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Using citizen science to understand river water quality while filling data gaps to meet United Nations Sustainable Development Goal 6 objectives

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HIGHLIGHTS

- Citizen scientist project to highlight pollution sources on a Dublin urban river
- High nitrates (NO_3–N) and phosphates (PO_4-P) indicate low quality water relating to inputs
- Rainfall did not have a widespread effect on nutrient level occurrence
- Aims to fill data gap for United Nations (UN) Sustainable Development Goal (SDG) 6
- Citizen scientist qualitative observations important in environmental reporting

GRAPHICAL ABSTRACT

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ABSTRACT

This study investigates water quality along the river Liffey in Dublin city with the help of citizen scientists, including the community of river users such as paddle boarders and those accessing the river from the bank. The primary objective was to evaluate water quality near sources of pollution observed by citizens, while filling data gaps for the United Nations (UN) Sustainable Development Goal (SDG) 6, Indicator 6.3.2. The participants used field chemistry kits to measure nitrate (NO_3-N) and phosphate (PO_4-P) at 19 locations on a monthly basis over the course of nine months, recording the results on a smartphone app. 10% of nitrate samples were indicative of low quality water values while 35.6% of phosphate samples were indicative of low quality water. Rainfall over the study period was analysed to investigate the impact of run-off from rainwater on the river. Results indicated that excessive rainfall was not a factor in lower water quality in this area. Citizen scientists' observational notes and photographs entered onto the database, with accompanying test results were key to highlighting pollution sources at specific locations which correlated with high levels of nitrate and phosphate resulting in low quality water. Land use was a factor in these areas of recent housing development indicating possible domestic misconnections. Citizen scientist data has the potential to fulfil UN SDG 6, in contributing to Indicator 6.3.2 while detecting contamination.

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1. Introduction

“Ambient fresh water quality is at risk globally”. This is one of the key messages from the United Nations (UN) Sustainable Development Goal (SDG) 6 Synthesis Report on Water and Sanitation (UN, 2018). Target 6.3 of Goal 6 aims to improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials by 2030, with Indicator 6.3.2 defined as the “proportion of bodies of water with good ambient water quality”, where ambient water is defined as “natural, untreated water in rivers, lakes and groundwater, and represents a combination of natural and anthropogenic influences” (UN, 2018). This global goal is supported in numerous member states by existing and new national and regional legislation. For example, in the European Union (EU), the Water Framework Directive (WFD) (2000/60/EC) aims to maintain the quality of all fresh waters across member states by a) retaining “good status” in currently healthy water bodies, and b) raising the status of poorly performing waterbodies to “good” level. The status of waterbodies is monitored through national monitoring programmes, with management actions based on the catchments of water bodies (EPA, 2006).

The involvement of communities in water resource management at the catchment scale is also central to SDG 6, as Target 6b aims to support and strengthen their participation which can contribute to the conservation, restoration and sustainable use of freshwater ecosystems and their services (UN, 2018). The WFD also aims to have citizen participation, stating that public and stakeholder participation in water resource management is required. It thus aims to enhance resource management and involve individuals and groups in a democratic way. Evaluation is also required of any participatory projects to assess whether objectives are being achieved and to identify how improvements can be made (Carr et al., 2012). Thus clear guidance is needed so that data generated is fit-for-use by national agencies, and therefore included in the SDG reporting process (Fritz et al., 2019) as well as for the WFD.

Citizen science (CS) (i.e. the involvement of non-professional scientists in scientific research and data gathering (Bonney et al., 2009), presents opportunities for both data collection and public participation. It has for some years now gathered large amounts of scientific information over long timescales in many disciplines, including freshwater science and water resource management (Buytaert et al., 2014). Over the past decade, it has become widespread (Follett and Strezov, 2015). It has been used to pinpoint urban pollution locations (Scott and Frost, 2017) and has strong potential to address the lack of water quality data in relation to SDG indicator 6.3.2. (Bishop et al., 2020; Hegarty et al., 2020; Quinlivan et al., 2020b; San Llorente Capdevila et al., 2020). Beyond simply producing data, citizen science is also recognised to have broader environmental, social, economic, and political benefits (Hecker et al., 2018), with the extent to which these are realised dependent upon the type of citizen science deployed (Van Noordwijk et al., 2021). The UN recognises that citizen science has the potential to increase the knowledge base that underpins progress towards the SDGs by increasing the frequency and geographic range of available data, making better use of local knowledge, and educating the public (UN Environment, 2019). The EU has also identified the need for complementary data while monitoring EU environment policy, stating that citizen science offered an alternative and cost-effective way to collect environmental data which may be useful in providing early warnings about environmental trends and specific problems (EC, 2020).

Against a background of increasing concern for the status of fresh water across the world, the Water Institute of Dublin City University (DCU) launched BACKDROP in May 2019. This project aimed to train a team of citizen scientists with limited prior experience of freshwater research to understand and regularly measure water quality along different parts of the river Liffey in Dublin city, Ireland. Dublin, along with most cities worldwide, is experiencing increasing urbanisation and land-use change which has impacted on freshwater ecosystems, their biodiversity and recreational use. The river Liffey, which flows through the centre of Dublin city on its final course to the sea, is subject to run-off from urban surfaces and through storm water drains. This input into fresh water can have a detrimental effect on the water quality as increased nutrients from anthropogenic activity can damage freshwater ecosystems (Paul and Meyer, 2001; Sonoda et al., 2001; UN Water, 2018). There is also anecdotal evidence of residential discharges from misconnected sewer pipes into areas along the river's course, similar to what has been reported in other cities (Ellis and Butler, 2015). The Irish Environmental Protection Agency (EPA), which monitors water quality nationwide in line with the WFD, has monitoring stations along the course of the river Liffey (Fig. 1). However as with all statutory monitoring networks, some areas may be overlooked, due to resourcing, or may not be sampled at a time when pollution incidents are occurring. For the BACKDROP project, citizen scientists, in particular the community of urban paddle boarders and other river users (kayakers, rowers), collected data along the urban Liffey from the west of the city to its point of entry into the Irish Sea. This meant that data was collected at more granular spatial and temporal scales than is typically achieved by statutory monitoring, allowing localised impacts of urban drainage on the river Liffey to be investigated.

This paper focusses specifically on the utility of data collected by the citizen scientists in the BACKDROP project, and asks the following questions:

1. Do urban drainage systems have localised effects on water quality?
2. Does the Liffey experience localised water quality responses to rainfall events as a result of urban drainage systems?
3. To what extent can the spatially and temporally granular data collected by citizen scientists be used to fill gaps in data and information in the statutory monitoring programme?

Using data collected by citizen scientists over the course of nine months from the urban stretch of the river Liffey in Dublin, Ireland, this study aims to answer these questions.

2. Methods

2.1. Site description

The river Liffey rises 125 km from Dublin city in the Wicklow mountains and drains a catchment area of 1616 km^2 containing a population of 1.26 million people. This catchment comprises 17 sub-catchments with 77 river water bodies, six lakes, six transitional and five coastal water bodies, and 16 groundwater bodies (EPA, 2018a). This study is concerned with the last 16 km of the Liffey's journey, from Lucan in the west of the city to where the river enters the Irish Sea at the East Link Bridge (Fig. 1). The main inputs in this section are the rivers Griffeen, Rusk, Camac, Poddle (culverted) and Dodder (Fig. 1). The Liffey is monitored by the EPA along its course with freshwater monitoring stations in the area of concern at Lucan (CS site 1, Fig. 1) and Chapelizod (CS site 4, Fig. 1). The EPA monitors the estuarine waters to the east of the Islandbridge area. For the purposes of this study, the EPA stations which coincide with CS points 10, 18 and 19 are of particular importance (Fig. 1; EPA, 2020a).

Under the WFD, the main river body is assigned good status at Lucan (CS site 1, Fig. 1) but becomes unassigned from this point as it enters the suburban and urban area of Dublin. Its tributaries have varying status from good to poor (EPA, 2020b). The Liffey flows through suburban parkland for 7 km from Lucan to Chapelizod (between CS sites 1 and 3, Fig. 1) where land use changes to pockets of suburban and industrial development for another 3 km to Islandbridge (between CS sites 3 and 9, Fig. 1). For the remaining 6 km the river continues through an urban landscape. Anecdotal evidence of residential discharges into areas along the river's course where land use changes to suburban with an increased housing stock as a result of a building boom in the past 20 years makes this a particular area of interest for this study. The suburban

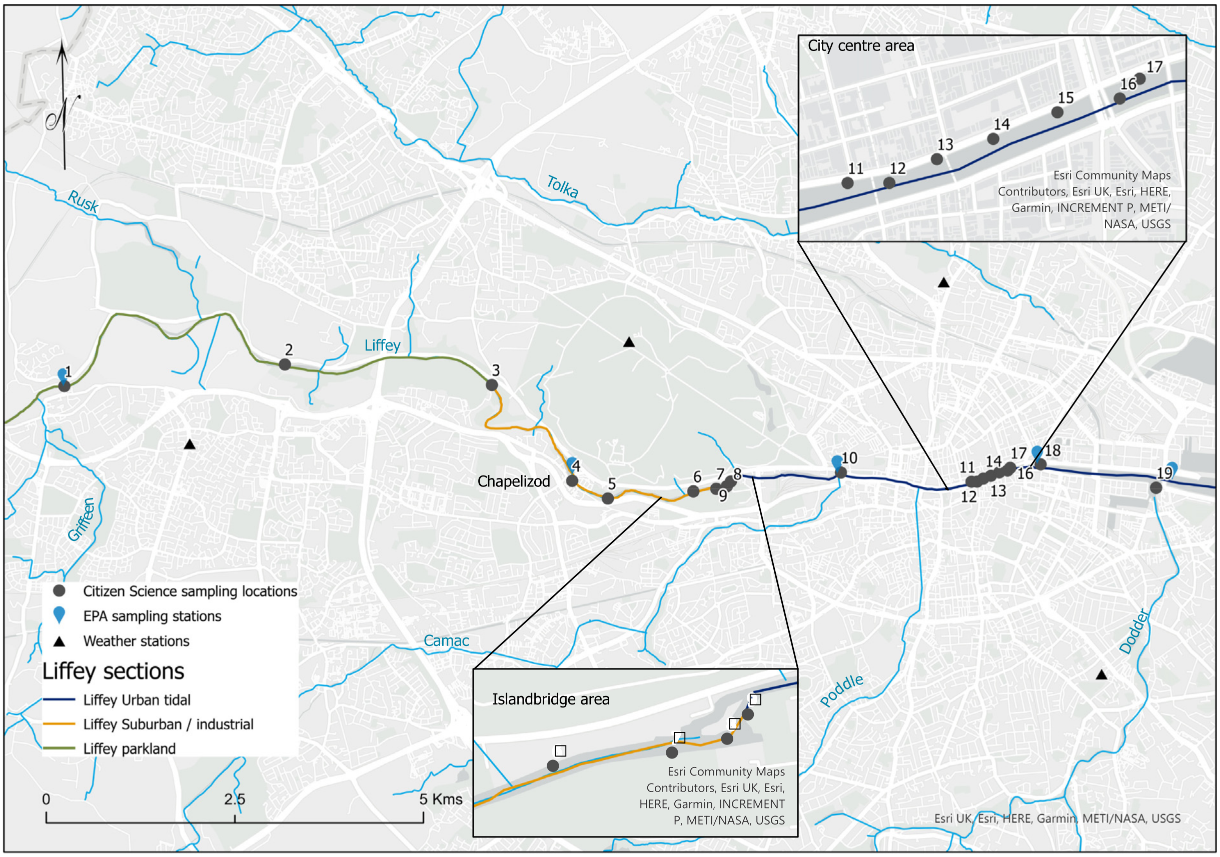

Fig. 1. Study location, citizen science sampling sites, EPA sampling sites and weather stations referred to in the text.

and urban reach of the river also has a limited number of agency sampling sites (Fig. 1).

2.2. Citizen recruitment

Two different groups of citizen scientists were recruited for this project. Staff from the Dublin offices of the project funders (Royal Bank of Canada, RBC) were offered the opportunity to become citizen scientists on the project as part of the company's Social Corporate Responsibility programme. Those who volunteered were trained in sampling techniques and in health and safety at the Liffey quayside beside the funder's offices by the principal investigators, and were allocated sample points along the Liffey within easy reach of the RBC offices. Further participants were recruited through the research institute's social media channels, from university staff and by word of mouth. This broad group of citizens, who could access the river Liffey from the banks or bridges are termed 'pedestrians' in this study. The second group of citizen scientists consisted of members of urban community of paddle boarders and other river users (kayakers, rowers), some of whom were members of water-based clubs along the Liffey. These were recruited through leaflet drops in water clubs, through personal contacts and through social media channels.

2.3. Citizen science methods and training

Volunteers were trained via the pre-existing FreshWater Watch (FWW) citizen science programme (https://freshwaterwatch.thewaterhub.org/). FWW is a well-established global citizen science research project studying freshwater ecosystem dynamics. Within FWW, 80 local projects in more than 20 different countries have been established to date. This has generated 27,000 data points from across the world, all of which have been recorded by citizen scientists using the same universal method. The method incorporates a series of visual observations (e.g. visible signs of pollution, evidence of residential or industrial discharge), as well as in-situ measurements of nitrates and phosphates. Volunteers also take a photograph of their site. Citizen scientists availed of the FWW website (https://freshwaterwatch.thewaterhub.org/) and smartphone application to record data, photographs and comments which can be shared with the project leaders and also a worldwide audience who have the ability to inquire into the status of their local waterbody, or one thousands of miles away.

All citizen scientists took part in training workshops with field-based activities with project leaders. Such training sessions are not only vital to ensure volunteers are collecting high quality data, but also help to ensure volunteer retention (August et al., 2019). During these sessions they were instructed in health and safety requirements and signed a declaration of their knowledge. They were trained in the sampling methods outlined below, as well as in using and interpreting their data via the FWW global database. The FWW training scheme uses a Methods Manual (https://freshwaterwatch.thewaterhub.org/sites/default/files/fww-methods-manual.pdf) that is available to all project members on their website so that standardised methods are used worldwide by all citizen scientists taking part in local water quality projects.

In this study, nitrate and phosphate were used as the parameters to assess nutrients present in the river on a monthly basis. Water was collected by citizen scientists using sampling devices created by the participants, such as a bucket attached to rope. These sampling devices which were rinsed with river water before taking the test sample to avoid contamination with other substances. Participants were provided with a sampling cup, which was rinsed with the river water twice before being filled with the water for testing that had been collected using the citizen's own sampling device. These sampling cups ensure that all participants use the same amount of water for sampling purposes. Testing of nutrients took place in situ using nitrate (NO_3-N) and phosphate (PO_4-P) Kyoritsu PackTest (Kyoritsu Chemical-Check Lab., Corp., Yokohama, Japan) water chemistry kits supplied by FWW. These kits consist of transparent plastic tubes, in which citizen scientists mix unfiltered water samples from the sampling cups with pre-measured reagents that produced increasing colour values with increasing concentration (McGoff et al., 2017; Scott and Frost, 2017). The PO_4 method uses 4-aminoantipyrine with phosphatase enzyme (Berti et al., 1988) which provides nutrient level categories in the test kits ranging from <0.02 - >1.0 mg/l (Table 1). The NO_3 test kits ranges from <0.2 - >10 mg/l (Table 1) and the reaction is based on a zinc reduction to convert nitrate to nitrite leading to a colorimetric reaction by the Greiss method (Nelson et al., 1954; Scott and Frost, 2017). The colour change in the sample tube is compared visually to a six point colour chart in both NO_3-N and PO_4-P testing kits, and the range value between the two closest colour matches is recorded as the test result (McGoff et al., 2017). Although these kits are less precise than laboratory methods, they allow citizen scientists to obtain results quickly in-situ, as well as being simple and safe for volunteers to use unsupervised. They are widely used in FWW projects around the world (Thornhill et al., 2018), and previous studies have compared the accuracy of these kits to professional laboratory methods with good results (McGoff et al., 2017; Quinlivan et al., 2020a; Scott and Frost, 2017).

After conducting the tests, participants added their data to the FWW database, including taking observational notes or photographs of any of the following in the local environment: presence of algae, surface foam, oily sheen, pollution discharges, litter and signs of aquatic life. Location coordinates were entered manually or by map geolocation from the citizen scientist's smart device to the database on the FWW website or smartphone application. 101 samples were taken at 19 locations during the sampling time period by 15 participants or groups of participants, and 202 tests were carried out; 101 of nitrate (NO_3-N) and 101 of phosphate (PO_4-P).

While RBC participants were allocated sampling sites in the city centre, other sampling sites were selected by pedestrian participants based on where they lived or worked (Fig. 1). Thus the convenience of access became a factor in regular sample-taking, and some bias towards sampling sites was also evident, as has been reported elsewhere (Hegarty et al., 2020; McGoff et al., 2017). This led to a concentration of sampling in the Islandbridge area, as well as within the city centre (Fig. 1). A sense of place is an important factor in site selection as it draws on people's knowledge and affinity for their locality motivating them to engage with environmental issues (EC, 2018). Thus any potential bias can be turned to the benefit of the study, with participants examining areas where they suspect there may be pressures on the river. River users were asked to sample at multiple locations as they travelled downstream each month, thus they were able to access areas of the river that might otherwise be inaccessible for sampling. Again, the river users themselves picked locations for sampling where they saw indications of pollution, as will be seen later. Participants were asked to sample the river monthly where possible, so that a profile of the water quality could be built across all seasons.

2.4. Supplementary data

In order to investigate the impact of rainfall on the CS nutrient measurements, daily rainfall data from the Irish Meteorological Service (Met Éireann, 2020) for four weather stations in proximity to the BACKDROP sample locations for the study period (Fig. 1) were analysed in relation to the nutrient levels recorded in this study. Where a sample location had recorded a low water quality result, with either phosphates or nitrates being recorded as high, the rainfall data was investigated to look for local rainfall events at the time of sampling.

To determine the lag time between rainfall events and peak river flow, a proxy for the river Liffey was required. The river Liffey is controlled by a dam before Lucan and the nearest hydrometric gauge is just downstream of the dam. Therefore, the hydrograph from this station could not be used to examine the influence of rainfall events on flows in the river Liffey within the study area. The river Tolka was used as a proxy for the Liffey in this context. The Tolka is located approximately 2.5 km to the north of the Liffey (Fig. 1) and flows through a similar suburban/urban landscape before reaching the sea. Discharge of the Tolka is continuously measured at the National Botanic Gardens (EPA Hydronet, 2020), where there is also a Met Éireann rainfall monitoring station, thus allowing the influence of precipitation on the water flow of the Tolka to be ascertained. This is further analysed below in the results section.

To assess the complementarity of citizen science and agency data, BACKDROP's dataset was analysed against Irish EPA data for comparisons and validation where monitoring locations were similar. These EPA sampling locations are shown in Fig. 1. EPA data was accessed from the EPA open access online platform available at: https://www.catchments.ie/data. The relevant chemistry data were extracted from each sub-catchment area in accordance with the parameters being investigated for the corresponding timeframe (July 2019 to May 2020). In locations downstream where the Liffey is tidal, EPA sampling consisted of surface and bottom samples of each location (EPA, 2020d). In these tidal locations to the east of Islandbridge, only EPA samples recovered from the surface were taken into consideration, to replicate citizen science sampling. Where there was more than one sample taken on the same day, a median of the sample results was used.

2.5. Data analysis

To analyse the nutrient levels and water quality of the river Liffey, indicator thresholds used by the Irish EPA are referenced. This facilitates comparison between Irish EPA data in the study area and the data collected for this study. The EPA indicator thresholds are based on their scientific value, ease of detection and relevance to policy implementation, both nationally and internationally, and in line with the implementation of the UN SDG, especially Goal 6: clean water and

Table 1
EPA nitrate and phosphate limits for water quality and associated FWW parameter categories with midpoints values as used in this study.

EPA Standards	EPA NO_3-N limit mg/l	Relevant FWW NO_3 - N categories mg/l	Midpoint values of FWW Nitrate categories	EPA P limit mg/l	Relevant FWW PO_4 - P categories mg/l	Midpoint values of FWW Phosphate categories
High Quality	<0.9	0–0.2	0.1	<0.025	0–0.02	0.01
		0.2–0.5	0.35			
		0.5–1.0	0.75			
Good Quality	<1.8	1–2	1.5	<0.035	0.02–0.05	0.035
Lower Quality	>1.8	2–5	3.5	>0.035	0.05–0.1	0.075
		5–10	7.5		0.1–0.2	0.15
					0.2–0.5	0.35
					0.5–1	0.75

sanitation (EPA, 2018b). There are no national environmental quality standards for nitrate in Ireland, but average nitrate concentration values less than 0.9 mg/l NO_3-N (4 mg/l NO_3) are considered as indicative of high quality water by the EPA. Values between 0.9 mg/l and 1.8 mg/l NO_3-N (8 mg/l NO_3) are considered by the EPA to be indicative of good water quality (EPA, 2020e).

Average phosphate concentrations of less than 0.025 mg/l P and less than 0.035 mg/l P have been established in Ireland as environmental quality standards (EQS), which are legally binding to support the achievement of high and good ecological status as required by the WFD (European Communities Environmental Objectives (Surface Waters) Regulations, 2009; EPA, 2018b). The resultant nitrate and phosphate limits for the study are outlined in Table 1 with associated FWW parameter categories and midpoint values. For the purposes of this study, nitrate values of <1.0 mg/l NO_3-N are deemed to be indicative of high quality water, values 1.0–2.0 mg/l NO_3-N are interpreted as indicative of good quality, and values >2.0 mg/l NO_3-N indicative of lower quality. For phosphates, values <0.025 mg/l P are described as indicative of high quality water, values of 0.025–0.035 mg/l P as indicative of good quality water while values >0.035 mg/l P were deemed indicative of lower quality water.

3. Results

3.1. Spatial patterns of water quality

Fig. 2 shows a box plot of the midpoint values of all samples of nitrates (a) and phosphates (b) recorded at 19 locations along the Liffey. The site locations are as per Fig. 1. This data represents 101 samples taken and 202 tests carried out by citizen scientists over nine months. The most easily accessed sampling points, which were located in the city centre (CS sites 11–18), were more closely spaced than those points that were least accessible (CS sites 1–3). The Islandbridge area, where pedestrian citizen scientists could access the river from a riverside path running through a park (CS sites 7 to 9) had also a closer spatial frequency of sampling. Water user citizen scientists sampled sites 2–6 and sites 8, 10, 16 and 19 with pedestrians sampling the other points.

Across the reach of the river studied, nitrate levels indicated that water quality was high in 57.4% of these samples ($n = 58$), good quality in 32.7% ($n = 33$) and low quality in 9.9% ($n = 10$). Phosphate measurements were indicative of high water quality in 28.7% ($n = 29$) of samples, good quality in 35.6% ($n = 36$) and of lower quality in 35.6% (n = 36). There were spatial differences in nutrient concentrations across the sample locations, shown in Fig. 2. These differences can be understood by examining the three distinct types of land use through which the river flows: parkland; pockets of suburban and industrial development; and urban tidal landscape (Fig. 3).

The parkland section (sites 1–2) was less accessible, therefore fewer samples were obtained (5 in total, compared to monthly samples at other sites). In this stretch of the river, there were no measurements indicative of low water quality. However, the lack of sampling along this stretch makes it difficult to determine whether these results are representative of the overall water quality for this section over the study period. The sites within the suburban and industrial section (sites 3–9) were more frequently sampled, giving a wider range of data for both nitrates and phosphates. Within this stretch, high nitrate levels indicating low water quality were recorded in 6 samples (16%). High phosphate levels, indicative of low water quality, were recorded in 22 samples (21.7%). 61% of all high phosphate samples indicating low water quality were found within this stretch, and 60% of nitrate samples which indicate low water quality located here. Sample numbers in the urban tidal landscape were higher ($n = 66$) due to greater accessibility. Here, the river runs through the centre of Dublin city (Fig. 1). In this stretch of the river, there were 4 samples with high nitrate levels (lower water quality) and 13 phosphate results indicating lower water quality.

The data suggests that the suburban/industrial section of the study area (that area between site 3 and site 8 on Fig. 1) has a lower water quality than other sections of the river. This will be discussed further below.

3.2. Impacts of rainfall on water quality

By examining the hydrometric data for the river Tolka at the Botanic Gardens and the rainfall data for the same time period at the monitoring station at the same location, it was found that rainfall of up to 5 mm had no impact on the water flow in the Tolka, while flow increased by 2–3 m^3 the day following a rainfall event of up to 10 mm. Water flow at least doubled the day following a rainfall event of greater than 10 mm. This suggests that surface runoff from rainfall is a contributor to the rivers in this area when daily precipitation is more than 5 mm.

By applying these criteria to the data collected by the citizen scientists on the Liffey, the day preceding low quality water results were checked for significant rainfall that may have influenced water flow, and therefore the potential quality across the study area. Of the 9.9% of samples ($n = 10$) in the low quality category for nitrates (>2.0 mg/l NO_3-N) (Fig. 4a), six were collected after some or significant precipitation. Three of these were taken at sample sites within the transitional, estuarine waters of the city centre area on different dates, while a further three were taken on the same date (14 October 2019) in the

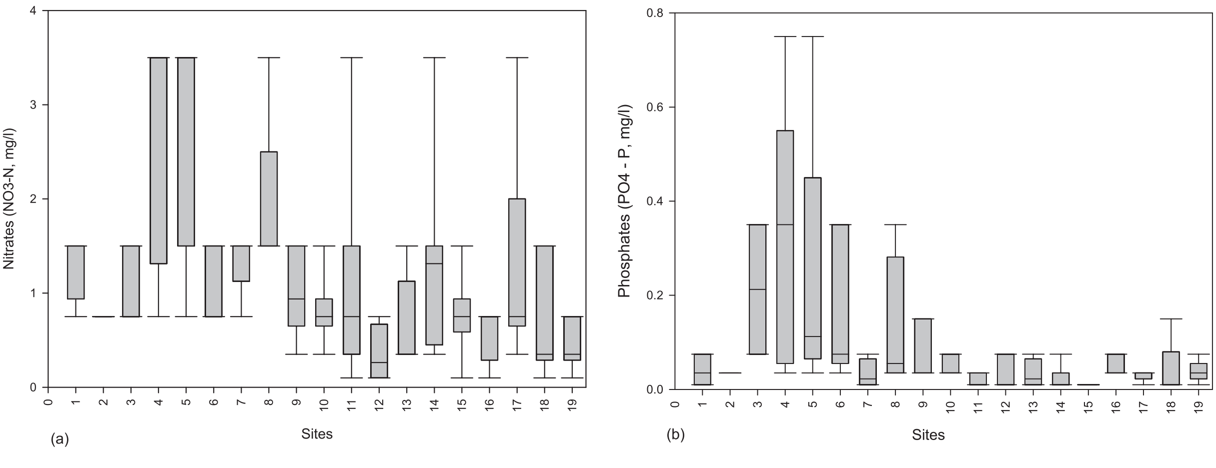

Fig. 2. Nitrate and phosphate results (with result ranges) from the citizen scientist sample sites along the river Liffey.

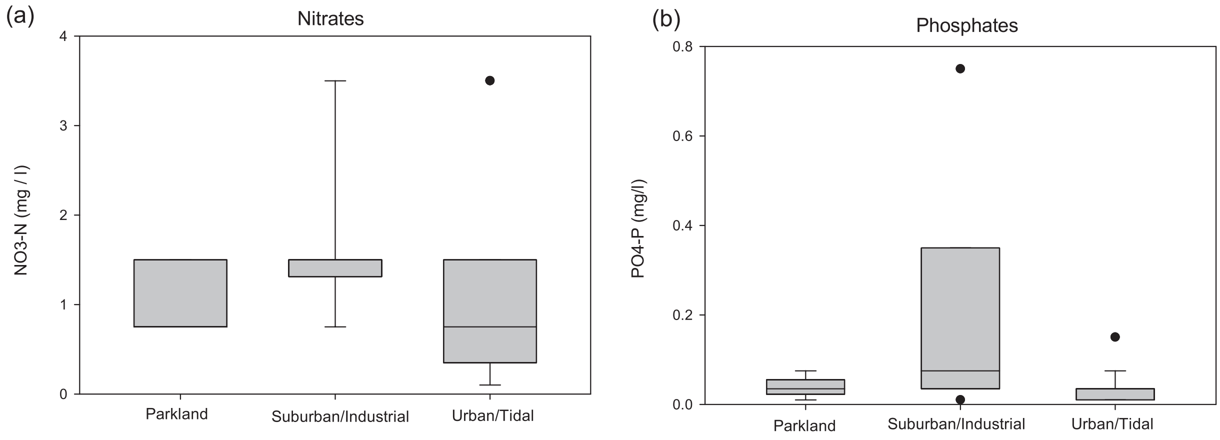

Fig. 3. Nitrate (a) and Phosphate (b) data ranges in the three river study sections ($n = 5$ for parkland, $n = 30$ for suburban/industrial and $n = 66$ for urban/tidal for each parameter). The mid line represents the median, the box represents the interquartile range (25%–75%), and the whiskers the minimum and maximum values. Data points outside the box are outliers.

Chapelizod area (Fig. 1). This is suggestive of nitrates being flushed into the Liffey at this point by runoff from hard urban surfaces during precipitation events.

For phosphates, 35.6% of all samples ($n = 36$), were in the low quality category (<0.035 mg/l PO_4-P; Fig. 4b). Six of these samples (17% of the total of high phosphates) were taken on days after some rainfall, with the remaining 83% of samples from days of no rainfall. The highest phosphate sample located within the estuarine, transitional reach of the Liffey was recorded after a very significant rainfall event - phosphate levels in the range of 0.1–0.2 mg/l PO_4-P were recorded on the 5th November 2019, after 18.9 mm of rainfall the previous day. Fig. 4 shows the levels of nitrates (a) and phosphates (b) when plotted against the average of the daily rainfall from four weather stations within the study area for the day preceding sampling. From Fig. 4, it is evident that most samples recording higher phosphates are associated with little or no rainfall in the day preceding sampling. The relationship between nitrate levels and rainfall is less conclusive, with the data suggesting that there may be some relationship between runoff and elevated nitrate levels, particularly in the city centre (Fig. 2).

3.3. Evidence of localised pollution events

For the samples of low quality water where rainfall was not a significant factor ($n = 7$ for nitrate and $n = 30$ for phosphate), location and supplementary data obtained from the FWW database are noteworthy. All 7 high-nitrate and 28 of the 36 high-phosphate samples are from locations to the east of Islandbridge weir (in the Suburban/Industrial section of the river). In the 'Notes' and 'Pollution Sources' columns of the FWW database, entries were made for at four of these locations of visible residential discharge such as the example in the supplementary data, while eutrophication was evident at six locations with entries in the 'Algae' column. All of these locations were in the parkland and suburban/industrial sections of the river, and several co-occurred with high phosphate and/or nitrate concentrations.

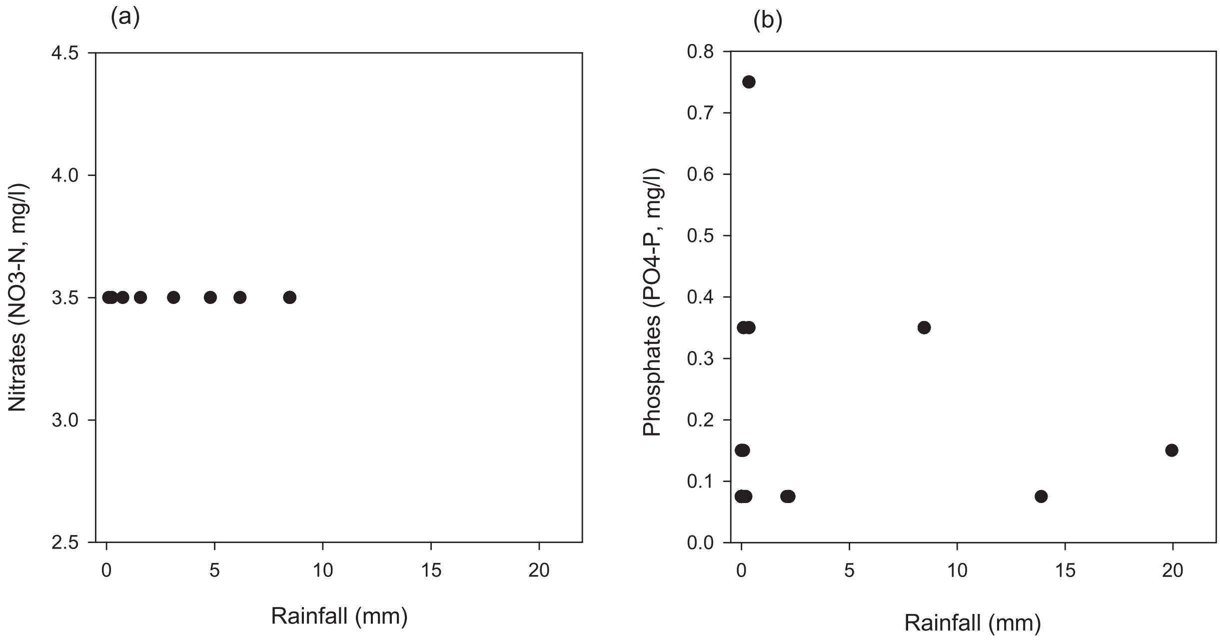

Fig. 4. Average daily precipitation data (mm) from four weather stations within the study area the day preceding sampling (Met Éireann, 2020) plotted against low quality water data points in (a) nitrate (n = 10) and (b) phosphate samples (n = 36). Some samples were taken on the same day and returned the same result and are plotted together.

Four sites (CS sites 4, 5 and 6, Fig. 1, all within the Chapelizod / Islandbridge area) recorded both nitrate and phosphate levels indicative of low water quality on the same sampling occasion. One of these sites, site 4, recorded nutrient levels indicative of low water quality on three distinct occasions. It is noteworthy that these three sites are adjacent to each other, suggesting a localised issue of pressures on water quality at this location around Chapelizod. The citizen scientists reported seeing water discharged into the river at these points, and on three sampling occasions, recorded in the notes: 'discharge smells of detergent' / 'cloudy discharge from pipe directly into river' / Unknown cloudy discharge from beneath the water level'. The significance of these notes and findings will be discussed further below.

3.4. Complementarity of citizen science and agency data

EPA sampling took place at 5 locations which correlated with BACKDROP citizen scientist sampling locations (Fig. 1). 39 samples were tested for nitrate and 38 for phosphate by the EPA at these locations during the period covered by the BACKDROP project. The correlation of EPA results with BACKDROP results in the brackish water transitional section of the Liffey, and upstream, suggests that the methodology used in FWW is robust also for this section of the Liffey (Fig. 5). However, the data collected by the citizen scientists in this study showed a greater range of phosphates in particular than those recorded by the EPA at the Chapelizod site.

35.9% of the EPA samples ($n = 14$) were indicative of low water quality because of excessive nitrates (>2.0 mg/l NO_3-N). Of these samples, 7 occurred during some or significant rain and 7 after little or no rain, and all were from locations upstream of the weir at Islandbridge. For phosphates, the EPA recorded no phosphate levels which were indicative of lower water quality (Fig. 5).

4. Discussion

Citizen science has the potential to produce data at a much higher spatial frequency than traditional monitoring techniques, and for this reason it is commonly cited as a means to increase data coverage and to fill gaps in regulatory monitoring (Quinlivan et al., 2020b). In this study, the spatial and temporal frequency of citizen science monitoring allowed trends in water quality relating to land use and rainfall events in an urban area to be understood at a granular, local level. The local knowledge of the citizen scientists also added valuable data, with citizen scientists able to target areas that they had observed may be under pressure.

4.1. Granularity of understanding from citizen science data

Citizen science monitoring was conducted in 19 locations along the urban river Liffey, at a spatial resolution that captured changes in land use across the city, and at a resolution greater than that carried out by agency monitoring. This allowed trends in water quality related to these land use changes to be examined. The data showed that nutrients, particularly phosphate, were elevated as the river flowed through suburban and industrial land, particularly in the Chapelizod area. This is

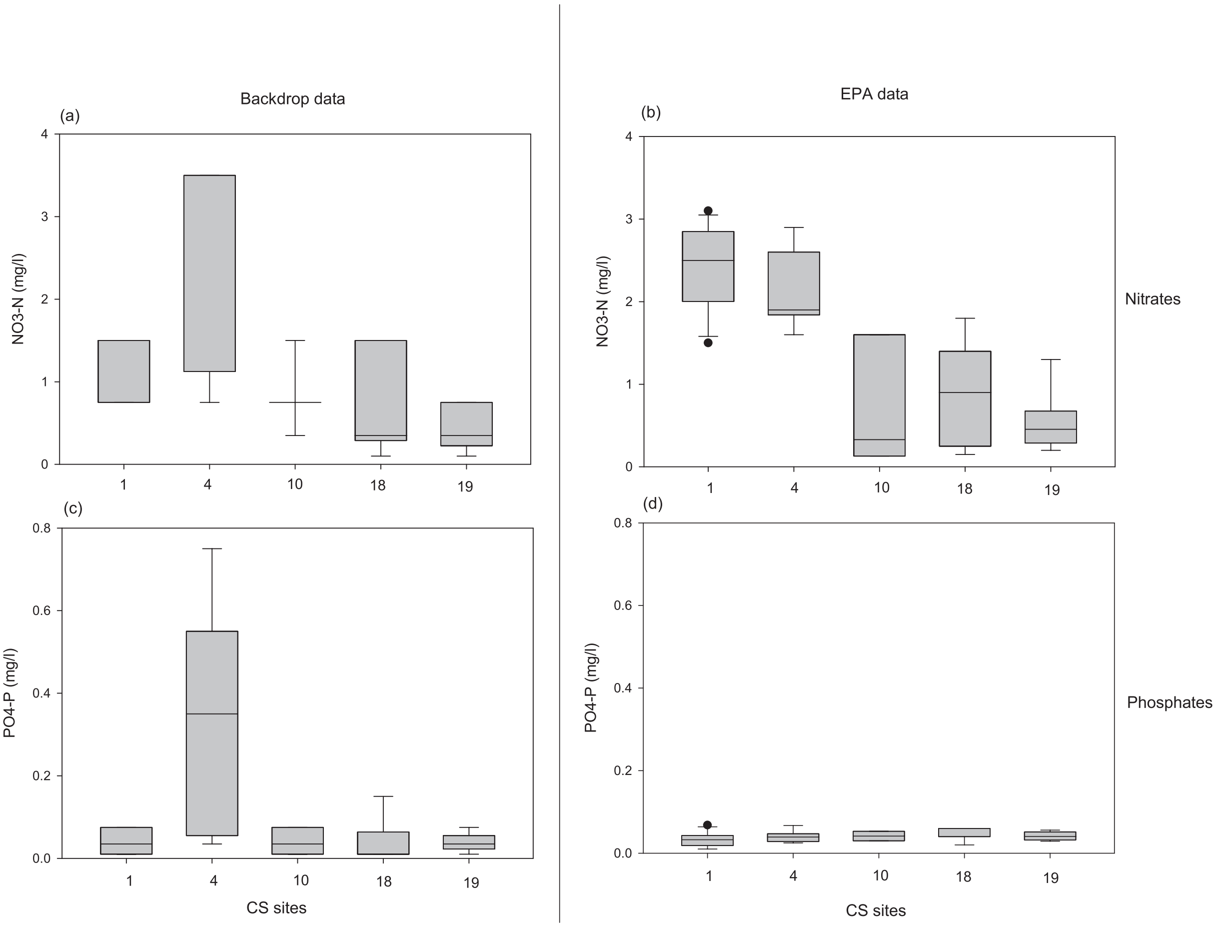

Fig. 5. Ranges of data from five locations sampled by both EPA and Backdrop citizen scientists over the same period. Locations are as per Fig. 1. Nitrates BACKDROP, (b) nitrates EPA, (c) phosphates BACKDROP and (d) phosphates EPA. Backdrop samples CS site 1 ($n = 3$), 4 ($n = 5$), 10 ($n = 7$), 18 ($n = 6$), 19 ($n = 5$). EPA samples CS site 1 ($n = 14$), 4 ($n = 7$), 10 ($n = 3$), 18 ($n = 7$), 19 ($n = 8$).

likely due to phosphate inputs from urban discharges, which are common in urban areas (Ternus et al., 2011). It also showed decreases in nutrients further downstream, towards the highly urbanised city centre. Here, tidal dilution as well as inputs from rivers and canals along this stretch may also be a factor, but this has not yet been formally assessed (Caccia and Boyer, 2005; EPA, 2019a,b).

Research has shown that water quality can also be impacted by seasonal variations in nitrate and phosphate which also relate to land cover (Mouri et al., 2011; Pratt and Chang, 2012; Shi et al., 2017; Shupe, 2017). Because citizen scientists in BACKDROP measured monthly, it was possible to investigate the interactions between weather, land-use, and water quality at a more granular level. Indeed, the data revealed differences in the impacts of individual rainfall events on nutrients in the upstream areas versus the downstream areas. Upstream of Islandbridge, where land cover was either parkland or suburban, poor water quality was associated generally with periods of lower rainfall. However, in the estuarine stretch, where the river runs through the city centre and is subject to runoff from hard urban surfaces, a number of high nutrient measurements occurred in association with rainfall events.

It is important to note that the use of citizen science does not always guarantee higher spatial or temporal resolution of data. In this study, as in many other citizen science studies, volunteers were encouraged to self-select their sampling locations based on their interests and ease of access. This meant that high numbers of measurements were made in the city centre, while very few were made in the less accessible parkland sections on the outskirts of Dublin (sites 1 and 2). Increased analysis of this section would be useful in the future in determining any additional inputs that may occur from nearby recreational sectors such as golf courses. Research has shown that the intensive management of turfgrass systems of golf courses requires inputs of fertilisers, pesticides and irrigation which can have an environmental impact with nutrient losses (nitrogen and phosphorus) through run-off and leaching, especially with excessive rainfall (Bock and Easton, 2020).

4.2. Significance of qualitative data from citizen scientists

In addition to quantitative measurements of water quality, various qualitative and photographic observations from BACKDROP citizen scientists measuring locations upstream of Islandbridge indicate instances of pollution. Photographs showed cloudy, frothy discharge from pipes into the river, while citizen scientists noted evidence of eutrophication and floating mats of algal growth in these locations, some of which correlated with high nitrate and phosphate results during periods without rainfall. Many studies have cited the presence of algal blooms as an indicator of the degradation of water quality based on measurements of nutrient (nitrate and/or phosphate) concentrations (Cunha et al., 2017; Thornhill et al., 2017). Frothy discharge from pipes, meanwhile, is indicative of drainage system misconnections; indeed, as noted above, some participants recorded witnessing a smell of detergent at some locations. Household appliances that are wrongly connected to separate surface water sewers can potentially lead to pollution of receiving waters with elevated concentrations of nutrients (phosphate, ammonia, nitrates) and non-compliance with statutory water quality standards (Ellis and Butler, 2015). The main pollutant loading contribution to misconnections arising from washing machines and dishwashers is PO_4-P. Even with substantial dilution in the order of 50–100:1 to conform to ecological criteria, the receiving water would be of poor quality status (Revitt and Ellis, 2016).

The EPA have cited urban domestic misconnections as a concern for urban freshwater quality in Ireland (EPA, 2017). Dublin local authorities have estimated that 8% of houses are misconnected with other sewers, and have suggested that this figure may be as high as 20% in some areas (EPA, 2019b). In 2020 one of Dublin's local authorities, South Dublin Council, began a project (Dublin Urban Rivers Life) to map and remedy these. While the study area is not within the catchments covered by the Dublin Urban Rivers Life, the methodology in this study can inform this type of remedial work, and can add valuable data if similar projects are rolled out in other local authority areas.

Interestingly, the qualitative observations of citizen scientists described above all relate to locations where land use changes and parkland gives way to pockets of suburban and industrial development. Both the qualitative observations and areas of high phosphates measured by BACKDROP citizen scientists also correspond to areas where intensive housing development took place along the course of the Liffey in the early 2000s, during what was termed the Celtic Tiger period (Fig. 6). Urbanisation generally tends to decrease water infiltration into the soil and concentrate flows in storm drains and channels as the percentage of impervious surface is increased, with a resultant impact on the ecology of nearby rivers and streams (James and Lecce, 2013). Furthermore, during the Celtic Tiger period, Ireland experienced rapid economic growth and a building boom and strategic planning practices were absent or poorly implemented; many housing developments consisted of suburban sprawl on greenfield sites (Winston, 2007). Urban land expansion had an annual growth rate of 2.5% in Ireland between 2000 and 2012, among the highest rates in Europe (Ahrens and Lyons, 2019). This unprecedented growth took its toll however, with concern relating to the quality of dwellings constructed during the Celtic Tiger era (Kitchin et al., 2015).

Based on the BACKDROP citizen scientist observations, this paper suggests that there is evidence of drainage system misconnections arising from the Celtic Tiger period that are impacting water quality in the river Liffey, particularly in the Chapelizod area. Qualitative findings collected by participants support the quantitative nitrate and phosphate data, and strengthen this hypothesis that misconnections are responsible for the poor water quality in this area. Previous studies have demonstrated the value of community-based qualitative observations in adding value to their body of data (Cunha et al., 2017; Scott and Frost, 2017; Starkey et al., 2017), and the BACKDROP study further supports this.

4.3. Citizen scientists' contribution to monitoring schemes

Research has shown that citizen science has potential to augment professional water quality monitoring by generating additional data on previously under-reported freshwater ecosystems (Hadj-Hammou et al., 2017), and also fill the data gaps as suggested by the UN and EU (McGoff et al., 2017; Scott and Frost, 2017). In its recommendations in ‘Best Practices in Citizen Science for Environmental Monitoring’, the European Commission has suggested that citizen science could be a cost-effective way to complement environmental reporting in the priority areas of the Green Deal, and initiatives to fight environmental pollution could be identified and supported as part of the zero pollution ambition (EC, 2020). The report also recommended that both the EU and its member states could provide funding and support for these initiatives to contribute to the knowledge base required, while evaluating their policy and societal impacts (EC, 2020).

This study not only shows that citizen science data can detect the same environmental trends as data collected by statutory agencies, but also demonstrates that citizen science data can capture additional relevant information. The data collected by BACKDROP citizen scientists aligned well with statutory (EPA) data both spatially and temporally (Fig. 5). Both datasets showed a lowering of nitrate and phosphate concentrations and a reduction in their range as sampling locations move to the mouth of the river and waters are diluted by the tides. Additionally, there were some nuances in the data that were not visible in the EPA dataset but were revealed by the citizen scientists. In particular, the range of data for BACKDROP samples is wider in the Chapelizod area of the study region, where citizen scientists took measurements at different times and in different locations to the EPA. Here, the range of nutrient concentrations recorded by citizen scientists was greater than those recorded by the EPA (Fig. 5), and citizen scientists are therefore possibly detecting pollution instances that are not being picked up

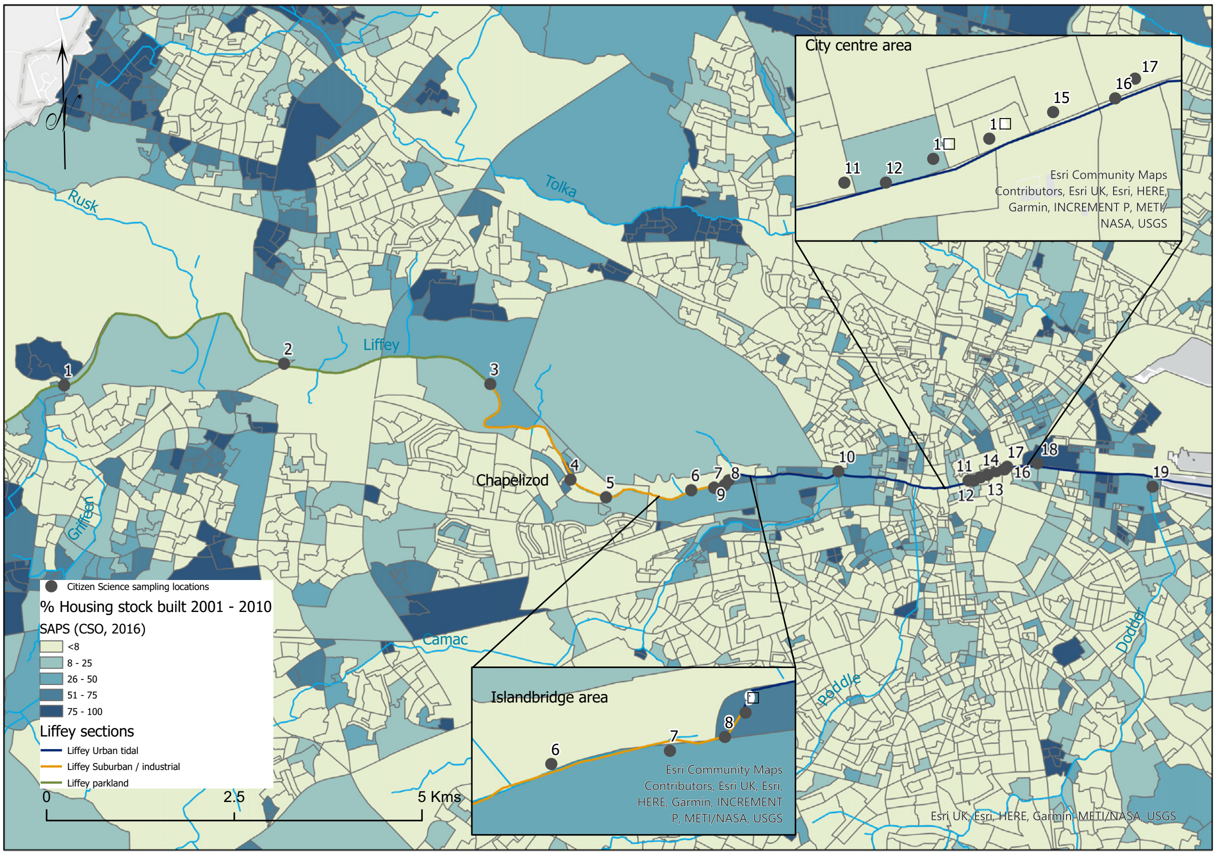

Fig. 6. Percentage housing stock built between 2001 and 2010 and CS sampling sites. Note the proximity of site 4 to the area of high percentage housing built during the Celtic Tiger (2000–2008) period (Central Statistics Office (CSO). 64% of the housing stock at this location was built during the Celtic Tiger.

otherwise. This is supported further by the qualitative observations of citizen scientists described in Section 3.3 and discussed in 4.2, in particular the mapping of inputs into the river by citizen scientists – inputs that would suggest domestic misconnections. By pinpointing pollution sources and filling gaps on the effect of land use and its impact on the nutrient load of the river Liffey, citizen scientists have made a valuable contribution to the data bank on water quality in Dublin.

While it is clear that citizen science can play an important role in complementing national agency monitoring in Dublin, the potential for these findings to be applied more widely should not be underestimated. To monitor progress towards SDG target 6.3 ('by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally'), all UN member states are expected to measure and report the 'proportion of water bodies with good ambient water quality' (indicator 6.3.2). SDG Indicator 6.3.2 is classified as Tier 2 by the UN which states the "indicator is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries", whereas Tier 1 produces data regularly and Tier 3 does not have an internationally established methodology or standards (UN, 2020). Fritz et al. (2019) identifies the importance of new and non-traditional sources of data such as citizen science in progressing indicators upwards through the tiers suggesting a roadmap at global, national and local levels that can ultimately integrate citizen science into the formal SDG reporting process.

The UN recommends five core monitoring parameters for rivers and lakes towards facilitating global comparability of the ambient water quality SDG Indicator 6.3.2: dissolved oxygen, electrical conductivity, pH, total oxidised nitrogen (TON) and orthophosphate (or phosphate) (UN-Water, 2018). FWW measures two of these five core parameters, and has frequently been cited as an example of a citizen science project that can support production of data for this indicator (Fritz et al., 2019; Quinlivan et al., 2020a; Fraisl et al., 2020; Hegarty et al., 2020). It has been suggested that a well-designed citizen science water quality monitoring project can support monitoring for SDG Indicator 6.3.2 both alongside existing statutory monitoring programmes and in situations where statutory monitoring is limited (Bishop et al., 2020). By providing a case study showing how citizen science can support and add value to statutory monitoring, this paper provides further support for the use of citizen science to monitor ambient water quality in this context.

The potential for citizen science to complement more traditional ways of scientific data collection, especially for hydrological sciences and water resources management, has been well documented in this paper and beyond (Buytaert et al., 2014; Cunha et al., 2017; Hadj-Hammou et al., 2017; McGoff et al., 2017; Hadj-Hammou et al., 2017). The contribution by citizen scientists is especially relevant in freshwater ecosystems where the importance of increased sampling of freshwater systems for safeguarding biodiversity, understanding human impact, and mitigating and adapting to climate change makes this a top priority for national and international agencies. However, the instance of CS data being used to inform water policy at any level of government was less than 50% in a study of over one hundred community-based monitoring programmes by Carlson and Cohen (2018), while respondents in a study involving the implementation of the WFD in the Netherlands found that the active involvement of the public was unsuccessful (van der Heijden and ten Heuvelhof, 2012). To further facilitate the use of citizen science in policymaking, professional scientists should play a central role in guiding local communities to participate in citizen science programmes thereby contributing to environmental monitoring (Loiselle et al., 2017; van Noordwijk et al., 2021). While there have been concerns regarding the quality of data from these programmes

(Bonney et al., 2014; Dickinson et al., 2010), extensive research such as that undertaken by Burgess et al. (2017) which explored the barriers of its use as a research tool, concluded that programmes which partnered with academic institutions and whose participants had sufficient training using standardised protocols with an accessible dataset were more likely to be utilised.

As part of its recommendations in ‘Best Practices in Citizen Science for Environmental Monitoring’ (EC, 2020), the European Commission has many suggestions for public authorities at EU level and in member states. These include reviewing and communicating relevant data-quality requirements and methodologies to CS programmes to enable the use of citizen science data that meet quality standards in official monitoring, and to promote the availability of citizen science data on open platforms, while ensuring that official reporting mechanisms can accept and integrate this data (EC, 2020). As policymakers continue to embrace the potential of citizen science in the coming years, it is more important than ever that programmes like BACKDROP, with trained participants who use standardised protocols and methodologies from organisations like FWW, which are available on an open platform, continue to monitor water quality and bring the findings to the notice of relevant environmental bodies.

5. Conclusions

This citizen science project assessed water quality along the river Liffey to fill the data gaps in environmental monitoring for UN SDG Indicator 6.3.2, while detecting any significant detrimental nutrient inputs to the river that may have come from storm drains and residential discharges. Instances of low quality water in nitrate and phosphate parameters were detected. While rainfall events may have been a factor on some of these occasions, urban discharges, especially domestic misconnections due to urban expansion were deemed more important contributions to detrimental water quality through additional qualitative, observational data recorded by citizen scientists. Data from the EPA was also analysed to assess the complementarity of CS data and the findings concluded that the range of data from the BACKDROP project spatially and temporally enhanced national agency monitoring. An expansion of the programme to better distribute sampling points and continued monitoring would also strengthen the case for use of the data by the appropriate national agencies. The use of the tried and tested FWW methodology by a CS programme partnered with an academic institution and carried out by trained citizen scientists has the potential to assist in progressing SDG Indicator 6.3.2 upwards from Tier 2 to Tier 1. The results produced from this study demonstrate the value of citizen scientists in assessing water quality which cannot be underestimated.

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CRediT authorship contribution statement

Susan Hegarty: Conceptualization, Data curation, Visualization, Formal analysis, Writing – review & editing, Supervision. **Anna Hayes:** Writing – original draft, Visualization, Formal analysis. **Fiona Regan:** Writing – review & editing, Funding acquisition. **Isabel Bishop:** Resources, Writing – review & editing. **Ruth Clinton:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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