Thermal Stratification in Small Lakes with TELEMAC-3D: Showcase “Lake Monsterloch”

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***Abstract*—This paper shows ways to configure and optimize TELEMAC-3D, to get ready for the calibration of temperature stratigraphies in small lakes. Thermal stratifications are very sensitive to numerical instabilities and dispersion. Small lake models are additionally dominated by a high percentage of boundary nodes, a source of instabilities in numeric models.**

The small “Lake Monsterloch” (english: “Monsters Hole”) is a good prototype study for the many central european lakes, that suffered the same problems in the exceptional hot summers of the last decade. The lack of rain and river discharge, plus the long heat periods from 2016 to 2019 and the rising agriculture based fertilisers in the water reduced the dissolved oxygen to nothing. Without vertical mixing effects, the consequence is the dying flora and fauna as well as the resulting rot odour nuisance.

Telemac proofed to be the right tool to solve vertical heat exchange and simulate mixing solutions with low or no current, if one understands the definition ranges of the core routines well and if a couple of minor code fixes are added.

Fig 1: Impression of the boundary dominated lake with dead fish and firefighters trying to pump in fresh water. (Source: Rhein Neckar Zeitung, 22.09.2016)

I. Project & Site “Lake Monsterloch”

The eastern neighbourhood is dominated by agricultural land, while the western river shore is one of Germany’s oldest cities, Speyer. The riparian corridor is only narrow at the project site, but it is a funnel in the vast riparian forests and water networks of the Upper Rhine Valley, an important corridor on the North-South bird migration routes and an important breeding ground for fish, like the almost extinct German salmons. It is part of the “Blue Rippon” project, which focuses on the revitalization of riparian systems along the waterways. The River Rhine is Germany's most important inland waterway, engineered for ship dimensions of 195 m x 22,8 m x 4 m. As the river itself is quite shallow and under permanent dredging maintenance, any kind of discharge diversion to the lake might lead to sediment disposals in the shipping corridor.

The project task is to prevent future lake ecosystem collapses due to overheating and oxygen loss without taking too much water from the main river.

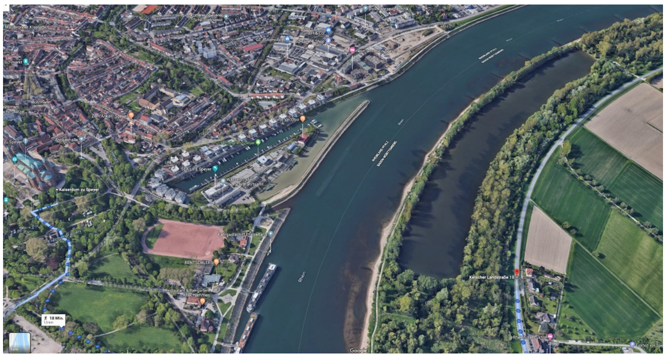

*Fig 2: Lake Monsterloch is located 1km east of the touristic UNESCO World Heritage site “Imperial Cathedral of Speyer” and only separated by a thin gravel damm from the River Rhine main channel. Dimensions: approx. Y: 1000 m * X: 150 m * Depth: 14 m (maps.google.de / 2.9.2019)*

II. Knowns & Unkowns

A. *Temperature*

Temperature measurements are available at two depth profiles close to the geometrical lake center over 2 years. Dissolved oxygen (most fish die below 3 mg/l) and conductivity (an indicator for salts) are available for some datasets. Missing is a gauging and monitoring system for the inflow and outflow. Discharge, temperature, oxygen and conductivity had to be approximated by values of the Rhine gauge in Speyer. The measurements show clearly the well known 3 zones Epilimnion, Metalimnion and Hypolimnion. The model calibration is based on these two temperature depth profiles.

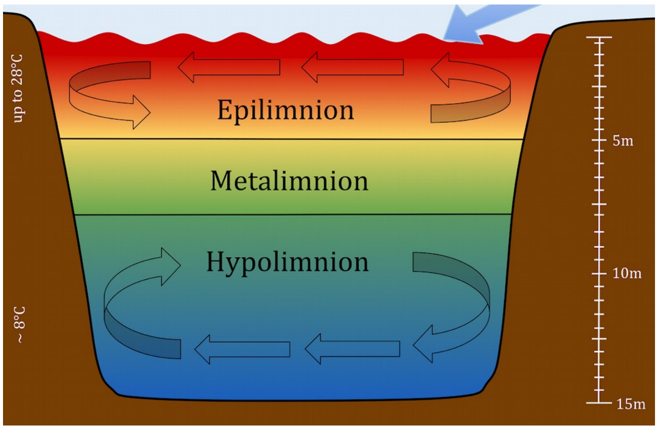

Fig 3: Typical temperature profile in summer (Source: Lake_Stratification_(11).svg / wikimedia.org / modified by author)

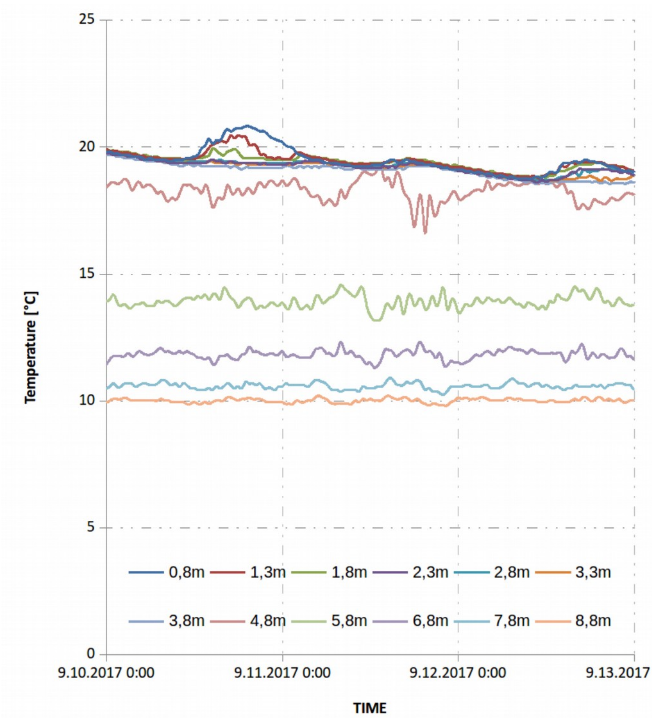

Fig 4: 3 days temperature recordings of 12 sensors on a rope: Some mixing processes only occure in the upper 2 m (day 1), others only in 4.8m depth, the thermocline (day 2).

B. Groundwater

Additionally, three groundwater control points on the land site measure temperature, oxygen and conductivity, but do not show flow directions. Depending on the Rhine water levels, which might change one meter per day, the flow direction can change: towards and away from the river. The groundwater temperature is approx. 10-11 °C, it is higher than the lake bottom temperature and it is normally free from dissolved oxygen. Depending on the Rhine, lake and groundwater levels, groundwater could enter or leave on the eastern site. The sources are normally spots, but not greater zones, due to the sediment's fluvial history. This type of sources, which might bring a few cubicmeters per second and hectare, are well known from neighbouring lakes, but were neither located nor monitored in the Monsterloch itself. There are some indications that cold oxygen free groundwater enters from east and exits to the west without reaching the warm surface, as well as warm and oxygen rich Rhine water could leak through the narrow damm the opposite way. As there are not enough fine resolution datasets, this potentially important component is not part of the calibration and stays the greatest unknown.

C. Entry of sunlight and shade

Missing as well is the grade of coverage by water plants and turbidity, as well as the area percentage of shading by the surrounding trees. It is clearly visible in the calibration datasets, that in spring, when the water is clear and no water plants cover the surface, the irradiation is distributed over the upper 3-4 meters. By the end of summer, when the surface is covered and the turbidity rises, the energy input is only directly at the surface, this is the best time to calibrate the diffusion model.

Fig 5: Water plants like duckweed and water lilies plus floating dead organic material can occasionally cover the Rhine old arms to 100%.

III. THE HYDRO-NUMERIC CRUX

Before the water quality tool WAQTEL can be used and mixing solutions can be studied, the model itself has to be carefully tweaked to calculate the thermal stratigraphy right, with as few software features as possible.

The problem presented here and the solution approaches differ in many aspects from the usual recommendations for temperature mixing in *streaming* water.

The main parameter “temperature” is not only a tracer, but also a driver of movements, due to the temperature dependent density. Tracers are advected and diffused, separately from the movement of the water itself. If the resulting temperature values are only a little bit randomly biased locally, in one time step, a flow will be generated.

E.g. the tidal flat handling of tracers often ends up with infinity clippings or threshold handling. Even this minor residual temperature error noise at boundary points introduces a small current which mixes a lake model without inflow over weeks.

In difference to river flow models, which are dominated by horizontal eddies and velocities above 0.5 m/s, the lake model shows especially vertical movements with very low velocities. But, over weeks, even fake velocities of 0.01 m/s can mix up the whole lake. This small dispersion and computer algebra truncation based errors would be concealed if the main current is above 0.1 m/s, as for most cooling water mixing processes below power plants.

At a later model stage the use of WAQTEL is planned. Currently the temperature is only imposed at the surface layer by a Fortran routine to keep the model as simple as possible.

Most of the developments and analysis were done on an academic, cubic tank model (T10) of only 10 m x 10 m, as it runs 14 days in 1 h. Severe disadvantages are listed in the following chapters.

Another academic, tank model (T125) was used to identify scale effects. Dimensions: 125 m x 1000 m x 14 m.

The final lake model runs 14 modeldays for ~1 000 000 cells with dt=1 s in 6 h on 100 Xeon E5 v3 cores.

The kernel of the brute are the advection schemes. None is perfect, the ones which are good in tidal flat handling (LIPS, N) are not good enough in dispersion. The ones which are good in dispersion are weak with many industrial grade demands.

A. *Diffusion and Dispersion*

Many subroutines and especially most advection schemes have an internal method imminent diffusion, called dispersion, which is not a physical process, but a byproduct of the linearisation mathematics and computer engineering. Only if this dispersion is minimised, the diffusion step is clearly calibratable and no density error based currents mix up the model.

The best example to learn about dispersion effects is the rotating “cone” example distributed with TELEMAC-3D. Initially a tracer is given in a rotating field of flow, its concentration is 1. After 64 steps of advection without a diffusion calculation one would expect the tracer to remain unmixed. But the peak values in the table above show, that the “weak form of characteristics” advection scheme is the least dispersive option currently available, while others tend to mix the tracer to an unusable result.

Advection Scheme			**Minimum Value**	**Peak Value**
CHARACT.	WEAK		-0,0007	0,9579
SUPG			-0,0353	0,5653
LPO			0,0000	0,1794
NSC			0,0000	0,1794
N	PR-COR	OP2	0,0000	0,7235
N	PR-COR	OP3	0,0000	0,6631
PSI			0,0000	0,2139
PSI	PR-COR	OP2	0,0000	0,7241
PSI	PR-COR	OP3	0,0000	0,6618
LIPS			0,0000	0,7910
LPO_TF			0,0000	0,3433
NSC_TF			0,0000	0,3433

a. *Results of the official Telemac-3D “Cone” test*

The downside of the weak characteristics gets visual with the minimum value, which gets negative for the “cone” case, when mixing 0 with 1. The algorithm, which is superior when using averaged values, tends to overswing in single points, especially when the gradients are high. This problem reaches its maximum at tidal flat points, inflow cross sections, sources etc. If the weak characteristic advection is used for the flow field itself, than it is frequently showing pulsating boundaries. But on the other hand, inner eddies are not killed by strong dispersion of the velocity vectors. See [1,2,3] for advanced explanations on the principle of advection schemes and especially the weak form of charactersitics.

As none of the other advection schemes comes close in terms of low dispersion, the weak characteristic scheme was used to test TELEMAC-3D against the measured thermocline over 14 days. As no external forces or flows were needed to test vertical temperature diffusion, the small tank of 10m x 10m with 1m edge length and 14 meters of depth seemed good enough and suitable fast for testing purposes. After some tweaking of thresholds, diffusion coefficients and other numerical parameters, the calculated results were less than 1°C in average from the measured values.

But the step to the real world model disappointed due to a surprising large number of overlapping problems which were hard to disassemble. Therefore a larger academic model was introduced: 125 m x 1000 m x 14 m with a plain or a V-shaped bottom, 55 vertical layers with no inflow or driving forces.

This 3rd model was used to search for scale effects and to accumulate the background velocity field noise which develops from truncation errors in various algorithms. This noise is amplified by the temperature-density algorithm and leads to physically not existing mixing processes. As this model should not develop any velocities at all, the parameter |U_mean| is an identifier for this background noise based mixing.

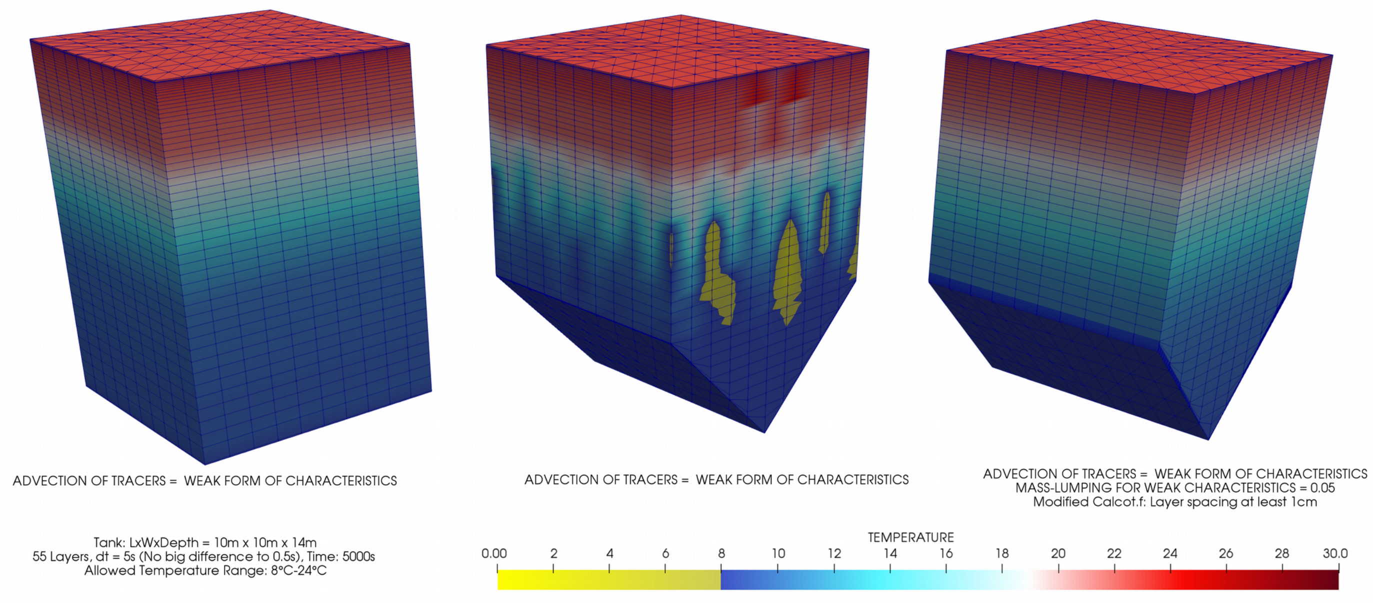

Fig 6: The least dispersive advection scheme does not work reliable with every mesh. It occasionally develops extreme temperatures which drive mixing flows.

Fig. 6 shows what happened when the tank only had an uneven bottom: Some layers are squeezed to zero strength, some bottom near cells get degenerated shapes.

The weak characteristics overswing here again especially for the temperature. The resulting error patterns generate local turbulences and finally, if the model doesn't crash, a 100% mix. The MASS-LUMPING stabilizes the problem, better than other parameters, but introduces dispersion again, what makes the whole model useless. See the following sections for more disadvantages and workarounds of the least dispersive advection scheme "weak form of characteristics".

Finally, despite all the later recommended improvements, the model was configured to the advection scheme "strong form of characteristics". Which is much more stable for practical projects, but had an up to 1°C higher rest error in the final calibration.

B. *Meshing & Inflow*

The mesh brings in many parameters which generate dispersion or which force the use of helper subroutines, which bring in dispersion.

- Number of vertical layers

First tests showed that a good reflection of the thermocline can only be reached with at least 3 to 5 layers around the maximum curvature sections of the temperature depth profile. This results in up to 55 layers for the Monsterloch model on 14 m depth, where the first, second and last layer are 1 cm in thickness only.

- Less degenerated mesh elements

The "weak form of characteristic" instabilities could be reduced 100 times by a couple of changes in calcot.f. Mainly the introduction of a minimum layer thickness of 0.1cm brought success. Truncation errors and instabilities are removed by a new mesh check section.

- Vertical layer spacing

A further significant source of dispersion is the mesh transformation handling. Neither sigma meshes nor the AMR technique were useful on longer time scales. Only hard coded elevations brought success, as they skip the reassignment of the z-coordinate at every time step with the following mass balancing. This is only possible, because the water level of the lake is close to constant and the topmost layer is the only one set dynamically.

- The Appendix

The boundary problems with the characteristic advection scheme got especially obvious when an additional tracer was introduced. "Fresh Water" with a concentration of 1 was pushed in at 2 m^3/s over the inflow boundary or source points. But the balance showed only 1.6m^3/s after 1 second, when there should be 2m^3/s.

This problem does not occur with the other advection schemes. It is the result of the before mentioned tendency to overswing in zones of strong gradients and at boundary points. The problem can be tackled with a cheat: By adding a little inflow channel of only 5x5 mesh points where all tracers are surely 100% mixed.

This appendix (fig. 7) gets the tracer concentrations assigned in all inner and outer points, what overwrites the instabilities at the direct inflow boundaries. At the main model now enters the real concentrations (Share of fresh water, Share of groundwater, Temperature, Oxygen, Conductivity). This is for sure not a good universal solution, but a robust workaround.

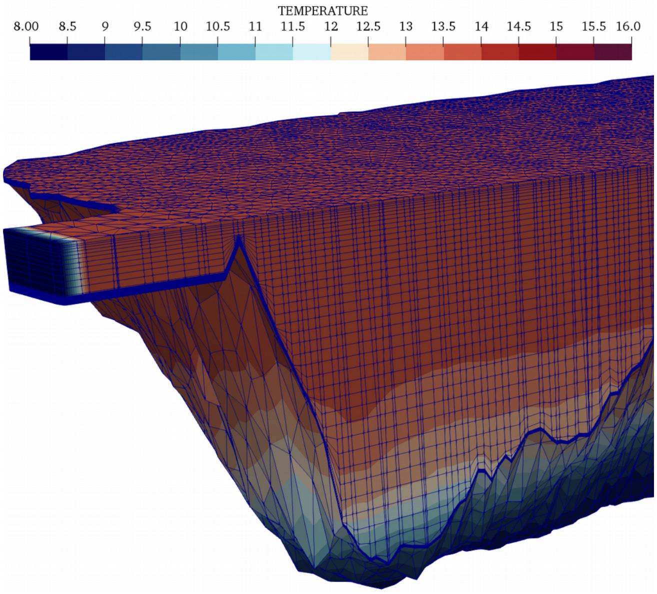

Fig 7: Every boundary and inner point of the short channel gets its tracer values assigned by Fortran code, not via the build in functions, to guarantee a noise free inflow temperature.

- Coordinate systems

The German standard coordinate system ist Gauss-Kruger, a Transverse Mercator variant with 7-digit coordinates.

X_ORIGIN / Y_ORIGIN: 0 m / 0 m
X_MIN / Y_MIN: 3460249.1860 m / 5464833.5055 m

The conversion of the geometry file to the coordinate system origin brought additional stability. Which subroutine produces the dispersion and truncation errors from the origin distance is still unknown.

X_ORIGIN / Y_ORIGIN: 3460249 m / 5464833 m
X_MIN / Y_MIN: 0.1860 m / 0.5055 m

Unfortunately, the values of X_Origin and Y_Origin, which are in the Selafin specs since two decades are still not fully supported by all pre- and post processing tools and occasionally even lost in the TELEMAC result file.

C. *Other submodels w. significant dispersion effects*

- Tidal flats

The tidal flat algorithms have to deal with cells that run dry. Different options are possible for this case, but none of them works acceptable on temperature as tracer. The resulting residual temperature errors are not relevant as absolute values, but because they produce density variations which drive slowly, but always present velocity fields. The only way to get rid of them at present is to cut the very shallow parts from the model, to reduce it to at least 10cm depth under all conditions.

- Turbulence models

All T3D turbulence models were tested. Even though the "constant viscosity" produced the least velocity noise, and k-epsilon seams to produce the best mixing for the high inflow discharge tests, the combination of Smagorinsky (horizontal) and Mixing Length (vertical, NEZU & NAKAGAWA + Munk & Anderson) are recommended for the final productive runs, as they run more robust and reliable than K-Epsilon.

- Time steps

Shorter time steps with lower CFL numbers are commonly assumed to produce better velocity fields. But if more iterations are necessary, the amount of velocity noise accumulates to a visible niveau, once the model reaches a general low dispersion quality.

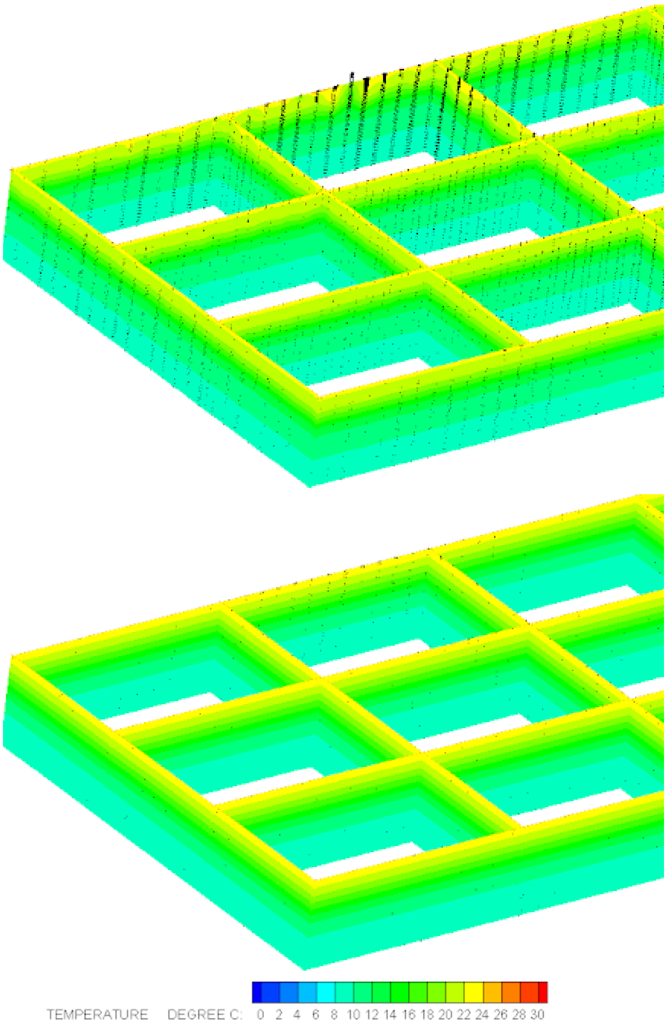

Fig. 8: Thermic stratification and velocity fields (arrows), that developed due to truncation and threshold errors in the temperature tracer after 4 hours. (Larger academic model T125, cross sectional view) Upper: dt=1s, |U_MEAN| = 0.0162 m/s. Lower: dt=5s, |U_MEAN| = 0.002 m/s.

Additionally advection schemes have an optimum point for the dispersion minimum, which correlates to the CFL number and is not necessarily at the shortest time step.

The conclusion is to harmonize the mesh edge length and time step length carefully to get the highest possible CFL number for the expected velocities. Tests with the “cone” model help to find suitable combinations.

IV. Calibration Results

The first calibration of the tank model, based on lake data, met the thermocline better than the final lake model displayed in figure 9. But, as some model parameters (exsp. the weak characteristics) were not transferable to a large scale model with irregular bottom and tracer inflow from outside, the concession to a practical model afteruse was the switch to the strong form of charcteristics. The 16.5 °C warm epilimnion is 1 m too strong in the final timestep.

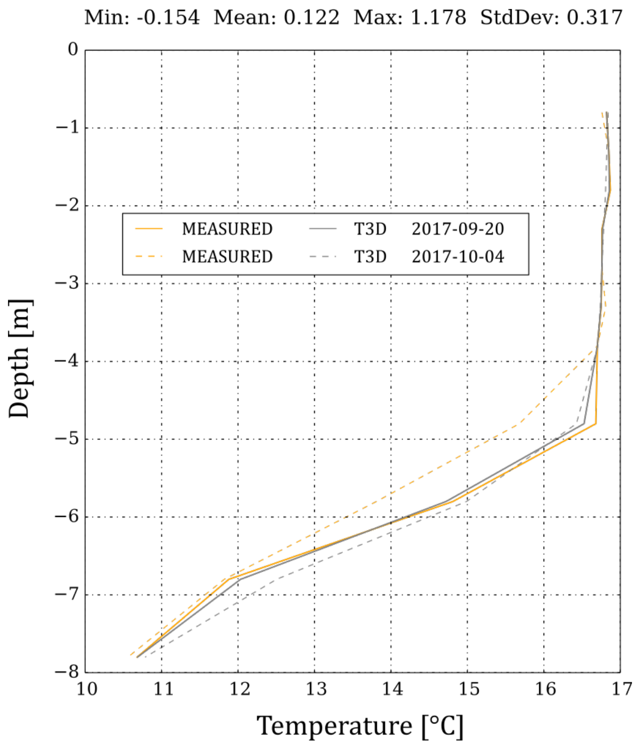

Fig. 9: Final model calibration: Temperature depth profile close to the lake center, without inflow.
Solid lines: Initial values.
Dashed lines: 14 days (~1 209 600 iterations) later.

One shall not forget: The calibration only tweaks parameters that are included in the model. The before mentioned missing groundwater, the unknown inflow temperature and the unknown shadeing percentage might shift the epilimnion up or down.

But as the final purpose of this model is the search for a mixing strategie, robustness is more important.

To get an impression how senistive the model is to the (not measured!) inflow temperature and to show the mixing effects, see fig. 10 to 12.

Fig. 10 shows 14 °C warm water crossing the lake just on the surface without any significant impact on the deeper layers until it hits the opposite shore. (This happens at 2am, when the surface water is 1-2° colder than at 2pm) In most cases, the river water is constantly mixed, while the lake surface is even warmer (weather dependent) and the bottom stays colder (average annual temperature ~8.5 °C). Therefore the usual case would be fig. 12: Medium temperatures cross close to the thermocline at low velocities.

Tests with higher discharges of 10 m³/s showed first signs of vertical mixing by vertical eddies, driven by the inflow jet. But still, after 14 days, the water is not exchanged to 100 % in all zones.

At 100 m³/s (fig.11), the old water is exchanged to ~95% after 4 days.

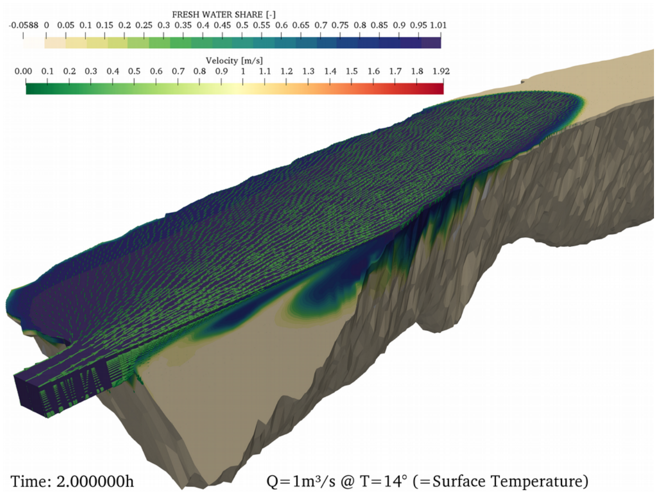

Fig. 10: 14°C fresh water crosses the lake without contact to deeper layers

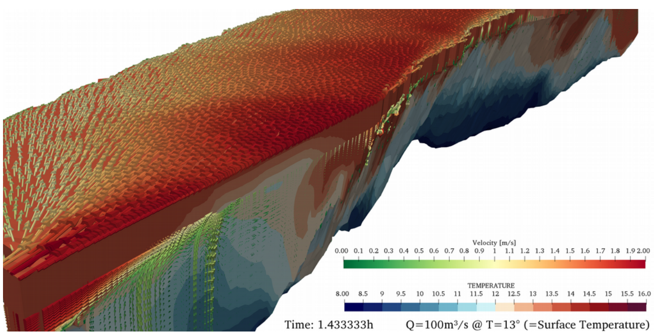

Fig. 11: Even a jet with 100 m³/s leaves zones with old water in the depth

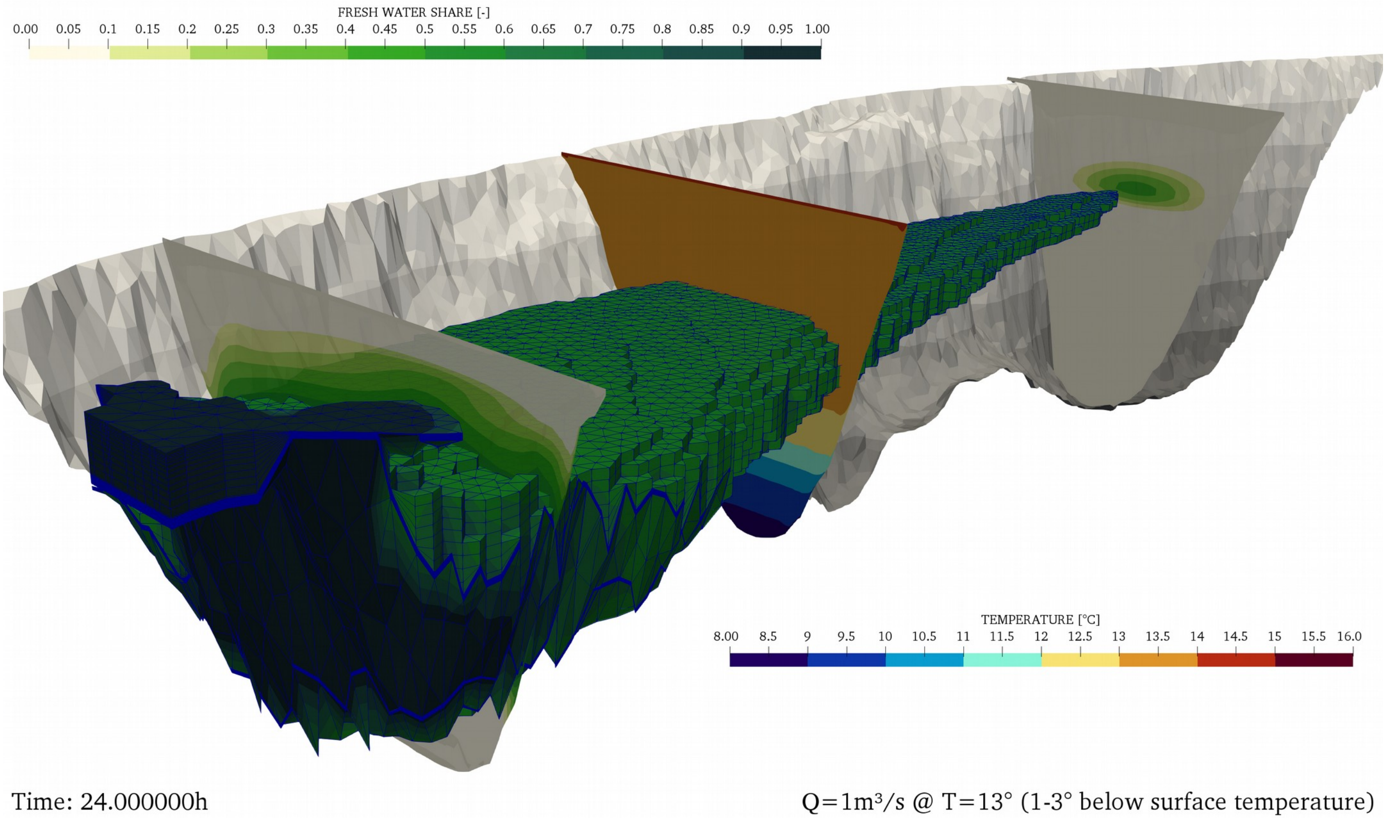

Fig. 12: Fresh water at 13°C immediately sinks and builds a bubble of fresh water in ~ 6 meters depth. (the fresh water bubble is displayed here if the share > 50%). The second slice shows the temperature profile at midnight, but the surface temperature follows a measured daily cycle.

V. Conclusion & Recommendations

Temperature driven mixing prozesses without externally driven velocity fields reveal the accuracy and definition range of several TELEMAC-3D submodels and features. These models are not wrong from a mathematical point of view, but they have some limitations from the computer hardware architecture or just from the fact that one describes the real world with linearized and discretized models.

The verdict of this project is, that TELEMAC-3D is ready for vertical thermal stratification studies, if one cares for the here mentioned traps and if the dataset is good enough.

The recommendation for data collecting is to collect temperature, oxygen and other parameters not only in one depth profile, but also at inflow and outflow and in occasional measured cross sections. Shading by trees and water plants should be documented by a webcam or drones especially for small lakes.

For TELEMAC-3D it would be a big improvement if there would be further research and developments about the "weak form of characteristics", e.g. a new tidal flat algorithm that conserves tracers and a new inflow algorithm that prevents the excessive mass loss of tracers.

The model is now usable to study mixing effects of geometry changes and to add WAQTEL features.

Acknowledgement

This project was a contract R&D work for the German Federal Waterways Engineering and Research Institute / Bundesanstalt f. Wasserbau (BAW). All datasets are owned and provided by the client. The client designs the new geometrical solutions for lake Monsterloch based on this model.

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