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Innovative Water Quality and Ecology Monitoring Using Underwater Unmanned Vehicles: Field Applications, Challenges and Feedback from Water Managers

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Abstract: With climate change and urban development, water systems are changing faster than ever. Currently, the ecological status of water systems is still judged based on single point measurements, without taking into account the spatial and temporal variability of water quality and ecology. There is a need for better and more dynamic monitoring methods and technologies. Aquatic drones are becoming accessible and intuitive tools that may have an important role in water management. This paper describes the outcomes, field experiences and feedback gathered from the use of underwater drones equipped with sensors and video cameras in various pilot applications in The Netherlands, in collaboration with local water managers. It was observed that, in many situations, the use of underwater drones allows one to obtain information that would be costly and even impossible to obtain with other methods and provides a unique combination of three-dimensional data and underwater footage/images. From data collected with drones, it was possible to map different areas with contrasting vegetation, to establish connections between fauna/flora species and local water quality conditions, or to observe variations of water quality parameters with water depth. This study identifies opportunities for the application of this technology, discusses their limitations and obstacles, and proposes recommendation guidelines for new technical designs.

Keywords: water quality monitoring; ecology scan; underwater drones; underwater inspections

1. Introduction

The adequate use, management and conservation of water and soil resources are crucial to human and ecological survival. Climate change and increasing urbanization are causing rapid changes to aquatic systems, such as affecting ecological services, increasing soil impermeability, or a rapid increase of nutrients available [1,2]. The monitoring of water quality, soil and ecology is important for the understanding, modeling and prediction of hydrological processes, and to ensure adequate environmental management and decision-making, to face the different challenges and problems in each region [3,4]. To ensure the preservation of water resources and ecological habitats, European regulations (e.g., water framework directive) require extensive monitoring and the classification of water bodies based on environmental indicators, and set high standards to comply with [5,6]. Data accessibility and readiness for use is crucial to enable real-time water management [7]. There is a growing demand for innovative and efficient methods and approaches that can take advantage of the high potential of new technologies that are increasingly accessible to professionals from different areas [8].

Currently, the monitoring of water quality is primarily conducted by collecting samples to be analyzed in laboratories, which are sometimes complemented with static continuous sensors for certain parameters. These methods are labor intensive, expensive, and only provide results after several days or weeks, and are therefore incapable of mapping rapid changes in the environment [9,10]. Static water quality sensors can provide valuable time series of the seasonal variation of parameters, but require frequent maintenance and have high costs and short lifetimes. For these reasons, only a few units are installed in specific locations of water bodies (e.g., near water supply inlets), resulting in high costs and inefficiency in monitoring large areas. Ecological research and the inspection of underwater objects and infrastructure are often performed by divers or from visual observations and manual collection of samples.

There are several examples of successful environmental applications using different mobile platform setups [11]. In maritime environments, underwater drones/ROVs (underwater remote-controlled vehicles) have been extensively used in past decades to explore and monitor deeper layers of the ocean [12–18]. Ramadass et al. [19], for example, describe how a ROV equipped with cameras was used to monitor reef fishes in deeper water using video cameras mounted on ROVs, or the ecological observations described by Pacunski et al. [20], that collected quantitative data in high-relief outcrop and bank habitats. The use of these aquatic vehicles for this purpose is reported to have significant potential to contribute to a better understanding of fish communities and habitat dynamics (e.g., stock assessment). There are reported examples of unmanned underwater vehicles equipped with water sampling devices that can collect water samples [21]. Klump et al. [22] describe their pumping system associated with Niskin bottles, and their results of the surveying in sublacustrine hydrothermal springs, and in complex topography and the narrow confines. The advantage of collecting water samples is that it allows one to perform additional laboratory analyses that cannot be obtained in situ (e.g., microscopic plankton), and are useful for validation purposes. Biogeochemical sensors (e.g., nitrate, oxygen, fluorescence) can be installed in unmanned underwater vehicles to perform measurements at different depths of the water column. These are frequent in oceanography studies. Wulff et al. [23] describes applications in ice-covered areas, where a large scale autonomous underwater vehicle (AUV) was used and allowed to study the dynamic interaction between ice plates and the ocean. Finally, another example of water quality monitoring in freshwater bodies and, in particular, for applications in port areas, is described by Speller [24]. It consists of an intelligent robotic fish (i.e., AUV) that is capable of detecting and identifying pollution by patrolling port waters, identifying security threats or inspecting underwater infrastructure.

The collection of data by using sensors, sampling devices, and imaging equipment combined with mobile platforms is gradually becoming more common, appraised and affordable, with novel applications and uses in the water sector being explored every day [25]. In recent years, unmanned aquatic vehicles are becoming more and more accessible to water managers. This is the result of the rapid development and price reduction of components, which is fueled by IoT (internet of things) developments related to the aerial drone and smart sensor market. However, despite all the described examples of successful and advanced applications, smaller and cheaper ROVs are not yet part of the common monitoring tools used by water managers responsible for freshwater systems. Water resources management agencies or authorities are still prioritizing conventional methods (e.g., point sampling), although unmanned based tools are already able to provide important information about the heterogeneity of water quality parameters, at different scales [10].

In other respects, the inspection of underwater assets is currently a challenging task worldwide. The Netherlands has extensive underwater infrastructures that needs to be maintained, and therefore there is a strong need for innovative solutions that can provide cost-effective information about the condition of underwater assets. The most frequent inspection method is the deployment of divers, which involves high operational costs and requires the implementation of safety measures. Due to high costs, inspections are often not performed at all. The use of underwater drones for this purpose could become an innovative and potentially cost-effective way to gain a dynamic understanding of water-bodies.

While there has been a rapid development of unmanned tools and sensors for environmental monitoring and inspections in recent years [26–30], it is not yet clear if the use of these methods by water managers in their daily practice, and the extent to which they can replace or complement existing techniques, should be further explored. There still seems to be technical, social, legislative and operational limitations and barriers for the large-scale use of this technology. The main objective of the work reported in this paper is to evaluate the potential of the use of aquatic drones to perform different monitoring tasks in water systems, based on the testing of this technology in multiple case study locations of different water authorities in The Netherlands, and based on the collection of feedback from the participating water management professionals. Additionally, the field experience contributed to get better insight into data collection and processing issues, with implications for further use of the data in models. This study reports the main challenges and limitations for the successful application of this type of technology, illustrates the main advantages and added value of the data that these emerging tools can provide, and makes recommendations for future research and development. By directly involving water managers in this study, it is expected to improve the transfer of the research outcomes to the water sector and decision makers.

2. Materials and Methods

This paper pursues a participatory action research approach in investigating the use of unmanned underwater drones in environmental monitoring. For this purpose, different monitoring setups consisting of different types of underwater drones combined with water quality sensors and cameras were tested in the field (Section 2.1) for applications in water management and environmental monitoring activities, and efforts were made to involve water managers in the different stages of research (i.e., planning of measurements, fieldwork, discussion of results). The feedback and experience of different water managers, when confronted with the field implementation and resulting data, was documented through semi-structured interviews (Section 2.2). The design and planning of the field tests were drafted in collaboration with water managers (Section 2.3). The fieldwork activities and consultations with practitioners took place in the period between February 2015 and December 2018.

2.1. Monitoring Setup: Field Testing with Underwater Drones and Sensors

2.1.1. Underwater Drones (ROV)

In this work, multiple mini/observation/exploration class ROVs were used for data collection campaigns (Figure 1). Their specifications vary between the different models, resulting in different advantages, as well as limitations. The propulsion and diving configurations range from using a single propeller, a rudder for steering and a ballast tank for diving (e.g., Neptune drone), to a vectored thruster configuration that allows motion in multiple directions (e.g., BlueROV2). The drones are either tethered, with a real-time video feed, or controlled wirelessly via radio signals: operational depth restricted to a maximum of 5 m water depth. Some of the tested models allow features such as the ability to set a fixed depth and/or a fixed direction that is automatically maintained through the self-adjustment of the speed of the thrusters, based on the real-time processing of the onboard pressure sensor and compass. The characteristics of the underwater drones are further compared in Table 1. The drones were deployed from bridges, boats, or from the margins of the water bodies. The tether cable could be used to sustain the vehicle weight when the water was not within direct reach.

Table 1. Overview of the different ROVs that were used in this research, with information about their main characteristics and specifications.

Underwater Drone/ Manufacturer/ Location	Shape/Weight/ Dimensions (L × W × H)	Depth Rating	Price (ca.)	Communication	Configuration/ Diving	Special Features	Payload/ Expandable/ Battery (ca.)
Neptune, Thunder Tiger, Taichung, Taiwan	Cylindrical; 7.7 kg 77.4 × 29 × 28.5 cm	10 m [1]	600 €	Wireless; no real time video/data	Single propeller; Ballast tank	Re-surfaces when lost connection	3 Kg; No (closed source) 1 h; replace time-consuming
SeaWolf, TTR Robotix, Taichung, Taiwan	Cylindrical; 7.7 kg 77.4 × 29 × 8.5 cm	15 m	1200 €	Wireless; no real time video/data	Single propeller + Rudder Ballast tank	Re-surfaces when lost connection	3 kg; No (closed source) 1 h; replace time-consuming
OpenROV 2.7, OpenROV, Berkeley, USA	Cubical; 2.6 Kg 30 × 20 × 15 cm	100 m	900 €	Tethered, real time video and navigation data	3 propellers 1 Vertical propeller	Auto-depth and heading hold;	3 kg; Yes 1.5h; replaceable
PowerRay, Powervision, Beijing, China	Flat; 3.8 Kg 46.5 × 27 × 12.6 cm	70 m	2000 €	Tethered. real time video and navigation data	3 propellers 1 Vertical propeller	Auto-depth hold	0 kg; No (closed source) 1 h; Not replaceable
BlueROV2, BlueRobotics, Torrance, USA	Cubical; 10 kg 45.7 × 33.8 × 25.4 cm	100 m	3000 €	Tethered, real time video and navigation data	Vectored (4 + 2) 2 Vertical propellers	Auto-depth and heading hold;	8 Kg; Yes 2 h; Replaceable
Sibiu Nano, Nido Robotics, Murcia, Spain	Cubical; 5.15 kg 23.7 × 25.8 × 35 cm	100 m	1600 €	Tethered, real time video and navigation data	Vectored (4 + 2) 2 Vertical propellers	Auto-depth and heading hold;	5 kg; Yes 1.5 h; Replaceable
BlueROV Heavy, BlueRobotics, Torrance, USA	Cubical; 11.5 kg 57.5 × 25.3 × 45.7 cm	100 m	3500 €	Tethered, real time video and navigation data	Vectored (4 + 4) 4 Vertical propellers	Auto-depth and heading hold	15 kg; Yes 2 h; Replaceable
Gladius, Chasing, Shenzhen, China	Flat; 3.2 kg 43.2 × 27 × 11.4 cm	100 m	2000 €	Tethered, real time video and navigation data	3 propellers 1 Vertical propeller	Auto-stabilization, Wi-Fi buoy	0 Kg; No (closed source) 1 h: Not replaceable

[1] Loss of radio signal at around 5 m deep.

(**a**) (**b**) (**c**) (**d**)

Figure 1. Illustration of multiple underwater drones equipped with cameras, lights, or water quality sensors. (**a**) Neptune; (**b**) OpenROV 2.7; (**c**) BlueROV2; (**d**) PowerRay.

2.1.2. Sensors and Equipment

The combination of underwater drones with a variety of equipment allowed the collection of high-frequency multi-dimensional data of multiple environmental and water quality parameters, and to obtain visual insights into underwater environments and ecosystems. Figure 1 illustrates some of the underwater drones equipped with measuring devices. Table 2 provides an overview of the equipment used in the field test, i.e., which was installed on the underwater drones.

Table 2. List and characteristics of the equipment used on the ROVs.

Name	Manufacturer/Location	Type	Parameters/Specifications
Troll 9500	In-Situ, Fort Collins, USA	Multi-parameter probe	Dissolved oxygen, turbidity, pH, nutrients (ion-selective electrodes)
CTD Diver	Van Essen Instruments, Delft, The Netherlands	Multi-parameter probe	Electrical conductivity, temperature, pressure
AP2000	Aquaread, Broadstairs, UK	Multi-parameter probe	Dissolved oxygen, turbidity, pH, temperature, nutrients (ion-selective electrodes)
MiniDOT Logger	PME, Vista, USA	Multi-parameter probe	Dissolved oxygen, temperature
GoPro 3+ and 5	GoPro, San Mateo, USA	Camera (Submersible)	40m depth rating
Algae Wader TriLux	Chelsea Technologies, Molesey, UK	Algae sensor	Chlorophyll-a, phycocyanin/phycoerythrin, turbidity
Algae Torch	Bbe Moldaenke, Schwentinental, Germany	Algae sensor	Chlorophyll-a, phycocyanin/phycoerythrin
eTrex 30x	Garmin, Olathe, USA	Handheld GPS logger	Logs GPS coordinates
Lumen Subsea Light	Blue Robotics, Torrance, USA	Lights for integration in ROV	1500 lumen; dimmable control
Light	ScubaPro, Racine, USA	Diving light	Designed for scuba diving;
Typhoon SkyView	Yuneec, Jiangsu, China	VR/FPV headset	First person view HDMI screen

These state of the art sensors and sondes (Figure 2) are allowed to monitor water quality parameters such as pressure/depth, temperature, conductivity, nitrate, ammonium, dissolved oxygen and turbidity, chlorophyll-a and phycocyanin. A pressure/barometric sensor was placed onshore to allow posterior compensation for the atmospheric pressure in water depth computations. Although most sensors allow a sample rate of 1 s, data was collected every 10 s, due to a frequency limitation of the dissolved oxygen sensor. The sensors, in particular the ion-selective electrodes (ISE—nitrate and ammonium) require frequent calibration to provide accurate measurements.

Figure 2. Examples of water quality sensors used in this research.

Most drones have built-in cameras, but additional cameras were used with the drones, due to their video quality and versatility for underwater video recording. They provide a wide angle of view, and automatic image adjustments of focus, brightness, contrast, and color saturation. Depending on the needs of each task, the cameras were placed underneath, above, or in front of the vehicle. Different light systems were used as light sources to improve underwater visualization when operating at low-light underwater conditions.

The position of the underwater drones was recorded during the measurements by a GPS logger (at the water surface), that was connected to the drone with a retractable cable. In some of the tests, a GPS logger was used to record the coordinates of the route followed by the drone. Because GPS has no signal underwater, it had to remain at the surface, and it was placed on a floating platform above the water, and connected to the drone by a self-retractable cable. The used cable was limited to a depth of 3 m. Additionally, audio and video logging were used. The depth of the underwater drones was logged by pressure sensors onboard, and compensated with a barometer for atmospheric pressure variations.

Due to the external equipment attached to the drones and different needs of each task, it was necessary to perform trial and error adjustments before each dive to ensure the maintenance of neutral buoyancy and balance of the vehicles, by compensation of the extra weight of the equipment added with floats, usually polystyrene. This proved essential for a smooth and trouble-free dive and underwater drone operation.

2.1.3. Data Collection

Most fieldwork campaigns were conducted in the presence of the local water authority (Figure 3). In some of the tests, their operational staff collected data simultaneously using conventional/standardized measurement methods, and/or collected water and benthic/sediment grab samples, that were analyzed in laboratories for the validation of sensor data.

Figure 3. Impression of the field monitoring, often with the participation of water managers.

The drones were either operated from land, or from boats when the study area was not reachable from the margins. To map water quality parameters within a certain area, the drones were guided to slowly travel through the water bodies (lakes/canals/ponds), while logging data from sensors every 10 s. The distance the drone is able to travel away from the operator is limited to the length of the tether, which was up to 150 m long, depending on the drone used. Although the deepest dive performed was up to 45 m (Sloterplas Lake, Amsterdam), most used drones are designed to dive up to 100 m, and most components of the BlueROV2 up to 300 m.

The underwater drones were able to dive and collect data at multiple water depths on the water column, generating three-dimensional datasets. These were used to obtain depth profiles and maps at specified water depths. Sensors have a response time of a few seconds, which means that the drone had to descend in small steps, in order to allow the sensors to stay for some time at each desired depth.

Underwater drones were used to scan aquatic ecology, in particular to assess the presence of fish, aquatic plants or other aquatic organisms, and to identify and compare characteristics of underwater environments in different zones. The drones were guided to different regions of water bodies and collected images at multiple water depths. The underwater images were collected simultaneously with data collected by sensors. When surveying aquatic fauna, care was taken to minimize noise and disturbances underwater while operating the underwater drone. Lighting conditions were adjusted at each location to ensure optimal underwater image quality.

2.2. Semi-Structured Interviews of Water Managers

To assess the receptivity of water managers towards unmanned drone technology and the potential of the data for water management applications, a methodology based on semi-structured interviews [31] was implemented in this research. This method stimulated the discussion of new ideas and results by water managers. Table 3 shows a list of water managers and end-users that contributed to this study.

Table 3. List of participating water authorities and other end-users.

Name	Type	Water System	Location(s)	Period
Gemeente Groningen	Municipality	Urban ponds, canals/waterways	Floresvijver (Groningen)	2015–2017
Provincie Overijssel	Province (regional)	Waterways/quay walls	Almelo/Coevorden	2017, 2018
Rijkswaterstaat,	Ministry	Rivers; Waterways	Nieuwe Waterweg	2014
Waterschap Hunze en Aas	Water Authority	Lake, waterway	Zuidlaardermeer; Termunterzijldiep	2016
Natuurmonumenten	Nature Conservation	Natural Reserves	Tiengemeten	2015
Gemeente Leeuwarden	Municipality	Urban canals;	Leeuwarden	2017
Hoogheemraadschap van Delfland	Water Authority	Lakes; pond; culvert,	Delftshout; Kruithuis, Naaldwijk	2015; 2018
Waternet	Water Authority	Lake, lock, pumping station	Sloterplas; Nigtevecht; Weesp.	2015; 2019
Hoogheemraadschap Hollands Noorderkwartier	Water Authority	Lake	Twiske	2018
Waterschap Noorderzijlvest	Water Authority	Canals, Lake	Paterswoldsemeer	2017
Waterschap Zuiderzeeland	Water Authority	Lake, urban canal	Zeewolde, Urk, Weerwater, Bovenwater	2016
Waterschap Rijn en IJssel	Water Authority	Lock, pumping station, River	Ijssel River; Doetinchem (de Pol)	2016; 2019
Waterschap Brabantse Delta	Water Authority	Waste water treatment plant	Rijen	2019
Waterschap De Dommel	Water Authority	Waste water treatment plant	RWZI Eindhoven	2016
Wetterskip Fryslân	Water Authority	Lake	De Leien, Sneekermeer	2017; 2018
Waterschap Drents Overijsselse Delta	Water Authority	Constructed Wetland	Oude Diep, Drenthe	2015

The feedback from these meetings/semi-structured interviews was collected and included in the results section of the present paper. The interviews took place on four different occasions: (i) during workshops and conferences where participants were asked to provide input by writing suggestions and ideas on post-its and placing them on a flipchart; (ii) planning of field tests to discuss problems and define concrete problems to be investigated during field testing, along with the owner/responsible of each test location; (iii) during the field testing (including operational staff); (iv) after the measuring campaign, to discuss results/data and lessons learned. Table 4 consists of the guide used during the interviews, including objectives, topics and (open) questions asked to the participating entities.

Table 4. Objectives and examples of questions asked to water managers during different steps of the research.

(i) Workshops and Conferences	**(ii) Pilot Planning Meeting**
Objectives: • Brainstorm about new applications and possibilities of underwater multi-dimensional real-time data • Match potential applications of underwater drones with expected challenges and limitations **Questions:** • What possible applications of unmanned drone technology in water management can you think of? • What are potential barriers and limitations do you see? • What opportunities for this type of technology do you see in your daily activities? • What is the added value of using drones in comparison with methods you currently use? • What the bigger challenges being experienced now with conventional monitoring methods	**Objectives:** • General meeting to define concrete problems and locations, to define monitoring strategies, and data outcome expectations • Selection of examples of cases where the drone will be tested **Questions:** • How can this technology contribute to solve each issue • Detailed discussion about feasibility and barriers/limitations • What parameters or measurements are suitable for each problem • Draft of monitoring plan and task description • What are your expectations towards this type of unmanned technology for each case study (e.g., data outcomes, resolution)
(iii) During Field Measurements	**(iv) Discussion of Results**
Objectives: • Gathering field experience and knowledge from stakeholders • Assess feasibility of incorporating drone technology in daily activities of stakeholders. • Data collection by stakeholder's staff with conventional monitoring methods **Questions:** • Are the drones within expectations? • Is such monitoring equipment suitable to be used by your staff? • Is it clear what data the drone is collecting? • Do you see new barriers/opportunities you had not thought about before? • Is there comparable data that can be used to compare results?	**Objectives:** • Review results and lessons learned • Discuss potential new applications based on experiences **Questions:** • What is the collected data useful for • Do you have suggestions for further data analysis • What type of data is more useful and unique • Other ideas for other measurements • What is the added value of this tool • What steps are needed for this tool to be more effectively used in practice

2.3. Selection of Applications for Field Testing

The outcomes of the semi-structured interviews organized during this study provided feedback from potential end-users of this technology and its usability and limitations or envisioned barriers for water management. Additionally, the sessions with the end-users resulted in a list of potential applications. Based on these outcomes, the tests presented in this work were structured under three main categories: (1) water quality monitoring, (2) ecology surveying, and (3) underwater inspections.

In accordance with the nature of the participating end-users and background of the research team, the discussed opportunities focused on inland freshwater systems.

Several individual consultations with end-users took place after the semi-structured interviews, to define the locations and aspects to investigate during the field testing. The participating water managers proposed different locations with a multitude of problems that they are facing, or locations where they have to deal with a lack of updated spatial data and other challenges. Aspects such as the type of water body, technical feasibility, the potential of results, and adequacy of technique to solve each problem, and the needed data were considered as selection criteria for the locations. These work sessions resulted in the design of monitoring plans for the deployment of unmanned underwater tools, as well as a strategy for the assessment of the data. With this method, the selection and definition of each task were based on end-users' suggestions and took into account their views and ideas about the potential uses of this technology. The involvement of end-users from different regions of The Netherlands resulted in multiple case studies locations spread out around The Netherlands, with different regional constraints and characteristics.

3. Results

3.1. Outcomes of Field Measurement Campaigns

The variety of tasks involved in the field measurement campaigns gave insight into the practical feasibility and challenges of using underwater drones for different purposes, and illustrated the versatility and flexibility of the tool. Table 5 gives information about the different case studies; it summarizes the multiple locations where data were collected, the aim of the study, data type, and main outcomes and lessons learned. Table 6 illustrates examples of the resulting maps/images/data collected.

Table 5. Summary of the different Dutch case studies.

Location; Type; Nature of Pilot	Aim and Outcomes	Main Challenges
Tiengemeten, Natural reserve Ecological scan	Identification of fish and characterization of local habitats	Water too shallow for operation of the submarine
Nieuwe waterweg, Waterway Ecological scan	Underwater footage of fish and sediments	Low underwater visibility; strong currents/waves difficult operation of drone
Sloterplas, Lake Water quality + eco-scan	Benthic/Quaggamussels survey allowed estimation of the coverage of the bottom of the lake. Images matched with dissolved oxygen concentrations	Difficult to retrieve the position of each measurement (no GPS underwater)
Naaldwijk, Culvert Water quality; Inspection	Underwater drone successfully entered up to 30m of culvert. Sudden variation in water quality data indicates the presence of illicit discharge	Concern about being unable to retrieve drone if stuck inside culvert
Kruithuis, Surface water Water quality + eco-scan	Spatial mapping of water quality parameters	Shallow water; battery depleted fast and not possible to replace batteries
Floresvijver, Urban pond Water quality	Mapping of dissolved oxygen concentrations in the pond allows one to assess the effectiveness of the aeration measure	Shallow water; balancing of drone with sensors
Noorderhaven, Urban Port Water quality; Inspection	The use of underwater drones allowed easy access and data collection underneath floating houseboats	Concerns about drone getting stuck in unknown obstacles and/or mooring system of floating objects
Termunterzijldiep, Canal Water quality	Salt intrusion in canal mapped by performing transect along canal that showed the variation of electrical conductivity	Not possible to perform long distance scans with tethered ROVs
Complex de Pol, Sluice/Weir Inspection	Underwater images of the condition of the sluice mechanism, and of the position of energy dissipation rocks	Low visibility due to turbid water; difficult to match video footage with the real position of drone
Ijssel, River Water quality	Water quality data collected across the river in along transversal transects, and near margins	Strong currents push drone downstream, making maneuverability impossible
Delftsehout, Lake Water quality + eco-scan	Identification of fish species, characterization of aquatic vegetation and mapping/profiling of water quality	Boat with drone operator needed to position ROV in the middle of the lake

Table 5. *Cont.*

Location; Type; Nature of Pilot	Aim and Outcomes	Main Challenges
Twiske, Lake Water quality	Mapping and profiling of water quality, including the variation of chlorophyll-a and blue/green algae concentrations with water depth.	Limited tether range; limited number of parameters
Ijsselmeer, Lake Water quality	Unique dataset of three-dimensional water quality data at different moments of the day (day/night comparison)	Lack of knowledge about the exact position of outlet; measurements during the night difficult to perform logistically
Zeewolde, Urban Canals Water quality	Mapping of spatial distribution of different water quality parameters	Length of tether cable unsuitable for the length of canals to be monitored: time consuming task
Bovenwater, Lake Water quality	Mapping of spatial distribution of different water quality parameters	Limited number of parameters needed for WFD
Zuidlaardermeer, Lake Water quality	Comparison of average of water quality parameters values between different zones of the lake	Bad weather (heavy rain) complicates operation and threatens the electronics needed for the test
Weerwater, Lake Water quality + eco-scan	Clear visualization of thermocline and stratification of the lake	Dense vegetation occasionally blocks drone thrusters
Sneekermeer/De Leiein, Lakes Water quality	Mapping of water quality parameters, and underwater scan of macrophyte growth	Problems with nutrient sensor: sensor data start drifting shortly after calibration
Nigtevecht/Weesp, Lock Inspection	Underwater images of submerged infrastructure, which were heavily covered in biofouling and bivalve communities	Currents generated by boat traffic cause difficult maneuverability
Almelo, Waterway Inspection	Detailed underwater inspection in points of interest that had been previously identified with other methods (sonar scanning)	Limited tether length and battery life hinders effective scan of several km of quay walls, limited visibility
Leeuwarden, Urban canals Water quality	Detailed mapping of water quality in the vicinity of sewage overflow outlets, to detect the impact/reach of overflowing events	Need for quick deployment of the drone during/shortly after high intensity precipitation events (often unpredictable)
Paterswoldsemeer, Lake Water quality	Combination and comparison of water quality mapping with quality of sediments measured using other methods (gamma-ray spectrometer)	Time-consuming task to measure water quality across the whole lake: limited range of the tether/umbilical
Rijen, WWTP Inspection	Underwater images showed unexpected sedimentation patterns, indicating erratic functioning of the sedimentation tank	Low visibility near the center of the sedimentation tank
Eindhoven, WWTP Water quality	Baseline three-dimensional measurements of dissolved oxygen near/downstream of outlet before implementation of oxygenation measures	Lack of accurate positioning of drone makes repetition of measurements in follow-up measuring campaigns difficult
Oude Diep, Wetland Water quality + eco-scan	Measurement of water quality conditions in different parts of the filter; insight into aquatic life from underwater images	Not possible to sail through parts of the filter due to tall vegetation

Table 6. Examples of different types of data collected during the measurement campaigns using underwater drones equipped with cameras and sensors.

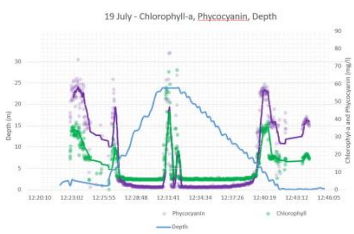
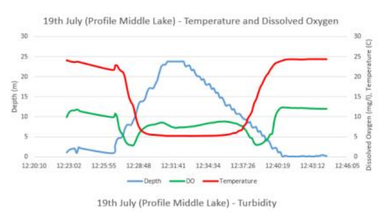
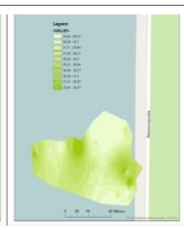
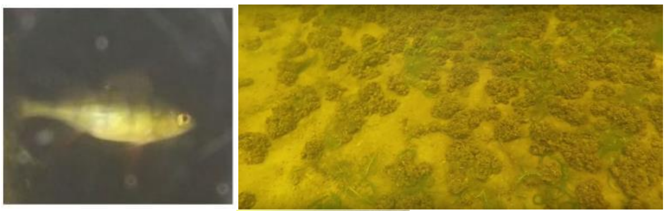
Type of Data	Result Impression
Depth profiles of the concentration of water quality parameters collected during the field tests	 
Water quality maps (at the water surface, or at specific depth range)	  

Table 6. *Cont.*

Type of Data	Result Impression
Underwater image of fish/vegetation Contrasting underwater environments with different levels of density of aquatic vegetation	
Underwater images of aquatic fauna (fish, benthic organisms [32])	
Images of submerged infrastructure (remote inspection)	

3.2. Feedback from Water Managers during Semi-Strutured Interviews

Water authorities, companies and research institutes from the Netherlands showed interest and the willingness to participate in this research by actively searching for suitable pilot applications and locations of their interest, and by sharing their perspective on the use and outcomes of this type of tool. Outcomes of the semi-structured interviews and workshops indicate that water authorities see underwater drones as a stepping stone for the autonomous collection of data, real-time access to datasets and quick response triggered by events as top needs for monitoring improvement. They recognize the potential of the technology to provide unique 3D data and underwater insights that can contribute to support their water management decisions. End-users valued the potential of the tool to perform fast surveys that would collect high spatial resolution data sets with lower costs than current practices. Participants envisioned that drones can be used to identify and pinpoint problem areas and gather information that can help improve water quality, by being able to quickly map different parameters and indicators and access difficult to reach locations (e.g., deeper water, culverts). Additionally, the autonomous operation of these tools, including the ability to follow and adjust pre-defined waypoint routes, open possibilities for systematic data collection that could be repeated to build unique time-series. These are useful, for example, for calculating percentages of benthic/vegetation coverage over time, mapping the concentration of water quality parameters, and inventorying changes in fauna/flora species in water bodies.

The fact that the drones are limited to existing sensors and therefore can only measure a limited number of parameters is presently still a limitation of the application of this tool, due to policy guidelines. These guidelines often require that specific conventional/standardized methodologies are used and indicate a wide list of parameters that have to be monitored, including microbiological or toxicology parameters, that can only be quantified by analyzing water samples in laboratories. Moreover, in the field tests, the ROVs were used to collect data in a single moment in time, but end-users reiterated the added value for the data sets if the same measurements are repeated in different days/seasons, as this would provide much more comprehensive information about what is happening in the water system. Other aspects that generated concerns and discussions include: (i) the suitability of the aquatic drones to be used in areas with dense vegetation that would cause the clogging of propellers; (ii) the potential entanglement of the tether with underwater objects and obstacles; (iii) the effect on water quality and ecology of the movement, noise and turbulence caused by the propellers; (iv) lack of temporal data series, accuracy in determining/counting aquatic species; (v) knowledge of the position of the drone underwater; (vi) limitation of range and battery life; (vii) legal feasibility (e.g., suitability for complying with water framework directive monitoring requirements); (viii) limitations when navigating high turbidity and poor visibility conditions; (ix) problems caused by the interaction with other boats in waterways; (x) technology shortcoming regarding swarming and underwater communications; (xi) resources needed for data processing and analysis.

During fieldwork activities, water managers considered that the method to obtain water quality profiles was very effective, as it did not require the deployment of manned boats and it would efficiently be able to plot stratification and thermocline layers. The mobility of sensors is novel for them, and they confirmed that the resulting high resolution datasets provide more information than only point samples, and can be very illustrative for mapping and spatial analysis. Water authorities indicated that an even less invasive tool would be desired, as the strong colors of the drones (white/yellow/blue) and propeller noise that can be heard in the videos are not ideal for blending in the environment. Further research is needed to optimize the drone being able to penetrate the ecosystems more quietly. For example, the Neptune drone is able to dive and stay submerged without the use of propellers, creating less noise. The knowledge of the distance between the ROV and the bottom of the water body would allow better control and avoid damage to habitats, which is important when in the presence of vulnerable benthic organisms.

During the discussion of the collected data, water managers highlighted unexpected findings, such as the possibility of identifying low dissolved oxygen concentrations, by observing large groups of the freshwater zooplankton Daphnia that were displaying a distinctive red color, which indicates the presence of low dissolved oxygen conditions, the observation of certain species of fish (e.g., eels) in locations where ecology experts had not expected their presence according to the known conditions of the lake, or the possibility to combine underwater images/footage with data, which allows to establish relationships between aquatic habitats (e.g., images of mussels, fish, macrophytes) and various water quality parameters. Moreover, the success of using unmanned aquatic drones to inspect underwater infrastructure or to study underwater ecosystems was observed to be highly dependent on the turbidity/transparency of the water. It was discussed that it is difficult to estimate the sizes of objects or fish only based on video images: the size on the screen depends on the distance of the drone to the object.

An example often mentioned by water managers regards the monitoring of algal blooms in surface water in recreational waters in the Netherlands, which requires quick action from water managers if high concentrations are detected. In such situations, conventional monitoring is labor-intensive, provides only limited point sampling information about the spatial distribution of algae, and laboratory results are only available after several days. Water managers report that the algae sensor mounted on the aquatic drones allows them to quicken their algae surveying, and to identify the areas with higher chlorophyll-a and cyanobacteria concentrations. In one of the tests, and considering that algae travel cyclically up/down in the water column according to sunlight exposure due to the photosynthesis cycle, the use of the underwater drone allowed one to take measurements during the night/early morning. These data could then be compared with measurements taken during the day, which allowed water managers to better understand the behavior of the algae in their lakes and confirm if, during the night, higher algae concentrations are usually found at higher depth.

Water managers see this tool as a valuable solution to quickly gain insight into the condition of the infrastructure underwater, as the available alternatives either include the use of divers or involve draining the water and performing a dry visual inspection. Both options are costly and complicated logistically, and may in some cases not even be feasible (e.g., divers are unable to access certain areas, such as inside culverts or under floating structures [33,34]). Nonetheless, there are still shortcomings of using unmanned technology when compared to divers, such as it not being possible to clean surfaces before inspection (e.g., remove biofilm/shells that cover most of the submerged surfaces, blocking the view to eventual pathologies), or to touch/feel objects.

Water managers have requested/suggested different features to include in new designs of aquatic drones. These include having real-time access to data from sensors, as it would allow discussing/adjusting the monitoring plan onsite based on measured values, and would allow one to actively adjust transects or to follow pollution sources. The ability to remotely collect water and/or sediment samples at different locations and different depths is relevant for water managers, as the samples can be analyzed in laboratories to obtain accurate and detailed information about a wider range of parameters, as well as be used in the validation of data from water quality sensors.

3.3. Field Challenges and Lessons Learned

During field data collection and/or the discussion of results with end-users, multiple practical issues and problems were experienced and identified (Figure 4). Table 7 reveals an outline of the challenges encountered. Potential solutions and/or alternatives are discussed below, as well as characteristics and features that new designs of underwater drones should take into consideration. These include the requests and expectations that water managers raised during the discussions.

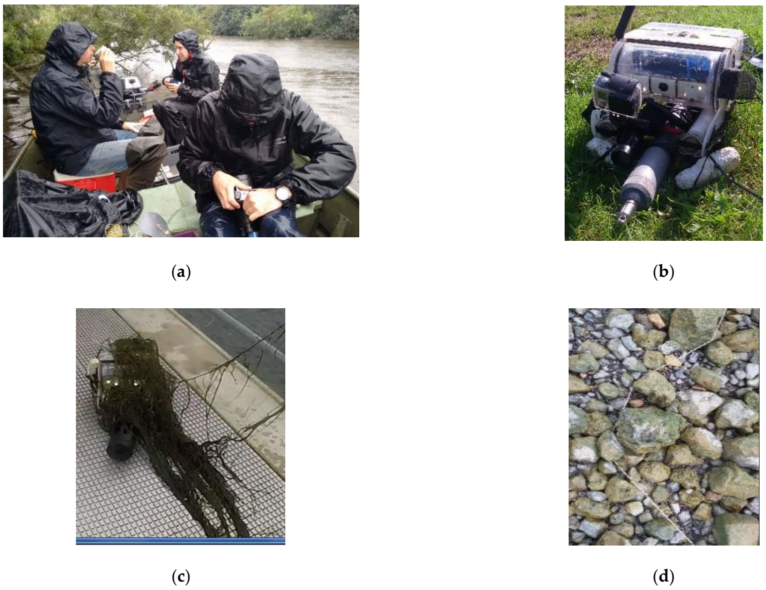


Figure 4. Field challenges: (**a**) operation under rain conditions, where a laptop is needed to operate some drones, (**b**) adjusting the buoyancy of small drones with heavy sensors is a time-consuming task; (**c**) excess of vegetation blocks thrusters; (**d**) tether tangled in rocks/obstacles.

Table 7. Categorizing of field occurrences observed in the field; numbering refers to the text in Section 3.3.1.

Navigation/Operation	Data	Practicability
I. Manoeuvrability II. Reduced underwater visibility III. Condensation in the dome blocking view IV. Delay of the real-time video stream V. Protection from vegetation VI. Vertical diving VII. Total depth measurement VIII. Tether management IX. Experience of the drone operator/pilot X. Autonomous Navigation XI. Depth rating	XII. Logging of underwater position XIII. Data processing XIV. Wireless/Real-time data transfer XV. Data suitability XVI. Stealth/Noise	XVII. Payload XVIII. Flexibility and interchanging sensors and cameras XIX. Balancing XX. Easy deployment/recovery and transport XXI. Weather-proof operating station XXII. Batteries

3.3.1. Navigation/Operation

The maneuverability and navigability of the underwater drones (I) is very important for the success of data collection missions. The built-in cameras provide video in real-time and dimmable lights proved to be crucial for navigation of the underwater drones. Additional features that ease the operation of underwater drones were identified, such as receiving real-time information about compass and depth, the ability to lock/fix a specific heading or depth based on real-time data from sensors, and the multiple degrees of movements that the drones with six vectored propellers allow. This type of feature is crucial when collecting data, as it aids the performance of transects or the maintenance of sensors at desired water depths. These features were not available in some drones, such as the Neptune drone, which uses a ballast tank for diving, and therefore it is not as agile, nor is it possible, to control the depth easily, contrarily to other drones that use highly responsive propellers.

In several of the case study locations, the water was very turbid. This is a frequent characteristic of Dutch surface water, which limited the visibility to a few cms (II). This complicates the operation of the drones and visual data quality. In particular, while performing underwater inspections in the presence of high turbidity, it was difficult to navigate and find the asset to be inspected. Adequate illumination helps when operating in low-light conditions, but in high turbidity conditions, they may worsen visibility, as the light reflects on the particles causing camera glare. Sonar systems/acoustic cameras may be an important feature to enhance underwater visibility. Additionally, some drones generated condensation inside the dome of the navigation camera (III), which compromises the images from the navigation camera. Most commercial ROVs include humidity absorbing material inside the electronic compartments that solves this issue (e.g., silica-gel). Alternatively, the navigation camera could be isolated from the main electronics compartment, reducing heat generation. Lastly, there was a noticeable delay in the video stream that reaches the operator (IV). This results in the drone being difficult to maneuver, and often resulting in undesired collisions with the bottom or other objects.

Vegetation occasionally blocked propellers (V), which requires the manual recovery of the ROV to remove the unwanted material. To reduce risks, when possible/visible, the operator can try to avoid zones with dense vegetation, or temporarily stop thrust when traveling through vegetation. A blocked propeller can lead to a damaged motor which incurs repair/replacement costs. The presence of strong currents (e.g., in rivers) hampers diving missions: lighter drones, such as the OpenROV 2.7, are easily dragged downstream, whereas heavier models such as the BlueROV2 are still able to travel against the water flow, but as soon as the vehicle steers perpendicularly to the current, it is no longer possible to maneuver.

To collect vertical profiles of water quality, or to perform underwater inspections, it is useful that drones can dive vertically (VI). Some of the tested drones struggle with this type of motion, namely the flat drones (e.g., PowerRay drone) that need to glide to be able to dive efficiently. Moreover, it is difficult to accurately control if the dives are performed vertically: currents and unbalances of the drones can cause the drone to deviate its position. Additionally, when performing dives, the distance between the drones and the bottom of the water body was unknown (VII), resulting in the vehicle hitting the bottom of the water body, which increases the sediments in suspension, immediately visible in the video stream. This may influence the data collected after that moment, as noticeable in the graph: a sudden increase in chlorophyll/phycocyanin concentrations coinciding with the maximum recorded water depth (see graph in Table 6). Although not yet available during data collection of this research, there are already available affordable acoustic sonar systems that can provide this distance in real-time. Nonetheless, the drones are equipped with depth sensors that provide information about the water height above ROV in real-time, which is beneficial for navigation and posterior data interpretation.

Due to technological limitations regarding underwater communications, the drone is always connected to the operator by a tether (VIII). If the ROV is given too much cable slack, this cable can become entangled or stuck. The live stream available may actively help to detect and avoid obstacles (e.g., ropes, chains). Deploying drones from land in zones with rocks and other objects near the margins usually generates problems. If it happens, an experienced operator is usually able to retrieve the ROV by guiding the drone back over the route it had followed, or by forcing the ROV to dive/move, which provides different recovery angles. In more extreme situations, divers may be necessary to retrieve the drone and equipment. Solutions such as using a floating tether, or equipping the drone with a sonar system, allows the operator to better detect and avoid obstacles, and reduce the risk of the tether becoming locked in rocks or objects laying underwater. The tether limits the range and reach of the drone, which was limited to 150 m in this research.

The successful operation of drones was therefore challenging and required an experienced operator with extensive knowledge of the aquatic drone (IX). Newer drone models often use apps and smartphones to intuitive operating software to control the ROV, but it is still challenging to use the drone without specific training. The ability to travel autonomously (X) is not yet possible for unmanned underwater vehicles within this price range. Following pre-defined routes would allow the repetition of measurements at different moments in time, which is valuable for the collection of time series of data. Additionally, self-decision making and autonomously adapting their route to follow/track pollution sources based on real-time data could become valuable features for water management applications in the future. The autonomous/unsupervised operation of unmanned vehicles may raise legal feasibility and liability questions regarding interaction with other manned boats, for example in busy port areas.

The depth rating (XI) of most underwater drones was not a limitation for the dives in the Netherlands (deepest dive of 45 m in Sloterplas Lake, Amsterdam), as drones are designed to dive up to 100 m, and the BlueROV2 up to 300 m. Only the Neptune drone has a limited depth rating of around 15 m. Some water quality sensors with membranes (e.g., ion-selective electrodes) could not be submerged deeper than 10 m, as they can be damaged when subject to high pressures.

3.3.2. Data

Proper logging of the underwater position of the drone (XII) is crucial for navigation and post data analysis information in most applications. These data should be recorded and should allow easy export. The use of GPS equipment is limited for uses at the surface, as its submersion causes the loss of satellite signal. Currently, only the depth is known, from water pressure sensors installed on the ROV. Among the options for this task is the development of an acoustic positioning system, or the inclusion of an accelerometer and compass. This information is logged and can be used for posterior data analysis. Additional estimation regarding the position of the drone can be obtained from observing the direction of the tether and measuring tether length, whenever the monitoring strategy consists of performing straight transects. For example, the estimation of the position of the drone inside the culvert was obtained from measuring the length of the tether cable. In some of the tests, a floating platform with a GPS logger (at the water surface) was connected to the ROV with a retractable cable and was used. Alternatively, the use of auxiliary underwater positioning equipment, such as acoustic positioning, or inertial accelerometers or acoustic positioning systems, would allow one to compute/obtain underwater coordinates. Unfortunately, with the technology available for this research (and at this price point), it is still unfeasible to program a route to be followed by the underwater drone (while submerged). None of the drones used had this feature, which hinders the accurate repeatability of measurements (of interest for comparing measurements collected in different moments in time).

The setup used in this research consisted of collecting information from multiple sources, and from multiple programmable data loggers. This resulted in the need to combine high volumes of data in a single dataset, before being able to prepare plots or maps, or perform other types of analysis (XIII). Filtering, organizing and labeling the data turned out to be a time-consuming process. A few automation routines were developed for this purpose and helped to agile the process. Moreover, the representation of multi-dimensional datasets is complex and it takes time to prepare for an easy understanding by the water managers. With the sensors system configuration available for this research, access to the data sets was only possible after the measurement activities. Real-time information about the parameters (XIV) would allow one to actively adjust the measurement campaign to what is being observed.

Due to the fact that the camera is mobile (XV), the captured footage is not suitable for quantifying the amount of fish in the water (fish counts). It is, however, possible to identify species of fish. Not much precise information could be obtained about the size of the encountered specimens, as it depends on the distance from the fish to the camera. A possible solution is to use two parallel lasers beams calibrated at a specific distance that allow estimating dimensions from collected footage. Additionally, it is beneficial that the drones can sail without being noticed by the surrounding environment (XVI). This is not relevant when performing inspections, but it may frighten away fish when performing ecological surveys. It was noticed that the motors are noisy, as they need to be continuously working for the ROVs (BlueROV2; OpenROV 2.7) to maintain its position underwater. The drone that achieved the best results for ecological observations was the Neptune drone, as it uses a ballast tank to sink/resurface without activating propellers, and its elongated shape allows it to keep sliding quietly through the water using momentum, without needing thrusters. In this drone, the single propeller is located in the back, around 50 cm from the camera in the front.

3.3.3. Practicability

Considering the multitude of tasks of interest for water management, it is important to have a flexible method to interchange equipment and adjust its best placement on the drone (XVII). For this research, tie ribs and elastic bands were used to fix the equipment to the drone, which made it possible to easily and quickly change and rearrange the placement of cameras and sensors to achieve a proper setup for each task (XVIII). Adding/moving the payload of the drone affects the center of gravity of the drone, and the drone may become difficult to operate if it is not well balanced (XIX). In this research, floats were used to compensate for the added weight in a time-consuming trial and error process, which often hindered a quick start of measuring activities. Heavier drones such as the BlueROV2 could cope more easily with unbalanced weights, as it uses the two vertical propellers for maintaining the horizontal position. Attempts to streamline the preparations included the use of floats with exact volume for each sensor/camera, or to fully prepare the drone prior to the measurement day, which was not always possible, as adjusting the monitoring setup based on the characteristics of each location is often needed, and this is only known onsite on the measurement day. New designs could include already balanced plug and play modules, or the implementation of an automated solution to balance the drone before the measurements (e.g., using ballast tanks). The drones should allow space for payload without compromising navigation, and should have enough power to cope with the extra mass. It was not possible to install large multi-parameter probes on the flat drones such as the PowerRay or the Gladius. Smaller drones, such as the OpenROV 2.7, could manage the added weight of the equipment, but it did affect maneuverability and battery life, as the motors were not strong and the payload affected aerodynamics. For example, the BlueROV2 was able to handle payload with less effort due to its larger size.

In most drones, many components need to be transported and re-assembled in each new measurement location, which is time-consuming (XX). The drone and all accessories (e.g., laptop, remotes) are hardly handled by a single person. Additionally, a deployment/recovery system for locations where the water is not within easy reach is not currently available. Manufacturers indicate that the tether can be used for this purpose, but occasionally this practice led to faulty tether connections.

In the Netherlands, measurements often take place under rain conditions and inside boats (XXI), which are not favorable circumstances to operate the drones and most of the necessary accessories and electronics (e.g., OpenROV 2.7 and BlueROV2 require connection to a computer). The equipment necessary to operate the ROVs should be rain-proof, and ready to withstand unfavorable weather conditions. The protection of the laptop and other equipment can be accomplished with impermeable surfaces. It should be possible to use within a boat with limited space available, as this is frequently requested by the water authorities and end-users. Moreover, devices such as remote controls are prone to falling on the water, and should, therefore, be designed to be as waterproof as possible. Finally, excessive sunlight impedes the proper visualization of the screens. For the latter, the solution used consisted of using virtual reality sets to enhance the visualization of the computer screens.

The autonomy (battery life; XXII) of the drone is crucial to ensure the productivity of field monitoring campaigns. Contrarily to some drones that can no longer be used once the battery is depleted after usually 2 h of operation, some drones allow one to easily replace batteries (each set lasts for over 2 h, depending on usage). Additionally, enough battery for laptops and cameras is required. Large power banks for laptops were used in this research, which provided enough power for day-long measurement campaigns.

4. Conclusions

This work reported experiences and observations collected from the application of underwater drones in practice, with the direct involvement of water authorities and end-users. The technical and practical feasibility of this monitoring method was assessed, as well as the usability of the data and the need for future technical developments. The insights gained by using underwater drones as a mobile monitoring system showed that, in many cases, these tools are a valuable complement to other methods, as it provides a unique combination of three-dimensional data and underwater footage/images collection. The versatility and flexibility of the monitoring setup allowed water authorities to obtain visual insight into underwater aquatic ecosystems and enabled the visualization of the spatial patters of water quality parameters, including variations of multiple parameters with water depth. It was possible to map different areas with contrasting vegetation, and to establish connections between the detection of different fauna/flora species and local water quality conditions. Underwater drones provided a fast method to perform baseline surveys and inspections. The ability to easily access zones of difficult access with a multitude of equipment and instruments is promising, as it allows obtaining information that would be difficult, costly and unsafe to obtain with other alternatives. Potential follow-up steps of this research include adding additional sensors and sampling equipment, as well as repeating measurements to gather data and images from the same locations in different seasons to build time-series of the data collected. The main challenges encountered during the fieldwork activities included the underwater positioning of the ROVs, the limited range of operation due to difficult underwater communication and the consequent need for a tethered connection, and the limited underwater visibility in turbid water conditions. There are already possible existing solutions, such as accurate accelerometers, acoustic positioning systems, sonar systems, and acoustic cameras, but these are only available at a higher price range. The presence of dense vegetation often clogged and strangled the propellers, which is a limitation to the operation of this type of vessel. Moreover, there are still bottlenecks regarding the water quality parameters that can currently be measured by sensors, as several chemical parameters still require the analysis of water samples in laboratories. Nonetheless, new options of sensor technology (e.g., optical nutrient sensor, BOD/COD spectrometer) are becoming increasingly available, which would expand the possibilities regarding the number of parameters that are possible to measure in-situ. The large-scale implementation in the Netherlands and in other countries worldwide is dependent on policy acceptance toward innovative methodologies. Despite these aspects, the used setup was already able to yield successful results and provide high-resolution data for water managers. Water managers explained that the equipment setup used is still too complex for them to conduct measurements on their own without specialized staff, and therefore further development is still needed for the underwater drones to become more user-friendly.

In this work, the use of different models of ROVs and system configurations allowed one to identify aspects that could be improved and taken into consideration for new designs, as well as features that stood out as bringing significant added value for data collection purposes. In the coming years, with the growing interest and developments in unmanned systems, image recognition software or machine-learning, not only remote controlled, but also self-navigating underwater drones will become more and more accessible and reliable. The integration of different systems will contribute to the operation of this technology becoming more user-friendly. The research and commercialization of new types of sensors will expand the range of parameters that can be measured and empower these mobile systems to address other complex water management challenges.

Water management decisions and strategies are frequently based on results from models. The development, validation, and calibration of water quality and ecology models rely on high resolution temporal and spatial data obtained by field monitoring to improve the simulation and prediction results of models. The lack of detailed, reliable and recent water quality data is usually the main obstacle for the proper application of models [35,36]. This leads to inaccurate results and predictions, and it is thus difficult to properly judge environmental indicators and provide a realistic overview of aquatic environments, which may result in poor water management decisions. In parallel with the collection of environmental data, a simulation framework must be in place to support decision making for the implementation of adequate control steps and water management actions. Geo-referenced data collected by aquatic drones can be used to validate and calibrate physically and empirically based numerical hydrodynamic, water quality models. Further research is needed to determine which variables need to be measured more extensively, and the needed spatial density and temporal frequency.

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