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In Support of the Sustainable Development Goals: Citizen Science Monitoring of Ambient Water Quality

Thesis presented by

Lauren Quinlivan, BSc

orcid.org/0000-0003-4326-1625

for the degree of

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School of Biological, Earth & Environmental Sciences

Head of School: Professor Andrew Wheeler

Supervisors: Dr. Deborah Chapman, Dr. Tim Sullivan

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Declaration

This is to certify that the work I am submitting in this thesis is my own and has not been submitted for another degree, at University College Cork or elsewhere. All references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.

_____

Lauren Quinlivan

Abstract

The United Nations has voiced its support for the use of citizen science to aid ambient water quality monitoring for the Sustainable Development Goals. Engaging the efforts of both professional scientists and members of the general public, citizen science has gained significant attention in recent years as a means of increasing the spatial and temporal coverage of data collection. However little research has been conducted on the use of citizen science in water quality monitoring for the UN Sustainable Development Goals to allow for the establishment of any sort of monitoring framework involving citizen science. A literature review as part of this thesis discusses the current state of knowledge on volunteer involvement in water quality monitoring and identifies the challenges and opportunities for applying citizen science to the monitoring of ambient water quality under the Sustainable Development Goals. Considerable potential exists for citizen science to contribute to the SDGs yet concerns over data collection, use and organisational issues like lack of volunteer motivation and interest continue to plague the realm of volunteer monitoring and inhibit its use in many fields. Based on the conclusions drawn from the literature, this thesis aimed to address each key issue which currently presents a challenge for the application of citizen science to the monitoring of ambient water quality for the Sustainable Development Goals. In support of work towards the achievement of Sustainable Development Goal 6: "Clean Water and Sanitation", this thesis tested the use of simple and inexpensive field equipment by citizen scientists for monitoring the SDG Indicator 6.3.2: "*Proportion of bodies of water with good ambient water quality*". Data generated by 26 citizen scientists were compared with the results produced by an accredited laboratory. The results compared well for most parameters, suggesting that citizen science may be able to contribute towards monitoring ambient water quality for the Sustainable Development Goals as long as data quality is maintained. This thesis also examined the effects of participation in an SDG-focused citizen science water quality monitoring programme on volunteers' attitudes and interests. The positive results support conclusions from other studies suggesting that experience of partaking in citizen science may increase volunteer interest and positively influence attitudes towards global environmental issues, though the resulting influence on behaviour will require further investigation. Lastly, through a focus on waterbodies of known water quality in southwest Ireland, this thesis aimed to assess one potential

method for incorporating citizen science data into the reporting methodology for the ambient water quality indicator. The investigation reported mixed results, revealing that the incorporation of citizen science data into the reporting methodology through the method employed would be relatively simple, however more recent data is needed from professional organisations on the quality of the waterbodies examined before the accuracy of the data may be determined. Through an examination of the three most significant barriers to the application of citizen science to the UN ambient water quality indicator this body of research concludes that, if implemented correctly, citizen science may prove an essential resource for supporting the achievement of the Sustainable Development Goal Indicator 6.3.2 on ambient water quality.

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Chapter 1: Introduction

The 2030 UN Agenda for Sustainable Development is “a plan of action for people, planet and prosperity” (United Nations General Assembly, 2015). The Agenda encompasses 17 Sustainable Development Goals (SDGs), to expand on the success of the Millennium Development Goals (MDGs) of 2000 (UNEP, 2015). The sixth SDG to “ensure availability and sustainable management of water and sanitation for all” recognizes that human and environmental health, as well as economic prosperity, relies heavily on access to safe water supplies and sanitation facilities stemming from the proper management of freshwater resources (United Nations Economic and Social Council, 2017). Target 6.3 requires that countries improve water quality by reducing pollution, increasing recycling, and ensuring proper treatment of wastewater. Progress towards achieving target 6.3 is measured using information provided by the SDG indicators 6.3.1 on “the proportion of wastewater safely treated” and 6.3.2 on the “proportion of bodies of water with good ambient water quality”. Data for SDG Indicator 6.3.2 are gathered from monitoring programmes that require the collection and analysis of water samples (UNEP, 2018). Through the monitoring of five core physiochemical water quality parameter groups (oxygen, salinity, nitrogen, phosphorus and acidification), the SDG Indicator 6.3.2 methodology can be adapted and applied to all waterbodies in countries globally, regardless of socio-economic status, in order to assess changes in water quality (UNEP, 2018). However challenges remain in obtaining adequate spatial and temporal coverage in the collection of data necessary to support SDG Indicator 6.3.2 at the global scale. For this reason, the United Nations has voiced its support for the increased use of citizen science as a fresh approach to water quality monitoring, and has identified it as a potentially cost-effective solution to supporting SDG Indicator 6.3.2.

Citizen science may be described as research carried out by members of the public with the aim of gathering scientific information that can be used in decision-making processes (McKinley *et al*., 2017). Tracing its roots back to the beginnings of modern science (Cohn, 2008), citizen science employs the joint efforts of both professional scientists and members of the public, who need not hold any preliminary knowledge or training on the subject matter but who volunteer to collaborate with

professional scientists to conduct scientific research (Cappa *et al*., 2018; Dickinson & Bonney, 2012). Citizen science is becoming a prominent tool for carrying out scientific research, particularly in the area of conservation as the scale and urgency of environmental issues surpass available resources for data-gathering (Cooper *et al*., 2007; Danielsen *et al*., 2010; Cosquer *et al*., 2012; Newman *et al*., 2011; Theobald *et al*., 2015; Thornhill *et al*., 2016; Tulloch *et al*., 2013). New organisations devoted entirely to citizen science conservation-based research have formed in recent years, while government agencies and universities finally begin to realise the potential for citizen science to contribute to their work (Ellwood *et al*., 2017). In the field of water quality monitoring alone there was a near tripling of new community-based monitoring programmes over the four year period from 1988 to 1992 (Kerr *et al*., 1994), and publications on citizen science have increased 10-fold from the early 2000s (Tipaldo & Allamano, 2016).This increase appears to be due, in part, to a continued increase in public environmental consciousness, a decrease in the ability of governments across the world to monitor environmental issues, as well as the recent widespread availability of technical tools, such as the internet, mobile phones and cheap sensors, for sharing information and gathering data (Au *et al*., 2000; Conrad & Daoust, 2008; English *et al*., 2018; Huddart *et al*., 2016; Newman *et al*., 2017; Savan *et al*., 2003; Silvertown, 2009). Certainly, the accessibility of inexpensive field equipment to citizen science networks for water quality monitoring suggests its potential for increased spatial coverage beyond that of traditional, laboratory-based monitoring networks (UNEP, 2018). Public interest in the protection of water resources has grown significantly in recent decades and volunteer monitoring of waterbodies around the world has also grown in practise (Firehock & West, 1995; Kerr *et al*., 1994; Loperfido *et al*., 2010; Penrose & Call, 1995). Given the positive outcomes associated with increased utilization of volunteers in water quality monitoring, expanding the role of citizen science in SDG monitoring could potentially be the next plausible step in the path to achieving SDG 6 (Farnham *et al*., 2017), through support for its targets and indicators.

Despite recognition of its potential for water quality monitoring, citizen science remains most commonly used in the field of ecology for monitoring of biodiversity, invasive species and climate (Dickinson *et al*., 2012). Although the United Nations has recognized citizen science as a potential source of support for the

ambient water quality SDG Indicator 6.3.2, a number of challenges remain before it can be seen as a viable method of scientific research that produces reliable data that can be used to support decision-making processes across a diversity of fields, as well as the Sustainable Development Goals (United Nations, 2018). These challenges may relate to everything from data collection and subsequent use to the organizational structure of monitoring programmes themselves and retention of participants for long-term sustainable monitoring (Conrad & Hilchey, 2011). The challenges and opportunities for applying citizen science to the monitoring of ambient water quality under SDG Indicator 6.3.2 are discussed in a literature review conducted as part of this thesis (**Chapter 2**). Despite the number of challenges to applying citizen science in an effective manner, citizen monitoring efforts should not be devalued in their significance (Conrad & Hilchey, 2011) as it has been noted that the benefits of employing citizen science as a scientific method are substantial, and any challenges which present themselves, although not insignificant, can likely be overcome (Aceves-Bueno *et al*., 2015).

Outlined in **Chapter 2**, concerns over the quality of data gathered by non-professionals, as well as lack of volunteer interest and motivation, remain central challenges to the application of citizen science across a diversity of fields. Though many published research studies exist which investigate the quality of water quality data gathered by citizen scientists, as well as the factors behind motivating and retaining participants, little research has been conducted which has specifically focused on the use of citizen science to monitor water quality for the purpose of achieving the Sustainable Development Goals. This knowledge formed the basis for the first published research study into the use of citizen science to monitor the ambient water quality SDG Indicator 6.3.2 (Quinlivan *et al*., 2019). The investigation, outlined in **Chapters 3 and 4**, examined the quality of data generated by volunteers as part of a citizen science SDG-focused water quality monitoring study, and further observed the impacts of participation in a study of this nature on the participants. The investigation identified and reiterated the importance of a number of common issues which prevent the widespread use of citizen science for environmental monitoring, including lack of volunteer interest and motivation and difficulty incorporating citizen-generated data into professional monitoring activities (Conrad & Hilchey, 2011). The knowledge obtained from this investigation will contribute to providing a better understanding of the quality of data generated by volunteers on the SDG

Indicator 6.3.2, as well as the potential effects on environmental attitudes and interests in volunteers through participation in SDG-focused citizen science. The study aims to provide useful insight should the time come for a citizen-led monitoring programme to be established as a source of support for the SDG Indicator 6.3.2. The results of the study highlighted a further key issue surrounding the use of mon-professional data for scientific reporting: difficulty integrating volunteer data with those gathered by professional researchers. Based on this finding, the study outlined in **Chapter 5** chose to comprehensively investigate the potential for volunteer data to be integrated into data gathered by professional scientists on the SDG Indicator 6.3.2, using results from the Irish EPA's Quality Rating System. This study built upon findings observed in **Chapters 3 and 4**, though with a greater goal of setting an example for the establishment of future monitoring programmes supporting the Sustainable Development Goals.

The aim of this body of research was to provide a fundamental understanding of how citizen science can support monitoring for the United Nations Sustainable Development Goal Indicator 6.3.2 on the "proportion of bodies of water with good ambient water quality". This thesis has identified key knowledge gaps and hurdles hindering the widespread adoption of citizen science as a means of monitoring the ambient water quality indicator and has sought to address each challenge individually and specifically. The thesis has produced one of the first published research studies demonstrating the use of citizen science for monitoring ambient water quality in support of the Sustainable Development Goals. It has also examined the potential impacts of involvement in an SDG-focused water quality monitoring programme on citizen scientists, and has demonstrated new opportunities for integrating volunteer water quality data with those of professional researchers and organisations.

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Chapter 2: Supporting SDG Indicator 6.3.2: Challenges and Opportunities for Citizen Science

A comprehensive review by Conrad and Hilchey (2011) highlighted that the challenges facing citizen science usually relate to three key areas: (1) data collection and (2) subsequent use, and sometimes (3) the organisational structure of the monitoring programme itself. All of these challenges are relevant to and must be included in the discussion on how citizen science could be applied to ambient water quality monitoring in support of SDG Indicator 6.3.2.

Data Collection Issues

Numerous challenges surround the collection of water quality data that professional researchers would regard as reliable and trustworthy, and in the context of SDG Indicator 6.3.2, could be applied to the calculation of a national indicator score for ambient water quality. Within the world of science, experts are often sceptical about the ability of non-professionals to mitigate data errors, calibrate equipment, or conduct robust data analyses where these actions are required; they also lack confidence in the level of training received by volunteers (Carlson & Cohen, 2018; Royle, 2004). Data fragmentation and inaccurate measurements taken during collection, as well as lack of participant objectivity, have also been presented as problems when conducting volunteer monitoring programmes (Whitelaw *et al*., 2003). Despite this, numerous studies on water resources have concluded that citizen scientist-generated data on chemical (Obrecht *et al*., 1998; Loperfido *et al*., 2010), physical (Rodrigues & Castro, 2008), and biological (Fore *et al*., 2001; Vail *et al*., 2003; Gowan *et al*., 2007; Stepenuck *et al*., 2011) monitoring are generally comparable to professional data. In order to ensure the production of reliable, high-quality data that could be used to support SDG Indicator 6.3.2, significant thought will have to be given to how data quality should be maintained throughout the life of a monitoring programme. Based on conclusions drawn from the published literature on volunteer water quality monitoring, it is possible this could be achieved through a combination of participant training and the use of simple yet accurate technology.

Participant Training

As the level of training among citizen scientists can affect the quality of the data gathered (Fore *et al*., 2001), the use of volunteers to monitor water quality in support of SDG Indicator 6.3.2 would require a rigorous form of training to ensure citizen scientists consistently meet the standards set out by professionals for monitoring ambient water quality. Of the peer-reviewed research studies on the use of citizen science for water quality monitoring, the majority report some form of participant training, though this training may differ in nature from one study to the next. While some researchers opted to train volunteers for the specific study at hand (Fore *et al*., 2001; McGoff *et al*., 2017; Quinlivan *et al*., 2019; Shelton, 2013; Wanda *et al*., 2017), others chose to involve citizen scientists who had already undergone external training as part of their participation in existing volunteer monitoring networks (Au *et al*., 2000; Canfield *et al*., 2002; Loperfido *et al*., 2010; Moffett & Neale, 2015; Overdevest *et al*., 2004; Wilderman & Monismith, 2016), and thus provide little information on the nature of the training methods used. A research investigation into the quality of data produced by citizen scientists monitoring water quality in Toronto's urban stormwater ponds (Scott & Frost, 2017), opted to train participants according to the materials and methods devised by FreshWater Watch (https://freshwaterwatch.thewaterhub.org/), the freshwater initiative of global NGO Earthwatch. This training consisted of presentations on freshwater ecosystems, issues with water quality, and the FreshWater Watch programme, which were followed by field activities in which volunteers were provided with hands-on instruction by professionals in how to use the FreshWater Watch materials to sample water quality (Scott & Frost, 2017). While it cannot be assumed that most monitoring programmes employ similar training methods due to the number of studies lacking in detail on this matter, it does appear that a mixture of both theoretical and practical activities is a popular training method used in studies found within the published literature, many of which were carried out by or in association with FreshWater Watch (Levesque *et al*.,, 2017; Loiselle *et al*., 2016; McGoff *et al*., 2017; Quinlivan *et al*., 2019; Scott & Frost, 2017; Thornhill *et al*., 2017; Thornhill *et al*., 2018). Other investigations have referenced the use of training quizzes (Quinlivan *et al*., 2019; Shupe, 2017) and courses (Shelton, 2013) to ensure competency, debriefing sessions following fieldwork to assess data quality (Wanda *et al*., 2017), and periodic testing and review of data by professionals (Gowan *et al*., 2007) as a means of ensuring that volunteers

meet the training requirements to participate in the research. Based on information gathered from the published literature, the use of both theoretical and practical training methods could prove useful as a baseline level of training for citizen scientists monitoring water quality under SDG Indicator 6.3.2, which could be supplemented with periodic testing of volunteer knowledge, use of equipment and data quality.

Citizen Science, Technology and SDG Indicator 6.3.2

The United Nations has expressed its support for increased use of volunteer efforts in monitoring ambient water quality (UNEP, 2018), yet only one study to date has specifically examined the SDG Indicator 6.3.2 water quality parameter groups using citizen science (Quinlivan *et al*., 2019). However, numerous studies can be found in the literature reporting on the high standard of data produced by non-professionals on many of the individual parameters (Dyer *et al*. 2014; Herman-Mercer *et al*., 2018; Levesque *et al*., 2017; Loiselle *et al*., 2016; Safford & Peters 2017), though the testing equipment used, as well as their accuracy, has varied widely across the different studies.

The current methodology for the Indicator requires monitoring of five core physicochemical water quality parameter groups which may all be measured using simple and inexpensive field techniques suitable for citizen science programmes (Table 2.1) (UNEP, 2018). Within citizen science it is generally understood that volunteers should not be expected to use sophisticated analytical instruments or participate in any activity for which extensive training or certification would be required (McKinley *et al*., 2017). Simpler methods are encouraged in order to ease the engagement of citizen scientists in the collection of high-quality data (Parsons *et al*., 2011), yet professional scientists often express concerns that the use of simpler technology may come at the price of accuracy (Scott & Frost, 2017). Studies produced by FreshWater Watch, for example, have made use of Kyoritsu PackTest water chemistry kits to measure Orthophosphate and Nitrate through a colorimetric method, drawing mostly positive conclusions (Loiselle *et al*., 2016; McGoff *et al*., 2017; Quinlivan *et al*., 2019; Shupe, 2017; Thornhill *et al*., 2017; Thornhill *et al*., 2018; Xu *et al*., 2017), however some studies have noted difficulties in using the kits to conduct finer scale analyses of nutrient concentrations (Levesque *et al*., 2017; Quinlivan *et al*., 2019; Scott & Frost, 2017). Though the kits may be applauded for their price, reported

ease of use, rapid assessment and large dynamic range (Scott & Frost, 2017), the data produced by the kits is categorical in nature, falling into one of seven concentration ranges and thus limiting the precision with which results can be obtained (Quinlivan *et al*., 2019). A study by Shelton (2013) observed that volunteers were capable of collecting precise, high-quality data on electrical conductivity using the YSI Professional Plus multi-probe which, though accurate and precise, is unrealistic for use in citizen science monitoring due to price. Conversely, the results produced for dissolved oxygen using the YSI probes were less comparable (Shelton, 2013), echoing other studies which have identified dissolved oxygen as a frequent source of inaccuracy or unreliability in citizen science (Dyer *et al*., 2014; Safford & Peters, 2017; Storey *et al*., 2016). Citizen science investigations analysing pH using field test strips (Muenich *et al*., 2016; Storey *et al*., 2016) and pH meters (Shupe, 2017) have also recorded mixed results. As studies to date have clearly shown, technology does exist to enable citizen scientists to monitor the SDG Indicator 6.3.2 parameters, however the question lies in whether the technology is accurate enough to produce data of the standard needed to be able to report on the indicator. Quinlivan *et al*. (2019) found that while citizen scientists, using equipment provided through FreshWater Watch, were not able to report precise numerical measures of water quality parameters to the same degree as an accredited laboratory, they were able to indicated correct concentration ranges for three of the SDG Indicator 6.3.2 parameters: orthophosphate, nitrate and electrical conductivity. The results open up discussion on the potential for citizen science to be integrated with professional monitoring as part of a revised SDG Indicator 6.3.2 methodology, in which target ranges are used in place of specific target values (Quinlivan *et al*., 2019). While a review of the SDG Indicator 6.3.2 reporting methodology may be required in order to determine the best methods of incorporating citizen science and data quality standards required, ongoing developments in sensor and indicator technologies should continue to allow for improved detection limits and resolution (e.g. Moonrungsee *et al*., 2015).

Table 2.1. Core monitoring parameters (in bold) required for the calculation of SDG indicator 6.3.2 for three water body types. Alternative parameters (in italics) may be substituted for the recommended core parameters, depending on data availability and applicability for specific water body types (UN Water, 2018).

Parameter group	Parameter	River	Lake	Groundwater
Oxygen	**Dissolved oxygen** *Biological oxygen demand, Chemical oxygen demand*	x	x	
Salinity	**Electrical conductivity** *Salinity, Total dissolved solids*	x	x	x
Nitrogen*	**Total oxidised nitrogen** *Total nitrogen, Nitrite, Ammoniacal nitrogen*	x	x	
	Nitrate**			x
Phosphorus	**Orthophosphate**	x	x	
	Total phosphorous			
Acidification	**pH**	x	x	x
***** Countries should include the fractions of N and P which are most relevant in the national context				
****** Nitrate is suggested for groundwater due to associated human health risks				

Organisational Issues

Significant issues for citizen science occur at the organisational level and include challenges such as lack of volunteer interest (Conrad & Daoust, 2008), low participation rates, and lack of participant diversity (Pandya, 2012) which will have to be seriously considered if citizen science is to be effectively applied to monitoring for SDG Indicator 6.3.2. Few water quality monitoring studies that have employed the efforts of citizen scientists reference difficulties with successfully engaging and retaining volunteers, though this appears to be due to a greater focus on discussing results and data quality and is unlikely to be due to these studies being free from organisational issues entirely. However, Scott & Frost (2017) discussed at length the number of approaches that were employed in order to engage volunteers in their study, having recognised that motivating participants to continue their involvement with a citizen science campaign is an important aspect to the campaign's success (Newman et al., 2011). Earthwatch incorporated gamification into the FreshWater Watch website which allowed volunteers to collect points based on activities completed involving science communication, water quality sampling and skills development. This points system also featured an automated feedback mechanism able to provide immediate feedback to participants (Scott & Frost, 2017), which has been shown as important for motivating citizen scientists (Lowry *et al*., 2019). Feedback was

provided through email, along with encouragement, to participants every 2-3 months, and volunteers were offered the chance to engage individually through meetings, fieldwork opportunities and web-based Q&A sessions. Results were also compiled into an annual report that was distributed to all participants at the end of a year, along with messages detailing how the research was progressing. Despite the application of all these engagement methods, the researchers found that participation rates were still too low (approximately 30%) to address fully the research question at hand, though this participation rate remains comparable to the FreshWater watch global average (approximately 27%) (Scott & Frost, 2017). The researchers also noted an inequality in sampling effort among the participants, which is not uncommon in citizen science projects (Lowry *et al*., 2019; McGoff *et al*., 2017; Sauermann and Franzoni, 2015; Shupe, 2017) yet would present an issue should citizen science be applied to monitoring for SDG Indicator 6.3.2. The study found that data were concentrated on a few ponds, rather than derived from many which, if considered with respect to the indicator, would not provide an accurate representation of national ambient water quality. As well as low participation rates and unequal sampling effort, lack of volunteer interest can also result in issues with data quality, with another study focused on using citizen science to monitor macroinvertebrates taking note of volunteers who rushed through identification during field days because they did not want to commit to staying for a 3-hour event (Nerbonne & Vondracek, 2003). On the other hand, sometimes the focus of interest in an investigation simply differs for volunteers and professional researchers, with one water quality study observing citizen scientists expressing a desire to focus research efforts on questions beyond the scope of the project (Jollymore *et al*., 2017). Monitoring programmes which are heavily scientist-led are less likely to address public interests (Shirk *et al*., 2012), which has been suggested as a potential limiting factor to volunteer motivation to contribute data in the long-run, as participants do not feel like they have ownership of the results or are considered partners working towards a common scientific goal (Rotman et al., 2014). A final issue worth mentioning is the lack of participant diversity in citizen science, with most volunteers being well educated, affluent members of majority groups (Overdevest *et al*., 2004; Pandya, 2012). Numerous reasons have been suggested as contributing to this lack of diversity, including a lack of access to natural settings for urban dwellers; lack of familiarity with science and research methods which can inhibit the participation of those with less formal education; and the challenge of

balancing citizen science commitments with other responsibilities, which is possibly greater for low-income individuals (Evans *et al*., 2005). Considering many developing nations could benefit significantly from the application of citizen science to the SDG Indicator 6.3.2 methodology (UNEP, 2018), this issue is of great importance.

Before citizen science can be applied to ambient water quality monitoring for SDG Indicator 6.3.2, these challenges must be addressed. Low participation rates and volunteer disinterest may be tackled through positive reinforcement of how their efforts are contributing to the goals of the programme or project (Conrad & Hilchey, 2011), which in the case of SDG Indicator 6.3.2 would be to gather sufficient data on ambient water quality to help target efforts to improve water quality. This communication between scientists and volunteers is critical to ensuring long-term participation and sustaining commitment over time (Rotman *et al*., 2014). Lowry *et al*. (2019) encourages the use of gamification in monitoring programmes in order to establish personal connections and gentle competition among participants that would invigorate them to engage repeatedly over time. Scott & Frost (2017) further suggest increasing the ease of sampling for citizen scientists, or limiting the duration and extent of sampling expected of participants. The success of the Florida LAKEWATCH monitoring programme suggests that making sampling easy and painless for participants is the key to continued volunteer engagement: as pointed out by Canfield *et al*. (2002), "*if you make the volunteer's life difficult, they will quit*". Increasing the level of oversight and interaction of volunteers with project researchers (Scott & Frost, 2017) and other volunteers could also prove effective, allowing for data checking and discussion in order to ensure the quality of volunteer data and increase volunteers' confidence in their results, thus motivating them to continue (Storey *et al*., 2016). A structured monitoring programme in which volunteers are told where and how often they must sample could further be used to combat unequal sampling efforts which could produce a biased image of national ambient water quality. Safford and Peters (2017) compared two volunteer water quality monitoring programmes, the Georgia Adopt-A-Stream (Georgia AAS) and University of Rhode Island Watershed Watch (URIWW), revealing that allowing citizen scientists to freely select where and how often to sample will result in less frequent sampling that is concentrated close to population centres, though participation rates will be high. Conversely, telling participants where and when to sample will increase the spatial and temporal scale of

sampling at the expense of participation rates (Safford and Peters 2017). Similarly, Scott & Frost (2017) discovered that volunteers' willingness to sample was influenced by ease of access and proximity to the study location. Safford and Peters (2017) therefore suggest a hybrid approach in which volunteers are encouraged but not required to gather data in under-sampled areas. This may prove to be the most useful approach for retaining participants and collecting sufficient data on SDG Indicator 6.3.2, as well as the subsequent calculation of a national indicator score, as the distribution of data would be more representative of national ambient water quality. Encouraging participation from a more diverse community of citizen scientists should also play a central role in the application of volunteer monitoring to the support of SDG Indicator 6.3.2. This could potentially be encouraged through the establishment of a suite of place-based, culturally-relevant, community-driven programmes (Pandya, 2012). Building personal networks has been discovered to be a valuable motivator for continued volunteer participation over time (Gooch, 2005; Ryan *et al*., 2001) - communication will therefore play an essential role in overcoming the organisational challenges facing citizen science before its application to ambient water quality monitoring as part of SDG Indicator 6.3.2.

Data Use Issues

Citizen science also suffers from issues surrounding data usage, with Conrad & Hilchey (2011) identifying it as one of the greatest challenges facing volunteer monitoring. Though many examples of volunteer water quality monitoring exist, and some volunteers do report data to state agencies for official uses (Overdevest *et al*., 2004), many projects are established primarily as education and outreach opportunities for citizens (Savan *et al*., 2003), with groups often finding that the data they have collected are never used in decision-making processes or published in the peer-reviewed scientific literature (Conrad & Hilchey, 2011). Concerns over data quality (Burgess *et al*., 2017) and difficulty getting the data to an appropriate journal or decision-maker have been cited as reasons for the limited use of volunteer data compared to the number of volunteer programmes operating (Milne *et al*., 2006; Conrad & Daoust 2008; Conrad & Hilchey, 2011). Many of the peer-reviewed studies

which have been published in recent years focus on the validation of citizen science data and few subsequently reveal any particular impacts on science, policy or society achieved by the monitoring activities. Scott & Frost (2017) focused on using citizen scientists to examine spatial and temporal variability in water quality in Toronto's urban stormwater ponds, while McGoff *et al*. (2017) trained citizen scientists to sample various types of waterbodies in search of nutrient trends, to reasonable success. Apart from these studies, which included data quality validation as part of a broader research question on water quality, most other studies focus primarily on data quality validation and do not reference use of the data beyond the scope of the study. Conversely, numerous examples of community-based water quality monitoring programmes having an impact on policy and decision-making have surfaced in recent years, such as the Neighborhood Pond Associations of Martha's Vineyard and University of Rhode Island Watershed Watch in the USA (Conrad & Hilchey, 2011), yet these impacts are not documented in the scientific literature to provide peer-reviewed evidence into how citizen science data can contribute to both science and society. This presents an issue for the use of citizen science to monitor ambient water quality for SDG Indicator 6.3.2, as little peer-reviewed scientific evidence exists to guide the process of successfully integrating volunteer data with those of professionals.

Attempting to use citizen science to support monitoring for the ambient water quality indicator and then not actually using the data gathered would prove a total waste of resources, therefore an organisational framework would need to be established prior to the first sampling by volunteers to reconcile many of the challenges that would inevitably appear (Milne et al. 2006). A basic framework outlined by Conrad & Daoust (2008) suggests a number of steps, including the identification of stakeholders, skills and resources and the creation of communication and monitoring plans, which may prove applicable for using citizen science as part of ambient water quality monitoring for SDG Indicator 6.3.2. Best practices would have to be reinforced in order to overcome issues with data quality and credibility that contribute to the lack of use of volunteer data (Conrad & Hilchey, 2011), and the best methods of integrating citizen science data with that of professionals for the purpose of supporting SDG Indicator 6.3.2 would need to be established. Based on research conducted by both Scott and Frost (2017) and McGoff *et al*. (2017) there may be potential for volunteer water quality monitoring to play a valuable part in the

identification of pollution “hotspots“ under SDG Indicator 6.3.2, i.e. areas where finer scale analysis is required by professionals. Quinlivan *et al.* (2019) also discusses the potential for citizen data to be integrated with that of professionals through the use of target ranges for SDG Indicator 6.3.2. It is essential that the questions surrounding the integration of volunteer and professional data on ambient water quality be answered long before citizen scientists take to the field to monitor ambient water quality.

Conclusions

The SDG Indicator 6.3.2 data drive in 2017 highlighted the differences in resources invested in ambient water quality monitoring across the world, with many developing countries able to calculate the indicator with full national coverage yet many developing nations unable to report due to insufficient data or a lack of operational monitoring programmes (UNEP, 2018). The United Nations has called for increased use of citizen science in scientific research in order to close the data gap that exists for SDG Indicator 6.3.2. Not all nations have the capacity to monitor ambient water quality for SDG Indicator 6.3.2 due to lack of financial resources, equipment and/or trained analytical staff; however, all nations possess passionate and motivated citizens willing to volunteer their time and efforts as citizen scientists. However, many challenges continue to hinder the use of this cost-effective resource in the field of water quality monitoring which must be addressed before it may be perceived as a reliable scientific approach. To overcome the particular challenges that prevent citizen science being used as a form of data gathering for SDG Indicator 6.3.2, a greater number of investigations are needed which firmly address the issues outlined above first-hand, specifically for the ambient water quality indicator. While numerous peer-reviewed investigations exist on the use of citizen science for ambient water quality monitoring, only one study to date has examined this topic for the purpose of SDG Indicator 6.3.2 specifically (Quinlivan *et al.*, 2019). This study focused solely on issues surrounding data collection and quality, yet a suite of other challenges common to citizen science monitoring have yet to be investigated with regard to the ambient water quality indicator. Further research is needed on how citizen data will be integrated with that of professionals for SDG Indicator 6.3.2, as well as how

researchers may appeal to the public in order to ensure long-term commitment to monitoring ambient water quality.

The SDG 6 Synthesis Report 2018 (United Nations, 2018) identified four main challenges to the achievement of this goal: political engagement, data scarcity, climate change and a financing gap. It suggests methods of good governance, capacity development, the elimination of inequalities, and use of smart technologies as solutions to these issues (United Nations, 2018). Most relevant to citizen science is the role it may play in closing the data gap that currently exists for SDG 6: Clean Water and Sanitation, and in particular SDG Indicator 6.3.2, the ambient water quality indicator. However it could be argued that citizen science can contribute in many more ways to the achievement of SDG 6. As noted in the synthesis report, "*public concern is often the instigator of change*" (United Nations, 2018). McKinley *et al.* (2017) examined how citizen science can improve conservation science, natural resource management, and environmental protection, and showed how citizen science has contributed to building scientific knowledge, informing policy and encouraging public action across the United States of America within the field of conservation biology. Therefore, the inclusion of citizen science as a means of data gathering for SDG Indicator 6.3.2 could potentially prove fundamental to driving political engagement and encouraging governments and communities across the world to invest available resources in the establishment of water quality monitoring programmes (United Nations, 2018). The potential for citizen science to have a positive and significant influence on our path to achieving the Sustainable Development Goals calls for greater effort to be put into encouraging the use of this cost-effective and abundant resource.

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Chapter 3: Validating Citizen Science Monitoring of Ambient Water Quality for the United Nations Sustainable Development Goals

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Introduction

As outlined in **Chapter 2**, SDG Indicator 6.3.2 is defined as the "proportion of bodies of water with good ambient water quality" (UNEP, 2018). Together with SDG Indicator 6.3.1 on the "proportion of wastewater safely treated", these indicators provide a means of monitoring progress towards achieving SDG Target 6.3 with the aim of improving global water quality. Due to the issues facing many Member States regarding the collection of sufficient data on ambient water quality, the United Nations has expressed significant interest in the potential for citizen science to contribute to supporting progress towards achieving SDG Indicator 6.3.2 (UNEP, 2018).

The five core water quality parameter groups of the ambient water quality SDG Indicator 6.3.2 (oxygen, salinity, nitrogen, phosphorus and acidification) may be measured using a range of simple and inexpensive field techniques that are accessible to citizen science networks (UNEP, 2018). Thus, where the proper resources are put in place to ensure responsible data collection and submission, citizen science networks could prove a vital source of additional data on ambient water quality by providing greater spatial and temporal coverage of data than is currently possible through the sole use of traditional, laboratory-based monitoring networks (UNEP, 2018). Yet challenges remain to the use of this potentially cost-effective resource for ambient water quality monitoring. One of the most significant barriers to the widespread use of citizen science is the perception of scientists who question the quality and reliability of data produced by non-professionals (Burgess *et al*., 2017; Fore *et al*., 2001; Penrose & Call, 1995; Riesch & Potter, 2013). Data quality issues are not isolated to citizen science monitoring programmes – experienced researchers also make errors.

However, the perception that volunteer-generated data would not be well received by the scientific community contributes to a prejudice against its use (Crall *et al*, 2011; Dickinson *et al*., 2010; Foster-Smith & Evans, 2003; Riesch & Potter, 2013). In contrast, numerous studies have shown that volunteers are capable of collecting data of equal quality to that of professional scientists, provided they are given the proper training and resources, and provided the study design matches the collectors' abilities, and many validation studies to date have reported the high standard of water quality data collected by citizen scientists (Dyer *et al*. 2014; Herman-Mercer *et al*., 2018; Levesque *et al*., 2017; Loiselle *et al*., 2016; Loperfido *et al*., 2010; McGoff *et al*., 2017; Muenich *et al*., 2016; Safford & Peters, 2017; Scott & Frost, 2017; Shelton, 2013; Thornhill *et al*., 2017; Thornhill *et al*., 2018; Wilderman & Monismith, 2016). Yet despite these numerous validation studies and the encouragement of public input with regard to monitoring for the ambient water quality SDG Indicator 6.3.2 (UNEP, 2018), only one published study to date has explored the potential for citizen science to support ambient water quality monitoring as part of the SDGs specifically, with a central focus on the quality of data collected by volunteers (Quinlivan *et al*., 2019).

This study chose to investigate some of the issues highlighted in **Chapter 2** on volunteer data collection, exploring whether a group of citizen scientists based in Killarney, Co. Kerry, Ireland, were capable of collecting high-quality data on a number of the core and alternative ambient water quality parameters associated with SDG Indicator 6.3.2. The citizen scientists conducted analyses on water samples using simple citizen science field kits provided by FreshWater Watch (https://freshwaterwatch.thewaterhub.org/), the freshwater initiative of the global NGO, Earthwatch (https://earthwatch.org/). The overall accuracy of the citizen science field kits was evaluated by comparison with an ISO/IEC 17025:2017 accredited laboratory in Co. Kerry, Ireland. The feasibility of citizen science to support monitoring of ambient water quality parameters for the SDGs was assessed. The challenges and opportunities encountered with applying this scientific approach to monitoring for the ambient water quality SDG Indicator 6.3.2 are discussed here.

Methods

Participant Recruitment

Participants were recruited from St. Brendan's College, Killarney, Co. Kerry, Ireland, from a class of 74 male students, between the ages of 16 and 17. Each student was given a screening survey to assess their interest in science, environmental issues and working outdoors. A total of 34 students were identified as potential participants for the project, based on the level of interest shown by their responses to the screening survey. They then took part in a briefing session and underwent training. The level of training among citizen scientists can influence the accuracy of monitoring data (Fore *et al*., 2001), therefore a mixture of both theoretical and practical training was provided to all potential participants. During the training session, students were taught about water quality issues within freshwater ecosystems and the background to the research project, namely the UN Sustainable Development Goals and the potential for citizen science to contribute to supporting SDG 6. FreshWater Watch training materials provided the baseline for training of all participants, and this was supplemented with a demonstration of the analysis techniques using water samples provided for the purpose of training. Having been split into small groups, the students were allowed time to practice using the analytical kits within the classroom under the supervision of the trainer, who was able to provide feedback and answer questions. Following this practical training session, all students were required to complete a training quiz, to confirm that the participants were sufficiently trained and that their results could be trusted for uploading to the FreshWater Watch global database (https://freshwaterwatch.thewaterhub.org/content/data-map). Based on the results of the training quiz, 28 students were selected to participate in the research study.

Site Description

Lough Leane is a freshwater lake located within Killarney National Park, draining a catchment of 553 km^2 near the town of Killarney, County Kerry in southwest Ireland. The rivers Flesk, Deenagh and Long Range are the main sources of input to Lough Leane, which flows to the Atlantic Ocean via the River Laune (Jennings *et al*., 2013). The Folly stream is a minor stream of approximately 1.5 km in length that drains a small area of roughly 0.9 km^2 and enters Lough Leane near Ross Bay. The main wastewater treatment plant for the town of Killarney is located 1km upstream of Ross Bay. Two Storm Water Overflows (SWOs) carrying untreated wastewater enter the

Folly stream during times when the WWTP is under stress from high-inputs (Irish Water, 2018).

The River Deenagh and Folly stream were identified as suitable for inclusion in this study due to the evident differences in water quality between the two waterbodies. Monitoring at the Folly stream has indicated that good status surface water standards for ammonia and biochemical oxygen demand (BOD) are exceeded both upstream and downstream of the wastewater treatment plant. Good status standard for orthophosphate is also exceeded downstream of the plant (Environmental Protection Agency, 2012). It was acknowledged in the last waste water discharge license application that the Folly stream was unable to accommodate the discharge from the WWTP, despite the fact that it operated well within its design parameters and capacity (Environmental Protection Agency, 2012). The Folly stream has appeared as a cause of local concern in recent years due to the deteriorating water quality, though it is currently not monitored by the EPA and is not assigned a status under the Water Framework Directive (Environmental Protection Agency, 2012). Conversely, a number of EPA monitoring stations are located along the length of the River Deenagh, with the most recent assessment determining that the two lower stations located near Killarney town achieved "Good" ecological status (Environmental Protection Agency, 2019). The differences in water quality between the two waterbodies allowed for an examination of the effectiveness of the FreshWater Watch equipment in more and less polluted environments.

A preliminary survey was carried out on 24th February 2019 and two sampling sites were carefully selected based on accessibility and safety, one located on the River Deenagh (52˚ 3' 17" N, -9˚ 31' 38" W) and another along the Folly stream (52˚ 2' 56" N, -9˚ 31' 44" W) (Figure 3.1). On the day of sampling conditions at both sites were calm with a steady water flow and average water levels. The sampling site at the River Deenagh was located upstream of a bridge and featured clear water and a rocky bottom with bank vegetation on one side of the river and a small pedestrian path on the other. The surrounding and overhead vegetation consisted of deciduous forest. The sampling site along the Folly stream featured murky water and a muddy bottom, with thick bank vegetation and a surrounding deciduous woodland.

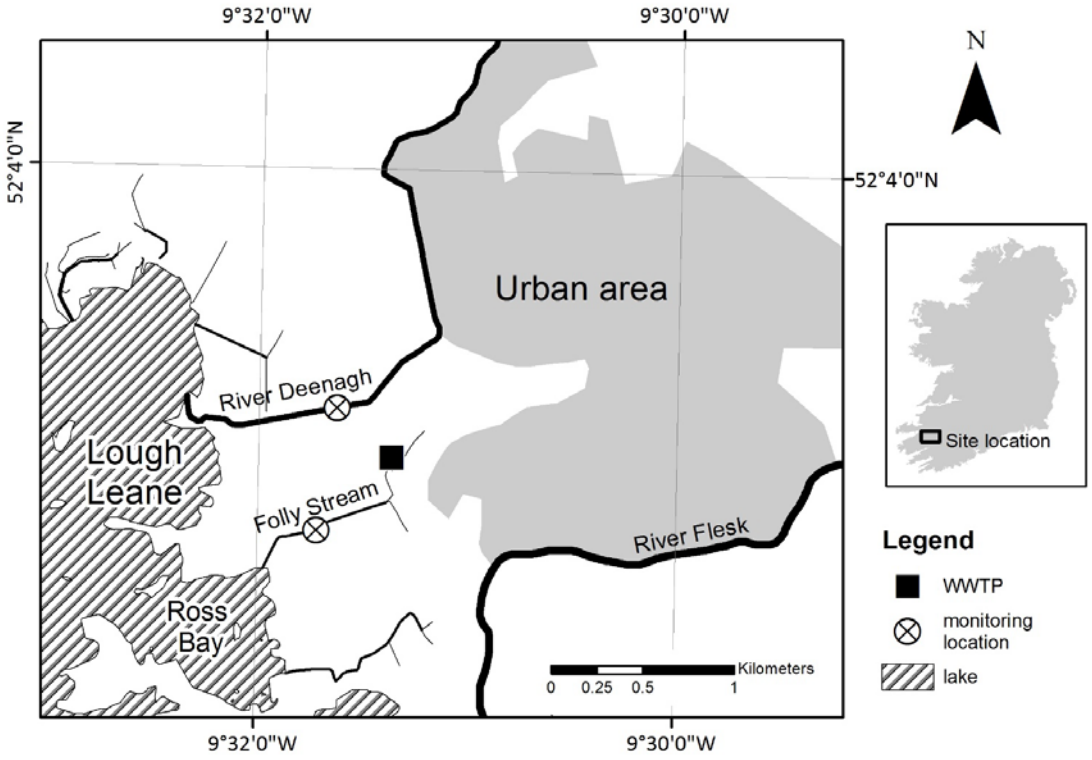


Figure 3.1. Locations of the monitoring sites within the River Deenagh and Folly Stream catchments in southwest Ireland.

SDG Indicator 6.3.2 Parameters

The five core water quality parameter groups for the ambient water quality SDG Indicator 6.3.2 are outlined in Table 3.1. Some parameters are included in the methodology in order to characterize the water quality in a particular waterbody, while others provide a direct measure of water quality for ecosystem or human health (UN Water, 2018). Deviation from normal ranges (such as with salinity and acidification) and comparison of measured values with target values (in the case of phosphorus, nitrogen and oxygen) allow for the detection of instances where the waterbody may be experiencing harmful impacts. This enables the classification of water quality as either "good" or "not good" in relation to these target values for each monitoring location. The classifications are aggregated by catchment, and then nationally, to generate the indicator percentage (UN Water, 2018).

The water quality data which feed into the indicator are derived from in-situ measurements and analysis of water samples. The citizen science field kits provided by FreshWater Watch (FWW) were capable of measuring four of the recommended

ambient water quality parameters: Orthophosphate, Nitrate, Electrical Conductivity and pH. The field kits did not include tests for the other recommended parameter, dissolved oxygen (DO), so Chemical oxygen demand (COD) was included here.

Table 3.1. Recommended monitoring parameters (in bold) required for the water quality index used for SDG Indicator 6.3.2 for three water body types. Alternative parameters (in italics) may be substituted for the recommended parameters, depending on data availability and applicability for specific water body types (UN Water, 2018).

Parameter group	Parameter	River	Lake	Groundwater
Oxygen	**Dissolved oxygen** *Biological oxygen demand, Chemical oxygen demand*	x	x	
Salinity	**Electrical conductivity** *Salinity, Total dissolved solids*	x	x	x
Nitrogen*	**Total oxidised nitrogen** *Total nitrogen, Nitrite, Ammoniacal nitrogen*	x	x	
	Nitrate**			x
Phosphorus	**Orthophosphate**	x	x	
	Total phosphorus			
Acidification	**pH**	x	x	x
***** Countries should include the fractions of N and P which are most relevant in the national context				
****** Nitrate is suggested for groundwater due to associated human health risks				

Citizen Analyses

Sampling took place on 22nd March 2019 as part of an activity for World Water Day. At each sampling site a large plastic bucket was first rinsed three times in the water from the sampling site. Taking care not to disturb the sediment, the bucket was then filled from the centre of the waterbody and placed in a secure location on the bank, where the sample water was mixed well with a clean plastic spatula. All sampling by citizen scientists was conducted using the sample water contained in the bucket, therefore minimizing any spatial and temporal differences between results. The samples taken for analysis at an accredited laboratory were also taken from the same sample of water in the same bucket.

Nitrate (NO_3-N), phosphate (PO_4-P) and chemical oxygen demand (COD) Kyoritsu PackTest (Kyoritsu Chemical-Check Lab, Corp., Tokyo, Japan) water chemistry kits were obtained from FreshWater Watch (Earthwatch Institute, Oxford,

United Kingdom). All parameters were measured in transparent plastic tubes which are designed to mix a small water sample with reagents that produce increasing colour values with increasing concentration (Scott & Frost, 2017). The PO_4-P method using 4-aminoantipyrine with phosphatase enzyme (Berti *et al*., 1988), and nitrate NO_3-N method using zinc and subsequently following the Greiss method (Nelson *et al*., 1954), provided nutrient concentrations that fell into one of seven categories ranging from <0.02 - >1.0 mg/L P and <0.2 - >10 mg/L N (Table 3.2) (Scott & Frost, 2017). Chemical oxygen demand was determined by an oxidation reaction with potassium permanganate in an alkaline medium, which provided concentrations ranging across seven categories from 0-5 to >100 mg/L O_2 (Table 3.2) (Kyoritsu, n.d.). pH was determined with Simplex Health (Simplex Health, Wollaston, United Kingdom) pH test strips which were held in the sample water for 3 seconds and subsequently matched to a colour chart. Electrical conductivity was measured using hand-held Lohand Biological (Hangzhou Lohand Biological Co., Ltd, China) conductivity meters dipped into the sample water for approximately 15 seconds until the reading in µS/cm stabilized (Table 3.2). Each participant received a copy of the instructions on how to conduct each test and recorded all their data on their own individual datasheet, covering both sites. Replicate samples were taken by citizens at each site – fourteen students sampled each parameter twice in Site 1 and three times in Site 2, while the other half of the participants did the opposite, thus taking a total of five measurements for each parameter across the two sites.

A total of 27 datasheets were received following sampling and one was rejected because it was incorrectly completed. Data analysis was conducted on the results collected by 26 participants in the study, resulting in a total of 66 measurements for most parameters at Site 1 and 64 measurements for each parameter at Site 2 (Table 3.5).

Table 3.2. Ranges of measurement of the equipment used by citizen scientists to analyse various water quality parameters at the River Deenagh and Folly stream.

Parameter	***Units***	**FWW Equipment Range**								
Orthophosphate	*mg/L P*	<0.02	0.02-0.05	0.05-0.1	0.1-0.2	0.2-0.5	0.5-1.0	>1.0		
Nitrate	*mg/L N*	<0.2	0.2-0.5	0.5-1.0	1.0-2.0	2.0-5.0	0.5-10.0	>10.0		
Chemical Oxygen Demand	*mg/L O2*	0.0-5.0	5.0-10.0	10.0-13.0	13.0-20.0	20.0-50.0	50.0-100.0	>100.0		
pH	*pH Unit*	< 4.5	4.5 – 5	5 – 5.5	5.5 – 5.75	Increments of 0.25 up to 7.5	7.5 - 8	8 – 8.5	8.5 - 9	> 9
Electrical Conductivity	*µS/cm*	10 - 1990 +/- 10 µS/cm precision								

Laboratory Analyses

At each site three samples were taken from the bucket of sample water and transported to the Southern Scientific Services laboratory at Farranfore, Co. Kerry within 20 minutes of collection for preservation and analysis. The laboratory holds ISO/IEC 17025:2017 accreditation for general requirements for the competence of testing and calibration laboratories (Southern Scientific Services, 2019). All methods used for the analysis of the various parameters are listed in Table 3.3. Orthophosphate and Nitrate were determined by spectrophotometry; pH and electrical conductivity were analysed using Rohasys MINILAB Multi Parameter robot (ROHASYS BV, Rijen, Netherlands); chemical oxygen demand was determined using a closed-reflux, colorimetric method (Table 3.3).

Table 3.3. Laboratory methods from Standard Methods for the Examination of Water and Wastewater 23rd Edition (Baird *et al*., 2017) used in the analysis of water samples as part of this study by the accredited laboratory.

Parameter	Standard Reference/SOP	Range of Measurement	Accuracy of Measurement	Equipment/Technique
Orthophosphate	APHA, 4500P-E, 23Ed., (2017) / SPC 027c	0.01-12 mg/L P	+/- 0.001	Spectrophotometry by Aquakem 250 Autoanalyser
Nitrate	APHA, 4500NO3-E, 23Ed., (2017) /SPC 027g	0.25-45 mg/L N	+/- 0.001	
Chemical Oxygen Demand	APHA, 5520D, 23Ed., (2017) / SPC 016	10-30,000 mg/L	+/- 0	HACH/Colorimetric
pH	APHA, 4500B-H+, 23Ed., (2017) / SPC 052	4 - 10 pH Units	+/- 0.01	Rohasys Minilab
Electrical Conductivity	APHA, 2510B, 23Ed., (2017) / SCP 052	14.7 -111,900 µS/cm @ 20°C	+/- 0.1	

Data Analyses and Considerations

The test kits provided by FreshWater Watch produced a categorical classification for the concentration of various water quality parameters within a sample of water. The categories for each parameter are outlined in Table 3.2. The outcomes of citizen scientist sampling are displayed in a frequency distribution table – the most frequently chosen concentration range, as well as the range containing the "true" laboratory value, are shown (Table 3.5). As the data are categorical, the concentration range containing the laboratory value could be considered the "correct" result, while results in all other categories could be considered incorrect. However due to the nature of the

testing kits and the colorimetric method by which a value is determined, difficulty can arise for users when deciding between concentration ranges, as there is no distinctive colour difference between one concentration range and the next. When the "true" laboratory value falls close to the border of one of the concentration ranges it is understandable for citizen scientists to struggle with choosing the correct result. For this reason, results recorded one concentration range outside the "correct" concentration range are included in the discussion on percentage agreement and the accuracy of citizen science monitoring of ambient water quality. Opinion is also divided on an adequate level of percentage agreement in research. To one researcher 70% agreement is adequate, whereas another would not consider 70% agreement a sufficient level to answer their research questions (Aceves-Bueno *et al*., 2017). A general rule of thumb describes an agreement level of 75% as a minimum acceptable level of agreement (Graham *et al*., 2012; Hartmann, 1977; Stemler, 2004). This was the acceptance level adopted by this investigation.

Results

Water Quality Testing

Table 3.4 shows the results of water quality analyses conducted by an accredited laboratory in Kerry on samples taken from the River Deenagh (Site 1) and Folly stream (Site 2). Results of analyses of the same water quality parameters by citizen scientists are displayed in Table 3.5, and the percentage of their results in agreement with those obtained by the laboratory are highlighted in bold (Table 3.5). Of the five ambient water quality parameters analysed, citizen scientists demonstrated good agreement in their measurements of three – Orthophosphate, Nitrate and Electrical Conductivity. The other two parameters, pH and Chemical Oxygen Demand, showed less agreement with the laboratory results (Table 3.5).

Across both sites the majority of volunteer results for Orthophosphate were either in agreement with the laboratory value or else fell into a concentration range just above or below this (Table 3.5a). A similar result can be seen for Nitrate where between 81.3-84.8% of results across both sites fell within or just outside the concentration range corresponding to the laboratory value for Nitrate (Table 3.5b). However, greater variation can be seen in the distribution of results outside this concentration range

(Table 3.5b). The results of electrical conductivity tests by citizen scientists at the River Deenagh were also positive, with 77.4% of results falling within or just outside the laboratory value of 180 µS/cm. At the Folly stream the results showed less agreement, with many citizen scientists overestimating the conductivity value at that site (Table 3.5e).

The results of Chemical Oxygen Demand tests were less compatible with the laboratory results; citizen scientists showed poor agreement of COD values in both the River Deenagh (0.0%) and Folly stream (2.6%) (Table 3.5c). The percentage of citizen scientist results recorded within or just outside the laboratory result was lower at 28.8% and 11.0% for sites 1 and 2 respectively. Citizen scientists were unable to measure pH accurately to within or just outside the concentration range agreeable with the laboratory result in either the River Deenagh (0.0%) or Folly stream (21.9%) (Table 3.5d).

The contrasting nature of the River Deenagh and Folly Stream is reflected in the results obtained by both citizen scientists and the accredited laboratory. Though Nitrate and pH levels did not appear to differ much between the two sites, Orthophosphate, Chemical Oxygen Demand and Electrical Conductivity levels were noticeably higher at the Folly Stream than in the River Deenagh (Tables 3.4 & 3.5). Irrespective of the levels of agreement between citizen and laboratory results, the volunteers and FWW testing kits were capable of revealing a difference in water quality between the two sites that supports current conclusions on the nature of these waterbodies.

Table 3.4. Results of analyses of water samples taken from the River Deenagh (Site 1) and Folly stream (Site 2) by an ISO/IEC 17025:2017 accredited laboratory. The means of the three laboratory analyses was calculated for each parameter and used for comparison with results gathered by citizen scientists.

Parameter	*Units*	Site 1				Site 2			
		Sample 1	Sample 2	Sample 3	Mean	Sample 1	Sample 2	Sample 3	Mean
Orthophosphate	*mg/L P*	0.02	0.01	0.02	0.02	0.10	0.10	0.10	0.10
Nitrate	*mg/L NO3-N*	2.4	2.5	2.6	2.5	2.5	2.4	2.4	2.4
Chemical Oxygen Demand	*mg/L O2*	<10	11	10	11	15	14	17	15
pH	*pH Unit*	7.5	7.5	7.5	7.5	7.2	7.1	7.1	7.1
Electrical Conductivity	*µS/cm @ 20˚C*	180	179	180	180	427	434	432	431

Table 3.5. Results of citizen scientist water quality sampling at the River Deenagh (Site 1) and Folly stream (Site 2) using the FreshWater Watch water quality testing kits. The number and percentage of results obtained by citizen scientists within each concentration range are shown. The citizen scientist

results in agreement with the results obtained for each parameter by an accredited laboratory are highlighted in bold.

a) Orthophosphate			b) Nitrate			c) Chemical Oxygen Demand		
Range (mg/L P)	**Site 1 Results**	**Site 2 Results**	**Range (mg/L N)**	**Site 1 Results**	**Site 2 Results**	**Range (mg/L O2)**	**Site 1 Results**	**Site 2 Results**
<0.02	29 (43.9%)	0 (0.0%)	<0.2	0 (0.0%)	0 (0.0%)	0.0-5.0	46 (69.7%)	22 (34.4%)
0.02-0.05	***35 (53.0%)***	13 (20.3%)	0.2-0.5	1 (1.5%)	6 (9.4%)	5.0-10.0	19 (28.8%)	35 (54.7%)
0.05-0.1	2 (3.0%)	*27 (42.2%)*	0.5-1.0	9 (13.6%)	5 (7.8%)	10.0-13.0	***0 (0.0%)***	4 (6.3%)
0.1-0.2	0 (0.0%)	***23 (35.9%)***	1.0-2.0	12 (18.2%)	4 (6.3%)	13.0-20.0	0 (0.0%)	***2 (3.1%)***
0.2-0.5	0 (0.0%)	1 (1.6%)	2.0-5.0	***42 (63.6%)***	***31 (48.4%)***	20.0-50.0	1 (1.5%)	1 (1.6%)
0.5-1.0	0 (0.0%)	0 (0.0%)	0.5-10.0	2 (3.0%)	17 (26.6%)	50.0-100.0	0 (0.0%)	0 (0.0%)
>1.0	0 (0.0%)	0 (0.0%)	>10.0	0 (0.0%)	1 (1.6%)	>100.0	0 (0.0%)	0 (0.0%)
Total	66 (100.0%)	64 (100.0%)	Total	66 (100.0%)	64 (100.0%)	Total	66 (100.0%)	64 (100.0%)

d) pH		
Range (pH Units)	**Site 1 Results**	**Site 2 Results**
< 4.5	0 (0.0%)	0 (0.0%)
4.5 – 5	0 (0.0%)	0 (0.0%)
5 – 5.5	10 (15.2%)	0 (0.0%)
5.5 – 5.75	45 (68.2%)	2 (3.1%)
5.75 – 6	8 (12.1%)	14 (21.9%)
6 – 6.25	2 (3.0%)	26 (40.6%)
6.25 – 6.5	1 (1.5%)	4 (6.3%)
6.5 – 6.75	0 (0.0%)	2 (3.1%)
6.75 - 7	0 (0.0%)	1 (1.6%)
7 – 7.25	0 (0.0%)	***6 (9.4%)***
7.25 – 7.5	*0 (0.0%)*	7 (10.9%)
7.5 - 8	***0 (0.0%)***	2 (3.1%)
8 – 8.5	0 (0.0%)	0 (0.0%)
8.5 - 9	0 (0.0%)	0 (0.0%)
> 9	0 (0.0%)	0 (0.0%)
Total	66 (100.0%)	64 (100.0%)

e) Electrical Conductivity			
Range (µS/cm)	**Results Site 1**	**Range (µS/cm)**	**Results Site 2**
110	1 (1.6%)	410	1 (1.6%)
130	4 (6.5%)	420	8 (12.9%)
150	3 (4.8%)	430	***10 (16.1%)***
160	6 (9.7%)	440	11 (17.7%)
170	*15 (24.2%)*	450	20 (32.3%)
180	**30 (48.4%)**	460	9 (14.5%)
190	3 (4.8%)	470	1 (1.6%)
		480	2 (3.2%)
Total	62 (100.0%)	Total	62 (100.0%)

Discussion

Can citizen science help support monitoring for SDG Indicator 6.3.2?

Overall the results of the water quality analyses indicated that citizen scientists were able to measure water quality parameters to within or just outside the laboratory value for between 79.7% and 99.9% of measurements for Orthophosphate and Nitrate, establishing them as two of the parameters most compatible with the laboratory results (Table 3.5a-b). Electrical conductivity measurements were a little more variable, with between 46.7% and 82.3% of results falling within or just outside the laboratory value (Table 3.5e). Chemical oxygen demand and pH were the parameters showing the least agreement with the laboratory results (Table 3.5c-d). Concentration ranges just outside the concentration range containing the laboratory result were taken into account when discussing percentage agreement and the overall accuracy of results. While this was deemed necessary to account for the difficulty volunteers experienced in choosing between concentration ranges due to the colorimetric nature of the testing kit, it must be recognized that this method likely overestimates the percentage agreement due to the inclusion of results at the extreme, opposite ends of the outer concentration ranges which were not in any way misinterpreted.

The five water quality parameters chosen for inclusion in this research study form the basis of the most basic monitoring level for ambient water quality under SDG Indicator 6.3.2, the ambient water quality indicator for SDG 6 (UNEP, 2018). Results of citizen testing of Orthophosphate, Nitrate and Electrical Conductivity proved reasonably accurate based on the percentages of results in agreement with laboratory analyses for these parameters (Table 3.5a-b & 3.5e). This was partly expected for both nutrient tests given the positive conclusions drawn by other researchers who have used the Kyoritsu PackTest water chemistry kits provided through FreshWater Watch to allow citizen scientists to measure Orthophosphate and Nitrate (Levesque *et al*., 2017; Loiselle *et al*., 2016; McGoff *et al*., 2017; Scott & Frost, 2017; Shupe, 2017; Thornhill *et al*., 2017; Thornhill *et al*., 2018; Xu *et al*., 2017). Two of these studies (Levesque *et al*., 2017; Thornhill *et al*., 2017) noted that between 65.8% and 81% of results obtained by citizen scientists for both parameters were in agreement with laboratory results, a slightly higher level of agreement than was noted in this investigation. Interest level has been identified as an important motivational variable in a student's

academic performance and an influencing factor in how much attention is paid to a particular activity (Hidi & Harackiewicz, 2000; Schiefele, 1991, 1996). It is therefore possible that the slightly lower level of agreement with laboratory results witnessed in this study compared to others involving FreshWater Watch volunteers could be attributed to lower interest levels on the parts of the students, compared to those of volunteers giving time out of their everyday schedule. An investigation into whether differences in interest levels influence the accuracy of results obtained using the kits may prove beneficial for recruitment purposes for future citizen science projects. Other published research studies focusing on testing water quality using citizen scientists have opted for the use of total reactive phosphorus (Hach Aquacheck Cat. 27571-50) and nitrate field test strips (HACH, 2745425; Hach Aquacheck Cat. 27454-25) (Loperfido *et al*., 2010; Muenich *et al*., 2016) and observed mixed results. No other published studies could be found on citizen science water quality testing involving the use of the Lohand Biological meters for conductivity. The performance of the meters in the field and their agreement with the laboratory results was very good at the River Deenagh (Table 3.5e), though they did not perform as well at Folly stream, potentially indicating that they are less reliable in more polluted environments. Other published studies have made use of YSI Professional Plus multi-probes (Shelton, 2013), EuTech ECTestr™ 11 probes (Storey *et al*., 2016), Oakton PCtestr meters (Shupe, 2017), and the LaMotte PockeTester meter (Wilderman & Monismith, 2016) for measuring electrical conductivity and have reached mostly positive conclusions on their use. However, while also useful, these instruments are considerably more expensive than the Lohand Biological meters provided through FreshWater Watch.

The test for Chemical Oxygen Demand followed an identical procedure to those used for Orthophosphate and Nitrate, albeit with a slightly longer time for colour development before reading the result, yet the accuracy of the results was vastly different (Table 3.5c). The test procedure for pH was also extremely simple, involving dipping a Simplex Health test strip into the water for 3 seconds and determining the result after 15 seconds. The simplicity of these tests would suggest that less accurate measurements of both parameters potentially stemmed from a difficulty in interpreting the results rather than a difficulty in correctly carrying out the tests themselves (Table 3.5c-d). Further investigations using these tests may prove beneficial in determining their accuracy, and the ease with which results can be interpreted, before they could be applied to routine monitoring of ambient water quality for the Sustainable

Development Goals. Other published studies have investigated pH using pH field test strips (Sigma-Aldrich, P-4411; Aquaspex™ pH-Fix 4.5-10.0) (Muenich *et al*., 2016; Storey *et al*., 2016) and Oakton PCtestr meters (Shupe, 2017) with mixed reviews. Citizen science studies to date measuring dissolved oxygen have made use of the YSI Professional Plus multi-probes (Shelton, 2013) and LaMotte Direct Reading Titrator kits (Storey *et al*., 2016) with mixed results. This study measured Chemical Oxygen Demand as an alternative to dissolved oxygen, yet also recorded mixed results on the test's accuracy, possibly suggesting that the technology behind citizen science tests has not yet advanced to the stage where accurate measurements of oxygen or oxygen demand can be taken (Table 3.5c). However, given the multitude of published studies revealing positive results for orthophosphate, nitrate and electrical conductivity with the use of various citizen science equipment, finding affordable and reliable testing equipment for these parameters especially should not be too great a challenge. This may allow for the initial establishment of citizen science as a core source of support for ambient water quality monitoring as part of the SDGs.

As noted above, the percentage agreement between citizen scientist and laboratory results was slightly lower in this investigation than in others involving FreshWater Watch volunteers using identical testing equipment (Levesque *et al*., 2017; Thornhill *et al*., 2017). While the lower interest levels of the students may have had an effect on the accuracy of the results, neither study carried out by Levesque *et al*., (2017) or Thornhill *et al*., (2017) revealed a 100% agreement rate between volunteer and laboratory results. This may suggest that while interest and training levels do hold some influence over operator error and the accuracy of results (Fore *et al*., 2001), technology is the main limiting factor when it comes to the accuracy and success of citizen science. Though technology has been a huge contributor to the advancement of citizen science in recent decades (Silvertown, 2009) it also remains as a barrier in certain circumstances where it is considered unreliable or unaffordable. Other published studies have opted for the use of more accurate equipment with positive results (Shelton, 2013), though this is unrealistic for most citizen science programmes due to the substantial associated cost. Though extremely affordable, a limitation of the equipment provided by FreshWater Watch for the purpose of monitoring for the ambient water quality indicator is the colorimetric method by which the range of values is determined. This rather subjective process provides difficulty for the user when determining whether the result lies within one range or another when

the true result may in fact lie on the border of the kit ranges. This happened at both sites in this study when analyzing Orthophosphate, for example (Tables 3.2 & 3.4). Other studies using the same equipment provided by FWW have also cited difficulties in determining results where the existence of low nutrient concentrations means results falling into the two lowest concentration categories limit finer scale analysis of nutrient patterns (Levesque *et al*., 2017; Scott & Frost, 2017). A review by Newman *et al*., (2012) into the future of citizen science using emerging technologies concluded that future citizen science programmes will need to "choose appropriate technology" for the project participants. Based on these observations, it is clear that further advancements in technology, whether to produce a more precise and accurate result that cannot be misinterpreted, or to allow for easer interpretation of a more ambiguous result, are still necessary before citizen monitoring may be accepted as reliable enough to support data collection on ambient water quality as part of SDG 6: "Clean Water and Sanitation".

On the other hand, adjustments to the assessment methods themselves may further increase the ease with which citizen and professional data may be integrated for the purpose of ambient water quality monitoring. During the global roll-out of the ambient water quality SDG Indicator 6.3.2 a number of challenges regarding the methodology were identified, namely issues surrounding the establishment of target values to determine whether a waterbody has good ambient water quality or not. The current method of determining an absolute measure of water quality through the comparison of measured values with target values is greatly influenced by the target values selected, and thus could result in misleading interpretations of water quality depending on whether the target values selected are lenient or strict (UNEP, 2018). As this study has revealed, while citizen science cannot provide numerical measures of the parameters for the ambient water quality indicator that are as accurate as those obtained by an accredited laboratory, it can indicate a concentration range for each parameter (Table 3.5a-b & 3.5e). Citizen science may therefore be more applicable to a monitoring methodology in which the focus shifts from target values to target ranges, allowing for the easier integration of citizen science data with that of professionals. A less specific assessment method, in which the results of water quality tests may encompass a range of values rather than conforming to a black-or-white target value may therefore prove more approachable and applicable for citizen science monitoring networks hoping to aid in the determination of ambient water quality. Assessing the

appropriateness of potential methods for applying citizen science monitoring to target ranges in support of the ambient water quality SDG Indicator 6.3.2 should prove an important focus of future studies. Another factor which must be considered is the comparability of citizen science data worldwide. Differences in study design and data validation procedures have oftentimes resulted in difficulty when determining the accuracy of citizen science (Storey *et al*., 2016). This study therefore chose to assess the quality of citizen data through comparisons made with professionally-generated laboratory data, a validation procedure common in citizen science water quality monitoring programmes (Muenich *et al*., 2016; Levesque *et al*., 2017; Loiselle *et al*., 2016; Scott & Frost, 2017; Thornhill *et al*., 2017; Thornhill *et al*., 2018). When it comes to applying citizen science monitoring programmes to the collection of data on ambient water quality for SDG Indicator 6.3.2, guidelines and protocols will have to be clearly established in order to allow for the generation of comparable data, as is the case with laboratory results worldwide through the use of Standard Operating Procedures (SOPs). At the time of writing FreshWater Watch had collected 22,092 datasets on water quality throughout the world, over 10,000 in Europe alone. While this database is a wonderful resource for comparing water quality worldwide through the use of FreshWater Watch testing equipment, comparisons and the integration of data with other citizen science programmes will prove complicated should the advantages offered by the collection of vast amounts of data be overcome by the unavoidable biases introduced via the use of different testing kits and procedures. Careful consideration must therefore be given to how citizen science may be used to effectively support the monitoring of ambient water quality for the Sustainable Development Goals when there currently exists so many options for testing equipment, as evidenced above. While greater leniency is called for through the use of target ranges for monitoring under the ambient water quality indicator, stricter regulations will need to be put in place in order to establish the guidelines and protocols necessary to ensure the generation of high-quality and intercomparable volunteer data on ambient water quality. These considerations would allow for the production of more comparable data in both developed and developing nations with well-established citizen science communities. Applying citizen science in an approach as such should also allow for the more effective integration of volunteer monitoring programmes with current professional activities in developing nations where a lack of

capacity to collect and analyse water quality data required for SDG Indicator 6.3.2 hinders their ability to report on ambient water quality (United Nations, 2018).

Conclusions

This study assessed the applicability and feasibility for citizen science to contribute high-quality data towards monitoring activities supporting SDG Indicator 6.3.2 on the "Proportion of bodies of water with good ambient water quality". It showed that trained citizen scientists can produce data on Electrical Conductivity and on Orthophosphate and Nitrate concentrations, in two Irish waterbodies, that agreed with the analysis of these parameters at an accredited laboratory. However, technology proved a limiting factor and the precision and accuracy of the tests used for Chemical Oxygen Demand and pH need further development. Through the positive conclusions drawn for three of the five water quality parameters analysed, this study has demonstrated the potential of citizen science to contribute to water quality monitoring for the Sustainable Development Goals. The limitations in accuracy of the field kits used here may present challenges for how the data can be integrated into existing monitoring activities, which should form the basis of future investigations.

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Chapter 4: An Examination of Attitudes and Interest Following Involvement in an SDG-focused Citizen Science Study

Introduction

As pointed out in **Chapters 2 and 3**, the United Nations has encouraged greater participation of volunteers in scientific research relating to the Sustainable Development Goals, including the SDG Indicator 6.3.2 on the "proportion of bodies of water with good ambient water quality" (UNEP, 2018). Many challenges exist with incorporating citizen science data into the reporting methodology for SDG Indicator 6.3.2, yet the potential for citizen science to support monitoring for the indicator has been well recognised (UNEP, 2018). As outlined in **Chapter 2**, organisational issues present one of the key challenges to the widespread adoption of citizen science in environmental monitoring. Therefore, if citizen science is to someday become a prominent feature of SDG Indicator 6.3.2 monitoring it is critically important that researchers understand how the experience of participating in a water quality monitoring programme focusing specifically on the SDG Indicator 6.3.2 influences volunteer interest levels, attitudes, behaviour and motivation to continue participating and engaging with a programme.

Citizen science holds many of the same characteristics as free-choice learning, often considered an important aspect in the development of scientific literacy (Falk & Dierking, 2010; Falk *et al*., 2007), and is based on the concept of experiential learning, in which effective learning takes place as part of a transformative experience (Kolb, 1984; Price & Lee, 2013). Through citizen science, participants work on real and pressing research problems, collecting and analyzing data and establishing a connection to it in the same way a professional researcher would (Price & Lee, 2013). Citizen science can furthermore foster environmental stewardship through encouraging participants to care more for their local environment and thus develop a sense of place, which in turn inspires greater engagement in decision-making processes (Ballard *et al*., 2016; Evans *et al*., 2005; Newman *et al*., 2017; Zerbe and Wilderman, 2010). The engagement of participants in conservation actions has also been cited by authors to result from the development of pro-environmental attitudes

and behaviours following participation in citizen science projects, though this area has not been well documented (Cooper *et al*., 2007; Danielsen *et al*., 2009). This research study did not attempt to answer the complex questions that surround volunteer motivation and behaviour change, but to simply assess changes to the attitudes and interest levels of volunteers following their participation in a citizen science study aimed at examining the applicability of citizen science to monitor for SDG Indicator 6.3.2. Citizen scientists' interest levels in various fields, as well as any potential changes to their attitudes towards environmental science were investigated through the use of simple surveys in order to explore the potential for SDG Indicator 6.3.2 monitoring to promote environmental awareness and stewardship.

Methods

*The volunteers participated in the study conducted by Quinlivan et al. (2019), outlined in **Chapter 3**, as part of an investigation into the use of citizen science for water quality monitoring under the SDG Indicator 6.3.2.*

When participants for the project were first being identified they were given a screening survey to assess their interest in science, environmental issues and working outdoors. At this point no participant had any knowledge that a project was taking place or that they were being screened for interest as part of the project. The screening survey was offered to 74 students, of which 28 participated in the study and results from 26 were included as part of data analyses. The participants self-identified as 88% male and 12% did not choose a gender. The mean age was 16 years old.

Following field sampling on 22nd March, the 26 participants received a survey to gauge their experience of taking part in an SDG-focused citizen science water quality monitoring study and to assess whether participation in the research project resulted in a change in their attitudes and interests towards environmental issues. A total of 26 students completed the survey (N = 26). Responses were scored using a 5-point Likert scale by assigning categories a "1" for "Strongly Disagree," "2" for "Disagree," "3" for "Not sure," "4" for "Agree," and "5" for "Strongly Agree", or similarly for "Not at all interested", "Not very interested", "Neither interested or disinterested", "A little interested", and "Very interested". Unanswered questions

were treated as missing data. Participants were also offered the opportunity to provide further comments and recommendations on their experience of the study. The survey instrument asked questions focusing on the volunteers' level of confidence in using the water testing kits and the training they received, as well as other questions on their perceptions of skills and knowledge development, changes in their interest levels and behaviour, and demographic information.

Results

The before and after survey responses from students showed an increase in their interest in various subjects such as global development, environmental and water science and sustainability (Figure 4.1a-d). A greater number of students regarded themselves as being "a little interested" or "very interested", as can be seen from the higher percentages of students identifying themselves as falling within these interest categories after completion of the study (Figure 4.1a-d). The most notable change came in the students' attitudes to environmental science and water-related science, where 80.8% of students regarded themselves as having an interest in environmental science following the study, compared with 53.9% before taking part. Similarly, following the study interest in water science increased by 26.9%, from 50% of students to 76.9% (Figures 4.1c and 4.1d).

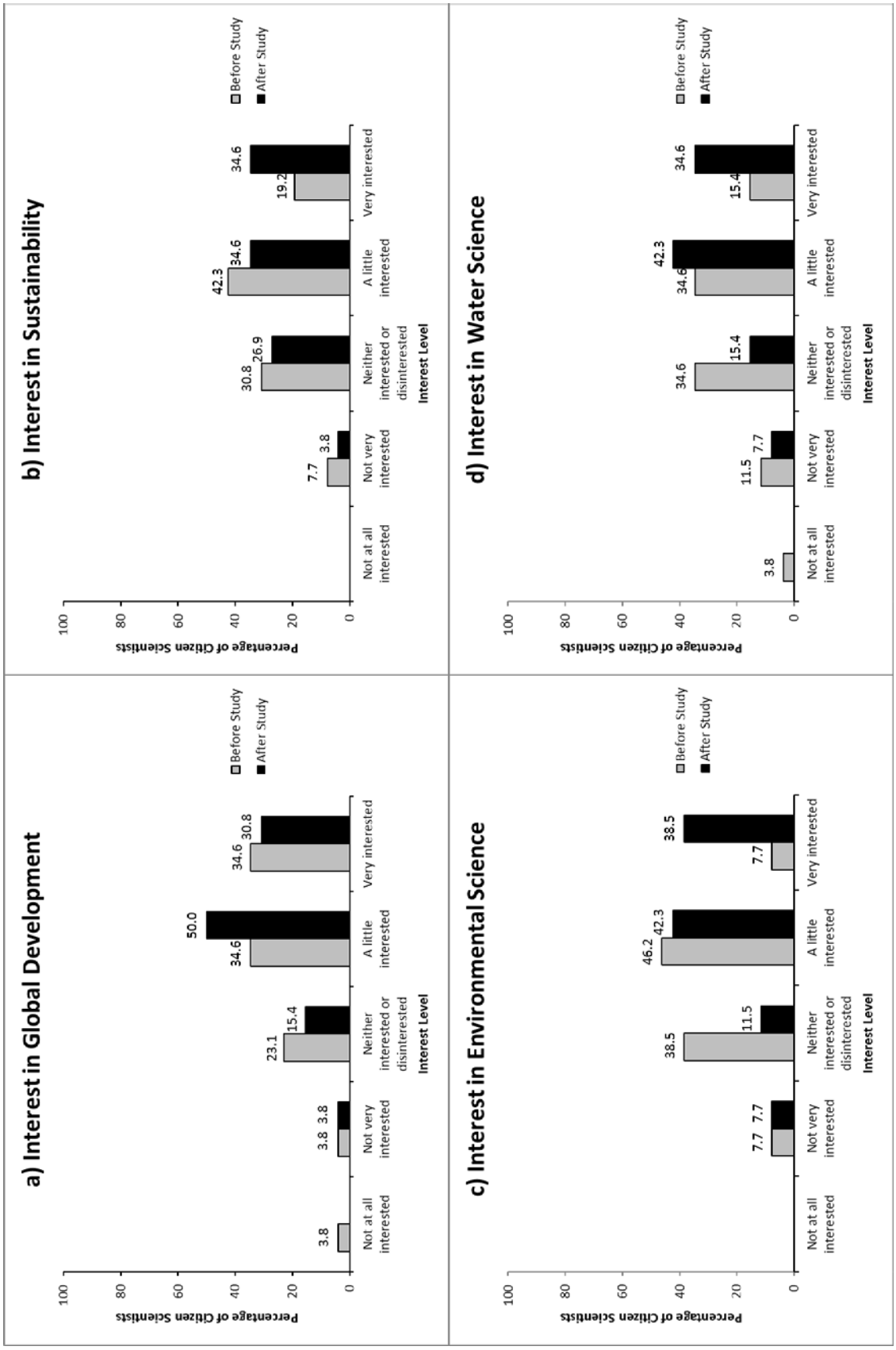


Figure 4.1. Percentage of citizen scientists and their corresponding level of interest in various topics preceding and following participation in a citizen science water quality monitoring programme.

Other survey responses indicated that the majority (96-100%) of participants agreed that they felt confident using the citizen science field equipment provided as part of the study to measure the five water quality parameters mentioned above (Table 4.1). Most (88.4%) citizens agreed that they received enough training to take water quality measurements correctly, although responses to whether additional training beyond the baseline level provided would have been helpful were mixed (Table 4.1). The majority of participants, 96.2%, said that they enjoyed taking part in the study and 84.6% agreed that they would participate in a research project similar to this again. The majority also felt that they had gained a better understanding of the importance of water quality, as well as new skills and knowledge, following their participation in the study, and agreed that they would now make a greater effort to protect water quality in future (Table 4.1). A total of 86.4% of participants agreed that they would participate in a citizen science water quality monitoring programme in future (Table 4.1). Respondents also commented that the study was very interesting while others felt that the whole process would have been much faster had the citizens had more training.

Table 4.1. Survey responses from participants (n = 26) of a citizen science water quality monitoring study focusing on their experience of the research project.

Statement	Response (% of Participants)				
	Strongly disagree	Disagree	Not sure	Agree	Strongly agree
I felt confident that I was using the FWW kit to correctly measure Orthophosphate	0.0	0.0	3.8	46.2	50.0
I felt confident that I was using the FWW kit to correctly measure Total Oxidised Nitrogen	0.0	0.0	0.0	50.0	50.0
I felt confident that I was using the FWW probes to correctly measure Electrical Conductivity	0.0	0.0	3.8	42.3	53.8
I felt confident that I was using the FWW dip sticks to correctly measure pH	0.0	0.0	3.8	61.5	34.6
I felt confident that I was using the FWW kit to correctly measure Chemical Oxygen Demand	0.0	0.0	0.0	46.2	53.8
I would have preferred more training before using the kits in the field	15.4	46.2	3.8	23.1	11.5
I believe that I used the equipment correctly	0.0	0.0	15.4	53.8	30.8
I received enough training to take measurements correctly	0.0	3.8	7.7	76.9	11.5
I believe that my results are of high quality	0.0	0.0	19.2	65.4	15.4
I would like to know how my results are used in future	0.0	0.0	15.4	42.3	42.3
I enjoyed taking part in this study	0.0	3.8	0.0	42.3	53.8
I would participate in a study like this again	0.0	0.0	15.4	38.5	46.2
I have a better understanding of the importance of water quality after taking part in this study	0.0	0.0	7.7	46.2	42.3
I learned new skills during this study	0.0	0.0	3.8	46.2	50.0
I gained knowledge during this study that I can use in future	0.0	3.8	19.2	69.2	7.7
I will make a greater effort to protect water quality in future	0.0	0.0	11.5	61.5	26.9
I would participate in a citizen science water quality monitoring programme in future	0.0	0.0	15.4	50.0	34.6
This study was easy to take part in	0.0	0.0	0.0	46.2	53.8

Discussion

If one of the goals of citizen science is to bring the public and science closer together, then greater effort is needed to engage a wider variety of audiences and participants. Citizen science projects involving students have great potential for engaging underserved participants as students often have no choice but to participate once their teacher has chosen to involve them in such projects (Bonney *et al*., 2016). While the students who participated in this research study had been screened for interest in the project's subject matter and were always given a choice as to whether or not they wanted to participate, citizen scientists are typically well educated, affluent members of the public who volunteer their time to be involved in a project (Bonney *et al*., 2016). The students chosen for this study, therefore, could not be considered a particularly representative group of citizen scientists. Nonetheless, the students who participated reported many of the same social outcomes for the project as other citizen science projects involving volunteers, i.e. greater understanding of certain ecological and science content (Brossard *et al*., 2005; Evans *et al*., 2005), the development of new skills (Evans *et al*., 2005), and a possible commitment to carrying out future environmental stewardship activities (Crall *et al*., 2012) (Table 4.1).

Survey responses revealed that following the project, the majority of students (88.5%) showed greater appreciation of the importance of water quality, as well as more positive attitudes towards protecting it (88.4%) (Table 4.1). While participating in a citizen science programme cannot guarantee changes in behaviour and conservation actions, this result does support the idea that citizen science may encourage participants to make different personal choices and change their own management practices (Brossard et al., 2005; Cooper et al., 2007; Danielsen et al., 2005; Danielsen et al., 2007; Johnson et al., 2014; Jordan et al., 2011; Stepenuck and Green, 2015). First-hand experience of engaging with research relating to local environmental issues appears to make citizens more responsive to issues of personal interest to them, as they deepen their relationship with the local environment and develop a sense of place (Ballard *et al*., 2016; Evans *et al*., 2005; Newman *et al*., 2017; Zerbe & Wilderman, 2010). It was therefore somewhat expected that participants would report much greater interest in areas such as environmental and water-related sciences following their participation in the study, given the fact that the research was

conducted on local waterbodies located in close proximity to the students' school (Figures 4.1c and 4.1d). On the other hand, results would also appear to show that participation in a study focusing on the UN Sustainable Development Goals can also affect the participants' interest in topics of a more global nature, as can be seen from the increases to the participants' level of interest in global development and sustainability (Figures 4.1a and 4.1b). While changes to the interest levels of participants have not been noted as part of a study focusing specifically on the SDGs, they have been previously observed in other citizen science investigations. Miller *et al*. (2018), for example, noted changes to students interest levels in science, technology, engineering and mathematics (STEM) following participation in volunteer STEM competitions, corresponding to a 5% greater likelihood of interest in pursuing a STEM-related career at the end of high school. Similarly, the majority of students that took part in this study reported an interest in participating in a citizen science water quality monitoring programme in future (Table 4.1). While this expression of interest in taking part in a monitoring programme is positive with regard to how citizen science could potentially be used to support SDG Indicator 6.3.2, the response does not offer any assurance as to whether the students will ever go on to act on this interest. Changes to interest levels and attitudes do not necessarily imply changes in behaviour, as has been noted by the existence of a "gap" between attitudes towards the environment and related conservation behaviours (Kaiser *et al*., 1999; Kollmuss & Agyeman, 2002). It has been noted that participation in citizen science sometimes leads to changes at the individual level, for example, becoming more environmentally conscious with regard to personal decisions, whereas involvement in further collective management efforts is a less common outcome (Overdevest et al. 2004; Jordan et al. 2012). In order to leverage the full power of citizen science for supporting SDG Indicator 6.3.2, more research is needed on how citizen science can promote conservation action, as well as increased interest, with regard to protecting ambient water quality.

Conclusion

Understanding how environmental and science learning and education can be related to conservation behaviours and attitudes is perhaps essential for addressing current

and future global conservation challenges, such as degrading water quality, for example (Monroe, 2003). Documenting the impact of participation in citizen science on learning and other social outcomes is not a straightforward task, however, particularly because of the suite of intrinsic and extrinsic variables which collectively impact on the connection between environmental learning and conservation behaviours (Heimlich & Ardoin, 2008). However, a lack of knowledge on this topic can hinder effective design and development of future citizen science projects (Jordan *et al*., 2012). Citizen science is only now being explored for its applicability to support monitoring for SDG Indicator 6.3.2 (Quinlivan *et al*., 2019). This simple investigation is the first to examine the potential social and educational outcomes stemming from participation in a citizen science water quality monitoring study focused specifically on monitoring for SDG Indicator 6.3.2. Although somewhat basic in approach, this examination of the attitudes and changes to the interest levels of participants following their participation in the study offers promising results for the future application of citizen science to water quality monitoring as part of supporting SDG Indicator 6.3.2.

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Chapter 5: Assessing Potential Use Methods for Citizen Science Data as Part of the SDG Indicator 6.3.2 Methodology

Introduction

As discussed in **Chapters 2 and 3**, the ambient water quality SDG Indicator 6.3.2 provides a means of determining the effectiveness of water quality management measures at improving the water quality in inland water bodies, an essential aim in the fight to both preserve aquatic ecosystems and their services and protect human health (UN Water, 2018). The methodology established for the monitoring and calculation of SDG Indicator 6.3.2 recognises that countries have different capacity levels to monitor water quality. While developed countries often have the capacity to report on the indictor through means beyond the scope of the SDG Indicator 6.3.2 methodology, many developing countries either operate limited monitoring programmes or are completely prevented from monitoring water quality due to lack of resources (UN Water, 2018). The methodology therefore aims to enable these countries to contribute to the global indicator through whatever means they can, while research continues on the most feasible methods for incorporating additional data sources such as citizen science projects into the reporting methodology (UNEP, 2018). As was pointed out in **Chapter 2**, numerous volunteer water quality monitoring programmes exist, yet the results gathered by citizen scientists are rarely used within the peer-reviewed literature or to influence policy and society, mainly due to mistrust of the data as well as issues integrating it with those of professionals. This challenge will need to be addressed before citizen science may be applied to ambient water quality monitoring under the SDG Indicator 6.3.2, the first step to which is determining the most applicable method for incorporating volunteer data into the indicator reporting methodology.

This research study investigated a potential method for incorporating citizen science data into the existing SDG Indicator 6.3.2 methodology. The research presented explored whether water quality sampling using simple citizen science field kits could be used to produce a representative image of ambient water quality in southwest Ireland which could be used to report a representative indicator score as part of the SDG Indicator 6.3.2 methodology. Waterbodies of known water quality were chosen for investigation, and the ability of the kits to detect water of “good” or

"not good" status was assessed through the application of specific target values and ranges, as outlined by the indicator methodology.

Methods

Ireland's Reporting on SDG Indicator 6.3.2

The SDG Indicator 6.3.2 relies on water quality data obtained from *in situ* measurements and analyses of water samples taken from surface and groundwaters. Core physical and chemical water quality parameters are measured and compared with target values and ranges used to classify water quality as either "good" or "not good" (UN Water, 2018). Not all pressures on water quality are reflected through the recommended core parameters. However water quality that meets the target values set for the parameters does generally indicate that the water is not suffering from any major water pollution stresses, such as domestic and industrial wastewaters, saltwater intrusion and agricultural runoff (UN Water, 2018). By recommending the measurement of a number of simple core parameters (Table 5.1), the SDG Indicator 6.3.2 methodology aims to produce an indicator which is globally comparable. However, countries may expand on or adapt the recommended parameters to suit national interests (UN Water, 2018). The targets set may be national values that apply to all waterbodies of a particular type, or may be site specific. Furthermore, they need not be legally binding water quality standards, and instead may be based on knowledge of the waterbodies chosen for monitoring (UN Water, 2018).

Three types of target values are currently in use, depending on the parameter being measured. Negative impacts on water quality may be observed through values which exceed an "upper" target value, fall below a "lower" target value or deviate from normal "ranges". In Ireland, for example, dissolved oxygen should not fall below 9.5 mg/l in rivers at 20°C, and a pH value falling outside a range between 6 and 9 for a particular waterbody may also imply impacts to water quality (UN Water, 2018). Comparison with target values allows for the classification of water quality as either "good" or "not good" for each monitoring location. The indicator percentage is calculated by aggregating the classifications by catchment, and then nationally (UN Water, 2018).

The water quality parameters and associated target values used for reporting to the UN by Ireland during the 2017 data drive are shown in Table 5.2. The target values and ranges chosen are derived from the European Communities Environmental Objectives (Surface Waters) Regulations 2009 (S.I. No. 272 of 2009), which determines the physiochemical elements supporting the characterization and classification of waterbody status under the Water Framework Directive (WFD), Directive 2000/60/EC (The Stationary Office, 2009).

Table 5.1. Recommended monitoring parameters (in bold) required for the water quality index used for SDG indicator 6.3.2 for three water body types. Alternative parameters (in italics) may be substituted for the recommended parameters, depending on data availability and applicability for specific water body types (UN Water, 2018).

Parameter group	Parameter	River	Lake	Groundwater
Oxygen	**Dissolved oxygen** *Biological oxygen demand, Chemical oxygen demand*	x	x	
Salinity	**Electrical conductivity** *Salinity, Total dissolved solids*	x	x	x
Nitrogen*	**Total oxidised nitrogen** *Total nitrogen, Nitrite, Ammoniacal nitrogen*	x	x	
	Nitrate**			x
Phosphorus	**Orthophosphate** *Total phosphorous*	x	x	
Acidification	**pH**	x	x	x
***** Countries should include the fractions of N and P which are most relevant in the national context				
****** Nitrate is suggested for groundwater due to associated human health risks				

Table 5.2. Target values set by the Irish EPA for monitoring and reporting on SDG Indicator 6.3.2 during the 2017 UN GEMS/Water data drive, derived from the European Communities Environmental Objectives (Surface Waters) Regulations 2009 (S.I. No. 272 of 2009) (The Stationary Office, 2009). Parameters reported on by the Irish EPA as part of the data drive included pH, DO (dissolved oxygen), TAM (total ammonia), DRP (dissolved reactive phosphorus), DIN (dissolved inorganic nitrogen), NO_3 (nitrate), EC (electrical conductivity), and NO_2 (nitrite).

Waterbody Type	Parameter	Unit	Lower Limit	Upper Limit
River	pH	*pH Units*	4.5	9
	DO	*%*	80	120
	TAM	*mg/L*	0.04	0.14
	DRP	*mg/L*	0.045	0.075
Open Water	DO	*%*	80	120
	DIN	*mg/L*	0.17	0.25
	DRP	*mg/L*	0.04	0.06
Groundwater	NO3	*mg/L*	37.5	
	DRP	*mg/L*	35	
	EC	*µS/cm*	800	1875
	NO2	*mg/L*	375	
	TAM	*mg/L*	65	175

Providing a baseline: Ireland's Q Value System and the Water Framework Directive

The health of 13,000 km of river channels throughout Ireland is assessed through the national monitoring programme, which has used biological monitoring of macroinvertebrates to assess water quality and the general health of rivers since the 1970s (Environmental Protection Agency, 2018). This biological monitoring programme is carried out at designated sites at least once every three years during the summer/autumn period (June-September). The health of the macroinvertebrate community in a river is assessed through sampling, and an overall river quality value (Q-Value) is assigned to the river station through the Quality Rating system. The Quality Rating (Q-Value) system categorises the quality of a river into five classes (high, good, moderate, poor and bad) based on the diversity and abundance of the biological community (Environmental Protection Agency, 2018) (Table 5.3). The EPA's Quality Rating (Q-Value) system is also used as a classification system for macroinvertebrate community health within rivers as part of Ireland's reporting to the European Union under the Water Framework Directive, which was adopted in 2000 as a single piece of legislation covering waterbodies in Europe (Environmental Protection Agency, 2006) (Table 5.3).

Table 5.3. The EPA Biotic Indices ("Q-Values") chosen to reflect average water quality at a given location. The values are primarily based on the relative proportions of pollution sensitive and pollution tolerant macroinvertebrates at a river site. Intermediate values (Q1-2, Q2-3, Q3-4, Q4-5) denote transitional conditions. This classification scheme mainly reflects the effects of organic pollution,

observed as de-oxygenation and eutrophication, but can also indicate toxic effects (Environmental Protection Agency, 2019).

Q-Value	WFD Status	Pollution Status	Condition
Q5, Q4-5	*High*	Unpolluted	Satisfactory
Q4	*Good*	Unpolluted	Satisfactory
Q3-4	*Moderate*	Slightly Polluted	Unsatisfactory
Q3, Q2-3	*Poor*	Moderately Polluted	Unsatisfactory
Q2, Q1-2, Q1	*Bad*	Severely Polluted	Unsatisfactory

Site Description

The field investigations took place at a number of EPA monitoring stations throughout Co. Kerry, southwest Ireland (Figure 5.1). A total of 24 stations, of known Q value, were identified through the EPA website (www.epa.ie) for inclusion in the study. Of the 24 sites identified six sites were of poor water quality (Q3); six were of moderate water quality (Q3-4); six were considered to have good quality water (Q4); and six were designated as sites of high water quality (Q4-5 or Q5). Only sites for which a Q value had been assigned within the last three years (2016-) were chosen for inclusion in the study. The sites were also evaluated for their accessibility and safety. Sites were included from a number of different rivers throughout Co. Kerry (Figure 5.1).

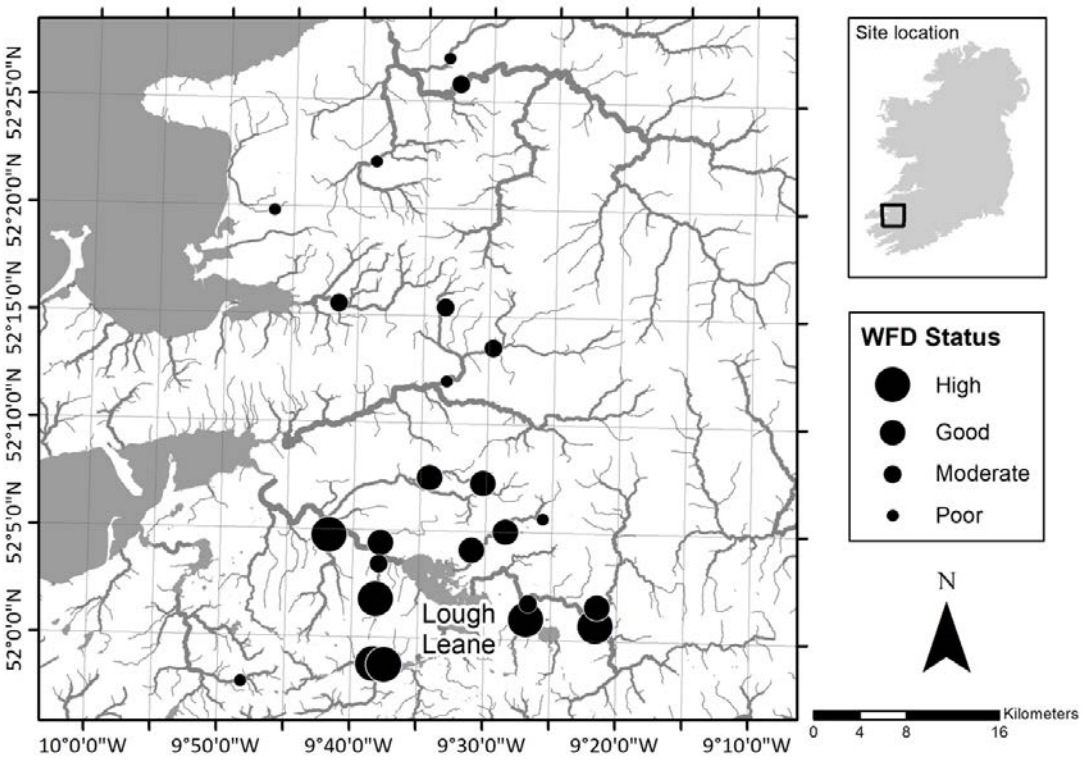


Figure 5.1. Map of Co. Kerry showing the EPA monitoring sites of different Q-Value/WFD status included in this study.

Field Analyses

Sampling took place on four individual days within the period from the 30th August – 7th September 2019. At each site, sampling took place from the safety of a bridge; a rope was attached to a large plastic bucket and lowered from the bridge into the waterbody to collect the sample water. Care was taken not to disturb the sediment. The bucket was filled from the centre of the waterbody and placed in a secure location on the bank, where the sample water was mixed well with a clean plastic spatula.

Nutrient concentrations of nitrate (NO_3-N) and phosphate (PO_4-P), and values for electrical conductivity, were determined according to the methods outlined in **Chapter 3** (Quinlivan *et al*., 2019). pH was determined with LaMotte pH test strips (LaMotte Company, Chestertown, Maryland, USA) which were held in the sample water for 2 seconds and subsequently matched to a colour chart. Based on the conclusions drawn in **Chapter 3** by Quinlivan *et al*. (2019) on the accuracy of the oxygen equipment used, this final core parameter was excluded from this

investigation. Five replicates were taken for each parameter and all data were recorded on a single datasheet for each site.

Selected Parameters and Target Values

The parameters and accompanying target values used by the Environmental Protection Agency for the purpose of reporting on SDG Indicator 6.3.2 during the 2017 data drive are shown in Table 5.2. The citizen science field kits provided by FreshWater Watch were capable of measuring four of the recommended core parameters for SDG Indicator 6.3.2: Orthophosphate, Nitrate, Electrical Conductivity and pH (Table 5.1). The target values used by the EPA for both pH and dissolved reactive phosphorus/orthophosphate could easily be applied to the citizen science field kits (Table 5.5). As the water in Co. Kerry is mostly hard, with an average total hardness greater than 100 mg/l $CaCO_3$ (Tedd *et al*., n.d.), the pH range was narrowed for this study according to the pH range for hard water outlined in the European Communities Environmental Objectives (Surface Waters) Regulations 2009 (S.I. No. 272 of 2009) (The Stationary Office, 2009). The EPA document "*Water Quality in 2017: An Indicators Report*" (Environmental Protection Agency, 2018) references that the EPA considers average nitrate concentration values less than 8 mg/l NO_3 (1.8 mg/l N) to be indicative of good quality water. Therefore, a target value of 1.8 mg/l N was selected for nitrate as part of this study, which could again be applied to the field kits with relative ease. UN Water recommend the inclusion of electrical conductivity as a core parameter of the SDG Indicator 6.3.2 due to the simplicity with which it can be measured and because deviations from normal ranges may indicate pollution of the waterbody (UN Water, 2018). However values of electrical conductivity change naturally due to changes in flow and temperature, making the selection of a universally applicable target value or range rather difficult. As no specific target range or value could be applied to the numerous waterbodies included in this study, electrical conductivity was measured at each location, however it was not included in the final determination of waterbody status.

The ranges of measurement of the citizen science field equipment used as part of this study are shown in Table 5.4. As the citizen science equipment is limited by the colorimetric method by which a range of values is returned (see **Chapter 3** and Quinlivan *et al*., 2019), target values had to be applied to the most appropriate

concentration range of the kits in order to provide a representation of "good" quality water when conducting field analyses with the equipment. The target values and concentration ranges chosen to represent "good" quality water are given in Table 5.5.

Table 5.4. Ranges of measurement of the citizen science equipment used to analyse various water quality parameters at EPA monitoring sites around Co. Kerry, Ireland.

Parameter	***Units***	**FWW Equipment Range**						
Orthophosphate	*mg/L P*	<0.02	0.02-0.05	0.05-0.1	0.1-0.2	0.2-0.5	0.5-1.0	>1.0
Nitrate	*mg/L N*	<0.2	0.2-0.5	0.5-1.0	1.0-2.0	2.0-5.0	0.5-10.0	>10.0
pH	*pH Unit*	4	5	6	7	8	9	10
Electrical Conductivity	*µS/cm*	10 - 1990 +/- 10 µS/cm precision						

Table 5.5. Concentration ranges of the citizen science equipment considered to represent "good" water quality based on the application of selected target values to the most appropriate concentration range.

Parameter	***Target Value/ Range***	***Kit Limit Applied***	***Units***	**"Good" Water Quality Concentration Ranges**			
Orthophosphate	0.045	0.05	*mg/l P*	<0.02	0.02-0.05		
Nitrate	1.8	2.0	*mg/l N*	<0.2	0.2-0.5	0.5-1.0	1.0-2.0
pH	6 - 9	6 - 9	*pH Unit*	6	7	8	9

Data Analyses

A simple index was used in order to classify a site as either good or not good water quality, according to the SDG Indicator 6.3.2 methodology. This index is based on compliance of the monitoring data gathered with the selected target values and ranges (UN Water, 2018). The index is defined as follows:

$$C_{wq} = n_c/n_m \times 100$$

Where C_{wq} is the percentage compliance [%]; n_c is the number of monitoring values in compliance with the target values; and n_m is the total number of monitoring values (UN Water, 2018). Using the five recommended core parameters for the ambient water quality indicator, a threshold value of 80% compliance is defined to classify water bodies as "good" quality. A waterbody is therefore classified as having a good quality status if at least 80% of all monitoring data are in compliance with the respective targets (UN Water, 2018). The threshold value of 80% compliance was therefore upheld for this investigation, requiring that all three parameters had to comply with

their selected target values/ranges in order for a waterbody to be classified as of good quality status.

Results

Applying the target values and ranges, the citizen science field kits classified 100% of the high and good status waterbodies as "good", while only 16.67% of moderate and poor waterbodies were classified as "not good" (Table 5.6). Most waterbodies which had been assigned a status of moderate or poor under the WFD were classified as good according to the results obtained by the field kits (Figure 5.2).

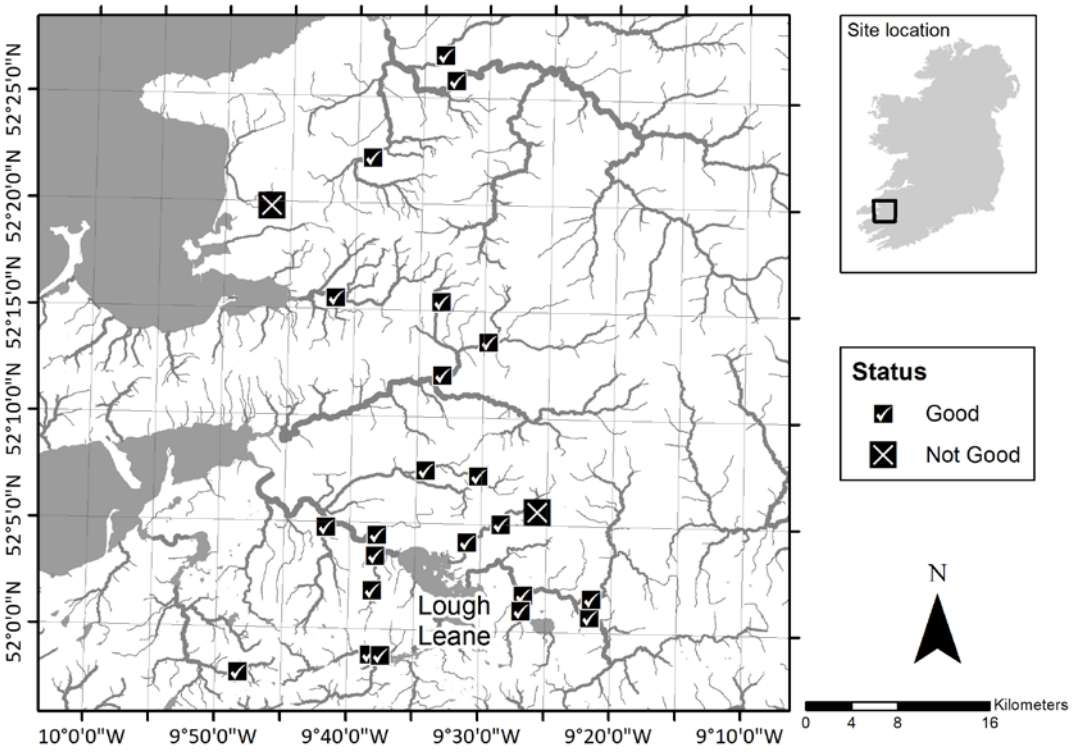


Figure 5.2. Map of Co. Kerry showing the EPA monitoring sites classified as either good or not good water quality according to the SDG Indicator 6.3.2 using citizen science.

Table 5.6. Number and percentage of EPA water quality monitoring sites classified as either "good" or "not good" based on assessments using citizen science field equipment in 2019.

WFD Status 2016-	**Status Assigned**	
	Good (%)	*Not Good (%)*
High/good (n = 12)	12 (100)	0 (0)
Moderate/poor (n = 12)	10 (83.33)	2 (16.67)

Though conductivity can be highly variable, measurements taken at each site provide some reflection of conditions at sites of different status, with high status sites displaying low conductivity and poor status sites generally displaying quite high levels (Table 5.7). Sites classified as both good and moderate under the WFD reported a wide range of values with no distinct trends in conductivity levels due to status (Table 5.7).

Table 5.7. Electrical conductivity measurements at sites of different WFD status.

WFD Status 2016-	**Electrical Conductivity (µS/cm)**					
High	75	40	35	40	30	40
Good	134	102	156	90	105	90
Moderate	40	50	285	115	405	155
Poor	128	40	355	745	240	215

Discussion

This investigation aimed to assess whether citizen science data could potentially be incorporated into the SDG Indicator 6.3.2 reporting methodology through the classification of waterbodies of “good” and “not good” water quality which could then be used to calculate a national indicator score and reported to the United Nations. The investigation revealed that the application of specific target values to the categorical ranges on the FreshWater Watch kits (Table 5.5) was a simple task which allowed for an easy classification of waterbodies as either good or not good water quality. However, because of a lack of recent data on professional analyses of the waterbodies under investigation, the accuracy of the citizen science classifications remains questionable (Table 5.6).

Based on the most recent Q-value assigned to each site by the EPA (Environmental Protection Agency, 2019), the results of this investigation indicated that the citizen science field kits were capable of distinguishing between waterbodies of “good” and “not good” water quality 58.33% of the time. Through applying the Irish SDG Indicator 6.3.2 target values and ranges to the citizen science field kits, all waterbodies which under the Water Framework Directive had been classified as of high or good status were demonstrated in this study to be of “good” water quality (Table 5.6). Conversely, only 16.67% of waterbodies classified as of moderate or poor

status under the WFD were reported as of "not good" water quality based on results from the citizen science sampling (Table 5.6). The results gathered by Quinlivan *et al*. (2019) (see **Chapter 3**) demonstrated the abilities of the kits to obtain measurements of the concentrations of various parameters in reasonable agreement with laboratory results – it was therefore anticipated that the results of this investigation, assigning a status to various waterbodies based on water quality, would appear similar to those obtained by the Environmental Protection Agency during their last classification of the waterbodies in question, assuming no changes in water quality since the last professional classification. However this was not the case (Figures 5.1 and 5.2).

Due to logistical and time constraints, most of the monitoring sites chosen for inclusion in this study were last investigated and assigned a Q-value back in 2016. The EPA's *Water Quality in 2017: An Indicators Report* reveals how, of the 24 catchments surveyed in 2016 and 2017, five showed an overall improvement in the number of river bodies classified as of high or good status, one of which was the Tralee Bay catchment (Environmental Protection Agency, 2018), where most of the moderate and poor sites included in this study were located (Figure 5.1). It is therefore quite possible that the results of this investigation reflect changes in water quality which have occurred in the past three years, but are not reflected by the Q-value currently assigned to the waterbody. The Q-values which will be assigned in 2019 will be required in order to assess whether the citizen science data was in fact correct in the classification of most sites as of "good" water quality (Figure 5.2). On the other hand, it is also quite possible that the results of water quality analyses using the kits were misinterpreted, as results in **Chapter 3** from Quinlivan *et al*. (2019) show that citizen scientists can struggle to correctly read the colorimetric scale of the FreshWater Watch kits, which may result in under- or overestimation of the concentration of a particular parameter. As discussed in **Chapter 3**, the colorimetric method of the kits can be rather ambiguous, and it is thus possible that misinterpretation of results could have skewed the data. Again, the latest Q-values assigned by the EPA will be needed in order to examine this possibility. As the EPA's Q-Value system is based on the results of biological monitoring, and this investigation sought to examine water quality via physiochemical parameters, it is also possible that the "snapshot" of water quality obtained at each site during this study was simply not enough to provide a representative assessment of long-term water quality, which is generally more accurately reflected through biological monitoring. Furthermore, as only three of the

five core parameters for the SDG Indicator 6.3.2 were used for the classification of waterbodies as either good or not good water quality, a bias exists to the data which may account for the greater number of good status waterbodies compared to not good status (Figure 5.2). The inclusion of an oxygen parameter in this investigation could potentially have resulted in different conclusions on the status of various EPA sites, however dissolved oxygen has been identified as a source of inaccuracy in citizen science investigations (Quinlivan *et al*., 2019; Shelton, 2013; Storey *et al*., 2016) and accurate citizen science equipment could not be obtained before this investigation took place. The inclusion of an oxygen parameter should therefore be an important consideration of future studies of this nature. Similarly, as electrical conductivity measurements can vary naturally, there is no universally applicable target value or range which can be applied to all sites, and thus this parameter was also not included in the classification of waterbodies as of good or not good quality. The investigation revealed that higher-quality sites generally had lower levels of electrical conductivity than sites of poorer quality, though this is not always true (Table 5.7). From this perspective, professional background data on electrical conductivity levels at various sites will have to be made available to citizen scientists involved in monitoring as a means of comparison, in order for citizen science data on electrical conductivity to be included in the calculation of a national indicator score for the SDG Indicator 6.3.2.

Overall results of the study were mixed in that the citizen science field kits were able to categorise both high- and good-quality sites as of “good” water quality, yet were incapable of classifying more polluted waterbodies as of “not good” water quality (Table 5.6), though without the most recent Q-values from the Environmental Protection Agency it is not possible to determine whether this is due to misinterpretation and bias of results or changes in water quality which have occurred in the past few years (Environmental Protection Agency, 2018). Should the most recent Q-values determine that the classification of many moderate and poor sites as of “good” water quality was inaccurate, the conclusion could be drawn that citizen science may be more applicable to the validation of waterbodies of “good” water quality, rather than the examination of more polluted waterbodies, and further research will be needed into how this could potentially be applied to the calculation of a national indicator score for ambient water quality. Though results were mixed, this study demonstrated one particularly simple method for integrating citizen science data into the current SDG Indicator 6.3.2 monitoring methodology through the application of

select target values and ranges to simple citizen science field kits for the purpose of determining between “good” and “not good” water quality. Further investigations using all five core SDG Indicator 6.3.2 parameters and examining a greater number of sites which have more recently been monitored professionally will be needed in order to put the results of this research study into perspective and determine the ease with which citizen generated data could be incorporated into the SDG Indicator 6.3.2 reporting methodology using this method.

Conclusions

As discussed in **Chapter 2**, while citizen science is currently a popular practice, the use of citizen science data for environmental monitoring is not a particularly common or straightforward task, and research continues into the best methods for incorporating citizen science data into the monitoring of the ambient water quality SDG Indicator 6.3.2. This study has demonstrated that citizen science can be applied to monitoring activities as part of the SDG Indicator 6.3.2 methodology, though without accurate equipment or appropriate target values for all five recommended core parameters currently available, further research will be needed to assess the appropriateness of employing only three parameters, as was done in this study, which may slightly misconstrue the classification of waterbody status. The results show that while the application of select target values and ranges was successful and easy to implement, and the kits are capable of correctly classifying waterbodies of “good” status, they may struggle in the classification of more polluted waterbodies. Thus, while incorporating citizen science data into the reporting methodology may be relatively simple, based on this method, the representativeness of the data remains in question, which may limit the use of citizen science data for reporting a national indicator score for SDG Indicator 6.3.2.

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Chapter 6: General Discussion

Citizen science has been acknowledged as a potential source of support for the UN Sustainable Development Goal Indicator 6.3.2 on the "*proportion of bodies of water with good ambient water quality*" (United Nations Environment Programme, 2018). As outlined in **Chapter 1**, citizen science is now contributing to the advancement of many different fields as science becomes more open to engaging the public in environmental issues (Cooper *et al*., 2007; Danielsen *et al*., 2010; Cosquer *et al*., 2012; Newman *et al*., 2011; Theobald *et al*., 2015; Thornhill *et al*., 2016; Tulloch et al., 2013). Greater public environmental consciousness surrounding issues currently surpassing professional monitoring resources, as well as the globalisation of technology, have contributed to promoting the use of citizen science in environmental monitoring, as an aid to both governments and professional scientists alike (Au *et al*., 2000; Conrad & Daoust, 2008; English *et al*., 2018; Huddart *et al*., 2016; Newman *et al*., 2017; Savan *et al*., 2003; Silvertown, 2009).

The potential for volunteer monitoring efforts to contribute data beyond the spatial and temporal scope of that presently being gathered for the UN ambient water quality indicator has not gone unnoticed (United Nations Environment Programme, 2018). At the present rate, data generation within many UN Member States is insufficient to provide a representative image of national ambient water quality. Yet while the great potential of this cost-effective and abundant resource has been recognised, confusion remains as to how to overcome some of the more significant issues surrounding citizen science monitoring before it could be applied in support of the ambient water quality indicator (United Nations Environment Programme, 2018). Three key issues exist within the world of volunteer environmental monitoring (Conrad & Hilchey, 2011), which are described in detail in **Chapter 2**. These issues usually stem from both challenges surrounding the motivation and retention of participants and a mistrust of the data gathered by volunteers, which contributes to a lack of use of citizen-generated data in decision-making processes and the peer-reviewed literature (Conrad & Hilchey, 2011). Numerous individual studies exist which advocate for the quality of water quality data collected by volunteers (Obrecht *et al*., 1998; Fore *et al*., 2001; Rodrigues & Castro, 2008; Loperfido *et al*., 2010) and analyse organisational issues surrounding volunteer disinterest, unequal sampling

efforts and participant dropout (Jollymore *et al*., 2017; Lowry *et al*., 2019; McGoff *et al*., 2017; Sauermann and Franzoni, 2015; Scott & Frost, 2017; Shupe, 2017). Fewer examples of methods behind the integration of citizen and professional environmental data can be found in the peer reviewed literature (Conrad & Hilchey, 2011). Based on conclusions drawn from the experiences of other researchers, a mixture of specific participant training (Fore *et al*., 2001; McGoff *et al*., 2017; Quinlivan *et al*., 2019), continued advancements in technology (Quinlivan *et al*., 2019), increased effective communication between scientists and volunteers (Rotman *et al*., 2014; Scott & Frost, 2017), and a potential review of the current indicator reporting methodology may all contribute to the establishment of citizen science as a reliable source of support for ambient water quality monitoring. The Sustainable Development Goals were adopted in 2015, therefore few studies to date have focused on applying citizen science to environmental monitoring specifically in support of the SDGs (Quinlivan *et al*., 2019). Through the identification of key challenges and opportunities for the application of volunteer ambient water quality monitoring to the SDG Indicator 6.3.2, the literature review conducted as part of this thesis established a solid foundation for the focus and direction of this research, which sought to identify and provide potential solutions and insights into these key challenges through the application of citizen science to water quality monitoring activities in southwest Ireland (**Chapters 3, 4 & 5**).

The study outlined in **Chapter 3** focused on issues surrounding data collection and quality through an examination of the data produced by a number of citizen scientists on the ambient water quality SDG Indicator 6.3.2 (Quinlivan *et al*., 2019). School students conducted water quality sampling of the five core parameters of the SDG Indicator 6.3.2 in at-risk waterbodies in southwest Ireland using simple citizen science field kits provided through FreshWater Watch. Results for three of the parameters, orthophosphate, nitrate and electrical conductivity, proved positive, with volunteers capable of recording concentrations of the parameters to within or just outside the correct concentration range determined by an accredited laboratory (Table 3.5) (Quinlivan *et al*., 2019), echoing other studies which have seen positive results with the FreshWater Watch materials (Levesque *et al*., 2017; Loiselle *et al*., 2016; McGoff *et al*., 2017; Scott & Frost, 2017; Shupe, 2017; Thornhill *et al*., 2017; Thornhill *et al*., 2018; Xu *et al*., 2017). Conversely, the results for both pH and chemical oxygen demand were less agreeable, echoing other studies which have noted oxygen parameters as a source of inaccuracy in citizen science freshwater monitoring

(Table 3.5) (Shelton, 2013; Storey *et al*., 2016), and highlighting issues with the monitoring technology currently available. The researchers identified difficulties the citizen scientists had with interpreting the colorimetric nature of the FreshWater Watch field kits and noted the challenge of incorporating the categorical data gathered into the current monitoring methodology for the SDG Indicator 6.3.2. Therefore, while it was revealed that is it quite possible to overcome issues surrounding data collection and quality to allow trained citizen scientists to accurately monitor most of the SDG Indicator 6.3.2 parameters, other compounding issues which have been described in the literature also presented during the study. The investigation therefore provided a foundation for further research on organisational (**Chapter 4**) and data use (**Chapter 5**), the remaining key issues described in **Chapter 2**.

The effect of participation in a citizen science SDG-focused water quality monitoring study on volunteers was investigated (**Chapter 4**) as part of the research carried out by Quinlivan *et al*. (2019). Though citizen science has been shown to foster engagement in environmental issues and reveal subsequent effects of increased environmental stewardship (Ballard *et al*., 2016; Evans *et al*., 2005; Newman *et al*., 2017; Zerbe and Wilderman, 2010)., lack of volunteer interest and questions on the factors motivating citizen involvement in a study remain a hindrance to the effective application of citizen science in many fields (Conrad & Hilchey, 2011). However, exposure to citizen science has been shown to promote further engagement in conservation actions (Cooper *et al*., 2007; Danielsen *et al*., 2009), begging the question of what potential effects exposure to SDG-focused citizen science could have on a group of participants. Before-and-after responses from participants in the study outlined in **Chapter 3** indicated that, for the majority of students, their interest in areas which surround the Sustainable Development Goals, such as global development, sustainability, and in particular, environmental and water-related sciences, had increased following their taking part in the research carried out by Quinlivan *et al*. (2019) (Figure 4.1). Further responses indicated that the study had a positive effect on the attitudes of participants towards the environment, had gained skills through their participation in the study, and would potentially participate in a water quality monitoring programme in future (Table 4.1), responses which echoed other citizen science studies which have reported similar social outcomes (Brossard *et al*., 2005; Evans *et al*., 2005; Crall *et al*., 2012). The study therefore demonstrated the positive effects participation in SDG-focused citizen science can have on the attitudes and

interests of atypical citizen scientists in global environmental issues. However the investigation acknowledged that, while the responses were positive and demonstrated further support for the use of citizen science for monitoring under the SDGs as a means of both gathering data and increasing pubic environmental awareness, changes to interest levels do not necessarily imply changes in behaviour or further involvement in environmental management efforts (Kaiser *et al*., 1999; Kollmuss & Agyeman, 2002; Overdevest et al. 2004; Jordan et al. 2012). More detailed investigations beyond the scope of this thesis will therefore be required on how both volunteers and researchers may reap the benefits of citizen science monitoring for the Sustainable Development Goals, with the purpose of both gathering high-quality data and educating, motivating and retaining citizens.

The investigation of the final key issue surrounding citizen monitoring dealt with in **Chapter 2** also built upon the work carried out in **Chapter 3**. The third main challenge to the adoption of citizen science for ambient water quality monitoring under SDG Indicator 6.3.2 was identified as difficulty with integrating volunteer data with those of professionals as part of a water quality monitoring programme, a very common issue within the realm of citizen science (Conrad & Hilchey, 2011). This issue was examined as part of the research described in **Chapter 5**, where waterbodies of known water quality in southwest Ireland were used to assess the potential for incorporating citizen-generated data into the SDG Indicator 6.3.2 methodology through the application of specific target values and ranges (Environmental Protection Agency, 2018; The Stationary Office, 2009). The main focus of the investigation was an assessment of the ease with which volunteer monitoring data, obtained through similar methods to those described in **Chapter 3**, could be incorporated into the SDG Indicator 6.3.2 reporting methodology, a task which is currently being researched elsewhere (UNEP, 2018). Through the simple application of specific, Irish target values to the categorical ranges on the citizen science field kits, the study noted that the classification of waterbodies as either good or not good water quality was relatively easy. However, the investigation yielded mixed results, with the citizen-generated data on waterbodies of good water quality status mirroring results reported by the Environmental Protection Agency, yet citizen results obtained from waterbodies of moderate or poor status appearing to misinterpret the correct status which should be assigned (Table 5.6, 5.7). The study recognised that without the most recent results from the EPA it is unknown whether the citizen-generated data on the waterbodies

originally classified as of poorer quality (Environmental Protection Agency, 2019) is inaccurate and therefore unfit for use in an SDG-focused water quality monitoring programme, or in fact accurate and simply reflecting changes in water quality that have occurred since it was last professionally analysed. Based on the findings of this investigation, should data quality be upheld and a greater number of the recommended core parameters be included in the index, the inclusion of citizen-generated data in the calculation of a national ambient water quality indicator score for the SDG Indicator 6.3.2 using a simple method as such should not prove too onerous a task, and could potentially be applied in other countries using the same equipment to allow for intercomparability of citizen data between UN Member States.

The knowledge gained from this thesis provides a greater understanding of the key hurdles and opportunities for incorporating citizen science into ambient water quality monitoring for the Sustainable Development Goal Indicator 6.3.2. Based on extensive examination of the literature, the thesis provides an overview of the main issues which need to be overcome before the United Nations may be able to properly incorporate citizen monitoring into the SDG Indicator 6.3.2 methodology. The research presented offers the first insight into the abilities of citizen scientists to use simple equipment to monitor for the ambient water quality parameters (**Chapter 3**), as well as how participation in an SDG-focused water quality monitoring programme may potentially influence environmental conservation and support of the SDGs in future (**Chapter 4**), through the effects on participant attitudes and interests. The thesis further provides an overview of one potential method for including citizen science data in the current SDG Indicator 6.3.2 reporting methodology (**Chapter 5**). This thesis offers some of the first examples of SDG Indicator 6.3.2-focused citizen science research and lays the foundation for future investigations in this area. It is believed that the knowledge gained from this research will contribute to a growing body of literature on how volunteer efforts may contribute to solving some of the world's most pressing environmental issues.

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