3D hydrodynamic modeling of Lake Zürich

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It’s been five incredible years, and I can’t help feeling a little nostalgic when I realize that it is now almost over.

“It is good to have an end to journey toward; but it is the journey that matters, in the end.”

Ursula K. Le Guin, The Left Hand of Darkness
Abstract

A three-dimensional hydrodynamic Z-model was conceived for Lake Zurich (Switzerland, ZH) using the modeling software Delft3D. Calibration was performed on the thermal profile in 2017 at three monitoring stations located in both basins, and was validated on years 2015 and 2016 with the same method. The model reproduced effectively thermal stratification and water temperature’s spatial and temporal variability. Specific hydrodynamic events were correctly simulated: upwellings were detected but their amplitude was underestimated; seiches periods were found accordingly to values reported in the literature. Hypolimnion’s temperature was nicely reproduced but results were less accurate in the epilimnion and especially in the metalimnion. Flow velocities were qualitatively evaluated and exhibited realistic values; the model was able to reproduce clockwise and counterclockwise flow rotation motions. Suggested improvements imply collecting more data about rivers, the importance of the latter on Obersee dynamics having been demonstrated, and the focus on wind drag coefficients in the calibration process.

Keywords: Lake Zurich, 3D modeling, Delft3D, calibration, hydrodynamics, water temperature, currents

Un modèle hydrodynamique 3D a été conçu pour le lac de Zürich (Suisse, ZH) à l’aide du logiciel de modélisation Delft3D. L’étalonnage a été effectué sur le profil thermique en 2017 et a été validé en 2015 et 2016 avec la même méthode. Le modèle reproduit efficacement la stratification thermique ainsi que la variabilité spatiale et temporelle de la température de l’eau. Les événements hydrodynamiques spécifiques sont correctement simulés: des remontées d’eau (upwellings) sont ainsi détectées mais leur amplitude a été sous-estimée. Les périodes des vagues internes (seiches) reportées dans la littérature ont été observées. La température en profondeur est bien reproduite mais est moins précise à la surface et surtout dans le thermocline. Les vitesses d’écoulement ont été évaluées qualitativement, et la plage de valeurs est réaliste; le modèle a été capable de reproduire des mouvements d’eaux tournant dans le sens normal et inverse des aiguilles d’une montre. Une amélioration du modèle passerait notamment par la collecte de données sur les rivières, l’importance de celles-ci ayant été démontrée pour la dynamique interne d’Obersee, ainsi qu’en axant principalement la calibration sur les coefficients de résistance au vent.

Mots-clés: Lac de Zürich, modèle 3D, Delft3D, calibration, hydrodynamique, température de l’eau, courants
## Contents

1 Introduction 1
   1.1 Water monitoring: a critical concern 1
   1.1.1 Lakes: a complex and vital ecosystem 1
   1.1.2 Lakes modeling and its importance 1
   1.2 Goals and ambitions of the project 2
   1.3 Study area: Lake Zurich 2
   1.3.1 Hydrology 2
   1.3.2 Climate 3
   1.3.3 Anthropogenic activities 3

2 Physics of lakes 5
   2.1 Energy transfers 5
      2.1.1 Heat transfer 5
      2.1.2 Momentum transfer 6
   2.2 Vertical stratification and seasonality 6
   2.3 Horizontal gradients 8
      2.3.1 Layers inclination and internal waves 8
      2.3.2 Upwellings 8
      2.3.3 Gyres 9
   2.4 Physics of Lake Zurich 10

3 State-of-the-art: context and background 12
   3.1 Lakes modeling: a worldwide challenge 12
      3.1.1 From 1D to 3D models 12
      3.1.2 Previous studies 12
   3.2 Lake Zurich: studies and modeling 17
   3.3 An online tool: meteolakes.ch 20

4 Methodology and Modeling 23
   4.1 Data and inputs 23
      4.1.1 Model forcing data: meteo and Secchi depth 23
      4.1.2 Water temperature data: calibration and validation 25
   4.2 Modeling Lake Zurich 25
      4.2.1 Delft3D: three-dimensional hydrological modeling 25
      4.2.2 Horizontal and vertical resolution 25
      4.2.3 Parameters considered 26
   4.3 Method 30
      4.3.1 Baseline 30
      4.3.2 Calibrated model 31

5 Results and Discussion 33
   5.1 Results 33
      5.1.1 Model calibration 33
      5.1.2 Model validation 34
      5.1.3 Water temperature profile: in-depth analysis 35
      5.1.4 Physical processes 38
   5.2 Discussion 42
      5.2.1 Model setup 42
      5.2.2 Sensitivity analysis 43
      5.2.3 Water temperature profile: model validation 44
5.2.4 Physical processes .......................................................... 45
5.2.5 Upwellings ................................................................. 45
5.2.6 Flow velocity .............................................................. 45
5.2.7 Perspectives ............................................................... 45

6 Conclusion 47

Appendices 52
A Monitoring stations’ depth profiles ....................................... 52
B Comparison: Stäfa and Thalwil’s simulated temperature profile ........................................ 53
C Comparison: Stäfa and Thalwil’s observed temperature profile ........................................ 54
D Baseline results ................................................................. 55
E Model 1 (M1) calibration results .......................................... 58
F Model 1 (M1) validation ....................................................... 59
  F.1 Performance in 2015 ..................................................... 59
  F.2 Performance in 2016 ..................................................... 60
G Thalwil water temperature profiles in 2017 .............................. 61
H Daily temperature profile for Limmat .................................... 63
I Upwelling events ............................................................. 64
1.1 Impact of the climate change. Monthly averaged temperature differences between the 25 last years (1992-2017) and the 25 first years of measurements (1936-1961) show a global warming of the water body. ................................. 3

1.2 Map of the wastewater treatment plants around Lake Zurich. The installations are represented by red dots (Source: Swiss Geocatalog, ARA - Capacity(PE) [47]). The dam separation between the two basins is highlighted in yellow. The Etzelwerk powerplant location is indicated by a blue square. From left to right, yellow triangles indicate the location of the Thalwil (T), Stäfa (S) and Lachen (L) monitoring stations. ......... 4

2.1 Summary of the main external driving forces exerting water motions as a dynamic response of the lake. Adapted from Hoffmann, 2015 [28] and Socolofsky & Jrka, 2005 [69]. ......................................................... 6

2.2 Freshwater density function. Source: The Sextant ......................................................... 7

2.3 Illustration of an upwelling event. Source: National Oceanic and Atmospheric Administration (NOAA). ......................................................... 9

2.4 Illustration of a strong and wide oceanic gyre. Source: National Geographic Society. . . 9

2.5 Water temperature profile observed at the Thalwil monitoring station at several depths in 2015, 2016 and 2017. The thermal homogeneity, linked to the almost complete mixing between the layers, can be observed each year in the January-March period. ................................. 10

2.6 Quarterly averaged temperatures observed at the Stäfa, Thalwil and Lachen monitoring stations in Lake Zurich (2017). A strong vertical mixing and thermal homogeneity are present in the first quarter (light green, dots). The sinking of the thermocline is visible through the rest of the year. ......................................................... 10

2.7 Water temperature profiles for the three monitoring stations in 2017, between a depth of 0 and 24 m. Color shading is obtained by linearly interpolating between measured values. Once again, thermal homogeneity can be observed at the beginning of the year, while a strong thermal stratification is established and the metalimnion sinks noticeably as time goes on. Spatial variability can be observed between the stations. ......................................................... 11

3.1 Results of the settling basin test showing accumulation of initially suspended sediment at the bed. Three simulations show the influence of the computational time step on the computed result. Source: Lesser, 2004 [42] ......................................................... 13

3.2 Hourly mean profiles of observed and simulated (a) water temperature and (b) horizontal current velocity at a given point C in Lake Créteil (France), along with the difference of water temperature between two other points P and R (c) for the calibration period between 17/09/2013 and 15/10/2013. The model’s performance can be qualitatively assessed. Source: Soulignac, 2017 [70]. ......................................................... 14

3.3 Comparison between observed and simulated water temperature (on the left) and Power Spectral Density (PSD) for water velocities in Lake Okeechobee (South Florida, USA). The model does reproduce the variability but amplitudes are underestimated. Source: Jin, 2000 [35] ......................................................... 15

3.4 Effect of warming and increased wind speed on mixing intensity during 51 winters from 1961 to 2011 in Lake Constance (Germany, Europe) assessed with numerical tracer experiments. The mixing index values $M_{idx}$ for various scenarios of (A) increased temperatures and (B) increased wind velocities are depicted as gray bars. The mixing index values of $S_{ref}$ are plotted as dots for the purpose of comparison. Source: Wahl & Peeters, 2014 [79]. ......................................................... 16
3.6 Comparison of the response of Lake Zurich (Switzerland) temperature to an air temperature raised by 4°C as predicted by continuous modeling (A, C, E) and by discontinuous modeling (B, D, F). Shown is the change in mean monthly water temperature in the epilimnion (A, B), the hypolimnion (C, D), and the temperature difference (\(T_{em} - T_h\)) (E, F) caused by raised air temperatures. Mean monthly temperature profiles were determined from temperature profiles simulated at 10-min intervals. Shown are mean values for a year after a winter with warm water temperatures (1989, open circles), for a year after a winter with cold water temperatures (1987, open triangles) and for the time period from 1985 to 1997 (solid triangles). Source: Peeters et al. (2002) [55].

3.7 Spectra of fluctuations of hourly mean temperature in Lake Zurich for the 1'000-h interval beginning 1'500 hours GMT on 10 August 1978: (a) at 14- and 30-m depth at mooring 9; (b) at seven depths (1.5-m spacing) at mooring 5 (7 August-22 September) plotted on common scales. The lower portion of panel b also displays the frequency distribution of coherence between temperature records from 10.5 and 18 m at mooring 5. In this and later figures, the TVDM-predicted periods for the first five internal (two-layer) modes are indicated by vertical broken lines; the 95% CL is a measure of the statistical significance of individual spectral estimates. The broad energy peak near 100 h is theorized to be linked to effects of topography and Earth’s rotation. Source: Schwegel et al., 2016 [64].

3.8 Computed (red) and measured (blue) water temperature profiles in Lake Zurich at the Thalwil monitoring station location. Differences between the two profiles are represented by black lines. Source: Hoffmann, 2015 [28].

3.9 Water velocities map for Lake Geneva on 1st July 2017 at 06:00 AM. Rotating currents can be found along the centered profile of the lake. Source: meteolakes.ch

3.10 Water temperature for Lake Geneva on 1st July 2017 at 06:00 AM. The upwelling predominantly localized at the north-western shore is reproduced by the model and affects a third of the lake. Source: meteolakes.ch

3.11 Surface water velocities Lake Geneva on 6th August 2018 at 06:00 PM. Strong currents are observed near the northern shore. Source: meteolakes.ch

4.1 Satellite image of Lake Zurich, and location of the monitoring stations used for calibration. From left to right: Thalwil (T), Stäfa (S) and Lachen (L). ©2018 Google

4.2 Secchi disk and its use (Source: IISG).

4.3 Secchi depth measurements at the Thalwil monitoring station over the years (Source: Wasserversorgung Zürich).

4.4 Final grid resolution and bathymetry of Lake Zurich. Thalwil (T), Stäfa (S) and Lachen (L) monitoring stations are represented by yellow diamonds, and rivers by purple dots. Blacks cells correspond to dry points. Vertical transects 1 (north) and 2 (south) are indicated by purple lines.


4.6 Delft3D wind drag coefficients pivots. A, B and C are set up by the user. Source: Delft3D-FLOW manual.

4.7 Wind speed distribution on Lake Zurich for year 2017. The median and the mean values are respectively indicated by a green and a red bar.

4.8 Temperatures differences between the baseline and observations at each station. The shading is obtained by linearly interpolating the values between each calculated difference.

4.9 Theoretical example of a Taylor diagram. The model (in red) can be visually compared to the observations (in grey) : the closer the model is from the center of the target, the highest is the performance.
5.3 Differences between simulated and observed temperature profiles in 2017 at the three monitoring stations. Over-estimations are highlighted in red, under-estimations in blue. Shading is obtained by linear interpolation between the values.  

5.4 Model performance for Stäfa. The final model (red line) is compared to the baseline (black dashed lines) and the observations (blue points). The thermocline is globally situated 1 m too high (as noticeable on 7th August). The unusual low temperature gradient on 8th May is also not reproduced.  

5.5 Model performance for Thalwil. The final model (red line) is compared to the baseline (black dashed lines) and the observations (blue points). In the lower part of the thermocline, the temperature gradient is too high.  

5.6 Model performance for Lachen. Observations are represented by blue points, while the baseline by the black dashed line and the final calibration by the red line. Huge improvements have been made since the baseline, but the position of the thermocline and the temperature gradient at its lower boundary remain problematic.  

5.7 Visualization of the simulated horizontal temperature distribution in Lake Zurich at 0.25, 2.5 and 4 m depth on 27th April 2017. Seedamm acts as a thermal separation between the two basins.  

5.8 Comparison between the Limmat modeled (red) and observed (blue) temperature profile at a depth of 7 m. Temperatures were measured every 10 min (Source: Canton of Zurich) and simulated every 2 hours. Main potential upwelling events are indicated by orange arrows.  

5.9 Temperature profile at 0.25 m, 2.5 m and 4 m depth on a) 7th June 2017 at 6:00 PM and b) 8th June 2017 at 2:00 AM.  

5.10 Temperature profile at the Thalwil monitoring station, from 1st to 7th September 2017, with a timestep of 15 min. Internal waves can be seen in the isotherms.  

5.11 Raw (orange) and smoothed (blue) periodogram of the temperature profile at a depth of 9 m. From left to right, the three black vertical lines correspond respectively to the 44h, 24h and 17h-periods found by Horn [29].  

5.12 Velocity map on 1st August, at 6:00 AM. Counterclockwise rotation can be observed in Obersee near Lachen’s location.  

5.13 Velocity map on 11th August, at 6:00 PM. Clockwise rotating flow is observed in Zurichsee near Stäfa.  

5.14 Velocity map on 14th December, at 16:00 PM. Strong currents are observed on the lake’s surface and are oriented towards the west.  

1 Simulated temperature profiles at Stäfa’s (blue) and Lachen’s location (green). Thalwil is not shown, as measurements were not made on the same days.  

2 Observations for Stäfa and Lachen monitoring stations. The difference of the thermoclines’ slope is clearly visible.  

3 Thalwil water temperature profile at Thalwil (baseline). While deep-water temperatures are correctly estimated, small difference can be seen at the surface and the thermocline’s depth is clearly overestimated.  

4 Thalwil water temperature profile at Stäfa (baseline). The same flaws than those observed at Thalwil are observed, but the higher slope of the metalimnion reduces the error between the computation and the observations. Deep-water temperature is also less precise and over-estimated.  

5 Temperature profile comparison after initialization: Lachen  

6 Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (darker tones) is compared to the final model M2 (lighter tones). Grey figures on the x-axis correspond to the observations.  

7 Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole in 2015. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (colored) is compared to the final model M2 (black). Grey figures on the x-axis correspond to the observations.  

8 Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole in 2016. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (darker tones) is compared to the final model M2 (lighter tones). Grey figures on the x-axis correspond to the observations.  

9 Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole in 2016. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (colored) is compared to the final model M2 (black). Grey figures on the x-axis correspond to the observations.  

10 Daily means of water temperature for the river Limmat. Source: canton of Zürich.
Temperature profile at 0.25 m, 2.5 m and 4 m depth on A) 19th April at 8:00 PM and B) 27th at 6:00 AM. Upwellings can be seen on the last layer, at the extremity of the lake.

Temperature profile at 0.25 m, 2.5 m and 4 m depth on a) 16th June 2017 at 2:00 PM and B) 17th at 4:00 AM. Once again, the upwelling event can mainly be observed on the last layer.
List of Tables

1.1 Zurichsee (Lower Lake) and Obersee (Upper Lake) characteristics. *Source: EAWAG*

4.1 Usual range of values used in previous lake and basin models for the parameters considered in the calibration and validation of the model. Note that all models were not conceived on Delft3D, thus the exact meaning in the model of these parameters may differ.

4.2 Baseline main parameters in Delft3D-FLOW, initial values and physical meaning.

5.1 Values of the parameters used in the baseline model and in the two calibrated models. The models performance is presented for a comparison.


5.3 Baseline’s and calibration’s performance indicators for each station.

5.4 Sensitivity analysis for the RMSE. Values indicated correspond to the increased (positive) or decreased (negative) performance percentage.

1 Measurements’ depth profiles for the stations, in meters.
1 | Introduction

1.1 Water monitoring: a critical concern

About 71% of Earth’s surface is covered by water: our "blue planet" shelters more than 1’260 million trillion liters of the precious liquid. Nonetheless, 96.5% of this tremendous quantity of water is contained in the oceans and is therefore saline, unfit for human consumption: only less than 3% of all water on Earth is freshable, with more than two thirds of this fraction trapped in ice caps and glaciers [51]. Finally, only about 0.036% of the planet’s total water supply is found and directly accessible in lakes and rivers, the rest being present in our atmosphere or in groundwaters.

Though water is present all around the globe, it is unequally distributed. Switzerland is known as “Europe’s water castle” [19] or “Europe’s water reservoir” [3] as it concentrates 6% of Europe’s freshwater storage despite the small size of the country. With several thousands of lakes, both natural and artificial, Switzerland has to fight against oxygen depletion and pollution (with micropollutants being the latest main challenge), though water quality improved since the 1980’s [21]. This requires a close monitoring of the lakes, especially when it comes to forecasts or to flood protection.

1.1.1 Lakes: a complex and vital ecosystem

From water storage, drinking water supply, buffering capacity against high flows or potential use for energy generation to tourism, fishing and other recreational activities, lakes offer many useful functions for human population on its shores. In Switzerland, natural lakes represent 50% of the country’s total water storage, which corresponds to \( \sim 2 \) years of precipitation [3]. Their environmental importance is also well-known: their role as a nutrient reservoir attracts various species in this particular habitat, making them shelter diverse and fragile ecosystems. Through evaporation or groundwater replenishment, lakes also play a vital role in water cycle.

However, anthropogenic activities are pressurizing more and more the environment: our own rejects decreases water quality and therefore its drinkability. Chemical compounds and pollution negatively affect biodiversity, and can cause such events as fishes feminizing or harmful algal blooms, the latter being expected to increase by at least 20% until 2050 in lakes [76]. The increasing urbanization of their shores also erodes their structure.

Ecological concerns have made their way in public opinion and in political agendas, as it became evident that a sustainable water management is impossible without assuring ecosystems’ health [75]. Efforts have been made, like the daily improvement of wastewater treatments or the banishment of phosphorous detergents which reduced significantly the overgrowth of aquatic plants and algal blooms.

1.1.2 Lakes modeling and its importance

Human pressure on lakes is inevitable. However, it is possible to design a sustainable way to exploit their resources and functions without harming the environment. Understanding the hidden hydraulic mechanisms, the natural evolution of the habitat and the impact of anthropogenic activities on it is necessary to achieve this goal. Since each lake possesses unique characteristics determining its hydrodynamics, it is vital to develop a realistic model to assess them. Multiple models already exist and have been presented in the literature; depending on the subject of interest and the lake, several parameters will have to be studied and calibrated to fit the reality at its best.
1.2 Goals and ambitions of the project

This project aims to develop a realistic, up-to-date physical three-dimensional model of Lake Zurich, whose validation will be based on real data collected on the field. The model should be able to reproduce water temperature’s and current velocities’ behaviour for the previous years, and should be robust enough to allow 5-days forecasts of these parameters.

If the results are conclusive, the model will be implemented on meteolakes.ch, an online tool developed by Theo Baracchini. As of today, only Lake Geneva, Lake Biel and Lake Greifen are being monitored on this site.

Another indirect goal of the project is to provide a model robust enough to base a future biological model on it, thus allowing the study of chemical compounds or phytoplankton.

1.3 Study area: Lake Zurich

In the literature, the term “Lake Zurich” sometimes refers to the western, lower basin Zürichsee. However, in this study, it is used in its second meaning to designate the lake as a whole, meaning that both basins Zürichsee and Obersee are considered.

Lake Zurich (47°13 N, 8°44 E) is located at the south-east of the eponym agglomeration, in the northern perialpine region of Switzerland. Enclosed by two ridges protecting it from the direct exposure to western winds, it is surrounded by cities, fields and forests and small mountains in a lesser way. The lake is constituted by two basins separated by a dam at Rapperswil: Zurichsee and Obersee, whose characteristics are presented in Table 1.1. Considered as a whole, Lake Zurich has the vague shape of a 42-km long banana, with an average depth of 49 m; the deepest location (136 m depth) is located near the Thalwil monitoring station, from which data was collected (see section 4.1.1). With a total surface of 88.6 km², Lake Zurich is the 6th largest lake in the Switzerland, and the third largest one located totally within the country [84].

As its neighbour Greifensee, Lake Zurich used to be eutrophic [87], meaning it was highly rich in nutrients. However, while Lake Greifen remains one of the most eutrophic lakes in Switzerland [8], the situation greatly improved in our lake and it is now considered as mesotrophic [40], meaning that it is only moderately rich in nutrients.

<table>
<thead>
<tr>
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<th>Zurichsee</th>
<th>Obersee</th>
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<td>Trophic state:</td>
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</tbody>
</table>

Table 1.1: Zurichsee (Lower Lake) and Obersee (Upper Lake) characteristics. Source: EAWAG [16, 17]

1.3.1 Hydrology

Lake Zurich main affluent is the river Linth, which discharges in the shallow Upper Lake on the north-east. Basins are separated by Seedam; since Obersee and Zurichsee have the same elevation, narrow channels allow water from the upper layers to enter from the first into the second with an average flow rate of ∼76 m³/s [54]. This inflow accounts for 84% of the Lower Lake’s total inflow. Water then runs out through the river Limmat, Lake Zurich’s main effluent, with an average flow rate of ∼90 m³/s [54]). The whole process leads to an average lake’s residence time of about 440 days (∼1.2 years) [54].

Kunz showed in 1977 that the outflow through the close-by Schanzengraben (near Limmat) and through exfiltration was negligible [41].
1.3.2 Climate

**Winds**

Based on data available for the city of Zurich, an oceanic, temperate climate rules over the lake [80]. A preliminary study revealed that winds acting on the lake had an average of ~2 m/s in 2017 (see Figure 4.7). Most of them were western winds, the latter often bringing precipitations, but the Bise (an north-eastly wind) also blows on the lake and is usually associated with high-pressures situations [85].

**Climate change**

In more than 80 years, the climate has changed in a significant way, affecting Lake Zurich’s temperature along the way: an overall warming of the water as been observed. Upper layers are especially affected, especially the thermocline whose monthly averaged temperature rose by more than 3.5°C in Fall. Surprisingly, the surface became up to 1°C colder from March to May (Figure 1.1).

![Figure 1.1: Impact of the climate change. Monthly averaged temperature differences between the 25 last years (1992-2017) and the 25 first years of measurements (1936-1961) show a global warming of the water body.](image)

**Mixing regime**

Rarely, the lake is known for freezing, but the last occurrence of such an event was back in 1963 [44]; therefore, it is usually considered as monomictic [16, 17] or optionally (and rarely) dimictic [55]. Warmer winters reduce the efficiency of vertical mixing and deep-water exchanges, thus allowing thermal stratification to remain at least partly [58]. In this case, Lake Zurich’s hydrological regime is not monomictic but meromictic, meaning it does not complete mix every winter.

1.3.3 Anthropogenic activities

**Water use and sanitation**

Prehistoric pile dwellings are found around Lake Zurich and prove that its shores has been populated for a long time. Nowadays, the lake’s area is heavily urbanized: recreational activities are widely developed, from passenger transport to fishing. Lake Zurich is also used as a huge drinking reservoir for the neighbourhood: 72 million m³ of water are withdrawn every year, the city of Zurich itself pumping more than two thirds of it [52, 54]. To assure the water quality, twelve wastewater treatment plants (WWTPs) are directly installed on its shores, with many others implanted farther, as seen in Figure 1.2.

**Water level regulation**

A dam has been constructed near the Platzspitz about 70 years ago [14], between Rapperswil and Pfäffikon, and separates Lake Zurich in two basins (Untersee and Obersee). Designed to regulate Limmat’s (and, by extension, the lake’s) water level and to offer flood protection, he is still used to this day and a wooden footbridge had been installed along the dam for pedestrians [81]. Since both basins are at the same elevation, the adjustment of the roof dam does not require any source of energy but only forebay’s static pressure.

While it usually fulfills its role, some limitations have been shown for high-flow events, like in 1999 [14].

**Power station**

Owned by the CFF, the 135 MW-Etzelwerk power station near Altendorf (47°11’40"N, 8°48’40"E) uses the Sihlsee water to produce 260 GWh of electricity. A part of the water used this way is then discharged in Obersee, near Lachen [1, 10].
Figure 1.2: Map of the wastewater treatment plants around Lake Zurich. The installations are represented by red dots (Source: Swiss Geocatalog, ARA - Capacity(PE) [47]). The dam separation between the two basins is highlighted in yellow. The Etzelwerk powerplant location is indicated by a blue square. From left to right, yellow triangles indicate the location of the Thalwil (T), Stäfa (S) and Lachen (L) monitoring stations.
Lakes are far from being calm and static water bodies. Constantly interacting with their environment, complex processes occur under the duress of external driving forces and build an elaborate hydrodynamic system whose comprehension might be more challenging that it appears at first sight. Understanding underlying and hidden mechanisms occurring in the lake is nonetheless critical to build a hydrological model, as the latter is no more than a mathematical approximation of these processes through equations and parameters.

Limnology, initially defined by its founder François-Alphonse Forel as “the oceanography of lakes”, has been taking interest in the physical and biological properties of lakes for decades, trying to show and define the relationships between them and to find a way to represent them in a mathematical way. In this chapter, we aim to present the fundamentals about the physical processes that our project is interested in. We relied essentially on the three volumes of Physics of Lakes by Hutter, Wang and Chubarenko [31, 32, 33] and the EPFL course of Limnology [87]. As for mixing processes, readers are also referred to the work of Socolofsky and Jirka on the subject [69].

2.1 Energy transfers

Interactions between the lake and its surroundings, from topographic and hydrological conditions to meteorological variables, animate the water body and define its temperature and hydrodynamics. In this section, we give some insight on the critical energy transfers taking place in this environment and the way they rule this project’s variables of interest.

2.1.1 Heat transfer

The lake’s temperature mainly depends on heat transfers between the water body and its surroundings. Most of these interactions occur between the lake and the atmosphere: a high air temperature will not only warm the upper layers up but also increase evaporation, the latter increasing heat transfer between the two environments and usually causing a slight cooling of the surface. Short-wave solar irradiation will cause the same effect but usually with a greater impact depending on the light’s ability to penetrate the water (and thus to its transparency) and on cloud coverage. Clouds can also bring up precipitations, which will bring higher discharges along with an often colder water input in the lake, but they will also improve the atmosphere’s ability to stay warm.

Rivers can also regulate a lake’s water temperature: inflows are usually colder than the lake’s water since their residence time is much smaller than the water body’s. Groundwater exfiltrations and infiltrations might also influence the temperature profile in a lesser extent.

A quick overview of the key external driving forces acting on the lake is schematized in Figure 2.1.

However, external driving forces are not the only processes ruling heat transfer. Through advection, a warm spot in the lake can be found later downstream. Moreover, heat will naturally propagate from the warmer zones to the colder ones in its close environment in order to reach an equilibrium: this process is called diffusion.

Transport of heat and dissolved substances can then be described by the advection diffusion equation (ADE) described by:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = \frac{\partial}{\partial x} \left( D_H \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_V \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_V \frac{\partial C}{\partial z} \right) + S$$

(2.1)

where $C$ here represents heat, $u$ and $v$ are the respective horizontal velocities in the $x$- and $y$-direction, $w$ is the velocity in the vertical $z$-direction, and $S$ takes into account all sources and sinks, such as short-wave radiation, long-wave radiation or latent/sensible heat. Note that the horizontal diffusivity $D_H$ is usually much larger than the vertical diffusivity $D_V$ [42].
2.1.2 Momentum transfer

Heat is not the only way that energy can be transferred into a system: motions can also be ignited by the action of external processes. For example, rivers do not only impact water temperature but also have a critical role in the lake’s hydrodynamics, as they influence the water level but the discharge rate and thus the residence time as well. Moreover, influents do also bring mixing at the inlets.

Winds also play a critical hydrodynamic role as they bring energy to the system, mostly under the form of waves. Winds velocity and direction determine the currents formation along with their shape and their amplitude; at the surface, waves usually cause mixing, cooling and re-oxygenation of the upper layers. Along with the lake’s shores and depth profile (called bathymetry), wind will be responsible of the formation of specific hydrodynamics events, such as internal waves (or seiches) or upwellings. These processes are more detailed in their respective sections 2.3.1 and 2.3.2.

Water viscosity will determine the fluid’s ability to resist deformation and shear or tensile stress, which greatly influences the formation of surface or internal waves. Viscosity is also influenced by temperature, highlighting again the crossed influence of every variable.

Main equations

Vertical accelerations resulting from buoyancy effects or abrupt variations in the lake’s bed topography can be neglected. This shallow water assumption is widely used in lakes modeling and simplifies the vertical momentum equation into the hydrostatic pressure equation [42]:

\[
\frac{\partial P}{\partial z} = -\rho g
\]

(2.2)

As for the horizontal momentum, it can be described in both x- and y-directions by the equations:

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + v \frac{\partial U}{\partial y} + \omega \frac{\partial U}{\partial z} - fV = -\frac{1}{\rho_0} P_x + F_x + M_x + \frac{\partial}{\partial z}(\nu \frac{\partial u}{\partial z})
\]

(2.3)

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + \omega \frac{\partial V}{\partial z} - fU = -\frac{1}{\rho_0} P_y + F_y + M_y + \frac{\partial}{\partial z}(\nu \frac{\partial v}{\partial z})
\]

(2.4)

in which \(U\) and \(V\) are the generalized Lagrangian mean (GLM) horizontal velocities, \(u\) and \(v\) are the Eulerian velocity components, \(P_x\) and \(P_y\) the horizontal pressure terms, \(F_x\) and \(F_y\) the horizontal Reynold’s stresses, and \(M_x\) and \(M_y\) the contributions due to external sources or sinks of momentum [42].

2.2 Vertical stratification and seasonality

Salinity and density are positively and linearly dependent in water, the second increasing as the first one does too. However, in lakes with low salinity, water density can be approximated as a function of temperature only: in that case, density reaches a maximum at 4°C, as seen in Figure 2.2.
Due to this physical property, strong thermal stratification can be observed in lakes at our latitudes as they are usually not saline. In the case of an upper layer being colder than the lower layer of the lake (but still less dense, as seen before), we talk about an inverse thermal stratification.

While the surface (also called epilimnion) is heavily influenced by meteorological variations, the lower layer of a lake (or hypolimnion) is known for its stability, with an almost constant temperature (near 4°C) observed from the beginning of the layer to the bottom of the lake. This stability limits water exchanges, therefore this thick layer is in a stationary state most of the year and is, by far, the less oxygenated and the less illuminated part of the water body.

Epilimnion and hypolimnion are separated by a transition layer called the thermocline (or metalimnion). Characterized by high vertical density and temperature gradients, it is by far the most mobile zone of a lake, as its thickness and depth varies greatly through the years.

Because of the climate reigning in Switzerland, water in lakes is not in a steady-state but its movements and exchanges follow a seasonal cycle. During summer, higher air temperature and strong solar irradiation warm up the surface of the lake: this lighter layer stays therefore at the top and a strong, stable thermal stratification occurs. However, with fall comes colder temperatures, higher cloud coverage (and therefore less solar irradiation) and stronger winds as well: not only does this cause the epilimnion but also the thermocline to cool down and sink due to the increased water density. The metalimnion becomes thinner and the temperature difference between the top and the bottom of the layer decreases.

This tendency keeps going as winter comes until, finally, the lake achieves homothermy around spring: all layers mix and the thermocline disappears. From this point, surface cooling induces a decreased density in the upper layer and a stable inverse thermal stratification can then occur, until it eventually warms up again (thus causing a second homothermal state in the process) and the cycle begins again.

Not all lakes show the same mixing regime. A classification has been made for the latter based on the efficiency and the frequency of the mixing [30]: this heavily influences the fauna and the flora as other natural processes, and it is therefore a crucial lake’s characteristic studied in limnology.

- If a complete mixing occurs at least once during the year, the lake is called holomictic. Such regime allows a good reoxygenation of all layers.
- Meromictic lakes show an incomplete mixing, which usually doesn’t affect the lowest layer, called monimolimnion. The latter is therefore always present, at least for one annual cycle. This mechanism prevents water exchanges between this layer and the others (grouped under the name mixolimnion); usually, this also comes with anoxic conditions at the bottom of the lake [5].
- More occasionally, amictic lakes can be found. In general, these lakes where no mixing occurs are covered by ice, preventing them to be affected from any external driving forces, which can also lead to a severed vertical mixing in the water column, affecting again biogeochemical processes [30].
- Dimictic lakes follow the whole seasonal process described in the previous subsection, with surface temperature cooling down after the first homothermal state and then re-achieving this state a second time: such lakes are therefore mixed twice a year. Monomictic lakes, however, mix only once per year: water temperature always allow the density to be less than the maximum, and
therefore only the first homothermal state is achieved. Polymictic lakes, finally, show multiple periods of mixing per year, usually either because of very strong winds or weak stratifications.

- At last, oligomictic lakes are so thermally stable that they mix only rarely, with periods greater than a year. In contrary to amictic lakes, these lakes are usually found among tropical lakes with very high (20-30°C) surface temperatures.

2.3 Horizontal gradients

Examining the local vertical layering at one point in the lake can give the illusion of a homogeneous distribution of temperature along the horizontal direction. It is not true. Under the influence of external driving forces, complex three-dimensional dynamics are created and can affect the whole water body. In this section, we will look into the mechanisms taking place in the horizontal water column and the ensuing phenomenons.

2.3.1 Layers inclination and internal waves

Though thermal stratification can separate the water body in multiple layers, it doesn’t always imply that isotherms can be found at a constant depth. In fact, under the duress of wind-induced shear stress, not only the surface layer of the lake but also deeper ones will be inclined. However, while the surface will show a higher water level downwind than upwind, the thermocline will be tilted in the opposite direction.

Once the stress is released (either because the wind is weaker or because it simply stops blowing), both layers will oscillate around their equilibrium position, thus causing the formation of internal waves, also called seiches [2], sometimes several hours after the end of the wind stress itself. This phenomena has been observed in multiple lakes [28, 29, 66]. It is easily detected in the water body due to thermal stratification, as their occurrence induce thermal layer shifting and deformation. The amplitude of these internal waves varies but is higher in high-vertical density gradient zones; in a lake, this zone also corresponds to the high-vertical temperature gradient zone, which is none other than the thermocline (or metalimnion); the amplitude of the seiches can go up to the scale of a meter.

Mainly because of each lake’s unique topography, internal waves can show different amplitudes, frequencies and modes. As the amplitude and velocity are decreasing rapidly for higher order internal waves, only the lowest and the first higher order modes can usually be observed and identified [28].

2.3.2 Upwellings

Wind shear-induced vertical mixing and internal waves are not the only way to force exchanges between the layers. The counter-directed slope of the isotherms in the stratified thermocline and deep layers can combine with the transformation of wind kinetic energy into the free surface tilt potential energy [48]; given a sufficiently strong slope of the isotherms, cold water can rapidly rise from the bottom of the lake to upper layers and bypass thermal stratification for a short amount of time [59]. This leads to an abrupt and significant cooling of a portion of the lake. This event, called an upwelling, has been observed in oceans as in lakes and can play an important role in coastal dynamics [26, 57, 62, 74] and in plankton dynamics in the water body, bringing nutrient-rich deep-water to the surface [27, 46, 82, 83].

The chance of observing an upwelling event in a stratified lake can defined by the condition [34]:

\[
Cr = \frac{R_i \cdot h}{L/2} \leq 1
\]

where \( R_i \) is the Richardson number, \( h \) is the meta- or hypolimnion’s upper boundary depth, and \( L \) the lake’s horizontal dimension (length or width).
2.3.3 Gyres

Mainly depending on wind conditions and the lake’s topography, local whirlpools can form in the water: these gyres can bring mixing in the upper layers and play an important role in long-term horizontal transport [66]. The chance for a gyre to appear in a lake can be defined by the criterion:

$$ R = \frac{U}{f} $$

where $U$ is the usual horizontal velocity, and $f = 2\,\Omega T\sin\phi$ is the Coriolis parameter.

This radius $R$ defines the radius of the “separation bubble” from which the gyre grows [6]. If $R$ is lower than the lake’s width, it is possible for the whirlpool to build up in the lake. Therefore, such structures are usually characteristic of wide lakes.
2.4 Physics of Lake Zurich

Mixing regime

As indicated in section 1.3.2, Lake Zurich is usually considered as a monomictic lake. Data collected from monitoring stations on the lake (see section 4.1) showed an annual mixing cycle around the period of January-March (Figures 2.6 and 2.5).

Figure 2.5: Water temperature profile observed at the Thalwil monitoring station at several depths in 2015, 2016 and 2017. The thermal homogeneity, linked to the almost complete mixing between the layers, can be observed each year in the January-March period.

Figure 2.6: Quarterly averaged temperatures observed at the Stäfa, Thalwil and Lachen monitoring stations in Lake Zurich (2017). A strong vertical mixing and thermal homogeneity are present in the first quarter (light green, dots). The sinking of the thermocline is visible through the rest of the year.

The thermocline usually lies between 8 and 18 m in average; thermal stratification begins around April and becomes stronger as summer comes (Figure 2.7). Complete mixis isn’t frequent, water temperature usually staying above 4°C, and occurs only during cold winters where an inverse stratification can then be observed [91]. This highlights the influence of winter warming on the mixing processes in the lake, as observed by Straile, Jöhnk, and Rossknecht in 2003 [71] and reported again by Posch et al.
Figure 2.7: Water temperature profiles for the three monitoring stations in 2017, between a depth of 0 and 24 m. Color shading is obtained by linearly interpolating between measured values. Once again, thermal homogeneity can be observed at the beginning of the year, while a strong thermal stratification is established and the metalimnion sinks noticeably as time goes on. Spatial variability can be observed between the stations.

**Internal waves**

Multiple studies revealed the presence of *seiches* in the lake as main responses to wind impulses [28, 29]. Their periods of 44 h, 24 h and 17 h have been reported in the literature [29] and can serve as reference for our own model.

**Upwellings**

Though no record of an upwelling event was reported in the literature or was mentioned in the media for the year of interest, such processes are expected in the lake. Moreover, studies reported a Richardson number value up to 0.35 [29], above the 0.25 critical value under which the flow near the metalimnion can become temporarily unstable. Remember that the Richardson number expresses the ratio between buoyancy and shear and is defined by:

\[
Ri = \frac{g}{\rho} \frac{\partial g/\partial z}{(\partial u/\partial z)^2}
\]

(2.7)

\(Ri = 0.35\) corresponds to criterion values (defined back in section 2.3.2) of \(Cr_x = 1.3310^{-4} \leq 1\) and \(Cr_y = 0.028 \leq 1\), thus assuring the potential existence of upwellings in Lake Zurich.

**Gyres**

On the contrary, gyres are not expected to occur, as these structures are typical of wide lakes while our lake’s width ranges between 1 and 2.5 km.
3 State-of-the-art: context and background

3.1 Lakes modeling: a worldwide challenge

3.1.1 From 1D to 3D models

**Definition**

Hydrology is “the science dealing with the occurrence, circulation, distribution, and properties of the waters of the earth and its atmosphere”; hydrodynamics are only dealing with the motion of fluids and the forces acting on solid bodies immersed in fluids and in motion relatively to them. However, water reservoirs such as oceans, seas, rivers or lakes are governed by a tremendous amount of processes: waves formation, currents, sediments stratification and transport, water level, temperature layering, etc. A hydrodynamic model is a mathematical tool which aims to efficiently simulate and reproduce these processes and dynamics, based on several physical or biological parameters.

The need for our society to understand the mechanisms of water bodies, to monitor them and to be able to predict their reaction to natural and anthropogenic pressure has been recognized for decades. Lakes are no exception: given the identification of the processes occurring in water, a good assumption of the parameters values linked to the latter, mathematical equations, simplifications and spatial and temporal discretization (in order to solve differential equations), it is possible to reproduce their behaviour in a realistic way. Usually, models are either physical, taking interest only in the hydrodynamical characterization of the lake, or biological, also considering such processes as chemicals diffusion, plankton growth, etc.

**Model types**

1D models were widely used in the past and are still conceived today for most applications. They are able to obtain good, realistic results for simple mechanisms, and can even account for three-dimensional phenomena such as internal waves with an appropriate parametrization. However, the development of 3D models offered the ability to resolve these processes at the large variety involved in lake dynamics; moreover, they provide results closer to reality as they take into account other parameters (difference between open, surface water and boundary layers, bathymetry, etc).

3D models come with their downsides: they are sensitive to wind direction and therefore include effects depending on the shape and orientation of the water body, while 1D models usually depend on the hypsographic curve, or on wind fetch empirical parametrization [79]. They are also dependent on the chosen grid resolution, and calculations cost much more resources and time. However, an intelligent design coupled to the increased power of computers nowadays allow this approach to be more feasible and reduce the time of computation.

3.1.2 Previous studies

For decades, numerous studies have been made to develop hydrodynamic models of lakes. However, each water body is unique and possesses specific characteristics: influents and effluents, water depth profile, meteorological conditions, etc. Moreover, the subject of interest and the goal of the model vary from one study to another, from flood control to water quality assessment, or even the ability to use the water as a thermal reservoir. Though such diversity implies various approaches, similar patterns can be found along the studies and help the comprehension of the mechanisms of interest, along with the choice of the parameters that rule them and the range of the latter’s values.
Model calibration and method

Calibration goal
The ultimate goal of a model is to faithfully reproduce the known behaviour of a variable. If the mathematical approach is able to obtain values similar to reference data, the model is considered as calibrated. However, calibration can only be achieved by setting the model’s multiple parameters to the right value. This task can be tedious and quite time-consuming, especially if this work is done “by hand”, as some parameters are interconnected and can have an influence on each other [13]: the effect of two parameters set to constant values in the same model won’t be the same as the combined effect of said values in two separate models.

DUD method
To facilitate this process and avoid the “subjective” choice of the parameters’ values, several mathematical approaches were developed. Among them, the DUD (Does not Use Derivative) method developed in 1978 by Ralston & Jennrich [60] was used by Brière et al. in 2011 to optimize the roller, flow and transport modules of the DELFT3D software calibrations and their ability to reproduce bar dynamics [7].

The method proved to be effective and successfully reproduced the expected behaviour. This result is encouraging since the DUD method is “optimally designed for least squares criteria”, which is used for the model performance assessment in many studies [24, 35, 70, 79, 89].

Baseline choice
Moreover, Briere et al. proved the importance of the initial guesses used for the baselines’ parameters’ values: not only the number of evaluations required was about “5 to 8 times the number of uncertain model parameters”, but the calibrations results also depended greatly on said baseline. This comes from the fact that calibration algorithms are suboptimal and can fall into local minima. Unfortunately, this is inevitable as global algorithms are too computationally heavy for 3D models; a tradeoff is therefore necessary. Briere et al. advised future researches to base the baseline on physical knowledge and previous modeling experiences.

The importance of a good, thoughtful baseline has also been highlighted again in a study conducted by Lesser in 2004 [42] at it was also shown to reduce drastically the model’s calibration time. The calculation timestep was also highlighted as a parameter of importance as it greatly impacted the computed results (Figure 3.1).

![Figure 3.1: Results of the settling basin test showing accumulation of initially suspended sediment at the bed. Three simulations show the influence of the computational time step on the computed result. Source: Lesser, 2004 [42]](image)

Validation and model performance
Once the model has been calibrated, its ability to reproduce an expected behaviour not only once, in one particular case, but constantly throughout different configurations, has to be assessed either qualitatively (for example, by visualizing the phenomena) or quantitatively (by comparing computed results to measurements or theoretical data). In the case of a hydrodynamic model, natural processes are supposedly well-reproduced if the model manages to reproduce the lake’s characteristics’ temporal and spatial variability, with very little difference between the simulation and the reality.

In 2017, a study conducted by Soulignac et al. showed that high-frequencies measurements were especially useful to assess the capability of a model to reproduce local events [70] which might occur in a short amount of time. Moreover, it gives more weight to the performance indicators and show the robustness of the model, while also allowing a clear visualization of the model’s performance (Figure 3.2).
However, Brière et al. (2011) reminded readers that good results don’t always come with a realistic description of the underlying physical processes occurring the lake. While this can be done with tests of known dynamics in practice, this also shows that one of the key roles of the researchers is to bring some criticism to the mathematical optimization.

Figure 3.2: Hourly mean profiles of observed and simulated (a) water temperature and (b) horizontal current velocity at a given point C in Lake Créteil (France), along with the difference of water temperature between two other points P and R (c) for the calibration period between 17/09/2013 and 15/10/2013. The model’s performance can be qualitatively assessed. Source: Soulignac, 2017 [70].
Subjects, studies and results of interest

**Hydrodynamic models: a vital role**

Society has built itself around water sources. This proximity with this vital resource provides many advantages but also comes with its cons, as cities are therefore more threatened by floods and the exploitation of the environment puts more and more pressure on these fragile ecosystems to the point where it might backfire and affect our lives.

To prevent such events and allow a sustainable use of the lakes, models have been developed all around the globe to reproduce their behaviour and predict the evolution of many variables. The needs and subjects of interest vary among the countries depending on political issues, environmental differences and goal of use, but nevertheless similarities can be found between the studies. Knowing the critical variables to consider, the range of values for the parameters linked to these processes or the limitations previously found will allow us to have some insight on the complex subject of lake modeling and give us criticism. Interesting results highlighted and advises from researchers will guide us, allow us to elaborate a realistic, well-thought model and to make potential improvements in the field.

**Salinity and hydrodynamics**

While salinity was not a studied variable in our project (because of the low salinity of Lake Zurich), the study conducted by van den Heudel in his master thesis [77] on the subject was of interest as he aimed at modeling the hydrodynamics (focusing on tidal propagation) along with the salinity of the Pontchartrain basin (Louisiana, USA), the second biggest salted lake in the United States. To do so, they did of course use salinity measurements, but also the basin’s bathymetry. Rivers discharges were also considered, and tides and wind data were forced into the model. Finally, the influence of horizontal diffusivity on hydrodynamics was studied, and horizontal viscosity was considered as well.

The study showed a positive correlation between salinity and wind: more precisely, it showed that (fresh) water staying in the top layers was pushed in the same direction as the wind, while deep ( saline) water was however pushed in the opposite direction. This highlighted the role of wind in horizontal transport and proved that wind effects were not negligible, which was the main admitted flaw in the calibration. Therefore, he suggested to add non-tidal water level elevations and currents to the boundary conditions.

**Temperature and currents dynamics**

The study conducted by Soulignac et al. in 2017 [70], previously mentioned in the last section, did not only show the usefulness of high-frequencies measurements for models’ performance assessment: it also gave some insights on the crucial processes ruling temperature and currents dynamics. Wind influence was reflected by wind drag coefficients, and evaporation and heat convection were considered and respectively represented by the Dalton and Stanton numbers. Finally, horizontal viscosity and diffusivity were again estimated to contribute in hydrodynamics, though vertical ones were disregarded.

This model successfully reproduced the behaviour of Lake Créteil (France, Europe), from horizontal temperature differences to mixing cycles, stratification periods and internal waves. Calibration were based on many performance indicators, from absolute mean errors (MAEs) and root mean-squared errors (RMSEs) to the coefficient of determination $R^2$ and the use of Taylor’s diagrams [72].

**Heat transport method**

In 2000, a study of K-R Jin [35] took interest in heat transport in the very shallow Lake Okeechobee (Florida, USA). They considered meteorological conditions such as rainfall (though little of it did occur), solar radiation or wind velocity, but also the bathymetry and the influence of rivers (inflows and outflows). Water surface elevation, horizontal velocities, and temperature were computed. The
model’s evaluation was based on MAEs and root-mean-squared errors (RMSEs).

The model performed well and a good agreement was usually found between simulations and observations for the three variables: the variability of both water temperature and velocities were nicely simulated, though the amplitude were underestimated (Figure 3.3). Even so, the differences found were considered acceptable. The researchers suggested that “wind-wave and vegetation resistance algorithms” would improve the model, along with a spatially varying bottom roughness.

Figure 3.4: Effect of warming and increased wind speed on mixing intensity during 51 winters from 1961 to 2011 in Lake Constance (Germany, Europe) assessed with numerical tracer experiments. The mixing index values \( M_{idx} \) for various scenarios of (A) increased temperatures and (B) increased wind velocities are depicted as gray bars. The mixing index values of \( S_{ref} \) are plotted as dots for the purpose of comparison. Source: Wahl & Peeters, 2014 [79].

In 2014, Wahl & Peeters [79] showed that warmer winter temperatures were heavily affecting thermal stratification in Lake Constance (Germany, Europe), reducing deep-water exchanges and therefore causing more frequent years with an incomplete mixing. Their study also showed that an increased air temperature warmed up the water at all depths in monomictic lakes; such results were already revealed by Peeters et al. in 2002 [55] and 2007 [56] with a 1D model. It also increased the stability of the vertical water column in summer and autumn, but had no impact of the deep-water renewal in winter.

Higher wind speeds were also revealed again to influence vertical mixing and surface heat fluxes, and resulted in the warming of the depths in summer (Figure 3.4). Finally, they insisted on the importance of heat carryover between the years.

Despite obtaining results compliant with previous studies, the model showed limitations when it came to reproducing deep-water temperatures, and surface temperatures in a little extent. It was partly explained by the use of a constant Secchi depth.

Figure 3.5: a) Root-mean-square error of modeled temperature output, and b) deviation of the mean annual modeled temperatures from the measured mean values (1981–2012) in Lake Geneva (Switzerland). Both graphs shows the flaw of the modelization for the thermocline region. Source: Schwefel et al, 2016 [64].

Climate change and global warming have therefore an heavy impact on the lake’s stratification, but also on its oxygen content, especially in deep layers. Studies conducted on Lake Geneva (Switzerland, Europe) by Schwefel et al. in 2016 [64] and 2017 [65] showed that deep-water oxygen concentrations were predominantly controlled by resupply during the unstratified period in winter. The model predicted a
strong decrease of complete homogenization of temperature and oxygen in winter, by an order of 50% at the end of the century.

Researchers also highlighted the difficulty of setting the thermocline at the right position, and the strong differences resulting between the simulation and the observations (Figure 3.5). The hypothetical reason behind these results could be that baroclinic dislocations are considered in the observations but not in the model.

**Sedimentation**

Lesser et al. (2004) studied the modelization of sedimentation processes in Delft3D [42]. Three kinds of tests were conducted to validate the ability of the software to reproduce these mechanisms: comparisons were either made with (1) existing analytical solutions; (2) known initial, boundary and final conditions; and (3) other models results and theoretical considerations.

The paper demonstrated the software's ability to reproduce various processes, and the model was validated. The latter’s responses to multiple currents, wave or sediment’s stimuli were well-observed.

The necessity to use \( \sigma \)-layers in order to study sedimentation was discussed; it was also proven that the vertical concentration of particles could be quickly and efficiently solved given a sensible, smooth and logarithmic distribution of the layers thickness. The model sensitivity to bed roughness was also highlighted. Finally, they emphasized the amount of work needed to verify and enhance models.

In 2015, Luijendijk also studied the sedimentation processes, this time in the Marsdiep basin (Netherlands, Europe) [45]. The model validation was based on water level, discharges and currents measurements realized on a ferry. The model managed to reproduce fairly well currents, and their amplitudes as well as their phases. However, the results showed important deviations with the measured residual currents. These differences were hypothesized to be linked to an inaccurate bathymetry, to bottom roughness sensitivity in a lesser extent (the latter increasing with higher flow rates) and to the influence of wind wave processes, which were not considered before and were advised to be added in further researches.

**Water quality**

Water quality is a concern for societies all around the globe. In 2009, Zhu et al. combined a 3D hydrodynamic model made on Delft3D with a 2D water quality model in order to simulate pollutants diffusion in the Yangchenghu Lake (Jiangsu, China) [90]. The model used rivers inflows and outflows along with wind conditions. Once again, \( \sigma \)-layers were used for the vertical grid, while the horizontal one was orthogonal and curvilinear. Calibration was based on water levels and flow velocity.

This study demonstrates the efficiency and usefulness of such hydrodynamics models, as the latter identified the main sources of pollution and indicated which solutions should be chosen and when they should be applied in order to improve water quality. Researchers suggested to use the model to guide the lake’s management.

A study conducted by Chanudet et al. in 2012 emphasized the importance of water and currents dynamics in the modelization of the water quality. Though their model was developed for a reservoir, they assured that a similar approach could be used for lakes [11].

**Inundations and currents**

The importance of lake modeling is shown again in a study conducted by Zhang et al. in 2015, [89]. Variables and parameters used were the bathymetry of the Poyang Lake (Jiangxi, China), the Manning roughness coefficient, the eddy viscosity parameter and the critical water depth for wetting and drying. The validation was based on RMSE, NSE, \( R^2 \), PBIAS and RSR values.

They managed to build an efficient model, able to reproduce currents velocities and discharges in both wet and dry seasons. More importantly, the model was able to predict inundations events, which is both invaluable for water quality and human safety management.

**3.2 Lake Zurich: studies and modeling**

**Impact of climate warming**

Several studies were conducted on Lake Zurich and tried to reproduce its biophysical state. A continuous approach was advised by Peeters et al. (2002) [55], as the lake is only rarely dimictic; though they used a 1D-model, results were validated and already suggested that an increase in \( T_{\text{water}} \) is likely to lead an increase in \( T_{\text{water}} \) at all depths too and in more frequent suppression of deeply penetrative winter mixing events as well, the latter having a potential negative impact on the lake ecosystem (Figure 3.6). This study observed a difference between deep-water simulated temperatures and observations, and hypothesized that the constant Secchi depth could cause this deviation.

This effect was observed again in 2003 by Livingstone [44], who showed global warming’s impact on the Lake water mean temperature (\(-0.24 \) K per decade above 20 m and \(-0.13 \) K per decade below) resulting in a 20% increase in thermal stability and a consequent extension of 2-3 weeks in the stratification period. They discovered the temperature of the surface mixed layer of Lake Zurich reflected that of the regional daily minimum air temperature, and not that of the maximum. They presumed the nighttime convective cooling of the surface mixed layer was suppressed.
Once again, proofs that the water turnover of Lake Zurich is affected by warmer air temperatures were also reported by Posch et al. in 2012 [58].

Figure 3.6: Comparison of the response of Lake Zurich (Switzerland) temperature to an air temperature raised by 4°C as predicted by continuous modeling (A, C, E) and by discontinuous modeling (B, D, F). Shown is the change in mean monthly water temperature in the epi/metalimnion $T_{em}$ (A, B), the hypolimnion $T_h$ (C, D), and the temperature difference ($T_{em} - T_h$) (E, F) caused by raised air temperatures. Mean monthly temperature profiles were determined from temperature profiles simulated at 10-min intervals. Shown are mean values for a year after a winter with warm water temperatures (1989, open circles), for a year after a winter with cold water temperatures (1987, open triangles) and for the time period from 1985 to 1997 (solid triangles). Source: Peeters et al. (2002) [55].
In 1986, Horn et al. [29] demonstrated the presence of internal waves in Lake Zurich: the lake’s main responses to wind-induced forcing were seiches “of the first longitudinal mode”, though weaker signals from the second and third mode could still be perceived in temperature and current fluctuations. Their average periods were determined to be respectively of 44 h, 24 h and 17 h (Figure 3.7).

Their model was able to reproduce thermocline displacements and even water velocities, when the Defant model was flawed (especially for the last case), and highlighted the critical role of the wind in seiches formation, along with the impact of storms. Unfortunately, the model couldn’t reproduce clockwise- or anti-clockwise rotations in currents clockwise or anticlockwise rotation of currents direction.

In 2000, Hodges et al. [27] demonstrated the time lag between wind events and the formation of seiches. Their study highlighted the critical role of turbulence in the modelization of stratified lakes. This aspect should therefore be considered to predict correctly seiches’ amplitudes and to set the thermocline at the right depth.

In his master thesis, Hoffmann took interest in plankton dynamics [28]. This biological model was however based on a physical model that he also developed, which aimed at reproducing Lake Zurich hydrodynamics specifically. This paper proved itself to be of a vital importance as it was the only one reporting every value used for each parameter in his Delft3D calibration.

While the model performance in the deep-layers was good, showing very little difference between
computed and observed water temperature profiles, it showed lacking precision in the epilimnion and metalimnion zones, with consequent differences in the latter (Figure 3.8). Several explanations were hypothesized: among them, the influence of the constant Secchi depth, but also uncertainties about wind speed measurements and "local wind phenomena". Hoffmann suggested the use of a "more sophisticated wind field", giving the example of COSMO-2.

Figure 3.8: Computed (red) and measured (blue) water temperature profiles in Lake Zurich at the Thalwil monitoring station location. Differences between the two profiles are represented by black lines. Source: Hoffmann, 2015 ([28]).

Biological model

Finally, a biological model was developed by Omlin and al. in 2001 to assess nutrients, oxygen and plankton dynamics in Lake Zurich [53, 54]. Due to the tremendous amount of parameters linked to the processes studied, a systematic approach was applied by combining model sensitivity analysis with an analysis of the approximate linear dependence of sensitivity functions of parameters subsets.

This 1D model was able to reproduce the key features of these parameters’ interactions and the underlying processes but failed to predict rarely occurring phenomena. Moreover, while the dynamics of dissolved variables was easily described, the dependence of algae’s growth to light proved itself to be more recalcitrant to parametrization.

In 2015, Li et al. emphasized the difficulty of algae dynamics modelization as many interconnected processes have to be considered, from dissolved oxygen, plankton and pollutants concentrations to salinity, sedimentation and photosynthesis [43].

3.3 An online tool: meteolakes.ch

3D models parametrizations are tedious and their use is usually limited to the researchers themselves. In order to provide their services to a wider public, meteolakes.ch was developed by Theo Baracchini in partnership with EPFL, EAWAG and the European Space Agency (ESA). Meteolakes is an online platform displaying the biophysical state of several lakes (to this day, Lake Geneva, Greifensee and Lake Biel), from in-situ measurements, satellites remote sensing and real-time monitoring to 5-days
forecasts of water temperature and velocities, along with algae and dissolved oxygen concentrations. While initially addressed to the general public mostly interested in a lake’s temperature for recreational purposes, new tools allowed it to be also used by biologists and limnologists. It is still most widely used during summer, ~500 people visiting the website daily (up to 1'000 at some peaks).

The hydrodynamic and water quality models are based on the Delft3D software, and showed good results and close match to the reality. Regarding the physical part of the model, it is capable of reproducing spatially and time-varying complex processes, from clockwise or anticlockwise rotations of currents (Figure 3.9), whirlpools and gyres to upwellings (cold water ascending from the bottom of a water body to upper layers). It is able to reproduce local and occasional events; for example, the extreme cooling event that occurred on the 1st of July 2017 in Lake Geneva [12] has been observed on meteolakes too (Figure 3.10). The strong tempest that ravaged Lake Geneva on 6th August 2018 [9] was also predicted by its model (Figure 3.11).

Being able to make such forecasts is invaluable: not only does it show the understanding of the hydrodynamic system, but it can also help to limit the impact of natural hazards on the population, thus proving the crucial role of such models in lakes monitoring.

Figure 3.9: Water velocities map for Lake Geneva on 1st July 2017 at 06:00 AM. Rotating currents can be found along the centered profile of the lake. Source: meteolakes.ch
Figure 3.10: Water temperature for Lake Geneva on 1st July 2017 at 06:00 AM. The upwelling predominantly localized at the north-western shore is reproduced by the model and affects a third of the lake. Source: meteolakes.ch

Figure 3.11: Surface water velocities Lake Geneva on 6th August 2018 at 06:00 PM. Strong currents are observed near the northern shore. Source: meteolakes.ch
4 | Methodology and Modeling

4.1 Data and inputs

Figure 4.1: Satellite image of Lake Zurich, and location of the monitoring stations used for calibration. From left to right: Thalwil (T), Stäfa (S) and Lachen (L). Données cartographiques ©2018 Google

In this section, we will present the data used in our approach. Meteorological variables susceptible to influence the processes of interest were identified, selected and extracted from COSMO-1 data. Along with a variable Secchi depth observed in Lake Zurich, they were forced into the model. Calibration and validation of the model were based on the comparison between simulated temperature profiles and observations made by three monitoring stations along the lake (Figure 4.1).

4.1.1 Model forcing data: meteo and Secchi depth

Developed by the Consortium for Small-scale Modeling (COSMO) [20], COSMO-1 is at this day the highest-resolution weather forecast model for the Alpine region. Put online on 31\textsuperscript{st} March 2016 [50], its grid box resolution of 1.1 km\(^2\) makes it four times more accurate than its predecessor, COSMO-2 (whose resolution was 2.2 km\(^2\)). Not only is it able to make precise forecasts of the weather, it also collects and provides various meteorological data, such as wind speed, air temperature or precipitations [49].

Cloud coverage, atmospheric pressure, relative humidity, shortwave flux, air temperature and wind velocity and direction were chosen as variables susceptible to have an influence on water temperature and currents. Data was extracted from COSMO-1 files for the period of interest (year 2017) and provided to Delft3D as "forcing" conditions in order to reproduce the lake's behaviour under such external driving forces. Since the grid used in the software is finer and more precise than the grid of COSMO-1
(see section 4.2.2), the latter’s values were interpolated down to Delft3D’s grid size.

**Secchi depth**

![Image](see section 4.2.2), the latter’s values were interpolated down to Delft3D’s grid size.

**Figure 4.2:** Secchi disk and its use (Source: IISG).

A Secchi disk is a simple device taking the form of a black-and-white disk divided in four quarters. Once immersed, it allows to measure the water’s transparency and turbidity: the depth at which it disappears is called *Secchi depth* and represents the maximum depth of light penetration (Figure 4.2). Not only does this have a huge influence on photosynthesis and the distribution of organisms, in particular plankton, but it is also linked to an increased water temperature (especially at the surface) due to solar irradiation.

Secchi depth was therefore selected as the reflection of the solar irradiation potential. Setting this parameter as a constant was mandatory in older versions of Delft3D; however, previous studies showed the cons of this choice, and recommended future researchers to opt for a variable Secchi depth [28, 55]. Intending to take a step further to better and more realistic results, we followed their advice: measurements taken at the Thalwil monitoring station (provided by Wasserversorgung Zürich, who takes care of the city’s water supply) were smoothed to minimize extreme events’ influence and were then used as imposed conditions for the model (hence the term *forcing* data) along with meteorological data.

**Figure 4.3:** Secchi depth measurements at the Thalwil monitoring station over the years (Source: Wasserversorgung Zürich).

Secchi depth was monitored monthly from 1\textsuperscript{st} January 2010 to 6\textsuperscript{th} December 2017 and showed peak values around May each year. Other yearly maxima were observed in February 2010 and in March 2012, and would require further investigations if they were to be used in applications. As for minima, they were observed either in August or in November. Summer peaks might be due to photosynthesis linked to plankton growth. Secchi depth profile is presented in Figure 4.3.

24
4.1.2 Water temperature data: calibration and validation

To calibrate and validate the model, the simulated water temperature had to be compared to real measurements. To assess the model’s robustness and to avoid local effects, this data was collected by monitoring stations along the profile of the lake. Two stations were located in Zurichsee: Thalwil, close to the deepest point of the lake, and Stäfa, near a shallower part of the basin. Lachen was the only monitoring station in Obersee (see Figure 4.1). Data was once again provided by Wasserversorgung Zürich.

Measurements’ depth profile are presented for each monitoring station in Appendix A.

The Thalwil monitoring station (2°68’175 / 1°23’850) is close to the deepest spot of the lake (∼136 m deep), in the Zurichsee basin. Water temperature is measured monthly from the surface down to a depth of 135 m.

The Stäfa monitoring station (2°69’179 / 1°23’916) is situated in a much shallower part of the Zurichsee basin (∼25 m deep). Temperature measurements were reported for February, March, May, August, September and November, from the surface down to a depth of 24 m.

The Lachen monitoring station (2°70’5’134 / 1°22’910) is the only one located in the Obersee basin, which is vital to assess the ability of our future model to reproduce the hydrodynamics for both parts of Lake Zurich. Temperature measurements were done at the exact same date and time as Stäfa’s. However, the profile goes from the surface to a depth of 36 m.

The evolution of temperature at the three monitoring stations in 2017 was illustrated in section 2.4 (Figure 2.7).

4.2 Modeling Lake Zurich

4.2.1 Delft3D: three-dimensional hydrological modeling

A complete software

To reproduce the lake’s behaviour, we used Delft3D (version 4.01.00), a software developed by Deltares, an “independent institute for applied research in the field of water and subsurface”. The various tools that it offers allow the study and model of physical and biological processes in water bodies such as water temperature, salinity, currents, algae growth and chemicals diffusion. Delft3D has been successfully used and applied to various lakes studies [7, 18, 22, 24, 28, 61, 79, 90].

Delft3D-FLOW model solves the Navier-Stokes equations for an incompressible fluid under the shallow water and the Boussinesq assumptions, the latter meaning that a variable density’s effect is only taken into account in the pressure term [15].

In this project, only Delft3D-QUICKPLOT, RFGRID and FLOW modules were used, as we took interest in physical mechanisms solely.

4.2.2 Horizontal and vertical resolution

Grid resolution: the dilemma

To study the lake’s parameters and their evolution over time, one has to apply a grid over the area of study. If the cells are too large and the grid is too coarse, forecasts will not be accurate enough and small variations and events might remain invisible. However, while a finer grid gives better results, it also comes with a highly increased computation time. A compromise has therefore to be found between the model’s realism and efficiency, and the resources needed to design it and to make it run in the future.

Using Google Maps’ topography provided by the OpenLayers plugin on QGIS, the lake profile and its shores were cropped and exported as a shapefile (.shp); QUICKPLOT allowed its transformation to a land boundary file (.ldb), which was then used in RFGRID. Splines were then drawn accordingly to the lake’s shape, and a grid of 180x200 m cells was generated from them. The latter was orthogonalized several times to assure its quality, and cells with less than 50% content of water in area were deleted.

Bathymetry

This grid, however, only covers the surface of the lake and not his depths. The depth profile, called bathymetry, is necessary in a three-dimensional model, especially since it plays an important role in various hydrodynamic processes. Depth contour were extracted from Swisstopo (with a resolution of 50 m) for the whole lake, and were combined with high-resolution (1 m) measurements provided by Michael Strupler, from the Swiss Seismological Service (SED) of ETH Zurich.

These samples were then provided to Delft3D-QUICKIN and grid-cell averaged, this method showing better results for dense data (several points per cell) than the triangular interpolation, more fitted for sparser data (one point per cell or less). Internal diffusion is then used so that each cell has an attributed depth. Finally, a minimum depth of 2 m is used to prevent border effects and the eventual
drying of several cells.

The final grid and bathymetry used in our model are represented in Figure 4.4.

![Figure 4.4: Final grid resolution and bathymetry of Lake Zurich. Thalwil (T), Stäfa (S) and Lachen (L) monitoring stations are represented by yellow diamonds, and rivers by purple dots. Blacks cells correspond to dry points. Vertical transects 1 (north) and 2 (south) are indicated by purple lines.](image)

Bathymetry was extracted as a .dep file and provided to the FLOW module. The latter offers to use either \( \sigma \)-layers or \( Z \)-layers for the vertical resolution of the lake: \( \sigma \)-layers follow the shape of the water depth profile and therefore none of them are empty. On the contrary, \( Z \)-layers upper and lower boundaries are horizontal and their width never changes, thus the amount of non-empty cells in the water column might differ from one location in the model to another.

The choice was made to use 75 \( Z \)-layers. The resolution varies from 10 cm to 30 cm (for the first meter, at the surface) to 25 or 50 cm (for the thermocline, from 8 m to 18 m) and up to 10 m (as deep-water temperature is almost stable). The upper limit \( Z_{\text{top}} \) was set to 1 m above water level as a “security layer”; this allows the model the run even in the case of strong oscillations at the surface.

### 4.2.3 Parameters considered

**Numerical parameters**

Delft3D’s model relies on multiple numerical and physical parameters, each of them influencing the behaviour of a physical variable. Their values are specific to each case, and though similarities can be found between lakes, they need to be calibrated to match Lake Zurich hydrodynamics to the best. However, the parametrization can be tedious because of the amount of parameters considered, especially since some of then can be partially linked to the same variables and are therefore correlated.

Since we only took interest in the water temperature and the currents, we selected the main parameters linked to heat transport and hydrodynamics that were identified in the literature: the bottom roughness \( z_{\text{bott}} \) (the choice was made to consider the \( Z_0 \) formula), the wind drag coefficients \( C_{10} \), the horizontal diffusivity \( D_{\text{H}}^{\text{back}} \) and viscosity \( \nu_{\text{H}}^{\text{back}} \), the Dalton number \( c_e \) and Stanton number \( c_h \).

According to several previous models, it was decided to set \( z_{\text{bott}} \) U- and V-components to the same value, and to consider "bottom roughness" as one unique parameter. The same was done for horizontal parameters \( D_{\text{H}}^{\text{back}} \) and \( \nu_{\text{H}}^{\text{back}} \).

The vertical viscosity and diffusivity influences were studied. While the first one proved to be negligible, the vertical diffusivity \( D_{v}^{\text{back}} \) greatly impacted the thermocline’s position and was therefore
added to the set of parameters to counterbalance the critical role of the wind drag coefficient. The influence of each parameter on water temperature was then studied again, but this time after the implementation of rivers and separately (by comparing with the same model reference each time).

The vertical background eddy viscosity $\nu_{\text{back}}$ and diffusivity $D_{\text{back}}$ were initially dismissed as the possibility to calibrate the model without vertical components was discussed. They were therefore set to zero in the baseline (see section 4.3.1).

However, it was revealed in the calibration process that only the wind drag coefficient regulated the thermocline’s position in the model. While $\nu_{\text{back}}$ was found to be negligible, $D_{\text{back}}$ was shown to greatly impact the thermocline’s position, and was therefore added to the set of parameters to counterbalance the critical influence of the wind drag coefficient on the matter.

One must not forget that the baseline must use values within reasonable and realistic limits. Therefore, values reported in lake modeling literature were collected and used for comparison. A summary table is presented in Table 4.1.

While this summary gives us an insight of the parameters’ usual range of values, it also highlights the differences between each lake’s calibration. Therefore, almost all of our baseline values were based on the final calibration provided for Lake Zurich by Manuel Hoffmann in his master thesis [28]. Our goal would then be to improve his already existing and functioning model. As advised by the researcher, the use of both COSMO-1 data and a variable Secchi depth were theorized to improve his results and provide a more realistic and performing model, and were integrated in our model.

Only one parameter was modified from the calibration provided by Hoffmann: the wind drag coefficients were chosen accordingly to a study by A. Wüest and A. Lorke [86] relying on the studies conducted by Geernaert et al. [23], Simon et al. [67], Yelland & Taylor [88] and Charnock [25].

![Figure 4.5: Wind speed / drag coefficient relation. Source: Wüest & Lorke, 2003 [86]](image)

In this paper, the relation between wind speed and surface drag coefficient was presented (Figure 4.5): under the critical wind speed of $W_{10} = 4$ m/s, the surface drag coefficient $C_{10}$ decreases following the equation:

$$C_{10} = 0.0044 \, U_{10}^{-1.15}$$

(4.1)

Interestingly, with a higher wind velocity (above 4 m/s), the coefficient doesn’t drop anymore but increases again, following Charnock’s law:

$$C_{10} = \left[ \frac{1}{k} \ln \left( \frac{10g}{C_{10}U_{10}^2} \right) + K \right]^{-2}$$

(4.2)

Where $k = 0.41$ (von Kármán’s constant), $K = 11.3$ [68, 88] and $U_{10}$ is the wind speed at 10 m above the water surface.
Since Delft3D can only take 3 pivot points (Figure 4.6), it is impossible to represent accurately the left part of the wind speed/wind drag relationship (see Figure 4.5), and values will be either overestimated or underestimated depending on our choice. A critical wind speed has to be chosen, for which the wind drag coefficient will be calculated according to literature.

From this point, the term “wind drag coefficient” will only apply to the first pivot point unless specified otherwise.

An initial wind drag coefficient of 0.0098 (for a critical wind speed of 0.5 m/s) was chosen for the baseline. This value was previously used in a calibration for Lake Geneva and offered a trade-off between the value used by Hoffmann and the one used by Gonzales for Greifensee, a lake in the close neighborhood of Lake Zurich [24].

Using values from previous studies conducted on other lakes proved to be a bad choice during the calibration process. The distribution of winds speed acting on the surface of the lake only in 2017 was therefore studied instead. The resulting histogram is presented in Figure 4.7.

The figure reveals that the distribution peak is centered around 1.2 m/s and highlights the poor choice of 0.5 m/s as the critical setting value. Both median and mean values were tested as the new setting value, as they are representative of the distribution.

The influence of constant plateau values for wind speeds outside boundaries (see Figure 4.6) was also studied and was proven to be of a great importance. Therefore, the wind speed values were linearly interpolated at 0.01 m/s, based on the literature values at 5 m/s and at the chosen critical wind speed.
Table 4.1: Usual range of values used in previous lake and basin models for the parameters considered in the calibration and validation of the model. Note that all models were not conceived on Delft3D, thus the exact meaning in the model of these parameters may differ.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{hott}$</td>
<td>0.005</td>
<td>m</td>
<td>0.0015</td>
<td>m/s</td>
</tr>
<tr>
<td>$C_{10}$</td>
<td>-</td>
<td>-</td>
<td>0.0015</td>
<td>m/s</td>
</tr>
<tr>
<td>$D_{back}$</td>
<td>-</td>
<td>-</td>
<td>0.0015</td>
<td>m/s</td>
</tr>
<tr>
<td>$C_e$</td>
<td>-</td>
<td>-</td>
<td>0.0015</td>
<td>m/s</td>
</tr>
<tr>
<td>$c_h$</td>
<td>-</td>
<td>-</td>
<td>0.0015</td>
<td>m/s</td>
</tr>
<tr>
<td>$D_{back}$</td>
<td>-</td>
<td>-</td>
<td>0.0015</td>
<td>m/s</td>
</tr>
</tbody>
</table>

*Indicates that value correspond to the *default* setting and was precised as such.

Rivers influence

During the process of calibration, Lachen caused several issues as its behaviour was the inverse of the two other monitoring stations: the model performance usually worsened in Obersee basin when it improved in Zurichsee.

A close study revealed that the metalimnion’s temperature gradient in the Upper Lake is actually much lower than it is in the Lower Lake, while the ones the model computes are actually similar in both basins (see Appendixes B and C). This difference could not be explained by a difference of climate, as the stations are relatively close.

A correction was crucial, especially since the smallest misfit of the thermocline can result in large differences of temperature between the model and the observations. However, no combination of the parameters could fix this flaw without significantly affecting negatively the model’s performance in the other basin.

A study conducted by Kobler et al. in 2018 [37, 38] showed the Linth channel, the rivers Jona and Wägitaler Aa contributed respectively by 83%, 5% and 5% to Obersee’s catchment. However, the flow rate was not monitored by the FOEN for these three inflows, but was measured every 10 minutes for the outflow Limmat. Assuming $Q_{in} = Q_{out}$ (to keep water balance in the Lake), these percentages were increased while keeping the ratio of each contribution:

$$Q_{Linth} = 0.892 \times Q_{Limmat}$$

$$Q_{Jona} = 0.054 \times Q_{Wägitaler} = 0.054 \times Q_{Limmat}$$

Water temperature was not monitored either for rivers Jona and Wägitaler, and were set by default to the same values as the one provided every 10 minutes for Linth.

This change proved to be efficient and corrected partly the simulated temperature profile for Lachen: deep layers were warmed while the surface became much colder, and the thermocline temperature gradient decreased.

Rivers catchments were also indicated in Figure 4.4.
4.3 Method

4.3.1 Baseline

A first simulation was run to identify the model’s limitations and flaws. The parameters values used in this baseline and their hypothetical influence on the lake’s internal dynamics can be found in Table 4.2. We remind the readers that vertical diffusivity or viscosity were not considered, and that the rivers were not implemented yet at the time.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Physical meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom roughness (Z⁰ formula):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-U</td>
<td>0.01 [-]</td>
<td>Determines the shear stress between water and lake bed. Higher values imply more energy dissipation in the basin (causing seiches to dissipate faster).</td>
</tr>
<tr>
<td>-V</td>
<td>0.01 [-]</td>
<td></td>
</tr>
<tr>
<td>Wind drag coefficients</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0098 [-]</td>
<td>0.5 m/s</td>
</tr>
<tr>
<td></td>
<td>0.0011 [-]</td>
<td>5 m/s</td>
</tr>
<tr>
<td></td>
<td>0.0021 [-]</td>
<td>25 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Characterizes the stress produced by the wind on the water surface; the highest the coefficient, the highest the mixing and the more momentum is transferred.</td>
</tr>
<tr>
<td>Background eddy viscosity:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- horizontal</td>
<td>0.1 m²/s</td>
<td>Characterizes the turbulent transfer of momentum by eddies (on a much larger scale than molecular viscosity). Higher values result in higher internal fluid frictions.</td>
</tr>
<tr>
<td>- vertical</td>
<td>0 m²/s</td>
<td></td>
</tr>
<tr>
<td>Background eddy diffusivity:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- horizontal</td>
<td>0.1 m²/s</td>
<td>Defines the diffusion or dispersion caused by turbulent motions. This effect takes place on a much larger scale than molecular diffusion. Higher values result in more mixing in the fluid.</td>
</tr>
<tr>
<td>- vertical</td>
<td>0 m²/s</td>
<td></td>
</tr>
<tr>
<td>Dalton number</td>
<td>0.0016 [-]</td>
<td>Defines the forced evaporation rate. The higher it is, the fastest the evaporation and therefore the cooling of water.</td>
</tr>
<tr>
<td>Stanton number</td>
<td>0.0016 [-]</td>
<td>Represents the forced convective heat flux. The highest it is, the more air temperature influences lake’s top layers temperature.</td>
</tr>
</tbody>
</table>

Table 4.2: Baseline main parameters in Delft3D-FLOW, initial values and physical meaning.

The results exhibited in Figure 4.8 show that, despite our modifications, the same flaws can be observed in our baseline model than the ones observed by Hoffmann in his master thesis: temperatures at the surface are underestimated and the thermocline is not well situated, causing a overestimation of the water temperature up to 6°C (Stäfa and Lachen) or 10°C (Thalwil).

For more detailed profiles, readers are referred to Appendix D.
4.3.2 Calibrated model

Calibration method

Calibration was conducted by minimizing the root-mean-squared error (RMSE) and mean absolute error (MAE) between the simulated and observed temperatures profiles at the three monitoring stations for the year 2017. MAE is less sensible to high differences and is therefore less influenced by the thermocline’s eventual misposition. Along with RMSE, MAE is an usual performance indicator often used in the literature [11, 35, 70, 78, 89].

While RMSEs and MAEs were evaluated separately for each station, they were also calculated for the three of them considered together as a whole: only these "global" model performances values were considered for the calibration.

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_{sim,i} - T_{obs,i})^2}
\]  \hspace{1cm} (4.3)

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |T_{sim,i} - T_{obs,i}|
\]  \hspace{1cm} (4.4)

Going further than the simple use of these numerical values, the use of Taylor’s diagram [72] was expected to give more insight on the model’s behaviour and performance and has also been used in previous studies [70, 78].

As seen on Figure 4.9, the diagram takes into account data’s standard deviation \(\sigma\), Pearson product-moment correlation coefficient \(R\) and centered root-mean-square difference (RMSD). While numerical values can be extracted from it, the diagram allows the visualization of the model’s performance by looking at its closeness to the observations.

First approach

Initially, the calibration was conducted by choosing a parameter which was then attributed several values, in order to study its influence on the water temperature profile. The “best” simulation obtaining the lowest global RMSE was then chosen as a new basis, meaning the chosen parameter value would be kept in further simulations. Another parameter would then be studied with the same method.

However, the method showed its limits: not only seemed it impossible to improve the model’s performance this way, but each parameter’s influence could be biased by an interaction with one or several others previously studied.
Figure 4.9: Theoretical example of a Taylor diagram. The model (in red) can be visually compared to the observations (in grey): the closer the model is from the center of the target, the highest is the performance.

**Calibrations dilemma**

The combination of rivers implementation and the new first wind drag coefficient, along with the new approach were enough to give better results: for the first time, all stations RMSE went under the target threshold of 1°C.

The two best 2017 calibrations obtained close RMSE and MAE values. While one performed slightly better, the similarity between the two calibrations could not be dismissed, even after the analysis of their respective Taylor’s diagram. The choice was therefore made to test both models on 2015 and 2016, but only the one with the best performance would be chosen as the final model.
Results and Discussion

5.1 Results

5.1.1 Model calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hoffmann</th>
<th>Baseline</th>
<th>Model 1 (M1)</th>
<th>Model 2 (M2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom roughness (20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-U [m]</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>-V [m]</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Wind drag coefficients [-]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0022 at 0 m/s</td>
<td>0.0098 at 0.5 m/s</td>
<td>0.00247 at 0.01 m/s</td>
<td>0.00247 at 0.01 m/s</td>
<td></td>
</tr>
<tr>
<td>0.0032 at 20 m/s</td>
<td>0.0011 at 5 m/s</td>
<td>0.0011 at 5 m/s</td>
<td>0.0011 at 5 m/s</td>
<td></td>
</tr>
<tr>
<td>0.00723 at 100 m/s</td>
<td>0.0021 at 25 m/s</td>
<td>0.0021 at 25 m/s</td>
<td>0.0021 at 25 m/s</td>
<td></td>
</tr>
<tr>
<td>Background horizontal eddy:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Viscosity [m²/s]</td>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>-Diffusivity [m²/s]</td>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Dalton number [-]</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td>Stanton number [-]</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0012</td>
<td>0.0012</td>
</tr>
<tr>
<td>Background vertical eddy diffusion [m²/s]</td>
<td>0</td>
<td>0</td>
<td>1.0·10⁻⁶</td>
<td>5.0·10⁻⁷</td>
</tr>
<tr>
<td>RMSE [°C]</td>
<td>-</td>
<td>1.70</td>
<td>0.74</td>
<td>0.72</td>
</tr>
<tr>
<td>MAE [°C]</td>
<td>-</td>
<td>1.04</td>
<td>0.48</td>
<td>0.46</td>
</tr>
</tbody>
</table>

*Linear interpolation of the wind drag coefficient $C_{10} = 0.0019$ at $U_{10} = 2.07$ m/s (mean wind speed value).

Table 5.1: Values of the parameters used in the baseline model and in the two calibrated model. The models performance is presented for a comparison.

Two models were calibrated for the year 2017 period (Table 5.1) using 6 temperature profiles for Stäfa and Lachen and 15 for Thalwil.

Both obtained good results, RMSE and MAE values under the respective thresholds of 0.75 °C and 0.5 °C. As their performance were very similar, it was decided to test them both on years 2015 and 2016. The result of this validation is presented in Table 5.2. The model M2 was chosen as the final validated model and will therefore be the only one presented in this chapter; readers are referred to Appendix E for more details on M1.

A Taylor diagram was presented for each monitoring station and for the model itself. It compared the baseline and the final model performances in the epi-, meta- and hypolimnion (Figure 5.1).

Globally, the improvement realized by our model in 2017 compared to the baseline is significant. Better correlation coefficients have been obtained, and the centered root-mean-squared difference (RMSD) was reduced by a factor of 2. In particular, the performance in the thermocline zone is way more precise. The variability of each layer was also closer to reality for the hypolimnion and metalimnion, but slightly worsened at the surface.

While the performance decreased very slightly for the deep layers at Lachen’s location, the improvement realized at the surface and in the thermocline is especially encouraging and emphasized again the role of the rivers in Obersee’s hydrodynamics.
5.1.2 Model validation

<table>
<thead>
<tr>
<th>Performance indicators</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE [°C]</td>
<td>0.79</td>
<td>1.01</td>
</tr>
<tr>
<td>MAE [°C]</td>
<td>0.57</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Table 5.2: Validation: performance indicators for M1 and M2 models in 2015 and 2016.

Both models performed well on 2015 on 2016, with a RMSE below or close to 1°C and a MAE below or close to 0.7°C (see Table 5.2). 2016 obtained significantly worse results for the two models, with a RMSE and a MAE ~ 30% above the mean of 2015 and 2017. Nonetheless, the two models could be considered as validated on the period of interest.

Again, the two models performed with similar efficiency. The study of their respective Taylor diagrams in 2015 and 2016 (Figure 5.2) revealed that M1 reproduced more precisely the water temperature variability. However, the differences were not too important; moreover, considering both the calibration and validation steps, M2 was the only one obtaining RMSE values strictly below 1°C for the three years considered, and it globally obtained better results for each station (Appendix F). For these reasons, it was chosen as the final model.
Figure 5.2: Taylor diagrams for both models in a) 2015 and b) 2016. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The M1 model (darker tones) is compared to the M2 model (lighter tones). Grey figures on the x-axis correspond to the observations.

5.1.3 Water temperature profile: in-depth analysis

Figure 5.3: Differences between simulated and observed temperature profiles in 2017 at the three monitoring stations. Over-estimations are highlighted in red, under-estimations in blue. Shading is obtained by linear interpolation between the values.

<table>
<thead>
<tr>
<th></th>
<th>Stäfa</th>
<th>Thalwil</th>
<th>Lachen</th>
<th></th>
<th>Stäfa</th>
<th>Thalwil</th>
<th>Lachen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RMSE [°C]</strong></td>
<td>1.78</td>
<td>1.59</td>
<td>1.92</td>
<td><strong>RMSE [°C]</strong></td>
<td>0.67</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td><strong>MAE [°C]</strong></td>
<td>1.16</td>
<td>0.89</td>
<td>1.38</td>
<td><strong>MAE [°C]</strong></td>
<td>0.47</td>
<td>0.42</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table 5.3: Baseline’s and calibration’s performance indicators for each station.

To assess the model’s ability to reproduce the lake’s thermal variability (both spatially and temporally), the water temperature profile computed by our model was compared to the measurements.
carried out at each monitoring station in 2017. The baseline results were also represented to highlight the improvements realized since the beginning of the project.

These results can be visualized in Figure 5.3. RMSE and MAE values are summarized in Table 5.3, which reveals respective increased performances by 59% and 57% (meaning the calibrated model is more than two times more efficient than the baseline).

Zurichsee basin

![Figure 5.4: Model performance for Stäfa. The final model (red line) is compared to the baseline (black dashed lines) and the observations (blue points). The thermocline is globally situated 1 m too high (as noticeable on 7th August). The unusual low temperature gradient on 8th May is also not reproduced.](image)

Globally, the model reproduced well Stäfa’s water temperature profile at every level. Its shape follows more the one described by the observations, and the overestimation of deep-water temperature in the baseline was corrected, along with a few deviations at the surface (Figure 5.4). However, the
model seems to be struggling occasionally with the thermocline, as seen on 8th May 2017, where the temperature gradient in the lower part of the layer was overestimated. Moreover, the thermocline’s position is \(~1\) m too high this time (instead of up to 3.5 m to low in the baseline), resulting in temperature differences up to \(2.5\)°C between the simulation and the samples.

For clarity and readability reasons, only six dates distributed over year 2017 are presented in Figure 5.5. The complete water temperature profile can be found in Appendix G.

The shape of the water temperature profile at Thalwil’s location has significantly improved since the baseline: the consequent under-estimation of the temperature at the surface has been corrected and the thermocline’s height enhanced. Nevertheless, the thermocline is still causing issues, as a small height difference is still observed sometimes. This, combined with a really high temperature gradient, results in a temperature up to 4.5°C warmer than the observations (Figure 5.5).

While the shape of the profile is still realistic, the temperature gradient in the transitional layer between the thermocline and the depths is shown to be too high in our model. Moreover, sudden events and changes are sometimes not reproduced, as seen on 19th April (see Appendix G).

**Obersee basin**

Figure 5.6: Model performance for Lachen. Observations are represented by blue points, while the baseline by the black dashed line and the final calibration by the red line. Huge improvements have been made since the baseline, but the position of the thermocline and the temperature gradient at its lower boundary remain problematic.

Figure 5.6 highlights the positive impact of the rivers implementation in the model: the simulated thermocline’s temperature gradient decreased noticeably. Moreover, the M2 model obtained a temperature profile closer to the reality in general, with a consequent improvement at the surface (which was too warm in the baseline) and in the upper part of the thermocline.

However, for both epi- and hypolimnion, temperature differences up to 1°C are still observed, the upper layers being usually too warm and the lower layers being too cold. The upper part of the thermocline is the most flawed zone in our model, its depth being overestimated at several points in time; its shape can also be far different, as seen on 7th August 2017. On 8th May 2017 (same day as the most flawed thermal profile at Stäfa’s location), the thermocline’s position is shown to be too high (\(~4\) m). Note however that the thermocline is also bouncing in nature, so large deviations are normal and can be expected.

**Surface temperature in the two basins**

The study of temporal and spatial evolution of the water temperature in the upper layers of Lake Zurich revealed a significant difference between the average temperature in Obersee and Zurichsee: despite being shallower, the first basin is usually colder than the second (as illustrated in Figure 5.7).
5.1.4 Physical processes

Upwellings

Deep-water can sometimes rise in upper layers due to internal currents, resulting in an abrupt cooling of the metalimnion and the surface. This event, called \textit{upwelling}, has already been observed on Lake Zurich in previous studies \cite{48}.

Daily temperature data (Annexe H) provided by the canton of Zurich (\textit{Baudirektion / Amt für Abfall, Wasser, Energie und Luft}) for the Limmat river in 2017 reveals four sudden and important drops of water temperature around the 19\textsuperscript{th} April 2017 (∼-4°C), 27\textsuperscript{th} April 2017 (∼-6.5°C), 7\textsuperscript{th} June 2017 (∼-9.5°C) and 17\textsuperscript{th} June 2017 (∼-5°C). Such peaks can be indicators of an upwelling event in the lake as the latter causes the outflow to cool heavily in a short amount of time.

To assess the model’s ability to reproduce such dynamics, the simulated temperature on the lake was extracted again at 0.25, 2.5 and 4 m deep and observed for the two concerned months.

A particular interest was also taken in the region near the outflow position, and the simulated temperature profile was compared to data collected by a station in the river (2’682’510/1’249’125) at 7 m depth (Appendix H). The comparison is shown in Figure 5.8.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5_8.png}
\caption{Comparison between the Limmat modeled (red) and observed (blue) temperature profile at a depth of 7 m. Temperatures were measured every 10 min (Source: Canton of Zurich) and simulated every 2 hours. Main potential upwelling events are indicated by orange arrows.}
\end{figure}
Only the most important cooling event on 7th June 2017 is detailed in this section; others events are discussed in Appendix I.

Figure 5.9: Temperature profile at 0.25 m, 2.5 m and 4 m depth on a) 7th June 2017 at 6:00 PM and b) 8th June 2017 at 2:00 AM.

The study of the simulated temperature at this date reveals a sudden cooling of the upper layers at the northern shore of Zurichsee, near 2:00 PM. Appearing from the middle of the basin, the cooling strengthens as the phenomenon spreads to the north-western extremity of the lake, near Zurich, and lasts until the 8th June at 8:00 AM (Figure 5.9).

While this colder water doesn’t rise to surface the of the lake, the event can still be observed up to 2 m deep.

Finally, every upwelling was reproduced by the model. The temporal variability of the water temperature was well-replicated, and a particularly good match is found in unstratified periods (January-March) and from autumn to winter. However, the model lacked precision in the March-September period: high variations of temperature were underestimated systemically (with observable differences up to 6 °C), and the simulated profile was in average ~0.93 °C colder than the reality.

The amplitude of the thermal variation caused by the upwellings was also underestimated: for example, the two events occurring in April could only be seen at 4 m depth while the one occurring in June could be seen up to 2 m depth. Since Thalwil measurements on 19th April showed an overes-
timation of the temperature, this could indicate that such events of lower intensity are not perfectly reproduced by the model.

Seiches

Since the presence of internal waves in Lake Zurich was demonstrated in the literature, the model’s ability to reproduce seiches dynamics was studied, and the temporal evolution of the water temperature was plotted.

**Figure 5.10:** Temperature profile at the Thalwil monitoring station, from 1st to 7th September 2017, with a timestep of 15 min. Internal waves can be seen in the isotherms.

**Figure 5.11:** Raw (orange) and smoothed (blue) periodogram of the temperature profile at a depth of 9 m. From left to right, the three black vertical lines correspond respectively to the 44h, 24h and 17h-periods found by Horn [29].

The presence of internal waves were indeed detected in the isotherms (Figure 5.10). Several periodograms were conceived to analyze their periods. The three main periods were found to be of 44 h, 25.6 h (though less visible) and 17h (Figure 5.11).

Smaller periods of 15 h, 12.6 h, 11.3 h and 9.6 h, 8.1 h, 7.4 h, 6.4 h and 6 h on average were also observed (Figure 5.11).
Water velocity and currents

Currents were simulated by the model for the whole year. At the surface, currents values ranged within 0 and 0.43 m/s, but the mean value was only of 0.0324 m/s. Without a surprise, the velocity map revealed that the flow followed the lake’s shape along the direction of the wind.

Figure 5.12: Velocity map on 1st August, at 6:00 AM. Counterclockwise rotation can be observed in Obersee near Lachen’s location.

Figure 5.13: Velocity map on 11th August, at 6:00 PM. Clockwise rotating flow is observed in Zurichsee near Stäfa.
No gyres were observed in the Lake, which was expected since Lake Zurich is much narrower than Lake Geneva for example and is therefore less susceptible to welcome the formation of such structures. However, the topography of the lake and strong winds could allow the occasional formation of clockwise and counter-clockwise flow rotation, as depicted in Figures 5.12 and 5.13).

![Velocity map on 14th December, at 16:00 PM. Strong currents are observed on the lake's surface and are oriented towards the west.](Image)

**Figure 5.14:** Velocity map on 14th December, at 16:00 PM. Strong currents are observed on the lake’s surface and are oriented towards the west.

The model seems to be able to reflect the influence of strong wind events on currents: the passage of the "Zubin" storm on 14th December 2017 [63] coincided with high flow rates in the entire lake (Figure 5.14).

## 5.2 Discussion

### 5.2.1 Model setup

The combination of a calculation timestep of $dt = 30$ sec and the curvilinear grid used for spatial discretization, with a cell size of 180x200 m and 75 layers with varying thicknesses, resulted in a three-cores-processing time of 45 h for a simulation time of one year. This is estimated to be a good compromise between spatial resolution and calculation time. Nevertheless, the amount of vertical layers could probably be reduced to increase the latter; a study would be needed to evaluate the impact of a slightly increased thickness for the thermocline layers on the computed temperature.

The implementation of rivers proved to be of great importance, especially for reproducing Obersee’s basin behaviour. Due to the proximity of Etzelwerks’ powerplant discharge and the Lachen monitoring station, a potential improvement would be to implement this inflow and to study the effect on the water temperature profile. However, the increase of performance is expected to be low and bounded to close points from the discharge.
After the implementation of rivers and the addition of vertical diffusivity to the studied parameters, we looked into each parameter’s influence on the water temperature profile. This time, parameters were compared separately, by a comparison with a reference model.

- A higher wind drag coefficient $C_{10}$ made the thermocline sink and warmed up the hypolimnion. This also caused the epilimnion to cool from March to June, and to cool at the end of the year (November-December).
- Increasing the vertical diffusivity $D_V^{back}$ resulted again in the sinking of the thermocline, along with a warming of deep-water temperature and a cooling of the surface from April to September. The last effect is reversed the rest of the year.
- A high Stanton number $c_e$ cooled up the whole water body.
- Increasing the Dalton number $c_h$ gave the same cooling effect but the latter was increased at the surface. This result came without surprise, as this parameter reflects the influence of evaporation.
- Bottom roughness $z_0^{bot}$ had to be increased greatly to observe an impact, taking the form of warmer deep-layers.
- Horizontal viscosity $v_H^{back}$ and diffusivity $D_H^{back}$ were again considered together (the two parameters were always set together at the same value). With high values came a cooling of the surface and a warming of the deep layers, resulting in a wider thermocline whose temperature gradient increased. The lower boundary of the thermocline also sank.

In addition to this analysis, the initial water temperature profile was adapted to correspond more closely to the observations measured at Thalwil’s location on the 4th January 2017 rather than using a constant value at all depths. The idea was to reproduce in a way the heat budget present at the beginning of the year.

Twenty-seven new simulations were processed so. The model parameters’ values were set accordingly to the supposed influence on the water temperature profile. Refinement was done according to the hypothesized correction of each simulation’s flaws and by minimizing again the RMSE and MAE.

This approach and these corrections allowed a better calibration of the model, resulting in really good results as shown in the previous section 5.1.

### 5.2.2 Sensitivity analysis

A change of value for one parameter of interest doesn’t always have the same influence on the results. The sensitivity $S$ of a model to a parameter $\Theta$ has to be defined to show the optimization state of a model and allow future researches to improve it by working on the most sensible parameters.

Therefore, each of the 6 studied parameters’ value was increased and decreased by 5% and by 30% for the model M2, and its new performance was calculated:

$$S = 100 \frac{P_{\Theta_{new}} - P_{\Theta_{old}}}{P_{\Theta_{old}}}$$

Where $S$ is the change in performance (in %), $P$ the performance indicator value (RMSE or MAE), $\Theta_{old}$ the initial value of the parameter of interest and $\Theta_{new}$ its new value. The higher $S$ is for the same parameter’s value’s percentage of change, the higher is the model sensitivity to this parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>-30%</th>
<th>-5%</th>
<th>5%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom roughness</td>
<td>0.091</td>
<td>0.013</td>
<td>-0.013</td>
<td>-0.073</td>
</tr>
<tr>
<td>Wind drag coefficient</td>
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<td>0.223</td>
<td>-0.392</td>
<td>-4.415</td>
</tr>
<tr>
<td>Horizontal eddy diffusivity and viscosity</td>
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<td>0.128</td>
<td>-0.146</td>
<td>-1.08</td>
</tr>
<tr>
<td>Dalton number</td>
<td>-7.22</td>
<td>-0.24</td>
<td>-0.125</td>
<td>-5.16</td>
</tr>
<tr>
<td>Stanton number</td>
<td>0.67</td>
<td>0.19</td>
<td>-0.22</td>
<td>-1.73</td>
</tr>
<tr>
<td>Vertical eddy diffusivity</td>
<td>-0.23</td>
<td>0.078</td>
<td>-0.123</td>
<td>-1.26</td>
</tr>
</tbody>
</table>

Table 5.4: Sensitivity analysis for the RMSE. Values indicated correspond to the increased (positive) or decreased (negative) performance percentage.

Table 5.4 recapitulates the results of this analysis. Positive values show that the optimum was not found for every parameter. However, the resulting increase of the model performance is very small (1%) and therefore assumed to be of no significance.
The most sensitive parameter is revealed to be the Dalton Number $c_e$: a reduction of this parameter would result in less evaporative heat loss, meaning the lake will globally be warmer through the year at all levels, and especially during summertime and at the surface. The model was negatively affected whether the value of $c_e$ was increased or decreased, meaning the optimum value was found.

The wind drag coefficient $C_{10}$ appeared to be one of the most critical parameters of the calibration. Not only was it the only one heavily influencing the thermocline’s position, but it also regulated the boundaries’ depth of both epilimnion and hypolimnion, along with their temperature. It was therefore not a surprise to find that it was coming in close second position in the sensitivity analysis.

Unlike the previous parameter, a decrease of its value can improve the model, but to a very little extent. This result is expected to be linked to the choice of the critical wind speed, already high on the wind drag/wind speed relation curve detailed by Wüest & Lorke (Figure 4.5): both the mean and the median wind speed values were tested as critical pivot in Delft3D. Results proved the "mean" approach to be more slightly more efficient (though RMSE improvement was only of 0.53%), giving us a wind drag coefficient of 0.0019 at 2.07 m/s; the corresponding interpolated value was 2.47·10$^{-3}$ at 0.01 m/s. This result suggests that extreme values do have an influence on the model, albeit small.

On the contrary, increasing $C_{10}$ drastically worsened the model’s performance in a significant way. This implies that the stress caused by weak winds (0 to 4 m/s) is slightly overestimated. It could also mean that the second wind speed pivot is too high: setting it at the critical speed of 4 m/s described in the paper could be an improvement, and studying the impact of its value would help in the identification of the underestimated mechanism.

In the order of sensitivity come then the Stanton number $c_b$, the horizontal components $v_{H}^{L}$ and $D_{H}^{L}$ of the vertical diffusivity $v_{P}^{L}$ and the bottom roughness $v_{bott}$. However, none of them seem to be very relevant as even a significant change of their values decrease the model’s performance by less than 2%, and the potential improvements are of less than 1%.

Globally, our model is found to be quite stable.

### 5.2.3 Water temperature profile: model validation

The model obtained very good results in the Zurichsee basin. Deep-water temperature was especially well-reproduced, and the differences between computed and observed temperatures in the epilimnion were little. However, the thermocline proved itself to be quite a challenge: even a small underestimation of its depth resulted in large differences of temperature between our model and the reality. Moreover, the temperature gradient at its bottom was usually too high (water should cool down way slower in the transitional zone between the thermocline and the hypolimnion).

The difficulty to reproduce the metalimnion’s behaviour is compliant with the literature. However, a difference of only 1 m in average between the simulated and the real depth of the layer is estimated to be good; increasing the performance of the model regarding the latter would probably require a good assessment of wind-induced mechanisms. This is also suggested by the incorrect reproduction of the sudden cooling event observed at Thalwil’s location on 19th April 2017, hinting that some transient physical processes might not be reproduced well enough by the model.

Nonetheless, the performance of the model remains very good, and it is estimated to be accurate enough to reproduce usual heat transport mechanisms in the lower part of Lake Zurich.

Through the entire duration of our project, the Upper Lake proved itself to be recalcitrant to the calibration. Most of the issues it caused were solved by the implementation of rivers in the model, highlighting their role in the basin’s hydrodynamics: the simulated thermocline’s temperature gradient became lower and closer to the reality, and the performance of the model at the surface was greatly improved.

However, small errors are still observed in the modeled surface temperature. The temperature gradient in the lower part of the thermocline is a little too high through the year, and it is also too low in its upper part in August and September. Several improvements are suggested to correct these flaws: a model grid with a better resolution, the calibration of the wind drag coefficient (as suggested before) but also the study of the discharges in this part of the Lake. The influence of setting the rivers discharge in the basin several meters deep instead of the actual inflow at the surface could also be studied.

Nonetheless, the model’s performance in Obersee remains good, and the thermal profile is well-reproduced overall. The addition of the upper basin is a noticeable plus to the model robustness and proves its ability to reproduce not only the temporal but also the spatial variability of water temperature in Lake Zurich. The current model can be used as a good basis for future refinement and is ready.
to use for forecasts.

**Conclusion**

Despite several imprecisions, especially in the thermocline for both basins, the model was able to reproduce the thermal profile in both basins along the year, with an acceptable accuracy in the epi-, meta- and hypolimnion. It is therefore expected to provide good forecasts several days in advance, given good meteorological and hydrological forecast data.

### 5.2.4 Physical processes

The model was able to reproduce seiches dynamics, and the three main periods of 44 h, 25.6 h and 17 h reproduced by our model are close to the ones found by Horn et al. in 1986, which were of 44h, 25.6 h and 17 h [29].

Smaller modes of 12.6 h and 11.3 h were also close to the ones reported by the researchers (13 h and 10.5 h). Finally, periods of 9.6 h, 8.1 h, 7.4 h, 6.4 h are close to the periods of the internal normal modes of Lake Zurich predicted by the two-layered variable-depth model (or TVDM) they used; for the record, the latter expected periods of 9.5 h, 8.2 h, 7.2 h, 6.7 h and 6.1 h.

### 5.2.5 Upwellings

Upwellings event were reproduced and detected, with a very good correspondence between the model and the reality on the 17th June 2017. The amplitudes and strength of the events were slightly underestimated.

As the flow is strong, the presence of the city on the shores of Lake Zurich’s outflow is not expected to have an influence on the water temperature profile. Though this could be due to the model’s underestimation of high wind events, the difference between the measured profile in the river Limmat and the computed water temperature at a depth of 7 m can also be linked to the topography of the beginning of the riverbed, as discussed with Prof. Wüest.

### 5.2.6 Flow velocity

As for now, water velocities can only be examined qualitatively, by making the assumption that the model’s performance regarding water temperature and the values range for the currents implies a good reproduction of the hydrodynamics in the lake. A quantitative way to assess the model’s performance for this variable would require in-situ measurements.

Nonetheless, the model was still able to reproduce flow rotation in the lake and detected extreme events, such as the storms Niklas (31st March 2015), Susanna (10th February 2016) and Zubin (31st December 2017). The unusual strong foehn blowing on the lake on 4th March 2017 and reported in the media was also reproduced and corresponded to the maximal flow velocity for year 2017, being 0.43 m/s. It was noticed that modeled flow velocities in Lake Zurich during tempest events were smaller than the ones modeled in Lake Geneva (the latter going up to 0.8 m/s). However, this remains consistent with reality, as tempests are usually weaker in the vicinity of Lake Zurich.

### 5.2.7 Perspectives

To improve the model, the suggestion is made to reevaluate inflows’ discharges and temperatures in Obersee; however, the resulting improvement is expected to be small. The implementation of Etzelwerk’s powerplant discharge to and withdrawal from the lake could be of potential interest. We also advise further calibrations to focus mainly on the wind drag coefficient $C_{10}$ in a first step, who proved to be of a critical importance for the simulated thermocline position and temperature profile. Studying the impact of the second Delft3D pivot point is advised, as is the setting of the third one for a higher wind speed in order to reflect better the influence of extreme wind events on hydrodynamics.

Further steps would be to study the influence of biological variables on physical processes, although it would require data on plankton growth, algae growth and oxygen dissolution along with the consideration of the sedimentation process in the lake.

Using data assimilation (DA) would also be the next big step further a more realistic model. This approach accounts for uncertainties in both the model and the data. This is of a particular interest as the wind was proven to be critical in the modelization, while it is also the most uncertain meteorological
variable. The use of DA on other lakes is currently studied and is expected to provide more faithful forecasts.
The goal of this thesis was to conceive a three-dimensional physical model capable of reproducing Lake Zurich thermal and hydrodynamical conditions. Regarding water temperature, the model obtained good results for his calibration on year 2017 and was validated on years 2015 and 2016 using established methods such as RMSE and MAE minimizing, along with the use of Taylor diagrams. It had been shown to reproduce well the spatial and temporal variability of the water temperature profile in the lake, being the first and most recent one to account for the Upper Lake. Though the thermocline’s behaviour is reproduced less precisely and the temperature gradient in the transitional layer between the meta- and hypolimnion is sometimes overestimated, the precision obtained for the thermocline position (∼1 m) is estimated to be excellent.

Internal waves dynamics were reproduced and their average period were consistent with literature. Upwelling events were correctly reproduced, but the strength of the events was underestimated by the model.

The ability of the model to reproduce flow velocities and directions was only studied in a qualitative way; the model did however reproduce the impact of strong wind events on the currents at the surface of the lake, and the values obtained for the flow velocities were consistent with reality. A quantitative assessment of the model’s performance would require additional data.

The Dalton number $c_e$ revealed itself to be the most sensible parameter for our model and had to be assessed carefully to reproduce water temperature in the upper layers. It is expected to be linked to the calibration of the wind drag coefficient $C_{10}$ and to the sensitivity of the model to the latter. Finally, the vertical diffusivity $v_{D,\text{back}}$ addition to the parameters of interest was proved to be relevant (as background diffusivity is important), and its usefulness in the thermocline’s position setting was highlighted.

The Delft3D-FLOW modelization of Lake Zurich is considered to be a success, with a good performance on the latest years coupled with the ability to predict strong local events and to reproduce hydrodynamics occurring in the water body. Its implementation on Meteolakes is therefore justified, and the latter will allow practical applications by the general public and by lakes professionals and scientists as well, given proper meteorological and hydrodynamical data. For example, the prediction of the impact of tempest events on Lake Zurich shores could contribute to the safety of its citizens while reducing the cost of the damage caused by strong winds and currents.

Companies providing drinkable water to the cities in the vicinity (such as Wasserversorgung Zürich) could benefit from the ability of the model to reproduce internal waves, as this could bring warmer water in the upper layers of the lake, and potential algae contamination with it. As for the matter, our model is also estimated to serve as a reliable and robust basis for a future biological model. As Lake Zurich’s water is known for its quality, this would help the monitoring of chemical compounds, and the water velocity map provided by our model would also be useful to study the impact and diffusion of an eventual chemical pollution. The biological model would also be useful to monitor nutrients’ availability and phytoplankton’s growth, such as the cyanobacteria P. rubescens, whose high concentration might be harmful for humans. Readers interested in the latter can refer to the study carried out by M. Hoffman and the Departement of Hydrology and Geohydrology (from the Institute for Modelling Hydraulic and Environmental Systems) [28].

The development of such models and their diffusion to the citizens with the help of online platforms such as Meteolakes allow the society to benefit from the services provided by the lakes in a sustainable way, while improving our ability to understand the mechanisms ruling their hydrodynamics.
Bibliography


timeanddate.com. *Climate & Weather Averages in Zürich, Zurich, Switzerland*.


## Appendices

### A Monitoring stations’ depth profiles

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*Table 1*: Measurements’ depth profiles for the stations, in meters.
B  Comparison: Stäfa and Thalwil’s simulated temperature profile

Figure 1: Simulated temperature profiles at Stäfa’s (blue) and Lachen’s location (green). Thalwil is not shown, as measurements were not made on the same days.

The computed water temperature profiles at both stations are presented in Figure 1. It is shown that both profiles act in a similar way, thermocline’s slope included.
Comparison: Stäfa and Thalwil’s observed temperature profile

Figure 2: Observations for Stäfa and Lachen monitoring stations. The difference of the thermoclines’ slope is clearly visible.

This time, observations are compared for both stations (Figure 2). The water temperature surface at Stäfa’s location is much warmer than Lachen’s; the inverse behaviour is observed in depth. As for the thermocline, it seems to be much steeper in Obersee than it is in Zurichsee.
D Baseline results

As seen in Figure 12, the same pattern observed by Hoffman at Thalwil is present despite our modifications: while deep-water temperature is nicely simulated, the surface temperature is globally underestimated (this tendency being inverted in November and December) and the thermocline position is also too low: this resulted in an overestimation of temperature in the layer, up to 10°C. These results are obtained again for Stäfa (with an overestimation of 6°C at the thermocline); though this time deep-water temperatures are slightly overestimated (Figure 4).

Figure 3: Thalwil water temperature profile at Thalwil (baseline). While deep-water temperatures are correctly estimated, small difference can be seen at the surface and the thermocline’s depth is clearly overestimated.
Figure 4: halwil water temperature profile at Stäfa (baseline). The same flaws than those observed at Thalwil are observed, but the higher slope of the metalimnion reduces the error between the computation and the observations. Deep-water temperature is also less precise and over-estimated.
As for Lachen, Figure 5 shows an interesting result: not only is the simulated epilimnion too warm and the hypolimnion too cold this time, but the slope of the thermocline differs greatly from the observations. A comparison between simulated and observed temperature profiles at Stäfa and Lachen reveals that while the simulated shape of the metalimnion (and especially its slope) was almost the same for the three monitoring stations (appendix B), observations showed a difference between the two basins, Obersee’s thermocline being steeper (appendix C).

![Water temperature profile at Lachen](06-Feb-2017 01:00:00)  
![Water temperature profile at Lachen](06-Mar-2017 01:00:00)  
![Water temperature profile at Lachen](08-May-2017 01:00:00)  
![Water temperature profile at Lachen](07-Aug-2017 01:00:00)  
![Water temperature profile at Lachen](04-Sep-2017 01:00:00)  
![Water temperature profile at Lachen](06-Nov-2017 01:00:00)

**Figure 5:** Temperature profile comparison after initialization: Lachen

Overall, this first simulation didn’t perform well: Stäfa, Thalwil and Lachen gave respectively a RMSE of 1.66, 1.97 and 1.74 °C (for a global RMSE of 1.71 °C) and a MAE of 1.16, 0.90 and 1.38 °C (for a global MAE of 1.0 °C).
The two models obtain really similar performances at the three stations and globally. When studying each station separately, M1 reproduces the variability of the temperature in the thermocline and at the surface slightly better than M2; this tendency is inverted for the temperature in depth. When taken as a whole, the negative and positive standard deviations compensate themselves, and M2 seem to reproduce quite precisely the thermal variability in the thermocline.

Nonetheless, no outstanding difference between the two models can justify its choice over the other one, thus the validation test for both of them.

**Figure 6:** Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (darker tones) is compared to the final model M2 (lighter tones). Grey figures on the x-axis correspond to the observations.
F  Model 1 (M1) validation

F.1  Performance in 2015

Figure 7: Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole in 2015. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (colored) is compared to the final model M2 (black). Grey figures on the x-axis correspond to the observations.

In 2015, when considered as a whole, M1 seem to reproduce the thermal variability in a better way among all years and layers. This result is less obvious when the performance in the thermocline at each station is detailed, and both models struggle noticeably with Obersee’s metalimnion.
F.2 Performance in 2016

Figure 8: Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole in 2016. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (darker tones) is compared to the final model M2 (lighter tones). Grey figures on the x-axis correspond to the observations.

The performance of both models in 2016 is noticeably worse than the other years. The variability in depth remains nicely reproduced, with a centered root-mean-squared difference under 0.5°C. This is also the case at the surface but the RMSD is more important. Finally, the thermocline remains problematic, especially at Lachen’s location.

Overall, M1 seems to reproduce more precisely the variability of the water temperature among all layers while M2 obtains better RMSD; however, the difference between the two performances is still negligible.
Figure 9: Taylor diagrams for a) Stäfa, b) Thalwil, c) Lachen specifically and d) M1 as a whole in 2016. Performances for deep layers, thermocline and surface are respectively represented by diamonds, triangles and squares. The model M1 (colored) is compared to the final model M2 (black). Grey figures on the x-axis correspond to the observations.
The calibration corrected party the temperature errors at the surface, and the thermocline position was set higher and closer to reality. The temperature gradient in the transition zone between the metalimnion and the hypolimnion is however too low.

The model globally performs well but struggles to reproduce specific and sudden events, like the cooling observed on 19th April 2017.
### Daily temperature profile for Limmat

**Figure 10:** Daily means of water temperature for the river Limmat. *Source: canton of Zürich.*
I Upwelling events

Figure 11: Temperature profile at 0.25 m, 2.5 m and 4 m depth on A) 19\textsuperscript{th} April at 8:00 PM and B) 27\textsuperscript{th} at 6:00 AM. Upwellings can be seen on the last layer, at the extremity of the lake.
Upwelling events are reproduced by the model but the cold water doesn’t rise up to the surface. For the events in April, a small time delay of several hours can occur between the model and the real event.

Figure 12: Temperature profile at 0.25 m, 2.5 m and 4 m depth on a) 16th June 2017 at 2:00 PM and B) 17th at 4:00 AM. Once again, the upwelling event can mainly be observed on the last layer.