An Economical Open-Source Lagrangian Drifter Design to Measure Deep Currents in Lakes

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Key Points:

- An economical, open-source Lagrangian drifter designed to collect current data on lakes <200km^2 was evaluated against existing designs.
- The new design was tested in deep inland lakes in the Finger Lakes region of New York, USA and is effective at tracking deep currents.
- The ease and low-cost of fabrication and launch/recovery should facilitate use of this design by less-advantaged communities & researchers.

Abstract

The objective was to construct and test an economical, accurate, and open-source Lagrangian drifter design suitable for lakes <200 km^2. Lagrangian drifters are used to trace water currents in marine and freshwater settings and comprise of a low-friction surface float containing instrumentation for location and environmental measurement, tethered to a high-friction drogue at the depth of interest. Oceanic drifters are robust but expensive, and this design tailored to inland lake waterbodies fills a durability and cost gap for lake environments. Water-following characteristics were tested using theoretical drag coefficient calculations, practical drag measurements, and comparison of wind and drifter vectors while deployed on two deep inland lakes (maximum area 175 km^2) in the Finger Lakes region of New York, USA. The ratio of drag between float and drogue met or exceeded the minimum value of 40 recommended in the literature, and the vectors of wind and drifter during deployment were independent of one another, meaning the device accurately traced the movement of water currents at depth without undue influence of wind and waves. Each device cost USD $265 in 2021 and was built from materials readily available at hardware and sporting goods stores, allowing their use by research institutions and communities with smaller budgets. This design reliably measured lake currents at sampling depths that ranged from 2 m to 30 m. We anticipate that this design will have application to a wide range of hydrodynamic and ecological research where empirical insights to physical processes like lake currents are sought by scientists and managers.

Plain Language Summary

Lake currents are complex, yet often lack data for scientists to analyze them. We built and tested a low-cost, accurate device that can follow water currents in lakes, made from easily available parts. Unlike similar devices for oceans which can be bulky and costly, this device is well-suited for lakes. It works by floating on the water's surface and has a part that hangs below it in the water to track water movement at different depths. Tests in two New York lakes showed it does a great job of tracking water without being thrown off by wind or waves. Making each device costs $265, using parts found in regular stores, so it’s affordable for smaller research teams or local communities. It's good for studying water movements from near the surface down to 30 meters or even deeper, helping scientists and local managers learn more about how water moves in lakes.

Keywords (up to 5 words)

Lakes, currents, Lagrangian, drifter

1 Introduction

Reliable measurements of currents in inland lake settings are often lacking, despite the potential for lakes to provide an equally dynamic setting relative to larger water bodies. For example, lake currents are a function of complex processes that may include highly variable wind inputs, river inflows, and variable bathymetry and morphological characteristics (Hutter et al,, 2011; Wetzel, 2001). Understanding such physical characteristics in lakes is crucial to shed light on physical, sedimentological, chemical, and biological processes that define the environmental health of the system. Currents have historically been investigated in marine settings using a variety of robust and capable sampling equipment, though often expensive and difficult to deploy (Edwards et al., 2006, and references therein). Currents in the Laurentian Great Lakes of North America and similar large lakes (Choi et al., 2020; Edwards et al. 2006), in the coastal zone (Sabet and Barani, 2011), and in estuaries (Spencer et al., 2014; Suara et al., 2018; Déjeans et al., 2021) have also been investigated, yet smaller and medium-sized lakes (~50-500 km^2) have received less attention than perhaps they should have, despite improvements in technology including the availability of small GPS units as tracking devices (McCormick et al., 2006; Manley, 2010). New technology and low-cost, high-performance materials are therefore unlocking opportunities to measure currents in a wider range of water body sizes, including smaller inland lakes. Here, we developed an economical Lagrangian drifter design assembled from readily sourced materials, and we validated its research potential with field deployments in the Finger Lakes region of New York State, USA.

Lagrangian drifters are devices used to directly trace currents at a discrete depth interval while minimizing the influence of wind and currents at the surface (Booth, 1981). They contrast with Eulerian-type sensors such as Acoustic Doppler Current Profilers (ADCP), which are usually moored to the bottom of a waterbody where they measure velocity at multiple depths through the water column. Lagrangian drifters comprise of a low-drag surface float containing positioning and communication equipment, and a high-drag drogue tethered beneath the float. Alternatively, drifters specifically designed for surface measurements have only a high-drag float. Commercial options for surface drifters vary in design and construction and include the CODE drifter (Davis, 1985) and the drifter design of Meyerjürgens et al. (2019). The CARTHE drifter (Novelli et al., 2017) is unusual in that it is a biodegradable surface drifter with a drogue suspended by a short chain directly underneath the float to address tilting of the device in large waves and modification of its current-attributed motion. Drifter designs for oceanography and Great Lakes research have evolved from TRISTAR (Mackas et al., 1989) and CODE drifters to the Surface Velocity Program ('SVP') drifters: (Sybrandy & Niiler, 1992; Lumpkin & Pazos, 2006; Poulain et al., 2022). SVP drifters have a cylindrical cordura nylon fabric drogue of 0.6 m diameter which extends vertically around 20 m, centered at a depth of 15 m. Ocean-going drifters are robust platforms for data collection, as they are designed to withstand rough ocean conditions and to transmit their location and environmental data for several months up to a decade. Accordingly, they range in cost from around USD$1800 for the basic structure to many thousands of dollars for fully instrumented drifters, which can be cost-prohibitive depending on the research setting (https://www.aoml.noaa.gov/phod/gdp/faq.php#cost, accessed 17 February 2023).

A drifter to be used on freshwater lakes (global mean depth 42 m; Cael, 2017) has differing requirements to ocean-going drifters (global mean depth 2660 m; Charette & Smith, 2010). Seasonal stratification and proximal flow boundaries (shoreline and lake bottom) mean that the vector of currents will differ vertically through the relatively shallow water column and over short time intervals of hours to days. The smaller extent of freshwater lakes compared to the oceans and the greater risk of grounding in shallow water compared to ocean-going drifters entails a shorter deployment duration, smaller battery capacities, but also a higher chance of encountering commercial or recreational vessels. A shorter mean fetch resulting in lower amplitude waves suggests that the design need not be as robust as ocean going drifters, decreasing material requirements, cost, and vessel size required for deployment and retrieval. Depending on the lake, we anticipate a higher chance of easy deployment and certainty of recovery using a transmitted GPS position, meaning that practical and cheap onboard logging of environmental sensor data is a viable alternative to telemetry. These factors and many studies (e.g. Gasser et al., 2001; Austin & Atkinson, 2004; Cadena et al., 2018; Agade & Bean, 2023) suggest that oceanographic designs are over-engineered for measuring currents in small to medium-sized lakes, and thus needlessly expensive. Although drifters for smaller waterbodies have been described (Mullarney & Henderson, 2013; MacDonald & Mullarney, 2015; Fuentes-Pérez et al., 2022 Table 1), many are optimized for specialist data collection (e.g. ADCP, video), are expensive, or incorporate proprietary designs that are not easily replicable.

Here, we demonstrate how a novel Lagrangian drifter design can provide reliable empirical insights to deep currents in freshwater inland lake settings. The drogue design was tested in lakes in the Finger Lakes region of New York State, USA, and provided sufficient information to evaluate local circulation patterns at relatively deep depths in waterbodies with much smaller surface areas than in the oceans and Great Lakes. The objectives of this study were to: 1) Design and construct a new, easily assembled, deployable, and retrievable, and open-source, economical Lagrangian drifter specifically for small to medium-sized lake settings, 2) estimate forces of drag on the design to ensure movement is a function of currents, 3) validate the drifter design through field deployments, and 4) obtain empirical measurements of lake currents with the instrument. For USD$265 (in 2021 costs) the drogue design met all criteria necessary for ease of deployment and reliable current measurement in deep water. We thus believe this design could broaden the availability of such drifters to research programs and communities with lower budgets and may have important applications in the water resources community.

2 Materials and Methods

2.1 Drogue Design

Our drogue design (**Figure 1**) consists of three square planes of High-Density Polyethylene (HDPE, density 915 g/L) arranged orthogonally, dimensions of width, breadth and height of 1.22 m (4 ft; 1.72 m diagonally), and joints cinched with cable ties (also known as ‘zip ties’, nylon, 20 kg breaking strength). Critical points such as the attachment point of tether to drogue had multiple zip ties to ensure redundancy. Each plane is built from four smaller panels of dimension 0.61 m (2 ft), which, with judicious folding, enables its easy transportation and later ability to reform prior to deployment. HDPE is stiff even when thin (2 mm), chemically inert, abrasion resistant, and with a finish that discourages encrustation, e.g., in our study system, encrustation by invasive *Dreissenid* mussels. Drifters were deployed with Hobo MX2201 temperature loggers attached to a drogue panel. Steel weights (1 – 3 kg) attached to the bottom of the drogue via zip ties were used to overcome drogue buoyancy and decrease the possibility of wind and wave rectification and lateral translation, and also enabled the cylindrical floats to remain upright. The design of drifter is a modification of that of Manley (2010), but differs in significant aspects (horizontal drogue plane, HDPE drogue material, use of Globalstar satellite system and SPOT Trace GPS units, and solar powered top beacon).

2.2 Float Design

The float design (**Figure 1b**) takes the form of a resealable buoy, comprised of Polyvinyl chloride (PVC) cylindrical tubing and end caps. PVC is inexpensive, robust, easy to fabricate and glue, and readily available. The float is approximately 0.6 m long, external diameter of 0.089 m (3.5 inches), filled with closed-cell foam to mitigate against leaks or damage. A 0.05 m (2 inch) eye bolt is mounted through the lower cap, secured in place with nuts and washers, and cemented in place with silicone sealant to prevent leaks. Approximately 0.1 m of the float is above water, plus whatever high-visibility beacon is attached. The top section is sealed via a water-tight thread, allowing access to a compartment for Global Navigation Satellite System (GNSS) device storage. We used SPOT Trace GPS units (https://www.findmespot.com/en-us/products-services/spot-trace, 6.8 cm × 5.1 cm × 2.1 cm, purchased 2021 and 2022) equipped with high-grade lithium batteries within the top compartment (**Figure 1c**), which transmit location via the Globalstar satellite network with options to program transmission frequency between 150 seconds and 1 hour. The upper cap screw-in surface has a solar-powered flashing beacon to aid in retrieval and avoidance of collisions. The tether was 3 mm braided nylon (breaking strain 50 kg), with an additional 1 m of elastic shock cord. This was needed because without elasticity in the tether system the vertical stability of the drogue in the water column, combined with the buoyancy of the float, could induce high dynamic loads on an inelastic tether in high wave conditions. Materials for each drifter cost around USD $265 in 2021, plus USD $30/month for GPS service subscription. Construction time is around three hours per drifter. A complete parts list and construction manual are available in Supporting Information (see Section **SI1**).

a) **b)** **c)**

Figure 1. Component parts of the drifter. Drifter design comprises of **a**) High-resistance drogue of three orthogonally-arranged HDPE plates each with a dimension of 1.22 m (4 ft) and **b**) Low-resistance foam-filled PVC float approximately 0.6 m in length, joined by a tether (not shown). The float top cap, **c**), is removable to access the SPOT Trace GPS unit, which sits on top of a rubber gasket secured in place with silicone sealant. Steel weights are added to balance buoyancy.

2.3 Establishing Water-following Characteristics

We used four methods to test the influence of the float on drogue movement:

1) Theoretical calculations of drag ratio based on drag coefficients and cross-sectional area;
2) Experimental measurement of drag forces on float and drogue at differing water velocities;
3) Graphical analysis of data from the deployment of drifters on Seneca and Keuka Lakes, showing drifter versus wind vectors; and
4) Statistical analysis of wind and drifter direction using both linear regression and Kendall's rank coefficient between hourly wind and drifter bearings.

2.3.1. Theoretical Drag Forces

A required design characteristic for a drifter is the tendency of the drogue to follow a water parcel while minimizing influences on the movement vector by other factors such as wind and surface gravity waves. The drag coefficients, C_D, of specific shapes (Nakayama 2018) is used with the dimension, A, of components of this and other drifters (**Table 1**) to calculate the drag area, $A_D = C_D A$, for the drogue and float, to arrive at a drag area ratio, R,

$$R = A_D^{drogue} / A_D^{float}$$

A large value of R (ratio of drogue/float drag areas) is desired, and a coefficient of 40 is described as a minimum for Lagrangian drifter devices (Niiler et al, 1996).

2.3.2. Experimental Drag Forces

Experimental measurement of forces due to drag were carried out either by: 1) Dragging the components sideways alongside a dock in static water, 2) pulling upwards from the bottom of a swimming pool, both at varying low (<0.5 m/s) velocities, or 3) by towing full-size drifter components from a boat (>0.5 m/s), while measuring the resultant force with a digital strain gauge (read in kg, converted to newtons; 1 kg = 9.81 N). Vertical and horizontal methods of drogue and float drag measurement were deemed equivalent because of the symmetry of the devices in three dimensions, and the forces induced by dragging either vertically or horizontally are much greater than those generated by those induced by sinking. In a lake, the components are never likely to experience these speeds through the water: the experiment is only to show the drag area ratio at a variety of speeds. The float was filled with water to approximate neutral density, and during experiments it was completely submerged; the force reported here is that experienced by the length of float below the surface during deployment (0.5 m). Drag force (F_d) is proportional to surface area A, square of the velocity V, density of fluid ρ, and drag coefficicent C_D,

$$F_d = \frac{1}{2} \rho v^2 C_D A$$

meaning that drag force ratios are better approximated using regressions expressed as a power, in the form of $y=ax^b$. Power regression lines were fitted to the data for each component. Drag area ratio at each velocity is equivalent to the difference in slope between fitted lines.

2.3.3. Field Deployment

Study system

The drifter design was tested in the Finger Lakes region of New York, USA (**Figure 2**) in October 2021 and October 2022. The Finger Lakes are glacially-formed (Mullins et al. 1996), elongate lakes oriented approximately north-south. All lakes drain northward into Lake Ontario within the Laurentian Great Lakes basin. Wind directions are often parallel to their long axes, resulting in the generation of surface and internal seiches (Ahrnsbrak 1974). We specifically deployed drifters in Seneca Lake and Keuka Lake (the latter is detailed in Supplemental Information, **S2**). Each lake is monomictic with strong seasonal thermoclines that persist until mid to late Fall (northern hemisphere Autumn). Seneca Lake has a simple morphology – essentially bathtub-shaped, with steep east and west sides, shoals at the north and south ends, and a mostly flat bottom. ADCP data over a 10-day period in 2018 at a northerly site in Seneca Lake (USGS, in prep) indicated currents had a maximum velocity of 0.43 m/s, although 95% (±2 standard deviations) were less than 0.3 m/s. This is in line with the author's (LM) personal experience when conducting lake profiles, that equipment being lowered into the lake on a calm day with no boat drift can be pulled strongly in various directions. No measurement has been made of current strength in the central section of the lake, where seiches might be expected to generate the highest velocity currents.

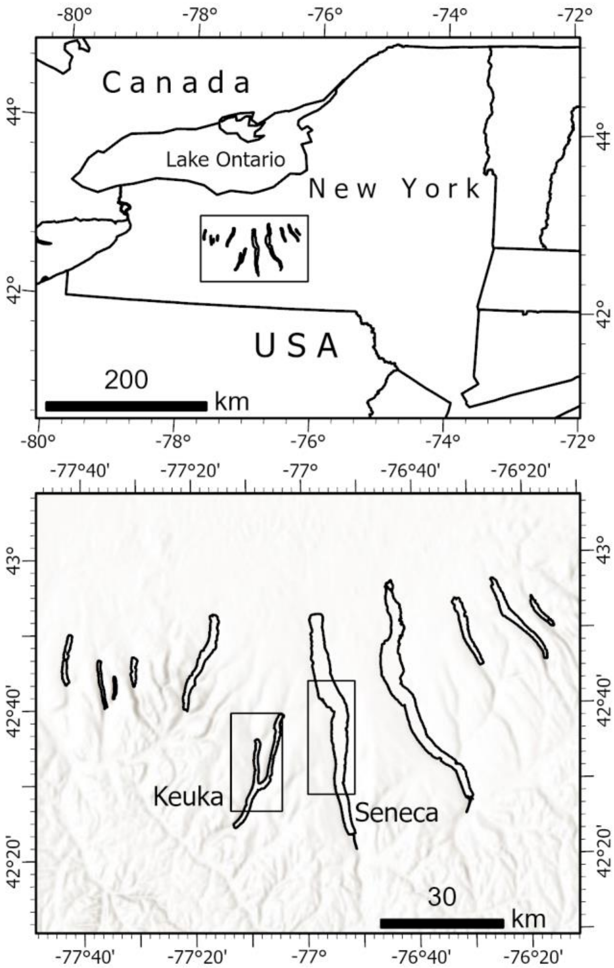

Figure 2. *Top*) Location of the Finger Lakes within New York State, USA, and *Bottom*) the Finger Lakes region, highlighting Seneca Lake and Keuka Lake, the sites of experimental deployments of this drifter design in Fall 2021 and Fall 2022. Boxes indicate areas of drifter movement during deployment.

Drifter configuration and deployment

Drogues were transported to deployment locations on boats folded upon themselves in one plane, then planes were unfolded and fixed in position either on shore or, space and wave conditions permitting, just before deployment from the boat. Drogues were deployed first, followed by tether, and then the float once the drogue reached sampling depth. Deployment took about five minutes with two people. Upon release we ensured, by the addition of extra ballast on the drogue if needed, that floats were vertical and there was no slack in the tether. We validated that all GPS devices were logging GPS coordinates upon their release.

Positions of the floats are transmitted via satellite to a data center; a subscription-based, shareable online map of last known and historic positions available through SPOT (https://www.findmespot.com/en-us/). We configured this map to a public setting and found that we increased local community participation during our lake experiments. Additionally, GPS points are available from SPOT at the time interval configured (e.g., 10-minute rate), which can be viewed via smartphone to enable drifter recovery if sampling in an area with cell reception. At night, the flashing beacon was also highly visible, even in choppy water. For instance, one SPOT Trace unit suffered a battery failure at nine days during the Seneca lake deployment, but the drifter was eventually retrieved via a social media campaign which led to multiple reports from shoreline residents of the flashing beacon at night. Retrieval of all other drifters was easily accomplished despite up to a 10-minute delay on position location. Upon retrieval, we observed no modification to the drogue and float design throughout deployment, including no zip tie failures, no water entry into the float, or degradation of the nylon tether.

Data processing

Latitude and longitude data for each drifter were downloaded from the SPOT website after drifter recovery, then converted to comma delimited files for processing. Wind and drifter data frequency was aggregated hourly using the Pandas Library (version 2.1.4; McKinney, 2010) in Python (version 3.9.13; Python Software Foundation 2024). All statistical analyses presented here used SciPy (version 1.12.0 2024-01-20; Pauli et al. 2020). Velocity between each location fix was calculated using the haversine formula (Van Brummelen, 2013) from sequential latitude and longitudes transmitted by the GPS units. Grounding of the drifter on the lakebed was indicated initially by a decrease in speed and localization of the drifter over several hours, and subsequently confirmed by a comparison of the drogue depth with bathymetric data. Vectors while the drifters were grounded and being relocated to a deeper water location were set to ‘null’ in files for analysis.

For deployment on Seneca Lake, wind speed was measured at a buoy (42°49'07.8"N, 76°57'36.6"W, 17km from the initial deployment location, 3.1m elevation above water) off Clark Point, using a RM Young 05106 instrument (wind speed accuracy of 0.3 m/s, wind direction accuracy of 3°, downloaded from http://fli-data.hws.edu/buoy/seneca/).

3 Results

3.1 Theoretical Design Validation

The R value for our float-drogue combination is around 90, 39% less than the R-value of the SVP-B drifter design (~140). The SVP-B drifter could be considered the ‘gold standard’ because of its ubiquity in oceanic drifter studies. The drag due to the tether is approximately 0.0022 N/m and has been ignored in the following calculations, given that all designs considered here have tethers.

Table 1: Dimensions and drag coefficients of this and other drifters. Drag coefficients from Nakayama (2018). SVP-B dimension from Sybrandy and Niiler (1992) and Lumpkin and Pazos (2006). Johnson drifter dimensions are from figure and text descriptions in Johnson et al. (2003) and CARTHE drifter dimensions are from Pacific Gyre (2023).

	This study	**SVP-B**	**Johnson**	**CARTHE**
Float submerged cross section A (m^2)	0.044	0.040	0.032	0.023
Float form	Cylinder	Hemisphere	Cylinder	Toroid
Drag Coefficient C_D	0.74	0.42	0.74	0.42
Float drag area A_D^{float}	0.033	0.017	0.024	0.010
Drogue Dimensions (m)	1.22 x 1.22	0.61 x 4.9	0.63 diameter	0.38 x 0.38
Drogue Cross section A (m^2)	1.49	2.99	0.31	0.14
Effective drogue form	Flat plate	Cylinder with holes	Hemisphere, type II	Flat plate
Drag Coefficient C_D	1.98	0.74	1.33	1.98
Drogue drag area A_D^{drogue}	2.95	2.45	0.41	0.286
Drag Area Ratio, *R*	89	146	17	28.6

3.2 Experimental Design Validation

For experiments measuring actual forces on drifter components, forces increased predictably, whether the experiment was conducted at low speed (dockside/pool) or towed behind a boat (**Figure 3).** Initially approximating the drag forces as simple linear regressions, the submerged area of float (0.5 m length) induced a drag of 21 N/m/s whereas a 0.61 m drogue (width, length, and height) induced a drag of 316 N/m/s, equivalent to a drag area ratio of approximately 15 (316/21 N/m/s), below the minimum required value of 40 (Niiler et al, 1996). Experiments with a 1.22 m drogue showed that drag forces were much higher (855 N/m/s), although not four times higher than the 0.61 m drogue, as might be expected from the increase of surface area by four times. These experiments confirmed the requirement to use larger drogues. In theory, all fitted regression lines should pass through the origin since there should be no drag at zero velocity, but we analyzed our experimental dataset as empirical, non-corrected data.

In order to determine when the ratio of drag forces between y^d (1.22 m drogue, $y^d=1204.62x^{1.4}$) and y^f (float, $y^f=18.37x^{1.34}$) meet the value of 40 stated in Niiler et al (1996), we set $y^d=(40)y^f$. In doing so we get $1204x^{1.4} = (40)18.4x^{1.34}$. When solved algebraically, x=0.0026 m/s, meaning at this velocity the drag ratio of y^d (drogue) to y^f (float) is 40. At velocities greater than 0.00026 m/s, the ratio will be greater than 40, as the drag force of y^d increases at a greater rate than the drag force of y^f, as the exponent of y^d is greater than the exponent of y^f.

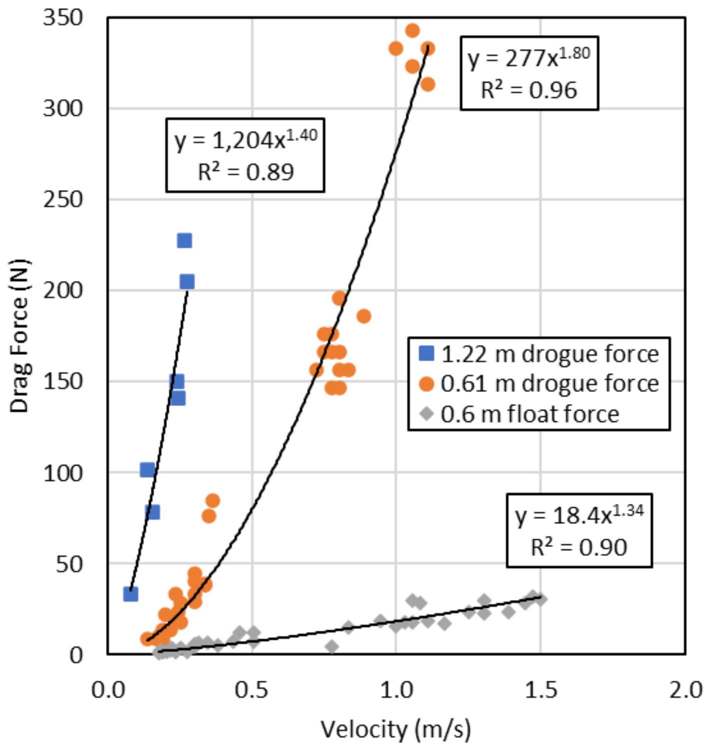

Figure 3. Drag forces on full-size drifter components. Values below 0.5 m/s were measured either at a dock or a swimming pool, those above 0.5 m/s were measured from a moving boat. Float was filled with water to achieve approximately neutral buoyancy. Equations for the power regression lines are given along with R^2 values for the best fit.

3.3 Field Experiments

We field validated the drifter design on two medium-sized inland lakes of up to 180 m depth and 17,000 ha (66 mi^2) in area (**Table 2**). We found that drifters moved up to several kilometers per day and GPS units successfully tracked location without important data gaps. Velocity and distance covered by drifters in the epilimnion (20 m deep) were greater than in the relatively thicker hypolimnion (120-160 m thickness).

Table 2: Deployment details for the current design on two Finger Lakes. The total deployment time is the sum of all drifter deployment durations, and includes time grounded or being redeployed to deeper water. Further details of the Keuka Lake deployment are found in Supplemental Information Section S2.

	Seneca Lake	Keuka Lake
Area (hectares)	17,540	4,688
Maximum depth (m)	188	56
Length (km)	61	31.5
Deployment Date	17 October 2021	30 September 2022
Number of drifters	3	6
Total deployment time (drifter-hours)	768	2734
Location frequency (minutes)	5	10

Case Study: Seneca Lake

Three drifters were deployed in Seneca Lake for 10-14 days in October 2021. They were configured for three levels: 2 m, 10 m, and 30 m (‘Upper’, ‘Middle’, and ‘Lower’, respectively). The Upper drifter had a 0.61 m wide drogue, whereas the Middle and Lower drifters had 1.22 m wide drogues. Wind and drifter vectors were plotted against time to illustrate the degree of coherence between the two data types (**Figure 4**). Mean drifter speeds were 0.15 m/s, 0.10 m/s and 0.025 m/s for Upper, Middle, and Lower drifters respectively, compared to 4.95 m/s for wind speed. Typically, winds are described in terms of the direction they are coming from, but wind directions and vectors in this paper refer to the direction the wind is going *towards* for easier comparison with the drifter information. Wind was predominantly towards ESE to SSE, and drifter movement was predominantly to N or S (**Figure 5**). Some degree of agreement between wind vector and Upper drifter vector is apparent but is not for Middle and Lower drifters.

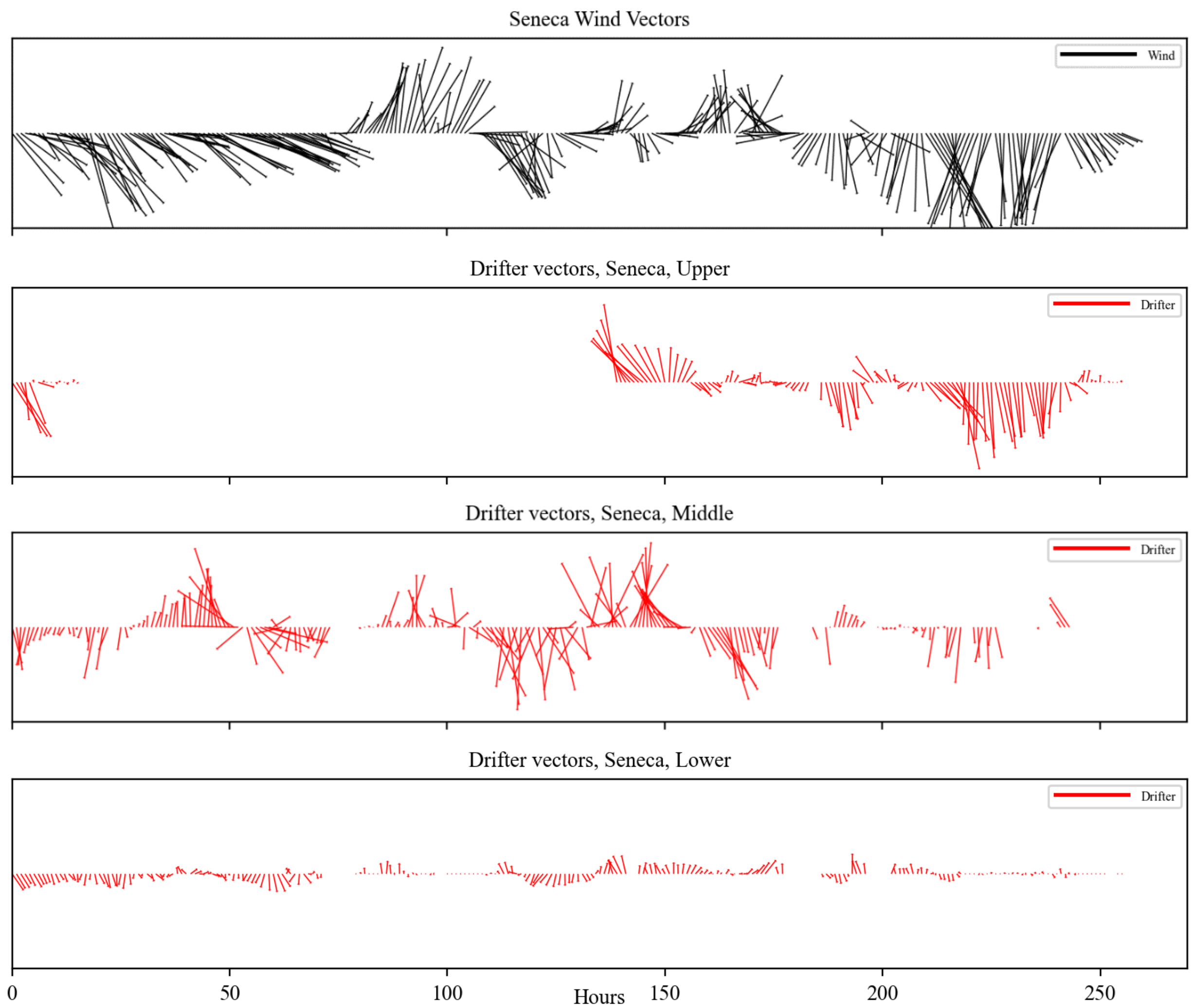

Figure 4. Comparison of hourly wind vectors with those of Upper, Middle, and Lower drifter vectors, Seneca Lake, New York, USA from 17 October 2021 to 28 October 2021. The origin of each vector line is marked horizontally in hours from the start of deployment. Length of line is proportional to velocity, and direction of the line from its origin represents the direction towards which the wind/drifter was moving. Velocity scale is proportional to the line length in the legend: Wind, 0 to 7.2 m/s; drifters, 0 to 0.3 m/s. The scale has been adjusted (x24 exaggeration for visualization) between wind and drifter plots to allow easier visual comparison. Gaps in date are due to either grounding or failure to receive a positioning signal.

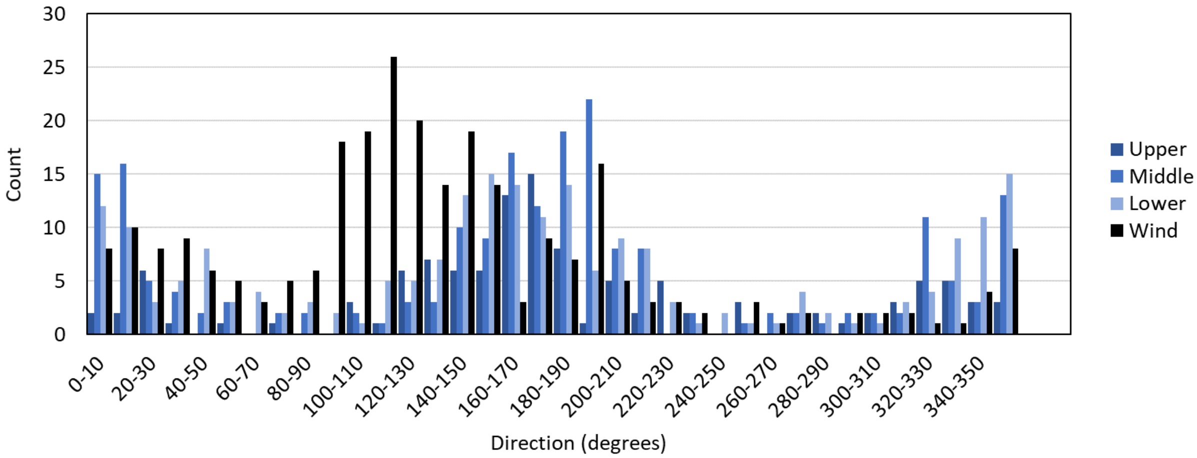

Figure 5. A histogram of wind and drifter direction over the course of experimental deployment (17 October 2020 to 27 October 2020) on Seneca Lake, New York, USA.

A linear regression of wind and drifter hourly bearings indicated low coefficients of determination (R^2) for Upper, Middle, and Lower drifters of 0.0439, 0.0003, and 0.004, respectively (**Figure 6**). Spearman rank correlation coefficients (τ) for hourly wind direction and Upper, Middle, and Lower drifter bearings indicated that middle and lower drifter direction of movement was unrelated to wind direction (τ = -0.0279 and 0.0813, p values = 0.5487 and 0.0743, n = 209 and 218, respectively). Upper drifter direction was weakly correlated to wind direction ((τ = 0.3391, *p*-value = 0.01, n = 116). Drifters moved many kilometers over the duration of deployment (**Figure 7**). Velocities aggregated over half an hour provide velocity estimates down to 0.02 m/s, based on the stated accuracy of the GPS system of ±5 m horizontal.

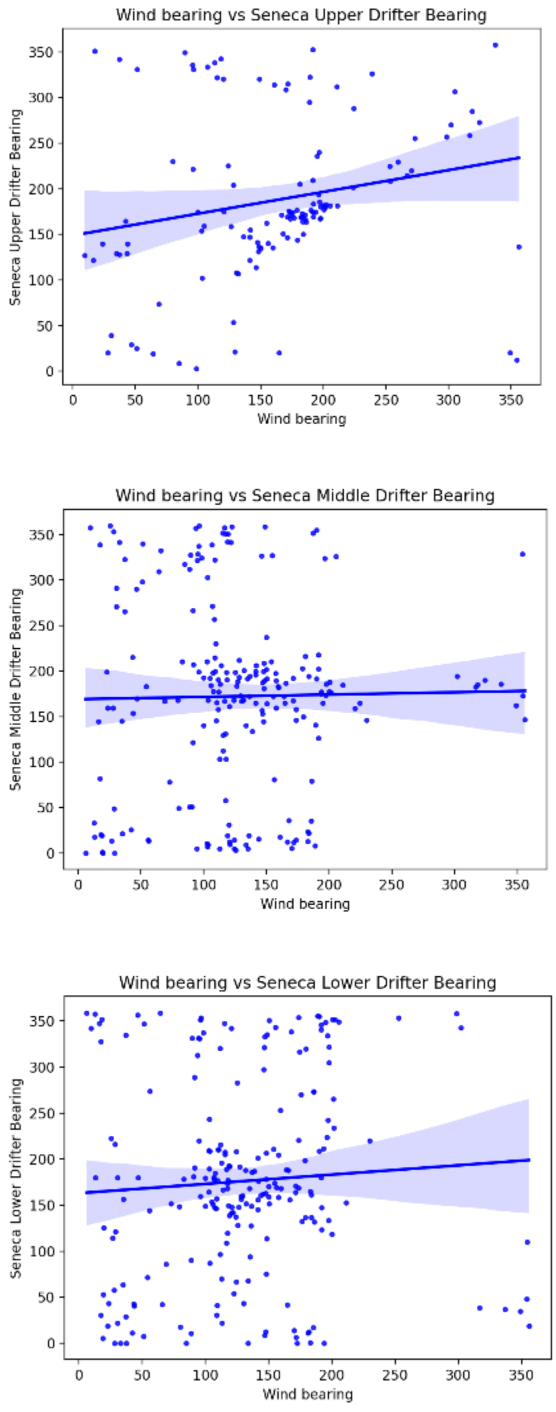

Figure 6. Comparison of hourly wind bearings with a) Upper, b) Middle, c) Lower drifter bearings while deployed on Seneca Lake, New York, USA from 17 October 2021 to 27 October 2021. The solid blue line is linear regression model fit, with shaded areas indicating 95% confidence interval band.

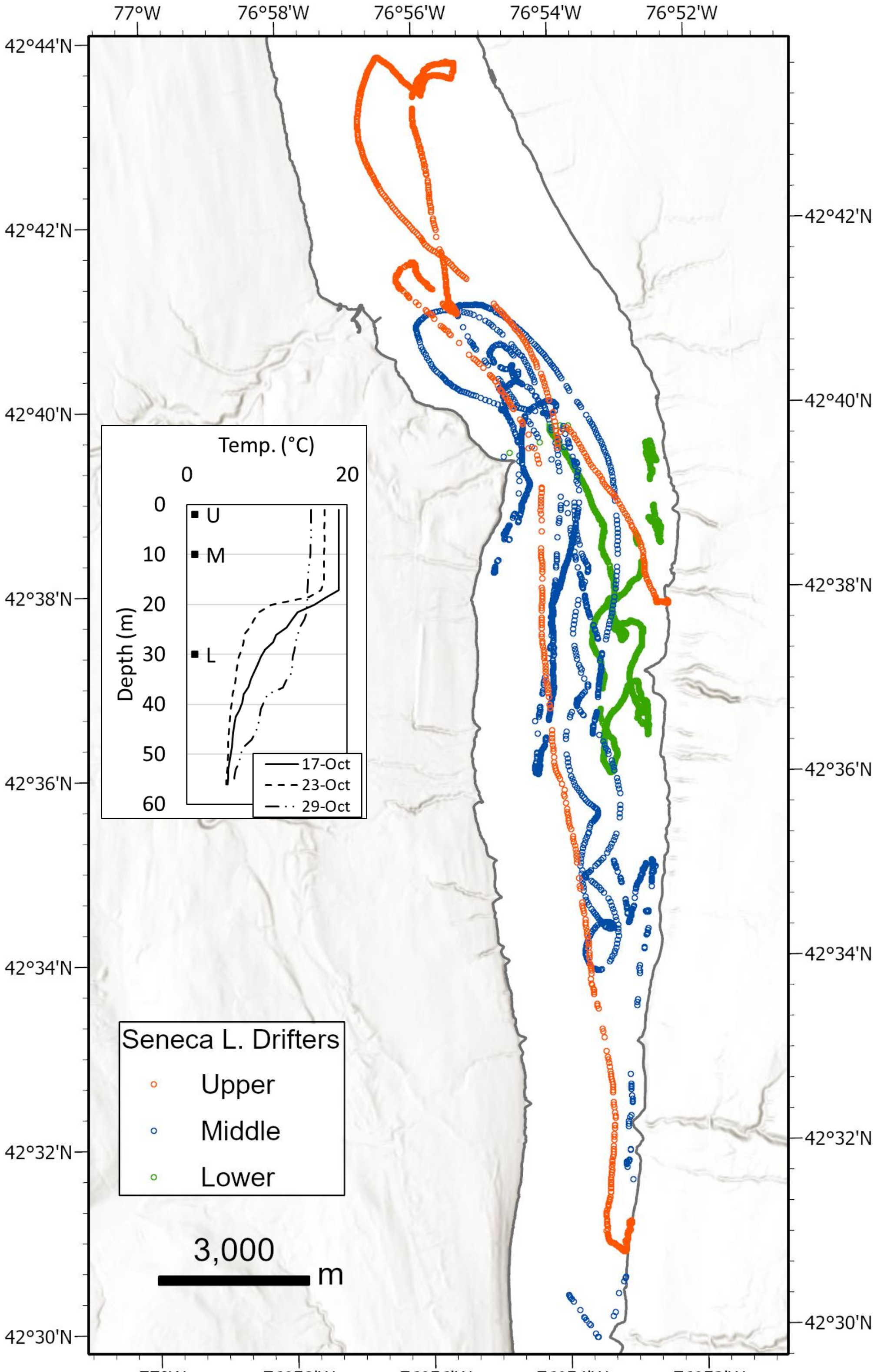

Figure 7. Drifter positions on Seneca Lake, 17-27 October 2021. Inset: Thermal profile and drifter depths ('U', 'M', 'L' = Upper, Middle, and Lower drifters, respectively).

5 Discussion

This study integrates multiple calculations and field-based testing to validate a novel Lagrangian drifter design. Experiments reveal that this design exceeded drag force thresholds between the suspended drogue and surface float, which indicates that movement of this device through the water column is a function of lake currents. Through extensive field deployments, we found that the design reliably measures deep current characteristics of direction and velocity in deep inland lakes By deploying our drifter design at scale, we demonstrate that this cost-effective, reliable design provided information useful for elucidating current patterns in lakes that have previously lacked measurements of deep currents.

The present drifter has a theoretical R = ~80, double the minimum value of 40 suggested by Niiler et al. (1995). Theoretical calculations of the float and drogue drag and several drifter designs documented in the literature (**Table 1**) show a range of drag area ratios, R, from about 17 for the Johnson et al. (2003) design to over 140 for the SVP-B design. The high R value for the SVP-B design is primarily due to the high cross-sectional area (particularly in the depth dimension) of the SVP-B 'Holey Sock' drogue. This large interval of measurement depth may not be a significant problem in oceanographic studies, but in a lake, current vectors may change over much shorter depth intervals. We note that the drifter of Johnson et al (2003) is comprised of a drogue using an 85-liter bucket. The stated drogue surface area of 2.25 m^2 is quite possible, but the cross-sectional area of a standard bucket, which is the relevant dimension for drag calculations, would vary between 0.17 and 0.31 m^2 depending on orientation to water flow. The resulting drag area ratio of the Johnson drifter using realistic drag coefficients at the high end of drogue cross-sectional area is well below 40. The CARTHE drifter has a theoretical R value around 29, despite the relatively modest size of its drogue, likely resulting from the notably low cross-sectional area of its toroidal float. Extensive lab measurements of the CARTHE drifter (Novelli et al. 2017) found it to have excellent water-following characteristics. We found it difficult to select the appropriate shape type from the available hydrodynamic drag literature, since none of the drogue configurations were present in existing literature (orthogonally arranged plates, cylinder with holes, bucket, and sideways-toroid). The reported drag values are conservative estimates based on the shapes of each drogue configuration – when unavailable or uncertain, we chose values to increase the value of R in other drifter systems.

Experimental measurement of drag on full-sized components confirmed the drag ratio of float to 1.22 m drogue was above 40, but only marginally. The 0.61 m drogue data is scattered at higher velocities, which fits with field observations of the difficulty of measuring those higher forces from the back of a boat. To the authors' knowledge no equivalent tests have been performed on other drifters, and it would be illuminating to see what the results of such experiments would be. However, this experimental approach to measurement of drag ratio may not be suitable for drogue designs which lack a method to prevent slippage when deployed in anything other than a vertical orientation, or those which would deform or collapse if subjected to lateral forces.

The graphical comparison of wind and drifter vectors over time lends support to the independence of the two vectors, particularly for middle and deep drifter deployments on Seneca Lake, and for all the drifters deployed to Keuka Lake. The speed and direction of the wind is often seen to disagree with the speed and direction of the drifters. In a mental exercise, one could imagine that if the two sets of vectors were in fact random and uncorrelated, they would still roughly coincide for some fraction of time. In the case of the experimental deployment, wind and drifter vectors do indeed coincide for part of the time. Drifter direction is limited by the roughly N or S movement of currents along the longitudinal axis of the two study lakes, while wind direction is at times modified from blowing towards eastern and northeastern direction by the funneling effect of the topography, modifying it towards the north along the lakes. The slightly increased value of Spearman rank coefficient for the Seneca Lake Upper drifter (with a smaller 0.61 m drogue set at 2 m depth) may be due to wind-induced movement in the top couple of meters but is most likely caused by an insufficient drag coefficient ratio. A comparison of drifter velocity data provided by SPOT, with velocity calculated from latitude and longitude indicates that SPOT velocities are not provided at very low speeds, possibly because of a threshold set in the SPOT reporting system.

The low values of the wind/drifter direction Spearman rank correlation coefficient confirm independence of these parameters. Drifters moved mostly north or south (longitudinally) in Seneca Lake, possibly due to internal seiche-induced currents. Temperature spikes detected and recorded by the attached HOBO sensors coincided with change in movement from north to south, suggesting passage of an internal wave. When drifters moved east or west (laterally) they were caught in a gyre, or about to change from north to south or vice versa. The drifter direction of movements on Keuka Lake was more complex, with one drifter ('East Shallow') eventually making its way into all three branches of the lake, against the prevailing wind direction (see Supplemental Information **Section S2** for further details).

Our practical drifter design has the potential to be deployed at scale in inland lakes with implications for both basic and applied research questions. For example, small and medium-sized lakes have been the focus of research on water quality issues worldwide, particularly resulting from a perceived increase in harmful algae blooms (Ho et al. 2020). Surface currents have been suggested as significant transport mechanisms for harmful bloom-forming cyanobacteria (Ishikawa et al. 2002), and deep currents have been suggested as a source of turbulent upwelling of nutrients (Bourgault et al. 2014) so an improved understanding of the scale, frequency and movement of lake currents could be a useful contribution to the study of blooms. The use of the design could enable harmful algae bloom forecasting based on hydrodynamic models (see Wynne et al. 2013) to be improved with empirical current data against which a model could be calibrated and validated (Mardani 2020), as an alternative or in addition to data from ADCP and thermistor strings. This economical drifter design also has potential for integration into ecological sampling methods such as environmental DNA (eDNA), a technique to detect the presence and distribution of aquatic organisms (Deiner et al. 2017; Beng and Corlett 2020) whereby current data can provide further insight to DNA particle transport in lake surveys. The design may provide lake scientists with datasets that bridge the gap between currents predicted by hydrological models and empirical, field-based measurements.

6 Comments and Recommendations

We conclude that the design when using 1.22 m drogues meets or exceeds the minimum suggested drag area ratio between surface float and drogue. The water-following characteristics of the present design are sufficient to suggest that this design is a true Lagrangian drifter in the horizontal plane, with minimal influence from wind or wave action. The simple and robust design is economical, easy to construct, and convenient to deploy and recover. The open-source drogue design can be assembled from components generally available at local hardware or sporting goods stores, without the need for proprietary material. We demonstrated that our design successfully collected field measurements of deep currents in inland lake settings and believe that this design can be applied economically to the broader water resources field to further shed light on deep currents.

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Open Research

The dataset used for this research has been deposited on Zenodo and consists of the drifter field deployment, drag experiment, and wind data files. All code using Python version 3.9.13 for statistical analyses is also available on Zenodo via [DOI link here].

McCaffrey, L. and Koeberle, A. (2024). Data for An Economical Open-Source Lagrangian Drifter Design to Measure Deep Currents in Lakes. Zenodo. https://doi.org/#####.

(Note to reviewers, code will be available if considered for publication. Please see code as attached in Supporting Information).

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