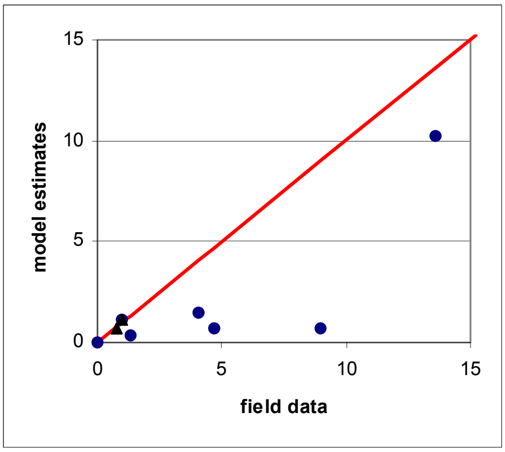
The model can present the separate contributions to the total load. Concentration of the load is calculated as the weighted average of the concentration of the different sources.

3. RESULTS

For 35 lakes the catchments has been assigned and the water inflow and loading with nutrients estimated. Lake characteristics and estimated catchment area are presented in Appendix 1.

The lake catchment model calculates the input for these 35 using the STONE input data for the period 1986-2000 and point emissions for 1995. The input load ranges between 0.35 and 15.6 g P m^{-2} $year^{-1}$ for phosphorus and between 10.6 and 178 g N m^{-2} $year^{-1}$ for nitrogen. The estimated input concentrations are compared with average in lake concentrations for the period 1990 to 1996. For nitrogen these in lake concentrations are assumed to be lower than the input concentrations due to retention in the lake. For phosphorus these retention fluxes can be compensated by the release of phosphorus from the sediments. For only 2 out of the 35 lakes the calculated nitrogen input concentrations lies around or slightly below the observed lake concentration. For phosphorus this is the case for 6 out of 34 lakes, whereas in 2 lakes the calculated input concentration is significantly higher than the lake phosphorus concentration. Yet all estimated concentrations lie in the same order of magnitude as the observed lake concentrations.

For some lakes field data on input concentrations are available. Most of them however are measured in the eighties. In a few years around 1990 many point source emissions are reduced substantially especially with respect to phosphorus. Hence our estimates for phosphorus, based on data on point sources for 1995, should in general lie below field data for the eighties. Figure 1a shows that all our estimates are lower than concentrations observed before 1990 and are almost equal to the 2



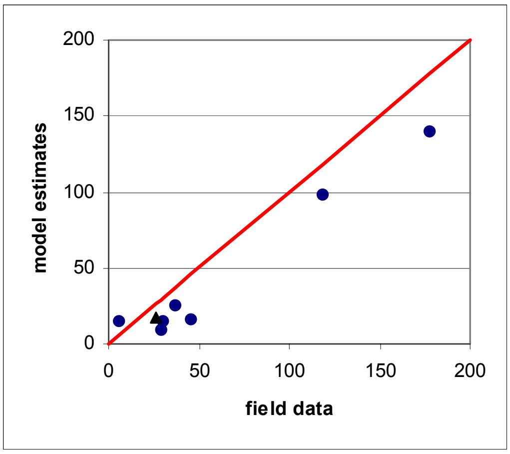


Figure 1: Comparison of field data with model calculations for phosphorus (a, left) and nitrogen (b) input concentrations in g m^{-2} $year^{-1}$ for several lakes. Spheres represent observations made before 1990, and triangles represent observations made after 1990. Model calculations are supposed to represent the nineties.

observations from the nineties. Figure 1b shows that but for one exception the model calculations for nitrogen lie slightly below the observations.

Detailed results are presented in figure 2 for lake Naardermeer and lake Westeinderplassen. Lake Naardermeer is a small lake east of Amsterdam with a surface of 204 hectare. The estimated catchment is 716 hectare. The lake and the catchment are nowadays ownership of an organisation for nature conservation and the catchment consists of extensive grassland and swamp. To maintain the high ecological value of the lake, phosphorus is removed from the inlet water. The residence time of the lake is about 90 days. Lake Westeinderplassen is situated South of Amsterdam with a surface of 3761 hectare. The lake is part of the Rijnland boezem system . The boezem water catchment is 1036 km^2, but the lake, with a residence time of 1.2 year, is only drained by part of the catchment. The main land use types in the catchment of the boezem are grassland and urban.

The first dry year resulted in a large amount of water inlet in the summer, especially in the Naardermeer. The next year had more rainfall, hence less water inlet. The total flux of water is less then the first dry year. In the last, very wet year, the deposition and catchment runoff is very important. But even then, a small amount of water inlet is calculated because of some dry months. The total summer waterflux is almost the same for all years but the origin differs considerably depending on the meteorological conditions.

Phosphorus has mainly entered the system by catchment runoff and leaching. In dry periods inlet is the main input for phosphorus in lake Naardermeer. In lake Westeinderplas the total input load is higher and the effect of inlet water is less important. The year 1997 with an average rainfall has the lowest input of phosphorus and nitrogen. In lake Westeinderplassen only a small effect of point emissions is calculated. Point emissions are not present in the lake Naardermeer. Atmospheric deposition direct on the lake is an important source for nitrogen.

This example clearly shows the ability of our approach to distinguish between different sources. The use of data with a high temporal resolution provides the opportunity to account for processes, like the inlet of water from the main Dutch water system, which occur within a short span of time but can contribute to a substantial part of the summer loading of a lake.

4. CONCLUSIONS AND DISCUSSION

This paper presents a generic model to calculate the load of nutrients for polder lakes in the Netherlands separated for different years and emission routes. The loading of nutrients of a lake is the result of runoff and leaching from the catchment, atmospheric deposition, point source emissions and the inlet of water from outside the polder. These input fluxes are modelled separately and the input is retrieved from other models and databases. The output of this model is input to the ecological model PCLake, which calculate the growth of algae, fish and plants in the lake. Using these models it is possible to calculate the chain from agricultural practice and reduction in point source emission up to ecological effect in the lake. The effect of water management options, such as phosphorus removing from inlet water or reducing inlet water by flexible water level, can also be estimated. The size of a lake catchment is

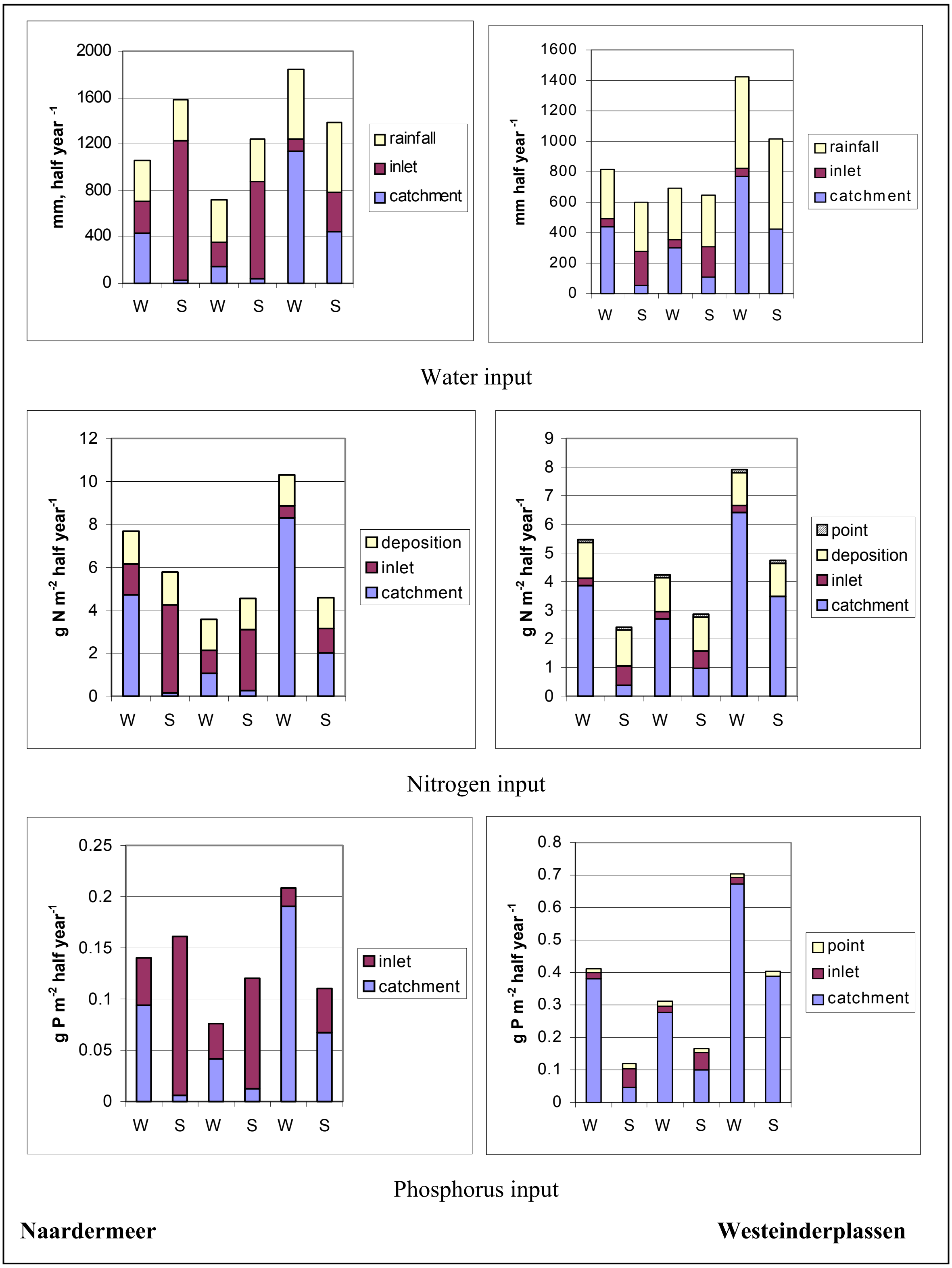


Figure 2: Calculated winter (W) and summer (S) fluxes for the discharge from the catchment, the inlet water, the deposition on the lake and the point emissions for both lakes for 3 consecutive years. The first year is a dry year (1996), the second a normal year (1997) and the last (1998) is an extremely wet year (respectively 688, 730 and 1200 mm year^{-1})

corrected with the use of known residence times. This approach implicitly assumes a homogeneous catchment. Especially in case of large corrections this may introduce substantial errors. More detailed information on the water system may be used to improve the model performance.

The most important source for nutrients is the catchment runoff and leaching, calculated by the STONE model. This model is validated on a national scale [Overbeek et al, 2001]. The spatial resolution of the STONE model constitutes a problem for small catchments consisting only of extensive grassland and wetlands. STONE data have to be extrapolated to make a consistent water balance.

The water and nutrient balance simulations explain the different water fluxes entering a lake. In a wet year a lake receives most of its water from the catchment, but in a dry year the water inlet is very important. The total load can be the same in a dry or a wet year, despite of a different water flux. For some lakes point sources are very important. Atmospheric deposition is an important nitrogen source.

Management options to reduce the trophic state can be analysed with this model. The nutrient load in the future is a result of measurements on a (inter)national scale (inlet water quality, atmospheric deposition), on a regional scale (agriculture in catchment) and local scale (hydrology of the lake). All scales are included in this model by using other databases en models.

5. REFERENCES

Ecotest. Naar een Natuurconvenant voor het Naardermeer. Technisch Rapport. N.W. Broodbakker, 1990.

Erisman, J.W., A. Bleeker & J.A. van Jaarsveld Evaluation of ammonia emission abatement on the basis of measurements and model calculations. Environmental Pollution 102, 269-274. 1998

Meetkundige Dienst, Waterstaatkundig Informatie Systeem, Delft, 1995

Janse, J.H. A model of nutrient dynamics in shallow lakes in relation to multiple stable states. Hydrobiologica (342-343), 1-8, 1997.

OECD. Cooperative programme for inalnd water (Eutrophication control). Project: shallow lakes and reservoirs. Final report. Vol. 1 Data analysis and results. 1979

CCDM, Coordinatiecommissie Doelgroepmonitoring. Ministerie of VROM. Emissies en afval in Nederland jaarrapport 1997 en ramingen 1998. Rapportagereeks Doelgroepmonitoring Nr 1, December 1999

RIZA/WL. Instrumentarium beleidsanalyse waterhuishouding PAWN. Documentatie deel I-IV. WL report T568, 1990.

RIZA, Relaties tussen eutrofiëringsvariabelen en systeemkenmerken van de Nederlandse meren en plassen. Deelrapport II voor de Vierde Eutrofiëringsenquête. R. Portielje, D.T. van der Molen. RIZA rapport 98.007, 1998 (a).

RIZA, Redesign Stone. De nieuwe schematisatie voor Stone: de ruimtelijke indeling en de toekenning van hydrologische en bodemchemische parameters. T. Kroon, P. Finke, I. Peereboom, A. Beusen. RIZA rapport 2001.017, 2001 (b).

APPENDIX 1

Lake	Surface [ha]	Catchment [ha]	Residence time [year]
Naardermeer	204	717	0.8
Slotersplas	150	310	0.9
Stichts ankeveen	118	494	0.7
Paterswoldemeer	281	681	1.0
Loosdrecht	1489	4483	0.8
Hollands ankeveen	80	380	0.6
Westeinderplas	1008	104478	1.2
Botshol	73	371	0.7
Kortenhoefse plassen	65	1711	0.5
Nieuwkoopsche plassen	662	2168	0.6
Schildmeer	288	21045	0.5
Langeraarsche plassen	177	457	1.0
Nannewijd	98	1337	0.5
Reeuwijksche plassen	728	3131	0.7
Vinkeveensche plassen	365	3005	0.5
Zwet	115	2233	0.6
Braakmankreek	161	5310	0.2
Kinselmeer	104	9836	0.5
Wieden	1872	49221	0.2
Tjeukemeer	1998	311498	0.2
Slotermeer	1103	311498	0.2
Fluessen	2230	311498	0.2
Groote brekken	693	311498	0.2
Langweerderwielen	225	311498	0.2
Gaasterpoel en -brekken	490	311498	0.2
Leekstermeer	157	5941	0.2
Sneekermeer	1107	311498	0.1
De Leijen	297	311498	0.2
Wijde Ee	101	311498	0.2
Grutte kritte	111	311498	0.2
Bergumermeer	406	311498	0.1
Zuidlaardermeer	564	26196	0.2
Braasemermeer	460	104478	0.2
Mooie Nel	87	104478	0.2
Kagerplassen & zweiland	235	104478	0.1

List of lakes with surface of lake and catchment and calculated residence time.