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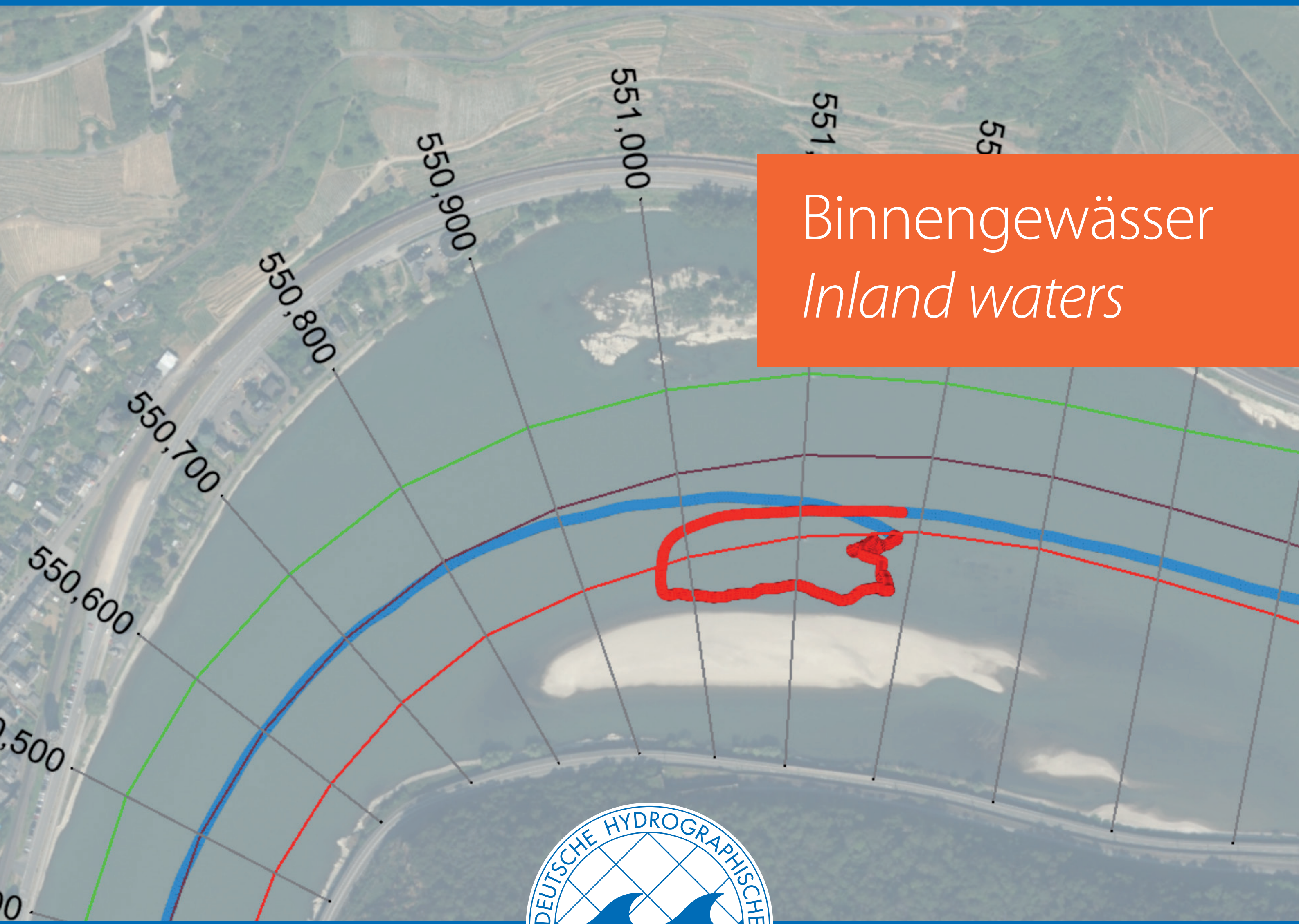

Binnengewässer
Inland waters

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Bathymetry measurements using recreational shipping equipment providing a huge dataset from lake Ammersee in southern Germany

An article by ANDREAS G. NIEDERMEIER and MANFRED MATHEIS

Large amounts of measurement data are essential for bathymetric documentation and analysis of water bodies around the globe. Even crowdsourced and amateur measurements can be helpful. Within this study we present a huge dataset collected at a German lake with a 25 ft/7.5 m sailing yacht and discuss various topics of methodology and data quality. Data visualisations are given on global and local scale. A second high-resolution dataset collected in a small region with a 3.6 ft/1.1 m software- and remote-controlled drone boat is used as reference.

bathymetry | crowdsourcing | pleasure craft | drone boat (USV) | Lake Ammer | OpenSeaMap
Bathymetrie | Crowdsourcing | Sportboot | Drohnenboot (USV) | Ammersee | OpenSeaMap

Große Mengen an Messdaten sind entscheidend für die bathymetrische Dokumentation und Analyse von Gewässern rund um den Globus. Selbst Crowdsourcing und Messungen von Amateuren können hilfreich sein. In dieser Studie stellen wir einen großen Datensatz vor, der an einem deutschen See mit einer 7,5-Meter-Segeljacht gesammelt wurde, und diskutieren verschiedene Themen der Methodik und Datenqualität. Gezeigt werden Datenvisualisierungen auf globaler und lokaler Ebene. Ein zweiter hochauflösender Datensatz, der in einer kleinen Region mit einem software- und ferngesteuerten Drohnenboot (USV, 1,1 m) erfasst wurde, dient als Referenz.

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1 Motivation

Sailing sport is a nice recreational activity, independent on the size or type of the boat. As co-owner of a medium size sailing yacht equipped with several sensors and digital network one also plays with various settings and readings, especially if scientific interest is given. The idea of collecting the data thus is obvious, further analysis easily follows, especially between seasons. Former activities in bathymetry studies (Niedermeier et al. 2000; Niedermeier 2002) give additional background to seriously deal with the data.

Concerning visualisation, given that the B&G chart plotter supports the nautical chart of openseamap.org, it was straight forward to establish contacts with the developers there to further analyse the data collections and determine reasons for missing data. This contact yielded in various developer meetings and measure campaigns together with heads of openseamap.org for enhancing algorithms, bathymetric datasets and data logger functionalities. A preliminary version of the main dataset (see Section 4) was also used as test data for the re-implementation of their bathymetry algorithm (Bärlocher and Over 2023).

Even professional services are in need of accurate maps and rely on both official measurements and crowd sourced input data (Jonas 2023; Lammers 2023).

2 Study region

The data used in this study was collected to examine Ammersee, a 16.2 km long and 5 km wide lake in southern Germany, located about 35 km west of Munich at roughly 11.12° eastern longitude and 48° northern latitude (BAYregio 2024; Wikipedia 2023b). Mean water level is around 533 m above sea level (Bayerisches Landesamt für Umwelt 2024b), maximum depth is around 81 m (Wasserwirtschaftsamt Weilheim 1979), lake surface is 46.6 km^2 (Wikipedia 2023b). Its origin are ice age glaciers.

Since mid 19th century it is a recreational region of the city of Munich with actually four tourist steamboats running between mid April and mid October. A few thousand sailing boats are used on the lake each season between April 1st and October 31st. They are based on land, buoy and berth locations. Motor vessels are strongly restricted on the lake, mainly on working licenses (e.g. lifeguard services of German Red Cross, small scale fishery by tiny family businesses, training and (sailing) boat racing support boats of sailing clubs). Only very few small recreational private motor vessels are licensed with licenses limited to a time span of just a few years. Water skiing is only allowed in a small region in the southern part of the lake during a short daily time window.

There is restricted navigation in several regions due to nature protection. A large nature reserve at the southern end of the lake and some more on land including the shore at some places, where entry is prohibited both from lakeside and landside (especially close to the southern end of the lake navigation could be also risky due to parts of trees lying or floating in the shallow water, as inside the protected area nature is left as is). There is also an agreement between sailing clubs and nature protection NGOs to abstain from water sports during winter (November till March), as the lake is a wintering ground for many migrating birds.

The water level varies on rain falls or melting snow in the 993 km² (Bayerisches Landesamt für Umwelt 2024a) drainage basin (which reaches to some of the summits of the nearby Alps), hydrologic discharge via river Amper at the northern end, and evaporation during hot summer timespans. There is a low-head dam at the northern end of the lake to regulate the amount of water exiting via Amper. Regular flooding occurring several times per decade can reach levels of 1 m above mean water level or even more in rare situations – the historic height record was 1.94 m in May 1999 (Bayerisches Landesamt für Umwelt 2024c). Water level in rare cases can drop down to 0.6 m below mean water level due to evaporation which is more than 0.3 m below the minimum water level fixed by the dam.

A gauge providing data in 15 minute intervals is located close to the point, where Amper is leaving the lake. Data is available since November 1963 on a daily basis (minimal/mean/maximal value).

An official bathymetry chart is available from the Wasserwirtschaftsamt Weilheim published in 1979 based on data from 1968 to 1977 (Wasserwirtschaftsamt Weilheim 1979). It only contains depth lines every 5 m starting with a water depth of roughly 3 m. A nautical chart based on this dataset was available for some time as well as a historical chart from 1809. Therefore, any additional and more recent measurements can assist navigation on the lake. Several persons doing regular recreational or business activities at certain shore locations were glad to get interpolated shallow water bathymetric information from our dataset in surroundings of their locations.

3 Methodology

3.1 Data collection using a sailing boat

The majority of input data was collected using a sailing vessel of type Archambault Surprise (Good 2017; Wikipedia 2023a) built in 1986, partially owned by one of the authors. The boats of this class are 25 feet/7.65 m long keel-boats with 1.25 t weight and 16.5 m² main sail. Top speed at usual wind conditions is around 6 knots (3 m/s). The boat used in our case (built as number 472) is a keel-centreboard variant, which allows reducing draft from 1.6 to roughly 0.7 m and thus passing shallow water areas downwind or in moderate wind conditions by pulling up the centreboard.

The ship has a history of trips on Lake Como and Adriatic Sea by former owners and is now based on Ammersee on a buoy location provided by a sailing club on the eastern shore close to the northern end of the lake since ten years. It is equipped with following technical devices:

- an echo sounder/log/water temperature sensor type Airmar DST 8000 close to the lower end of the mast;
- a wind/air temperature and GPS receiver Airmar 150WX at upper end of the mast;
- a chart plotter with built in GPS receiver type B&G model Zeus1 Touch 7 close to the cabin door. Additional B&G data displays in cockpit;
- NMEA 2000 network connecting the sensors and displays;
- electric support engine Torqeedo Cruise 2.0 FP (6 PS equivalent, built 2017) with 24 V/104 Ah Lithium battery. Due to restrictions of motor boating on the lake, this may only be used in certain cases. The motor electronics including an additional GPS receiver is not yet connected to the NMEA network;
- two solar panels to charge the battery;
- full set of navigational and support lights (basic position, motor, anchor/top, deck/working, cabin);
- registered UKW transmitter and receiver with maritime mobile service identification (MSSI) number for emergency cases;
- several tools for supporting rescue of persons in cooperation with the Freiwilliger Seenot-Dienst e.V. (FSD).

This allows a continuous and automatic data collection during all trips as long as the electronics is switched on.

3.2 Data collection using remote- and software-controlled drone boat

At the area of dangerous shallow waters, known as »Rieder Eck« a quite dense set of measurement data was collected using a small drone model boat, called »roboboat«. It was originally built simply for the sake of building an autonomous vehicle. Measuring capabilities using an echo sounder were added to provide some meaning to its autonomous movements. The »Rieder Eck« was chosen, as the exact knowledge of the shallows there is of special interest for sailors. Features of the model-boat are:

- hull: model of the fire-fighting boat *Weser* by »Graupner« (the choice was by accident, not special intention), length 110 cm, beam 23 cm, weight around 2.8 kg;
- two DC electric motors 12 V, maximum speed: 1.6 m/s, working speed: 1.0 m/s;
- RC: Open TX, sender: FrSky Taranis X9D Plus SE 2019 2.4GHz 24CH, receiver: RX;
- echo sounder: Lowrance HST-WSBL (Navico Group 2025) mounted 12 cm below water level, Actisense DST-2 200 kHz digitiser, 1 sample per second;
- Pixhawk Open Hardware PX4 PIX 2.4.8 32 bit flight controller;
- Ardupilot – Open Software for autonomous driving – SURFACE BOAT.

Building the boat with all technology, configuring and calibrating it properly roughly took one year. Collecting all measurements for the Rieder Eck also took about one year as well. Measurements could only be made during summer season weekends and only during calm winds as the model boat is quite sensitive to waves. Due to limitations in time and battery capacity the area was split into fifteen separate sections to be measured autonomously, which were covered in nine distinct days of measurement spread across one years' time. Mission Planner software on a Windows 10 Notebook was used for creating the sections. The model boat had covered each section in lanes in a distance of around 5 m from each other.

In total, 76,594 measurements have been taken. Challenges were not only waves, but also heat. At one of the summer days the boats electronics completely failed due to air temperatures above 30 °C, more in direct sunshine, thus the mission had to be aborted. All measurements were normalised to mean water level by considering gauge »Stegen« and the depth of the echo sounder of 12 cm. With the Open Software geographic information system QGIS a bathymetric map of the Rieder Eck was created and overlayed onto Google maps, so that the data can be used in real life sailing trips.

3.3 Data interpolation and visualisation

Data was interpolated to a regular grid using nearest neighbour and other interpolation techniques. When interpolating the whole lake we use a $1.4 \cdot 10^{-4} \times 10^{-4}$ degree grid in longitude/latitude which is roughly 11 m in both directions at 48 degrees northern latitude and close to the expected GPS location accuracy. For small sub-regions of special interest interpolation to higher resolutions was also used, e.g. $7 \cdot 10^{-6} \times 5 \cdot 10^{-6}$ degrees or about 0.6 m which is close to the source data quantification of the B&G Zeus device.

As additional support data a coarse polygon with some hundred coordinates was manually digitised from free charts and geocoded aerial photography in internet (e.g. Wikimapia, Google Maps/Earth, OpenStreetMap …). This polygon limits the interpolation area. The polygon points were included to the dataset with sea surface waterlevel (depth 0.0 m) thus allowing interpolation of shallow regions up to the shoreline.

As a more sophisticated interpolation technique we selected for each grid point 16 data points, the closest in each 22.5° sector, if one exists there. As depth value w for the grid point a weighted average of the selected data points w_j was calculated as

$$w = \frac{\sum_j \frac{w_j}{d_j + \varepsilon_0}}{\sum_j \frac{1}{d_j + \varepsilon_0}}$$

where d_j is the distance of the data point w_j from grid point and ε_0 is a small numerical quantity in the order of 10^{-20}. This gives kind of a two dimensional version of a linear interpolation avoiding the majority influence of one sampling line with lots of data points from a single boat passage of the grid point (and avoiding a division by zero). We therefore call it sector-linear interpolation.

Experiments with a Gaussian interpolation distance weight did not yield promising results.

All interpolation and correction was done using small C programs and CSV files (white spaces as field separator, constant column with to enhance human readability). Data was visualised using GnuPlot software.

Reference data was interpolated separately using the same techniques in the selected sub-region, where reference measurements were carried out. In addition reference data was converted to a bathymetric map via QGIS Software, results can be found at Matheis (2024).

4 Dataset

The data of the main dataset was collected during most sailing trips using the boat mentioned in Section 3.1 starting with some early datasets in 2017 and more and more regular since 2018. This includes recreational trips, boat races and special trips for measuring certain areas of the lake of special interest. During the flooding in May 2019 several shallow areas could be visited, where navigation is not possible at regular water levels.

To avoid running out of memory on the B&G Zeus usually one data point is stored every 10 seconds on ordinary trips (recreational or boat races), this is reduced down to one point per second when examining special interest regions.

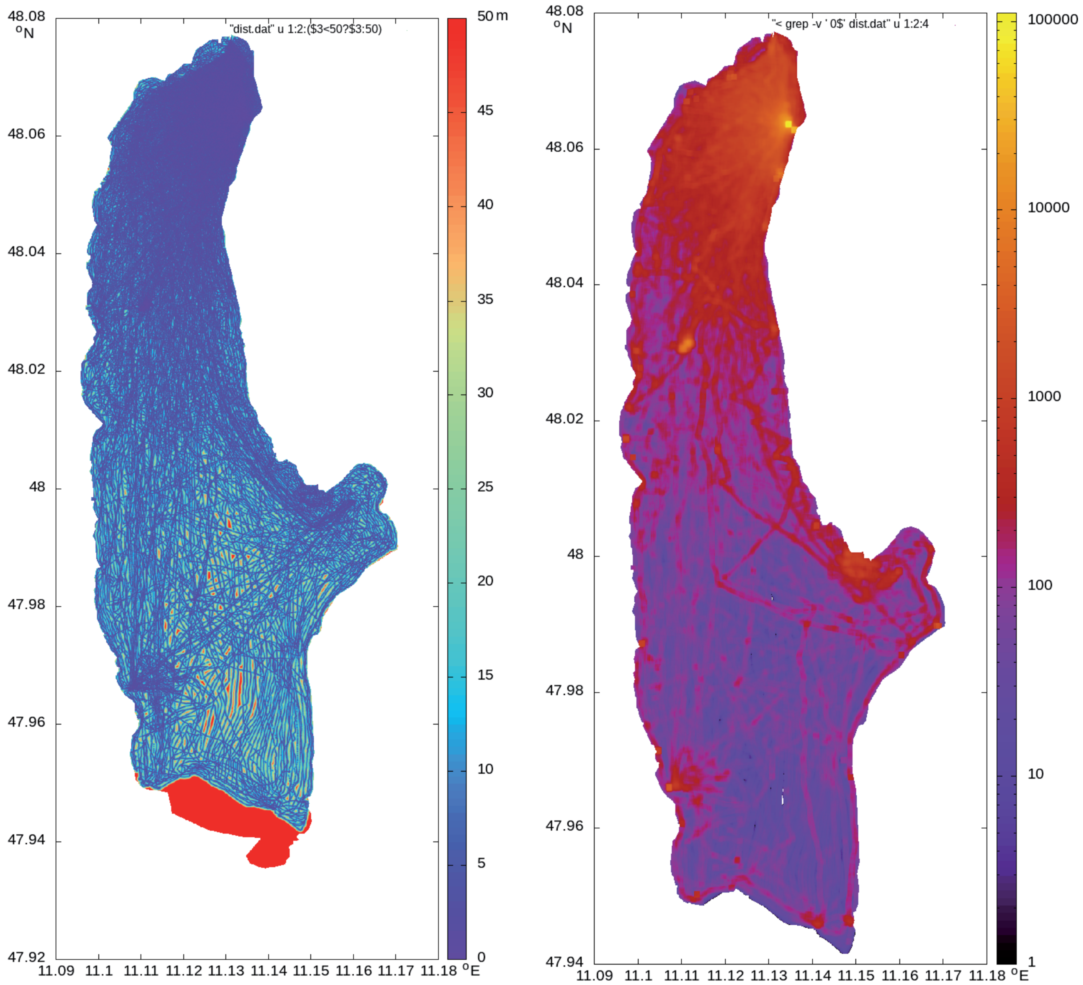

Fig. 1: Left: Distance to closest data point (where below 50 m); right: Number of data points per hectare (moving window, logarithmic colour scale)

Special interest regions are shallow water areas nearby the buoy and sailing club and well known dangerous/shallow water areas like the Rieder Eck west of Herrsching and the estuary of the river Rott at the southern shore of the lake.

Till end of 2024 season more than 1.2 million data points have been collected or in the order of 250 points per hectare in average. Naturally the density of points increases closer to the home buoy of the boat/in the northern part of the lake while still some gaps exist in the southern part of the lake (Fig. 1).

Reference high-resolution data was collected by the remote- and software-controlled tiny drone boat close to the dangerous shallow waters at Rieder Eck. Reference data consists of 76,594 data points roughly spaced one measurement per metre along track with 5 m track distance on a 950 × 500 m (longitude × latitude) area covering some 0.31 km^2. It was collected in 2023 season within nine full day campaigns, details about data collection are given in Section 3.2. The geographic distribution of the reference dataset from the drone boat is shown in Fig. 2 in comparison to the distribution of the main dataset from the sailing boat trips in this region.

Fig. 2: Measurement spacing of main (grey) and reference (purple) dataset

5 Accuracy and technical limitations

Within this Section we present a collection of various points influencing both the data quality and availability. Some solutions are not straight forward and were only found by lucky incidence or after longer examinations. To support other users interested in providing crowdsourcing echo sounder data we discuss these points in detail hoping to keep them from giving up. Furthermore the limitations should be kept in mind by the organisations collecting and processing the data for final use.

Nevertheless, as shown in Salaudeen (2023) the quality of crowdsourced data is astonishingly high and in lack of other data quite useful even for professional applications or official data collection (Jonas 2023).

5.1 GPS position accuracy

According to GPS specifications (Department of Defense 2020) from 2020 actually the location performance has a root mean square (RMS) error of 3.6 m, which means, that 95 % of the GPS measurements are within a 7.0 m circle around the correct location. On the other hand, positions off 10 or more metres are quite common in a huge dataset, especially when the number of visible satellites is reduced. Even when following the actual ship location on the chart plotter from time to time a large offset can be observed without clear cause. After some time, regularly up to 1 or 2 minutes, sometimes just after a few seconds, the position shifts (back) to a seemingly more correct one which means a change of the ship position at a speed far beyond the one physically possible by its construction. Reasons could be systematic (change in number of visible satellites) or software issues in the position derivation of the GPS receiver. Within the data-take both jumps in time and location were found when looking for extreme boat speed, in some cases just as the first values after switching on the devices.

This has to be kept in mind when evaluating the data quality of echo sounder data.

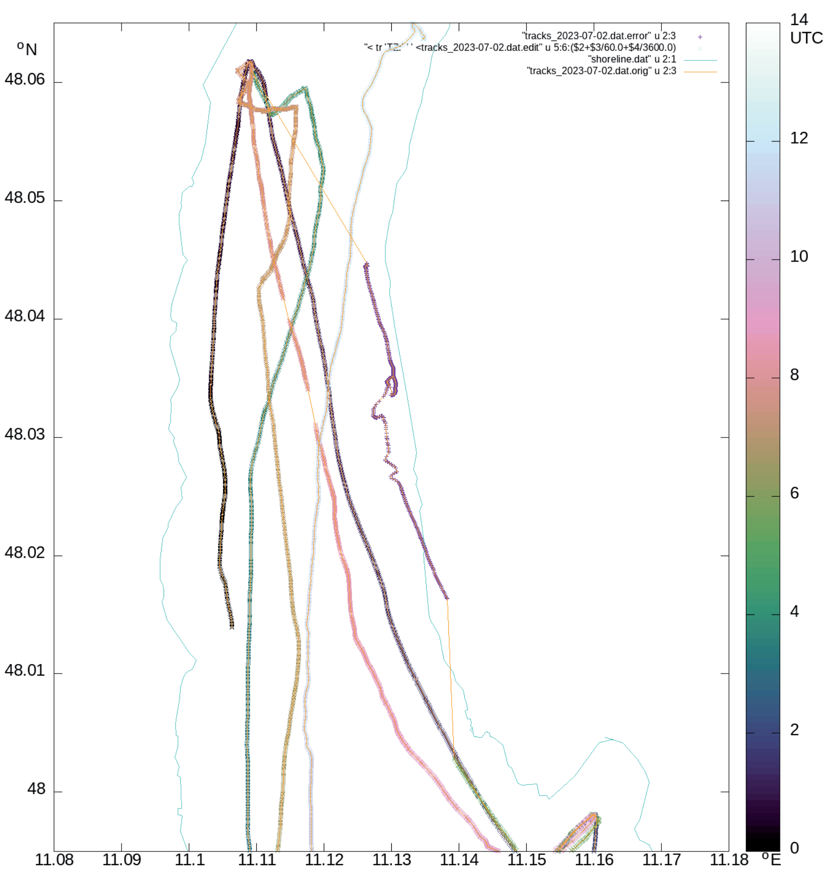

Fig. 3: Data points of July 2nd, 2023; colour-code: time of day

5.2 GPS jamming and spoofing issues

Due to the weak power of the GPS signal it is easy to prevent reasonable navigation by sending a signal on the same frequencies as the GPS satellites by purpose or accident. Therefore, the number of visible satellites is reduced or all are blocked for a longer time span over large regions on earth surface or even up to lower earth orbit satellites carrying own GPS receivers. Especially in warfare regions this is quite common, e.g. in Ukraine occasionally since 2014 and almost permanently since 2022.

This on the other hand means strong limitations in navigation due to heavy offsets in the resulting positions and – when retrieving echo sounder data – strong disturbances in data quality. Heavy position offsets have been reported by sailors and aircraft pilots e.g. in eastern Baltic Sea in recent months (Goward 2024; Shevchenko 2024).

A huge offset, possibly by GPS jamming was found in our echo sounder dataset within the data recorded in July 2023 during the yearly 24-hour sailing race. For a longer time period the position runs several kilometres off track even far beyond the shoreline and over some hills east of the lake. At roughly 4 a.m. the dataset stops for 25 minutes, most likely due to a freeze and reboot of the plotter. After this the position has an offset of about 1.5 km towards northerly directions relative to the correct position for around 37 minutes until jumping back within 5 seconds (selected data sampling rate). Compare Fig. 3, where the incorrect locations are marked in purple, the manually created coastline polygon in blue.

Such data has to be sorted out manually or by plausibility checks.

5.3 Water level correction

Due to the seasonal flooding the data has to be corrected according to the water level. As in almost all cases the water level is only changing a few centimetres per day or even less, considering other influences it is sufficient to carry out the corrections using the daily mean value of the gauge at the northern end of the lake as reference in order to reach the accuracy possible with sports-craft sensors. A noteworthy difference between minimal and maximal water level occurs only on very few days inside the gauge dataset, when there is ongoing heavy rainfall and therefore huge amounts of water running in from the whole drainage basin. At these conditions recreational vessel navigation is very improbable.

Furthermore, the vertical sensor location has to be calibrated relative to the water surface in order to get the correct absolute depth values. This was done the following way: In calm weather conditions the boat was brought from its buoy to the berth of the sailing club and fixed there in alongside direction with bow facing the shore of the lake. On both sides of the boat the water depth was measured by a metre stick, close to the alongside position of the echo sounder. The water depths at these points were around 1 m at this time. These measurements can reach an accuracy of roughly 5 to 10 cm, as there are lots of stones up to fist-size distributed all over the ground of the shallow water regions. Comparing the displayed water depth (0.7 m below sensor) at the same time yielded a sensor position of about 0.3 m below water level.

5.4 Disturbances in water body

Surface waves

Given a sound speed of 1.4 to 1.6 km/s in water (depending on temperature and salt content) and a maximal measuring depth of 100 m (Airmar Technology Corporation 2010, 2024) of the sensor, close to ten soundings per second are theoretically possible. Data sampling by the echo sounder is one value per second according to Airmar Technology Corporation (2010, 2024), track-point sampling rate of the chart plotter can be selected at values between 1 and 10 seconds. There is no documentation on averaging of several soundings or network values. According to the size of the lake low frequency/longer waves (swell) are very unlikely. Most waves are from direct wind fetch (up to 10 km at full lake length, up to 5 km at usual wind directions) or from bypassing motor boats. These are usually at wave frequencies of 0.2 to 2 Hz so within the order of the sampling window. Common wave heights are in the order of 0.1 to 0.2 m, only in rare cases above 0.5 m (stormy situations). So there might be a noticeable influence on the data in some cases depending on the averaging strategy of the devices.

In one occasion early 2024 season the boat was fixed perpendicular to the berth of the sailing club at around 1 m water depth in very calm sea state while one of the steamboats was passing. Slight periodic variations in depth measurements by several centimetres in a frequency of 0.3 to 0.5 Hz in a 1 second sampling could be caused by the waves from the steamboat yielding a strong roll movement of the sailboat with only slight possibility of position change (less than 0.5 m). This suggests that there is no averaging inside the devices at all.

To check this, an experiment using the sailing ship at a constant position and some close, controlled motorboat passages is planned.

Reflections inside water body

It is a well known issue, that large fish swarms can be seen in echo sounder data. Therefore, special high-resolution/multibeam sonar devices are sold for fishing boats, also smaller versions for hobby angling. The B&G Zeus chart plotter has a separate input port for such devices. On the other hand this means, if a fish swarm is located directly under the sensor, some of the echo will return early and the sampled depth value might be much lower than in reality. Some dataset spikes of 40 to 50 m in a surrounding of 70 to 80 m deep water might be caused by this (see Fig. 4).

In warm and sunny seasons water plants can grow up to almost lake surface in shallow to moderate water depth (2 to 5 m). This also affects the data sampling. Depth values below 1 m or even errors due to low depth were occasionally seen on the B&G displays while navigating close to the northern tip of the lake in September or October in some years. The leaves of the water plants moving around could be clearly seen in these circumstances.

When aiming at a high-quality dataset a manual or software-based removal of such effects from inside the water body should be taken into account.

5.5 Electronics, sensor and software issues

Mast tilt/GPS location on mast top

In moderate to strong wind conditions sailing boats tend to be tilted strongly along the roll axis away from the wind, so called heeling. A GPS receiver fixed to the top of the mast therefore can be shifted several metres across the movement track of the boat. This could be seen also in the location of the early data points in our dataset. Therefore we switched the input GPS receiver to the one inside the chart plotter which is located midships about 2.4 m behind the echo sounder (constant offset, usually in direction of motion). So far we did not apply any corrections on this due to the fact that the influence of both effects is in the order of the proposed GPS accuracy (RMS).

Echo sounder footprint

Although no detailed documentation from the supplier is available, one has to keep in mind, that the footprint size of the echo sounder should grow more or less linearly with the water depth. Thus especially in deeper water the structure of the lake bed is assumed to be blurred. A value found in the echo sounder brochure (Airmar Technology Corporation 2010) is a -3 dB beam width of $10° \times 44°$ which would mean a footprint, where the power is half as strong on sea floor outside a 12 m $\times$ 68 m window at a water depth of 70 m. Another value given in the sensor web page (Airmar Technology Corporation 2024) is a maximal dead-rise angle of 22°, yielding a footprint of up to some 28 m at 70 m depth.

Indeed the small sailing boat *Rosebud,* which sunk in a severe storm on July 7th, 2001 and lies in an upright position roughly 70 m below the water could not yet be localised with our equipment, although many measurements in this area were carried out. No significant variation in the water depth, e.g. from the mast, etc. could be recognised. On commercial side-scan equipment of a professional diving service it was visible, a diving robot with camera could identify and localise the boat providing live video footage.

GPS epoch looping

The GPS timestamp is transmitted in a $10+19$ bit format with 1.5 second accuracy and repeats every $2^{10} = 1024$ weeks ($\approx$ 19.6 years) (NOAA 2021; Wikipedia 2024). To derive the absolute GPS epoch, additional information is needed to derive the absolute date. Some GPS receivers are not able to cope with this, thus the internal GPS of the B&G Zeus chart plotter reset its date in the timestamp as after April 6th, 2019 the date started over with August 22nd, 1999 again.

To avoid this, it is possible within the B&G Zeus to select a different GPS receiver – namely the one in the mast top in our case, which provides the correct epoch – as source for just the date information. Some data incorrectly stored with 1999 timestamp in the dataset was manually corrected to 7,168 days later in order to select the proper day in the gauge level dataset.

Input sensor versus output format

The B&G Zeus chart plotter is able to display the water depth provided by the echo sounder via NMEA 2000 network. When exporting echo sounder data to SL2 data format – the format suggested by OpenSeaMap web page – it is not possible to select the network input but only an input port directly at the chart plotter, where a special multibeam echo sounder for fishing applications can be connected. Examining the SL2 output data in binary format using a format documentation reverse engineered by OpenSeaMap showed that in almost 99 % of the cases a depth of 0.0 m additionally flagged as invalid data is present in the files. In rare cases there are fancy depth values present (depth of several hundred metres, not possible within the study region with maximal water depths of 81 m).

This issue can be resolved using the GPX export of track data recorded by the plotter. These contain both reasonable position and depth information. Another advantage of GPX, being based on XML, is the easy human readable format which even allows corrections like the GPS epoch shift mentioned in the Section before using a simple text editor. This also allows easy data extraction using shell scripts or small C programs. Sadly, this is only possible with the first generation of B&G Zeus models, as starting with Zeus2 the depth annotation in GPX file format output (and input) was disabled according to the manuals (only water temperature is still present). Lowrance USR data file (version 6) can be used instead which is much more difficult to analyse being a binary format.

GPX output data contains a numerical accuracy of 10^{-8} degrees in both latitude and longitude while the values themselves are granulated on a $9 \cdot 10^{-6} \times 6 \cdot 10^{-6}$ degrees grid in longitude $\times$ latitude ($\approx$ 0.7 m in both directions). Thus the internal accuracy of the GPS receiver or the chart plotter itself might be around this value, the same granulation is also present in binary USR data file from Zeus2 model. Furthermore, one has to keep in mind, that the number of data points per track is limited to about 24,000, so one has to start new tracks regularly to avoid block-wise deletion of older data at the beginning of the track.

5.6 Estimation of error budgets

For a rough data quality estimation some typical error value contributions are discussed here. Table 1 gives an overview of the values. When calculation the depth error contribution from a location error the average slope of the lake's bathymetry was assumed to be 4.5 % which was derived as mean value based on the »sector-linear« interpolated bathymetry (Fig. 4).

The mean difference between maximal and minimal daily gauge value within the whole dataset (November 1963 till December 2024) is

Type	Location error	Depth error contribution
GPS position	3.6 m	0.16 m
GPS jamming/spoofing	up to some km	large
Water level change	–	0.005 m
Surface waves	–	0.1 m
Reflections	–	large
Sensor offsets	2.4 m	0.11 m
Echo footprint	40 % of depth	1.8 %

Table 1: Data quality estimation: Typical error contributions by error type

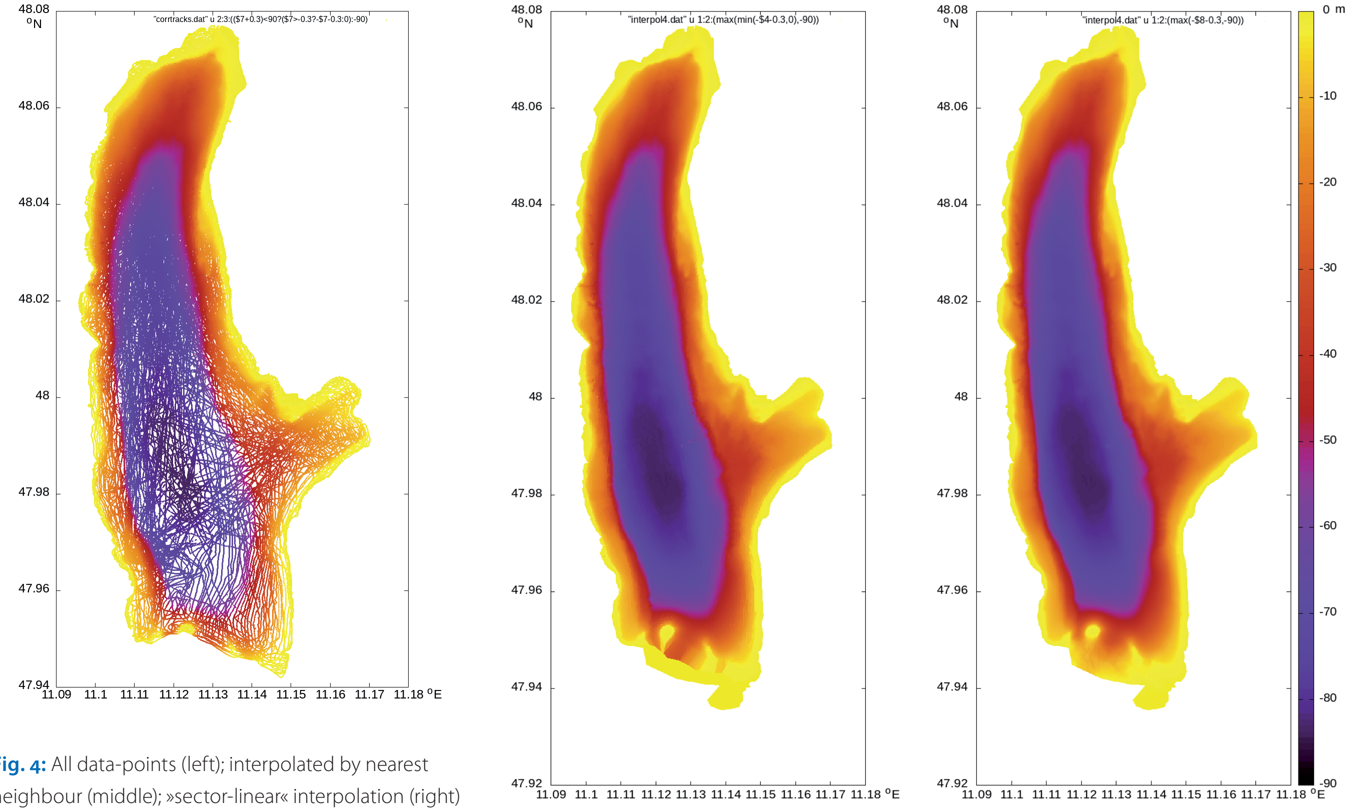

Fig. 4: All data-points (left); interpolated by nearest neighbour (middle); »sector-linear« interpolation (right)

1.03 cm, therefore considering the mean daily water level gives a typical error contribution of 0.005 m.

All in all the typical errors might sum up to a few decimetres, which is a fairly good value considering safe navigation. As mentioned in Section 5.3 the constant systematic offset of the whole dataset by calibrating the echo sounder vertical position relative to the water surface is also around 5 to 10 cm.

6 Results

After manually correcting and removing some of the critical data as mentioned in Section 5 the remaining 1,210,000 data points were interpolated and visualised (cf. Fig. 4). In addition to a nearest neighbour interpolation we also developed a »sector-linear« interpolation technique using a distance weighted averaging of selected data points, weighting method is given in the equation in Section 3.3.

As an exemplary detail study Fig. 5 shows the surroundings of the dangerous flat close to »Rieder Eck«, located near the northern edge of the bay of Herrsching, in the depth range up to 4 m. Reference dataset collection was carried out in this region. Both main and reference dataset are separately interpolated. Good agreement in the shape of the extracted bottom topography features can be seen when comparing local interpolations of main and reference data (Fig. 5), as far as the sampling point distance allows.

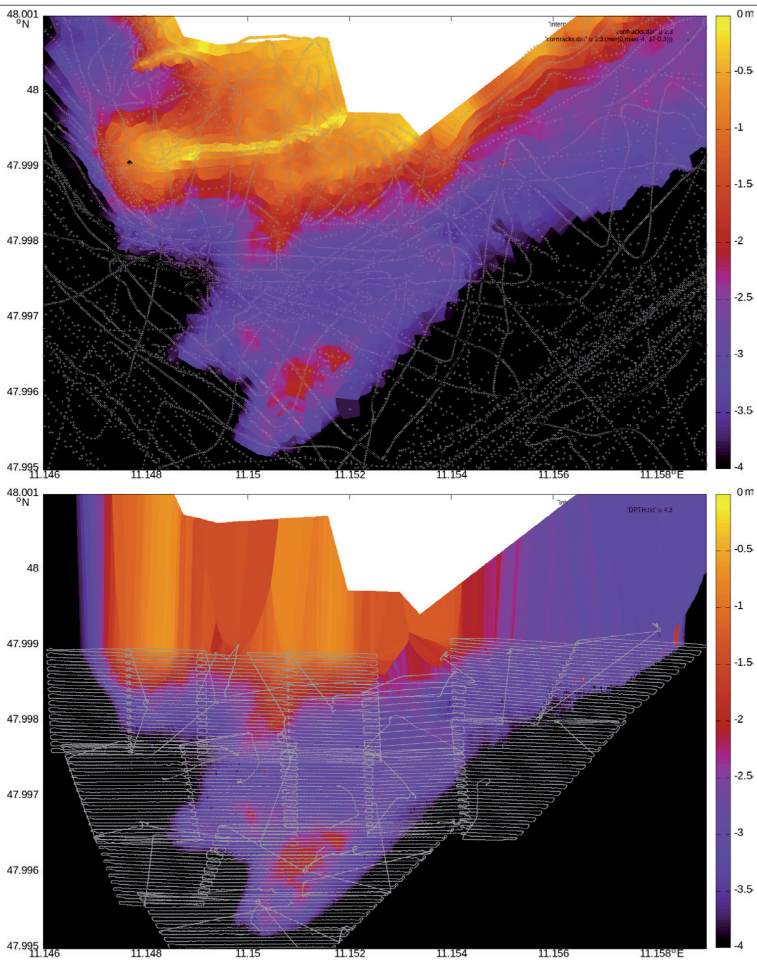

Fig. 5: Detail study of the flat near »Rieder Eck« using nearest neighbour interpolation. Main dataset (top), reference dataset (bottom)

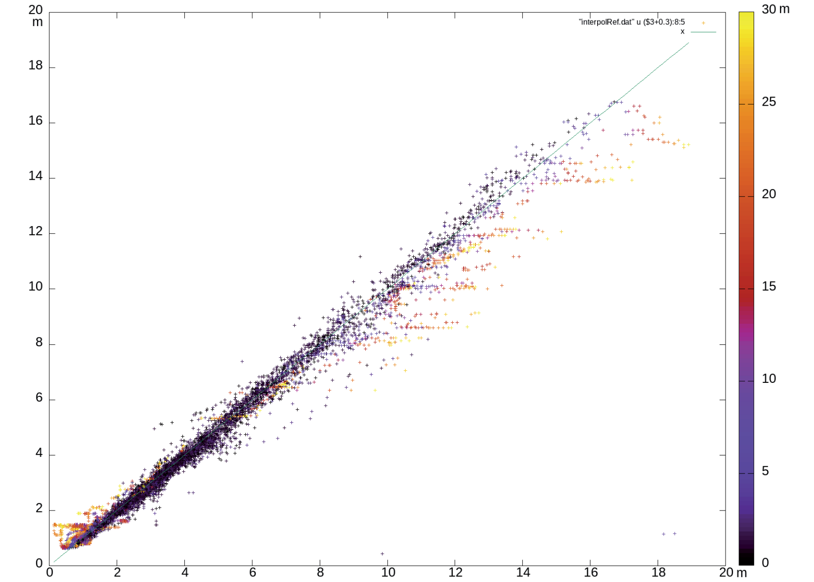

Fig. 6: Comparison of main and reference depth values

From the 75,054 main dataset points in the region, 15,432 have a reference point less than 30 m away. Comparing the main dataset depth values to the closest reference depth yields a Pearson correlation coefficient of 0.989. For 12,268 data points, reference points are less than 5 m away, their depth correlation coefficient is 0.995. Fig. 6 shows this comparison as a scatter plot with colour-coded reference point distance.

Based on the »sector-linear« interpolation to a rectangular grid ($10^{-4} \times 1.4 \cdot 10^{-4}$ degrees in latitude/longitude, which is roughly 11 m in both directions) we calculated vectorised depth polygons (isolines) for all depth values in 0.5-m steps (0.1-m steps for depths less than 3 m). When comparing the results to a geocoded version of the 1979 nautical chart with isolines every 5 m, provided by Wasserwirtschaftsamt Weilheim, typical structures of similar shape can be found, although their location is shifted by 50 to 100 m in some cases. Reasons might be the different measurement density, position accuracy – GPS became fully operational in 1993 (Department of Defense 2020) –, interpolation or post-processing steps (automatic versus manual vectorisation). Some additional features in our dataset might be caused e.g. by disturbances in the water body (Section 5.4.2) or GPS location issues (Section 5.1).

The comparison of the isolines from 1979 and 2024 is presented in Fig. 7. The depth lines from the official 1979 chart are given as elevation relative to sea level, lake surface at mean level is 533 m above sea level. The vectorised lines of the 2024 dataset are colour-coded, yellow for odd and green for even water depth, red for multiples of 5 m, black for multiples of 10 m. The background map was taken from opentopmap.org, for re-projection of the 1979 map from UTM to WGS84 we used QGIS, visualisation was done by Leaflet.

Acknowledgments

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7 Summary and outlook

When considering all critical points in Section 5, a large crowd-sourced dataset of echo sounder measurements like the one given in this study can certainly enhance knowledge about bathymetry for both ordinary and professional applications. The consistence of the data even allowed creating maps from the data itself. Nevertheless, there is much work to be done, like improvement of algorithms (e.g. speed/parallel execution), automatic outlayer detection or analysis of surface wave influences (see Section 5.4.1) or just the continuation of the data collection, especially in regions only accessible in high water level conditions. Further developments are from time to time presented on our web page: https://web.fs.tum.de/~niederma/segeln/tracks/Ammersee_Wassertiefenprojekt.html.

Experience with echo sounder measuring in other regions using charter boats showed up various additional challenges, like different NMEA network cable types (need of several adapters), various plotter export formats or even sensors not being connected to a network at all (historic vessels). On charter trips besides that an equipment like the remote controlled measuring model boat presented in Section 3.2 could be used to bathymetrically map an extended region around the anchor ground automatically over night (parts of or whole inlet, especially the interesting shallow waters between 0 and 10 m depth). //

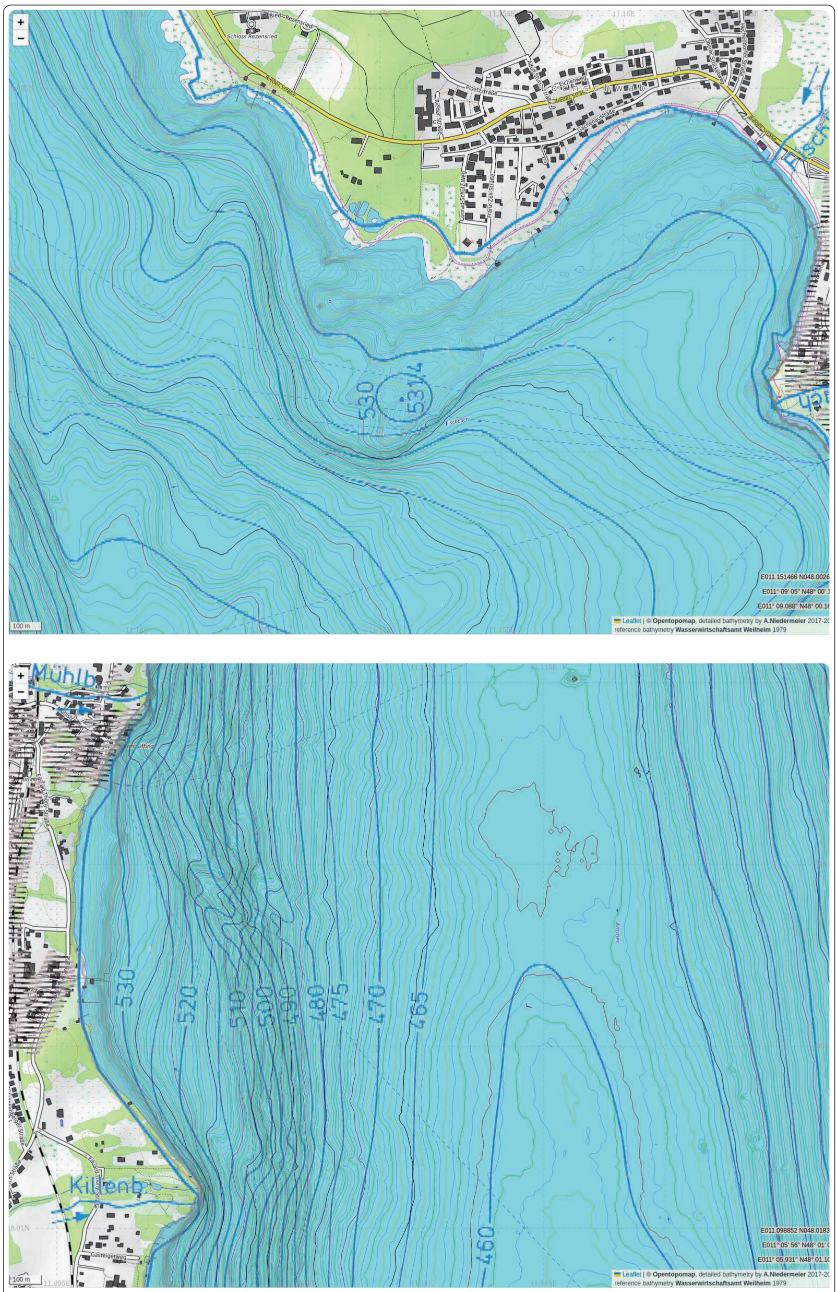

Fig. 7: Comparison of the isolines interpolated from the main dataset to the official 1979 sea chart in Herrsching/Rieder Eck (top) and in Utting (bottom)

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