DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2026/14**

Groundwater impact on lakes
Grundvandspåvirkningen af søer

Reporting of the project for Styrelsen for Grøn Arealomlægning og Vandmiljø

Jolanta Kazmierczak, Julian Koch, Georgios Ikaros Xenakis,
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Abbreviations

DCE	National Centre for Environment and Energy at Aarhus University
DK-model	National Water Resources Model
GEUS	Geological Survey of Denmark and Greenland
KDS	Danish Climate Data Agency
P	Phosphorus
SGAV	Styrelsen for Grøn Arealomlægning og Vandmiljø
SHAP	Shapley Additive Explanations
TP	Total phosphorus
Ortho-P	Orthophosphate
VP3	Vandområdeplan 3

Summary

Improved understanding of groundwater impact on phosphorus (P) concentrations in Vandområdeplan 3 (VP3) lakes is a crucial step in achieving good chemical and ecological lake status in Denmark. We have combined advanced geostatistical, modeling and machine learning methods with the existing national scale datasets relevant for groundwater and lake P concentrations to: 1) predict groundwater P concentrations relevant for ecological lake status and define the environmental factors governing high groundwater P concentrations, 2) estimate groundwater discharge and groundwater P loading into VP3 lakes, and 3) develop a preliminary machine learning model for predictions of the relationship between lake P concentrations, watershed and groundwater variables in 986 VP3 lakes.

Four groundwater P classes were predicted beneath 986 VP3 lakes. Groundwater P concentration thresholds separating the classes were 29, 51, and 63 µg/L. High groundwater P concentrations are related to thick Quaternary and clay deposits and low landscape areas. Additionally, groundwater P concentrations increase with depth. The predicted groundwater P concentrations exceed the lake-specific P target concentrations beneath 430 VP3 lakes. At the remaining lakes, groundwater may have a diluting impact. The predicted groundwater P concentrations are below 29 µg/L beneath seven out of ten lakes with the highest deep groundwater flux rates, and eight out of ten lakes with the highest shallow groundwater flux rates. These lakes have low lake P concentrations. Thus, discharge of groundwater containing below 29 µg P/L into lakes may potentially improve their ecological status. In contrast, lakes with the highest P concentrations interact with groundwater containing above 53 µg P/L.

There is no significant difference in the average groundwater P loading into VP3 lakes via deep (regional) or shallow (local) flow paths. The estimated mean groundwater P loading into VP3 lakes <10 ha is 0.4 kg/yr via both shallow and deep groundwater flow paths. At the larger VP3 lakes mean groundwater P loading equals 12.9 and 11.1 kg/yr via shallow and deep groundwater flow paths, respectively.

Based on the machine learning analysis, high lake P concentrations are found in the shallow lakes located low in the landscape in the catchments with high content of fine sand in the uppermost 0–30 cm soil layer and low precipitation. These lakes are also located in areas with a shallow redox interface (boundary between oxic and anoxic zones in the aquifer) and predicted groundwater P concentrations above 53 µg/L. These variables indicate an impact of the catchment weathering and groundwater P loading on the ecological lake status. The potential diluting role of precipitation is also highlighted.

We see overall meaningful outputs of the applied modeling framework; however, the presented predictions are connected to a range of uncertainties due to the limited groundwater field data availability in the vicinity of VP3 lakes. Ground truthing of the presented predictions at selected VP3 lakes and development of the modeling datasets with additional observations could potentially improve the model performance. Further, various conceptualizations of groundwater P predictions could be applied to investigate the impact of this variation on lake water P predictions.

1. Background and purpose

The Water Framework Directive requires all member states to reach good chemical and ecological status in rivers, lakes, groundwater, estuaries, and coastal waters by 2027. Ecological classification of Danish lakes indicates that bad and poor ecological lake status is associated with lake phosphorus (P) concentrations exceeding 50 µg/L for deep lakes, and 100 µg/L for shallow lakes (Søndergaard et al., 2005). Target P concentrations in Danish lakes range from 29 to 61 µg/L (MST, 2023). P concentrations in 180 monitored Danish lakes with an area >5 ha varied between 7–1842 µg/L, with a median of 89 µg/L for 2017–2022 (Johansson et al., 2022). This indicates that P loading into lakes poses a challenge in achieving good chemical and ecological lake status in Denmark.

While P transport to surface waters via catchment weathering and surface runoff under oxidizing conditions, as well as P cycling in soil, wetlands and muddy lake sediments have been studied extensively (Zak et al., 2010; Orihel et al., 2017; Moal et al., 2019; Andersen and Heckrath, 2020; Bennike et al., 2021; Ury et al., 2023), groundwater-driven P loading into lakes is often disregarded in the P cycle (Lewandowski et al., 2015; Moal et al., 2019; Elsayed et al., 2023). Groundwater P concentrations exceed 100 µg/L in ca. 30% of the monitored well intakes in Denmark (Thorling et al., 2019). Diffuse groundwater inputs of geogenic P into lakes in Denmark and the governing hydrogeochemical processes have been reported in recent local studies (Nisbeth et al., 2019a,b; Kazmierczak et al., 2020; Kazmierczak et al., 2021). However, the importance of these groundwater-driven P inputs for ecological lake status at the national scale remains unknown. In the proposed project, we aim to:

1) Predict groundwater P concentrations relevant for ecological lake status and define the environmental factors governing high groundwater P concentrations;
2) Assess groundwater discharge and groundwater P loading into VP3 lakes;
3) Develop a preliminary machine learning model to determine the relationship between lake P concentrations in 986 VP3 lakes and (i) groundwater P concentrations and redox conditions, (ii) groundwater-lake interactions metrics, (iii) catchment characteristics, and (iv) estimated surface P loading from catchment into lakes.

The project builds on the outputs of the relevant previous and ongoing projects at GEUS, SGAV, and DCE:

- Effects of climate change on geogenic compounds in groundwater – CHANGE (e.g. Xenakis et al., 2026).
- Predictions of depth to redox interface at national scale (Koch et al., 2024).
- New lake conceptualization in the DK-model (Troldborg et al., 2024).
- Estimates of the probability of groundwater discharge into lakes (Nilsson et al., 2023).
- National Groundwater Monitoring Programme (e.g. Thorling et al., 2019).
- National Lakes Monitoring Programme (e.g. Johansson et al., 2024).
- DCE watershed P model.
- Previous research projects at the University of Copenhagen and GEUS, looking into P in groundwater-lake interactions – CLEAR, HighPhos (e.g. Kidmose et al., 2013; Nisbeth et al., 2019a,b; Kazmierczak et al., 2020).

2. Task description, data sources, and workflow

The lakes monitoring programme and the watershed models developed by DCE provide insights into variation in lake water P concentrations at the national level, and their relationship to the watershed characteristics (Johansson et al., 2024). Merging the watershed and in-lake datasets with information on groundwater discharge into lakes and groundwater P concentrations in the vicinity of lakes could provide new insights on the impact of groundwater on the P-related ecological lake status. However, due to the complexity of the processes in aquifers and costs related to well installation and chemical sample analysis, national-scale information on groundwater discharge into lakes and groundwater P concentrations in the vicinity of lakes is greatly limited. This knowledge gap was currently reduced by advances in numerical models and machine learning (Ondracek et al., 2023; Koch et al., 2024; Xenakis et al., 2026).

In the past decade, significant progress was achieved in understanding groundwater-lake interactions in Denmark (e.g. Kazmierczak et al., 2016; Kidmose et al., 2025), and workflows were developed to estimate the probability of groundwater contact with VP3 lakes at the national scale (Nilsson et al., 2019; Nilsson et al., 2023). Recently, a new conceptualization of lakes in the DK-model allowed for more precise estimates of groundwater fluxes into lakes (Troldborg et al., 2024).

In parallel, local-scale studies shed new light on P mobilization and transport from sandy aquifers into lakes, resolving hydrogeochemical processes along the flow path to the sediment-water interface (Nisbeth et al., 2019a,b; Kazmierczak et al., 2020; Kazmierczak et al., 2021). Development of machine learning methods and high-quality, public datasets enabled predictions of depth to the redox interface and groundwater P concentrations at the national scale (Koch et al., 2024; Xenakis et al., 2026). These variables are crucial to estimate groundwater P loading into lakes.

This study attempts to advance understanding of the relationships between groundwater discharge and groundwater P concentrations and P-related ecological lake status in VP3 lakes based on the existing national scale datasets. The findings of machine learning and numerical predictions, where possible, were compared with the local-scale datasets.

SGAV, in collaboration with DCE, contributed with the following archive datasets:

- GIS theme with the VP3 lakes.
- Information on the area, mean, and maximum lake depth.
- Lake typology and target P concentrations in VP3 lakes (MST, 2023).
- Mean alkalinity, water color, and salinity in VP3 lakes for 2001–2020 (various monitoring programmes).
- Mean nitrate and P concentrations, and oxygen content in VP3 lakes for 2008–2020 (various monitoring programmes). The mean P concentrations were provided for 789 VP3 lakes.
- Data on P inflow, outflow, and water discharge from VP3 lakes, estimated from a watershed P model developed by DCE (Søndergaard et al., 2020).

- Mean annual water chemistry data in VP3 lakes for 2008–2023. The data series included water temperature, salinity, TP, ortho-P, pH, oxygen content, total nitrogen, nitrite and nitrate, electrical conductivity, iron, water color, ammonium, and alkalinity. The dataset included ortho-P measurements in 430 VP3 lakes, and total P measurements in 846 VP3 lakes.

GEUS contributed with the following archive datasets:

- Probability calculations of the contact between groundwater and 830 VP3 lakes (Nilsson et al., 2023).
- Groundwater and surface discharge to 980 VP3 lakes extracted from the DK-model.
- National map of depth to the redox interface (Koch et al., 2024).
- Groundwater P concentrations in 6959 well intakes.
- Geological and geomorphological datasets: 1) clay, silt, sand and gravel content in 0-2 m below ground surface (Adhikari et al., 2013), 2) vertical distance from terrain surface to chalk (National Hydrological Model – DK-model), 3) thickness of the uppermost sand and clay layers, from terrain (DK-model), 4) soil map (GEUS), 5) geomorphology map (GEUS), 6) pre-Quaternary geology map (Håkansson and Pedersen, 1992), and 7) buried valleys map (Sandersen and Jørgensen, 2015).
- Hydrological and climate datasets: 1) mean and maximum depth to groundwater table (DK-model), 2) groundwater recharge (DK-model), 3) thickness of the uppermost aquifer (DK-model), 4) precipitation (Danish Meteorological Institute – DMI), and 5) temperature (DMI).
- Other datasets: 1) landscape types of Denmark (DCE), 2) wetland classification (DCE), and 3) elevation and surface slope gradient (Danish Climate Data Agency – KDS).

The study objectives were achieved by the implementation of the following workflow:

- The national scale groundwater P predictions at the thresholds relevant for P-related ecological lake status were carried out based on the methods developed under the project CHANGE. These predictions were compared with the local-scale field data (Section 3).
- Predicted groundwater P concentrations were combined with estimated groundwater discharge into lakes based on the groundwater flux extracted from the DK-model to provide ranges of groundwater P loading into VP3 lakes. Insights on the adsorption of groundwater-derived P at the sediment-lake interface at various groundwater flux rates were provided (Section 4).
- Datasets on groundwater discharge, groundwater P concentrations, and in-lake and watershed information were combined in the machine learning model to define the impact of groundwater on the P-related ecological lake status (Section 5).

The datasets used for each workflow step are described in the chapter corresponding to the task. Groundwater P predictions at the national scale were financed under the project CHANGE.

The report includes the following information:

- Predictions of groundwater P in the vicinity of 986 VP3 lakes.
- Estimates of groundwater discharge into 981 VP3 lakes.
- Estimates of annual groundwater P loading into 832 lakes, and a description of the method limitations.

- Description of the relationship between the summer lake P concentrations, groundwater discharge, groundwater P concentrations, and watershed characteristics.
- Recommendations for future work and monitoring of groundwater impacts on lake ecology.
- Documentation on how the archive datasets were incorporated into analyses.

The electronic attachments to the report are:

- GIS theme containing groundwater P classes for 986 VP3 lakes.
- Estimated groundwater discharge (m^3/yr) and P loading (kg/yr) into 832 VP3 lakes.
- GIS theme with the predicted lake TP concentrations for 196 VP3 lakes.

3. Groundwater P predictions at the concentration thresholds relevant to the ecological lake status

3.1 Methods

A map of groundwater P concentrations at the national scale in 100×100 m resolution was developed in the project CHANGE (Xenakis et al., 2024; Xenakis et al., 2026). The original model was developed using a gradient boosted decision trees algorithm (Chen et al., 2016), and a threshold concentration of 100 µg/L. The model was trained on the average groundwater P concentrations in 6687 wells with 6959 well intakes for 2017–2024. 837 wells belonged to the national groundwater monitoring network, 93 wells to the agricultural catchment monitoring network, and 5757 wells were drinking water wells. The water chemistry data used in the predictions were extracted from annual reporting of the National Groundwater Monitoring Programme (Thorling et al., 2019). Geospatial predictions were based on the spatially continuous datasets and categorical variables (Table 1).

Key factors governing groundwater P were identified by feature importance analysis using point and mappable features. The feature importance analysis of the model was conducted using the Shapley Additive Explanations (SHAP) approach (Lundberg and Lee, 2017). The SHAP values highlight the features driving predictions toward high or low groundwater P concentrations.

The workflow developed under the project CHANGE was employed with two major modifications in groundwater P predictions carried out to explore the impact of groundwater on lakes: 1) we employed three concentration thresholds, and 2) groundwater P predictions were depth specific. The P concentration thresholds for the probability predictions were set at 29, 51, and 63 µg/L. These concentrations are target summer lake water P concentrations defined by SGAV (MST, 2023) for various lake typology groups. The defined target P concentrations are based on regression calculations of the relationships between P and lake quality components such as phytoplankton, chlorophyll, macrophytes, phytobenthos, fish, and benthic fauna. For the lake typology groups 1, 2, 5, 6, 10, the target lake water P concentrations are 29, 30, and 31 µg/L. Uncertainties of the machine learning predictions limit the possibility of capturing such small concentration variations in groundwater P predictions. Thus, we have applied the lowest threshold of 29 µg/L.

Three binary classification models were produced, and the training datasets included a target column classifying each well intake as above or below the selected concentration threshold of 29, 51, or 63 µg P/L. In addition to the water chemistry data, each training dataset included a 'depth' column with the well intakes depth in meters, and 34 columns with the spatially continuous datasets listed in Table 1. Distribution of groundwater P at various well intake depths and concentration thresholds is presented in Figure 1. 5% of the total 6959 well intakes have a depth between 0–10 meters below ground surface (mbgs). The mean well depth in the dataset is 48 mbgs. 38.8% of the well intakes at 0–10 mbgs have groundwater P concentrations above 29 µg/L, and in 21.5% of the well intakes at 0–10 mbgs, groundwater P concentrations exceed 61 µg/L.

Table 1. Overview of the covariates used in modeling. Categorical variables are marked with an asterisk (*).

Type	Covariate name	Description	Source
Topography	Elevation	Elevation above sea level (m)	KDS
	Slope	Surface slope gradient (°)	
Soil	Clay a, b, c, d	Content (%) of clay, fine sand, gravel, silt in 4 depth layers: a) 0–30 cm, b) 30–60 cm, c) 60–100 cm, d) 100–200 cm	Adhikari et al., 2013
	Fine sand a, b, c, d		
	Gravel a, b, c, d		
	Silt a, b, c, d		
Hydrogeology	Mean water table depth	Mean depth to groundwater table (mbgs)	DK-model
	Minimum water table depth	Minimum depth to groundwater table (mbgs)	
	Recharge	Groundwater recharge (mm/year)	
Geology	Aquifer thickness	Thickness of uppermost aquifer (m)	
	Clay above chalk	Accumulated clay above chalk (m)	
	Clay thickness	Thickness of clay deposits from terrain to first sand layer (m)	
	Depth to chalk	Vertical distance from terrain to chalk deposits (m)	
	Heterogeneity	Count of sand-clay transitions in the uppermost 30 m	
	Quaternary thickness	Thickness of Quaternary deposits from terrain to pre-Quaternary (m)	
	Sand thickness	Thickness of sand deposits from terrain to first clay layer (m)	
	Buried valleys	Buried valleys map *	Sandersen and Jørgensen, 2015
	Surface geology	Surface geology map *	Geology Portal – GEUS
	Geomorphology	Geomorphology map *	
	Pre-Quaternary Geology	Pre-Quaternary Geology map *	Håkansson and Pedersen, 1992
	Landscape	Landscape types *	DCE
	Wetland	Wetland classification *	

The binary classification models were produced using tuned hyperparameters, such as learning_rate, num_leaves, max_depth, and min_data_in_leaf. We used in all P models the hyperparameter set of the groundwater P model set up in the project CHANGE. The hyperparameter set was selected after empirical trials and an optimization process based on Logarithmic Loss (Xenakis et al., 2026). Class weights were used to address the class imbalance, and stratified splits were used to preserve the proportion of each class. A 10-fold stratified cross-validation was utilized to evaluate the model performance.

Finally, each model was used to predict and classify groundwater P concentrations across Denmark, including groundwater beneath the VP3 lakes, as above or below the threshold limit of 29, 51, or 63 µg P/L. The prediction dataset included the spatially continuous predictors (Table 1) and the 'depth' column with the maximum lake depths. In the grids outside of the VP3 lakes polygons, we have applied the mean maximum VP3 lakes depth of 7.6 m. Hence, the depth-specific groundwater P predictions are for the maximum lake depths where lake contact with the anoxic aquifers is expected.

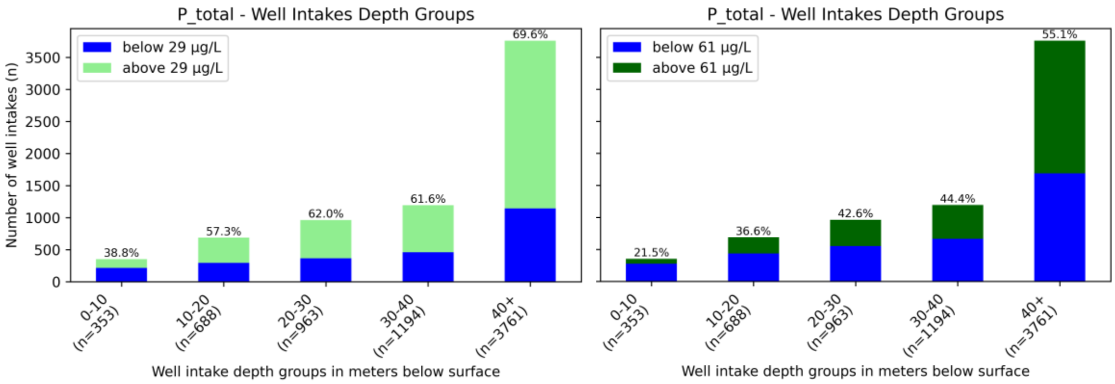


Figure 1. Depth distribution of measured groundwater P concentrations in 6959 well intakes used in groundwater P predictions.

The machine learning models provided probabilities of shallow groundwater exceeding each of the three threshold concentrations at a spatial resolution of 100×100 m. In the next step, the zone analysis tool in ArcGIS Pro was used to extract an average probability of groundwater exceeding the three P concentration thresholds at 986 VP3 lakes. The input datasets were a GIS theme with VP3 lakes and the groundwater P prediction maps. Based on these provided probabilities, 986 VP3 lakes were divided into four classes:

- Class 4 included lakes with >0.5 probability of groundwater P concentrations exceeding 61 µg/L.
- Class 3 included lakes with >0.5 probability of groundwater P concentrations exceeding 53 µg/L, and with ≤0.5 probability of groundwater P concentrations exceeding 61 µg/L.
- Class 2 included lakes with >0.5 probability of groundwater P concentrations exceeding 29 µg/L, and with ≤0.5 probability of groundwater P concentrations exceeding 53 µg/L.
- Class 1 included lakes with ≤0.5 probability of groundwater P concentrations exceeding 29 µg/L.

3.2 Groundwater P levels – probability maps and governing environmental factors

Figure 2 shows the probability of groundwater P concentrations exceeding the threshold values of 29, 51, and 63 µg/L. The predictions are depth-specific and related to the maximum depth of 986 VP3 lakes, and to the mean depth of 7.6 mbgs in the areas outside of 986 VP3 lakes. Thus, in the further analysis, only the groundwater P predictions within the polygons of 986 VP3 lakes are employed. The spatially continuous probability predictions presented in Figure 2 formed a baseline to estimate the average probabilities of groundwater P concentrations exceeding 29, 51, and 63 µg/L beneath the 986 VP3 lakes.

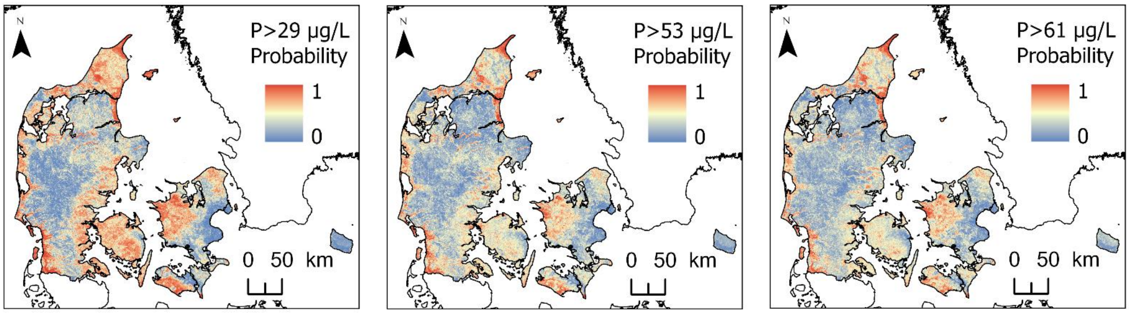


Figure 2. Depth-specific predictions of groundwater P concentrations exceeding the thresholds of 29, 51, and 63 µg/L at a 100×100 m resolution. Shallow groundwater in areas with a probability greater than 0.5 is likely to have P concentrations exceeding 29, 51, or 63 µg/L, with the highest exceedance likelihood at a probability of 1.

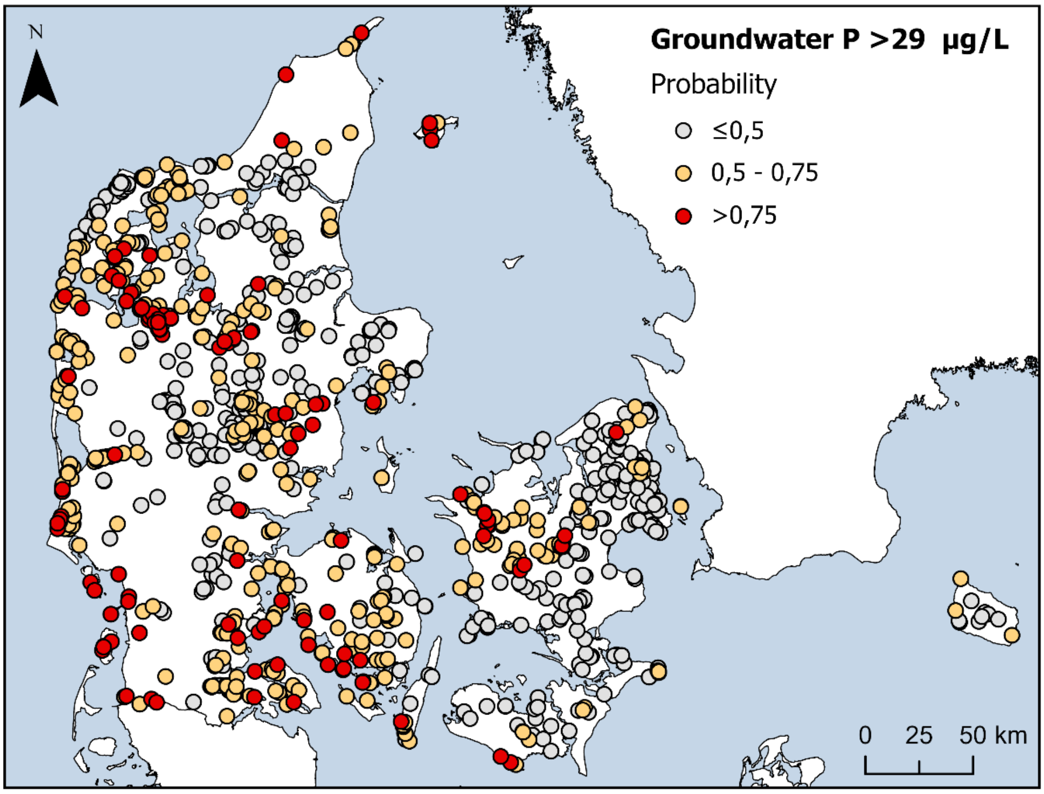


Figure 3. Average probability of the shallow groundwater P concentrations exceeding 29 µg/L beneath the 986 VP3 lakes.

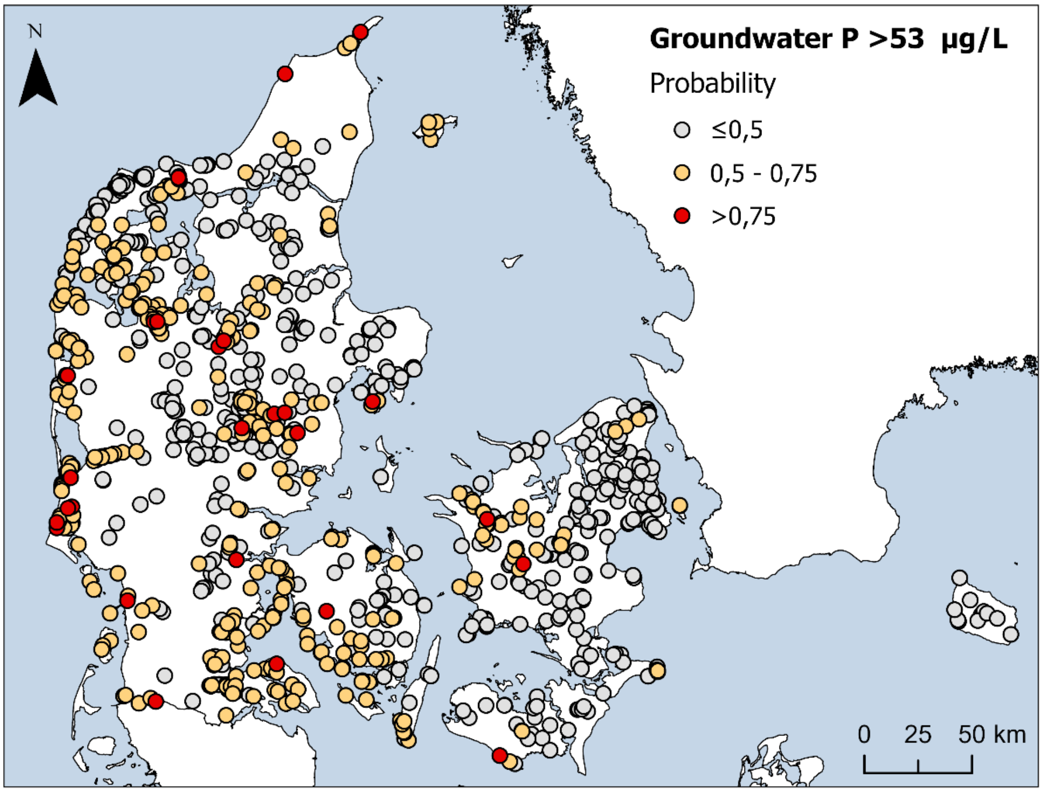


Figure 4. Average probability of the shallow groundwater P concentrations exceeding 53 µg/L beneath the 986 VP3 lakes.

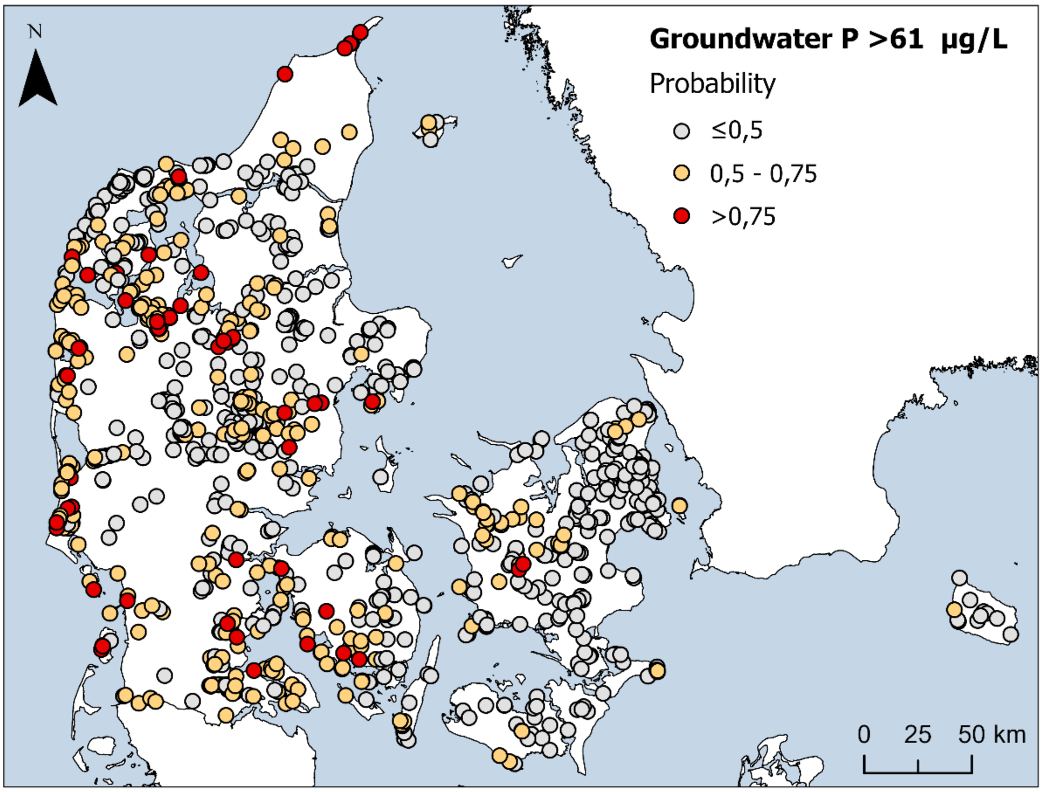


Figure 5. Average probability of the shallow groundwater P concentrations exceeding 61 µg/L beneath the 986 VP3 lakes.

The average probability of groundwater P concentrations exceeding the three ecological threshold values beneath 986 VP3 lakes is displayed in Figures 3–5. The average probability values are presented in three probability groups. The probabilities were calculated based on the 100×100 m grid values shown in Figure 2 and constrained within VP3 lake polygons.

Groundwater P concentrations below 29 µg/L are most likely found in the eastern and southern parts of Zealand, on Lolland and Falster, in the central parts of Bornholm, and in the central and north-east Jutland (Figure 3). However, there are also spots of low groundwater P concentrations scattered throughout the country, e.g. on Fyn. The extent of zones with groundwater P concentrations exceeding the threshold values decreases with transition to the thresholds of 53 and 61 µg/L. Groundwater P concentrations below these two thresholds are likely in northern and eastern Fyn, major parts of Zealand, Lolland and Falster, on Bornholm, and in the central and northern Jutland (Figures 4 and 5). The probability of groundwater P concentrations exceeding 61 µg/L is the highest in north-western and north-eastern Zealand, southern Fyn and Lolland, and along the coast in Jutland (Figures 2 and 5).

SHAP analysis showed that high groundwater P concentrations are related to thick Quaternary and clay deposits and low landscape areas (Figure 6). Additionally, groundwater P concentrations increase with depth, as also indicated in Figure 1. Nilsson et al. (2023) associated high groundwater P concentrations with non-carbonate geology, interglacial and Neogene marine sediments, and reduced groundwater types, which supports the relationships indicated by the applied machine learning models.

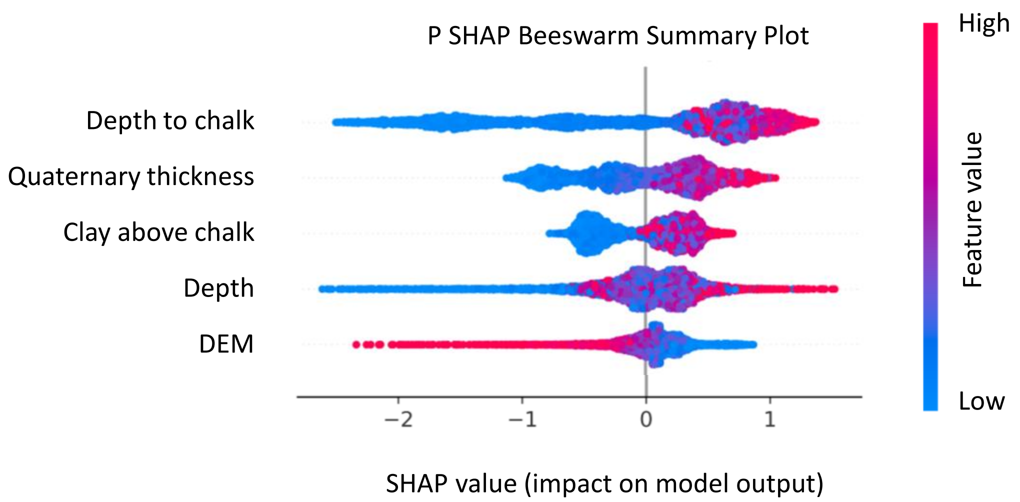


Figure 6. Impact of environmental covariates on groundwater P predictions.

3.3 Groundwater P classes *vs.* lake typology

Figure 7 and Table 2 show the P concentration classes in groundwater beneath 986 VP3 lakes. Class 1 comprises groundwater with P concentrations below 29 µg/L. Groundwater in class 2 contains 29–53 µg P/L, and in class 3, 53–61 µg P/L. Groundwater in class 4 contains above 61 µg P/L. The majority of the 986 VP3 is located in the areas with groundwater in the P classes 1 and 4 (Table 2). Groundwater P concentrations below 29 µg/L are likely to occur beneath 364 VP3 lakes. Groundwater P concentrations exceeding 29 µg/L may impact 119 VP3 lakes in typology classes 1, 2, 5, 6, and 10. 217 VP3 lakes in typology classes 9, 11, and 12 are in a potential contact with groundwater with P concentrations exceeding 53 µg/L, and 94 VP3 lakes in typology classes 13, 14, and 15 are in a potential contact with groundwater with P concentrations exceeding 61 µg/L. The probability of groundwater P concentrations below the target lake P concentration thresholds for the lake typology groups defined by MST (2023) is high beneath 447 VP3 lakes.

It is noted that the results presented in Section 3.3 do not indicate the likelihood of groundwater P loading into VP3 lakes, but the probability of high groundwater P concentrations beneath the 986 VP3 lakes. Groundwater P concentration classes derived from the groundwater P prediction maps (Section 3.2) are combined with the modeled groundwater discharge (DK-model) and likelihood of the contact of VP3 lakes with aquifers (Nilsson et al., 2023) in Section 4.

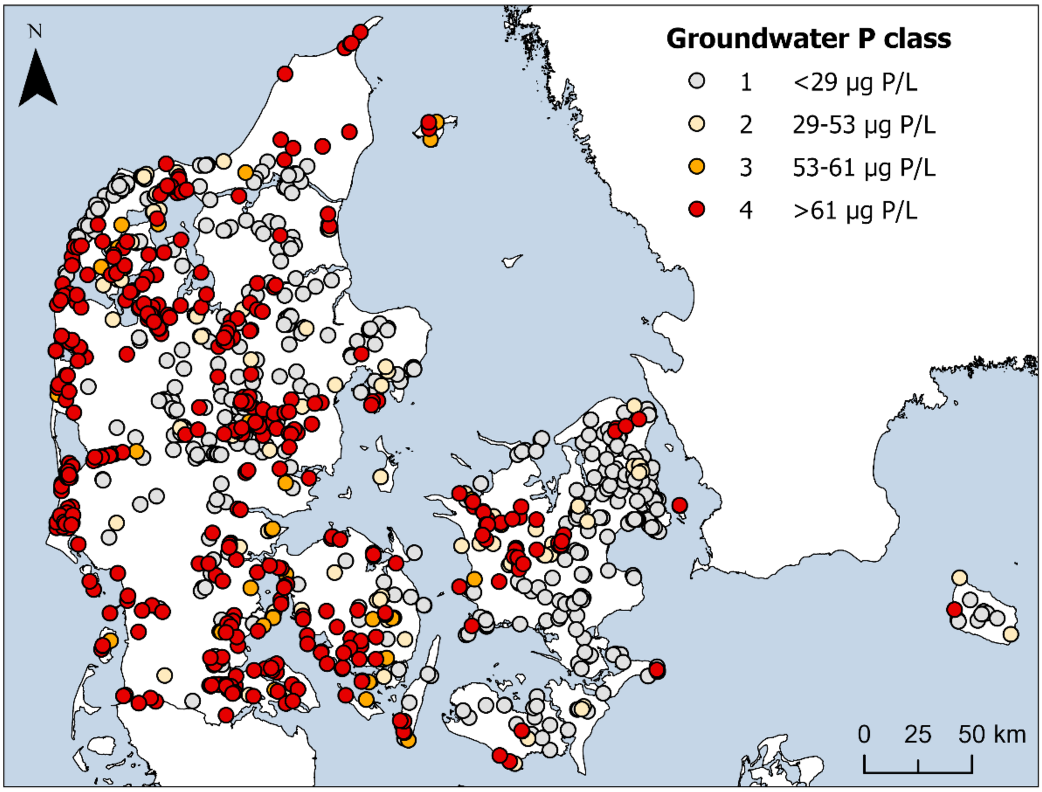


Figure 7. Groundwater P concentration classes beneath 986 VP3 lakes derived from the groundwater P probability maps.

Table 2. Groundwater P concentration classes beneath VP3 lakes, divided by lake typology derived by MST (2023). Cells highlighted in orange indicate the number of lakes with groundwater P concentrations exceeding the target lake P concentrations.

Typology	Target lake P concentration	Groundwater P class			
		1	2	3	4
1, 2, 5, 6, 10	29–31 µg/L	31	20	5	94
9, 11, 12	53 µg/L	251	46	25	192
13, 14, 15	61 µg/L	82	19	18	94

3.4 Comparison of the predicted P classes to the field-based observations

Comprehensive field studies of the external dissolved geogenic P in groundwater discharging into lakes have been conducted at eight lakes in Denmark and reported in both international and Danish literature (Table 3 and references therein). The predicted groundwater P classes (Section 3.3) have been compared with the mean TP and ortho-P concentrations in groundwater discharging to the eight extensively studied lakes. It is noted that TP and ortho-P were not determined at the same time in all studied lakes.

The model predictions are comparable to the field-based observations at half of the studied lakes. The best agreement is between predicted P classes and field-measured P at Lake Hampen, Lake Nørresø, Lake Skærsø, and Lake Vedsted. The most significant discrepancies between the predicted and measured groundwater P concentrations are seen at Lake Vandet and Lake Væng, where the machine learning model underpredicts groundwater P concentrations. Groundwater P concentrations at Lake Tissø are greatly overpredicted compared to the field-based measurements.

It is noted that the field-based measurements of groundwater P concentrations were calculated based only on the data from boreholes located upstream of the studied lakes, while groundwater P classes were estimated with both upstream and downstream grid cells within the VP3 lake polygons. Further, Kazmierczak et al. (2021) showed that groundwater ortho-P concentrations can vary by two orders of magnitude within tens of meters in the three-dimensional systems. The depth-specific groundwater P predictions in a 100×100 m grid are unable to capture these small-scale variations in the field-based measurements of groundwater P concentrations. Thus, the derived groundwater P classes beneath 986 VP3 lakes should be treated mainly as indicators of the areas where groundwater P loading may be an obstacle in achieving good ecological lake status.

Table 3: Mean TP and ortho-P concentrations measured in the field in groundwater discharging into Danish lakes. The predicted groundwater P concentrations in the best agreement with the measured TP and ortho-P are highlighted in green. The discrepancies are highlighted in orange.

Ref #	Lake name	MST ID	Mean TP µg/l	Mean ortho-P µg/l	P class, P µg/l
1	Lake Ejstrup	593	Nd	80	0-29 (class 1)
2	Lake Hampen	597	Nd	94–160	> 61 (class 4)
3	Lake Nørresø	197	≈175	142 (spring)	> 61 (class 4)
4	Lake Skærsø	144	50	Nd	0-29 (class 1)
5	Lake Tissø	682	1.8	Nd	> 61 (class 4)
6	Lake Vandet	26	240	480	0-29 (class 1)
7	Lake Vedsted	90	Nd	200 (gw) 600 (springs)	53-61 (class 3)
8, 9, 10	Lake Væng	552	162	43–60	0-29 (class 1)

nd: no data available

References: 1) Nilsson and Jessen (2017); 2) Ommen et al. (2011); 3) Nisbeth et al. (2019a,b); 4) Nilsson et al. (2007); 5) Sebok et al. (2018); 6) Frederikson (2021); 7) Hansen and Wodschow (2008); 8) Kidmose et al. (2013); 9) Kazmierczak et al. (2020); 10) Kazmierczak et al. (2021).

4. Groundwater P loading into VP3 lakes

4.1 Methods

P concentration ranges in groundwater P classes derived in Section 3.3 and groundwater fluxes into lakes estimated from the DK-model (Ondracek et al., 2023; Troldborg et al., 2024) were employed to estimate groundwater P loading into VP3 lakes.

The groundwater flux rates along the near-surface and deep flow paths modeled in the DK-model in mm/yr were converted into groundwater flow into VP3 lakes in m^3/yr. The inflow of groundwater from the deep groundwater flow path into the lake was converted into m^3/yr by multiplying the modeled flux in mm/yr by the calculated sub-area of the lakebed where the DK-model simulates a potential connectivity between the lake and the underlying groundwater body. The discharge into the lake via the near-surface groundwater flow path was calculated by multiplying the lake surface area by the modeled flux in mm/yr. The near-surface groundwater flow into the lake may be slightly overestimated, as 1) groundwater flux often decreases with increasing distance from lake shore, and 2) for flow-through lakes part of lake areas are losing water into aquifers. However, these two features are site-specific and cannot be captured in the DK-model. For consistency, we have applied a simplified assumption that the modeled average groundwater flux occurs throughout the entire lake area.

The DK-model results were cross-validated with the method developed by Nilsson et al. (2023). A qualitative probability analysis of the lakes' connectivity to groundwater bodies derived by Nilsson et al. (2023) assesses probability of groundwater discharge into VP3 lakes based on the information provided in the DK-model, comprising geology of groundwater bodies (DGVF), and distance between the top of groundwater body underneath the lake to the mean or maximum lake depth. Nilsson et al. (2023) estimate groundwater discharge probability into >10 ha lakes, as well as ca. 500 VP3 lakes with a smaller area.

Groundwater P loading into VP3 lakes was calculated by multiplying the calculated groundwater discharge from the shallow and deep flow paths by the ranges of groundwater P concentrations in the predicted P classes (Section 3.3).

A boxplot of the distribution of groundwater P loading into 833 lakes in the three groundwater-lake contact groups derived by Nilsson et al. (2023) was produced. Median, 25^{th} percentile, 75^{th} percentile, minimum, and maximum groundwater P loading were calculated for three groups with very high, high, and moderate to low probability of the lake being in contact with groundwater. Groundwater P loading into each VP3 lake shown in the boxplot represents:

- In class 1 (groundwater P <29 µg/L), the upper limit of the P loading range.
- In classes 2 and 3 (groundwater P between 29–53, and 53–61 µg/L), an average of the upper and lower limits of the P loading range.
- In class 4 (groundwater P >61 µg/L), the lower limit of the P loading range.

This means that groundwater P loading (kg P/yr) into lakes that are in contact with groundwater represented by class 1 is likely overestimated. In areas with class 4 of groundwater P concentrations, the P loading into lakes will likely be underestimated.

4.2 Estimated groundwater discharge into lakes

The key factors governing groundwater-lake interactions are geology beneath the lake, lake geometry, and lake distance to the aquifer (DK-model; Nilsson et al., 2023). Nilsson et al. (2023) defined three different groundwater-lake contact types based on two criteria: geology and lake depth. The geology surrounding the lakes is divided into three hydrogeological classes:

- In class A1, the subsurface (0–15 m) around the lake consists of more than 50% of sand or chalk/limestone.
- In class A2, the subsurface around the lake consists of 10–50% sand or chalk/limestone.
- In class A3, the subsurface around the lake is dominated by clay materials (>90% clay).

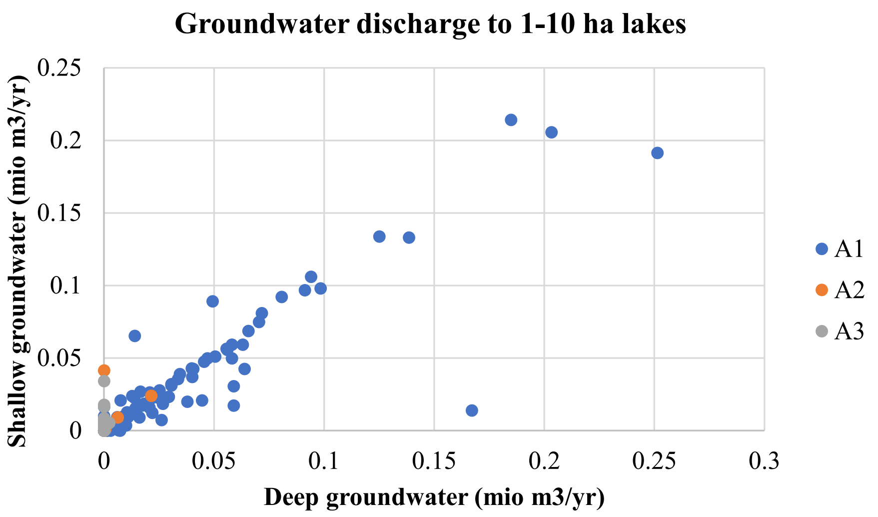
The groundwater inflow into lakes estimated from the DK-model is shown in Figure 8, divided into smaller (1–10 ha) and larger (>10 ha) lakes. The hydraulic conductivity of the geological layers surrounding the lakes in the DK-model is calibrated against the hydraulic head levels near the lakes. The figure shows that VP3 lakes with a good connectivity between groundwater and the lake (A1) have the most significant inflow of groundwater from both, deep and shallow groundwater flow paths. Conversely, groundwater discharge into the lakes with the subsurface dominated by clay materials (A3) is significantly lower. Further, groundwater discharge into small lakes (up to ca. 0.25 mio m^3/yr) is significantly lower compared to the lakes >10 ha with groundwater discharge up to ca. 5 mio m^3/yr, as the DK-model is scaled in relation to the lake area. Validation of the implemented lake concept in the DK-model is described in Troldborg et al. (2024). Moreover, model-estimated lake water balances have been compared to field-based water balances and related to lake geology and typology.

In the next step, the probability of groundwater-lake contact can be assessed based on the geological conditions near the lake and the distance from the top of the groundwater body (aquifer) underneath the lake to the mean or the maximum lake depth (Nilsson et al., 2023):

- B1 – Very high likelihood of contact: DGVF-Dmid <5m and DGVF-Dmax ≤3m.
- B2 – High likelihood of contact: DGVF-Dmid <5m and DGVF-Dmax >3m.
- B3 – Moderate to low (no) likelihood of contact: DGVF-Dmid ≥5m.

Here, DGVF represents depth to the top of the aquifer underneath the lake, and Dmid and Dmax are the mean and the maximum lake depths, respectively.

Table 4 shows the expected high probability of contact between groundwater and the majority of VP3 lakes surrounded by highly permeable geological material (B1-A1). Conversely, the majority of lakes located in clay layers are classified as having a low probability of contact with groundwater (B3-A3). However, there are 15 lakes located in sand/chalk (A1) and classified as having a moderate to low likelihood of contact with groundwater. In contrast, 17 lakes embedded in clay (A3) have a high to very high probability of contact with groundwater.



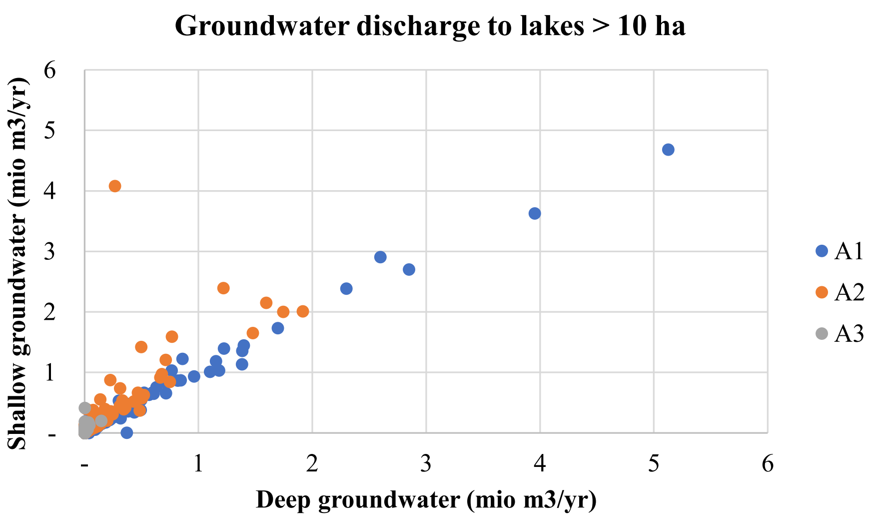


Figure 8. Groundwater flow into VP3 lakes via the near-surface and deep flow path, as estimated from the DK-model outputs and divided into the three groundwater-lake contact types A1, A2, and A3 derived by Nilsson et al. (2023).

Table 4. The number of lakes within the three geology scenarios of the likelihood of contact between groundwater and the lake.

Likelihood of contact	Geology scenarios		
	A1	A2	A3
B1	396	174	16
B2	21	9	1
B3	15	112	89
In total	432	295	106

4.3 Estimated groundwater P loading into lakes

The estimated P loading via groundwater to smaller (1–10 ha) and larger (>10 ha) VP3 lakes is shown in Figures 9 and 10.

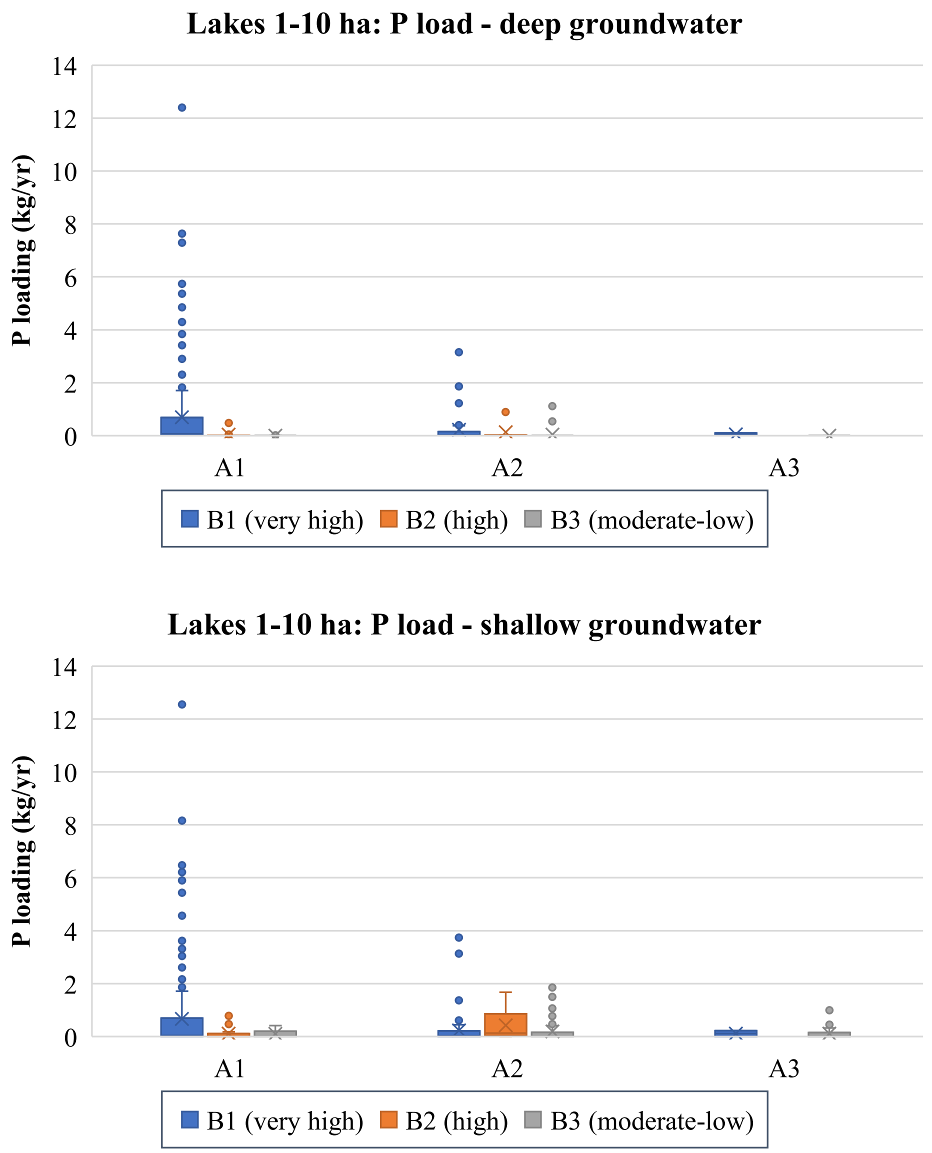


Figure 9. Box plot of P loading into smaller VP3 lakes (1–10 ha; n=426 lakes) via deep and shallow groundwater flow path. The VP3 lakes are classified into three hydrogeological classes: A1) >50% sand/chalk-limestone; A2) 10–50% sand/chalk-limestone; A3) >90% clay, with three likelihood sub-classes of groundwater-lake contact: B1) very high probability; B2) high probability; and B3) moderate to low probability.

It appears that there is no significant difference in the groundwater P loading into both smaller and larger lakes, via a deep (regional) or shallow (local) flow path (Figure 9, 10, and Table 5). Groundwater P loading into lakes >10 ha is at least an order of magnitude higher than into smaller lakes, which is related to higher groundwater volumes discharged into these lakes. Discharge of groundwater with high P concentrations via both local and regional flow paths has been reported in previous studies. Kazmierczak et al. (2020) documented mobilization of P in the shallow sandy aquifer near Lake Væng, while part of the groundwater P loading into the lake originated from the regional flow path. Groundwater P loading via a deep (regional) flow path into esker lakes was also reported from Finland by Ala-aho et al. (2013).

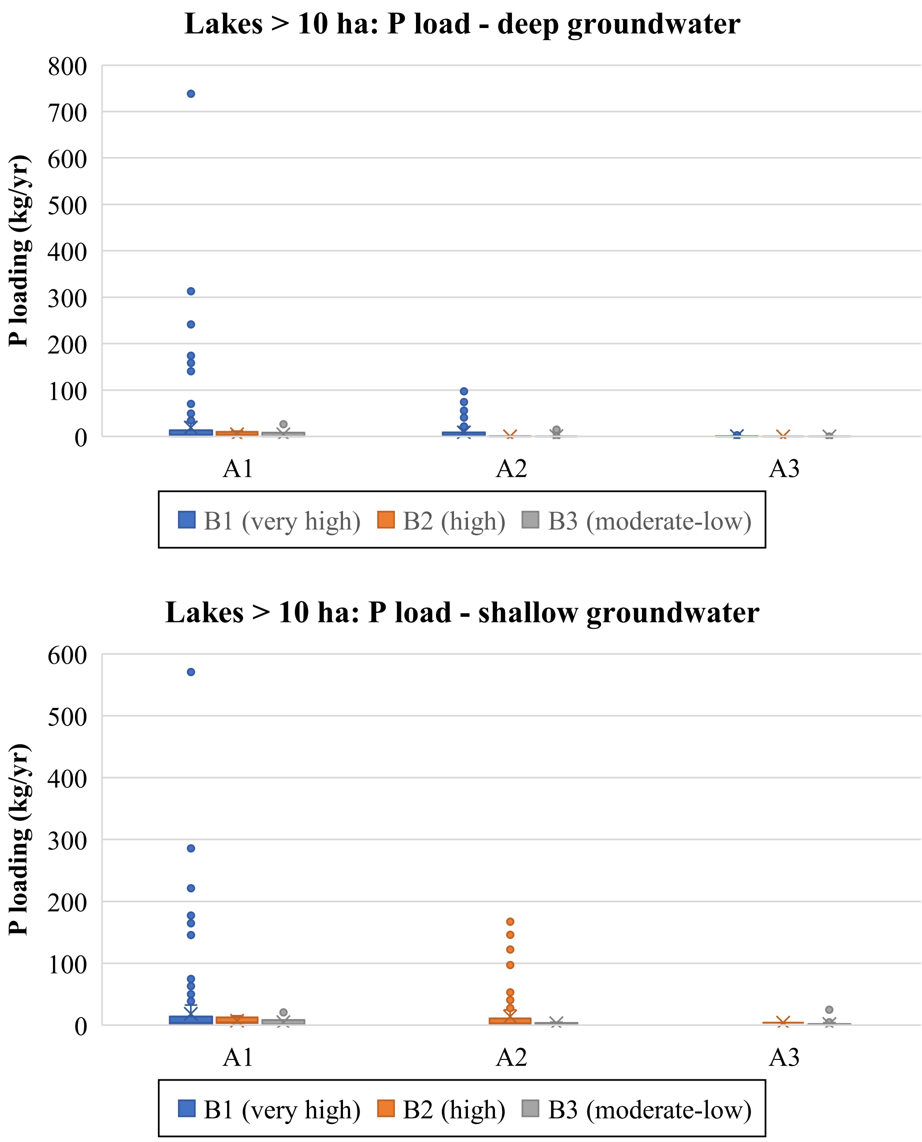


Figure 10. Box plot of P loading into larger VP3 lakes (>10 ha; n=406 lakes) via deep and shallow groundwater flow path. The VP3 lakes are classified into three hydrogeological classes: A1) >50% sand/chalk-limestone; A2) 10–50% sand/chalk-limestone; A3) >90% clay, with three likelihood sub-classes of groundwater-lake contact: B1) very high probability; B2) high probability; and B3) moderate to low probability.

The six lakes with the highest P loading via the deep groundwater flow path (>100 kg P/yr) are all lakes with a surface area >10 ha, categorized by Nilsson et al. (2023) as groundwater-lake contact type A1 with a very high probability of contact, B1 (Figure 10, Table 5). Loading of P from shallow groundwater to smaller lakes reaches a maximum of ca. 12.5 kg P/yr (Figure 9, Table 5). As expected, these lakes are linked to groundwater-lake contact types A1 and A2. 247 smaller lakes that do not receive external P loading via either deep or shallow groundwater flow path are in the contact probability classes high (B2) and moderate to low (no) contact (B3).

The estimated P loading via deep or shallow groundwater flow paths is summarized in Table 5. Larger lakes receive in total approximately 30 times more groundwater P than the smaller lakes. An average estimated P loading to the VP3 lakes >10 ha is 12.9 kg P/yr via shallow and 11.1 kg P/yr via deep groundwater flow path and larger than P loading to the small lakes. The average P loading to the smaller lakes is the same for shallow and deep groundwater flow path and of 0.4 kg P/yr.

Table 5. Summary of model-estimated P loads from shallow and deep groundwater to VP3 lakes.

P load (kg P/year)	**1–10 ha** n=426		**>10 ha** n=406	
	Shallow	Deep	Shallow	Deep
Min	0.0	0.0	0.0	0.0
Max	12.4	12.5	571	738
Mean	0.4	0.4	12.9	11.1
Mean A1-B1	0.7	0.7	18.4	18.8
Mean A1-B2	0.1	0.04	6.9	4.7
Mean A1-B3	0.1	0.003	4.7	4.8
Mean A2-B1	0.2	0.2	-	8.7
Mean A2-B2	0.4	0.13	13.9	0.3
Mean A2-B3	0.2	0.04	2.9	0.7
Mean A3-B1	0.1	0	-	0.5
Mean A3-B2	-	-	3.8	0.003
Mean A3-B3	0.1	0	1.7	0.1

Groundwater P loading into lake typology classes (MST, 2023) is presented in Figure 11. Lakes with the target lake water P concentrations between 29–31 µg/L, typology 1, 2, 5, 6, and 10, potentially receive the highest groundwater P loading. The highest mean groundwater P loading is estimated for lake typologies 9, 11, and 12, with the target lake water P concentration of 53 µg/L.

Although diffuse groundwater discharge of anthropogenic P to lakes has been reported in Europe (e.g. Lewandowski et al., 2015), geogenic P sources seem to be of major importance in groundwater-lake interactions in Denmark, as shown in the recent studies at Vængsø and Nørresø (Nisbeth et al., 2019b; Kazmierczak et al., 2020). Different geological conditions in these two areas underpin the possibility that geogenic groundwater P loading impacts other lakes in Denmark. P in anoxic Danish aquifers is mobilized by reduction of P-enriched iron hydroxides by organic matter (Kazmierczak et al., 2020). Under oxidizing conditions, P rapidly adsorbs onto iron hydroxides (Kazmierczak et al., 2020). Thus, in sandy areas with oxic unsaturated zones, groundwater P concentrations are low in the upper oxic groundwater and increase with depth, as the reducing conditions prevail (Figure 1; Thorling et al., 2019).

Significant fluxes of P from diffuse anthropogenic sources, e.g. fertilizers, can reach lakes via groundwater only under reducing conditions. In Denmark shallow redox interface (up to 5 m below ground surface) occurs in fully waterlogged areas along paleochannels in Jutland, and in the till deposits in the eastern part of the country (Koch et al., 2024). It is unlikely for leached anthropogenic P to reach aquifers below the till deposits with low permeability due to the sorption properties of the clay minerals. Further, lakes situated in till deposits only are not groundwater-fed (see Section 4.2). Thus, it is assumed that anthropogenic sources are not significantly contributing to groundwater P concentrations in Denmark, and to groundwater P loading into VP3 lakes.

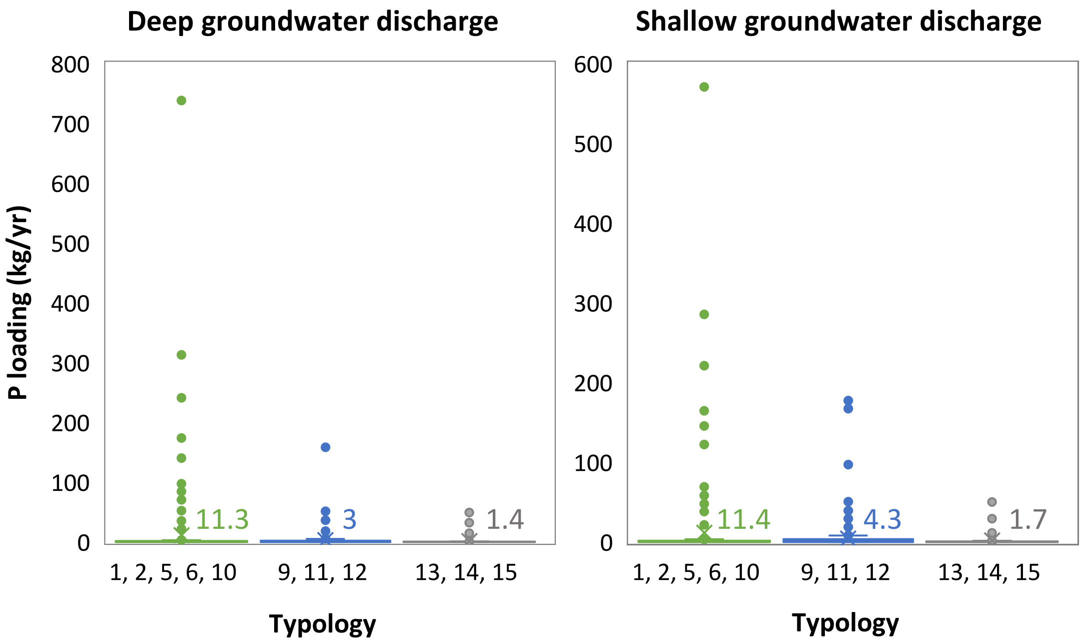


Figure 11. Groundwater P loading into lakes via deep and shallow flow path divided by lake typology classes. The target lake water P concentrations in classes 1, 2, 5, 6, and 10 are 29–31 µg/L, in classes 9, 11, and 12 the target is 53 µg P/L, and in classes 13, 14, and 15 the target was set to 61 µg P/L. Numbers in the figure represent mean P loading in each combined lake typology group via deep and shallow groundwater discharge.

4.4 P adsorption at the sediment-lake interface

Kazmierczak et al. (2020; 2021) showed that groundwater P loading into lakes is mainly controlled by groundwater flow velocity and redox conditions at the sediment-lake interface. At low groundwater flow velocities and under oxic conditions in the lake water column, oxygen back-diffuses from the lake into the aquifer, and P transported via groundwater is adsorbed into iron hydroxides at the sediment-water interface (Kazmierczak et al., 2020). At groundwater flow velocities below 0.001 m/d, nearly all P transported via groundwater is adsorbed by iron hydroxides at the sediment-lake interface, while at groundwater flow velocities above 0.1 m/d, over 73% of P transported via groundwater discharges directly into the lake

(Figure 12). Thus, the groundwater P loading into lakes estimated in Section 4.3 may be significantly buffered under certain hydrogeochemical conditions at the sediment-lake interface.

Hydrogeochemical conditions favoring P adsorption at the sediment-lake interface may occur at low groundwater discharge zones, in areas where groundwater contains high iron (Fe^{2+}) concentrations. In contact with oxygen, Fe^{2+} readily precipitates as iron hydroxides to which the dissolved P is adsorbed (Figure 12). Xenakis et al. (2026) showed a strong relationship between high groundwater P and Fe^{2+} concentrations in Denmark, and hydrogeochemical buffering of the direct groundwater P loading into VP3 lakes may be expected. However, the scale of these buffering processes is still unexplored.

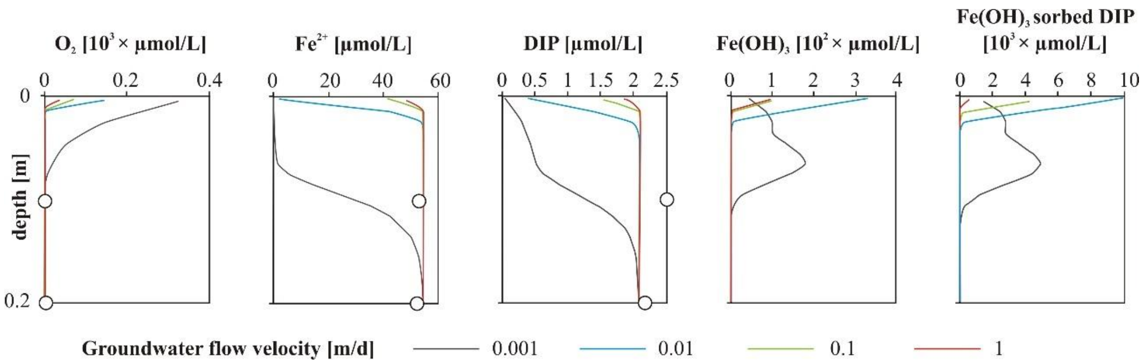


Figure 12. Groundwater P (here indicated as dissolved inorganic P – DIP) adsorption at the sediment-lake interface at various flow velocities (Kazmierczak et al., 2020).

It is noted that groundwater flow velocities at the sediment-lake interface can be highly heterogeneous and vary orders of magnitude over a small lakebed area (Kazmierczak et al., 2016). Thus, the preferential groundwater discharge and P loading paths can be expected at VP3 lakes, especially in the cases of a very high and high probability of groundwater-lake contact. On the other hand, groundwater, and thus P discharge rate into lakes, can be limited by thick, low-permeable gyttja layers acting as flow barriers at lake bottoms (Kazmierczak et al., 2016). The abovementioned factors should be taken into account when investigating the impact of groundwater on the individual VP3 lakes. However, the impact of these local processes at individual VP3 lakes cannot be assessed based on the currently available national datasets due to the discretization limitations. For instance, the coarse discretization of the DK-model (100×100 m) does not capture the observed high groundwater discharge zones at Danish lakes, e.g. approximately 2×20 m at Lake Væng reported by Kazmierczak et al. (2016).

5. Impact of groundwater on P-related ecological lake status

5.1 Methods

Machine learning models were developed to predict lake P concentrations based on the provided measured lake P concentrations as training data (Table 6). The models used the predictions of groundwater P concentrations performed in this study, and the identified archive datasets with environmental variables relevant to lake water P concentrations. The covariates employed in the machine learning models are summarized in Table 6. The catchment covariates, e.g. elevation and clay content, are an average value calculated for 1 km buffer zones around VP3 lakes using zonal statistics in ArcGIS Pro. For geomorphology and soil classes, the most frequent class occurring in the 1 km buffer zone around each VP3 lake was assigned, and for landfills in lake catchments, binary values yes/no were assigned. The near-lake covariates are average values of hydrogeochemical variables in a 100 m buffer zone around VP3 lakes. Prior to the machine learning analysis, we have analyzed the relationships between groundwater P classes, groundwater discharge rates, and lake P concentrations. The results are presented in Section 5.2.

The machine learning analysis was based on a regression model using the gradient boosting with decision tree implementation of Microsoft's LightGBM in Python. The preparation of the training dataset included the extraction of relevant environmental variables for the VP3 lakes with measured and unmeasured P concentrations. The following modeling steps were carried out: 1) hyperparameter tuning, 2) cross-validation, 3) sensitivity analysis, and 4) prediction of P concentrations in unmeasured VP3 lakes.

In the hyperparameter tuning step, selected model parameters were tested in a grid-search approach, covering all possible test combinations. The following model parameters were included in the hyperparameter tuning: learning_rate, num_leaves, max_depth, and min_data_in_leaf. The best performing parameter set was employed for further modeling.

The overall performance of the model was evaluated in a separate three-fold cross-validation step using the best-performing hyperparameter set. Here, three models were trained, each on a subset of randomly selected 66% of lakes with measured P concentrations. The models were validated on the remaining 33% of lakes with measured P concentrations. Mean error (ME), mean absolute error (MAE), root mean squared error (RMSE), and Pearson correlation coefficient (r) were calculated for each of the models.

For the sensitivity analysis, we employed the SHAP method that outputs the sensitivity of the in-lake P predictions to the used environmental variables. SHAP provides both an estimate of the magnitude of sensitivity and the direction of impact.

In the last step, the unmeasured lake P concentrations were predicted with a model trained against all available lake P concentration data to obtain the best possible generalizability.

Table 6. Overview of the covariates and the training datasets used in modeling. The training datasets are highlighted in orange.

Type	Covariate name	Description
Groundwater P predictions	P_0029	Probability of groundwater P concentration >29 µg/L
	P_0053	Probability of groundwater P concentration >53 µg/L
	P_0061	Probability of groundwater P concentration >61 µg/L
	P_class	Groundwater P classes derived in Section 3.3
Catchment 1 km buffer	Clay_a	Content (%) of clay in 0–30 cm bgs
	Clay_b	Content (%) of clay in 30–60 cm bgs
	Clay_c	Content (%) of clay in 60–100 cm bgs
	Clay_d	Content (%) of clay in 100–200 cm bgs
	Silt_a	Content (%) of silt in 0–30 cm bgs
	Silt_b	Content (%) of silt in 30–60 cm bgs
	Silt_c	Content (%) of silt in 60–100 cm bgs
	Silt_d	Content (%) of silt in 100–200 cm bgs
	Fsand_a	Content (%) of fine sand in 0–30 cm bgs
	Fsand_b	Content (%) of fine sand in 30–60 cm bgs
	Fsand_c	Content (%) of fine sand in 60–100 cm bgs
	Fsand_d	Content (%) of fine sand in 100–200 cm bgs
	Gsand_a	Content (%) of coarse sand in 0–30 cm bgs
	Gsand_b	Content (%) of coarse sand in 30–60 cm bgs
	Gsand_c	Content (%) of coarse sand in 60–100 cm bgs
	Gsand_d	Content (%) of coarse sand in 100–200 cm bgs
	DEM	Elevation above sea level (m)
	Slope	Surface slope gradient in (degrees)
	Geomorphology	Geomorphology classes
	Soil	Soil classes
	Landfill	Landfills within 1 km buffer zone, 1 – YES, 0 – NO
Near-lake 100 m buffer	Dtp_mean	Mean depth to groundwater table from DK-model (m)
	Precip	Precipitation (m/yr)
	Redox	Depth to redox interface (mbgs); Koch et al. (2024)
	Wetland	Wetlands coverage in the buffer zone (%)
DCE water-shed model	DCE_VandUd	Calculated water outflow from lakes (m^3/yr)
	DCE_P_Ud	Calculated P discharge from lakes (kg/yr)
	DCE_P_Ind	Calculated P inflow to lakes (kg/yr)
Lake geometry	Depth_mid	Mean lake depth (m)
	Depth_max	Maximum lake depth (m)
	Area_m2	Lake area (m^2)
Ecology	Typology	Lake typology
DK model	Flux_deep	DK-model, deep groundwater flux into lakes (mm/yr)
	Flux_shallow	DK-model, shallow groundwater flux into lakes (mm/yr)
	MAX_Q90	DK-model, maximum upstream Q (mm/yr)
	MIN_Q90	DK-model, minimum downstream Q (mm/yr)
	MIN_average	DK-model, average upstream Q (mm/yr)
	MAX_average	DK-model, average downstream Q (mm/yr)

	Groundwater_m3_yr	Deep groundwater discharge into lake (m^3/yr)
	Shallow_m3_yr	Shallow groundwater discharge into lake (m^3/yr)
	Total_m3_yr	Groundwater discharge into lake (m^3/yr)
Nilsson et al. (2023)	Likelihood_depth	Likelihood of groundwater discharge to the lake based on depth relation to aquifers (Nilsson et al., 2023)
	Likelihood_distance	Likelihood of groundwater discharge to the lake based on distance relation to aquifers (Nilsson et al., 2023)
	Likelihood_geology	Likelihood of groundwater discharge to the lake based on geology (Nilsson et al., 2023)
SGAV calculations	SGAV_residence_time	Calculated water residence time in years
In-lake P concentrations	SGAV_TP_summer	Average TP concentrations in lakes in the summer (mg/L)
	SGAV_orthoP_summer	Average ortho-P concentrations in lakes in the summer (mg/L)
	SGAV_P_mean	Mean TP concentrations in lakes (mg/L)

5.2 Trend analysis

Mean TP concentrations in VP3 lakes were compared with 1) the estimated groundwater discharge via deep and shallow flow paths, and 2) the derived groundwater P classes. Figure 13 indicates a diluting impact of groundwater on lake water P concentrations. Low lake water P concentrations are measured at the highest groundwater flux rates. The predicted groundwater P concentrations are <29 µg/L (P class 1) beneath seven out of ten lakes with the highest deep groundwater flux rates, and eight out of ten lakes with the highest shallow groundwater flux rates. In the remaining three and two lakes with the highest deep and shallow groundwater flux rates, predicted groundwater P concentrations are above 61 µg/L (P class 4). These lakes belong to the typology classes 1, 5, 9, and 10. Although groundwater discharge into lakes may potentially improve ecological lake status, high groundwater flux rates are observed across all groundwater P classes and lake typology groups. Similarly, lakes with the highest lake P concentrations and lowest groundwater flux rates are connected to aquifers across all four groundwater P classes.

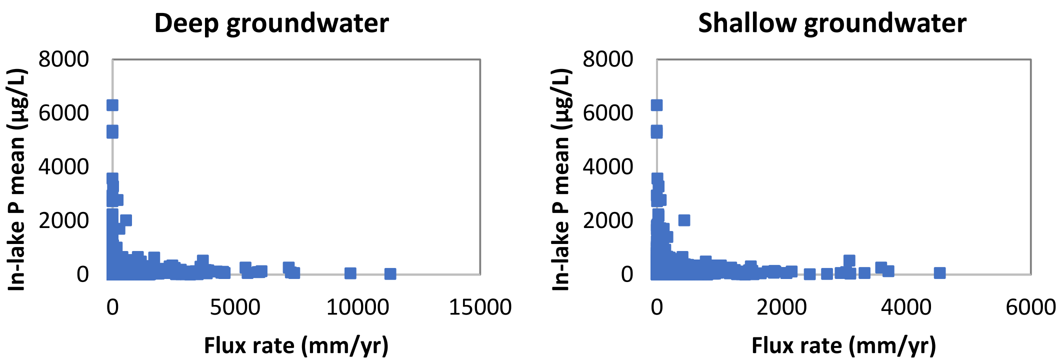


Figure 13. Lake water P concentrations at various deep and shallow groundwater flux rates into VP3 lakes derived from the DK-model.

VP3 lakes with the lowest deep and shallow groundwater flux rates have the highest mean TP concentrations. However, these lakes are interacting with groundwater in class 4 with P concentrations above 61 µg/L (Figure 14). Further, after excluding the outliers, VP3 lakes connected to groundwater in class 3 with P concentrations above 53 µg/L display the highest lake water TP concentrations. It shows that even at low flux rates, P-enriched groundwater may have a negative impact on the ecological lake status under certain hydrogeochemical conditions, preventing P adsorption at the sediment-lake interface (Section 4.4).

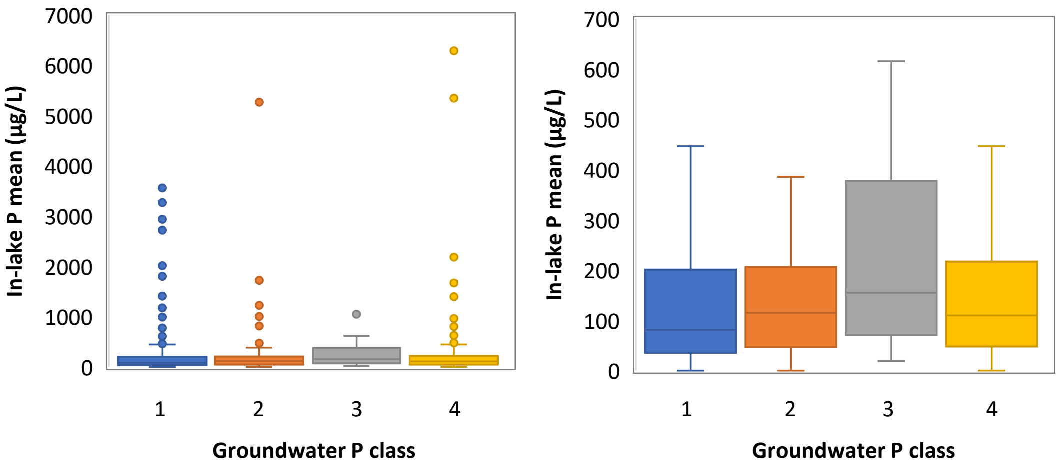


Figure 14. Distribution of the mean lake water TP concentrations in groundwater P classes. Groundwater P classes are described in Section 3.3. The boxplot to the right is a zoom-in of the boxplot to the left, excluding the outliers.

The relationships between lake water P concentrations, groundwater, and the catchment parameters are complex. It is noted that at the lake water TP concentrations below 1000 µg/L, there is no clear relationship between groundwater flux rates and lake water TP content (Figure 13). Groundwater TP and ortho-P concentrations below 1000 µg/L are common near the lakes (Table 3). Thus, we have applied machine learning models to gain new insights on the connections between lake water P levels, groundwater discharge, and groundwater P concentrations. The results of the preliminary machine learning models for predictions of lake water P concentrations are described in Sections 5.3 and 5.4.

5.3 Lake water P predictions

We trained the models for the mean summer ortho-P, mean summer TP, and mean TP in lake water. The results of the three-fold cross validation using the best performing hyperparameter set are shown in Table 7. Overall, all models have a low bias (ME), but errors are significant as indicated by high MAE and RMSE. Correlation is also low, especially for summer ortho-P and summer TP. The best performing model is the one trained on the mean TP lake water concentrations, and in the following sections, only the results from the mean TP model are shown.

The cross-validation results for the model trained on the mean TP lake water concentrations are shown in more detail in the scatter plot (Figure 15). High TP concentrations in VP3 lakes are generally underestimated, while low TP concentrations in VP3 lakes tend to be overestimated.

Table 7. Performance of the models trained on various datasets.

Training dataset	ME (µg/L)	MAE (µg/L)	RMSE (µg/L)	R
Mean ortho-P summer	10	130	330	0.06
Mean TP	10	190	420	0.5
Mean TP summer	20	240	740	0.30

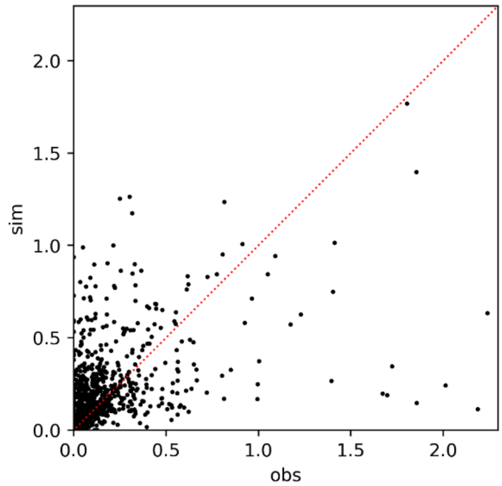


Figure 15. Simulated vs. observed mean TP concentrations in mg/L in VP3 lakes.

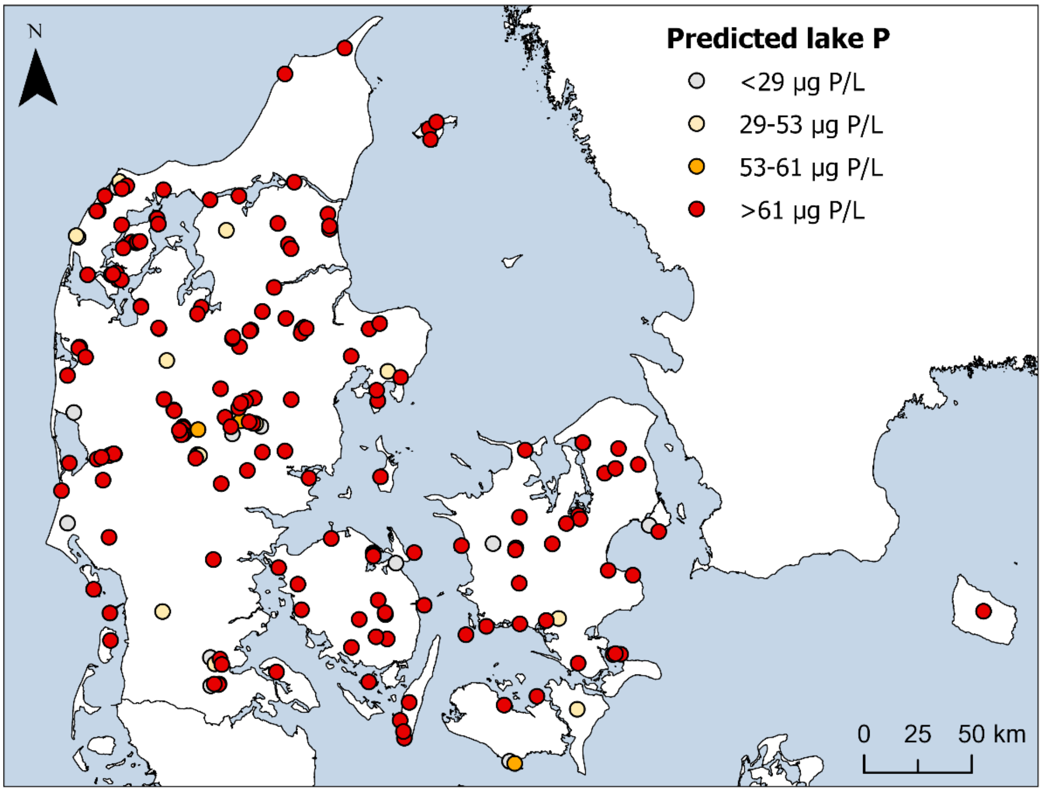


Figure 16. Predicted lake water TP concentrations in unmeasured VP3 lakes.

Predicted lake water TP concentrations in unmeasured VP3 lakes are shown in Figure 16. The model predicts lake water TP concentrations above 61 µg/L in the majority of the unmeasured VP3 lakes. The majority of these lakes are shallow with a small surface area. The distribution of predicted lake P concentrations in various groundwater P classes (Figure 17) is comparable to the distribution of the measured lake P concentrations (Figure 14), with the highest lake P concentrations related to groundwater P class 3. The significant MAE and RMSE indicates high uncertainty of the preliminary machine learning model for lake water P predictions. Thus, the modeling results displayed in Figures 16 and 17 should be regarded as an indicator of locations for ground truthing of impact of high groundwater P concentrations on ecological lake status.

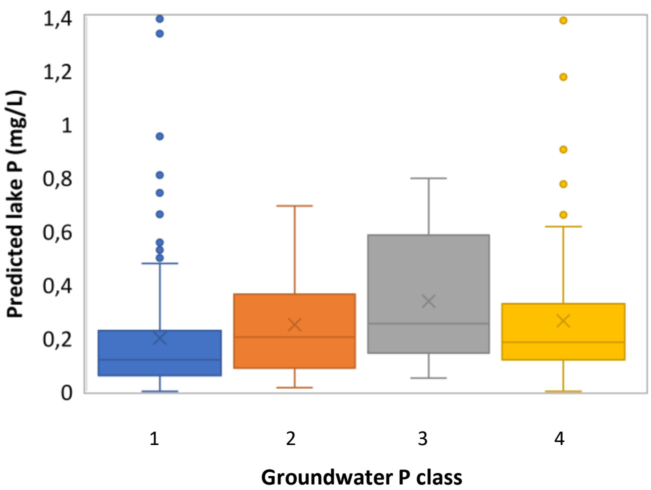


Figure 17. Distribution of the predicted lake water TP concentrations in groundwater P classes. Groundwater P classes are described in Section 3.3.

5.4 Groundwater P – watershed – lake P relationships

Based on the SHAP analysis, the most sensitive environmental variables were 1) typology, 2) content of fine sand in the catchment in the uppermost 0 – 30 cm soil layer, 3) catchment elevation, 4) precipitation, 5) mean lake depth, 6) content of silt in the catchment in the uppermost 0–30 cm soil layer, 7) maximum lake depth, 8) outflow of P in the DCE watershed model, 9) depth to the redox interface, and 10) water outflow in the DCE watershed model. In Figures 18 and 19, we show partial dependency plots that display the SHAP values, i.e. sensitivity scores, for all measured VP3 lakes, for selected environmental variables. The outflow variables from the DCE watershed model are omitted in Figure 18, as P concentrations in streams at outflow points from lakes depend on lake P concentrations.

The partial dependency plots contain the distribution of the environmental variable as a grey histogram on the x-axis and the SHAP value of each lake indicated as blue dots. Positive SHAP values contribute to higher predicted lake water TP concentrations in the final model, whereas negative SHAP values contribute to lower predicted lake water TP concentrations. The absolute SHAP value can be understood as the magnitude of the sensitivity. The changes from positive to negative SHAP values are of special relevance, as they allow for interpretation of the process-based relationships between lake water TP concentrations and groundwater and watershed variables.

High lake water TP concentrations are common in lake typology groups 13 and 15 that are characterized by the lowest mean lake depth among all typology classes (Figure 18).

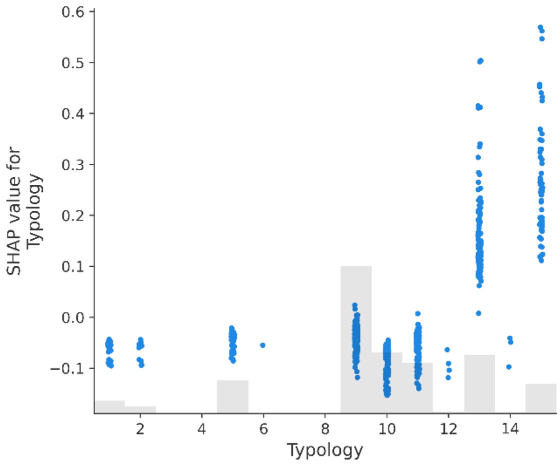


Figure 18. Relationship between lake typology and lake water TP concentrations.

An increase in the fine sand content in the uppermost soil layer in a 1 km buffer zone around lakes is connected to increasing lake water TP concentrations (Figure 19). Higher content of fine-grained particles in the catchment may indicate enhanced weathering processes, e.g. due to the forest removal or agriculture, and thus increased P loading via surface runoff from the lake catchment. Increased lake eutrophication during early Holocene forest clearance was reported for Lake Væng by Bennike et al. (2021).

High lake water TP concentrations are also common in the shallow lakes located low in the landscape (Figure 19). High groundwater P loading into the low-lying postglacial lakes was reported by Ala-aho et al. (2013) and Kazmierczak et al. (2020; 2021). The reasons for the observed relationship are: 1) low-lying lakes display a higher probability of groundwater discharge into the lake, 2) regional groundwater flow paths are often enriched in geogenic P due to the extended time of groundwater-rock interactions, and 3) old lake bottom sandy sediments may act as a source of the geogenic P (Ala-aho et al., 2013; Kazmierczak et al., 2020). These lakes also experience P loading from catchment weathering due to agricultural activities, e.g. forest clearance (Bennike et al., 2021).

Further, machine learning predictions indicate that precipitation has a diluting effect on lake water TP concentrations (Figure 19). The effect of groundwater chemistry on lake water TP concentrations is less pronounced, as lake water TP concentrations are a result of P inputs via multiple paths comprising surface runoff, groundwater and P release from in-lake sediments. However, VP3 lakes located in the areas with the redox interface (boundary between oxic and anoxic zone in the aquifer) occurring near the terrain surface have, in general, have higher lake water TP concentrations. High TP concentrations are also simulated for lakes located in areas with a high probability of groundwater P levels above 53 µg/L (Figure 19).

These observations are consistent with the findings by Kazmierczak et al. (2020; 2021) showing that under reducing conditions in areas with high groundwater dissolved P concentrations, high groundwater P loading into lakes may be expected. The reason for low predicted TP concentrations in VP3 lakes in the areas with shallow redox interface (1–2 mbgs) requires further exploration.

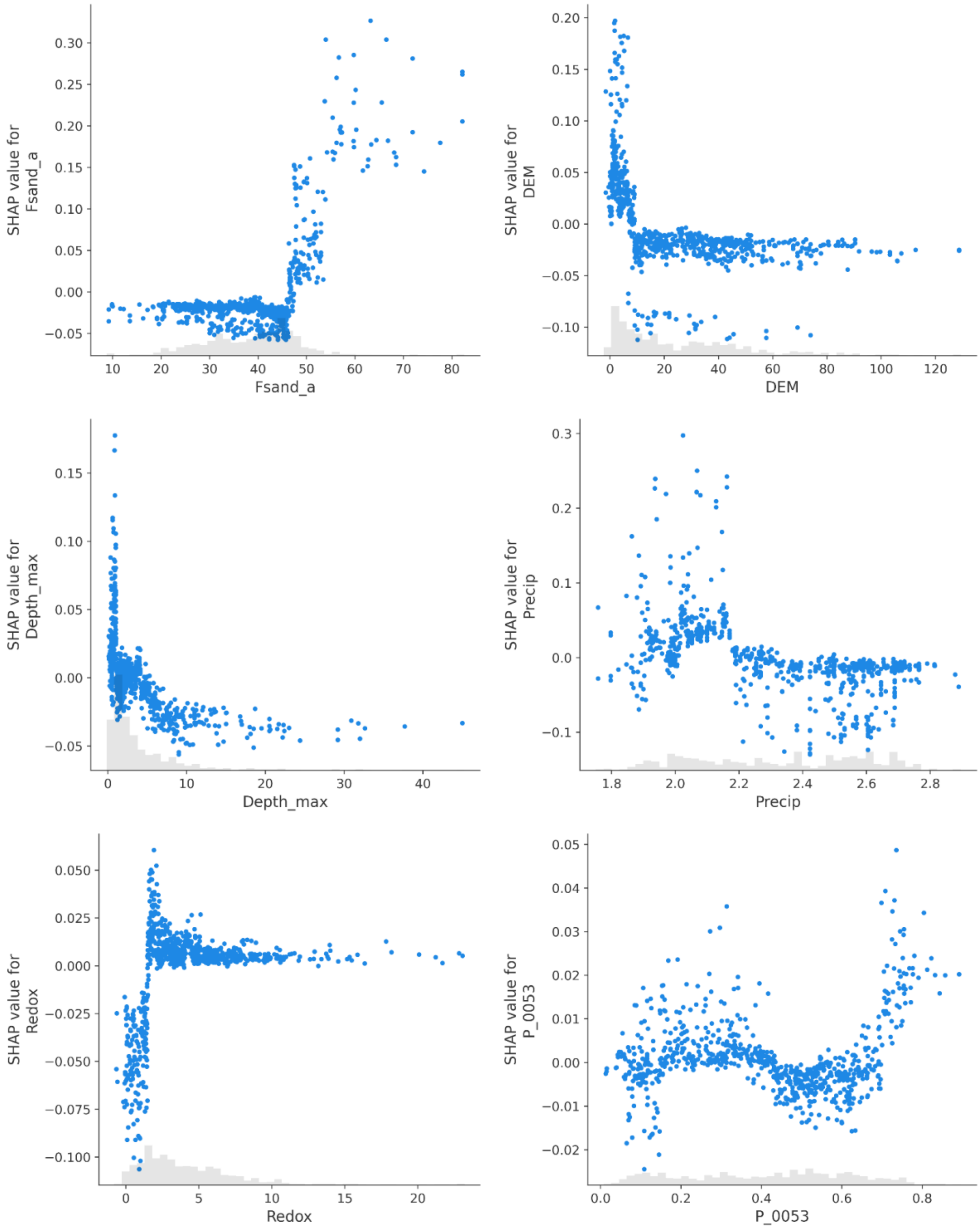


Figure 19. Relationship between the selected environmental variables and lake water TP concentrations. The covariate names are described in Table 6.

6. Uncertainty, limitations and recommendations

6.1 Groundwater P predictions

The groundwater P predictions at the threshold concentrations relevant for the ecological lake status are based on a national scale groundwater P models. These models may suffer from insufficient water chemistry from shallow wells. Only 353 out of 6959 well intakes with measured groundwater P are in the top 10 m below ground surface, coinciding with most of VP3 lake depths (average maximum lake depth of 7.6 m). Therefore, we evaluate that the groundwater P models are naturally most suitable for assessments of deeper aquifers, as the mean well intake depth in the training dataset is 48 m below ground surface. Neverthe-less, the derived groundwater P models fit well with field-based groundwater observations at four out of eight intensively studied lake catchments (Table 3).

Groundwater P predictions could be improved by accounting, in the modeling framework, for the complexity of groundwater-lake interactions, e.g. heterogeneous groundwater gradients and flow paths, and connections between lakes and groundwater. The follow-up predictions of groundwater P could be based, e.g. only on the wells located in the buffer zones around VP3 lakes from which groundwater discharge is expected (Figure 19) instead of the depth-specific predictions. This could be implemented by adding lake-specific covariates to include the spatial relationships between groundwater and lakes, e.g. well horizontal distance to the nearest lake, well depth relative to the nearest lake, or by the development of a three-dimen-sional groundwater P model.

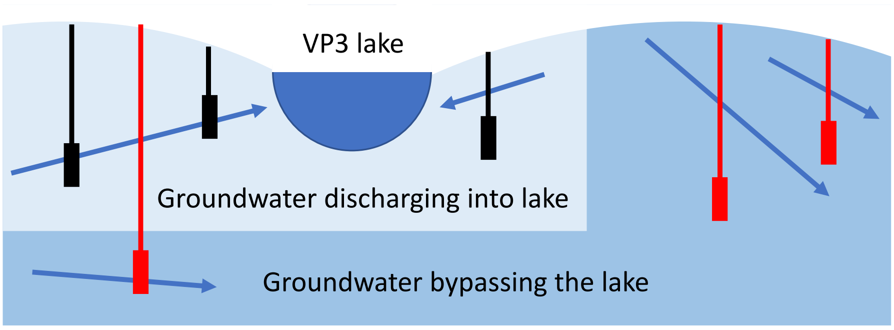


Figure 19. Concept for the improvement of groundwater P predictions related to the VP3 lakes. A systematic method should be developed to exclude from the training datasets wells capturing groundwater that bypasses VP3 lakes (wells marked in red), and include wells with groundwater potentially discharging into VP3 lakes despite the well depth exceeding the maximum lake depth. Blue arrows indicate simplified groundwater flow paths.

The models could also be improved by extending the dataset with groundwater P measure-ments in the samples collected in the vicinity of the selected lakes, e.g. from the private wells, as the highest groundwater P concentrations are expected at the end of the flow paths toward lakes (Ala-aho et al., 2013; Kazmierczak et al., 2020). These high P concentrations are likely not captured in the monitoring and waterwork wells, often located at distances above 0.5–2 km from lakes.

6.2 Modeled groundwater discharge into lakes

Groundwater discharge into lakes is highly heterogeneous, and the flux rate estimates are strongly connected to the numerical representation of the surface water bodies, including the model discretization (Kidmose et al., 2013; Karan et al., 2021). The discretization of the DK-model is 100×100 m, which significantly impacts the accuracy of the estimates of groundwater discharge into lakes with a surface area <10 ha. More precise groundwater discharge estimates into lakes larger than 10 ha could be provided by setting up lake-specific sub-models with a finer discretization based on the data from the DK-model.

Kazmierczak et al. (2016) showed that thick gyttja layers act as flow barriers for groundwater discharge into lakes. However, there is limited knowledge on the low-permeable in-lake sediments in VP3 lakes. Information on the presence/absence and extent of gyttja layers in VP3 lakes incorporated into the DK-model could significantly improve predictions of groundwater discharge.

6.3 Estimated groundwater P loading into lakes

Table 3 shows that there are very few field-based studies to compare the groundwater P predictions applied to estimate P loading from groundwater into VP3 lakes. We are aware of only eight field studies with extensive field-derived data on groundwater P. These data were applied for ground truthing of the groundwater P predictions. Seven out of the eight studied lakes are larger than 10 ha. Thus, there is a general lack of knowledge on field-measured groundwater P concentrations near the lakes, and especially near the smaller lakes. Further, all field-based observations are from the lakes with a very high to high probability of contact between groundwater and the lake. To our knowledge, there are no studies on P in groundwater-lake interactions at lakes with moderate to low probability of groundwater-lake contact. Thus, to improve groundwater P predictions and further validate estimates of groundwater P loading into VP3 lakes, we recommend a screening of groundwater P concentrations in the vicinity of the selected VP3 lakes, e.g. by sampling the private wells or hand-installed shallow piezometers.

6.4 Machine learning model for lake P predictions

We see an overall sensible sensitivity of the applied environmental variables in the predictions of mean TP concentrations in lakes. This underpins the general validity of the applied modeling framework. We observed an improvement in the model performance by shifting from the summer TP concentrations to the mean TP concentrations as the training dataset. The poorer model performance for the summer TP concentrations may be caused by the fact that the summer TP concentrations in lakes depend on numerous in-lake environmental variables that were not included in the modeling covariates, e.g. P release from the in-lake muddy sediments, biological activity. In the future, modeling of the winter P concentrations in lakes may be a more straightforward path with respect to understanding groundwater impact on lake P concentrations. The overall model could also be improved in collaboration with experts in e.g. ecology by the incorporation of in-lake covariates in the modeling framework.

It may also be of interest to investigate the performance of models using lake P predictions near groundwater P observations as substitute for the groundwater P variables presented in this report. In the suggested model setup, the well intakes should be characterized based on their elevation relative to the respective lake elevation and distance to the nearest lake. This would reflect the potential connectivity of well intakes with VP3 lakes, as in the study by Nilsson et al. (2023). The closest wells should then be used as direct inputs to the machine learning models of lake P predictions. The exact number of wells included in the new modeling framework should be investigated in different model scenarios. Application of the suggested model development would enable work with a single machine learning model instead of training two separate models, the first for the groundwater P concentrations and the second for the lake P concentrations.

Finally, lake P predictions could benefit from the additional field data collection suggested in Sections 6.1–6.3.

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