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Drones can reliably, accurately and with high levels of precision, collect large volume water samples and physio-chemical data from lakes

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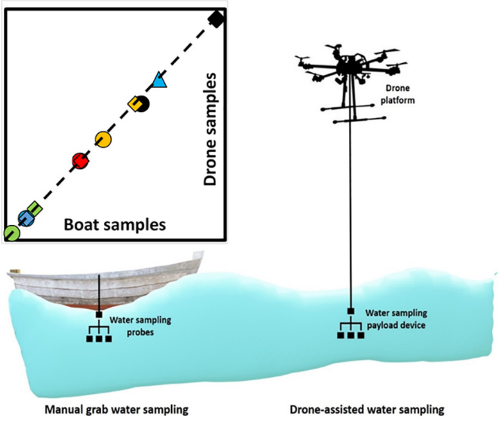
HIGHLIGHTS

- Significant potential for drones to rapidly and safely collect water samples.
- Two litres of water collected by drone on every flight in this study.
- Our results show no difference in water parameters collected via drone and boat.

GRAPHICAL ABSTRACT



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ABSTRACT

The rapid development and application of drone technology has included water sampling and collection of physio-chemical data from lakes. Previous research has demonstrated the significant potential of drones to play a future pivotal role in the collection of such data from lakes that fulfil requirements of large-scale monitoring programmes. However, currently the utilisation of drone technology for water quality monitoring is hindered by a number of important limitations: i) the low rate of successful sample captured; ii) the relatively low volume of water sample retrieved for analyses of multiple water chemistry parameters; and critically iii) differences between water chemistry parameters when using a drone versus samples collected by boat.

Here we present results comparing the water chemistry results of a large number of parameters (pH, dissolved oxygen concentration, temperature, conductivity, alkalinity, hardness, true colour, chloride, silica, ammonia, total oxidised nitrogen, nitrite, nitrate, ortho-phosphate, total phosphorous and chlorophyll) sampled via drone with samples collected by boat in a number of lakes. The drone water sampling method used here is the first to collect a sufficiently large volume of water to meet the monitoring requirements of large scale water monitoring programmes, 2 L, at a 100% success rate and most crucially, with water chemistry variables that are not significantly different to those taken using traditional boat water sampling. This study therefore shows that drone technology can be utilised to collect water chemistry data and samples from lakes in a reliable, more rapid and cost effective manner than traditional sampling using boats, that is safer for personnel and poses less of a biosecurity risk.

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1. Introduction

Over the last couple of decades, the rapid technological development of drones, also commonly referred to as unmanned aerial vehicles (UAVs) or small unmanned aircraft (SUA) has resulted in an ever-growing number of applications including aerial surveillance, search and rescue operations, border patrol exercises, facility inspections, precision agriculture, management of natural risks and intervention in hostile environments (Teh et al., 2008; Zhang and Kovacs, 2012; Niethammer et al., 2012; Beloev, 2016; Stone et al., 2017; Toro and Tsourdos, 2018).

Utilisation of drones has similarly been increasingly deployed within the areas of ecology and environmental monitoring (Hogan et al., 2017; Samseemoung et al., 2012). In terrestrial environments, drones offer many benefits including the opportunity to bridge the existing gap between field observations and traditional air and space-borne remote sensing via high spatial, spectral and enhanced temporal detail of large areas at exceptionally low altitudes in a rapid, repetitive and cost-effective way (Pajares, 2015; Manfreda et al., 2018). They have also been deployed to monitor rapid changes in environmental features such as plant growth (Hogan et al., 2017; Samseemoung et al., 2012), hydrological processes (Bandini et al., 2017; Rhee et al., 2018) and destruction following extreme weather events such as hurricanes (Greenwood et al., 2020). In addition, their use has also increased safety and accessibility to otherwise hazardous or inaccessible sites (Watts et al., 2012; Terada et al., 2018) and capacity to collect data in less-optimum weather condition such as cloudy or hazy conditions compared to satellite images (Van der Wal et al., 2013). Overall, drones are now more versatile, adaptable and flexible to use compared to manned systems or satellites (Pajares, 2015). For more detailed accounts of the application of drones for monitoring, conservation, advancements in sensor payloads tailored to environmental monitoring in the terrestrial environment see recent reviews by Chabot and Bird (2016), Manfreda et al. (2018), Toro and Tsourdos (2018), Wich and Koh (2018) and Librán-Embid et al. (2020).

In aquatic environments, the benefits of using drones offers scientists in depth detail and quantification of vegetational change, flow measurements and at-risk areas for flooding, in addition to gaining data from inaccessible reaches of freshwater and coastal systems in an affordable manner (Manfreda et al., 2018; Rhee et al., 2018). For example, Tyler et al. (2018) deployed drones to rapidly monitor the presence and size of an endangered freshwater fish, Taimen (*Hucho taimen*), in Mongolian rivers. Indeed, drones are increasingly utilised in the research of large marine vertebrates that have been historically difficult to monitor and study in aquatic systems such as large cetaceans (Schofield et al., 2019) and sharks (Butcher et al., 2021). Drones have been successfully utilised in measuring the activity budget of grey whales (*Eschrichtius robustus*), assess the body condition of southern right whales (*Eubalaaena australis*) (Christiansen et al., 2018) and even used to sample the blow or exhaled breath of humpback whales in order to characterise their virome (Geoghegan et al., 2018).

Despite the rapid technological development of both drone platforms and associated attached payloads in a wide range of monitoring and research, the application of drones to collect both hydrochemical data and water samples in freshwater environments has been comparatively low (Lally et al., 2019). This appears to have been due to the complication of retrieving water samples and in-situ physico-chemical data from the aquatic habitat using an aerial borne sampling device and resulting difficulties in the development of a bespoke drone to deploy such a sampling device (Lally et al., 2019). However, such an advancement is highly desirable in water quality monitoring, particularly for large-scale routine monitoring programmes (Vergouw et al., 2016; Lally et al., 2019) for example, European Union (EU) Water Framework Directive (WFD) (EC Environment, 2016) and Marine Strategy Framework Directive (MSFD) (EC Environment, 2017), United States National Aquatic Resource Surveys (US EPA, 2018) and the United Nation Global Environment Monitoring System for Freshwater (GEMS/Water) (UN Environment, 2019). The operation of such large-scale water quality monitoring programmes typically necessitates the deployment of significant personnel in the field and is therefore very expensive to run. Additionally, the requirement to utilise boats to collect samples (traditional boat sampling) poses significant risk to both the health and safety of personnel as well as biosecurity risks, which require significant time to mitigate, adding to financial costs as well as threatening the ecological integrity of the waters being monitored (Lally et al., 2019). The rapidly developing and improving abilities of both drones, in terms of battery endurance, resulting in increased flight time and payload weight capacity, as well as specifically tailored payloads, offers the potential to fulfil many of the sampling requirements of large-scale water sampling programmes in a safer and more cost efficient and biosecure manner (Lally et al., 2019), while also negating logistical issues associated with sampling sites with poor accessibility for boats (Tierney et al., 2015; Lally et al., 2019).

The development of drone-assisted water sampling is still at a relatively early stage, with the first publication in this area by Ore et al. in 2013. However, research in this area has increased significantly in the intervening time period around the world (Detweiler et al., 2015; Ore et al., 2015; Koparan and Koc, 2016; Doi et al., 2017; Song et al., 2017; Terada et al., 2018; Banerjee et al., 2018; Koparan et al., 2018a, 2018b, 2019, 2020; Benson et al., 2019; Castendyk et al., 2019; Castendyk et al., 2020), with significant progress towards the application of drone technology to play a substantial role in water quality monitoring. In a recent review, Lally et al. (2019) concluded that drones have significant potential to collect both water samples and in situ physiochemical data suitable for large scale water sampling programmes, in a safer and more efficient manner than using traditional boat water samplings. However, they concluded that in order for this potential to be realised, a number of key limitations in the application of drone technology need to be addressed including: i) the low rate of successful sample capture via drones; ii) the limited volume of water for analyses of water chemistry parameters; and iii) of critical importance, discrepancies in both physiochemical data measured in situ and water chemistry parameters of samples retrieved between drone technology and traditional boat samplings (Lally et al., 2019). This third point is of particular importance as before the use of drones can be contemplated for gathering hydrochemical data and retrieving water samples for laboratory analyses in large scale monitoring programmes, it is essential that the method of sampling does not influence the quality of such data.

The aim of this research was to investigate if a purpose-built payload, deployed by a drone (DJI Matrice 600 Pro), can: i) reliably collect physiochemical data and water samples ii) of sufficient volume required to satisfy the requirements of large scale water quality monitoring programmes such as the WFD and iii) obtain similar water chemistry and physiochemical results between drone retrieved samples and traditional boat water sampling.

2. Methods

2.1. Study sites

Field trials took place at six lakes in the west of Ireland; Ballquirke Lake and Loughs Fee, Inagh, Conn, Derg and Mask, from September and November 2019 (Fig. S1). The lakes chosen represented two of the main lake types found in Ireland (high and low alkalinity) and a range of trophic gradients (Table 1). There were a total of 12 sampling locations across the six lakes with one location sampled on Loughs Fee and Inagh, two locations on Lough Conn and Ballyquirke Lake and three locations on Loughs Mask and Derg.

2.2. Field trials

In order to compare water chemistry parameters between the two sampling methodologies and also to examine the variability associated with each sampling method, at each of the twelve locations, three water samples were collected using each of the two collection methods, traditional boat-based water sampling and drone-based water sampling, resulting in a total of 72 water samples. Water samples were collected 100 m offshore

Table 1
Key characteristics of lakes sampled during field trials.

	No. of sampling locations	Co-ordinates for sampling locations	Lake surface area (ha)	Maximum depth (m)	Altitude (m)	Water framework directive alkalinity status[a]	Water framework directive typology class[a]	WFD status[b]
Lough Fee	1	53.59122 −9.8381	174	23	60	–	–	–
Lough Inagh	1	53.5162 −9.73816	310	24	21	–	–	–
Lough Conn	2	53.9898 −9.25791 53.09365 −9.29682	4704	33.8	20	High	12	Moderate
Ballyquirke lake	2	53.32469 −9.15257 53.32603 −9.1543	73.6	12.2	15	Moderate	6	Bad
Lough Derg	3	52.90733 −8.50461 52.92032 −8.45241 52.91859 −8.45476	13,000	34	40	High	12	Moderate
Lough Mask	3	53.56779 −9.41073 53.56526 −9.41522 53.64387 −9.36527	8218	17	58	High	12	Good

[a] Data taken from Inland Fisheries Ireland National Research Survey Programme Fish Stock Assessments 2015 & 2016 (Kelly et al., 2016; Kelly et al., 2017a, 2017b; McLoone et al., 2017).
[b] Data taken from the EPA Maps portal (EPA, 2019).

in open water, similar to large scale water monitoring programme, and consisted of two 1 L samples taken simultaneously in opaque, wide mouthed, high density polyethylene (HDPE) bottles, that were prewashed in 0.1 M HCl and triple rinsed with distilled water prior to sampling. In addition to real-time physico-chemical data which were transmitted via a YSI EXO Go and EXO Sonde with EXO pH, dissolved oxygen concentration (mg/l O_2), temperature (°C), and conductivity (μS/cm) probes (Yellow Springs Instruments, Xylem Inc.). The volume of water collected by the drone was recorded in each of the 36 flights to assess the success rate of the drone method to collect 2 L of water.

Boat water samples and physico-chemical data via the EXO Sonde were collected subsurface from the side of the boat. Samples collected by drone were taken using a bespoke prototype water sampling payload pod deployed via a DJI Matrice 600 Pro hexarotor drone and carefully placed on the surface of the lake waters where sub-surface water was pumped into the sampling bottles. The water sampling payload pod also contained the same EXO Sonde attached to the undercarriage of the pod. After each sample was collected, all sampling equipment was washed with distilled water prior to subsequent sample collection and all field equipment was treated with Virkon Aquatic to negate any biosecurity risks. Water samples were transported on ice to the Environmental Protection Agency (EPA) Laboratories in Castlebar, Co Mayo for analyses of alkalinity (mg/l $CaCO_3$), hardness (mg/l $CaCO_3$), true colour (mg/l PtCo), chloride (mg/l), silica (mg/l SiO2), ammonia (mg/l N), total oxidised nitrogen (mg/l N) (TON), nitrite (mg/l N), nitrate (mg/l N), ortho-phosphate (mg/l P), total phosphorous (mg/l P) (TP), and chlorophyll *a* (mg/m^3) (Chl-a). After each sample collection, physico-chemical data were downloaded to a laptop.

2.3. Data analyses

For the physico-chemical parameters, only data produced from the last 90 s of the 4 min period the EXO Sonde was recording data while in the lake waters were retained to ensure that the probes had sufficient time to adjust from recording data while in flight. The average of these 90 s was calculated for each sample. For each water chemistry variable, each location was only included if all three paired water samples for each method exceeded the limits of detection (LOD). To examine if the variability and precision differed between boat and drone collected data, the coefficient of variation was calculated from the three samples at each sampling location for each variable and sampling methodology. Overall differences in the coefficient of variation between sampling methodologies (drone versus boat) for all variables combined, in addition to differences between both the coefficient of variation and the calculated average of each parameter between paired variables, were assessed using paired *t*-tests for data that met the assumptions of parametric tests (normality and homogeneity of variance). Data that were non-normally distributed and/or had heterogenous variability, even after appropriate transformation, were analysed using the non-parametric Wilcoxon signed-rank tests.

3. Results

Drone water sampling successfully collected 2 L of water from each of the 36 sampling flights. Paired sample t-tests found no significant differences for alkalinity ($t = -0.416$, df = 9, $p = 0.69$, mean difference = −1.27 mg/l $CaCO_3$), hardness ($t = 0.85$, df = 5, $p = 0.43$, mean difference = 1.67 mg/l $CaCO_3$), true colour ($t = -0.872$, df = 11, $p = 0.41$, mean difference = −0.78 mg/l PtCo), silica ($t = 0.89$, df = 11, $p = 0.39$, mean difference = 0.06 mg/l SiO_2), TON ($t = 0.775$, df = 3, $p = 0.5$, mean difference = 0.002 mg/l N), TP ($t = 1.19$, df = 4, p = 0.3, mean difference = 0.0005 mg/l P), Chl-a ($t = -1.99$, df = 7, $p = 0.09$, mean difference = −0.25 mg/m^3 Chl-a), and conductivity ($t = 1.89$, df = 11, p = 0.09, mean difference = 12.2 μS/cm) between traditional boat and drone water sampling methodologies (Fig. 1). With the Wilcoxon-signed rank test finding no significant differences in the median concentrations of chloride (Z = 0.614, df = 9, $p = 0.54$, mean difference = 0.04 mg/l Cl), dissolved oxygen (Z = -0.63, df = 11, $p = 0.53$, mean difference = 0.056 mg/l) and temperature (Z = -0.94, df = 11, $p = 0.35$, mean difference = −0.017 °C) between traditional boat and drone water sampling methodologies (Fig. 1). pH was the only variable to show a significant difference between traditional boat (mean = 7.47) and drone (mean = 7.51) water sampling methodologies ($t = -2.46$, df = 11, $p = 0.031$) although the mean difference in pH between sampling methods (0.04) was small.

A statistical assessment of variability (Wilcoxon signed-rank test) found no significant difference (Z = -0.197, p = 0.85, average boat = 3.29%, average drone = 3.76%) in overall variability between data collected by drone and boat water sampling methodologies. Additionally, the precision of each variable found only one significant difference, for hardness, with higher variability in boat collected samples than those collected by drone (Z = 2.87, p = 0.043, average boat = 7.3%, average drone = 3.9%) (Table 2).

4. Discussion

This study has realised the significant potential that drones have to successfully and reliably collect large volumes of water in a manner that is suitable for large-scale water monitoring programmes such as the EU WFD (EC (European Commission) Environment, 2016), United States National Aquatic Resource Surveys (US EPA, 2018) and the United Nation Global Environment Monitoring System for Freshwater (GEMS/Water)

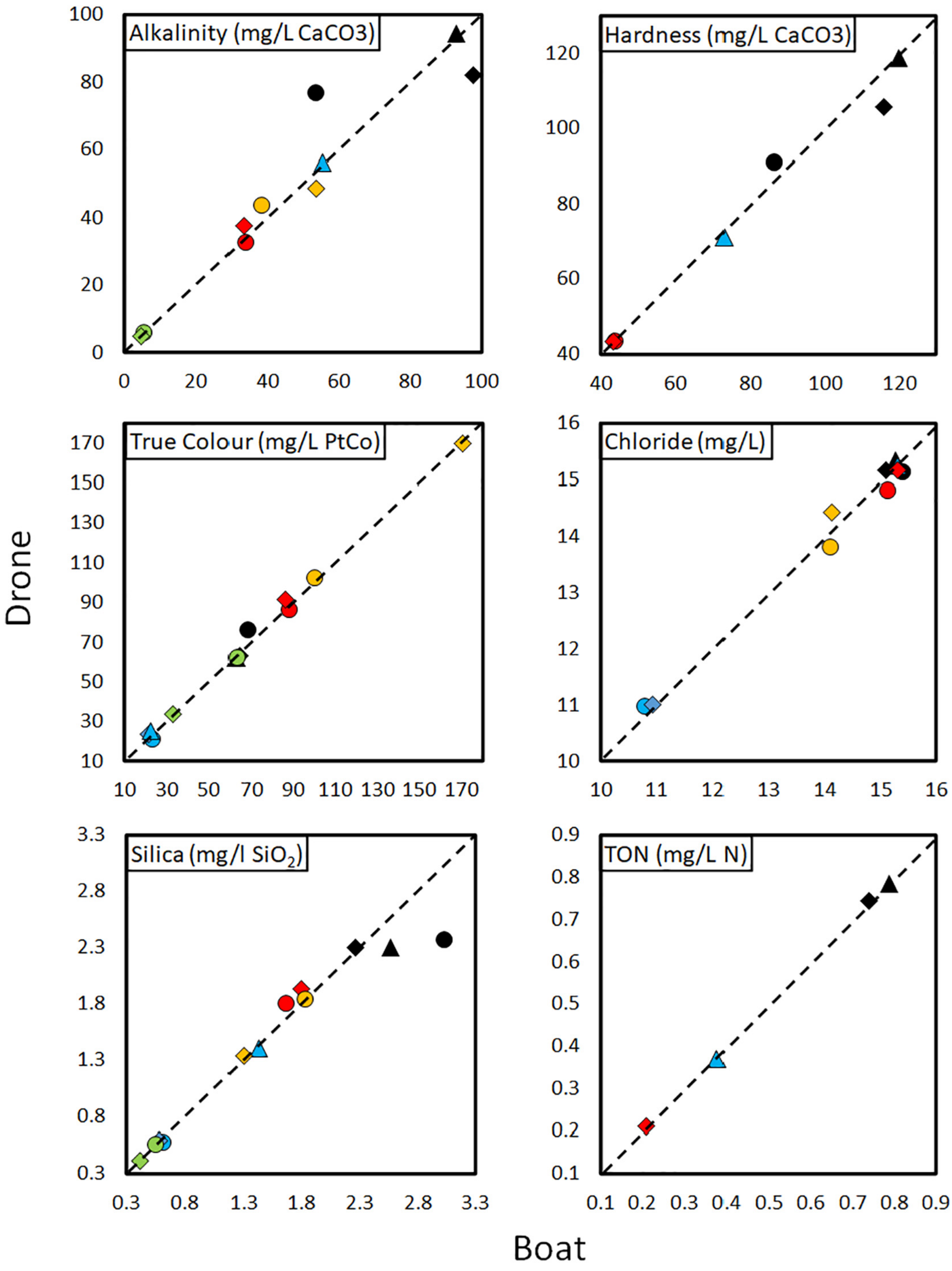

Fig. 1. Comparison of water chemistry variables collected using traditional boat (x-axis) and drone (y-axis) water sampling. Legend: ● Lough Inagh; ◆ Lough Fee; ● Lough Conn 1, ◆ Lough Conn 2; ● Ballyquirke lake 1: ◆ Ballyquirke lake 2; ● Lough Mask 1, ◆ Lough Mask 2, ▲ Lough Mask 3; ● Lough Derg 1, ◆ Lough Derg 2, and ▲ Lough Derg 3. The 1:1 line is shown for clarity.

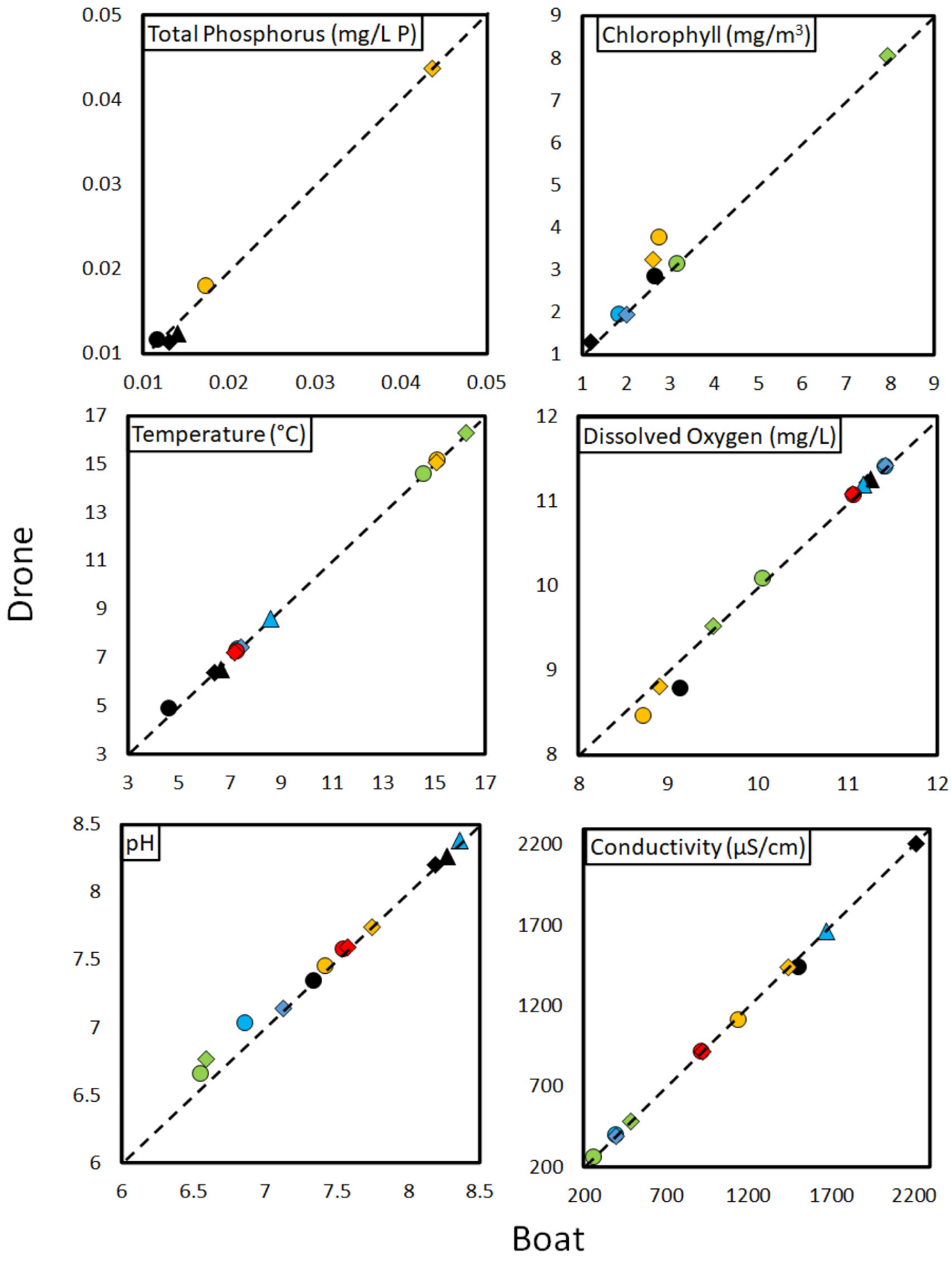

Fig. 1 (*continued*).

(UN Environment, 2019). The drone water sampling method used here is the first to collect a sufficiently large volume of water, 2 L, at a 100% success rate and most crucially, with water chemistry variables that are not significantly different to those taken using traditional boat water sampling.

While we recorded no significant differences in any of the water chemistry variables determined in the laboratory between samples collected via boat and drone, there was a significant statistical difference in pH recorded on the data logging EXO Sonde. However, average pH collected via the EXO Sonde deployed by the drone (average: 7.51) was just 0.04 higher than when the EXO Sonde was deployed from the boat (boat average: 7.47) which we suggest while statistically different, is hydrochemically and ecologically non-significant. While many researchers aim to develop the application of drone technology for the purpose of water sampling (e.g. Ore et al., 2015; Song et al., 2017; Castendyk et al., 2018; Koparan et al., 2019, 2020) there is currently a surprising lack of statistical comparison of water chemistry parameters between traditional boat and drone assisted water sampling in the published literature, seemingly due to limited sample size and replication (Lally et al., 2019). Koparan et al. (2018a) demonstrated no statistical difference between samples collected at the same location and depths by boat and drone water sampling methodologies for conductivity and temperature but they did detect statistically significant

Table 2
Results of paired t-test and Wilcoxon-signed rank tests used to assess precision, using coefficient of variation (CV%), between water chemistry variables at each sampling location between paired samples collected via traditional boat and drone water sampling methodologies. Significant differences highlighted in bold.

Variable	Test statistic	No. of pairs	*p* value	Average CV%	
				Boat	Drone
True colour[a]	−1.54	12	0.15	2.9	4.3
Hardness	2.87	6	**0.043**	7.3	3.9
Silica[a]	−0.89	12	0.4	7.6	8.7
TON[a]	−0.19	4	0.86	1.3	1.6
Chloride	−0.15	10	0.89	0.9	0.9
Alkalinity[b]	−0.77	10	0.44	6.6	9.4
Chlorophyll-a	−1.25	8	0.25	6.4	8.9
TP[b]	−0.41	5	0.69	6.9	5.9
pH[b]	−1.81	12	0.07	1.1	0.6
Temperature[b]	−1.73	12	0.08	0.6	0.4
Conductivity[a]	0.08	12	0.94	0.6	0.6
DO	0.2	12	0.84	0.5	0.5

TON = Total oxidised nitrogen, TP = Total phosphorous, DO = dissolved oxygen.

[a] Square root transformed.

[b] Wilcoxon signed rank test.

differences in dissolved oxygen, pH and chloride although the average differences in dissolved oxygen and temperature were minimal, at 3.6% and 0.03%, respectively. The difference in chloride was much more substantial, with the concentration of chloride 37.5% higher for water samples collected by drone (5.46 mg/L) compared to boat (3.97 mg/L). Similarly, Song et al. (2017) noted that while temperature and conductivity were similar between drone and boat collected samples, again they reported a significant difference in the concentration of chloride, with drone (3.17.2 mg/L) collected samples 75% higher than hand collected samples (182.2 mg/L).

While many other studies did not apply statistical tests to examine if the method of data and sample collection differed between drone and boat water sampling methodologies, relative comparisons have shown discrepancies for numerous parameters in particular for temperature. Ore et al. (2013, 2015) and Detweiler et al. (2015) recorded temperature which varied by ~1 °C using their UAV-assisted method relative to a probe deployed from a kayak. However, it is worth noting that to ensure water samples were taken for both methods at the same time, their aerial water sampling system was not UAV-assisted but held by an operator from the kayak and this may not therefore be a direct comparison between the two methodologies. Castendyk et al. (2020) also noted a considerable difference in temperature recorded between boat and drone water sampling methods, of up to 2.8 °C. Additionally, they recorded substantial percentage differences for a large number of water parameters between boat and drone collected samples of up to 11.3% for calcium, 14.6% for potassium, 16.7% for sodium, 12.6% for sulphate, 9% for chloride, 17.9% for manganese and 12.4% for zinc. While the results presented in the current study are considerably better, it must be highlighted that the Hydra Sleeve method developed by Castendyk et al. (2020) significantly advances the application of drone technology in water sampling as their method can collect water samples from various depths and up to a depth of 122 m.

For drone technology to be applied in a meaningful manner in large scale water monitoring projects and realise their potential to collect water samples in a safer and more efficient manner, it is critical that sufficient volumes of water can be collected by bespoke payloads deployed by drones and that these volumes of water can be reliably collected. Early studies in this field, that significantly advanced the application of drone technology in water sampling, had variable success rates in capturing the volume of water for which they were designed. Overall, success rates of water capture varied greatly among the water sampling payloads designed. Ore et al. (2013) had a 90% success rate (water filled to the neck of the vial) for indoor trials however this ranged from 69 to 83% once trials moved outdoors (Ore et al., 2013, 2015). Koparan and Koc (2016) and Koparan et al. (2018a) had a lower water capture success rate with initial outdoor trials successfully capturing water 60–66% of the time. As far as the authors are aware, the current study is the first to successful collect the desired sampling volume of water (2 L) via drone, with a 100% success rate in the field.

Previous studies demonstrating that water samples can be obtained from waterbodies are considerable and noteworthy in the development of the application of drones in hydrochemical monitoring. However, the volume of samples captured are relatively small, ranging from 60 mL for earlier studies (Ore et al., 2013, 2015; Detweiler et al., 2015; Chung et al., 2015; Song et al., 2017) to between 130 and 330 mL in later studies (Koparan and Koc, 2016; Koparan et al., 2018a, 2018b; Terada et al., 2018; Banerjee et al., 2018). Indeed, the significant difference in the chloride concentration in water samples collected by drone and boat by Song et al. (2017) was attributed to differences in the volume of water collected between the two sampling methods; three 20 mL vials were obtained from the drone-assisted method versus a 1 L Van Dorn manual sample. Therefore, the small volume of water collected using the drone-assisted sampling method, which is limited by payload weight, may have been less representative of the chloride levels in the mesocosm they sampled (Song et al., 2017).

More recent research by Castendyk et al. (2020 & 2019) has undoubtedly further advanced the application of drone technology in water chemistry sampling. Though capable of sampling at depth and retrieving 2 L, the reported success rate was 92% (Castendyk et al., 2019). The ability to collect 2 L of water, similar to the present student, is partially due to the utilisation of a large drone, DJI Matrice 600 hexarotor, the same drone as the present study, which facilitates the deployment of a larger payload (maximum payload capacity up to 6 kg) compared to the use of smaller drones used in earlier studies. However, it must be noted that the discrepancies in water chemistry parameters collected by their Hydra Sleeve method compared to samples collected via boat is concerning. While some of these discrepancies may be due to the added difficulty of retrieving water via drone from a variety of depths, the percentage relative difference between the two methodologies of samples collected at the surface was relatively high for a range of water chemistry variables, particularly temperature (Castendyk et al., 2020), and much higher than the present study. In comparison, the present study not only demonstrated no statistical difference between samples collected via drone and boat water sampling methodologies for either physiochemical data collected via the EXO Sonde nor in numerous water chemistry parameters determined in the laboratory, but also demonstrated that the level of precision between the two sampling methodologies were the same and is the first study to test the level of precision of drone water sampling.

Lally et al. (2019), in a review of the potential of drones to play an integral role in water quality monitoring, also highlighted that despite the anticipated labour and potential cost effectiveness of drone water sampling over traditional boat-based sampling, no such comparative cost benefit analyses had been attempted. Anecdotal evidence suggests that using drones is more time efficient compared to collecting water samples by boat. Several studies have estimated that the time required to collect a water sample via drone was approximately 20 min (Ore et al., 2013, 2015; Detweiler et al., 2015; Koparan and Koc, 2016; Koparan et al., 2018a). For example, Ore et al. (2015) recorded that their kayak based water sampling took between 10 and 15 h, considerably longer than the approximate 2 h when drone technology was used. Lally et al. (2020) recently analysed the cost benefit analyses of using drones versus traditional boat sampling, calculated using the same drone and bespoke water sampling payload that we utilised in this study. From their calculations, the capital costs of using this drone set up was approximately 2.7 times more expensive than when using boats but the time spent retrieving hydrochemical data and water samples, including all the time required to decontaminate all equipment for biosecurity purposes, was 2.3 to 3.4 times faster when using the drone. While such cost benefit analyses should always be interpreted cautiously, as capital costs can vary according to the type of boat, drone and payload utilised etc., it is worth noting the significantly shorter time required to collect samples via drone, considering that the largest expense for such activities in large scale water sampling programmes is likely the financial cost of personnel in the field.

5. Conclusions

In summary, this research demonstrates that drone technology can be utilised to safely and reliably collect highly precise, accurate water physiochemical data and large volume samples from aquatic ecosystems, fulfilling many of the requirements of large-scale water monitoring programmes. This study has successfully overcome many key technical limitations in the application of drone technology, namely the relatively small volume of water retrieved by drones for analyses, the low success rate at capturing the desired volume of water and of the highest importance, the clear inconsistencies in water chemistry results of previous studies between drone and traditional boat water sampling methodologies. Therefore, this study shows that drone technology can be used to collect water samples from lakes in a reliable, more rapid and cost effective manner than traditional methods such as using boats, that is safer for personnel and from a biosecurity risk point of view.

Further research is required to investigate if drone technology can be used in the collection of water samples for analyses of priority substances, usually collected in specialised glass vessels, and to test the ability and cost benefit analyses of the application of drone technology to collect large volume water samples in remote sites, inaccessible using traditional boat sampling.

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CRediT authorship contribution statement

Conor Graham: Conceptualisation, Methodology, Validation, Analyses, Investigation, Writing – Original Draft, Writing- Review & Editing, Visualisation. Ian O'Connor: Conceptualisation, Methodology, Validation, Investigation, Writing- Review & Editing. Liam Broderick: Methodology, Validation, Writing- Review & Editing. Mark Broderick: Methodology, Validation, Writing- Review & Editing. Olaf Jensen: Methodology, Validation, Writing- Review & Editing. Heather Lally: Conceptualisation, Methodology, Validation, Investigation, Writing- Review & Editing, Visualisation, Project Administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: We are currently completing an invention disclosure on the development of the technological know-how of the pod that was utilised in the collection of water samples by the drone.

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References

Bandini, F., Jakobsen, J., Olesen, D., Reyna-Gutierrez, J.A., Bauer-Gottwein, P., 2017. Measuring water level in rivers and lakes from lightweight unmanned aerial vehicles. J. Hydrol. 548, 237–250. https://doi.org/10.1016/j.jhydrol.2017.02.038.

Banerjee, B.P., Raval, S., Maslin, T.J., Timms, W., 2018. Development of a UAV-mounted system for remotely collecting mine water samples. Int. J. Min. Reclam. Environ., 1–12 https://doi.org/10.1080/17480930.2018.1549526.

Beloev, I.H., 2016. A review on current and emerging application possibilities for unmanned aerial vehicles. Acta Technol. Agric. 3, 70–76.

Benson, J., Hanlon, R., Seifried, T.M., Baloh, P., Powers, C.W., Grothe, H., Schmale III, D.G., 2019. Microorganisms collected from the surface of freshwater lakes using a drone water sampling system (DOWSE). Water 11 (157). https://doi.org/10.3390/w11010157.

Butcher, P.A., Colefax, A.P., Gorkin, R.A., Kajiura, S.M., López, N.A., Mourier, J., Purcell, C.R., Skomal, G.B., Tucker, J.P., Walsh, A.J., Williamson, J.E., Raoult, V., 2021. The drone revolution of shark science: a review. Drones 5 (1), 8.

Castendyk, D., Hill, B., Filiatreault, P., Straight, B., Alangari, A., Cote, P., Leishman, W., 2018. Experiences with autonomous sampling of pit lakes in North America using drone aircraft and drone boats. In: Wolkersdorfer, C., Sartz, L., Weber, A., Burgess, J., Tremblay, G. (Eds.), Mine Water – Risk to Opportunity. Tshwane University of Technology, Pretoria, South Africa, pp. 1036–1042.

Castendyk, D.N., Straight, B.J., Voorhis, J.C., Somogyi, M.K., Jepson, W.E., Kucera, B.L., 2019. Using aerial drones to select sample depths in pit lakes. Mine Closure 1113–1126.

Castendyk, D., Voorhis, J., Kucera, B., 2020. A validated method for pit lake water sampling using aerial drones and sampling devices. Mine Water Environ. 159. https://doi.org/10.1007/s10230-020-00673-y.

Chabot, D., Bird, D.M., 2016. Wildlife research and management methods in the 21st century: where do unmanned aircraft fit in? J. Unmanned Veh. Syst. 3 (4), 137–155. https://doi.org/10.1139/juvs-2015-0021.

Christiansen, F., Vivier, F., Charlton, C., Ward, R., Amerson, A., Bejder, L., 2018. Maternal body size and condition determine calf growth rates in southern right whales. Mar. Ecol. Prog. Ser. 592, 267–281.

Chung, M., Detweiler, C., Hamilton, M., Higgins, J., Ore, J.-P., Thompson, S., 2015. Obtaining the thermal structure of lakes from the air. Water 7, 6467–6482. https://doi.org/10.3390/w7116467.

Detweiler, C., Ore, J.-P., Anthony, D., Elbaum, S., Burgin, A., Lorenz, A., 2015. Bringing unmanned aerial systems closer to the environment. Environ. Pract. 17, 188–200. https://doi.org/10.1017/S1466046615000174.

Doi, H., Akamatsu, Y., Watanabe, Y., Goto, M., Inui, R., Katano, I., Nagano, M., Takahara, T., Minamoto, T., 2017. Water sampling for environmental DNA surveys by using an unmanned aerial vehicle. Limnol. Oceanogr. Methods 15, 939–944.

EC (European Commission) Environment, 2016. Introduction to the new EU Water Framework Directive. Available at:. http://ec.europa.eu/environment/water/waterframework/info/intro_en.htm.

EC (European Commission) Environment, 2017. Our oceans, seas and coasts. http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm.

Geoghegan, J.L., Pirotta, V., Harvey, E., Smith, A., Buchmann, J.P., Ostrowski, M., Eden, J.-S., Harcourt, R., Holmes, E.C., 2018. Virological sampling of inaccessible wildlife with drones. Viruses 10, 300.

Greenwood, F., Nelson, E.L., Greenough, P.G., 2020. Flying into the hurricane: a case study of UAV use in damage assessment during the 2017 hurricanes in Texas and Florida. PLoS ONE 15 (2), e0227808. https://doi.org/10.1371/journal.pone.0227808.

Hogan, S.D., Kelly, M., Stark, B., Chen, Y., 2017. Unmanned aerial systems for agriculture and natural resources. Calif. Agric. 71 (1), 5–14.

Kelly, F.L., Connor, L., Delanty, K., Coyne, J., Morrissey, E., Corcoran, W., Cierpial, D., Matson, R., Gordon, P., O'Briain, R., Rocks, K., Walsh, L., O'Reilly, S., O'Callaghan, R., Cooney, R., Timbs, D., McLoone, P., 2016. Fish Stock Survey of Lough Mask, June 2015. National Research Survey Programme, Inland Fisheries Ireland, 3044 Lake Drive, Citywest Business Campus, Dublin 24.

Kelly, F.L., Connor, L., Morrissey, E., McLoone, P., Kelly, K., Delanty, K., Coyne, J., Corcoran, W., Cierpial, D., Matson, R., Gordon, P., O'Briain, R., Rocks, K., O'Reilly, S., Puttharee, D., McWeeney, D., Robson, S., Buckley, S., 2017. Fish Stock Survey of Lough Derg, June 2016. National Research Survey Programme, Inland Fisheries Ireland, 3044 Lake Drive, Citywest Business Campus, Dublin 24.

Kelly, F.L., Connor, L., Delanty, K., McLoone, P., Coyne, J., Morrissey, E., Corcoran, W., Cierpial, D., Matson, R., Gordon, P., O'Briain, R., Rocks, K., O'Reilly, S., Kelly, K., Puttharee, D., McWeeney, D., Robson, S., Buckley, S., 2017. Fish Stock Survey of Lough Conn, August 2016. National Research Survey Programme, Inland Fisheries Ireland, 3044 Lake Drive, Citywest Business Campus, Dublin 24.

Koparan, C., Koc, A.B., 2016. Unmanned aerial vehicle (UAV) assisted water sampling. 2016 American Society of Agricultural and Biological Engineers (ASABE), Annual International Meeting, Orlando, Florida https://doi.org/10.13031/AIM.20162461157.

Koparan, C., Koc, A.B., Privette, C.V., Sawyer, C.B., Sharp, J.L., 2018a. Evaluation of a UAV-assisted autonomous water sampling. Water 10 (5), 655. https://doi.org/10.3390/w10050655.

Koparan, C., Koc, A.B., Privette, C.V., Sawyer, C.B., 2018b. In situ water quality measurements using an unmanned aerial vehicle (UAV) system. Water 10 (3), 264. https://doi.org/10.3390/w10030264.

Koparan, C., Koc, A.B., Privette, C.V., Sawyer, C.B., 2019. Autonomous in situ measurements of noncontaminant water quality indicators and sample collection with a UAV. Water 11 (3), 604. https://doi.org/10.3390/w11030604.

Koparan, C., Koc, A.B., Privette, C.V., Sawyer, C.B., 2020. Adaptive water sampling device for aerial robots. Drones 4 (1), 5.

Lally, H.T., O'Connor, I.O., Jensen, O.P., Graham, C.T., 2019. Can drones be used to conduct water sampling in aquatic environments? A review. Sci. Total Environ. 670, 569–575.

Lally, H.T., O'Connor, I.O., Broderick, L., Broderick, M., Jensen, O., Graham, C.T., 2020. Assessing the potential of drones to take water samples and physiochemical data from open lakes. EPA Research Report. EPA Research Programme 2014-2020 40 pp.

Librán-Embid, F., Klaus, F., Tscharntke, T., Grass, I., 2020. Unmanned aerial vehicles for biodiversity-friendly agricultural landscapes-a systematic review. Sci. Total Environ. 732, 139204.

Manfreda, S., McCabe, M.F., Miller, P.E., Lucas, R., Madrigal, V.P., Mallinis, G., Dor, E.B., Helman, D., Estes, L., Ciraolo, G., Müllerová, J., Tauro, F., de Lima, M.I., de Lima, J.L.M.P., Maltese, A., Frances, F., Caylor, K., Kohv, M., Perks, M., Ruiz-Pérez, G., Su, Z., Vico, G., Oth, B., 2018. On the use of unmanned aerial systems for environmental monitoring. Remote Sens. 10 (641), 1–28. https://doi.org/10.3390/rs10040641.

McLoone, P., Connor, L., Coyne, J., Morrissey, E., Corcoran, W., Cierpial, D., Delanty, K., Matson, R., Gordon, P., O'Briain, R., Rocks, K., O'Reilly, S., Puttharee, D., McWeeney, D., Robson, S., Buckley, S., Kelly, F.L., 2017. Fish Stock Survey of Ballyquirke Lough, September 2016. National Research Survey Programme, Coarse Fish and Pike, Inland Fisheries Ireland, 3044 Lake Drive, Citywest Business Campus, Dublin 24.

Niethammer, U., James, M.R., Rothmund, S., Travelletti, J., Joswig, M., 2012. UAV-based remote sensing of the super sauze landslide: evaluation and results. Eng. Geol. 128, 2–11. https://doi.org/10.1016/j.enggeo.2011.03.012.

Ore, J.-P., Elbaum, S., Burgin, A., Zhao, B., Detweiler, C., 2013. Autonomous aerial water sampling. Proceedings of the 9th International Conference in Field and Service Robots (FSR), Brisbane, Australia. 5, pp. 137–151.

Ore, J.P., Elbaum, S., Burgin, A., Detweiler, C., 2015. Autonomous aerial water sampling. J. Field Robot. 32 (8), 1095–1113.

Pajares, G., 2015. Overview and current status of remote sensing applications based on unmanned aerial vehicles (UAVs). Photogramm. Eng. Remote. Sens. 81, 281–329. https://doi.org/10.14358/PERS.81.4.281.

Rhee, D.S., Kim, Y.D., Kang, B., Kim, D., 2018. Applications of unmanned aerial vehicles in fluvial remote sensing: an overview of recent achievements. KSCE J. Civ. Eng. 22 (2), 588–602. https://doi.org/10.1007/s12205-017-1862-5.

Samseemoung, G., Soni, P., Jayasuriya, H.P.W., Salokhe, V.M., 2012. An application of low altitude remote sensing (LARS) platform for monitoring crop growth and weed infestation in a soybean plantation. Precis. Agric. 13, 611–627.

Schofield, G., Esteban, N., Katselidis, K.A., Hays, G.C., 2019. Drones for research on sea turtles and other marine vertebrates—a review. Biol. Conserv. 238, 108214.

Song, K., Brewer, A., Ahmadian, S., Shankar, A., Detweiler, C., Burgin, A., 2017. Using unmanned aerial vehicles to sample aqautic ecosystems. Limnol. Oceanogr. Methods 15, 1021–1030. https://doi.org/10.1002/lom3.10222.

Stone, H., D'Ayala, D., Wilkinson, S., 2017. The use of emerging technology in post-disaster reconnaissance missions. EEFIT Report. Institution of Structural Engineers, London, UK.

Teh, S.K., Mejias, L., Corke, P., Hu, W., 2008. Experiments in integrating autonomous uninhabited aerial vehicles (UAVs) and wireless sensor networks. Proceedings 2008 Australasian Conference on Robotics and Automation (ACRA 08), Canberra.

Terada, A., Morita, Y., Hashimoto, T., Mori, T., Ohba, T., Yaguchi, M., Kanda, W., 2018. Water sampling using a drone at Yugama crater lake, Kusatsu-Shirane volcano, Japan. Earth Planets Space 70 (64), 1–9. https://doi.org/10.1186/s40623-018-0835-3.

Tierney, D., Free, G., Kennedy, B., Little, R., Plant, C., Trodd, W., Wynne, C., 2015. Lakes. Water Quality in Ireland 2010-2012. Environmental Protection Agency, P.O. Box 3000, Johnstown Castle Estate, County Wexford, Ireland, Y35 W821.

Toro, F.G., Tsourdos, A., 2018. UAV Sensors for Environmental Monitoring. Printed Edition of the Special Issue Published in Sensors. 978-3-03842-754-4.

Tyler, S., Jensen, O., Hogan, Z., Chandra, S., Galland, L.M., Simmons, J., the 2017 Taimen Research Team, 2018. Perspectives on the application of unmanned aircraft for freshwater fisheries census. Fisheries https://doi.org/10.1002/fsh.10167.

UN (United Nations) Environment, 2019. Monitoring water quality. Available at: https://www.unenvironment.org/explore-topics/water/what-we-do/monitoring-waterquality.

US (United States) Environmental Protection Agency (EPA), 2018. National aquatic resource surveys. Available at: https://www.epa.gov/national-aquatic-resource-surveys.

Van der Wal, T., Abma, B., Viguria, A., Previnaire, E., Zarco-Tejada, P.J., Serruys, P., van Valkengoed, E., van der Voet, P., 2013. Fieldcopter: unmanned aerial systems for crop monitoring services. Precis. Agric. 13, 169–175.

Vergouw, B., Nagel, H., Bondt, G., Custers, B., 2016. Drone technology: types, payloads, applications, frequency spectrum issues and future developments. The Future of Drone Use. Information Technology and Law Series. 27.

Watts, A.C., Ambrosia, V.G., Hinkley, E.A., 2012. Unmanned aircraft systems in remote sensing and scientific research: classification and considerations of use. Remote Sens. 4, 1671–1692. https://doi.org/10.3390/rs4061671.

Wich, S.A., Koh, L.P., 2018. Conservation Drones: Mapping and Monitoring Biodiversity. Oxford University Press, New York.

Zhang, C., Kovacs, J.M., 2012. The application of small unmanned aerial systems for precision agriculture: a review. Precis. Agric. 13, 693. https://doi.org/10.1007/s11119-012-9274-5.