The Phosphorus Cycle of
Lake Tegel and Schlachtensee

Progress Report of the Project:

Threshold Values for Oligotrophication of
Lake Tegel and Schlachtensee, Berlin:
Analysis of System Components and Causalities

Dr. Ingrid Chorus and Dr. Inke Schauser, Umweltbundesamt,
in co-operation with Dr. Bernd Heinzmann, Berliner Wasserbetriebe
and Dr. Phillip Ford, CSIRO Land and Water

Content

Executive Summary

A suite of predictive quantitative models of phosphorus (P) dynamics in Lake Tegel and Schlachtensee has been developed. The results, specific to each lake, are set out below, together with general conclusions about management strategies, and some high priority areas for future research.

Lake Tegel

1. The inflow from the Havel to Lake Tegel has been estimated using both a discrete time step box model and a time integrated numerical model. There is good internal agreement between the 2 estimates of the Havel inflow as a mean fraction of the total inflows (~ 40 %) , as well as with the earlier work of Ripl (1993). The estimated residence times agree closely (~ 70 d).

2. There is considerable inter-annual and inter-seasonal variation in Havel inflows. The numerical model can be used to satisfactorily predict these as a function of the Havel discharge, OWA discharge, and water extraction (bank infiltration and recharge, r^2=0.76).

3. Over the past 15 years Lake Tegel has been both a net source (1984-1992;2000-2002), and a net sink (1993 – 1999), for phosphorus. The Havel inflow is the most important component in the P budget of Lake Tegel. When the sediment is a source, the modelled internal P load is 2-4 fold of the OWA annual load.

4. The internal P load can be satisfactorily modelled (r^2=0.72) as a function of the external P loads, the water works extractions, and the temperature and nitrate concentration in the hypolinmion. The sensitivity analyses indicate that temperature is the major controlling factor for the P release. The significance of nitrate has to be explored further, and identifying thresholds for parameters which trigger release remains to be done in years 2 and 3.

5.The sediment investigations indicate that the sediment P release is dominated by mineralisation, plus desorption at times of high mineralisation and FeS precipitation.

6. Sediment investigations indicate that artificial oxidation of the sediment surface will only impact on P release when the mineralisation is intense and sulphate reduction is prevented.

7. The internal store of mobilizable P in the sediments is small, the rate of mobilisation is high, and the water residence time is short; thus the internal P load will have no long term effects after the external load is reduced sufficiently (< 5 years, assuming an external load of zero). At present, the external P load is high enough to recharge the sediments.

Schlachtensee

1. The water balance of Schlachtensee can be modelled satisfactorily (r^2=0.89) by considering precipitation, storm water discharges and a term to reflect groundwater flows, which yet needs to be validated.

2. Groundwater inflows, as unknown parameter, were determined from modelling by a constant groundwater inflow plus other variable components dependent on precipitation, the level of Schlachtensee, the extraction at Well Rehwiese and of the temperature; this still needs to be cross-checked with a more detailed analysis of groundwater data.

3. The long time development of the P concentration is dominated by the reduced external load from the OWA Beelitzhof. The modelled long term steady state is about 0.02 g P m^3 (annual mean). Schlachtensee has been a sink for P since 1985.

4. Next to effects of the reduced external load, the P concentration in Schlachtensee is characterised by peaks occurring in autumn and winter. The cause is not conclusively identified, but is suspected to be due to loading from the steep shoreline, e.g. leaching P from fallen leaves or mobilisation of animal/human excreta deposited in the summer.

5. Modelling shows that in Schlachtensee the epilimnion exerts a dominant effect on the P dynamics. Although P accumulation occurs in the hypolimnion, this is only a small fraction of the total lake P content. P release is controlled mainly by temperature and redox conditions, as well as the hydrological regime. Whether or not thresholds for release can be identified from any of these remains to be investigated.

6.The sediment investigations indicate that the sediment P release is dominated by desorption due to FeS precipitation.

7. The internal store of mobilizable P in the sediments is small, the rate of mobilisation is moderate, and the water residence time is longer than Lake Tegel. Thus, though its contribution to the lake's P pool is much smaller, the internal P load will continue to exert an effect for longer than in Lake Tegel after the removal of the external load. Assuming the external load to be zero, the mobilizable P-Pool will be released in about 5 years.

Both lakes

Chlorophyll-a data is used to depict the reaction of phytoplankton biomass to reduced in-lake TP concentrations. Chlorophyll-a were recalculated without the phaeophytin correction, and investigations for TP thresholds that govern phytoplankton response were begun. TP thresholds in Lake Tegel appear to be higher (around 100 µg/L) than in Schlachtensee (around 30 µg/L). Further data evaluation, including analysis of monthly means and individual sampling dates, is needed.

Management implications

1. Lake Tegel and Schlachtensee have quite different behaviours and require different management strategies. The various models already developed provide a basis for exploring adapted management scenarios. An initial exploration has identified potentially effective strategies.

2. For Lake Tegel the results strongly point to the continuation of the current management strategy to limit the inflow of P rich Havel water into Lake Tegel, i.e. increasing the OWA discharge during summer, when the P concentration in the Havel, and the extraction by the Water Works, are at their highest.

3. As the P release from the sediment in Lake Tegel is mainly driven by the temperature above the lake bottom the stratification stability should be as high as possible.Therefore, operation of the aerators in a fashion to maintain the maximum possible stratification in summer is proving critically important.

4. The model results confirm that for Schlachtensee the P balance is no longer dominated by the inflows from the OWA Beelitzhof, thus any further efforts to reduce P loading will be more effective if concentrated on the other major external sources.

5. The dominant term in the P balance of Schlachtensee appears to be the autumn and winter deliveries, though the actual mode of delivery is still unclear. Identifying the source(s) is an important future research task.

6. Epilimnetic processes are dominant in Schlachtensee and thus no further measures are required to reduce the internal P loading from the sediments to the water column.

Future Research Goals

1. Improving the P models for both lakes, for Lake Tegel particularly for the calculation of the internal loads and for Schlachtensee for calculating the external loads,

2. Developing the P models towards management models for both lakes by improving the calculation of the internal loads for Lake Tegel and the external loads for Schlachtensee,

3. Including model components for biological interactions and interfacing them within a transferable P process model to explain the process of trophic recovery,

4. Using the improved models for assessing the relative effects of external and internal measures aimed at modifying the P budget, e.g. seasonality of OWA output, aerator operation and seasonal changes in water residence time,

5. Analysing which responses of the lake components are continuous and which show thresholds, and identifying threshold values for the latter; in a second step including other lakes using literature and data provided by other partners,

6. Conducting specifically targeted field investigations to fill gaps, to validate the models and as supplement of monitoring by ILAT in order to uphold the long-term data series, as detailed in the proposal for continuation of the project;

7. Using the outcomes of 1 – 6 for optimised management scenarios for the two Berlin lakes. Together with the evaluation of literature and data from other lakes undergoing trophic recovery, general guidance on managing restoration and predictions of responses to reduced nutrient loading will be developed.

1. Introduction

Importance of Phosphorus

Phosphorus (P) is a key element in algal dynamics and is frequently the limiting nutrient in freshwater systems. As a consequence, the role of anthropogenically generated increases in phosphorus loadings to rivers and reservoirs as cause of increased eutrophication (enhanced algal growth) became well established in the1950's. Such eutrophic systems are characterized by high algal production which often leads, in turn, to taste and odour problems in the water, reduction in fish populations due to summer anoxia, and frequently to potentially toxic blooms of blue-green algae (cyanobacteria). While phosphorus can exist in a variety of different chemical forms in aquatic systems, these can be interconverted by in-situ chemical and microbial processes. Thus, all strategies aimed at ameliorating the effects of eutrophication have, as their starting point, measures aimed at reduction of the total phosphorus loadings.

Background Information

Lake Tegel is situated in the north west of Berlin, in a densely populated area. Its major inflows are the Nordgraben and the Tegeler Fliess. Lake Tegel is multiply-connected at its western edge to the River Havel. Schlachtensee is situated in the south west area in Berlin, close to the River Havel. It is part of the little Grunewald lake chain, which had been fed by the highly eutrophic Havel since the early 20th century. Both lakes are affected by treated sewage, storm water flows, and overflows from the combined sewer system. Both lakes are used intensively for recreation. Lake Tegel also serves as reservoirs for drinking water, with drinking-water abstracted as bank filtrate mixed with groundwater, and Schlachtensee was used for this purpose until the mid 1990's. Despite the multiple surface water inputs, it has been possible to maintain the quality of the drinking-water supply without any further treatment except aeration and rapid sand filtration. The microbiological quality is so good that no disinfection of the drinking water is required.

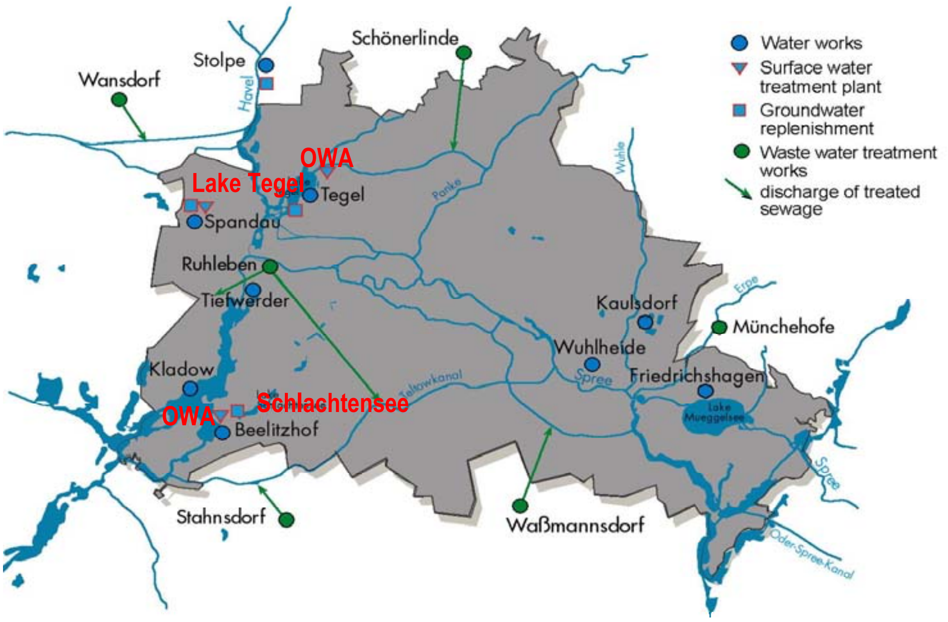

Fig. 1. Map of Berlin

In the 1970's, heavy eutrophication posed a threat to the continuing use of Lake Tegel and Schlachtensee as important drinking water resources (Fig. 1). Particular concerns included the potential break-through of organic metabolites from the heavy phytoplankton blooms, e.g. taste and odour substances, and substrate for bacterial re-growth. Thus, amelioration measures were needed: in Lake Tegel the first measure taken was to aereate the hypolimnion. However, this did not improve lake conditions substantially. To maintain the close-to-natural drinking-water supply with high quality and no need for disinfection, a restoration concept was developed which aimed at a drastic and quick reduction of the external phosphorus loads. The Vollenweider (1979) model for area loading provided the basis for calculation of acceptable inputs, and indicated that 0.2 – 0.35 g P m^{-2} yr^{-1} should not be exceeded. This corresponds to 0.8 – 1.4 t P yr^{-1} for Lake Tegel and 0.1 – 0.14 t P yr^{-1} for Schlachtensee (Hässelbarth 1979). At the time, however, their loading amounted to 100 – 300 t yr^{-1} and 1 - 4 t P yr^{-1}, respectively.

After a wastewater treatment plant with simultaneous precipitation went into operation in Schönerlinde (1985), loading to Lake Tegel declined to around 50 t P yr^{-1}. However, in the face of the goal of roughly 1 t yr^{-1}, this was still 1 to 2 orders of magnitude too high. Thus for both lakes, sufficient reduction of the external phosphorus loads could only be achieved by constructing phosphorus elimination plants to treat the inflowing water immediately before it entered into the lakes.

Thus, in 1981 and 1985, respectively, the phosphorus elimination plants (PEP) Beelitzhof (Heinzmann & Sarfert 1990) and Tegel (Heinzmann et al. 1991) started to treat the inflowing surface water in a four step process: precipitation/coagulation/flocculation – sedimentation – post precipitation – filtration. The PEPs reduce the total phosphorus concentration of the discharges to the Lakes to 8-10 µg L^{-1} at Schlachtensee (PEP intake concentration 0.3 - 0.5 mg L^{-1}) and down to around 20 µg L^{-1} at Lake Tegel (PEP intake concentration up to 5 mg L^{-1}). For Schlachtensee, this was supported by withdrawal of the hypolimnion for a period of several weeks towards the end of summer stratification up to the mid 1990's.

Both lakes responded to the dramatic reduction in external phosphorus loading with an immediate decline in total phosphorus concentration in the water column which followed a nearly exponential pattern during the first years (Fig. 2 and Fig. 3, upper panels). However, in Lake Tegel this recovery slowed at levels around 100 µg L^{-1}, which was just enough to produce small reductions in the phytoplankton maxima. Only in 1993, 8 years after the removal measures started, did the total phosphorus decline further, and phytoplankton started showing a pronounced response (Fig. 2, lower panel). In Schlachtensee, the phosphorus concentration declined further, showing a pronounced reduction of the biomass for the first time in 1985, just 4 years after restoration started (Fig. 3, lower panel). The diversion of storm water inflows in the mid-1990 appears to have led to a further slight decline in phosphorus concentrations.

For Lake Tegel, there are difficulties in differentiating between internal loading, and imports from the Havel River as ongoing sources of phosphorus. The Havel River flows past the mouth of Lake Tegel and is highly loaded with nutrients. Mean annual phosphorus concentrations range between 100 and 160 µg L^{-1} (1990-2002) (Fig. 4). Depending on water budgets, some inflow of river water into the lake is likely. Estimations by mass balance calculations, and by hydrodynamic modelling indicated that around 30 % to 40 % of the inflow of the lake may be Havel water (Ripl et al. 1993, Lindenschmidt & Fröhlich 2000). This was of special importance in 1997 to 2001, when the output of treated water by the phosphorus elimination plant was reduced to around 1,5 m^3/s, compared to a more or less constant level of 3 m^3/s during earlier years. Total P concentrations in the lake in these years closely followed those in the River Havel, suggesting the Havel was a major source (Fig. 4). Since 2002 this problem has been addressed by maintaining a higher throughput of 2.2 m^3/s during the critical summer months.

In both lakes, the patterns of phosphorus and nitrate concentrations in the hypolimnion indicated some phosphorus release from the sediment under anaerobic conditions. For Lake Tegel, after 1992 elevated nitrate concentrations from treated, nitrified sewage helped to keep the sediments oxidised. However, as EU legal requirements of sewage denitrification needed to be met, denitrification was introduced and nitrate loading has substantially decreased since the late 1990's.

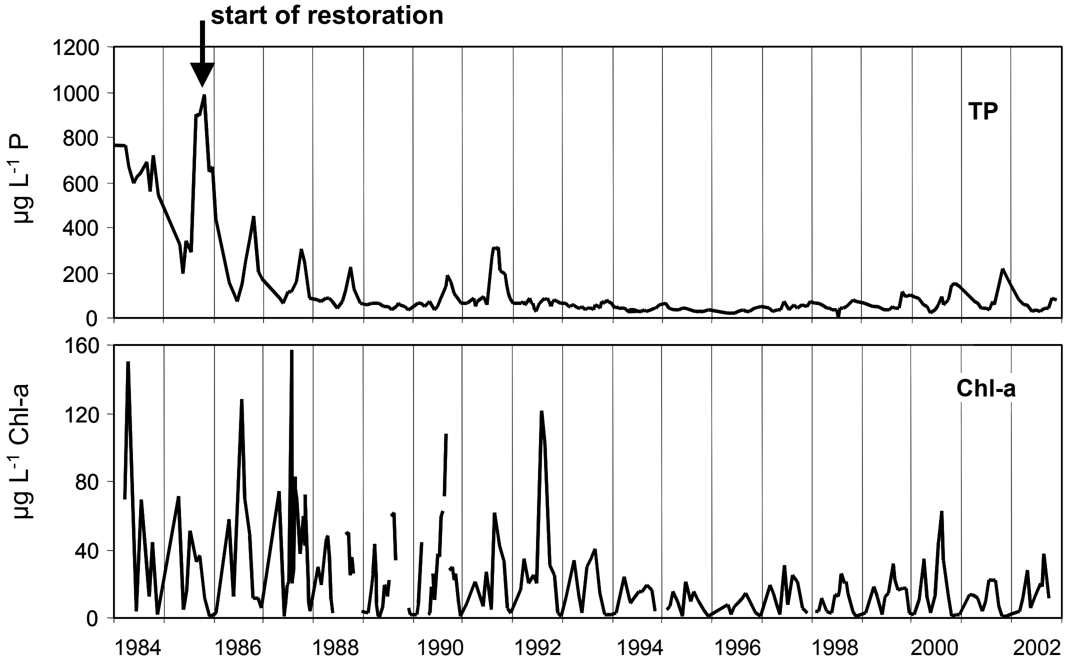

Fig. 2. Total phosphorus and chlorophyll-a concentrations in Lake Tegel (1984-2002) [µg L^{-1} in 1 m depth]

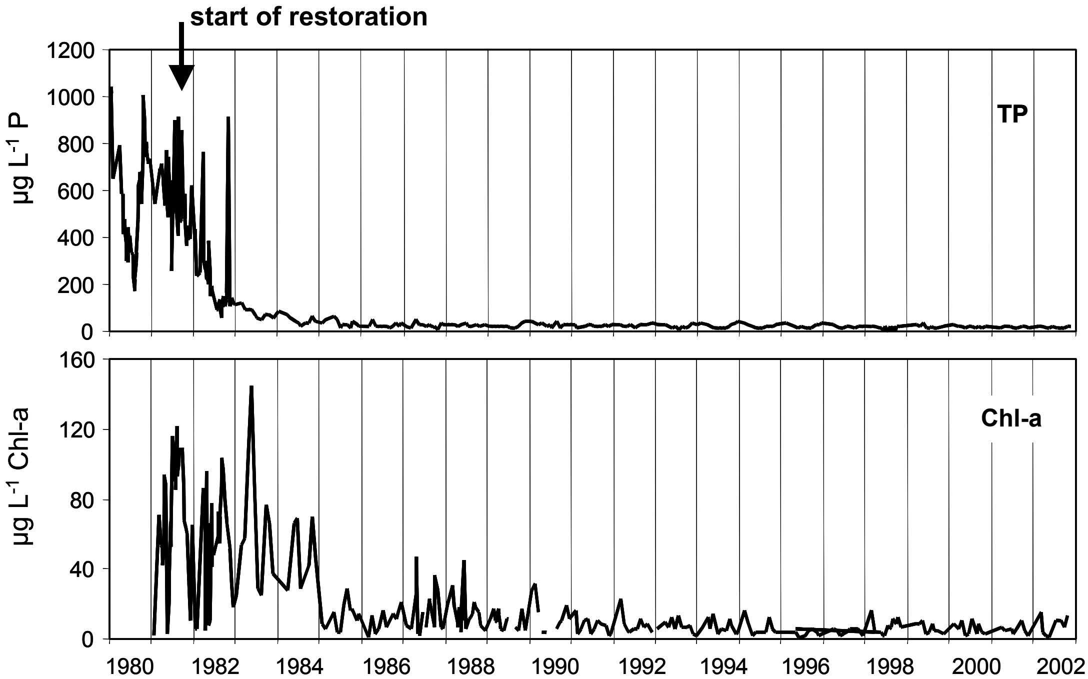

Fig. 3. Total phosphorus and chlorophyll-a concentrations in Schlachtensee (1980-2002) [µg L^{-1} in 1 m depth]

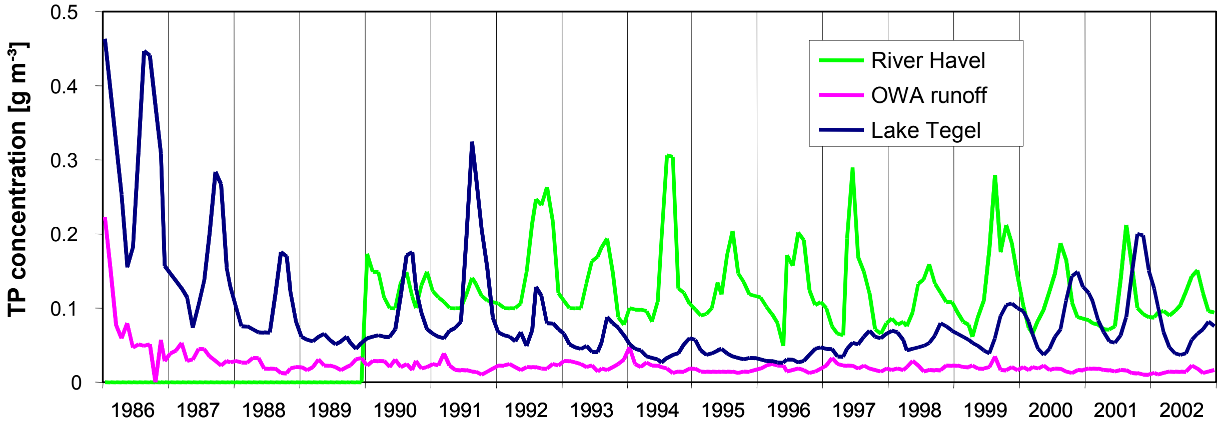

Fig. 4. TP concentration in the River Havel, OWA runoff, and Lake Tegel [g m^{-3}]

Aims and Approach of the Project

Both Lake Tegel and Schlachtensee experienced almost instantaneous and drastic reductions in the external P-load some time ago. Since then we have built up very extensive data sets of nutrient concentrations and phytoplankton abundance which document the recovery of both systems so far. The data demonstrate clear differences in the evolution of conditions between the 2 lakes. Stable control of algal biomass and particularly of cyanobacterial blooms remains a management priority for Lake Tegel, while conditions in Schlachtensee meanwhile meet the restoration target. This project aims to analyze the existent data sets, together with some specific supplementary data, to develop a mechanistic and process understanding of the course of lake recovery so far. This information, and the underpinning models and analyses, will provide the basis for informed management decisions aimed at further improvement in the water quality in Lake Tegel and potentially also for Schlachtensee, as well as providing guidance for amelioration strategies in other systems.

Our overall approach in this project has relied heavily on the development and application of mathematical models for the interpretation and analysis of the data. This methodology brings together the data, and our developing process and mechanistic understanding in a quantitative framework. This approach facilitates the inter-comparison of different ways of looking at the data, and produces validated models which can be used to characterize the present behaviour of the system, as well as to predict how it will change under different management strategies. In addition, a modelling approach ensures that the experimental investigations are firmly linked to provision of specific data either to parameterise or test a model. No single model can serve all purposes equally well and we have developed a suite of models of varying complexity to address specific questions.

2. Methods

Data Compilation

In addition to the extensive data sets (1990 to 2002) of nutrients and phytoplankton biomass available from within the project team it was necessary to compile time series of other parameters (primarily of chemical and hydrological data) which had been collected for both Lake Tegel and Schlachtensee by other agencies in the Berlin area (see Appendix). Through personal contacts these requisite complementary data have been obtained and the data put into a common format after quality control. This has involved inspection of the data for obvious outliers and for homogeneity. Unrealistic high values of the chloride concentration at Lake Tegel in the beginning of 1995 were removed and linearly interpolated. The hydrological and chemical data of the inflows were available as daily or monthly mean values. The lake data were measured very irregularly, one to five times a month and with winter breaks of up to 4 months. To calculate monthly mean values the data was linearly interpolated. Time series were compared where overlapping data sets existed.

Appendices 1 to 4 provide details of various data which has been assembled. We note that the combined data sets are a very significant resource bringing together for the first time in one place, multiple long term data sets characterizing 2 key components of the Berlin water system. They will provide the essential starting point for future investigations. Parameters taken from the literature and used in our calculations are listed in Appendix 5.

Please note that we have used a uniform system of symbols and abbreviations to denote the various parameters and variables used in the mathematical modeling. These are listed in Table 3 at the end of this chapter for convenience of the reader.

Physical Characteristics of Lake Tegel and Schlachtensee

The principal physical parameters characterizing Lake Tegel and Schlachensee are set out In Table 1. Note that Lake Tegel is about 10 times the volume as well as of the surface area of Schlachtensee. However the water residence time (see below) is considerably longer in Schlacthtensee than in Lake Tegel. Because of the morphological complexity of the shallow interaction zone between the Havel and Lake Tegel we consider only the main basin of Lake Tegel. Both lakes are seasonally stratified. Through an examination of the temperature profiles, the boundary between the upper (epilimnion) and lower compartment (hypolimnion) was set at 6 m depth for Schlachtensee, and at 8 m lake depth for Lake Tegel.

Table 1. Morphologic and hydrologic lake parameters (Morphological values of Lake Tegel from Office Wassmann)

Parameter (unit)	Lake Tegel	Schlachtensee
Area (km^2)	3.06	0.42
Area of hypolimnion (km^2)	1.47	0.13
Volume (10^6 m^3)	23.15	1.97
Volume of Hypolimnion (10^6 m^3)	5.28	0.20
Maximum depth (m)	16	9
Water retention time (days) (see chapter 3)	~ 70	~ 220

Mass Balance

Mass balance equations of water, chloride and phosphorus were set up for both lakes. By using chloride as a conservative tracer, as it is a not taken up by organisms nor removed by precipitation., and solving simultaneously the chloride and water balances it was possible to estimate components in the water balance which could not be measured directly. Thus, the size of the inflow of the Havel River into Lake Tegel could be estimated, and a possible groundwater inflow into Schlachtensee could be detected. The water mass balance was calculated for Lake Tegel by a simple box model mixing calculation, and for both lakes using the numerical capacities of ModelMaker as time integrated mass balance.

The water mass balance of the lakes was then used to construct the phosphorus mass balance. Phosphorus is taken up by organisms, removed by sedimentation with the detritus and released into the water column after transformation (diagenesis) in the sediments. Thus, a sediment layer had to be introduced into the model which functions as either a source or sink to maintain the equality between the total inflows and outflows of phosphorus. The exchange between water column and sediment were modelled step by step in increasing detail. First, the processes of P sedimentation from the water column and release from the sediment were summarized as net sedimentation (Eq. 1).

Net sedimentation = gross removal from water column – release to water column (1)

The temporal changes in net sedimentation could be adequately described by a simple time dependent model (Model A Schlachtensee). The influence of other lake components on the net sedimentation were established also (Model A Lake Tegel, Model B Schlachtensee).Then, the sedimentation and release were modelled separately (Model B Lake Tegel, Model C Schlachtensee). In the next step the water column was divided into an upper and a lower compartment (Model C Lake Tegel, Model D Schlachtensee). In Lake Tegel the P release from the sediments was an important P source. Therefore, in the next step the transformation and transport processes in the sediment were considered (Model D Lake Tegel).

The parameter values to describe sedimentation and release had to be estimated by calibrating a numerical model, using optimization routines of ModelMaker (see below). Then, the most important parameters were selected by sensitivity analysis.

Modelling with ModelMaker

ModelMaker® Vs. 4 (Family Genetix) is a tool for solving ordinary differential equations by numerical methods. It can be used to model time integrated mass balances. Due to its graphical user interface and its integrated mathematical routines, it is easy to use. The main components of a model are:

- compartments which represent integrators in a model. The value of a compartment represents the quantity held within it, and is calculated using a differential equation which gives the rate of change of the value.
- flows which represent the movement of something from one compartment to another, i.e. some quantity is subtracted from the source compartment and added to the destination compartment.
- variables which values are calculated as the model is run.
- parameters which fixed values are defined by the model user.

Optimization

Since not all parameters of a model are known, some have to be estimated by calibrating the model. Calibration is the process of finding the best concordance between computed and observed data by variation of some selected parameters. Optimization routines are automatic calibration procedures where the parameter values are systematically changed to minimize the difference between the calculated and observed data. In a numerical model simple analytical methods such as linear regression are not generally applicable. Therefore, iterative numerical methods of optimization (Marquardt and Simplex) are used in ModelMaker. Before using a optimization routine the user has to set at least the magnitude of the values. If the initial value is far away from a realistic value, the optimization routine might come out with unrealistic values.

Sensitivity Analysis

A sensitivity analysis measures the effect of a single parameter change on a target variable and thus indicates which components have the greatest effect on a target variable. The most sensitive parameters have to be determined as accurately as possible. Others with a small effect on the target variable can be excluded from the model. In our models, the chloride or P concentration in the lakes were used as target variables. The sensitivity of a target variable indicates the importance of a parameter for the chloride or P concentration in the lake.

For example: the net sedimentation flux for P (F_{ns}) depends on the P concentration in the lake (C_{lake}). It was modeled as a function of the OWA runoff (Q_{owa}) and precipitation (Q_{rain}) by using two parameters (ns_{owa}, ns_{rain}) (Eq 2):

$$F_{ns} = (ns_{owa} * Q_{owa} + ns_{rain} * Q_{rain}) * C_{lake} \qquad (2)$$

The value of the factors ns_{owa} and ns_{rain} were determined by optimization routine. Afterwards, a sensitivity analysis was used to check whether the parameters had an influence on the lake P concentration. This indicates also the importance of the OWA runoff or the precipitation for the net sedimentation (Table 2). The higher the absolute value of the sensitivity the more the net sedimentation is determined by the underlying time series. Thus, the precipitation has, in this example, an higher influence on the lake P concentration (and on the net sedimentation) than the OWA runoff. However, the sensitivity values can not be compared with their absolute numbers, e.g. precipitation does not have 6 times more influence than the OWA runoff on the target variable. A negative sensitivity indicates a negative connection: the higher the precipitation the lower the lake P concentration, because higher net sedimentation leads to a decrease in lake concentration.

Table 2. Optimised parameters

Parameters	Abbreviation	Value	Unit	Sensitivity for C_{lake}
Factor for net sedimentation affected by the OWA runoff	ns_{owa}	- 0.000013		0.053
Factor for net sedimentation affected by precipitation	ns_{rain}	1.94		-0.347

Pearson Correlation Coefficient

The correlation analysis investigates the stochastic connection between different variables. The Pearson correlation coefficient (r) describes the strength and direction of a linear connection. A zero values indicates no connection, and one a strong connection. The coefficient of determination (r^2) is the square of the correlation coefficient.

Sediment Investigations

Sediment cores were collected in the summer 1996 by the UBA and in summer 2002 by the IGB in Plexiglas tubes (inner diameter 5.8 cm) with a modified Kajak Sampler (UWITEC) at the deepest spot of Lake Tegel and Schlachtensee. In 1996 the sediment cores where sliced in 1 cm thick layers down to a depth of 10 cm and in 2003 into 3 layers (0-1, 1-4, 4-10 cm).

For small-scale determination of concentrations of dissolved ions at the sediment-water interface, dialysis samplers, so-called “peepers” (polysulfone membrane 0.2 µm pore size, HT-Tuffryn 200[7], Pall[7] Gelman Laboratory), according to the principle of Hesslein (1976) were exposed by the IGB in July (Lake Tegel) and October (Schlachtensee) 2003 for about 14 days in the sediment. All samples were stored at low temperatures (about 4 °C) until analysis. Soluble reactive phosphorus (SRP) in the water samples was measured using a segmented flow analyzer (Skalar San^{plus}) based on the photometric molybdenum-blue method described by Murphy and Riley (1962). Total phosphorus (TP) in water samples and in extracts of the P fractionation was measured as SRP after digestion at 121 °C and 0.12 MPa using peroxidisulfate. Non reactive phosphorus (NRP) is calculated as difference between TP and SRP. Sediment dry matter was determined after drying at 105 °C to constant weight and loss on ignition (LOI) after 3 hours of ignition at 450 °C. The TP in sediment samples was measured as SRP after 12-hour H_2SO_4-acid digestion with peroxide at 150 °C.

Phosphorus binding in sediment samples was determined by extracting P according to the scheme proposed by Psenner et al. (1984) and modified by Hupfer et al. (1995). Five fractions are obtained by the consecutive use of:
(1) 1 M NH_4Cl at pH 7 to determine loosely adsorbed P and SRP in pore water (NH_4Cl-P);
(2) bicarbonate buffered dithionite (0.11 M $NaHCO_3$ / 0.11 M $Na_2S_2O_4$) to release P mobilized under low redox conditions, especially iron bound P (BD-P);
(3a) 1 M NaOH to mobilize Al bound P and OH^- exchangeable P determined as SRP (NaOH-SRP) and
(3b) organic bound P in the same fraction detected after digestion (NaOH-NRP);
(4) 0.5 M HCl to determine P bound by carbonates and apatite; and
(5) digestion of the remaining sediment to obtain refractory P.
The fractions do not correspond to chemically exactly defined compounds, but are characterized by elution medium and conditions. Thus, they are called “operational phases” (Psenner and Pucsko 1988).

Iron extracted by BD and HCl was measured in the P fractionation procedure to determine the different iron forms. In the BD fraction, mainly oxidised iron species and in the HCl-fraction and rest fraction stable bound iron, mainly FeS_2, are expected. Total metal concentrations were analyzed with a flame atomic absorption spectrometer (Perkin Elmer) after an aqua regia digestion.

Phosphorus Treshold Values for Chlorophyll-a

Following recent developments questioning the use of correcting for phaeophytin in the DIN and ISO method for determination of Chlorophyll-a, values were recalculated for all of the data since 1981 to provide new concentrations for Schlachtensee (1982-2002) and Lake Tegel (1984-2002). Using these data, we then compared graphically the total P and Chlorophyll-a annual mean, annual maxima, summer mean, spring maxima (TP), summer maxima (Chl. A) values of the total lake, the euphotic zone, the epilimnion and the top 1 m layer.

Table 3: Abbreviations for parameters used in the report

Abbreviations	Parameter	Unit
A	Area of the lake	m²
A_{hypo}	Area of hypolimnion	m²
V	Volume of the lake	m³
V_{hypo}	Volume of hypolimnion	m³
z_m	Mean lake depth	m
C_{drain}	Concentration of Cl or P in stormwater inflow via drainage pipelines	$g\ m^{-3}$
C_{epi}	Concentration of P in the epilimnion	$g\ m^{-3}$
C_{gw}	Concentration of Cl or P in the groundwater	$g\ m^{-3}$
C_{havel}	Concentration of Cl or P in the Havel	$g\ m^{-3}$
C_{hypo}	Concentration of P in the hyplimnion	$g\ m^{-3}$
C_{hypo_diss}	Concentration of dissolved P in the hyplimnion	$g\ m^{-3}$
C_{hypo_part}	Concentration of particulate P in the hyplimnion	$g\ m^{-3}$
C_{others}	Load of P from other inputs from the shoreline (erosion; leaves)	$g\ mon^{-3}$
C_{owa}	Concentration of Cl or P in the OWA runoff	$g\ m^{-3}$
C_{rain}	Concentration of Cl or P in the precipitation	$g\ m^{-3}$
C_{sed}	Concentration of P in the sediment	$g\ m^{-3}$
C_{sed_diss}	Concentration of dissolve P in the sediment	$g\ m^{-3}$
C_{sed_org}	Concentration of organic bound P in the sediment	$g\ m^{-3}$
C_{sed_prec}	Concentration of stabile bound P in the sediment	$g\ m^{-3}$
C_{sed_sorb}	Concentration of exchangeable bound P in the sediment	$g\ m^{-3}$
C_{ss}	Concentration of Cl or P in Schlachtensee	$g\ m^{-3}$
C_{ts}	Concentration of Cl or P in Lake Tegel	$g\ m^{-3}$
d_{Pegel}	Change of lake level	m
F_{bi}	Flux of a substance (Cl or P) out of a lake by bank infiltration	$g\ mon^{-1}$
F_{drain}	Flux of a substance (Cl or P) into a lake by stormwater inflow	$g\ mon^{-1}$
F_{eva}	Flux of a substance (Cl or P) out of a lake by evapotranspiration	$g\ mon^{-1}$
F_{gs}	Sedimentation flux of P	$g\ mon^{-1}$
F_{gs_e}	Sedimentation flux of P out of the epilimnion	$g\ mon^{-1}$
F_{gs_h}	Sedimentation flux of P out of the hypolimnion	$g\ mon^{-1}$
F_{gw}	Flux of a substance (Cl or P) into a lake by groundwater	$g\ mon^{-1}$
F_{gwe}	Flux of a substance (Cl or P) out of Lake Tegel by groundwater enrichment	$g\ mon^{-1}$
F_{hwd}	Flux of a substance (Cl or P) out of Schlachtensee by hypolimnetic withdrawal	$g\ mon^{-1}$
F_{in}	Flux of a substance (Cl or P) into Lake Tegel by Havel inflow	$g\ mon^{-1}$
F_{mi}	Mixing flux of P between epimlimnion and hypolimnion	$g\ mon^{-1}$
F_{ns}	Net sedimentation flux of P	$g\ mon^{-1}$
F_{others}	Flux of a substance (Cl or P) into Schlachtensee by leaves	$g\ mon^{-1}$
F_{out}	Flux of a substance (Cl or P) out of Lake Tegel outflow	$g\ mon^{-1}$
F_{owa}	Flux of a substance (Cl or P) into a lake by the runoff of the OWA	$g\ mon^{-1}$
F_{prec}	Precipitation flux of P	$g\ mon^{-1}$
F_{pw}	Flux of a substance (Cl or P) into Lake Tegel by return of process water	$g\ mon^{-1}$
F_{rain}	Flux of a substance (Cl or P) into a lake by precipitation	$g\ mon^{-1}$
F_{rl}	P-release flux of of P	$g\ mon^{-1}$
F_{sorb}	Sorption flux of P	$g\ mon^{-1}$
F_{ws}	Flux of a substance (Cl or P) out of Schlachtensee into Waldsee	$g\ mon^{-1}$
F_{ww}	Flux of a substance (Cl or P) out of Lake Tegel by extractions of the Water Works	$g\ mon^{-1}$
$gs_{\_h}$	Factor for sedimentation from the hypolimnion into the sediment	-
gs	Factor for constant sedimentation	-
gs_{fin}	Factor for sedimentation affected by Havel load	-
gs_{other}	Factor for sedimentation affected by leaves	-
gs_{owa}	Factor for sedimentation affected by OWA runoff	-
gs_{pipe}	Factor for sedimentation affected by the discharge of the lake pipeline	-
gs_{rain}	Factor for sedimentation affected by precipitation	-

gs_{temp}	Factor for sedimentation affected by temperature	-
k_{bi}	Fraction of bank infiltrate in the water extracted at the wells around Lake Tegel	-
k_{mix}	Mixing coefficient in the lake	-
ns	Factor for constant net sedimentation	-
ns_{in}	Factor for net sedimentation affected by the Havel inflow	-
ns_{n}	Factor for net sedimentation affected by nitrate	-
ns_{o}	Factor for net sedimentation affected by oxygen	-
ns_{owa}	Factor for net sedimentation affected by the OWA runoff	-
ns_{pipe}	Factor for net sedimentation affected by discharge of the lake pipeline	-
ns_{rain}	Factor for net sedimentation affected by precipitation	-
ns_{rehw}	Factor for net sedimentation affected by the extraction at Well Rehwiese	-
ns_{t}	Factor for net sedimentation affected by temperature	-
ns_{ww}	Factor for net sedimentation affected by water works extraction	-
Pegel	Lake level	m
Q_{bi}	Bank infiltration	m^3 mon^{-1}
Q_{drain}	Inflow into Schlachtensee by drainage pipelines for stormwater	m^3 mon^{-1}
Q_{dw}	Extration of drinking water at wells by Water Works	
Q_{eva}	Evaporation	m^3 mon^{-1}
Q_{gw}	Groundwater inflow at Schlachtensee	m^3 mon^{-1}
Q_{gwe}	Extration of Lake Tegel water for groundwater enrichment	m^3 mon^{-1}
Q_{hwd}	Hypolimnetic withdrawal at Schlachtensee	m^3 mon^{-1}
Q_{in}	Flow from River Havel into Lake Tegel	m^3 mon^{-1}
Q_{others}	Time series of leaves input into Schlachtensee	-
Q_{out}	Flow from Lake Tegel into River Havel	m^3 mon^{-1}
Q_{owa}	OWA runoff into a lake	m^3 mon^{-1}
Q_{pipe}	Discharge of the lake pipeline of Lake Tegel	m^3 mon^{-1}
Q_{pw}	Discharge of process water of the water works Tegel	m^3 mon^{-1}
Q_{rain}	Precipitation	m^3 mon^{-1}
Q_{rehw}	Extraction of water at Well Rehwiese	m^3 mon^{-1}
Q_{ww}	Extration of Lake Tegel water by Water Works	m^3 mon^{-1}
q_{gwc}	Factor for constant groundwater inflow in Schlachtensee	-
q_{drain}	Factor for stormwater inflow into Schlachtensee dependent on precipitation	-
q_{hin}	Factor for Havel inflow dependent on Havel runoff	-
q_{oin}	Factor for Havel inflow dependent on OWA runoff	-
q_{pegel}	Factor for groundwater inflow dependent on lake level	-
q_{pin}	Factor for Havel inflow dependent on discharge of lake pipeline	-
q_{rain}	Factor for groundwater inflow dependent on precipitation	-
q_{rehw}	Factor for groundwater inflow dependent on extraction at Well Rehwiese	-
q_{rw}	Factor for bank infiltration dependent on extraction at Well Rehwiese	-
q_{temp}	Factor for groundwater inflow dependent on temperature	-
q_{win}	Factor for Havel inflow dependent on water works extraction	-
rl	Factor for constant release	-
rl_{n}	Factor for release affected by nitrate	-
rl_{nt}	Factor for release affected by nitrate and temperature	-
rl_{owa}	Factor for release affected by OWA runoff	-
rl_{rain}	Factor for release affected by precipitation	-
rl_{rehw}	Factor for release affected by extraction at Well Rehwiese	-
rl_{t}	Factor for release affected by temperature	-
sig	Factor for sediment retention	-
stability	Time series to describe the stratification stability	-

3. Results

Lake Tegel

Chloride and Water Mass Balance

Discontinuous Mixing Calculation under Steady State Assumption

The mixing calculation is based on the chloride and water mass balances (Eq. 3-5). It was used to estimate the Havel inflow (Q_{in}, Eq. 7) and the outflow (Q_{out}, Eq. 6) of Lake Tegel into the River Havel. It was assumed that all other in- and outflows are known. The components considered in the chloride balance of Lake Tegel are shown in Figure 5.

$dC_{ts}/dt*(V+d_{Pegel}*A)$	$= Q_{in}*C_{havel} - Q_{out}*C_{ts} + A$	[g mon^{-1}]	(3)
Q_{out}	$= Q_{in} + B$	[m^3 mon^{-1}]	(6)
Q_{in}	$= [(C_{ts}(t)-C_{ts}(t-1))*(V+d_{Pegel}*A)-A+C_{ts}*B]/(C_{havel}-C_{ts})$	[m^3 mon^{-1}]	(7)
A	$= Q_{owa}*C_{owa} + Q_{rain}*C_{rain}+(Q_{pw}-Q_{ww})*C_{ts})$	[g mon^{-1}]	(4)
B	$= Q_{owa}+Q_{rain}-Q_{eva}-Q_{ww}+Q_{pw}-d_{Pegel}*A$	[m^3 mon^{-1}]	(5)

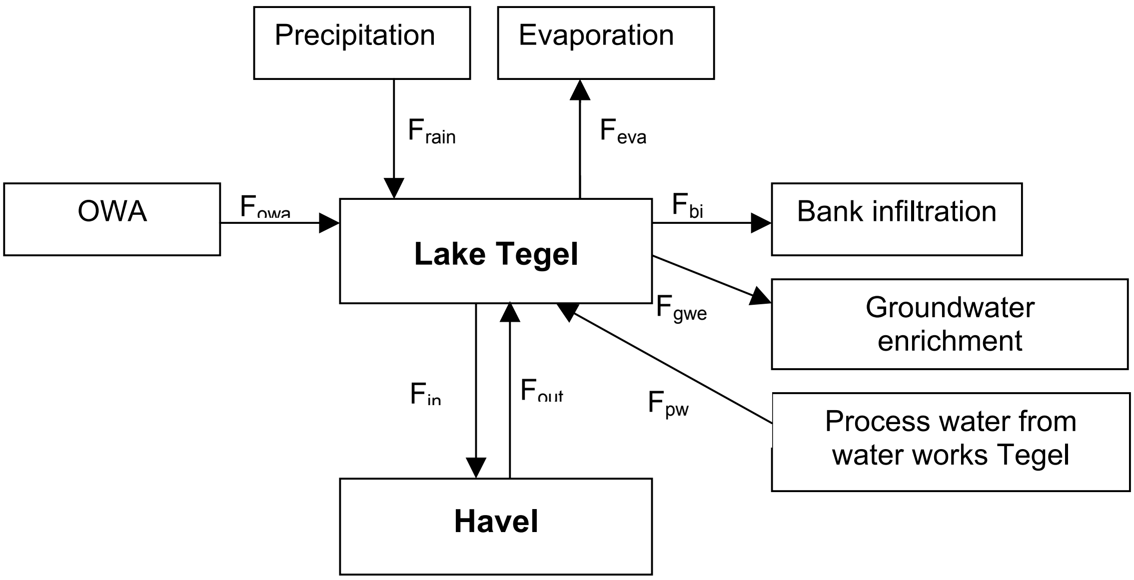

Fig. 5: Flow chart of the hydrological fluxes of Lake Tegel

Because of the hydrogeological setting of Lake Tegel, it is considered very unlikely that groundwater is flowing into the lake (Pekdecker, pers. com.). The fraction of lake water (bank infiltration) at the extraction well gallery was set to 80 % (Fritz et al. 2002). The time from the bank infiltration to the extraction of the water from the well varies, in addition to the extracted amount. Because it can be assumed that the bank infiltration itself is stable (Pekdeker, per. com.), a mean value (1983-2002) for the bank infiltration was used. The bank infiltration (Q_{bi}) and the direct extraction of lake water for groundwater enrichment by the waterworks (Q_{gwe}) were summed up in the parameter Q_{ww}. The water works Tegel also returns water from their processing plant (Q_{pw}) to Lake Tegel.

For this mixing calculation, a one box model approach was used, because the similarity of chloride concentration in 0.5, 7 and 14 m depth did not indicate a stable stratification, and even after 1996, when stratification was more stable, the chloride concentration in 14 m depth tended to be somewhat higher than at 7 m and at 0.5 m. Additionally, the hypolimnion has, compared to the epilimnion, only a small volume, so these slightly higher values have little impact on the resulting overall water budget. The unstable stratification in Lake Tegel can be explained by the influence of the wind, the aeration measures (especially before 1989, where the aerators were employed in a design that resulted in substantial mixing of the lake) as well as the inflow of the OWA runoff and the influence of the Havel (Ripl et al. 1993). The mean monthly change in lake level was integrated (d_{Pegel}).

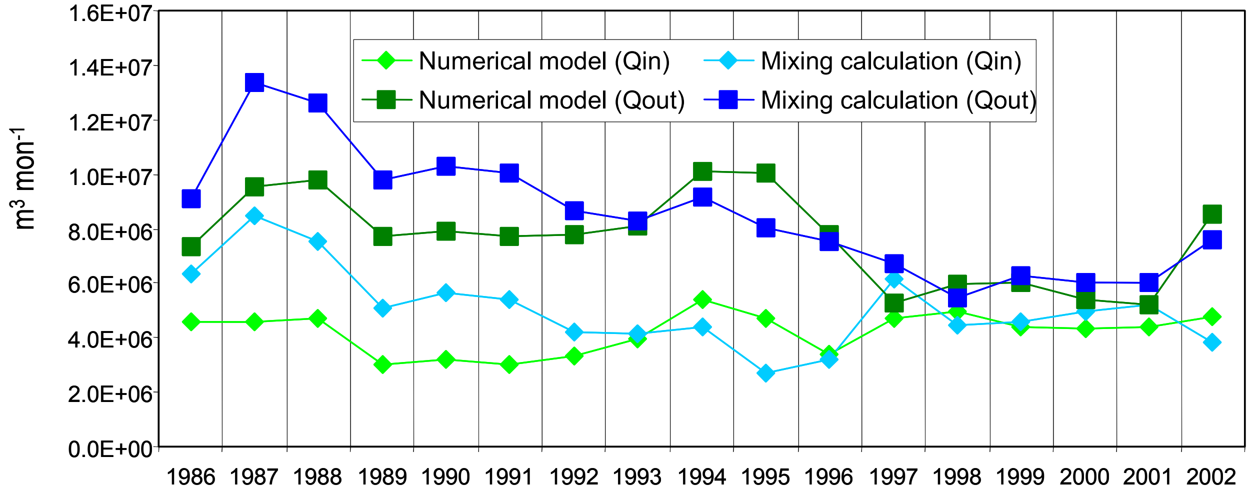

Fig. 6. Annual mean of the monthly Havel in- and outflow of Lake Tegel by mixing calculation and numerical model

The mixing calculation for the years 1986 – 2002 indicates great variations in the Havel in- and outflow, especially in the summers 1986-1989 (Fig. 6). Inflows were low in 1992 to 1994. By xy-plot no connection between the Havel inflow and the Havel discharge, the OWA runoff or the extraction by the water works could be established. The mean fraction of the Havel inflow based on the total inflow was 37 %. The value given by Ripl et al. (1993) was 30 – 40 %. The result of the mixing calculation was used to estimate the water retention time of Lake Tegel. It varies from year to year between 44 and 80 days (mean: 62 days).

Numerical Model

Additionally, the chloride balance was modelled time integrated with ModelMaker (Fig. 6). The same assumptions were used as for the mixing calculation, including a one box model approach (Fig. 5). The model was calibrated for the years 1991 – 2002 and validated for the years 1986 – 1990. The best model had a Pearson correlation coefficient of 0.89 (r^2 = 0.79) for the calibration period 1992– 2002, and a coefficient of 0.80 (r^2 = 0.63) for the validation periode of 1986 – 1991 (Fig. 7). Over the whole time period from 1986 – 2002 the correlation coefficient was 0.87 (r^2 = 0.76).

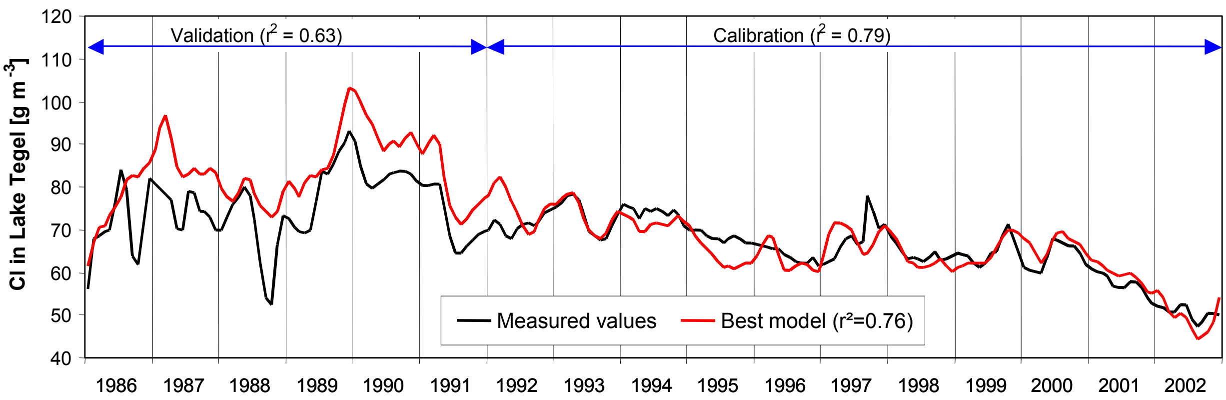

Fig. 7. Chloride concentration of Lake Tegel: measured and calculated by numerical model

The aim of the numerical model (Eq. 8 – 10) was to develop a function between the known in- and outflows of Lake Tegel and the unknown inflow from the River Havel (Eq. 11). The outflow to the River Havel was estimated by balancing the water balance (Eq. 12). The unknown parameters for the dependence of the Havel inflow on the inflow and known lake components, such as Havel discharge (q_{hin}), the OWA discharge (q_{oin}), the discharge of the lake pipeline (q_{pin}), or the extraction of the water works (q_{win}), were calculated using the optimization routines of ModelMaker. The parameters with no effect on the chloride concentration in Lake Tegel were excluded from the model.

$$dC_{ts}/dt = (F_{in}+F_{owa}+F_{pw}+F_{rain}-F_{ww}-F_{out}-F_{eva})/(V+A*d_{Pegel}) \quad (8)$$

$$F_{in} = Q_{in} * C_{havel} \quad (9)$$

$$F_{out} = Q_{out} * C_{ts} \quad (10)$$

$$Q_{in} = q_{hin}*Q_{havel}+q_{win}*Q_{ww}+q_{oin}*Q_{owa}+q_{pin}*Q_{pipe} \quad (11)$$

$$Q_{out} = Q_{in}+Q_{owa}+Q_{pw}+Q_{rain}-Q_{eva}-Q_{ww}-A*d_{Pegel} \quad (12)$$

The known chloride inflows to Lake Tegel are:

- Inflow from OWA ($F_{owa} = Q_{owa}*C_{owa}$)
- Process water discharge ($F_{cw} = Q_{cw} * C_{ts}$)
- Precipitation ($F_{rain} = Q_{rain}*C_{rain}$)

The known chloride outputs of Lake Tegel are:

- Extraction of lake water by the waterworks ($F_{ww} = Q_{ww} * C_{ts}$), separated into bank infiltration ($Q_{bi} = Q_{dw}*k_{bi}$) and direct extraction for groundwater enrichment (Q_{gwe}). The factor for the fraction of bank infiltration(k_{bi}) of the total drinking water extraction (Q_{dw}) was set to be 0.8 (Fritz et al. 2002)
- Evaporation ($F_{eva} = Q_{eva}*0$)

Table 4. Optimised parameters of the chloride balance model of Lake Tegel

Parameters	Abbreviation	Value	Unit	Sensitivity for Cts 1986-1991	Sensitivity for Cts 1992-2002
Factor for Havel inflow dependent on Havel discharge	q_{hin}	0.068	-	-0.05	-0.07
Factor for Havel inflow dependent on water works extraction	q_{win}	1.306	-	-0.22	-0.10
Factor for Havel inflow dependent on OWA runoff	q_{oin}	-0.295	-	0.12	0.05
Factor for Havel inflow dependent on lake pipeline discharge	q_{pin}	-0.002	-	0.001	0.000

This analysis shows that the Havel inflow is determined by the extraction of water by the waterworks, the River Havel discharge, and the OWA discharge (Table 4). These factors have the biggest influence on the chloride concentration in Lake Tegel (C_{ts}). As to be expected, the separate influence of the lake pipe flow was rather low, i.e. OWA discharge is the overriding parameter, regardless as to whether this water originates from the Havel through the pipe, or from Tegeler Fließ and Nordgraben. The influence of the OWA was higher in the years before 1992, when the lake pipe flow and therefore the OWA discharge was high. Including a measure for stratification stability, e.g. the temperature in 15m right above the lake bottom, in 5 m depth, or the temperatur gradient between 5 and 15m, did not improve the model results. The following exerted no influence on the lake chloride concentration: the precipitation rate (Q_{rain}) and the lake level (Pegel), as measure for a possible backflow of the River Havel.

The mean fraction of the Havel inflow in relation to the total inflow was 40 %. This is similar to the value estimated by mixing calculation. The resulting water retention time of Lake Tegel varies from year to year between 52 and 88 days (mean: 66 days).

Phosphorus Mass Balance

The total P concentrations of the River Havel were measured by the Senat Berlin from 1990 onwards. Therefore, the modeling procedure was done for the years 1990 to 2002. For the years 1986 until 1992 we inferred data from a figure given in a report by Ripl, and these still need to be checked for homogeneity, and if this proves possible, used for model validation.

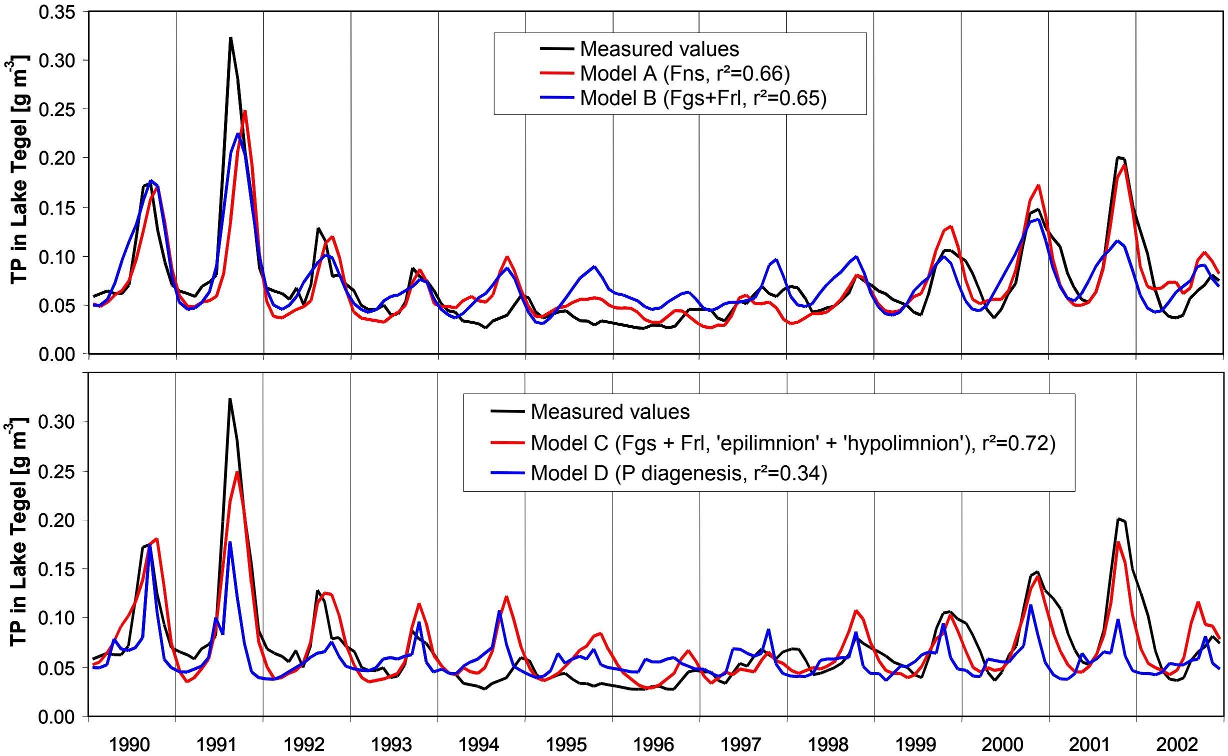

Fig. 8. P mass balance for Lake Tegel: measured and calculated values for Model A to D [g P m^{-3}, monthly mean values].

Model A: P Net Sedimentation

The P concentration in Lake Tegel was modeled using the water balance, determined from the chloride mass balance, and incorporating the interactions with the sediment such as net sedimentation (Fig. 9, Eq. 13). The P flux of net sedimentation was described as a function of the Havel inflow (Q_{in}), the discharge of the OWA (Q_{owa}), the flow through the like pipe (Q_{pipe}), the extraction by the water works (Q_{ww}), the nitrate concentration (C_{NO3}), and the temperature in 15 m depth (Temp) (Eq. 14). The oxygen concentration at the lake bottom, and the precipitation had no influence on the P concentration in the lake. This simple model had the Pearson correlation coefficent of 0.81 (r^2 =0.66, Fig. 8). The parameters were estimated by optimisation routine (Table 5).

$$dC_{ts}/dt = (F_{in}+F_{owa}+F_{pw}+F_{rain}-F_{ww}-F_{out}-F_{eva})/(V+A*d_{Pegel}) - F_{ns} \quad (13)$$

$$F_{ns} = (ns_{in}*Q_{in}+ns_{owa}*Q_{owa}+ns_{pipe}*Q_{pipe}+ns_{ww}*Q_{ww}+ns_n/C_{NO3}+ns_t*Temp)*C_{ts} \quad (14)$$

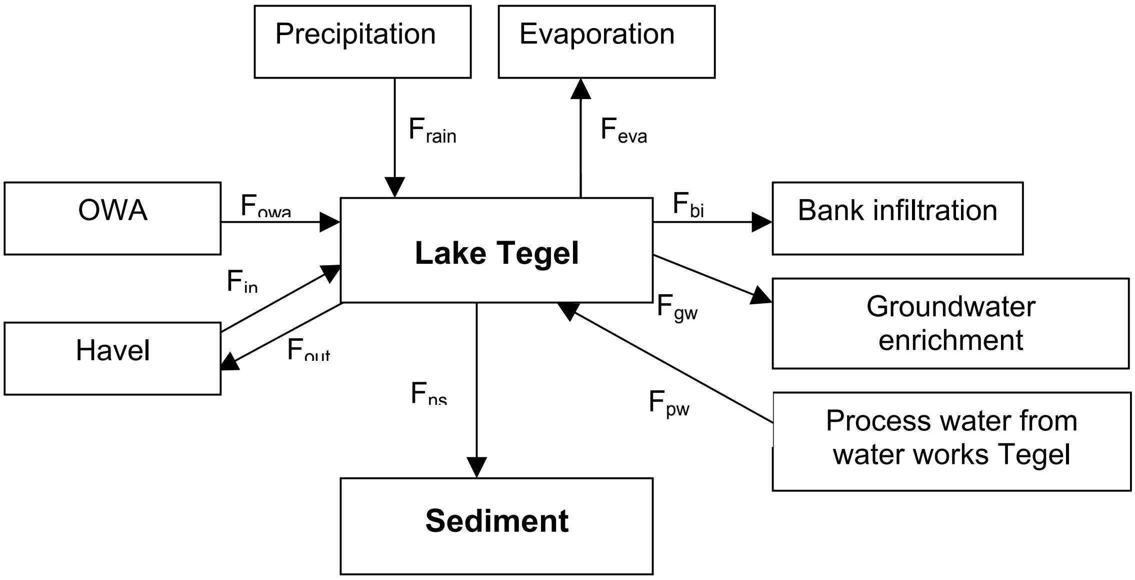

Fig. 9. Flow chart of Lake Tegel with sediment compartment

Table 5. Optimised parameters of Model A for Lake Tegel

Parameters	Abbreviation	Value	Unit	Sensitivity for C_{ts}
Factor for net sedimentation affected by the Havel inflow	ns_{in}	-2.15E-08	-	0.31
Factor for net sedimentation affected by the OWA discharge	ns_{owa}	-4.72E-08	-	1.21
Factor for net sedimentation affected by discharge of the lake pipeline	ns_{pipe}	4.61E-08	-	-0.38
Factor for net sedimentation affected by water works extraction	ns_{ww}	3.58E-07	-	-46919
Factor for net sedimentation affected by nitrate in 15 m depth	ns_n	-0.1127	-	0.47
Factor for net sedimentation affected by temperature in 15 m depth	ns_t	-0.087	-	48.99

The negative factor values indicate that the higher the Havel or OWA inflow or the temperature in 15 m depth, the lower is the net sedimentation which leads to a higher P concentration in the lake. Opposite to that, the model results indicate that the higher the extraction of the water works and the flow through the pipeline, the higher is the net sedimentation and, therefore, the lower the P concentration in the lake. The nitrate concentration influences the net sedimentation in the same way, because the nitrate concentration is a denominator. The negative value for factor of the nitrate concentration implies a higher decrease of the P net sedimentation (which means a higher P release) at lower nitrate concentrations.

The sensitivities of the lake P concentration to changes of the factors show that the factors for the extraction by the water works, and the temperature have an high influence on the P concentration. The model indicates that the P net sedimentation is especially low (and therefore the lake P concentration high) when the water works extract little water, and the temperature at the lake bottom is high.

Model B: P Sedimentation and P Release

The next step was to distinguish between P sedimentation and P release from the sediment (Eq. 15). To estimate the release, the P concentration of the sediment had to be calculated by the ordinary differential equation (Eq. 16). The active sediment layer was assumed to be 0.12 m. A constant retention factor (sig) was introduced. However, in consequence of the results of the optimisation runs of the model, it was deleted. The most influential parameters were selected by sensitivity analysis and included in the equations for sedimentation (Eq. 17) and release (Eq. 18). The model result showed an r²=0.65 (r =0.81, Fig. 8).

$$dC_{ts}/dt = (F_{in}+F_{owa}+F_{pw}+F_{rain}-F_{ww}-F_{out}-F_{eva}+F_{rl}-F_{gs})/(V+A*d_{Pegel}) \quad (15)$$

$$dC_{sed}/dt = (F_{gs}-F_{rl})/(0.12*A) \quad (16)$$

$$F_{gs} = (gs+gs_{fin}*F_{in}+gs_{owa}*Q_{owa}+gs_{pipe}*Q_{pipe})*C_{ts}*V \quad (17)$$

$$F_{rl} = (rl_n/C_{NO3}+rl_t*Temp^2)*C_{Sed}*(0.12*A) \quad (18)$$

Table 6. Optimised parameters of Model B for Lake Tegel

Parameters	Abbreviation	Value	Unit	Sensitivity for C_{ts}
Factor for constant sedimentation	gs	-0.07198	-	0.040
Factor for sedimentation affected by the Havel load	gs_{fin}	8.623E-07	-	-0.224
Factor for sedimentation affected by the OWA discharge	gs_{owa}	1.735E-08	-	-0.056
Factor for sedimentation affected by the discharge of the lake pipeline	gs_{pipe}	-1.150E-08	-	0.006
Factor for release affected by nitrate in 15 m depth	rl_n	0.00101	-	0.022
Factor for release affected by temperature in 15 m depth	rl_t	0.00016	-	0.228

The sedimentation is high when the P load by the Havel inflow, or the OWA discharge are high (Table 6). The constant sedimentation factor and the factor for dependency of the gross sedimentation on the discharge of the lake pipeline are negative. This indicates that the sedimentation is low when the P concentration in the lake is high, or the pipe flow is high. The P release depends on the nitrate concentration and the temperature above the bottom. The release increases at higher temperatures or lower nitrate concentrations (nitrate is in the denominator of Eq. 18).

The sensitivities of the P concentration in Lake Tegel are difficult to explain by physical, chemical or biological relationships. The sensitivity analysis indicates that the most influential factor for the P concentration in Lake Tegel is the temperature above the lake bottom. Other important factors are the ones for constant sedimentation, for the OWA discharge, for the Havel discharge and for the nitrate concentration in 15 m depth. Contrary to model A, in this model the extraction of the Water Works Tegel has no influence on the P concentration of

Lake Tegel. Also, the implementation of a constant release factor does not improve the model.

Model C: Epilimnnion and Hypolimnion

In this model (Fig. 10), the water volume was divided into a upper water column (“epilimnion”, <8 m, Eq. 19) and a lower water column (“hypolimnion”, >8 m, Eq. 20). The lower water column is mainly influenced by sedimentation from the upper column (F_{gs_e}, Eq. 22), the sedimentation out of the hypolimnion (F_{gs_h}, Eq. 24), and by P release from the sediment (F_{rl}, Eq. 25). Thus, the development of the P concentration in the hypolimnion as well as the sedimentation and release fluxes could be modelled more accurately. However, the process of mixing between the upper and lower water column had to be introduced (F_{mix}, Eq. 23). Therefore, a time series of stability was constructed (Eq. 26), depending on the temperature difference between 5 and 11 m lake depth. Thus, the mixing was low during stratification and high during destratification. The value of the mixing coefficient (k_{mix}) was optimised in the model (Table 7).

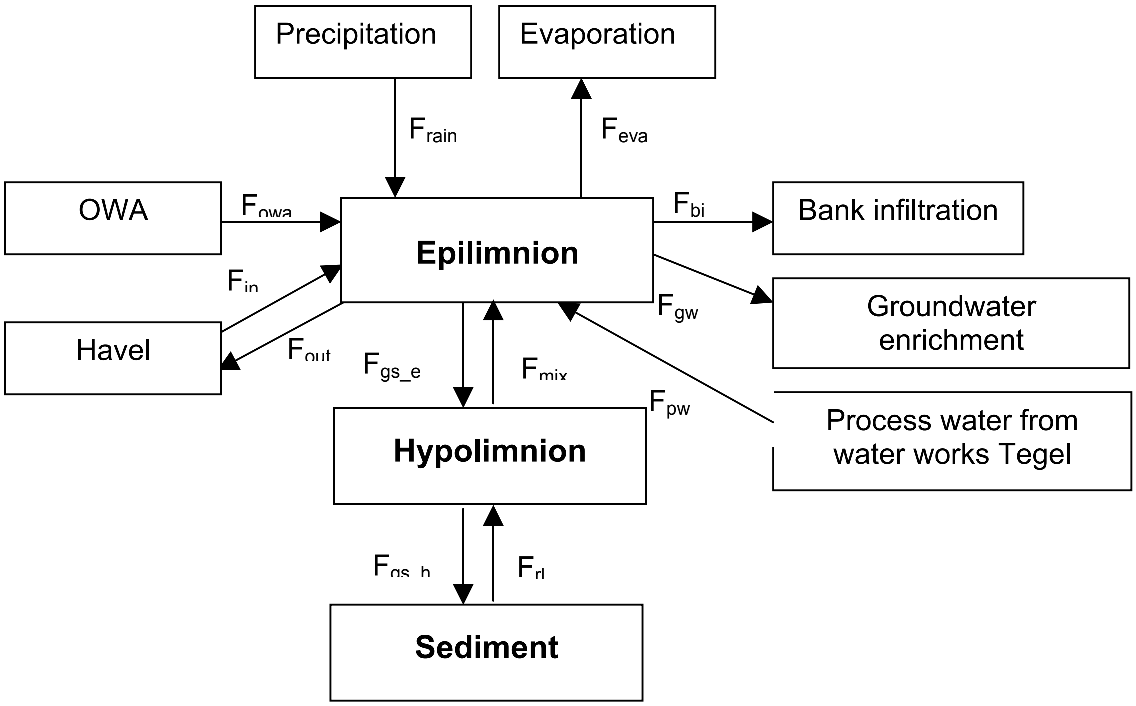

Fig. 10. Flow chart of Lake Tegel including epilimnion, hypolimnion and sediment

$$dC_{epi}/dt = (F_{in}+F_{owa}+F_{pw}+F_{rain}-F_{ww}-F_{out}-F_{eva}+F_{mix}-F_{gs\_e})/(V-V_{hypo}+A*d_{Pegel}) \quad (19)$$

$$dC_{hypo}/dt = (F_{gs\_e}+F_{rl}-F_{mix}-F_{gs\_h})/V_{hypo} \quad (20)$$

$$dC_{sed}/dt = (F_{gs\_h}-F_{rl})/(0.12*A_{hypo})-sig*C_{sed} \quad (21)$$

$$F_{gs\_e} = (gs_{in}*F_{in})*C_{epi}*(V-V_{hypo}) \quad (22)$$

$$F_{mix} = k_{mix}*(C_{hypo}-C_{epi})/z_m*stability*A_{hypo} \quad (23)$$

$$F_{gs\_h} = g_{s\_h}*C_{hypo}*V_{hypo} \quad (24)$$

$$F_{rl} = (rl_t*Temp^2+rl_{nt}/C_{NO3}*Temp^2)*C_{sed}*(0.12*A_{hypo}) \quad (25)$$

$$stability = Max(20; 1/abs(Temp\_11 - Temp\_5)) \quad (26)$$

The optimised model showed a result of $r^2=0.72$ ($r=0.85$, Fig. 8) for the P concentration in the lake and of 0.65 for the P concentration in the epilimnion (Fig. 11). The hypolimnion values were mostly overestimated by the model. However, the result of 0.5 for the hypolimnion could have been improved up to 0.66, with a loss in model accuracy for the P concentration in the whole lake.

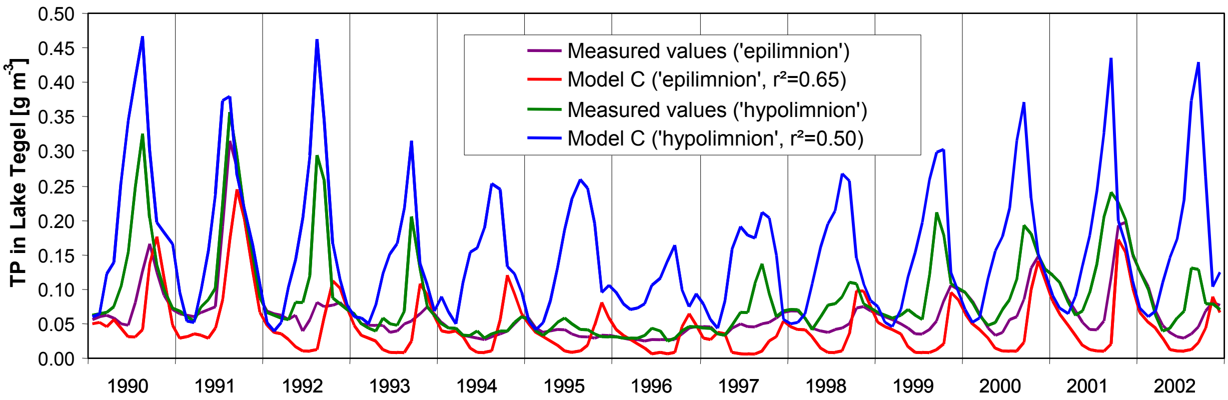

Fig. 11. P mass balance for Lake Tegel: results of Model C for the upper and the lower compartment [g P m^{-3}, monthly mean values]

Table 7. Optimised parameters of Model C for Lake Tegel

Parameters	Abbreviation	Value	Unit	Sensitivity for C_{ts}
Factor for sedimentation affected by the Havel load	gs_{fin}	0.000013	-	0.053
Factor for sedimentation from the hypolimnion into the sediment	g_{s_h}	1.94	-	-0.347
Mixing coefficient	k_{mix}	139.89	-	-0.023
Factor for release affected by temperature in 15 m depth	rl_t	0.00045	-	0.239
Factor for release affected by nitrate and temperature in 15 m depth	rl_{nt}	0.00029	-	0.103
Factor for sediment retention	sig	0.00757	mon^{-1}	-0.307

In this model, the sedimentation was only dependent on the Havel inflow and on a constant factor for the sedimentation out of the hypolimnion. The mixing coefficient for the transport of P was optimized to a very high value. The model indicates that the release is determined by the temperature and the combination of nitrate and temperature, but not by the nitrate concentration alone. However, a small sediment retention is also of importance for the lake P concentration. The model suggests that the following variables are not important for the P retention: a constant sedimentation factor, a factor for the dependency of the sedimentation on the OWA runoff and the pipe through flow, a constant release factor, and a factor for the dependency of the release on the nitrate concentration and the stability of lake stratification.

Model D: P Processes in the Sediment

Because the internal P load is of great importance for the P budget of Lake Tegel, the P transport and reaction processes in the sediment, which are the diagenetic processes, have been implementeted in this model. Therefore the PIEL model (Schauser et al., 2004) has been adapted (Fig. 12). It distinguishes between different P species: dissolved and particulate P in the water body, and in the sediment, between particulate organic P, particulate inorganic P which is either exchangeable or stably bound, and dissolved inorganic P. In the sediment the reactions mineralization (F_{mi}), sorption and desorption (F_{sorb}) as well as precipitation (F_{prec}) are included. Because many process parameters have still to be estimated, the preliminary result of r^2=0.34 (Fig. 8) can be improved.

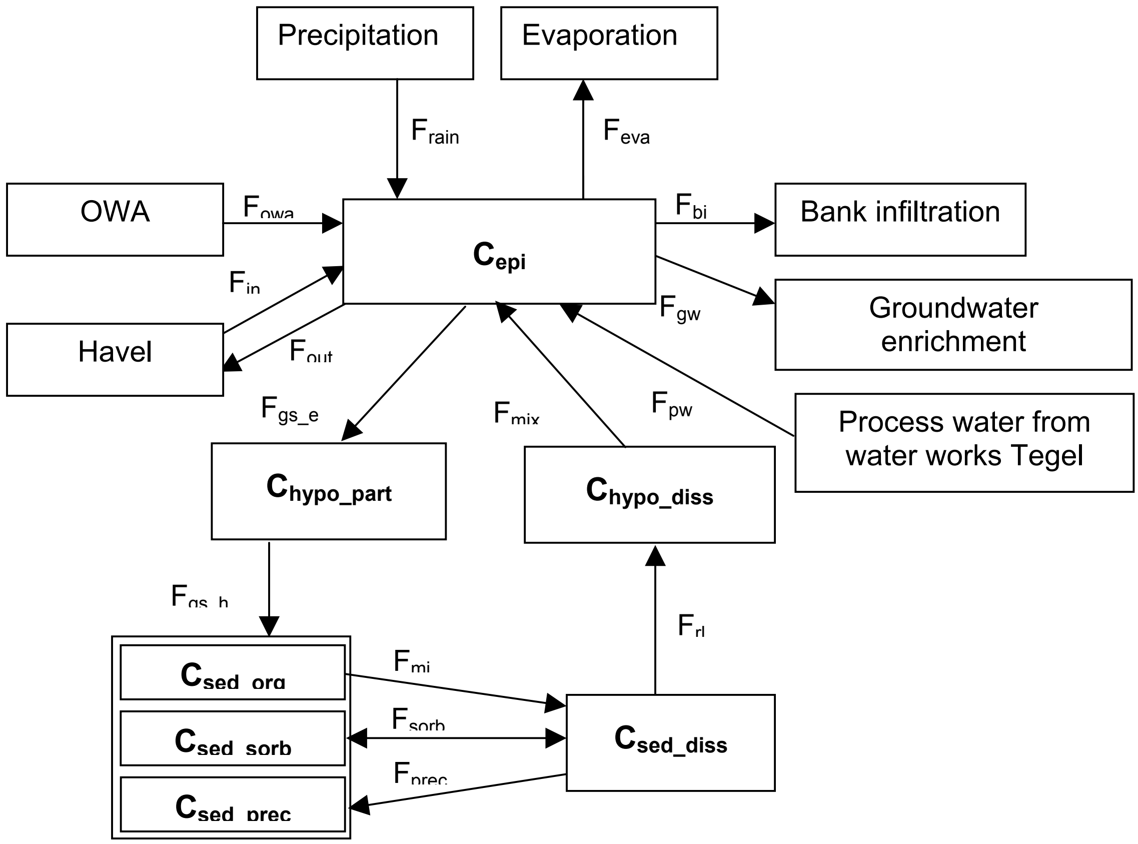

Fig. 12. Flow chart of Lake Tegel including P processes in the sediment

Summarizing the results of the P balance models, they indicate that the P sedimentation is determined by the hydrological inflows, mainly by the Havel inflow and less the OWA runoff. Both inflows seem to increase the sedimentation. The effect of the water works has be investigated closer in future. The P release is controlled mainly by the temperature and less by the nitrate concentration at the sediment surface. The stratification stability is rather small.

Sediment Investigations

P release and Fe/P cycle

P release is mainly due to two processes: mineralization of organic material and desorption of P, followed by a diffusive or advective transport out of the sediment. P is sorbed mainly to oxidised iron. The theoretical molar ratio of Fe~P is close to 1. Mineralization is temperature dependent and is accompanied – following the redox chain - by a reduction of oxygen, nitrate, manganese oxide, iron, sulphate, and in the last stage a production of methane. When iron is reduced, it dissolves, therefore P desorbs, and both species diffuse – following their concentration gradients – towards the lake water. As soon as oxygen or nitrate is available, iron is oxidised again, precipitates, and the dissolved P sorbs onto the iron. This Fe/P cycle happens normally around the sediment-water interface, therefore iron can accumulate at an aerobic sediment surface. When the mineralization in the sediment is more intensive and no oxygen, nitrate, oxidised manganese or iron are available, sulphate is reduced to hydrogen sulphide which precipitates together with iron as iron sulphide (FeS). Then, the Fe/P cycle is interrupted, and the P release is increased.

P release

The P release of the sediment can be estimated from the P accumulation in the hypolimnion during the stratification or from the P concentration gradient in the porewater at the sediment water interface. The P accumulation in the volume below 9.5 m lake depth indicates a high annual variance of the P release (Fig. 13). Assuming that all of this accumulated P results from release, the mean rate is 6.6 mg m^{-2} d^{-1} (1990-2002) estimated for the hypolimnion area below 9.5 m. This is comparable to the P release rate measured from the porewater profile of about 4 mg m^{-2} d^{-1}.

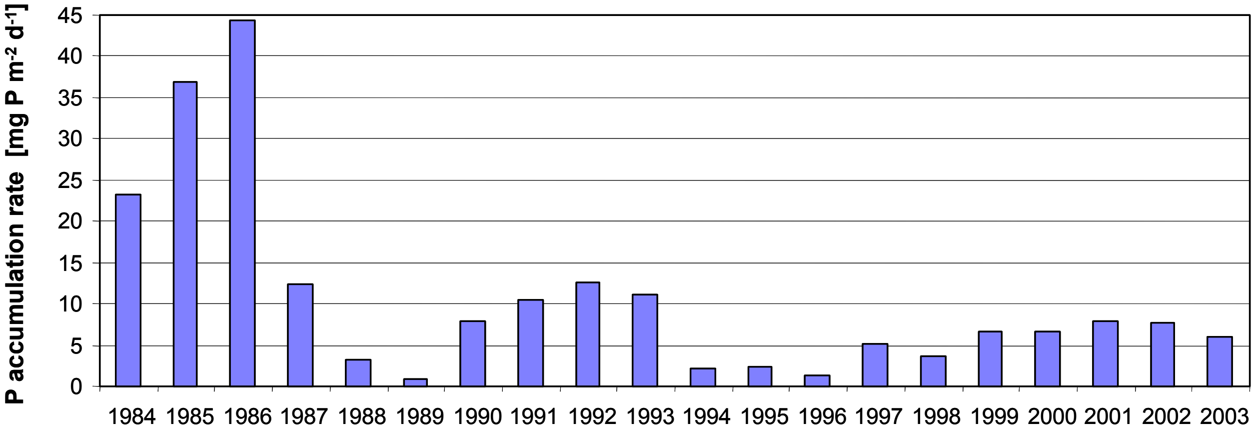

Fig. 13. P accumulation rate in the hypolimnion of Lake Tegel during stratification periods

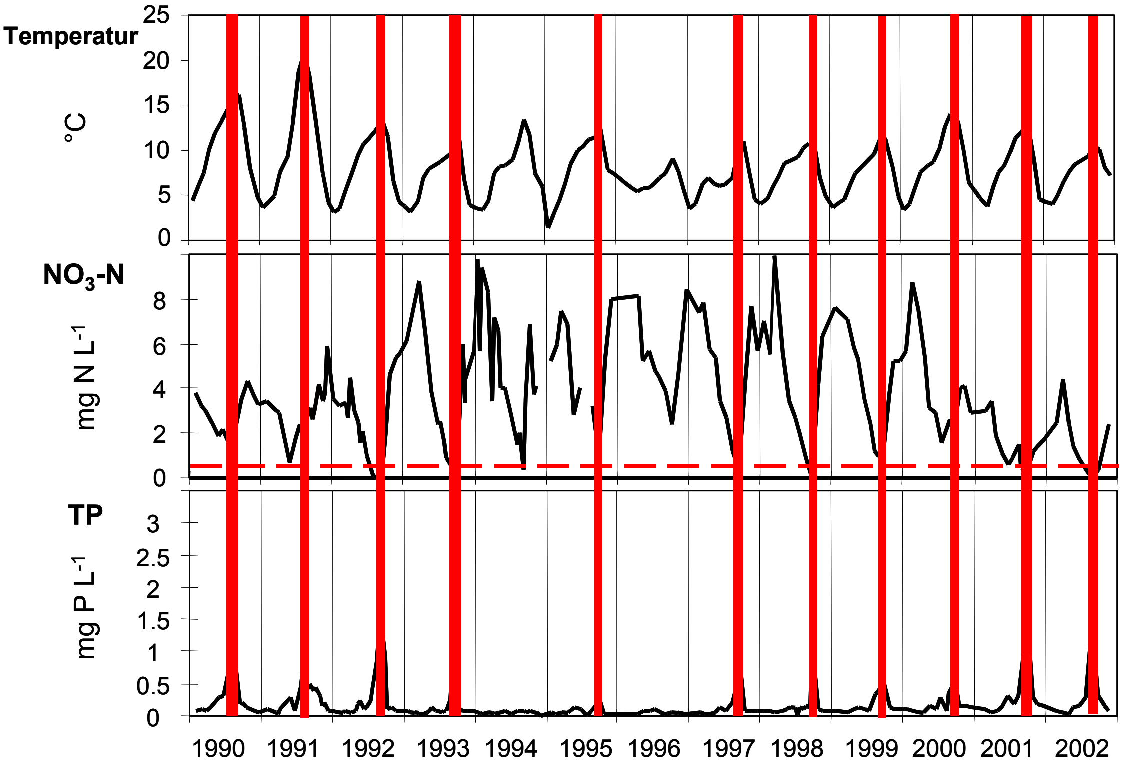

Fig. 14. Temperature, nitrate and phosphorus in 15 m depth in Lake Tegel

The intensity of the P release can be estimated from the rise of the P concentration above the sediment as long there is no current in the water above the lake bottom. This is the case as long the lake is stratified and the hypolimnion is not artificially mixed by aerators. Comparing the P concentration measured in 15 m depth in Lake Tegel with the nitrate and temperature in 15 m depth from 1990 to 2002 (Fig. 14), the P concentration is highest when the temperature is highest and the nitrate concentration is low. The connection between temperature and P is stronger, than between P and nitrate. P release occurred even when the nitrate concentration was above a value of 0.2 mg N L^{-1} (1990, 1991, 1999, 2000), and sometimes it did not happen, when nitrate concentrations were below this threshold value (1994).

P content in the sediments

Total P in the sediments goes up to 7.5 (1996) and 6.2 mg P g^{-1} DM (2003). Most of the P is redox-sensitively bound (BD-P) and only a small fraction organically bound (NaOH-NRP) (Fig. 15). In 1996, the BD-P concentration below 3 cm is nearly constant at 2 mg P g^{-1} DM. Therefore, the 2 mg P g^{-1} DM indicates the anaerobic P sorption capacity of the sediment under the conditions of 1996. To estimate the release potential of 1996, only the BD-P in the top 3 cm above 2 mg P g^{-1} DM is taken into account. This corresponds to 1.6 mg P g^{-1} DM, which is equal to a release potential of 2.2 g m^{-2}. Calculated accordingly in 2003, the release potential increased to 3.6 g m^{-2}. Compared with the mean P release rate of 6.6 mg m^{-2} d^{-1} during summer (approximately 185 days) the potentially mobilizable P could be released in about 2 (1996) or 3 years (2003), if no new P is added to the sediment, i.e. the external laod is reduced to zero and the internal P cycle is cut off. Since the release potential of Lake Tegel in absolute terms is quite high, the effect of the internal load on the lake P cycle is significant. However, because of the low total P release potential from the sediment and the short water retention time of the lake, the internal P cycle will not delay the effects of a sufficient external load reduction for a prolonged period of time (< 5 yrs.). Note this underlines the important impact of the external loads, mainly by the Havel, which have the effect of recharging the sediment P intermittently.

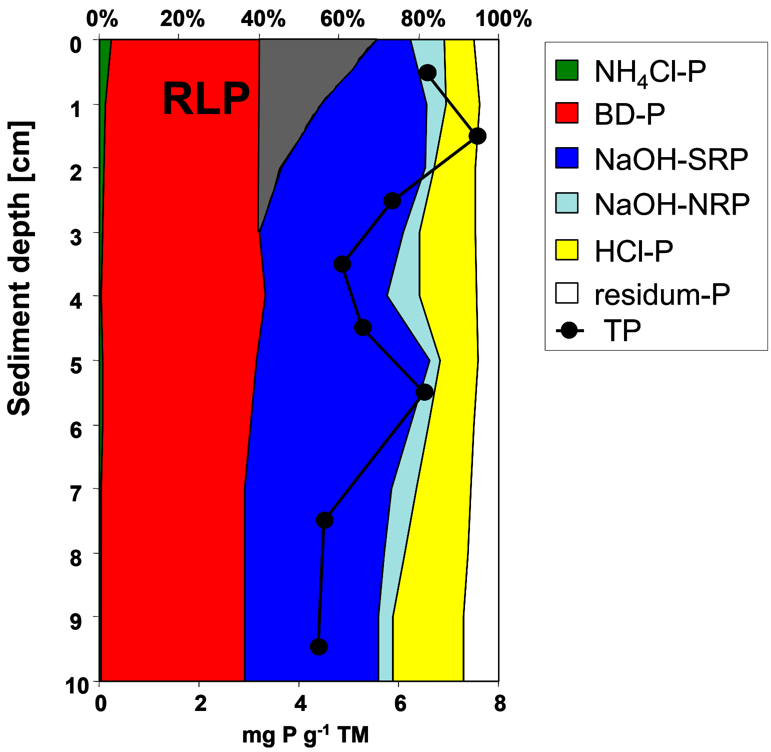

Fig. 15. Phosphorus fractions and P release potential (RLP) in the sediment of Lake Tegel

Iron dynamics in the sediment

In Lake Tegel most of the iron is stably bound in the HCl-Fraction. However, there is iron accumulation in the top layer in the BD-Fraction. Dissolved iron was measured in the porewater, but there is no evidence of hydrogen sulphide in the hypolimnetic water. All of this indicates that there is enough iron to precipitate the hydrogen sulphide, and that the Fe/P cycle is intact. However, the Fe/P ratio in the BD-fraction is close to 1. Therefore, the P sorption capacity of the iron is exhausted, i.e. there is little capacity to adsorb more P.

Phosphorus Threshold Values for Chlorophyll-a

As described above, all chlorophyll values were recalculated without correction for phaeophytin (i.e. using only extinctions prior to acidification). Furthermore, annual means were calculated from January to December, rather than using the hydrological year. Trophic recovery can now be analysed using different lake volumes (i.e. 1 m values versus depth-weighed epilimnion means) and time ranges (i.e. annual or summer means; annual maxima). As this work was just completed recently (end of October), only a very preliminary analysis of the results is presented here.

The results indicate a threshold around 100 mg/m³, which is higher than proposed earlier by UBA, and reasons for this still need to be explored further. A clear result is that the chlorophyll-a concentration was usually above 50 mg m^{-3} at TP concentrations higher than 100 mg m^{-3}, and below 30 mg Chl-a m^{-3} at TP below 100 mg m^{-3}.

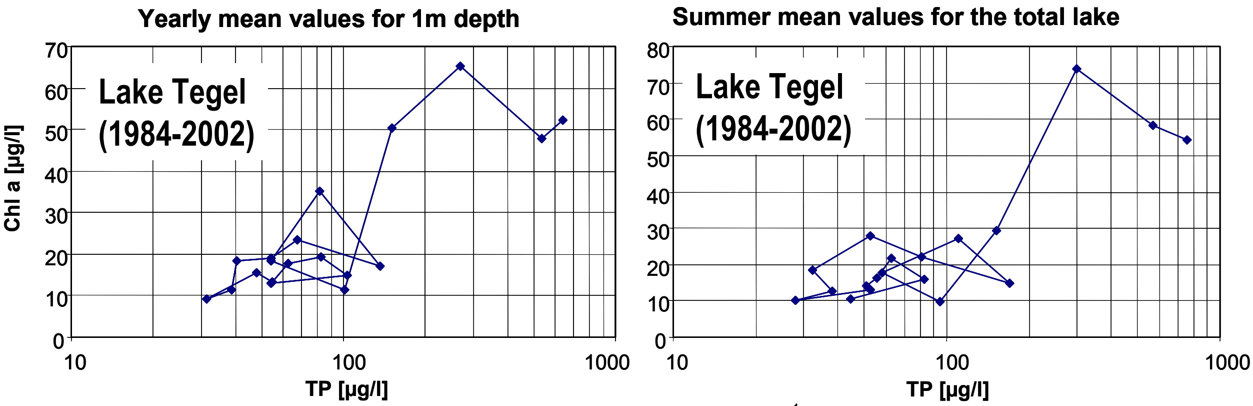

Fig. 16. Phosphorus and Chlorophyll-a in Lake Tegel in µg L^{-1} (1984-2002)

Schlachtensee

Chloride and Water Mass Balance

For Schlachtensee, chloride was measured only in 0.5 m depth. Therefore, it is only possible to use a one box model for the chloride and water balance. Because no chloride data are available for the outflow of the OWA Beeltizhof before 1987, the chloride balance was calculated for the years 1987 to 2002 only (Eq. 27). The chloride concentration in Schlachtensee is dominated by the OWA inflow (r^2 = 0.42). However, by considering all in- and outflows in a numerical model, including the bank infiltration (F_{bi}) and a groundwater inflow (F_{gw}), the correlation could be improved considerably. The best numerical model had a Pearson correlation coefficient of 0.94 (r^2 = 0.89, Fig. 18). From the water balance, the water retention time of Schlachtensee was estimated to be 220 days.

$$dC_{ss}/dt = (F_{owa} + F_{rain} + F_{drain} + F_{gw} - F_{hwd} - F_{bi} - F_{ws} - F_{eva} - F_{kl}) / (V + A*d_{Pegel}) \quad (27)$$

A flow diagram of the chloride mass balance is shown in Figure 17. Optimised parameter values are shown in Table 8. The chloride concentration in Schlachtensee was only sensitive to factors directly affecting inflows. Factors affecting outflows have no influence on the lake chloride concentration. For the lake concentration it is of no importance whether the water is flowing out of the lake into Lake Krumme Lanke or as bank infiltration into the groundwater.

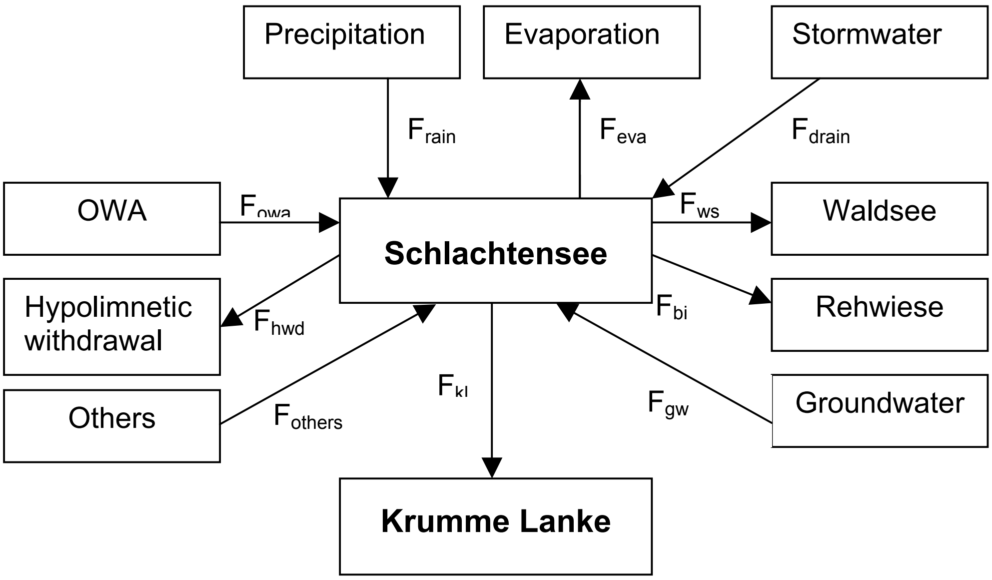

Fig. 17. Flow chart for the chloride mass balance of Schlachtensee.

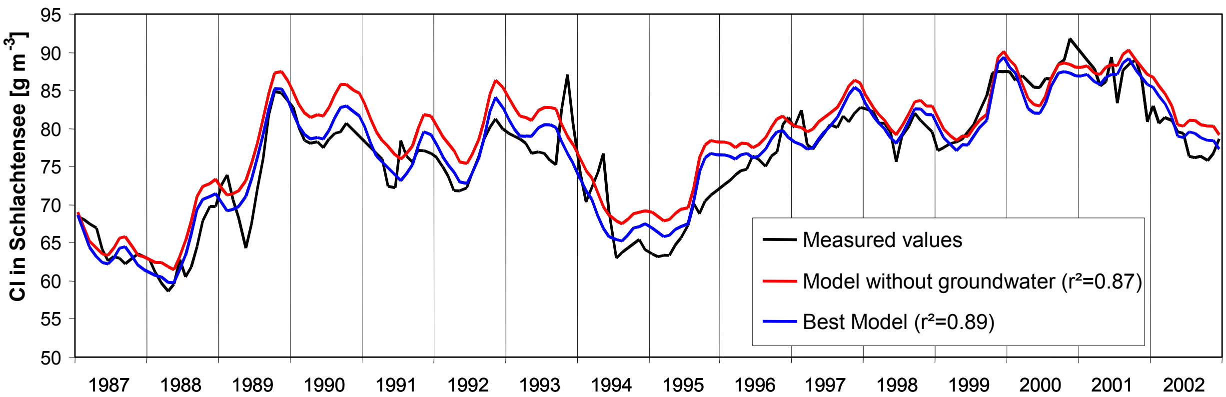

Fig 18. Chloride mass balance for Schlachtensee: measured and calculated data.

Table 8. Optimised parameters of the chloride mass balance model of Schlachtensee

Parameters	Abbreviation	Value	Unit	Sensitivity for C_{ss}
Factor for stormwater inflow into Schlachtensee before 1995	$q_{drain95}$	0.0295	-	0.002
Factor for stormwater inflow into Schachtensee after 1995	$q_{drain96}$	0.0015	-	0.000
Factor for bank infiltration dependent on withdrawal at Rehwiese	q_{rw}	0.0154	-	0.000
Constant bank infiltration	Q_{bi}	31749	m³/mon	0.000
Factor for constant groundwater inflow	q_{gwc}	4557.50	-	-0.013
Factor for groundwater inflow dependent on withdrawal at Rehwiese	q_{rehw}	0.0195	-	-0.005

Factor for groundwater inflow dependent on temperature[1]	q_{temp}	-96.72	-	0.004
Factor for groundwater inflow dependent on lake level at Schlachtensee	q_{pegel}	-95.90	-	0.009
Factor for groundwater inflow dependent on precipitation	q_{rain}	0.253	-	-0.018

Studying the chloride cycle started by setting up the water mass balance of Schlachtensee including all possible in- and outflows. In contrast to Lake Tegel, there is not one unknown major inflow, but many small ones.

The chloride inputs into Schlachtensee:

A. known:
- Inflow from OWA ($F_{owa} = Q_{owa}*C_{owa}$)
- Precipitation ($F_{rain}= Q_{rain}*C_{rain}$)

B. unkown:
- Stormwater inflow via drainage pipelines ($F_{drain} = Q_{drain}*C_{drain}$)
- Groundwater inflow ($F_{gw} = Q_{gw}* C_{gw}$)
- Other possible inflows and affecting factors (F_{others})

The chloride outputs of Schlachtensee:

A. known:
- Flow to Waldsee ($F_{ws} = Q_{ws}* C_{ss}$)
- Evaporation ($F_{eva} = Q_{eva}*0$)
- Hypolimnic water withdrawal ($F_{hwd} = Q_{hwd} * C_{ss}$)

B. unkown:
- Flow from Schlachtensee to Krumme Lanke ($F_{kl} = Q_{kl} * C_{ss}$)
- Bank infiltration including an influence by the withdrawal at well Rehwiese ($F_{bi} = (q_{rehw}*Q_{rehw} + Q_{bi})*C_{ss}$)

There are three main rainwater pipes draining the paved areas and roofs of the settlements in the catchment and ending at Schlachtensee. They drain an area of 1.5 ha, 5.6 ha, and 38.5 ha, respectively. The biggest one was moved 1995 to flow into Wannsee, with the exception of overflow during very heavy precipitation events. By comparing the water level changes of Lake Schlachtensee and the precipitation intensities from 1990 to 2002, no relationship between these time series indicating an impact of precipitation on chloride concentrations in the lake could be established. However, a sensitivity analysis indicated a weak relationship between the chloride concentration in Schlachtensee and the precipitation pattern before 1995, but no influence of the stormwater inflow via pipelines after 1995. Therefore, the water inflow through pipelines is described in the model with two different factors: one for the time before 1995 and one for the time after 1995 (Eq. 28 and 29). Both factors were optimised. The chloride concentration of 110 g m^{-3} for the stormwater was taken from literature (Heinzmann 1993).

$$Q_{drain} = q_{drain95}*Q_{rain} \quad (1987\text{-}1995) \tag{28}$$
$$Q_{drain} = q_{drain96}*Q_{rain} \quad (1996\text{-}2002) \tag{29}$$

[1] As surrogate of seasonal patterns of the groundwater level, influenced by trees, precipitation, etc.

There was no information available about a groundwater inflow. However, the model result could be improved by introducing a groundwater inflow. The coefficient of determination (r^2) could be improved from 0.87 to 0.89. The groundwater flow was calculated dependent on other hydrological influences (Eq. 30). The values for the parameters, determining the groundwater inflow were calculated by optimisation routine in ModelMaker. A sensitivity analysis was used afterwards to exclude the parameters with no influence on the chloride concentration of Schlachtensee. These were the OWA runoff, the inflow via drainage pipes, the flow to Waldsee, and the hypolimnion withdrawal. The value for the chloride concentration in the groundwater was measured at well Rehwiese (BWB 1992, Herr Deffke, pers. communication).

$$Q_{gw} = (q_{gwc} + q_{pegel}*Pegel + q_{rain}*Q_{rain} + q_{rehw}*Q_{rehw} + q_{temp}*Temp) \quad (30)$$

It was not necessary to include other factors into the model describing the chloride balance of Schlachtensee.

The flow into Lake Krumme Lanke was used to balance the water mass balance of Schlachtensee. It was not possible to calculate this flow by the water balance of Lake Krumme Lanke because the bank infiltration of Lake Krumme Lanke, which is influenced by the withdrawal at well Riemeisterfenn, is unknown.

The bank infiltration of Schlachtensee was modeled by using two terms. First, a term including a factor (q_{rw}) describing the bank infiltration dependent on the water withdrawal at the well Rehwiese and the second, a constant bank infiltration factor (Q_{bi}). Both factors were calculated by calibrating the model using the optimization routine of ModelMaker.

Phosphorus Mass Balance

In the first years after starting the inflow treatment at the OWA Beelitzhof autumn 1981, the reduction of the phosphorus concentration dominated all other processes in the lake. Therefore, the modeling procedure was done for the years 1985 to 2002. Such as for Lake Tegel, a sediment layer was included into the model (Fig. 19)

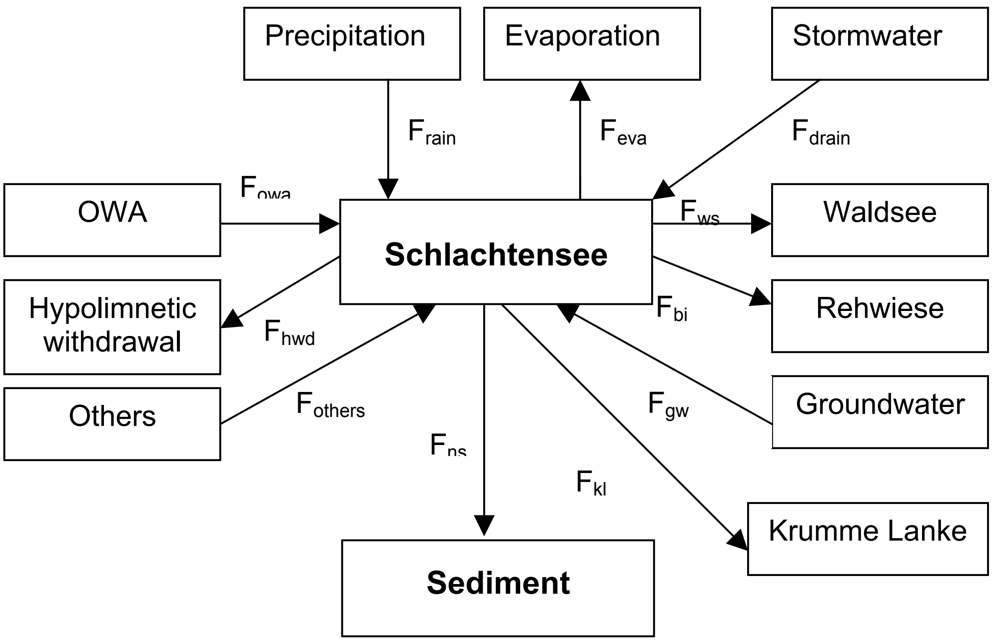

Fig. 19. Flow chart of the P mass balance of Schlachtensee with sediment compartment

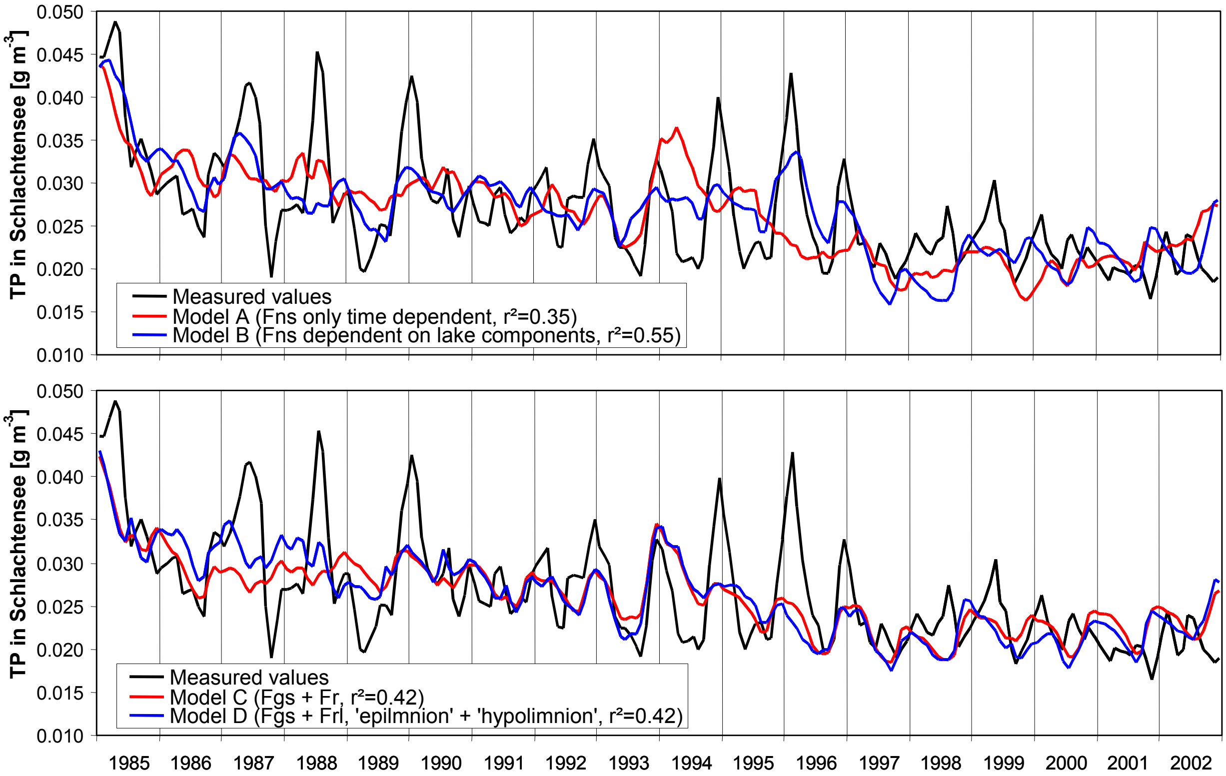

Fig. 20. P mass balance for Schlachtensee: measured and calculated values for Model A to D [g P m^{-3}, monthly mean values].

Model A: Time Dependency

The P concentration in Schlachtensee was modeled as depending on the hydrological fluxes quantified in the chloride mass balance and dependent on the interactions with the sediment (Eq. 31). The P flux of net sedimentation was described with only one parameter (a, Eq. 32). This very simple model actually gave a result of r^2 = 0.35 (Fig. 20). The mean P concentration in the years 1995 – 2002 was 0.02 g P m^{-3}. This is equal to the steady state P concentration estimated by a simple one-box model assuming a mean P concentration of the lake inflows of 0.031 g m^{-3} and a net sedimentation rate of 0.62 a^{-1}, both values derived from the P balance of the last years.

$$dC_{ss}/dt = (F_{owa} + F_{rain} + F_{drain} + F_{gw} - F_{hwd} - F_{bi} - F_{ws} - F_{eva} - F_{kl}) /(V + A*d_{Pegel}) - Fns \quad (31)$$

$$F_{ns} = a*t * C_{ss} \quad (32)$$

The parameter (a) was estimated by optimisation routine (Table 9). The time dependency of parameter a indicates that the P concentration in the lake is steadily decreasing over time, probably started by the external load reduction through the OWA Beelitzhof. The inclusion of a constant parameter did not improve the model.

Table 9. Parameter value for model A

Parameter	Abbreviation	Value	Unit	Sensitivity of C_{ss}
Time dependency	a	0.00017	-	-0.24

Model B: P Net Sedimentation

As for Lake Tegel in Model A, the net sedimentation was modelled as function of lake components (Eq. 33).

$$F_{ns} = (ns+ns_{owa}*Fowa+ns_{rehw}*Q_{rehw}+ns_{rain}*Q_{rain}+ns_o*C_{O2}+ns_t*Temp)* C_{ss} \quad (33)$$

The model result was good (r^2 = 0.50, Fig. 20). However, the winter peaks of the P concentration could not be modelled satisfactorily. Since Schlachtensee is rather small with a long and rather steep shoreline surrounded by trees, the seasonality of vegetation cover and thus of factors such as erosion and effect of leaves falling into the lake may be relevant. No seasonal values could be found in the literature up to now for P-content of leaves in autumn. To encompass these factors, a simple time series (Q_{others}) with an autumn peak (September = 0.2, October = 0.5, November = 0.3, rest of the year = 0) was established. The integrated value of the P load was estimated by optimisation routine to be about 18000 g P mon^{-1}. The integrated value of the P load was estimated by optimisation routine to be about 18000 g P mon^{-1} (Table 10). This flux (Fothers, Eq. 34) improved the model (r^2 = 0.55). Therefore, it was also used in the further models.

$$dC_{ss}/dt = (F_{owa}+F_{rain}+F_{drain}+F_{gw}+F_{others}-F_{hwd}-F_{bi}-F_{ws}-F_{eva}-F_{kl}) / (V+A *d_{Pegel}) - F_{ns} \quad (34)$$

The net sedimentation was determined in the model from the temperature and the O_2 concentration at 7 m depth, as well as the OWA P load, the precipitation and the withdrawal at the well Rehwiese. The main factors were the ones for constant net sedimentation and for precipitation influence. Other factors describing the influence on the net sedimentation flux, such as the factors for the hypolimnion withdrawal, the flow to Waldsee and the stormwater inflow as well as the nitrate concentration above the sediment, had no effect on the lake P concentration. The negative value of the factor for constant net sedimentation indicates a constant release. Surprisingly, the higher the temperature is the higher the net sedimentation. This can not be explained by known biogeochemical processes.

Table 10. Parameter values for Model B

Parameter	Abbreviation	Value	Unit	Sensitivity of C_{ss}
P load from other inputs from the shoreline (erosion; leaves)	C_{others}	18000	g mon^{-1}	0.27
Factor for constant net sedimentation	ns	-0.198	-	1.19
Factor for net sedimentation affected by the OWA runoff	ns_{owa}	2.241E-05	-	-0.18
Factor for net sedimentation affected by withdrawal at Well Rehwiese	ns_{rehw}	-2.401E-08	-	0.01
Factor for net sedimentation affected by precipitation	ns_{rain}	4.765E-06	-	-0.58
Factor for net sedimentation affected by oxygen	ns_o	0.0118	-	-0.36
Factor for net sedimentation affected by temperature	ns_t	0.0054	-	-0.23

Model C: P Sedimentation and P Release

To come a step closer to a mechanistic model of factors determining P concentrations in Schlachtensee, in Model C (Eq. 35) the net sedimentation was split into sedimentation (F_{gs}, Eq. 37) and release (F_{rl}, Eq. 38). To estimate the release, the P concentration of the sediment had to be calculated by an ordinary differential equation (Eq. 35), including a constant retention coefficient sig. The depth of the active sediment layer (0.06 m) was estimated by model calibration. However, the correlation analysis gave the result of r^2 = 0.42 (Fig. 20).

$$dC_{ss}/dt = [(F_{owa}+F_{rain}+F_{drain}+F_{gw}+F_{others}-F_{hwd}-F_{bi}-F_{ws}-F_{eva}-F_{kl})+(Frl–F_{gs})] / (V+A*d_{Pegel}) \quad (35)$$

$$dC_{sed}/dt = (F_{gs}-F_{rl})/(0.06*A) - sig*C_{sed} \quad (36)$$

$$F_{gs} = (gs_{owa}*F_{owa}+ gs_{rain}*Q_{rain}+ gs_{rehw}*Q_{rehw}+ gs_{temp}*Temp)*C_{ss}*V \quad (37)$$

$$F_{rl} = (rl_{owa}*Q_{owa}+rl_{rain}*Q_{rain}+rl_{rehw}/(Q_{rehw}+1000)+rl_{n}/(C_{NO3}+0.001)+rl_{t}*Temp)*C_{sed}*(0.06*A) \quad (38)$$

In this model the sedimentation was mainly affected by the precipitation rate. We found that the higher the precipitation rate, the lower the expected sedimentation (Table 11). Of less importance was the influx of P via the OWA, the withdrawal at Rehwiese and the temperature above the lake bottom. The release of P from the sediment depends on temperature also. Thus, the model suggested that higher temperatures led to both higher sedimentation and more release. Nitrate showed little effect on the release, and the concentration of oxygen was of no importance for the P release. The hydrological flows in and out of Schlachtensee also showed little influence on the P release from the sediments. The factor for sediment retention determines the amount of P which is not available for P release at all.

Table 11. Parameter values for Model C

Parameter	Abbreviation	Value	Unit	Sensitivity for C_{ss}
P load from other inputs from the shoreline (erosion; leaves)	C_{others}	13751	g mon^{-1}	
Factor for sedimentation affected by the OWA runoff	gs_{owa}	2.82E-06	-	-0.02
Factor for sedimentation affected by precipitation	gs_{rain}	3.79E-06	-	-0.43
Factor for sedimentation affected by extraction at Well Rehwiese	gs_{rehw}	2.15E-08	-	-0.01
Factor for sedimentation affected by temperature in 7 m	gs_{temp}	0.0014	-	-0.06
Factor for release affected by the OWA runoff	rl_{owa}	1.74E-09	-	0.02
Factor for release affected by precipitation	rl_{rain}	-7.13E-09	-	-0.01
Factor for release affected by withdrawal at Well Rehwiese	rl_{rehw}	0.516	-	0.01
Factor for release affected by nitrate	rl_{n}	2.27E-05	-	0.01
Factor for release affected by temperature	rl_{t}	6.06E-05	-	0.04
Factor for sediment retention	sig	0.0084	mon^{-1}	-0.10

Model D: Epilimnion and Hypolimnion

This model (Eq. 39-46, Fig. 21) is analogous to Model C for Lake Tegel. Here the water volume was divided into an upper water column ("epilimnion", <6 m, Eq. 39) and a lower water column ("hypolimnion", >6 m, Eq. 40). To model the mixing between both layers, a time series (stability, Eq. 46) was calculated, depending on the temperature difference between 4 and 6 m lake depth. The value of the mixing coefficient (k_{mix}) was optimised in the model (Table 12). The model result (Fig. 20) yielded an overall result of r^2= 0.42 (epilimnion: r^2=0.46, hypolimnion r^2=0.49, Fig. 22). This is no better than the simpler Models B and C.

While the model results for the hypolimnion could have been improved, this would have led to a deterioration in the model results for the whole lake.

$$dC_{epi}/dt = [(F_{owa}+F_{rain}+F_{drain}+F_{gw}+F_{others}-F_{hwd}-F_{bi}-F_{ws}-F_{eva}-F_{kl})+(F_{mix}-F_{gs\_e})]/(V-V_{hypo}+A*d_{Pegel}) \tag{39}$$

$$dC_{hypo}/dt = (F_{gs\_e} + F_{rl} - F_{mix} - F_{gs\_h}) / V_{hypo} \tag{40}$$

$$dC_{sed}/dt = (F_{gs\_h} - F_{rl})/(0.06*A_{hypo}) - sig*C_{sed} \tag{41}$$

$$F_{gs\_e} = (gs_{others}*Q_{others}+gs_{rain}*Q_{rain} +gs_{temp}*Temp) * C_{epi} * (V-V_{hypo}) \tag{42}$$

$$F_{mix} = k_{mix}* (C_{hypo}-C_{epi})/z_m * stability * A_{hypo} \tag{43}$$

$$F_{gs\_h} = g_{s\_h}* C_{hypo}*V_{hypo} \tag{44}$$

$$F_{rl} = (rl + rl_t*Temp\_7+rl_{nt}*Temp\_7/(C_{NO3}+0.001)) *C_{sed}*(0.06*A) \tag{45}$$

$$stability = Max (20; 1/abs(Temp\_6 – Temp\_4)) \tag{46}$$

The gross sedimentation in this model was mainly dependent on the precipitation, the temperature above the sediment (including the temperature in 1 m depth did not improve the model) and the P load from leaves or other sources in autumn. In contrast to the earlier models, the OWA input did not have any significant influence on the lake P concentration. The release was dominated by a constant release factor and the retention factor, both depending on the sediment P concentration. A further factor influencing release was the temperature at 7 m depth. Surprisingly, the nitrate concentration was only important in conjunction with the temperature.

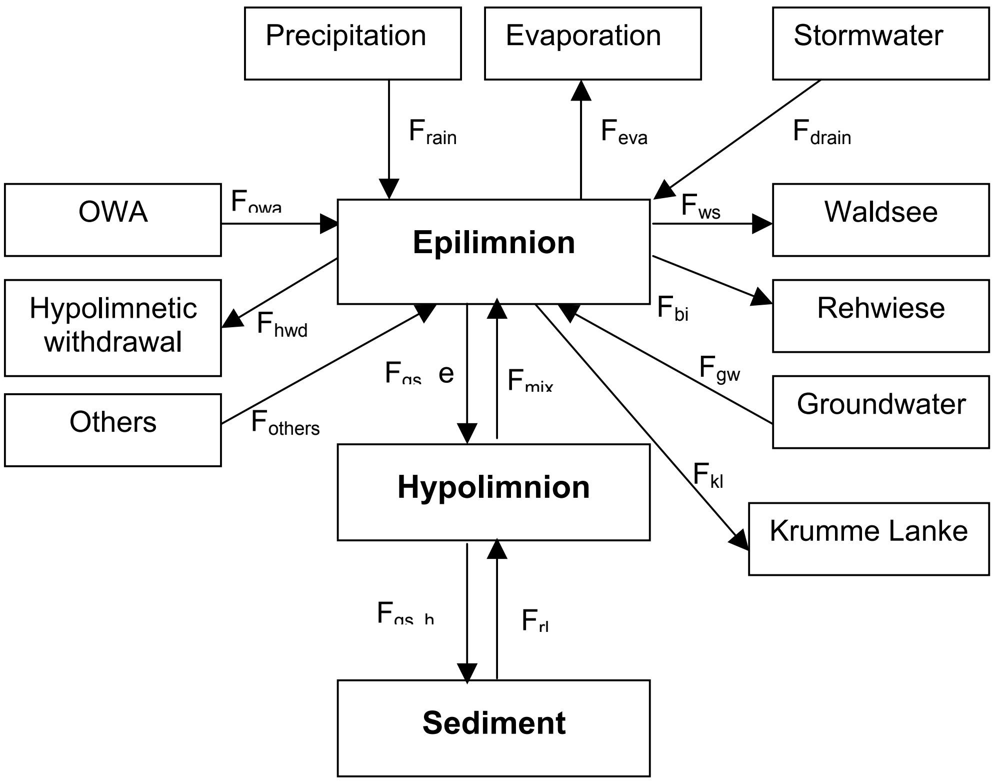

Fig. 21. Flowchart of P balance of Schlachtensee

Table 12. Parameter values for Model D

Parameter	Abbreviation	Value	Unit	Sensitivity for C_{ss}
Factor for sedimentation affected by the input from other sources (leaves)	gs_{others}	0.486	-	-0.02
Factor for sedimentation affected by the precipitation	gs_{rain}	3.33E-06	-	-0.06
Factor for sedimentation affected by temperature	gs_{temp}	0.0019	-	-0.02
Factor for sedimentation out of the hypolimnion	$gs_{\_h}$	1.318	-	-0.36
Factor for constant release	rl	0.0086	-	0.11
Factor for release affected by temperature	rl_t	0.00022	-	0.03
Factor for release affected by nitrate and temperature	rl_{nt}	1.82E-05	-	0.02
Factor for sediment retention	sig	0.010	mon^{-1}	-0.22
Factor for mixing	k_{mix}	6.24	-	0.03

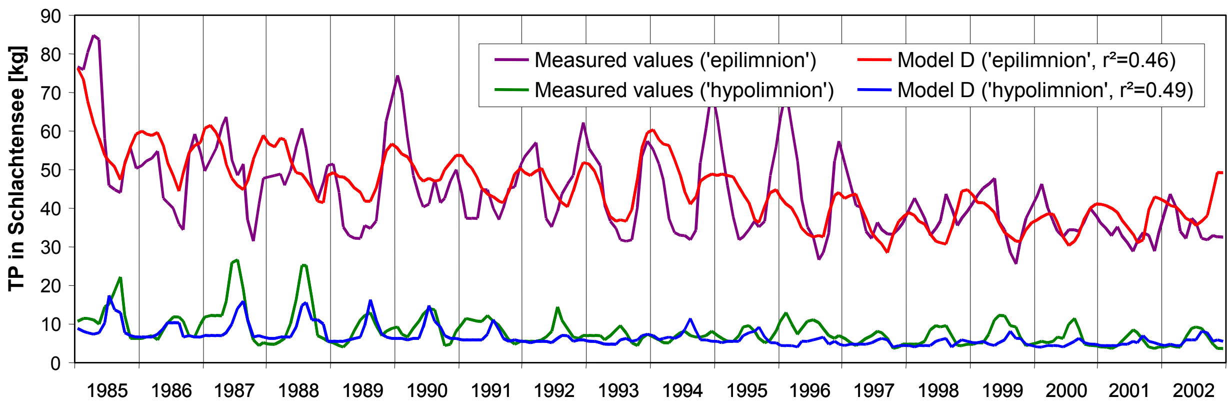

Fig. 22. P mass balance for Schlachtensee: results of Model D for the upper and the lower compartment [g P m^{-3}, monthly mean values]

Together, the models indicate that the P sedimentation as well as the release depends on the hydrological inflows, mainly on precipitation, as well as on the temperature and the redox conditions above the sediment. Because the P accumulation in the hypolimnion has only a small effect on the P concentration of the whole lake, the external load is more important than the internal one. In the present models, the uncertainy in the quantification of the external load is affecting the modelling of the P retention. Thus, to improve the results for the P retention of the sediments, the quanitification of the external loads has to be improved first.

Sediment Investigations

P release

The P release in Schlachtensee, calculated from P accumulation rate in the hypolimnion (below 6 m lake depth), has a mean rate of 0.6 mg m^{-2} d^{-1} (1990-2002) for the hypolimnion area (Fig. 23). The P release rate measured by the peeper was 0.3 mg m^{-2} d^{-1} and thus in the same range.

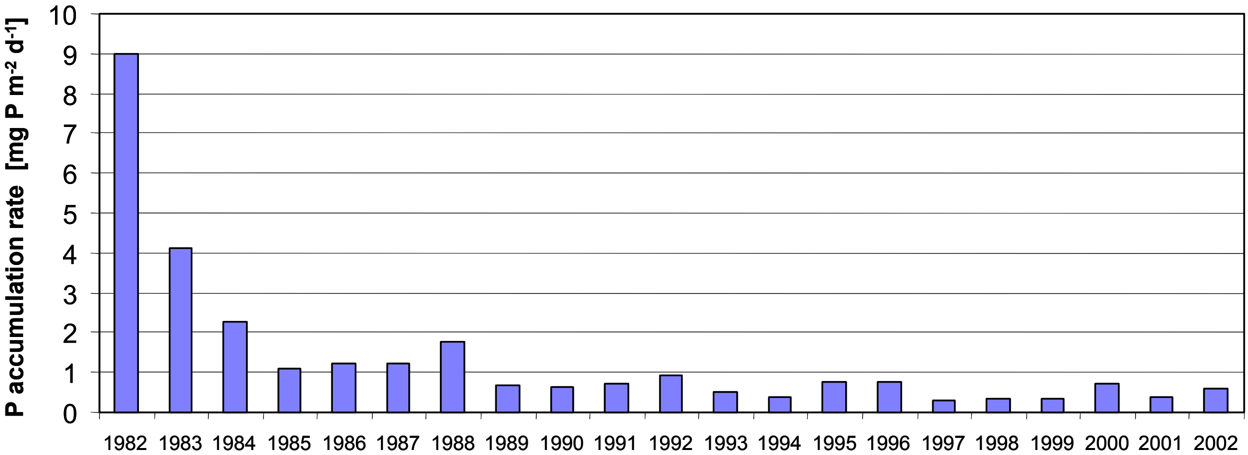

Fig. 23. P accumulation rate in the hypolimnion of Schlachtensee during stratification periods

The P concentration in 7 m depth is regularly highest in the late summer when the nitrate concentration above the sediment is below 0.2 mg N L^{-1}. Then, the temperature is also high in the hypolimnion (Fig. 24).

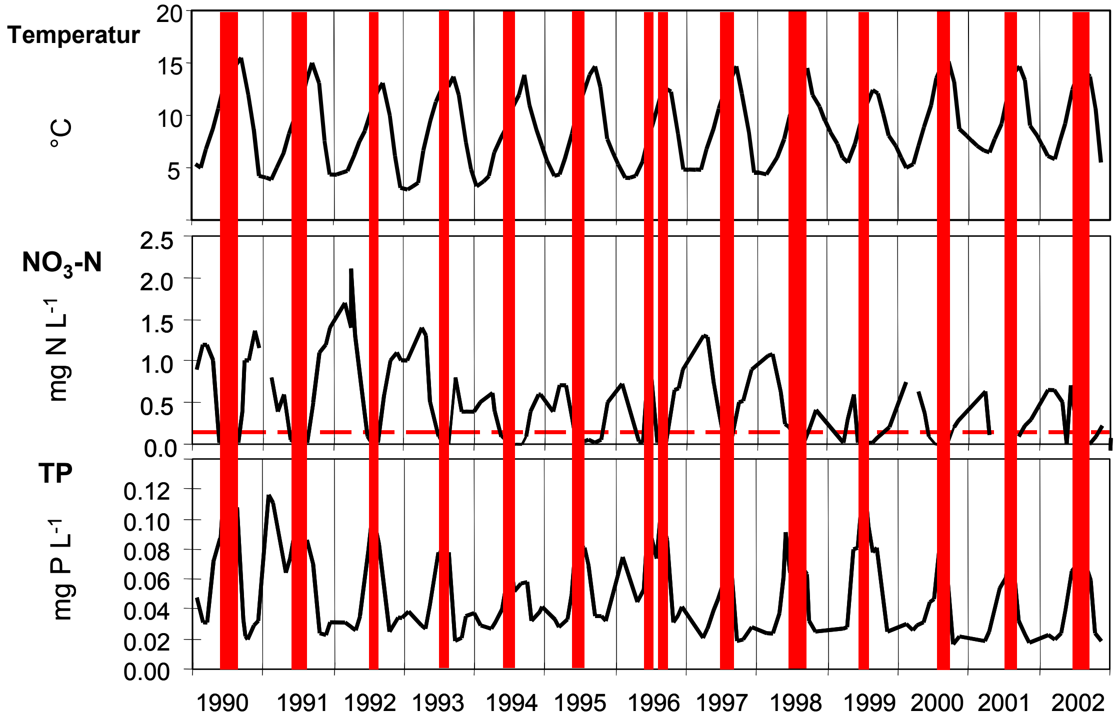

Fig. 24. Temperature, nitrat and phosphorus in 7 m depth in Schlachtensee

P content in the sediments

Total P content in the sediments ranges up to 1.5 mg P g^{-1} DM (1996 and 2002), which is 20-25 % of that found in Lake Tegel sediments, and only around 20 % is redox sensitively bound. However, more P is in the organic P fraction (NaOH-NRP) (Fig. 25), and in absolute terms, there is more organic bound P in Schlachtensee than in Lake Tegel. The release potential 1996 is estimated from the amount of the BD-P and the NaOH-NRP fractions in the top 3 cm of the sediment at concentrations greater than the cut off level of the anaerobic P sorption capacity, i. e. 0.47 mg P g^{-1} DM. The mobilizable P pool in this layer is 0.2 mg P g^{-1} DM which is equal to a release potential of 0.4 g P m^{-2} (1996). In 2003 the release potential was 0.5 g P m^{-2}. Using the mean summer release of 0.6 mg m^{-2} d^{-1}, this mobilizable P in the upper 3 cm could be released completely in about 4-5 years (1996, 2003). Since the release potential of Schlachtensee in absolute terms is quite low, the effect of the P release on the lake P cycle is small. Because of the relatively low release potential of the sediment, and because the water retention time of Schlachtensee is rather short, the internal P cycle will delay the effects of external measures only for a few years.

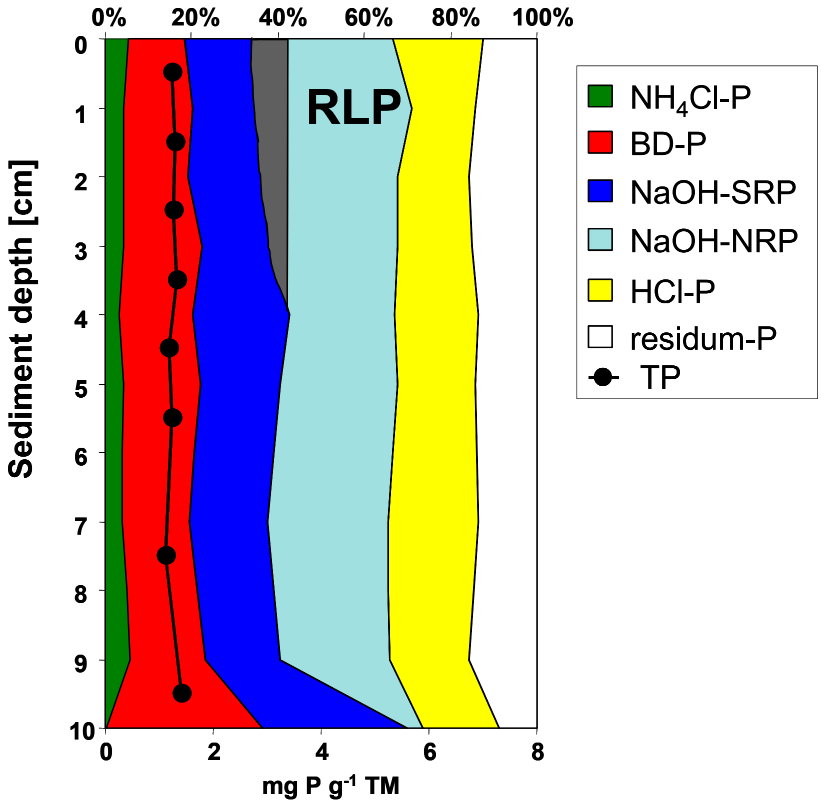

Fig. 25. Phosphorus fractions and P release potential (RLP) in the sediment of Schlachtensee

Iron dynamics in the sediment

In total there is only a very limited amount of reactive iron in Schlachensee. The majority of the iron is very stably bound. No iron was measured in the pore water, but high hydrogen sulphide concentrations are observed in the hypolimnion. Thus there is not enough iron to precipitate all the sulphide. Thus, the short Fe/P cycle, described previously for Lake Tegel, seems to be disrupted under anaerobic conditions in Schlachtensee leading to high P release as soon the sediment surface becomes anaerobic. Under aerobic conditions, however, there is enough iron to keep the P sorbed, since the molar Fe/P ratio in the BD-fraction of the top layers is around 5.

Phosphorus Threshold Values for Chlorophyll-a

In Schlachtensee, the threshold effect of Chlorophyll-a response to TP-reduction was even more pronounced than in Lake Tegel, and the threshold appears to be lower, i.e. at 30 mg P m^{-3}. In this range, the mean annual and summer chlorophyll-a concentration was mostly below a value of 20 mg m^{-3}.

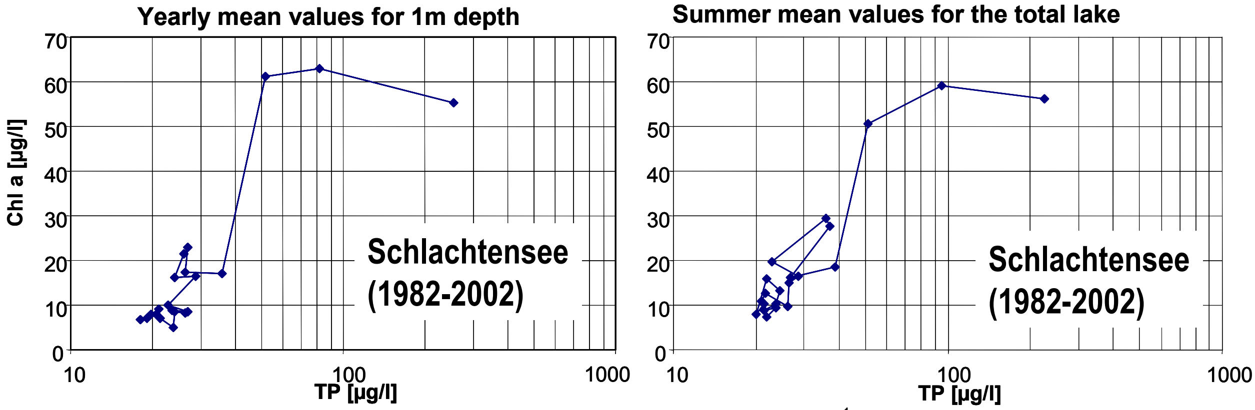

Fig. 26. Phosphorus and Chlorophyll-a in Schlachtensee in µg L^{-1} (1982-2002)

In Lake Tegel, Chlorophyll-a /TP ratios appear to be lower than in Schlachtensee (roughly 1/2 as compared to around 3/2). Two working-hypotheses for this phenomenon are to be explored in years 2 and 3 of the project:

1. Phases of light limitation interchange with phases of phosphorus limitation in determining carrying capacity for phytoplankton biomass. In Lake Tegel light limitation is more pronounced because the mixing of the epilimnion is deeper. Thus, the maximum carrying capacity in terms of TP is not attained as often as in Schlachtensee, because light limitation may set in before P becomes limiting.
2. Bioavailability of TP is lower in Lake Tegel, due to the origin of a larger fraction from the Havel River inflow.

4. Discussion and Conclusion

Lake Tegel

The chloride balance has been used to estimate the Havel inflow into the main basin of Lake Tegel. The results of the mixing calculation for the years 1986 – 2002 indicate considerable variations in the inflows from the River Havel, and the outflows from Lake Tegel, especially in the summers 1986-1989. Inflows were very low in 1992 to 1994. The mean fraction of the Havel inflow of the total inflow was 37 %. This corresponds to the value given by Ripl et al. (1993) with 30 – 40 %. The result of the mixing calculation was used to estimate the water retention time of Lake Tegel. It varies from year to year between 44 and 80 days (mean: 62 days).

The chloride balance result of the numerical model for the years 1986 – 2002 (r^2=0.76) shows a very close fit to the actually measured chloride data. From this the mean fraction of the Havel inflow in relation to the total inflow could be estimated to be 40 %. The result is similar to the value estimated by mixing calculation. The water retention time of Lake Tegel as calculated with the numerical model varies from year to year between 52 and 88 days (mean: 66 days).The differences between the mixing calculation and the numerical model are explained by different time integration methods. The numerical model can be used to forecast the Havel inflow depending on the hydrological situation of Lake Tegel. The Havel inflow depends on the Havel runoff, the OWA runoff and the water extraction by the Water Works Tegel (including bank infiltration and groundwater enrichment).

The P balance of Lake Tegel was modelled with models of increasing complexity. Results showed a good correlation between P concentrations predicted by the models and those measured in the lake (r^2=0.65 – 0.72). The fluxes from the sediment were calculated as functions of the lake components. Because Models A to C are purely empirical models, the model results are not always explicable in terms of biogeochemical relationships. The importance of one lake component (e.g. the water works extraction) for the lake P concentration, and for the single fluxes can change from one model to the other. This limits the use of a single model for predictions of conditions beyond the calibration and validation ranges. In general, the model results were improved by increasing complexity. The best model (Model C Lake Tegel) integrates the upper and lower water volumn as well as a sediment layer. The layers are connected by sedimentation, release, and mixing fluxes. The high value of the mixing coefficient indicates a great exchange between the upper and lower water volumes. The most complex model (Model D) which is able to model the P processes in the sediment has still to be improved by further adaption to the lake conditions. All models fail to calculate the sudden P reduction 1994/1995. However, they capture the P rise after 1996 well. The sensitivity analyses of the different models indicate that the sedimentation is mainly influenced by the Havel inflow, and less from the OWA runoff. The effect of the water works has still to be investigated. Interestingly, in comparing the impact of nitrate concentrations and hypolimnion temperatures, all models indicate temperature to be the stronger driver of P release, though nitrate also has some impact.

This is further substantiated by the results of the sediment investigations: For Lake Tegel they reveal that P release is probably driven by mineralization, except the high release peaks which are due to desorption. Because of the low Fe/P ratio in the BD-fraction, there is not enough sorption capacity to prevent release under aerobic conditions, although iron accumulates at the sediment-water interface. Under anaerobic conditions, iron gets reduced and P desorbs. However, as long as the iron is not precipitated as FeS, the Fe/P cycle at the sediment-water interface prevents a high P release. The highest P release happens when due to high temperature, high sedimentation of organic material and therefore high mineralization rates, sulphate is reduced to sulphide. Then, iron precipitates as FeS, and this leads to sharply increased P release. The role of oxdation of the sediment surface in preventing FeS formation in relation to the role of temperature as driver of mineralisation needs to be further explored by more detailed data evaluation.

Summarising: The lake P budget of Lake Tegel is characterised by high inter annual and seasonal differences (Fig. 27), which indicate that the lake reacts rather quickly to changes in the external and internal load. The variations are mainly due to the external load (inflow of Havel water, the OWA runoff) and the extractions of the Water Works, which also influence the external load (Fig. 28). Also, the internal load of Lake Tegel is of considerable significance for the lake P budget. The internal load itself is influenced by the external P loads (OWA runoff, Havel inflow), the extractions of the water works and the conditions above the lake bottom (mainly temperature, but also nitrate). The P release is mainly caused by mineralization, except the sharp release peaks which are triggered by desorption during times of high mineralization activity and FeS precipitation. Because of the low Fe/P ratio artificial oxidation of the sediment surface will only have an effect on the P release during intensive mineralization periods, when the aeration succeeds in preventing sulfate reduction. However, because of the low release potential of the sediment and the short water retention time of the lake, the internal P load will not have a long-term effect after the external load is sufficiently reduced. This explains why the sediments of Lake Tegel have been a source of P (years 1984-1992, 2000-2002) as well as a sink (years 1993-1999).

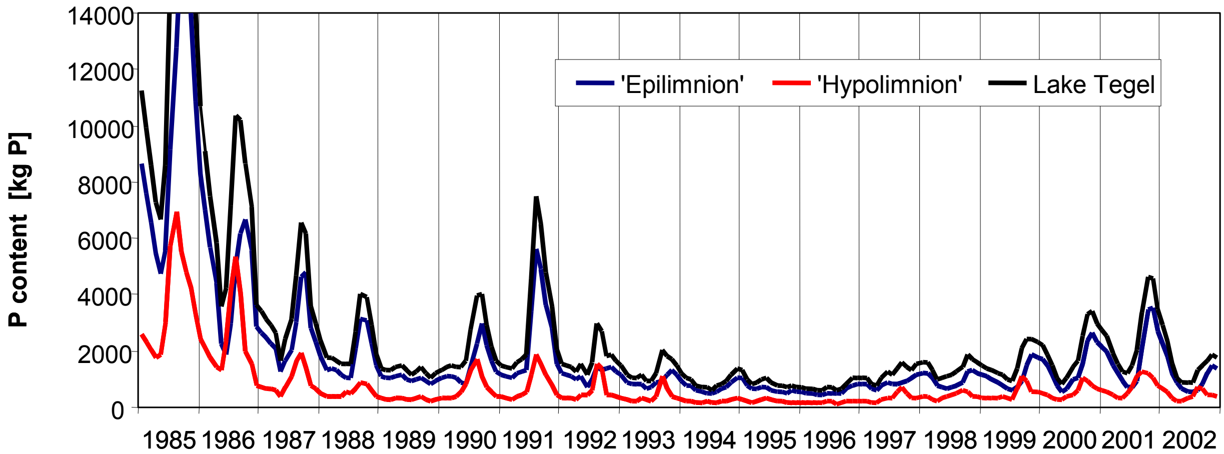

Fig. 27. P content in Lake Tegel, the upper (< 8m) and lower compartment (> 8m) [kg]

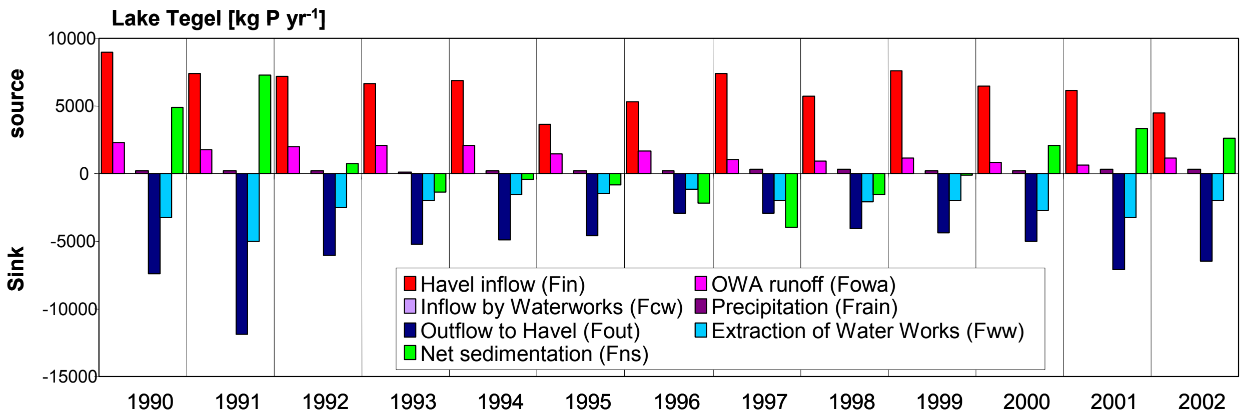

Fig. 28. P sources and sinks of Lake Tegel 1990-2002 [kg yr^{-1}]

Schlachtensee

The chloride mass balance is dominated by the OWA inflow. Therefore, while the mass balance is easy to describe mathematically, the other inflows, albeit small, are the major source of variation. The correlation between modelled and measured data was improved by considering other inflows into Schlachtensee, such as precipitation, the rainwater inflow via pipes, and the groundwater (r^2=0.89). The groundwater inflow could be modelled by including a constant groundwater inflow, and as function of the precipitation, the lake level of Schlachtensee, the extraction at Well Rehwiese and of the temperature.

The long time development of the P concentration is dominated by the external load reduction by the OWA Beelitzhof. The steady state concentration calculated with a simple one box model and Model A is 0.02 g P m^{-3} (annual mean). Next to the effect of the OWA, the P concentration in Schlachtensee shows a seasonal pattern with peak concentrations in winter. These peaks are difficult to explain and to model. Probably, they are due to ecological dynamics and external loads which mainly affect the epilimnion. Both processes are difficult to quantify. The external load could include the seasonal effects of swimmers, water birds, leaves, groundwater, etc.. The model result has been improved in the years 1993 to 1996 by considering an autumn effect, possibly caused by leaves. However, from 1997 onwards, the winter peaks are much lower. The model result and the sensitivity analysis indicate that the P net sedimentation, as well as the sedimentation and the P release, are influenced by the hydrological regime, mainly the precipitation, and the temperature as well as the redox conditions above the lake bottom. By estimating the regular P accumulation in the hypolimnion in comparison to the P content in the epilimnion, it can be concluded that the internal load is of less significance than the external loads (Fig. 29). This is supported by the relative small value for the mixing coefficient (k_{mix}).

The best model for the P mass balance is in good agreement with the measured data (r^2=0.55). Better values can be reached for the lower compartment. However, as the P concentration in the lake is mostly influenced by the processes directly affecting the epilimnion P concentration, and because the model result of the lower compartment is already quite good, it cannot be expected that the model result will be improved when the processes in the sediment are calculated in more detail.

The sediment investigations indicate that in Schlachtensee, the P release is mainly controlled by the redox conditions and by desorption. During aerobic conditions mineralised P gets sorbed onto Fe, because the free P sorption capacity (Fe/P ratio) is high. When mineralization is more intense due to high temperature and high sedimentation of organic material, iron is reduced. However, in Schlachtensee there is not much oxidised iron. Thus, sulfate gets reduced also and FeS precipitates. This leads to a quick P release as soon nitrate is below the threshold value of about 2 mg N L^{-1}. P release is, in absolute terms, much lower than in Lake Tegel because the sediment of Schlachtensee contain both less total P, and less redox sensitive bound P (BD-P).

Summary: While Schlachtensee is affected by many minor in- and outflows (Fig. 30), the long term development of the lake P concentration is dominated by the reduction of the external load by the OWA. The high winter P peaks are surprising, as they do not occur in the chloride concentration. Because of the low P concentration in Schlachtensee, small P loads can lead to high P peaks. In the hypolimnion, a regular accumulation of P occurs. This P accumulation has only a small influence of the overall P budget of the lake, because of the small hypolimnion volume. The P release in the hypolimnion depends mainly on temperature and redox conitions, but it is also influenced by the hydrological regime of Schlachtensee. Since the release potential of Schlachtensee is low, the effect of the P release on the lake P cycle has been small and Schlachtensee has been a sink for P since 1985. However, the sediment will release P a few years longer (> 5 yrs) than in Lake Tegel because the release potential of the sediment, in comparison to the release rate, is higher and the water retention time is longer than in Lake Tegel.

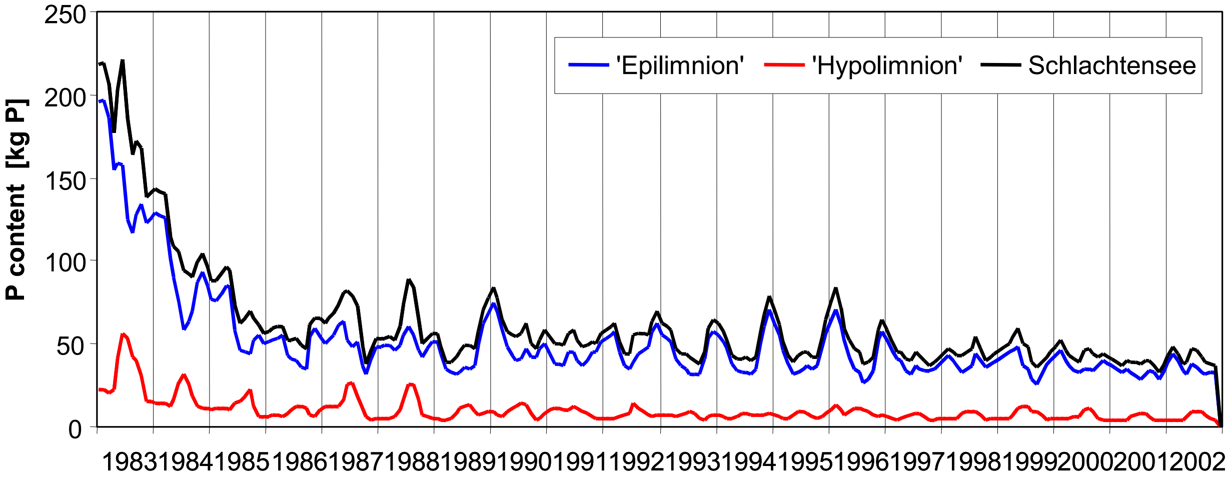

Fig. 29. P content in the Schlachtensee, upper (< 6 m) and lower compartment (> 6m) [kg]

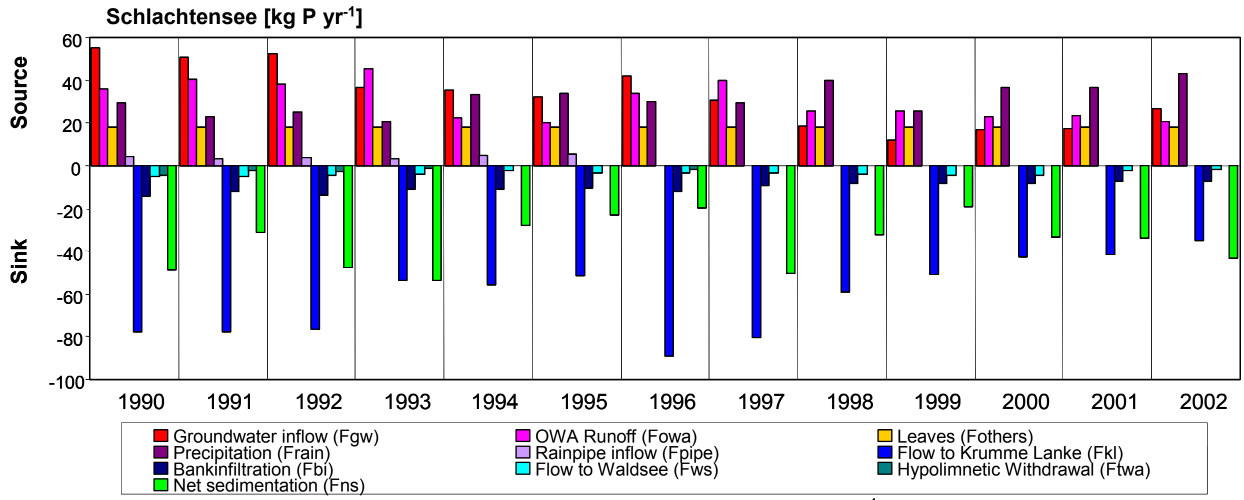

Fig. 30. Mean annual P sources and sinks of Schlachtensee [kg yr^{-1}]

Both lakes showed threshold values of TP below which phytoplankton biomass started to decline. At Lake Tegel this appears to be at 100 µg/L and and in Schlachtensee at 30 µg/L. Once these values are reached, chlorophyll concentrations decline abruptly to 10-30 µg/L. More detailed data analysis in years 2 and 3 of the project will investigate the causes of these differences.

5. Management Implications

This project targets improving the scientific understanding of trophic recovery (i) to provide general knowledge for the prediction of responses and thus the management of lake restoration, and (ii) specifically for the two Berlin lakes to provide improved process understanding as basis for optimising mangement strategies. Both objectives include defining the time scales for improvements to occur after changes to loadings, identifying threshold values for changes in water quality and developing guidance for the application of measures to accelerate the trophic recovery process.

Developing general guidance for managing lake restoration will be an objective for years 2 and 3 of the project, on the basis of the evaluation of the results gained from the two Berlin lakes and the collection of information on restoration responses of other lakes. However, from the preliminary results at the end of the first project year, management implications for the two Berlin lakes are emerging as follows:

Lake Tegel

1. Prediction of Lake Tegel/Havel water exchanges and implications for P balance.

   While exchange between the Havel and Lake Tegel had long been suspected and estimated, this project has developed a validated predictive model which quantifies the exchanges as functions of the other major hydrological drivers of the water balance (Havel discharge, WW abstractions, OWA inputs). Having the capacity to predict how the system responds to changes in these operating variables provides a means to optimise scenarios for minimizing P inputs from the Havel. The model confirms the current strategy of limiting the inflow of P rich Havel water into Lake Tegel by increasing the OWA discharge during summer, when the P concentration in the Havel and the extraction by the Water Works are highest. This measure not only effectively reduces the immediate external load from the Havel, but also diminishes the recharge of sediment P.

2. Diminishing sediment release processes.

   Though further detailed analysis of sediment/water processes are needed in years 2 and 3, the current results stronlgy suggest that P release from the sediment is mainly driven by the temperature above the lake bottom and only in the second step by redox conditions. In consequence, keeping hypolimnion temperatures low is critical for controlling P release, and stratification stability should therefore be as high as possible. The aerator operation strategy therefore optimally should maintain the maximum possible stratification in summer that is consistent with the target of avoiding FeS-formation.

3. Prediction of decrease of internal loading and implications for P export from the lake

   Until now, it has been unclear to which extend the releasable P pool in the upper sediment layers is likely to continue to be a significant load. The results of the in-situ investigations show that this pool could be “washed out” within a few years, provided it is not recharged from external P loads and renewed sedimentation from the lake-internal P cycle. This result may be useful for optimising seasonal patterns of aerator operation and throughflow. In years 2 and 3, the project will explore potential management options resulting from this understanding, e.g. to suppress release until late summer, but support release in conjunction with accelerated water exchange for some weeks between late summer and autumn turnover in order to achieve maximum P losses from the sediment and from the lake.

Schlachtensee

1. The model results confirm that the P balance is no longer dominated by the inflows from the OWA Beelitzhof:

   If further P load reduction is targeted, management measures should address the winter deliveries. For this purpose, more effort will go into understanding the source of this load, particularly towards differentiating between run-off from the steep banks and imports through groundwater flow (see future research).

2. Epilimnetic processes and external loading determine the lake's P content:

   No further measures are required to reduce the internal loading from the sediments to the water column. Though some anaerobic release can still regularly be observed, its contribution to the total load is negligible, and as the temporal and spatial extent of summer anoxia further decreases, this phenomenon will disappear.

3. A very good water balance model is now available for predicting the impact of increasing OWA inflow and reducing retention time:

   In the context of plans to increase OWA outflow in order to feed further lakes in the Grunewald lake chain with low P water, this model, in conjunction with a further developed P-budget model, will be valuable for predicting the impact of such a measure on Schlachtensee water quality.

6. Future research

In years 2 and 3 of the project, effort will focus on

(i) improving the P models for both lakes, for Lake Tegel particularly for the calculation of the internal loads and for Schlachtensee for calculating the external loads

(ii) including biological interactions by developing models that depict food web interactions and their impact on phytoplankton occurrence and P cycles,

(iii) interfacing the biological interactions in the lakes with the P models to explain the process of trophic recovery,

(iv) using the improved models for assessing the relative effects of external and internal measures on the P budget, e.g. seasonality of OWA output, aerator operation and changes in water residence time,

(v) analysing which responses of the lake components are continuous and which show thresholds, and identifying threshold values for the latter, in a second step including other lakes using literature and data provided by other partners,

(vi) specifically targeted field investigations to fill gaps, to validate the models and as supplement of monitoring by ILAT in order to uphold the long-term data series, as detailed in the proposal for continuation of the project,

(vii) using the outcomes of (i) – (vi) for optimising management scenarios for the two Berlin lakes and – together with the evaluation of literature and data from other lakes undergoing trophic recovery – for developing general guidance on managing restoration and predicting responses to reduced nutrient loading.

Futher work addressed in points (ii) – (vii) are not discussed in detail here, but will proceed as described in the proposal for continued funding. Here, we focus on the consequences of the results discussed in chapters 1-5 for the future work on the P-models.

Towards improving the P models, in years 2 and 3 the project will further develop the numerical models presented in chapter 3 above towards providing validated management models for Lake Tegel and Schlachtensee, in which only the most important processes and mostly empirical parameters will be included. Within their calibration and validation range, they are expected to be very effective for testing the potential response to different management options. Furthermore, particularly through collaboration with CSIRO Land and Water, Dr. Phillip Ford, we will develop a scientific, process based model, which includes mainly causal relationships. This model will be useful to explain cause and effect relationships and can be used for prognosis outside the calibration and validation range. For Lake Tegel, this includes a further quantitative analysis of the causal relationships between P release and the other major factors which are susceptible to management control. For both lakes, the data from the years 2003-2006 will be used to validate P model predictions.

The occurrence of threshold values can explain whether systems operate in multiple stable states with the transition between the different states occurring for example at particular P concentrations, or whether linear causal relationships between lake P and the biological components (Vollenweider model and variants) exist. If our systems do operate in the multiple stable state mode, it is of particular importance to establish whether threshold values are lake specific, or transferable between different systems. Therefore, we will compare our results with other lakes.

The results of the modelling procedure so far have highlighted some specific knowledge gaps which will be given emphasis in years 2 and 3. These areas are scientifically important as they bear on mechanistic and process issues which are not well understood and thus limit the accuracy and realism of the models. In addition, some of these issues have direct relevance to assessing the effectiveness of alternative management strategies.

For the P balance of Lake Tegel, work in years 2 and 3 will focus on:

1. Exploring how the stochiometry of P, Fe and S determine redox sensitive P release in relation to mineralisation in cooperation with the IGB, Dr. Michael Hupfer, in order to better understand the relative impact of temperature, nitrate and aeration on release and, if possible, to determine thresholds exceedance of which is likely to trigger P release (this will include further sediment investigations subcontracted to IGB);
2. Investigating the effect of Water Works extraction on P net sedimentation;
3. Effect of wind driven events and ice cover on P cycle (e.g. 1993/1994; 1996/1997)
4. The current empirical models are based on assumption that 80% of WW extraction comes from Lake Tegel by bank infiltration. This will be explored in more detail through collaboration with ongoing work at FUB, Prof. Pekdeger.
5. From 1-4, improving the P-budget model to better depict the situation in 1994-1996 and through understanding situations without net P release to identify the conditions controlling this.

For Schlachtensee the critical areas of the modelling of the P balance are:

1. Development of an improved understanding of groundwater flows. For this purpose, options for collaboration with the BWB and KWB in the context of current groundwater modelling work in the Beelitzhof region for the NASRI project will be explored, particularly to address the effect of water extraction at Rehwiese and to improve modelling by including information from the groundwater table mapping;
2. Investigation of the other external sources of P, especially surface run-off from the rather steep embankments in order to identify the sources of winter P inputs to Schlachtensee. This will include investigations to up-date the data used for P-content of precipitation in the Schlachtensee region, and collaboration with ILAT for data on P-content of rainwater run-off in order to improve the estimates used in the model;
3. Exploring the scope for use of an alternative tracer to better quantify the minor inputs. chloride is not a particular effective tracer for Schlachtensee due to the dominance of inputs from the OWA Beelitzhof, and in year 2 the project will check whether there is another tracer whose concentrations are higher in the groundwater than in Beelitzhof.

The following table gives an overview of how the objectives have been met in the first year and will be met in the following two years:

Table 13: Time table for the project

	1. year	2. year		3. year	
Months after onset of the project:		13.-18.	18.-24.	25.-30.	31.-36.
Continuation of the data series collected at Lake Tegel and Schlachtensee	✓	**x**	**x**	**x**	**x**
Analysis of the data in regard to external and internal P loads	✓	**x**	**(x)**		
Modelling water budgets in Lake Tegel and in Schlachtensee	✓				
Modelling P budgets in Lake Tegel and in Schlachtensee	✓	**(x)**	**(x)**		
Including biological interactions and interfacing the with the P-models		**x**	**x**	**x**	
Development of a process model including cause-effect chains	(✓)	**x**	**x**	**x**	**(x)**

Analysis of causal chains and reactions of ecosystem components	(✓)	**x**	**x**	**(x)**	
Analyses of differences in reactivity between the water bodies	(✓)	**x**	**(x)**		
Development of management models	✓	**x**	**x**	**x**	
Description of threshold values in Lake Tegel and Schlachtensee	(✓)	**x**	**(x)**	**(x)**	**x**
Comparison of thresholds with results from other lakes and reservoirs		**x**	**x**		
Comparison of the processes of eutrophication and trophic recovery in Lake Tegel		**x**	**x**	**(x)**	**(x)**
Deduction of targets for lake and reservoir therapy			**x**	**x**	**x**
Deduction of management guidance, potentially as decision support system				**x**	**x**
Publications, conference presentations, including interim and final reports	✓	**x**	**x**	**x**	**x**
Organisation of an international conference (in collaboration with KWB)					**x**

The international conference in the last half year of the project will be important both for dissemination of project results and for their further international contextualisation towards understanding key mechanisms and driving forces of trophic recovery. The conference is intended to address the interface between general ecologically targeted management plan development as required, for example, by the EU Water Framework Directive and protection concepts specifically for drinking-water resources.

A further important outcome at the end of year 3 is expected to position these two aquatic ecosystems in Berlin for inclusion in long-term programmes on assessing potential impacts of “global change”, e. g. in the context of EU „*Longterm Ecosystem Research*“. This research will thus provide a platform for continued involvement of BWB and KWB in such projects.

The restoration of Lake Tegel and Schlachtensee are success stories of unique value for urban water resource management. The Berliner Wasserbetriebe were involved in their observation and in generation of the data from the beginning of restoration. The current project on understand the recovery mechanisms aims to be a “flagship project” for KWB’s commitment to research on drinking-water resources in Berlin.

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Appendices

Appendix 1. Hydrological data for Lake Tegel: sources and length of time series.

- Runoff of the OWA, Qowa [m^3/mon] (1985-2002, Berlin Water Works)
- Discharge of lake pipeline, Qpipe [m^3/mon] (1988-2002, Berlin Water Works)
- Runoff of River Havel at Borgsdorf, Qhavel [m^3/d] (1983-2002, Senat Berlin)
- Extraction of drinking water from the wells surrounding Lake Tegel, Qdw [m^3/mon] (1983-2002, Berlin Water Works)
- Direct extraction of water for groundwater enrichment, Qgwa [m^3/mon] (1983-2002, Berlin Water Works)
- Discharge of process water from the water works Tegel, Qcl [m^3/mon] (1991-2002, Berlin Water Works)
- Precipitation, Qrain [mm/mon] (1983-2002, Berlin Water Works Tegel)
- Evaporation, Qeva [mm/mon] (1980-2002, DVWK 1996)
- Lake level [NN+m], Pegel (1980-2002, Senat Berlin, daily values)

Appendix 2. Additional chemical data important for the water balance of Lake Tegel.

- Chloride concentration of the Havel runoff at Konradshöhe, Chavel [mg/l] (1983-2002, Senat Berlin)
- Chloride concentration of the runoff of OWA Tegel, Cowa [mg/l] (1985-2002, Berlin Water Works, monthly mean values)
- Chloride concentration of Lake Tegel [mg/l], Cts (1983-2002, Senat Berlin, deepest spot, depths: 0,5, 7, 14 m)
- Total phosphorus concentration the Havel runoff at Konradshöhe, Chavel [mg/l] (1990-2002, Senat Berlin)
- Total phosphorus concentration of the runoff of OWA Tegel, Cowa [mg/l] (1985-2003, Berlin Water Works, monthly mean values)
- Total phosphorus concentration of Lake Tegel, Cts [mmol/m3] (1983-2002, Federal Environment Agency Berlin, deepest spot, depths: 0, 1, 2, 5, 8, 11,13, 15 m)
- NO_3 concentration of Lake Tegel, CNO3 [mg/l] (1983-2002, Federal Environment Agency Berlin, deepest spot, depths: 0, 1, 2, 5, 8, 11,13, 15 m)
- Oxygen concentration of Lake Tegel, CO2 [mg/l] (1983-2002, Federal Environment Agency Berlin, deepest spot, depth in 1 m steps)
- Temperature of Lake Tegel, Temp [°C] (1982-2002, Federal Environment Agency Berlin, interpolated monthly mean values, deepest spot, depth in 1 m steps)

Appendix 3. Hydrological data of Schlachtensee: sources and length of time series.

- Runoff of OWA Beelitzhof, Qowa [m^3/mon] (1982-2002, Berlin Water Works)
- Outflow to Waldsee, Qws [m^3/mon] (1982-2002, Berlin Water Works)
- Extraction from well Rehwiese [m^3/mon] (1981-2002, Berlin Water Works)
- Precipitation, Qrain [mm/mon] (1980-2002, Berlin Water Works, Beelitzhof)
- Evaporation, Qeva [mm/mon] (1980-2002, DVWK 1996, monthly values)
- Hypolimnic water withdrawal, Qhwd [m^3] (1981-2000 Berlin Water Works, values between sampling dates).
- Lake level, Pegel [NN+m] (1980-2002, Senat Berlin, daily values)

Appendix 4. Additional chemical data important for the water balance of Schlachtensee.

- Chloride concentration of the runoff of OWA Beelitzhof, Cowa [mg/l] (1987-2002, Berlin Water Works, monthly mean values)
- Chloride concentration of Schlachtensee, Css [mg/l] (1983-2002, Senat Berlin, sampling point southern edge, 0.5 m depth)
- Total phosphorus concentration of the OWA Beelitzhof, Cowa [mg/l] (1982-2003, Berlin Water Works, monthly mean values)
- Total phosphorus concentration of Schlachtensee, Cts [mmol/m3] (1982-2002, Federal Environment Agency Berlin, deepest spot, depths: 0, 1, 2, 4, 6, 7.5 m)
- NO_3 concentration of Schlachtensee, CNO3 [mg/l] (1982-2002, Federal Environment Agency Berlin, deepest spot, depths: 0, 1, 2, 4, 6, 7.5 m)
- Oxygen concentration of Schlachtensee, CO2 [mg/l] (1982-2002, Federal Environment Agency Berlin, deepest spot, depth in 1 m steps)
- Temperature of Schlachtensee, Temp [°C] (1982-2002, Federal Environment Agency Berlin, deepest spot, depth in 1 m steps)

Appendix 5. Chemical parameter values from literature

			Value	Unit	Source
Cl-concentration	Rainwater	Crain	0.74	g m^{-3}	UBA 1999
	Stormwater	Cdrain	110	g m^{-3}	Heinzmann 1993
	Groundwater at Schlachtensee	Cgw	37	g m^{-3}	BWB, Well Rehwiese 1992
TP-concentration	Rainwater	Crain	0.143	g m^{-3}	Klein & Wassmann 1986
	Stormwater	Cdrain	0.4	g m^{-3}	Heinzmann 1993
	Groundwater at Schlachtensee	Cgw	0.2	g m^{-3}	BWB, Well Rehwiese 1992