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Assessing the Potential of Drones to Take Water Samples and Physico-chemical Data from Open Lakes

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2014–2020

Assessing the Potential of Drones to Take Water Samples and Physico-chemical Data from Open Lakes

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EPA Research Report

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DISCLAIMER

This report is based on research carried out/data from March 2018 to February 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Water sampling remains a pivotal method for monitoring and understanding the condition of aquatic environments properly and effectively. Large-scale ecological water sampling and monitoring programmes require considerable field personnel and are hence resource intensive and time consuming and therefore expensive, while also posing many health and safety issues for personnel, as well as biosecurity risks.

Therefore, this research project had four major objectives:

1. to assess the applicability of drones for open lake water sampling;
2. to evaluate whether water samples and physico-chemical data collected using drones satisfy the European Union (EU) Water Framework Directive (WFD) requirements for monitoring lakes in Ireland;
3. to determine whether drones could be deployed to increase the accuracy of extrapolated trophic status for unmonitored lakes;
4. to examine whether drones could offer a quicker, cost-effective, less labour intensive and safer lake sampling protocol for use as part of the Environmental Protection Agency WFD Lake Monitoring Programme.

The application of drones to collect *in situ* hydrochemical data and retrieve water samples from freshwater environments provides the potential to fulfil some aspects of the biological and physico-chemical sampling required for large-scale water sampling programmes in a more efficient, safer and cost-effective manner.

Key Findings

The project team was the first research team in Europe to collect a 2-L water sample using a drone. This research has made several significant contributions to the advancement and application of drone water sampling methods. These include the successful deployment, as demonstrated during field trials, of a drone and attached prototype payload capable of collecting a 2-L water sample and real-time physico-chemical data, 100 m offshore, from lakes in the west of Ireland. Water sampling times using the drone were 4 minutes and water volume capture rates were 100%. Furthermore, the water chemistry of samples collected using the drone water sampling method was not significantly different from that of samples taken using a boat. In addition, accuracy and precision were not affected by the sampling methodology employed. This comparative analysis of water chemistry variables satisfies the requirements of the EU WFD lake water sampling and monitoring programme and thus demonstrates that drone sampling can be applied to large-scale water sampling programmes. The capital investment costs for boat sampling were found to be 1.2 to 1.5 times lower than those required for drone water sampling. However, and much more importantly, drone water sampling was found to be 2.3 to 3.4 times faster (in person-minutes) than boat sampling methods, depending on resource allocation. Moreover, drone water sampling reduced both risks to personnel health and safety and biosecurity risks associated with boat sampling. Moreover, drone water sampling offers a unique opportunity to sample unmonitored lakes under the WFD in Ireland, and remote and inaccessible lakes worldwide, and to confirm the water quality and ecological status of aquatic environments categorised using remote-sensing methods in a more efficient and safer manner.

Recommendations

This research has resulted in the following recommendations to further the advancement of drone water sampling over the coming years:

- Consideration should be given to deploying waterproof drones such as the Freefly Alta 8 or Alta X (https://freeflysystems.com). These drones would allow flights to operate in less than optimal weather conditions, including in wind speeds greater than 8 m/s and moderate rainfall.
- Smaller, lighter and cheaper real-time water chemistry probes should be integrated to reduce the weight of the payload and the associated capital costs required during project set-up. This

would, in turn, avoid the need for larger, more expensive drones and allow users to operate within evolving legislative and pilot training requirements.

- The design and build of the prototype payload, especially its size (height and length) and weight, should be refined to allow a greater number of off-the-shelf drones to be considered for use. The use of additive fabrication techniques, which would allow the printing of new or replacement parts when needed or damaged, should also be considered.
- Field trials should continue and should include a wider variety of aquatic environments including estuaries at high and low tides, marinas and streams and rivers at various flows, to demonstrate application across various aquatic environments.

1 Introduction

1.1 Background

The introduction of the European Union (EU) Water Framework Directive (WFD) (2000/60/EC) in 2000, and its subsequent adaptation into Irish law in 2003, saw a Europe-wide approach to surface water and groundwater conservation and management. The key aim of the WFD is to ensure the good ecological status of all European waters. For inclusion in the Environmental Protection Agency (EPA) WFD Lake Monitoring Programme, lakes must have a surface area greater than 50 ha, be an active source of drinking water or be protected under other EU legislation such as the Habitats or Birds Directive (Tierney *et al.*, 2015; O'Boyle *et al.*, 2019). To date, 812 Irish lakes are classified as WFD water bodies, of which a subset of 215 representative lakes were monitored during 2013–2018 (O'Boyle *et al.*, 2019). For the remaining (approximately) 597 unmonitored lakes, many of which are remote or have limited access, efforts have been made to extrapolate ecological status using land use and hydrogeomorphology data from monitored lakes (Wynne and Donohue, 2016) and using macrophyte remote-sensing data captured from Sentinel-2 data (Free *et al.*, 2020).

Ecological sampling and monitoring on such a large scale requires considerable field personnel and is hence resource intensive, time consuming and therefore expensive, while also posing health and safety issues for personnel and biosecurity risks. Currently, monitoring is undertaken by personnel from a number of agencies including the EPA, the Marine Institute, Inland Fisheries Ireland, Waterways Ireland, the National Parks and Wildlife Service and local authorities (O'Boyle *et al.*, 2019). The WFD places emphasis on the ecology and biology of lakes, with physico-chemical and hydromorphological components acting as "supporting elements" for the biota (Free *et al.*, 2007; Hering *et al.*, 2010; O'Boyle *et al.*, 2019). The biological status of lakes is determined using several biotic indices for phytoplankton, macroalgae, aquatic plants, macroinvertebrates and fish (O'Boyle *et al.*, 2019). Physico-chemical elements that affect the biological status of lakes include temperature, dissolved oxygen (DO), pH, conductivity and Secchi depth measured in the field (Free *et al.*, 2006). Additional variables, such as alkalinity, colour, total phosphorus (TP) and total ammonia, are measured in the laboratory following the retrieval of a water sample from the lake (EPA, 2006, 2011; Free *et al.*, 2006). Hydromorphological elements, which also affect the biological status of lakes, include morphological conditions (i.e. physical changes of the shoreline or alterations to the natural hydrological regime) and the water flow of the lake (EPA, 2006, 2011; O'Boyle *et al.*, 2019). The WFD ecological status of each lake is assigned by applying the "one out all out" principle whereby the lowest status achieved for any one biological, physico-chemical or hydromorphological element is the final status assigned to that water body (EPA, 2007; Tierney *et al.*, 2015; O'Boyle *et al.*, 2019).

The sampling of open lake waters requires the use of a boat and this, in turn, can lead to issues related to accessibility, particularly at remote lakes, where there may be a lack of slipway. In 2010, 15 lakes included in the EPA WFD Lake Monitoring Programme were replaced because of such issues related to accessibility (Tierney *et al.*, 2015). Sampling using boats can be very costly if different boat sizes are required for monitoring different lakes and can also lead to issues concerning personnel health and safety and biosecurity.

Streamlining the biological and physico-chemical sampling methods to meet the requirements of the EPA WFD Lake Monitoring Programme could be achieved using emerging and novel technologies. Autonomous systems such as unmanned aerial vehicles (UAVs), small unmanned aircraft (SUA), unmanned aerial systems (UASs), unmanned vehicle systems (UVSs) or remotely piloted aircraft systems (RPASs), all commonly referred to or known as drones (Chapman, 2014; Chabot, 2018), offer a unique opportunity to employ novel, versatile, adaptable and flexible technologies capable of gathering high-resolution data for monitoring and assessing the natural environment (Wich and Koh, 2018; Fráter *et al.*, 2015). The application of drones to collect *in situ* hydrochemical data and retrieve water samples from freshwater environments is relatively new. The increased capabilities of drone platforms (payload weight capacity, flight time, battery endurance, etc.) and the development of bespoke attached payloads offers a new and unique opportunity to potentially deploy drones in large-scale water sampling programmes (Vergouw *et al.*, 2016). The application of drones provides the potential to fulfil some aspects of the biological and physico-chemical sampling required for large-scale water sampling programmes in a more efficient, safer and cost-effective manner.

1.2 Objectives

This research project had four major objectives:

1. to assess the applicability of drones for open lake water sampling;
2. to evaluate whether water samples and physico-chemical data collected using drones satisfy the EU WFD requirements for monitoring lakes in Ireland;
3. to determine whether drones could be deployed to increase the accuracy of extrapolated trophic status for unmonitored lakes;
4. to examine whether drones could offer a quicker, less labour-intensive, cost-effective and safer lake sampling protocol for use as part of the EPA WFD Lake Monitoring Programme.

1.3 Project Work Packages

To achieve the research objectives, five core work packages were designed (Figure 1.1) in addition to communications and project management work packages.

1.4 Project Dissemination

The project team used a wide variety of approaches to disseminate the outcomes of this project.

These included:

- one international peer-reviewed journal article;
- attendance and presentations at European and national conferences and workshops in the field of drone research and water quality sampling and monitoring [e.g. the Commercial UAV Show 2018, UK (14 and 15 November 2018); the ShARE 5 – Shared Agencies Regulatory Evidence Programme – meeting, Ireland (12 March 2018) and Wales (28 January 2019); the UK and Ireland Lakes Network Conference, Ireland (16 and 17 October 2019); and the Irish Freshwater Biologist Association meeting, Ireland (6 March 2020)];
- the establishment of a project website and Twitter account (@DroPLEtS18, with over 179 followers);
- the organisation and facilitation of a project workshop attended by 21 delegates.

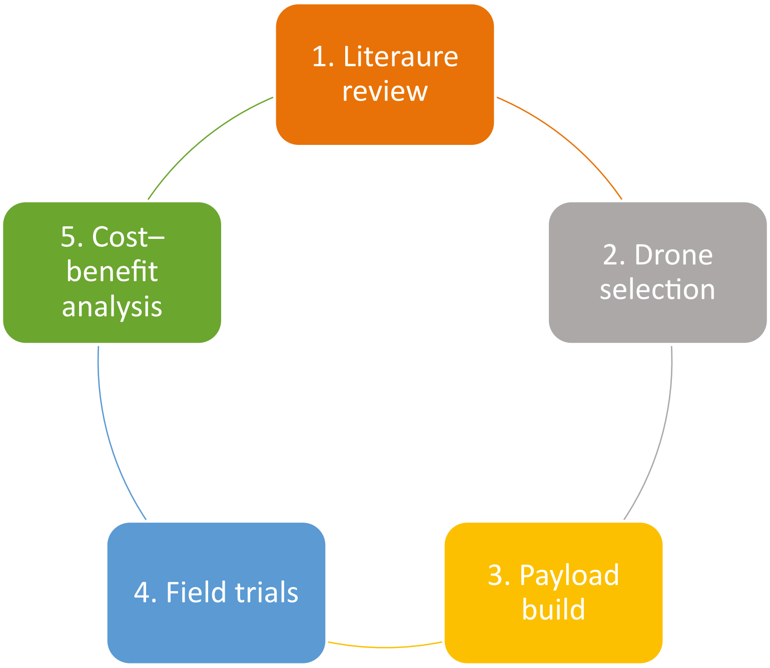

Figure 1.1. Core research project work packages.

2 Current Use of Drones to Conduct Water Sampling in Aquatic Environments

2.1 Aims of the Literature Review

The aims of the literature review were to:

- evaluate the use of drones to collect water samples and *in situ* physico-chemical data from freshwater environments, synthesising and reviewing the current literature on this topic; and
- identify knowledge gaps and technological developments needed to advance the use of drones to conduct water sampling in aquatic environments in the coming decade.

2.2 Current Use of Drones to Conduct Water Sampling in Freshwater Environments

2.2.1 *Research teams deploying/modifying drones to conduct water sampling*

The literature review highlighted several research teams, predominantly in the USA, Japan and Australia, working on deploying/modifying drones to take water samples (Table 2.1).

2.2.2 *Specifications of drone platforms used to conduct water sampling*

Specifications of drone platforms used to conduct water sampling varied among the various research groups. Over the past decade, a combination of off-the-shelf drones (e.g. Ascending Technologies Firefly hexarotor, six rotor LAB645 UAV and DJI Matrice 600) (Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015; Song *et al.*, 2017; Castendyk *et al.*, 2018, 2019, 2020; Terada *et al.*, 2018) and custom-built platforms (Koparan and Koc, 2016; Koparan *et al.*, 2018a,b, 2019) have been deployed (Table 2.2). Drone platforms have a maximum payload weight of between 600 g and 12 kg and a maximum flight time of 20–40 minutes depending on the amount of water to be collected. Some research groups apply autonomous operating systems and/or pilot-operated systems.

2.2.3 *Specifications of payloads used to conduct water sampling*

All water sampling payloads are custom-built with various types of water sampling systems having been trialled, including (1) complex chassis systems with three spring-lidded chambers operated by a servo-rotated “needle” where water fills a glass sampling container via a micro submersible water pump (Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015), (2) triple cartridge “thief style” water sampling systems (Koparan *et al.*, 2018a, 2019, 2020), (3) Niskin water sampling bottles (Castendyk *et al.*, 2018), (4) high-density polyethylene (HDPE) bottles consisting of a hollow tube structure that allows water to freely enter when lowered into the water (Terada *et al.*, 2018), and (5) HydraSleeve (Castendyk *et al.*, 2020) (Table 2.3).

Trials have demonstrated the ability of the water sampling payloads listed above to collect between

Table 2.1. List of research groups deploying/modifying drones to take water samples

Name of research lab	Location	Publications
NIMBUS research lab	Nebraska-Lincoln, USA	Scientific publication(s)
Chung research lab	UC Berkeley, USA	Scientific publication(s)
Koparan research lab	Clemson University, South Carolina, USA	Scientific publication(s)
Terada research group	Japan	Scientific publication(s)
HATCH Associates Consultants	Denver, Colorado, USA	Scientific publication(s), conference publication
Rise Above Custom Drone Solutions	Australia	Website information
Spheres Drones	Australia	Website information, leaflet

UC, University of California.

Table 2.2. Specifications of drone platforms used to conduct water sampling

Platform type	Maximum payload weight	Flight time	Communication software	Source
Off-the-shelf hexarotor – Ascending Technologies Firefly	600 g[a]	Total flight time = 15–20 minutes per battery with full payload[a]	• Robot operating system – low-level communication with the UAV, risk management, mission control, navigation and altitude estimates • Onboard custom microcontroller – operates aerial sampling system, reads sensors and status of water sampling system	Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015; Song *et al.*, 2017
Off-the-shelf six-rotor LAB645	12 kg[a]	Maximum flight time = 40 minutes[a]	• Operator controlled during take-off and landing • Autonomous flight via GPS waypoints	Terada *et al.*, 2018
Off-the-shelf DJI Matrice 600 Pro	6 kg[a]	Maximum flight time = 16 minutes[a]	• Operator controlled during take-off, flight mission and landing • Spotter ensuring “safe flight area”	Castendyk *et al.*, 2018, 2019, 2020
Custom-built hexacopter with flotation attachments	750 g[b]	Theoretical flight time = 8 minutes[c]	• Radio controller (Turnigy 9X) – manual control of hexacopter • Autonomous flight and ground control station – Pixhawk autopilot (GPS receiver, radio telemetry) – provides information on flight conditions • Mission planner software	Koparan and Koc, 2016 Koparan *et al.*, 2018a,b
Custom-built hexacopter with flotation attachments	2.1 kg[b]	Theoretical flight time = 8 minutes[c]	• Radio controller (Turnigy 9X) – manual control of hexacopter • Autonomous flight and ground control station – Pixhawk autopilot (GPS receiver, radio telemetry) – provides information on flight conditions • Mission planner software	Koparan *et al.*, 2019

[a] Manufacturers’ specification.

[b] Weight of components used to develop the custom-built payload.

[c] Flight time based on 80% battery life.

GPS, global positioning system.

60 mL (Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015) and 2 L of water (Castendyk *et al.*, 2019) with water sampling times ranging from 40 minutes (Song *et al.*, 2017) to 2 hours (Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015) and successful water capture rates varying between 60% (Ore *et al.*, 2013, 2015; Koparan and Koc, 2016; Koparan *et al.*, 2018a) and 100% (Koparan *et al.*, 2019). Issues with the complex chassis systems with three spring-lidded chambers were predominantly associated with faulty lid mechanisms, variations in the altitude of the pump, the pump not priming correctly, silt intake in the pump and environmental conditions such as increases in wind speed above 2.7 m/s, which significantly reduced sample capture success, with a linear decline with increasing wind speed resulting in a 25% decrease in sample capture at speeds in excess of 4.5 m/s (Ore *et al.*, 2013, 2015). Issues associated with the messenger on the “thief style” water sampler included the sampler not triggering or the servo-motor malfunctioning (Koparan and Koc, 2016; Koparan *et al.*, 2018a).

Research teams have also incorporated off-the-shelf multi-meter probes (temperature, DO, conductivity and pH) (Song *et al.*, 2017; Koparan *et al.*, 2018b, 2019), conductivity, temperature and depth (CTD) probes (Castendyk *et al.*, 2018, 2019, 2020) and turbidity (Koparan *et al.*, 2020) with the ability to autonomously relay real-time data back to nearby ground stations (Song *et al.*, 2017), greatly increasing the capacity of drones to monitor *in situ* water chemistry variables.

2.2.4 Comparison of water chemistry variables

Comparison of water chemical variables obtained using drone water sampling with those of more traditional methods (e.g. handheld probes and manual grab samples from land or boat) shows clear

Table 2.3. Specifications of water sampling payloads attached to drones to conduct water sampling

Sampling location	Water sampling payload	Physico-chemical sensors attached to drone	Quantity of water collected	Water sampling times using drone	Physico-chemical variables monitored	Source
Holmes Lake (Nebraska, USA)	Custom-built chassis – spring-lidded chambers operated by a servo-rotted "needle" with tube and micro pump	None	60 mL	Total time = 2 hours Estimate 20 minutes using the drone alone	Temperature, DO, sulphate and chloride	Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015
Mesocosms, University of Kansas Biological Field Station (Kansas, USA)	As above	Temperature (GP103J4F NTC Thermistor) and conductivity (Atlas Scientific) sensors	As above	Total time = 40 minutes 10 minutes per reading per mesocosm	Temperature, conductivity and chloride	Song *et al.*, 2017
Yugama crater lake (Japan)	Custom-built metal-free HDPE sampling bottle	None	250–330 mL	Not given	Conductivity, pH, chemical concentration (chloride, sulphate, aluminium, calcium, iron, potassium, magnesium, manganese, sodium, silicon dioxide) and stable isotope ratios (δD and $\delta^{18}O$)	Terada *et al.*, 2018
Lamaster Pond, Clemson University (South Carolina, USA)	Custom-built triple-cartridge "thief style" water sampler	pH, conductivity, temperature and DO (Atlas Scientific) sensors	130 mL	Total time = 1 hour Estimate 20 minutes using the drone	DO, temperature, pH, conductivity and chloride	Koparan and Koc, 2016; Koparan *et al.*, 2018a,b, 2019
Lake Issaqueena (South Carolina, USA)	Custom-built triple-cartridge "thief style" water sampler	Turbidity sensor (DFRobot)	130 mL	Total time = 1 hour Estimate 20 minutes using the drone	DO, temperature, pH, conductivity and chloride	Koparan *et al.*, 2020
Pit lakes (Ontario, Canada, and Nevada, USA)	Niskin water bottle (General Oceanographics, Florida, USA)	Conductivity, temperature and depth (CTD) (YSI CastAway) probe	1.2 L	Flight time of drone is less than 15 minutes	None	Castendyk *et al.*, 2018
Pit lakes (Montana and Idaho, USA)	As above	As above	2 L	As above	pH, calcium, magnesium, sodium, chloride, sulphate, total dissolved solids, total organic carbon, total sulphide, potassium	Castendyk *et al.*, 2019
Pit lakes (Nevada, Montana and Idaho, USA)	HydraSleeve (GeoInsight)	As above	1.75 L	As above	Temperature, specific conductance, bicarbonate alkalinity, chloride, sulphate, calcium, potassium, sodium, cadmium, manganese and zinc	Castendyk *et al.*, 2020

inaccuracies (Table 2.4). These can be attributed to variations in water sampling payloads used, the manner in which drones were deployed to collect water samples and physico-chemical data, and limited experimental design.

Ore *et al.* (2013, 2015) and Detweiler *et al.* (2015) reported similar trends for physico-chemical variables collected using drone and manual water sampling methods. However, DO levels were higher and temperature levels lower in waters collected using

Table 2.4. Comparison of water sampling methods and experimental design employed within freshwater environments

Sources	No. of sampling sites	Replication	Methods compared	Total sample size	Statistical comparison
Ore *et al.*, 2013, 2015; Detweiler *et al.*, 2015	5	3	Manual grab sample and use of handheld probes from kayak vs drone-assisted water sampling from kayak	30	None
Song *et al.*, 2017	9	3	Manual grab sample and use of handheld probes vs HOBO *in situ* sensors vs drone-assisted water sampling	81	None
Koparan *et al.*, 2018a	3	3	Manual grab samples and use of handheld probes from kayak vs drone-assisted water sampling	18	Paired *t*-tests
Castendyk *et al.*, 2020	1	3	Manual van Dorn samples and use of handheld multi-parameter probes from boat vs drone-assisted water sampling	6	RPD

RPD, relative percentage difference.

the drone water sampling method. Differences were attributed to interference or contamination of carryover by the pump and transit through the tubing, agitation during flight and in some instances changes in water properties between water collection and analyses (Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015). In comparison, sulphate and, in particular, chloride levels were lower in samples collected using the drone water sampling method than in simultaneously collected manual grab water samples. Differences were pronounced; values were deemed to be due to sampling variation (Detweiler *et al.*, 2015; Ore *et al.*, 2013, 2015).

Comparative statistical studies by Koparan *et al.* (2018a) found drone water samples to be significantly higher for DO, pH and chloride. However, the percentage difference between water chemistry variables was deemed small, highlighting minimal error between the sampling methods. Song *et al.* (2017) also reported significant differences in the levels of chloride between drone and manual grab water samples, which were attributed to interferences within the water column from using a boat and differences in the volume of water collected. The small volume of water collected (20 mL) using the drone sampling method may have been less representative of the chloride levels.

Finally, Castendyk *et al.* (2020) found *ex situ* handheld multi-parameter probe readings were 2.8 degrees higher for temperature than *in situ* drone water samples using CTD, although this temperature increase was attributed to natural warming during water retrieval, presumably due to the differences in air and water temperatures and the lack of insulation on the sampling device. In addition, they reported contract-required detection limits (CRDLs) exceeding five and relative percentage differences (RPDs) of less than 20% for a wide suite of water chemistry variables (Table 2.3) with the exception of cadmium and manganese. However, all samples were deemed to be within the range of the CRDL and therefore drone sampling methods were considered equivalent to those collected using traditional boat sampling under US EPA guidelines (US EPA, 1994).

Overall, limited sample size and replication and poor water capture rates may have prevented robust statistical comparison between water sampling methodologies in many of the reviewed studies (Tables 2.3 and 2.4).

2.3 Knowledge Gaps and Technological Advances Required to Deploy Drones for Water Sampling

2.3.1 *Current knowledge gaps to deploying drones for water sampling*

The studies reviewed highlight the potential use of drones to conduct water sampling and obtain physico-chemical data from freshwater environments. However, several key limitations were highlighted, which need to be addressed before the application of drone technology can be applied to large-scale aquatic sampling programmes worldwide.

Consideration should be given to the following:

- type and payload capacity of off-the-shelf drones, as many new large drones (less than 25 kg) have a payload carrying capacity of at least 10 kg (see Chapter 3, Table 3.1) and could be modified to allow larger volumes of water (minimum 1–2 L) to be collected;
- ability of the drone to successfully complete flights in less than optimal weather conditions if larger volumes of water are to be obtained;
- improving sampling success rates, if larger volumes of water are to be captured every time;
- obtaining samples beyond visual line of sight (BVLOS) (greater than 300 m) (EASA, 2015, 2018; ICAO, 2011; JARUS, 2013) especially on large open water bodies (greater than 2 ha or 20,000 m^2);
- increased costs, set-up times and legal requirements of deploying larger drones and associated payloads, and BVLOS.

2.3.2 Recommended technological advancements required to deploy drones for water sampling

Technological advancements in water sampling payload design are required if accurate and reliable statistical comparisons of water chemistry variables are to be determined.

Consideration should be given to the following:

- incorporating *in situ*, real-time data of physico-chemical parameters (temperature, DO, conductivity and pH) for meaningful comparisons of data obtained using drone and handheld sampling methods;
- deploying the same probes (from the same manufacturer) when comparing drone and handheld water chemistry data for clearer, transparent and consistent comparisons that are not potentially confounded by differences in performance due to different types of probe models;
- allowing sampling probes time to take readings (suggested minimum time of 4 minutes) when in the water, with sampling times dependent on both the probe used and physico-chemical conditions of the water body being sampled; for example, the minimum time is usually determined by the pH of the water body, with lakes with low pH and low buffering capacity generally requiring longer times than calcium-rich lakes;
- adapting robust statistical experimental designs to examine the data collected between sampling methodologies as well as the variability;
- incorporating a greater number and diversity of types of water bodies, an increased number of sampling sites per water body and greater replication of samples per sampling site per water body;
- testing a wider selection of water chemistry parameters (nutrients, suspended solids and heavy metals) and comparisons across various water sampling methodologies (manual grab samples and handheld probes vs drone water sampling vs *in situ* sensors);
- conducting a detailed cost–benefit analysis.

This literature review, entitled “Can drones be used to conduct water sampling in aquatic environments? A review”, by Lally, O’Connor, Jensen and Graham is published in *Science of the Total Environment*, 670 (2019), 569–575 (reused with permission from Elsevier).

3 Drone Platform Selection

3.1 Criteria for Drone Platform Selection

The research team developed a set of criteria specific to the needs of the proposed project in addition to setting out the specifications of the drone platform required.

The criteria and specifications included:

- the requirement for a drone with a stabilised three-axis zoom camera, foldable rotor arms and propellers;
- a drone platform able to lift a minimum slung payload of 6 kg;
- the ability to fly for a minimum of 10 minutes and a distance of 200 m carrying a 6-kg payload weight;
- the capacity to fly in wind speeds up to 8 m/s;
- the capability to provide “loss of a single motor” redundancy;
- having global positioning systems (GPS) and global navigation satellite system capabilities with redundancy between them;
- having a retractable undercarriage that does not interfere with the payload;
- having a first person view integrated zoom camera of at least 12 megapixels;
- being suitable for dual operators where the camera movements and control can be controlled by the second operator with two compatible pilot/ camera high-definition monitors supplied for live view with an HDMI (high-definition multimedia interface) output;
- the capability for the primary controller to provide additional channels for integration with the payload;
- having a controller system that allows for software development kit integration;
- having radios that operate on primary EU industrial, scientific and medical (ISM) band 2.4 GHz transmission with optional 5.8 GHz backup transmission;
- a platform that gives real-time telemetry information for the duration of the flight;
- a platform and all its accessories that are CE approved.

3.2 Drone Platforms

Eight off-the-shelf drone platforms were investigated based on the criteria set out in section 3.1 above (Table 3.1). A DJI Matrice 600 Pro platform [Shenzhen Dà-Jiāng Innovations (DJI) Sciences and Technologies Ltd, Shenzhen, Guangdong, China], hereafter referred to as the DJI M600 Pro drone, best matched the criteria set out by the project team and was therefore selected for use in field trials (Figure 3.1). The DJI M600 Pro drone was registered with the Irish Aviation Authority (IAA) through its ASSET drone registry programme operated by CGH Technologies Incorporated. Within the Marine and Freshwater Research Centre (MFRC) at the Galway-Mayo Institute of Technology (GMIT), the project team updated the MFRC Drone Operations Manual and risk assessments to include the DJI M600 Pro drone. In addition, the platform was added to the GMIT’s insurance policy.

3.3 Costs of Drone Platform

The unit cost of the DJI M600 Pro drone was €11,370.27 including the costs of purchasing the drone platform and accessory equipment necessary to modify the undercarriage and allow for communications with the water sampling payload (Table 3.2).

Table 3.1. Commercially available off-the-shelf drones suitable for adapting for water sampling

Name of UAV	Manufacturer	Size (diagonal) (mm)	UAV weight (kg)	Maximum payload weight (kg)	Flight speed (m/s)	Flight duration (minutes)	Wind speed (m/s)	Waterproof	EU regulatory legislation[f]
Matrice 600 Pro	DJI[a]	1133	10	6	17	16	8	Splashproof	Open category – A3 Register UAV operator with IAA Conduct theory and flight exams Hold third-party insurance
Alta 8	Freefly[b]	1325	6.2	9	–	17–20	–	Weather resistant	
Agras MG-1P and MG-1S	DJI[a]	1500 and 1515	10[d]	10–14[e]	7	20–22	8	Sprayproof	
Alta X	Freefly[b]	1415	10.4	15.9	–	10	–	–	Specific category – SOP required Register UAV operator with IAA Include risk assessment
Skymatrix X-FI	Prodrone[c]	1534	13.2	20[e]	16	13–25	8	Water- and all weather-proof	
Agras T16	DJI[a]	1833	18.5[d]	16	10	10	8	Sprayproof	
PD6B – Type II	Prodrone[c]	1348	11.5	30	16	10–30	10	–	

[a] Data on DJI UAV models were taken from the DJI official website (www.dji.com).

[b] Data on Freefly models were taken from the Freefly website (www.freeflysystems.com).

[c] Data on Prodrone models were taken from the Prodrone website (www.prodrone.com).

[d] Weight excludes batteries.

[e] Payload is a spray tank.

[f] EU regulatory legislation pertains to the new EU Implementing Regulation [Commission Implementing Regulation (EU) 2019/947] and Delegated Regulation [Commission Delegated Regulation (EU) 2019/945], which took effect on 1 July 2020. See www.iaa.ie/general-aviation/drones for more information.

SOP, special operating permission.

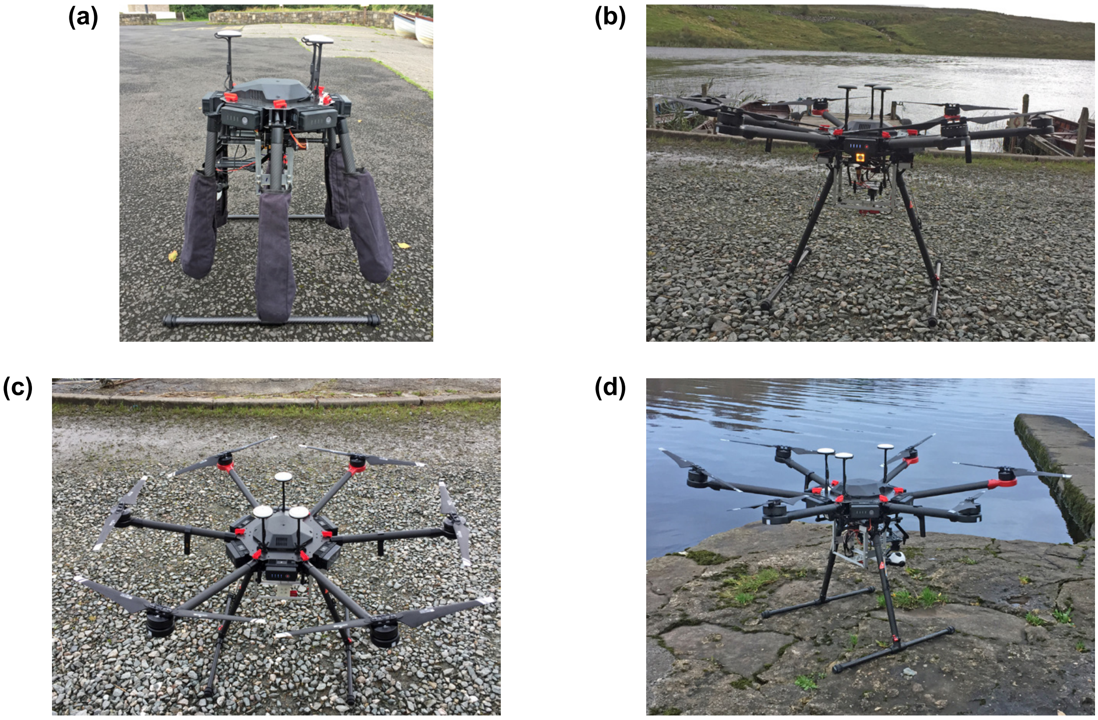

Figure 3.1. DJI M600 Pro drone platform selected for field trials: (a) arms and propellers folded, (b) arms and propellers extended, (c) top view of arms and propellers extended, and (d) drone on-site before payload attachment (photo credits: Heather Lally).

Table 3.2. Costs associated with purchasing the DJI M600 Pro drone, drone platform and accessory equipment

Description	Unit price excluding VAT (€)
Drone platform	
DJI M600 Pro drone	5522.70
DJI CrystalSky monitor 7.85 ultra brightness	1137.75
DJI CrystalSky bracket	90.00
DJI M600 propellers (one CW set/one CCW set)	61.50
Total	**6811.95**
Batteries	
DJI M600 flight pack (four sets of six TB47S batteries)	1102.08
DJI M600 Hex charger UK version including UK plug	332.10
DJI M600 battery case	584.25
Total	**2018.43**
Undercarriage accessories	
DJI Z3 camera	956.94
DJI M600 camera mounting plate for Z3 camera	209.10
Hooking system	130.00
DJI power hub	20.00
Total	**1316.04**
Communication accessories	
DJI M600 remote controller	774.90
DJI M600 channel expansion module (eight channels)	448.95
Total	**1223.85**
Total unit cost of DJI M600 Pro	**11,370.27**

CCW, counter-clockwise; CW, clockwise; VAT, value added tax.

4 Payload Design and Development

4.1 Criteria for Payload Operation

The research team developed criteria for the operation of the payload specific to the needs of the proposed project.

The criteria included the following:

- It must be able to retrieve 2 L of lake water from approximately 10 cm beneath the surface.
- It must be easily decontaminated to prevent the potential spread of invasive species.
- The design must include the ability to flush the system after each sample/site/lake to ensure no contamination of subsequent samples, including chemicals associated with biosecurity.
- The water sample must not be contaminated by any materials (e.g. metal components) used to develop the payload.
- It must be possible to collect and log “time stamped” chemical measurements using a data logger when the payload is in the water.
- The final payload weight should be suitable for transportation using the DJI M600 Pro drone.
- Payload operation from water entry to exit must be automated and triggered from the drone console.
- The payload should be waterproof and completely buoyant.

The payload design and build are proprietary and not described herein.

4.2 Key Features of the Payload Build and Design

Key features of the payload build and design include the following:

- The water sampling bottles used are 1 L, HDPE, opaque and wide mouthed.
- Real-time physico-chemical data are transmitted via a YSI EXO Go and EXO Sonde with EXO pH, DO, temperature and conductivity probes. The EXO Go communicates with the Sonde using Bluetooth and when paired with a Windows operating system device with KorEXO software the data can be live streamed in real time to the user on the shore.
- The prototype payload weight is 6 kg outbound and 8 kg inbound.
- The water sample weighs 2 kg.
- Samples are taken more than 100 m from the lake shore.
- The flight time from take-off to return is 6 minutes, including a water sampling time of around 4 minutes.
- The altitude for the flight is maintained at less than 15 m in all cases.
- The collection of a 2-L water sample and *in situ* real-time chemical analysis are performed with 100% reliability.
- A remotely operated camera and “live link” verify payload operations.
- Operational testing on site verifies that safe “one person” take-off and landing remote from the shoreline can be deployed in difficult locations if required.
- An emergency release has been incorporated and tested and can be deployed should the payload become fouled or entangled or drone performance deteriorate.

5 Field Trials Deploying the Drone Platform and Payload on Open Lakes

5.1 Lake Sampling Sites and Experimental Design

Field trials took place between September and November 2019 at six lakes (Loughs Fee, Inagh, Conn, Derg and Mask and Ballyquirke Lough) in the west of Ireland. The lakes chosen represent two of the main lake types found in Ireland (high and low alkalinity) and a range of trophic gradients. Loughs Fee and Inagh are currently not monitored under the EPA WFD Lake Monitoring Programme, while Loughs Conn, Mask and Derg and Ballyquirke Lough are included in the monitoring programme. Key lake characteristics are presented in Table 5.1.

One location was sampled on Loughs Fee and Inagh, two locations on Lough Conn and Ballyquirke Lough, and three locations on Loughs Mask and Derg. At each location, three paired water samples (traditional boat water sampling and drone water sampling) were collected ($n = 36$ paired water samples in total). Data and samples were collected at each location to examine the variability associated with each sampling method. On completion of sampling, water samples were delivered to the EPA laboratories in Castlebar for analysis of pH, alkalinity (mg/L $CaCO_3$), hardness (mg/L $CaCO_3$), true colour (mg/L PtCo), chloride (mg/L), silica (mg/L SiO_2), ammonia (mg/L N), total oxidised nitrogen (TON) (mg/L N), nitrite (mg/L N), nitrate (mg/L N), ortho-phosphate (mg/L P), TP (mg/L P) and chlorophyll-a (Chl-a) (mg/m^3).

Real-time physico-chemical data (pH, DO, conductivity and temperature) were captured using the EXO Sonde, which was deployed before sampling (traditional boat and drone water sampling) and recorded variables every second. On return to the lake shore, data were downloaded to a laptop. The project team used data produced from the final 90 seconds of the period in which the EXO Sonde was deployed in the lake water to ensure that the probe had sufficient time to adjust from recording data while in flight.

5.2 Comparison of Water Chemistry Variables Collected Using Traditional Boat and Drone Water Sampling

Both sampling methodologies (traditional boat and drone water sampling) collected 2 L of water on 100% of sampling occasions in addition to real-time physico-chemical data for pH, DO, conductivity and temperature.

For each water chemistry variable, each location was included only if all three paired water samples for each method exceeded the limits of detection. Paired sample *t*-tests, for data meeting the assumptions of parametric tests, indicated that there were no significant differences for alkalinity [$t = -0.416$, degrees of freedom (df) = 9, $p = 0.69$, mean difference = −1.27), hardness ($t = 0.85$, df = 5, $p = 0.43$, mean difference = 1.67], true colour ($t = -0.872$, df = 11, $p = 0.41$, mean difference = −0.78), silica ($t = 0.89$, df = 11, $p = 0.39$, mean difference = 0.06), TON ($t = 0.775$, df = 3, $p = 0.5$, mean difference = 0.002), TP ($t = 1.19$, df = 4, $p = 0.3$, mean difference = 0.0005), Chl-a ($t = -1.99$, df = 7, $p = 0.09$, mean difference = −0.25) or conductivity ($t = 1.89$, df = 11, $p = 0.09$, mean difference = 12.2) between traditional boat and drone water sampling methodologies (Figure 5.1). The Wilcoxon-signed rank test was used for data that were non-normally distributed and/or had heterogeneous variability. This indicated that there were no significant differences in the median concentrations of chloride ($Z = 0.614$, df = 9, $p = 0.54$, mean difference = 0.04), DO ($Z = -0.63$, df = 11, $p = 0.53$, mean difference = 0.056) or temperature ($Z = -0.94$, df = 11, $p = 0.35$, mean difference = −0.017) between traditional boat and drone water sampling methodologies (Figure 5.1). The only variable to show a significant difference between traditional boat and drone water sampling methodologies was pH ($t = -2.46$, df = 11, $p = 0.031$, mean difference = −0.048), although this is not deemed hydrochemically or biologically important.

Table 5.1. Key characteristics of lakes sampled during field trials

Lake	No. of sampling locations	Co-ordinates for sampling locations	Surface area (ha)	Included in the EPA WFD Lake Monitoring Programme	WFD alkalinity status[a]	WFD typology class[a]	WFD status[b]
Lough Fee	1	53.59122 −9.8381	174	×	–	–	–
Lough Inagh	1	53.5162 −9.73816	310	×	–	–	–
Lough Conn	2	53.9898 −9.25791 53.09365 −9.29682	4704	✓	High	12	Moderate
Ballyquirke Lough	2	53.32469 −9.15257 53.32603 −9.1543	73.6	✓	Moderate	6	Bad
Lough Derg	3	52.90733 −8.50461 52.92032 −8.45241 52.91859 −8.45476	13,000	✓	High	12	Moderate
Lough Mask	3	53.56779 −9.41073 53.56526 −9.41522 53.64387 −9.36527	8218	✓	High	12	Good

[a] **Data taken from Inland Fisheries Ireland National Research Survey Programme Fish Stock Assessments 2015 and 2016 (Kelly *et al.*, 2016, 2017a,b; McLoone *et al.*, 2017).**

[b] **Data taken from the EPA Maps portal (EPA, 2019).**

5.3 Comparison of Variability and Precision in Water Chemistry Variables Collected Using Traditional Boat and Drone Water Sampling Methodologies

A statistical assessment of variability, by calculating the coefficient of variation for each of the three repeated measurements at each sampling location for each variable and each sampling methodology, indicated that there was 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 by boat. Moreover, the precision of the data for each variable was also statistically analysed separately for both water sampling methodologies and only one significant difference, for hardness ($Z = 2.87$, $p = 0.043$, average boat = 7.3%, average drone = 3.9%) (Table 5.2), was found. Levels of hardness were found to be higher in water samples taken using the traditional boat method but are deemed within the range of detection.

Overall, natural variability and high precision in water chemistry variable data were evident from water samples taken using both the traditional boat and drone water sampling methodologies. Thus, water samples taken using the drone consistently matched those of samples taken using traditional methods.

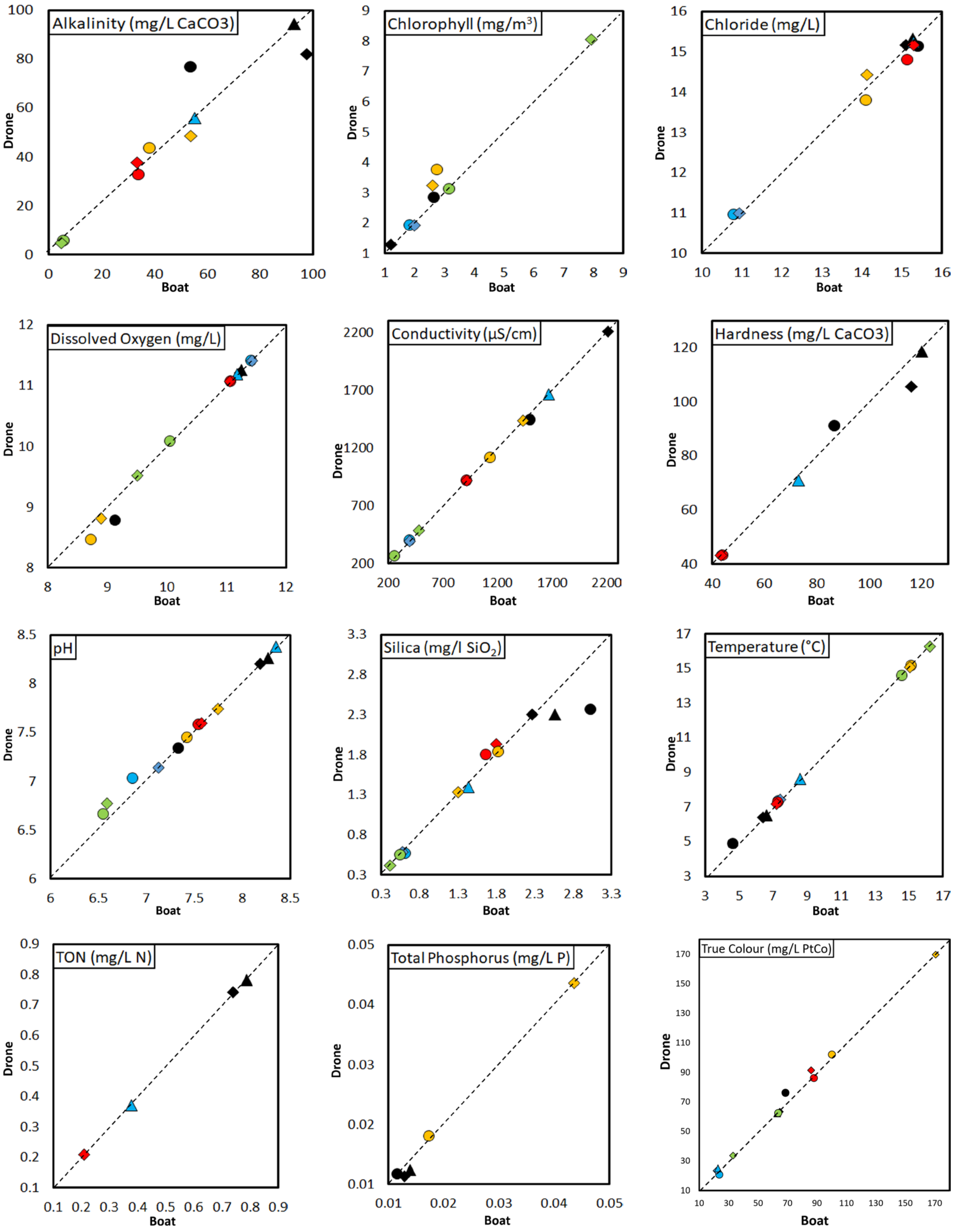

Figure 5.1. Statistical comparison of water chemistry variable data collected using traditional boat (*x*-axis) and drone (*y*-axis) water sampling. Legend: ● Lough Inagh, ◆ Lough Fee, ● Lough Conn 1, ◇ Lough Conn 2, ● Ballyquirke Lough 1, ◆ Ballyquirke Lough 2, ● Lough Mask 1, ◆ Lough Mask 2, ▲ Lough Mask 3, ● Lough Derg 1, ◆ Lough Derg 2 and ▲ Lough Derg 3.

Table 5.2. Statistical assessment of precision, using coefficient of variation, between water chemistry variable data at each sampling location between traditional boat and drone water sampling methodologies

				Average CV (%)	
Variable	Test statistic	No. of pairs	*p*-value	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
Chl-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

[a]**Square root transformed.**

[b]**Wilcoxon-signed rank test.**

CV, coefficient of variation.

Table 5.3. List of limitations encountered during the current study when using the drone and water sampling payload to collect water samples from Irish lakes

Limitations	DJI M600 Pro drone with attached water sampling prototype payload
Weather	Limited by wind speeds greater than 8 m/s
	Limited by moderate to high rainfall levels
	Limited number of suitable flying days in Ireland
Drone platform	Operational carrying capacity of DJI M600 Pro drone is exceeded
Payload	Payload[a] weight should be less than 6 kg
	Payload weight increases operational risk of the drone (ability to lift payload)
	Payload can swing below the drone in moderate to high winds making steady flight difficult
	Payload weight affects flight times and this, in turn, can limit the distance between consecutive sampling locations
	Payload weight limits battery endurance where one set of six batteries is utilised per flight
Personnel	Must have experienced drone pilots licensed with the IAA

[a]**Including weight of water sample.**

5.4 Limitations Encountered during Field Trials

Following completion of the field trials, several limitations regarding the use of the DJI M600 Pro drone and attached water sampling prototype payload were noted and require further consideration (Table 5.3). A key concern is the operational capacity of the DJI M600 Pro drone to carry an 8-kg payload. This is beyond the specifications indicated by DJI for the drone platform (see Chapter 3, Table 3.1). Options open to the team are to either reduce the weight of the prototype payload or employ a larger drone, although this would have knock-on cost implications.

6 Cost–Benefit Analysis

A cost–benefit analysis of the project focused on time, costs, resources, health and safety, and biosecurity risks.

6.1 Efficiency of Traditional Boat versus Drone Water Sampling Methods

At Ballyquirke Lough, on 29 November 2019, the timings of all activities related to traditional boat and drone water sampling methods were recorded (Table 6.1). All timings were calculated as person-minutes, e.g. it took two people a total of 26 minutes 49 seconds to wash the boat after sampling (for biosecurity reasons), which equates to 53 minutes 38 seconds in person-minutes. Using traditional boat water sampling, it took 99 person-minutes to take three replicate samples, while it took 45 person-minutes to complete the same task using drone water sampling. The time taken to clean and disinfect the boat was 54 person-minutes, while for the prototype payload cleaning and disinfecting took 29 person-minutes. Overall, where two persons are involved in undertaking traditional boat and drone water sampling, the drone is 2.3 times more efficient at capturing water samples (Figure 6.1a); with three persons (e.g. two on board the boat and one shore support person) involved in undertaking traditional boat water sampling, a two-person drone team is 3 times more efficient (Figure 6.1b). In the future, it is envisaged that drone water sampling could be conducted by only one person, making drone water sampling methods 3.4 times more efficient than a two-person team conducting traditional boat water sampling (Figure 6.1c).

6.2 Costs of Traditional Boat versus Drone Water Sampling Methods

The capital costs associated with the boat water sampling implemented by the project team were

Table 6.1. Timings of activities related to traditional boat versus drone water sampling at Ballyquirke Lough

Traditional boat water sampling	Estimated time	Drone water sampling	Estimated time
Activities related to sampling			
Boat set-up	00:20:41	Drone set-up	00:00:54
Initial set-up of PC and YSI Sonde and probes	00:06:17	Initial set-up of PC and YSI Sonde and probes	00:06:17
Bottle labelling	00:03:13	Bottle labelling	00:03:13
		Table set-up[c]	00:01:10
Boat sampling (from leaving shore to return and completion of data download)	00:10:00	Drone sampling (from leaving shore to return and completed data download)	00:11:04
Boat disassembly	00:09:10		
Total sampling time	00:49:21	Total sampling time	00:22:38
Person-minutes per sampling location[a,b]	01:38:42	Person-minutes per sampling location[a,b]	00:45:16
Biosecurity measures			
Boat cleaning including disinfecting PPE, mooring, ropes, oars, etc.	00:26:49	Drone and payload cleaning including disinfecting payload	00:11:03
Person-minutes to disinfect equipment[b]	00:53:38	Person-minutes to disinfect equipment[b]	00:22:06
Total person-minutes per boat sampling location[a,b]	02:32:20	Total person-minutes per drone sampling location[a,b]	01:07:22

[a] Sampling location refers to a lake site where three replicate samples were collected using either traditional boat or drone water sampling methods.

[b] Two persons were involved in sampling.

[c] Foldable table utilised by the drone team for changing batteries and YSI Sonde and probes on the prototype payload.

PPE, personal protective equipment.

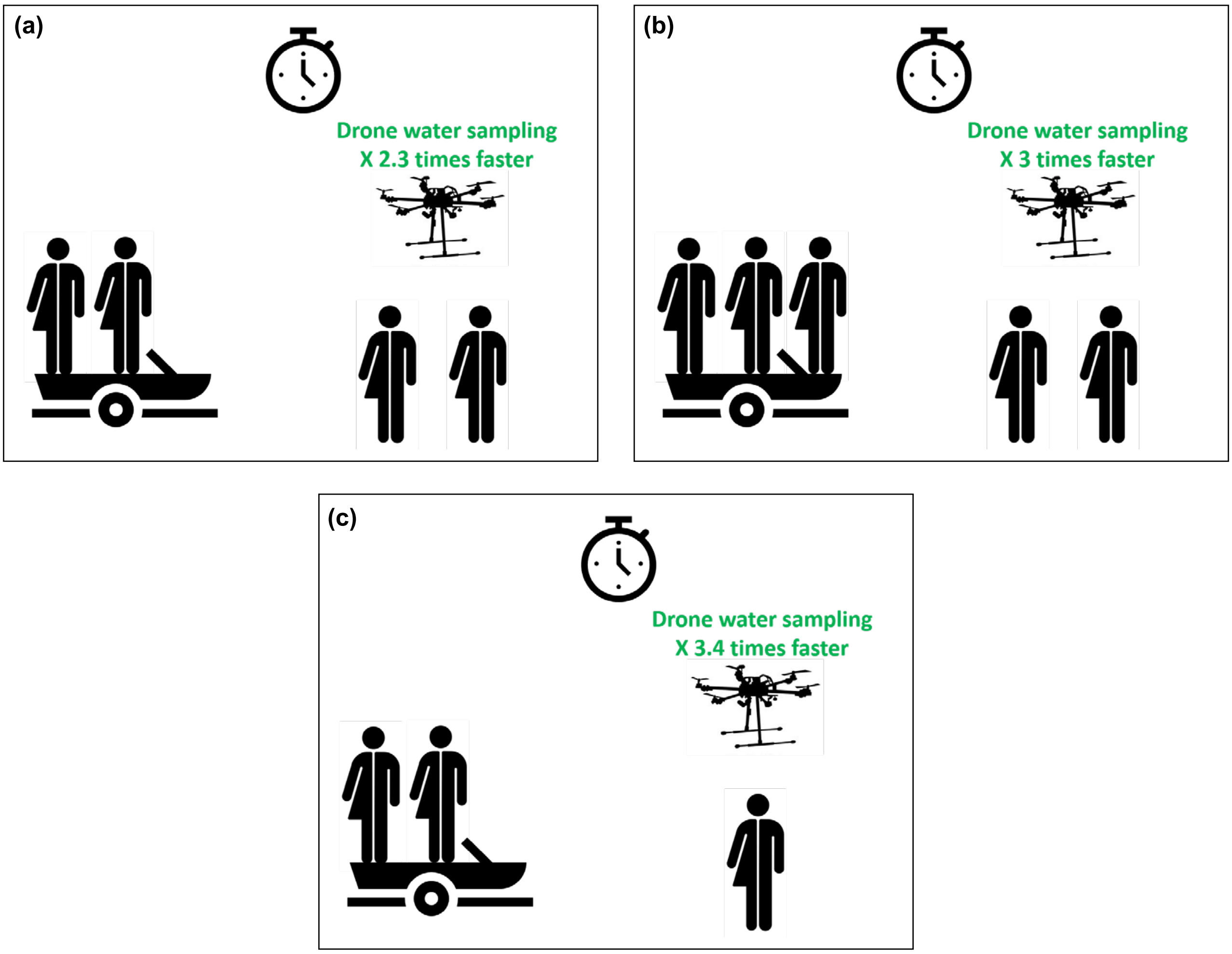

Figure 6.1. Efficiency of traditional boat versus drone water sampling under different resource scenarios.

compared with those of using the drone and prototype payload designed and developed during the project. Capital costs associated with boat water sampling employed during field trials were those of an inflatable Zodiac Classic Mark II (including the costs of oars and pump) and YSI Sonde and probes, which totalled €21,286.06 (Table 6.2). It is important to note that our capital cost comparison was made using the Zodiac Classic Mark II as a demonstrative comparison and therefore institutes and companies that utilise different types of boats should bear this in mind when evaluating the relative capital costs of a drone system versus a boat for water sampling. Similarly, the number of samples that can be collected in the lifetime of a boat varies considerably depending on the make, model, frequency of use and maintenance history. The capital investment costs associated with the drone water sampling employed during field trials were those of the DJI M600 Pro, batteries, undercarriage and communication accessories, payload build and YSI Sonde and probes, totalling €26,052.79.

The project team estimate that the DJI M600 Pro is capable of conducting 500 water sampling missions before renewal and so estimates for both the Zodiac inflatable boat and the DJI M600 Pro were based on 500 water sampling missions. Therefore, boat water sampling costs €42.57 per sample compared with €52.11 per sample for the drone water sampling method developed by the project team, making boat water sampling 1.2 times cheaper per sample based on capital investment costs.

However, traditional boat water sampling would typically employ the use of handheld probes such as a YSI Handheld Proplus with three probes and data-logging capabilities. This reduces the total capital costs associated with boat sampling further, to €9544.25, or €19.09 per sample, making traditional boat sampling 2.7 times cheaper per sample based on capital investment costs.

The capital costs associated with the DJI M600 Pro and prototype payload build are relatively high but

Table 6.2. Capital costs associated with boat and drone water sampling during this research project

	Estimated capital costs of boat water sampling during project field trials (€)	Traditional boat sampling (€)	Estimated capital costs of drone water sampling during project field trials (€)	Drone water sampling with *in situ* handheld physico-chemical data collection (€)	Drone water sampling with no *in situ* physico-chemical data collection (€)
Inflatable Zodiac (including oars, pump and engine)	6500	6500	–	–	–
DJI M600 Pro platform	–	–	6811.95	6811.95	6811.95
Batteries	–	–	1102.08	1102.08	1102.08
Undercarriage and communication accessories	–	–	2539.89	2539.89	2539.89
Prototype payload build	–	–	812.82	812.82	812.82
YSI Sonde and probes	14,786.06	–	14,786.06	–	–
YSI Handheld Proplus	–	3044.25	–	3044.25	–
Cost per 500 samples	21,286.06	9544.25	26,052.79	14,310.98	11,266.73
Cost per sample	42.57	19.09	52.11	28.62	22.53

expected for such new and innovative technology. The YSI Sonde and probe system is particularly costly and, while allowing the transmission of real-time data back to the ground station, may not be necessary for every sampling mission. Therefore, the project team proposes some alternatives at the current time. First, the YSI Sonde and probes could be removed. Second, pH, DO, conductivity and temperature could be measured *in situ* using a YSI handheld device (YSI Handheld Proplus) when water samples are returned to the shore following drone sampling. This would result in a cost of €28.62 per sample. However, this is not ideal for measuring parameters such as temperature and DO concentrations, although it is unlikely that temperature and DO concentrations would alter significantly or in an ecologically meaningful way in the time between collection and shore measurement. Alternatively, the team considered not conducting *in situ* physico-chemical measurements at all, which would reduce costs to €22.53 per sample (Table 6.2); however, this is undesirable for sampling conducted under many monitoring programmes such as the WFD monitoring programme. Therefore, the project team suggests replacing the YSI Sonde with a cheaper model to significantly reduce the capital outlay of the prototype payload. However, such an alternative model would have to undergo experimental trials to ensure that deployment via a drone would not significantly affect the data collected. Traditional boat water sampling remains 1.2 to 1.5 times cheaper than drone water sampling at the current time, although the project team expect the capital costs associated with the prototype payload to reduce if commercialised, as payload manufacturing costs are streamlined, reducing costs to be in line with those of traditional boat sampling.

Overall, the capital costs currently associated with traditional boat sampling are lower than those of drone water sampling. However, drone water sampling is far more efficient than the current traditional boat water sampling method. Therefore, there is a balance to be struck between the capital costs involved in setting up a new water sampling methodology and the longer term benefits of drone water sampling in reducing the much more significant labour costs, increasing the efficiency of sampling, reducing the use of resources, and decreasing health and safety and biosecurity risks.

6.3 Advantages and Disadvantages of Traditional Boat and Drone Water Sampling Methodologies

Following the completion of field trials and the cost–benefit analysis, the project team compiled a list of advantages and disadvantages requiring consideration when choosing either the traditional boat or drone water sampling methods (Table 6.3).

Key advantages of the drone water sampling method are (1) the efficiency of water sampling; (2) the ability to access water bodies in remote and inaccessible locations where boat access is unavailable; (3) the ease of transporting the equipment; (4) lower biosecurity risks and cleaning requirements;

Table 6.3. Advantages and disadvantages of traditional boat and drone water sampling methodologies [AQ1]

	Traditional boat water sampling	Drone water sampling
Advantages		
Efficient sampling method	✗	✓
Access to water bodies	Limited to sites with slipways	Safer access to remote and inaccessible sites
Transportation	Large boats can be cumbersome to transport	Ease of transport between sites and set-up
Relatively low biosecurity risks	✗	✓
Onboard camera capable of capturing aerial footage of additional physical and biological features of the water body	✗	✓
Potential to increase the number of monitored lakes sampled in a session	✗	✓
Cost-effective	✓	Costly during project set-up
Ability to sample large areas of the lake	Shallow waters and rocks can impede access to sampling locations by boats	Require multiple ground stations or SOPs to conduct flights BVLOS on large lakes
No weight restrictions on carrying capacity	✓	Dependent on specification of drone to be deployed
100% successful water capture	✓	✓
Ability to sample up to 300 m offshore	✓	✓
Reliable and accurate water chemistry measurements	✓	✓
No cross-contamination between samples	✓	✓
Drone platforms are affordable	✗	✓
Disadvantages		
Potential long-term impact on job security	✗	✓
Additional boat hire costs	✓	✗
Weather	Limited by wind speeds greater than 10 m/s	Limited by wind speeds greater than 8 m/s and moderate or heavy rainfall which could delay or cancel UAV operations
Cost of replacement parts	High (including the costs of the boat, boat trailer, boat repair)	High (including the costs of batteries, electronic equipment)
Real-time data capture	High cost of water sampling probes with real-time data transfer capabilities	High cost of water sampling probes with real-time data transfer capabilities
Requires adequate space and secure storage	✗	✗
Workplace health and safety concerns	✗	✗
High insurance costs	✗	✗

SOP, special operating permission.

(5) the onboard camera can also survey for hydromorphological and biological water features; and (6) the increase in the number of unmonitored lakes that can be surveyed in a session.

The advantages of the boat water sampling method are that (1) it is more cost-effective in relation to capital outlay; (2) it has the ability to sample large areas of a lake; and (3) there are no weight restrictions on equipment, although additional costs can be incurred if boats are rented.

6.4 Views Gathered from End-of-project Workshop Focus Groups

The project team gathered the views of participants attending the end-of-project workshop, held at GMIT on 25 March 2020, on several aspects of the research findings including drone water sampling, cost effectiveness, drone legislation, and health and safety and biosecurity risks (Table 6.4).

6.4.1 Drone water sampling

Overall, the focus groups indicated that they would consider the use of drone water sampling in the future but overwhelmingly felt that drone water sampling, in its current format, would not be able to completely replace traditional boat sampling methods (Figures 6.2 and 6.3). Rather, a tandem sampling approach was favoured that would complement sampling at remote and inaccessible locations, and where water chemistry data only were required.

6.4.2 Cost-effectiveness

Participants of the focus groups felt that the capital costs associated with drone water sampling were not good value for money. In addition, if drone water sampling was requested via a tender process the costs would be far beyond those of traditional boat sampling for many suppliers of such services. Thus, participants deemed the prototype drone water sampling method developed by the project team to be not competitive or not commercially or economically viable in its current format. They did, however, suggest a shared service as a means by which several agencies could come together and share the capital costs and benefits of drone water sampling, which would reduce the cost of water sampling for all.

In-house training would be deemed suitable if routine drone water sampling and shared services were to be undertaken by local authority agencies and permanent staff within the EPA but not for small consultancies or water testing laboratories.

6.4.3 Drone legislation

Overall, knowledge of drone legislation was limited and restricted to knowledge of the maximum height (120 m), maximum distance (300 m) and weight of

Table 6.4. List of questions posed to participants during the focus group session at the end-of-project workshop held at GMIT on 25 March 2020

Topic	Question	
Drone water sampling	Q1	Would you consider drone water sampling as a sampling methodology in the future? If so, for what purposes would you apply the system? If not, why?
	Q2	What do you consider to be the major benefits of applying such methodologies in your workplace?
	Q3	What would be the major considerations/constraints with applying such a methodology in your workplace?
	Q4	Would the methodology replace your current water sampling protocols or would you operate tandem methodologies?
Cost-effectiveness	Q1	How much would you be willing to invest in this new methodology if it were to be implemented in your workplace?
	Q2	Would you consider in-house training of personnel to conduct flight operations or would you tender a contract to external drone operators?
Drone legislation	Q1	What is your knowledge of drone legislation in Ireland?
	Q2	Do you know how drone legal requirements are applied within the workplace when conducting aquatic/terrestrial surveys using drones as part of your work/research?
Health and safety	Q1	In your workplace, would the drone water sampling method offer a safer working environment?
	Q2	Would this reduce the associated insurance and liability costs for your employer?
Biosecurity risk	Q1	How would you rate the biosecurity risk of the drone water sampling prototype device? Low, medium or high Why?
	Q2	How does this compare to the biosecurity risk associated with the boat?

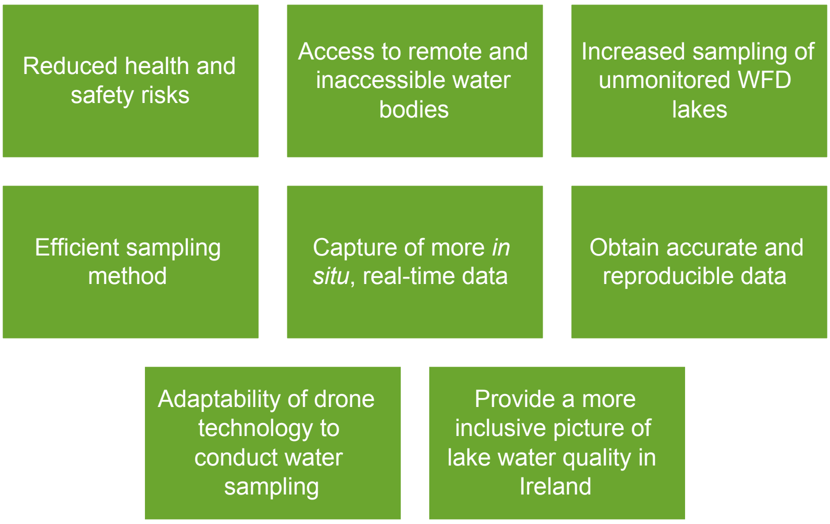

Figure 6.2. Benefits of drone water sampling highlighted by participants during the focus group session at the end-of-project workshop held at GMIT on 25 March 2020.

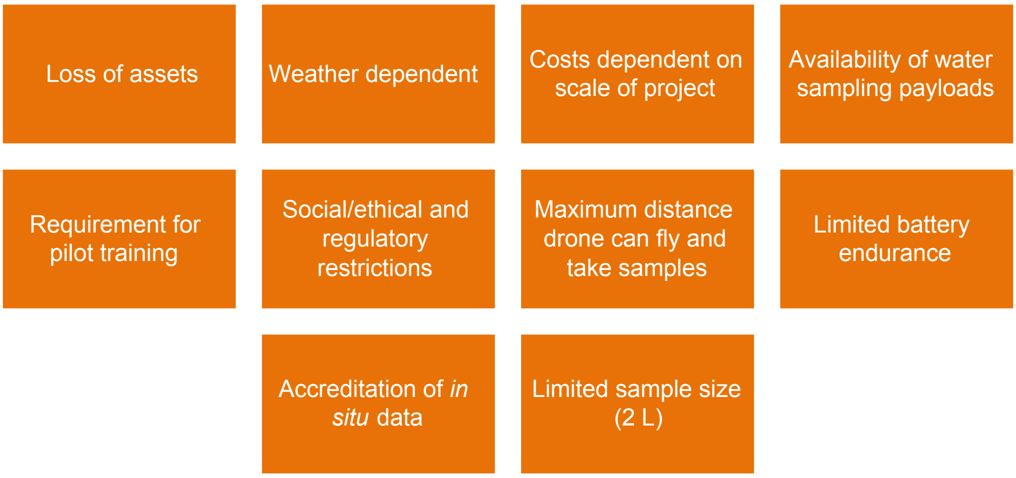

Figure 6.3. Limitations of drone water sampling highlighted by participants during the focus group session at the end-of-project workshop held at GMIT on 25 March 2020.

drones requiring registration with the IAA and distance required from 12 people or more (120 m).

In contrast, participants had a clearer understanding of drone rules and regulations when applied to their work/research, with many groups highlighting additional requirements for land owner/local authority permission; no fly zones around national parks, Special Protection Areas, Special Areas of Conservation, airports, aerodromes and Office of Public Works lands; that drones must operate within the visual line of sight and be added to company public limited liability insurance; and that pilots should have undertaken and completed ground school training with an approved provider.

6.4.4 Health and safety

All focus groups agreed that drone water sampling was safer for staff but that this alone would not reduce associated insurance or liabilities for their employers. In situations where employers operated both boat and drone water sampling in tandem, the combined insurance could increase liabilities.

6.4.5 Biosecurity risk

All focus groups deemed drone water sampling to be a lower biosecurity risk than boats and to be easier and to require less people power to clean and disinfect effectively.

7 Key Findings

This research has made significant contributions to (1) the advancement of drone water sampling technology, in particular the design and build of a prototype payload to consistently conduct water sampling; (2) the design of robust comparative experimental field trials that clearly demonstrate that the prototype payload designed collects both hydrochemical data and results from laboratory-tested water samples that are the same as those collected via traditional boat sampling; (3) conducting the first and informative cost–benefit analysis of the use of drones to collect lake water hydrochemical data and samples; and (4) publishing the first review of drone water sampling techniques used worldwide.

7.1 Achievements of this Research

Key achievements of this research:

- This was the first research team, worldwide, to publish a critical review of drone water sampling techniques.
- The drone and attached prototype payload, as demonstrated during field trials, can be used to successfully collect water samples from open lakes.
- The drone and attached prototype payload can successfully collect water samples from 100 m offshore.
- The water sampling time achieved using the drone and attached prototype payload is 4 minutes.
- The prototype payload developed by the project team is the first in Europe to collect 2 L of water using a drone.
- The water sampling rates are 100%.
- Real-time physico-chemical data capture is possible and allows users to review data before leaving a site.
- The comparison of a wide range of water chemistry variables showed no significant differences between traditional boat and drone water sampling methods.
- Precision was not significantly affected by the sampling methodology employed.
- A comparative analysis of water chemistry variables satisfies the requirements of lake water sampling and monitoring in Ireland under the EU WFD.
- The capital costs associated with water sampling methods were considered through a cost–benefit analysis as part of the project.
- The capital investment costs of traditional boat sampling were found to be 1.2 to 1.5 times lower than those of drone water sampling but, more importantly, drone water sampling was found to be 2.3 to 3.4 times faster than traditional boat sampling methods, depending on resource allocation.
- Drone water sampling reduces the health and safety and biosecurity risks associated with open lake sampling.
- Drone water sampling offers a unique solution to sampling in remote and inaccessible lakes and unmonitored lakes under the WFD, and to confirm the water quality of lakes categorised using remote-sensing methods, increasing our understanding of water quality in Irish lakes.
- The application of drone water sampling for large-scale water sampling programmes has been proven and can be adapted as needed to other aquatic environments.

8 Recommendations

The project team makes the following recommendations to further the advancement of drone water sampling over the coming years:

- Consideration should be given to deploying waterproof drones such as the Freefly Alta 8 or Alta X (see Chapter 3, Table 3.1). These drones would allow flights to operate in less than optimal weather conditions, including in wind speeds greater than 8 m/s and moderate rainfall.
- Smaller, lighter and cheaper real-time water chemistry probes should be integrated, to reduce the weight of the payload and the associated capital costs required during project set-up. This would, in turn, avoid the need for larger, more expensive drones and would allow users to operate within evolving legislative and pilot training requirements.
- The design and build of the prototype payload, especially its size (height and length) and weight, should be refined to allow a greater number of off-the-shelf drones to be considered for use. The use of additive fabrication techniques, which would allow the printing of new or replacement parts when needed or damaged, should also be considered.
- Field trials should continue and should include a wider variety of aquatic environments including estuaries at high and low tides, marinas and streams and rivers at various flows, to demonstrate application across various aquatic environments.

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Abbreviations

BVLOS	Beyond visual line of sight
Chl-a	Chlorophyll-a
CRDL	Contract-required detection limit
CTD	Conductivity, temperature and depth
df	Degrees of freedom
DO	Dissolved oxygen
EPA	Environmental Protection Agency
EU	European Union
GMIT	Galway-Mayo Institute of Technology
GPS	Global positioning system
HDPE	High-density polyethylene
IAA	Irish Aviation Authority
MFRC	Marine and Freshwater Research Centre
RPD	Relative percentage difference
TON	Total oxidised nitrogen
TP	Total phosphorus
UAV	Unmanned aerial vehicle
WFD	Water Framework Directive

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 341

Assessing the Potential of Drones to Take Water Samples and Physico-chemical Data from Open Lakes

Authors: Heather Lally, Ian O'Connor, Liam Broderick, Mark Broderick, Olaf Jensen and Conor Graham

Identifying Pressures

Water sampling remains a key component in the monitoring and assessment of aquatic environments. Sampling requiring the use of a boat can lead to issues around accessibility, particularly at remote lakes where there may be a lack of a slipway. In addition, there are considerable cost implications, mainly related to the boat costs, the need for different-sized boats for different lakes and the significant time and resource requirements. Boat sampling can also pose many health and safety issues, as well as biosecurity risks, which can be exacerbated in remote regions where access is difficult. The application of drones to collect in situ hydrochemical data and retrieve water samples from freshwater environments provides the potential to fulfil some aspects of the biological and physicochemical sampling required to meet large-scale water sampling programmes in a more efficient, safe and cost-effective manner.

Informing Policy

This research has successfully demonstrated that water chemistry data collected using drone water sampling methods are not statistically different from those produced by boat sampling. The studies undertaken have shown that data precision and accuracy are not adversely impacted when using drone sampling compared with traditional boat sampling methods. This comparative analysis satisfies the requirements of the European Union Water Framework Directive (WFD) sampling objectives for lake water monitoring and therefore can be applied to large-scale water sampling programmes worldwide, such as the United Nations Global Environment Monitoring System for Freshwater (GEMS/Water), Marine Strategy Framework Directive and US National Aquatic Resource Surveys. Drone water sampling also offers a unique opportunity to sample unmonitored lakes under the WFD in Ireland and remote and inaccessible lakes worldwide, and confirm the water quality and ecological status of aquatic environments determined using remote sensing methods.

Developing Solutions

The project team is the first research team in Ireland and Europe to capture a 2-L water sample using a drone. This research has made several significant contributions towards the advancement and application of drone water sampling methods. These include the successful deployment, as demonstrated during field trials, of a DJI M600 Pro drone and attached payload capable of capturing a 2-L water sample and real-time physicochemical data, 100 metres offshore, from open lakes in the west of Ireland. Water sampling times using the drone were 4 minutes and water volume capture rates were 100%. Drone water sampling was found to be 2.3 to 3.4 times faster than boat sampling, depending on resource allocation. In contrast, however, the capital investment costs for boat sampling were found to be 1.2 to 1.5 times lower than those required for drone water sampling. However, drone water sampling reduced the health and safety and biosecurity risks associated with boat sampling. Overall, the application of drone water sampling for large-scale water sampling programmes has been successfully demonstrated and can be adapted as needed to aquatic environments worldwide.

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