CITIZEN SCIENCE:
THEORY AND PRACTICE

How Certain is Good Enough? Managing Data Quality and Uncertainty in Ordinal Citizen Science Data Sets for Evidence-Based Policies on Fresh Water

COLLECTION:
CONTRIBUTIONS OF CITIZEN SCIENCE TO THE UN SDGS

RESEARCH PAPER

ubiquity press

JACEK STANKIEWICZ
ARIANE KÖNIG
KARL PICKAR
STEFAN WEISS

*Author affiliations can be found in the back matter of this article

ABSTRACT

This study investigates surface water quality in Luxembourg with the help of citizen scientists. The fundamental question explored relates to uncertainty and judgements on what constitutes adequate data sets, comparing official data and citizen science. The case study evaluates how gaps and uncertainties in official data for the United Nations Sustainable Development Goal 6 (UN SDG 6), Indicator 6.3.2 on water quality, and the EU Water Framework Directive (WFD), can be served with citizen science. In two Water Blitz sampling events organised in collaboration with the NGO Earthwatch, participants sampled water bodies at locations of their choice, using field kits to estimate nitrate (NO_3^--N) and phosphate (PO_4^{3-}-P) concentrations. Samples were collected (428 in total) over two weekend events, providing snapshots in time with a good geographic coverage of the water bodies across the country: 35% of nitrate and 29% of phosphate values were found to exceed thresholds used by the European Environment Agency to classify the nutrient content in water as good. Our study puts forward recommendations on how citizen science data can complement official monitoring by national agencies with a focus on how such data can be represented to serve the understanding and discussion of uncertainties associated with such ordinal data sets. The main challenge addressed is high levels of natural variation in nutrient levels with both natural and anthropogenic multi-factorial causes. In discussing the merits and limitations of citizen science data sets, the results of this study demonstrate that a particular strength of citizen science is the identification of pollution hotspots in small water bodies, which despite being critical for ecosystem wellbeing are often overlooked in official monitoring. In addition, citizen science increases public awareness and experiential learning about factors affecting surface water quality and policies concerning it.

CORRESPONDING AUTHOR:
Ariane König
University of Luxembourg, LU
ariane.koenig@uni.lu

KEYWORDS:
Social-ecological systems; Adaptive Governance; Water quality; Monitoring; Uncertainty

TO CITE THIS ARTICLE:
Stankiewicz, J, König, A, Pickar, K and Weiss, S. 2023. How Certain is Good Enough? Managing Data Quality and Uncertainty in Ordinal Citizen Science Data Sets for Evidence-Based Policies on Fresh Water. *Citizen Science: Theory and Practice,* 8(1): 39, pp. 1–15. DOI: https://doi.org/10.5334/cstp.592

INTRODUCTION

The quality of evidence and the process by which it is developed are main factors affecting the quality of environmental policies and the circumstances that allow for their implementation (Jasanoff 1999). Reliable monitoring and evaluation are essential in management of socioecological systems, and inadequate practices can negatively affect environmental policies designed to safeguard or improve the environment (e.g., Chapman 2012; Vinke-de Kruijf et al. 2015). National and regional public authorities are tasked with data collection, with official statistics, environmental accounts, and indicators developed in the context of EU Environmental Policies increasingly aligned with the suggested indicators for the purpose of monitoring progress towards attaining the United Nations Sustainable Development Goals (UN SDGs). Many of these agencies, however, face resource constraints preventing them from instituting sampling strategies that yield high data densities across space and time (e.g., MacFeely and Nastav 2019; Topping and Kolok 2021). With indicators concerning SDG 6 on surface water quality and the EU Water Framework Directive (WFD, EU 2000) this has sometimes led to the neglect of small streams and ponds, regardless of the biodiversity of their location (e.g., Beklioglu et al. 2016; Wohl 2017).

These official expert-driven collections could be complemented with data from citizen science. This refers to the participation of citizens, or members of the public, joining efforts with professional scientists with the objective of gathering scientific information (e.g., Silvertown 2009). Different forms of citizen science can be distinguished based on the nature and level of volunteer engagement (e.g., Shirk et al. 2012; Buytaert et al, 2014; Haklay 2015; Thornhill et al. 2019). In particular, the potential of citizen science to contribute to water quality data in the UN SDG framework has been highlighted (e.g., Hadj-Hammou et al. 2017; Fraisl et al. 2020; Pickar 2021; König et al. 2021). Nonetheless, there remains a debate about the utility of citizen science data sets in scientific projects and as a basis for policy-making, especially in the field of ecological monitoring (e.g., Kremen et al 2011; Munson et al 2010; Walker et al. 2016; Kasperowski and Haggen 2022). A critical step is to recognise the potential issues concerning sources of error and uncertainty, and to address them accordingly (e.g., Bonter and Copper 2012; Bird et al. 2014; Khajwal and Noshadravan 2021).

This paper describes a case study on requirements for data collection drawing on both expert-driven and citizen science–driven data pools. Specifically, the aim of the study is to evaluate how gaps in official data on surface water quality can be addressed with citizen science, exploring uncertainty and judgements on what constitutes adequate data sets. The purpose of the citizen science events reported here is not just to reveal additional data sources, but to open windows of accountability, and to create public awareness and allow for meaningful public engagement where environmental protection is concerned. This follows recommendations developed for Post Normal Science: On issues with high uncertainties, high stakes, and values in dispute, an extended peer review by diverse stakeholders including non-experts is desirable (Funtowicz and Ravetz 1993). The involvement of all actors should be a prerequisite for achieving societal objectives in the face of global change, especially considering the objectives set by the UN SDGs, which reinforce the need to consider socioecological systems and interconnections (e.g., Duit et al. 2010; Hajer et al. 2015). Suggestions for improvement of policy-driven data collection include more use of nontraditional data, and the growing need for more integration in sharing and processing of data used for policy-making (e.g., Buytaert et al. 2012; Waylen et al. 2019). The particular focus of this study is the data quality and the management of uncertainties in ordinal data sets. The study provides recommendations on how to improve the relation between the representations of the evidence base for policies and the way the policy measures may be better implemented.

One main concern in this framework is freshwater quality, specifically, elevated nutrient levels causing impoverishment of biodiversity through eutrophication (e.g., Chislock et al 2013). This process is a major cause for deterioration in aquatic ecosystem health and in diversity in surface freshwater bodies worldwide (e.g., Malone and Newton 2020), and has the potential for setting off major chain reactions in the ecosystem, affecting CO_2 and O_2 concentration, as well as other chemical and physical parameters, reducing biodiversity to species that thrive in nutrient rich environments. Eutrophic waterways are increasing in frequency and severity from the enrichment of anthropogenically-driven inputs of nitrate and phosphate (e.g., Withers et al. 2014; Topping and Kolok 2021).

In Luxembourg, the management of water systems is principally the responsibility of the Water Management Agency (Administration de La Gestion de l'Eau, AGE), an agency supporting the Ministry of the Environment, Climate and Sustainable Development. While the activities of the AGE are well ahead of the requirements of the WFD (AGE 2015), with 46 sites sampled regularly (Table 1), Luxembourg's small size often leads it to being treated as a statistical anomaly, with data not meaningfully interpreted in international reports.

The case study of the application of citizen science as an approach in the governance of water quality described in this paper is based on the organisation of a suitable data collection campaign for the engagement of citizen

	PHYSICAL AND CHEMICAL	BIOLOGICAL	HYDRO-MORPHOLOGICAL	NATURALLY OCCURRING SUBSTANCES ASSOCIATED WITH POLLUTION	OTHER POLLUTANTS
Description	Temperature, parameters concerning oxygen, turbidity, pH	Indicators concerning aquatic plants, other organisms.	Indicators concerning water flow, depth, width of riverbed and river bank	Salinity, nutrients*, chlorophyll, metals	Pesticides, pharmaceuticals, other chemicals
Sampling frequency in major rivers	Monthly	Monthly/ bimonthly	Continuously	Monthly	Monthly/ after screening
Sampling frequency in other water bodies	Monthly/ quarterly	Every 3 years	N/A	Monthly/ quarterly	Irregularly

Table 1 Selected Administration de La Gestion de l'Eau (AGE) data collection parameters (Pickar 2021; AGE 2015).

* Total phosphorus, ortho-phosphate, ammonia, nitrate, nitrite.

scientists. We collaborated with FreshWater Watch (FWW), a global initiative to allow citizen scientists to participate in freshwater research. FWW is organized by Earthwatch, an international NGO promoting the engagement of the public in environmental research. In the framework of their international activities, two sampling events were organised in Luxembourg in September 2019 and May 2021. Data were collected following the FWW sampling protocol to provide insights into all types of local water bodies in different settings.

This study offers detailed analysis, discussion, and evaluation of data quality and associated uncertainties of the two data sets (expert and citizen science). We then develop design recommendations for data collection by citizen scientists to complement expert-driven data on water nutrient levels. In this way, we believe the strength of citizen science data sets can be improved to meaningfully complement the official data on water quality collected by regular monitoring activities of the government agency tasked with monitoring of the quality of the national water bodies.

METHODS

The Water Blitz events coordinated by FWW were held in several countries. The Luxembourgish events, organised locally by the University of Luxembourg, took place from the 20th to 23rd September 2019, and from 7th to 9th May 2021, respectively. The events were open to all who wished to participate, with a registration required to allow for timely delivery of the instructions and the sampling kit. The advertisements inviting participation were distributed through various communication channels of the national government, nature reserves, and various organisations and societies. The sampling protocol of the FWW was followed. Each individual measurement involved the participant sampling a particular waterbody at the location of their choice. The kits allowed the participants to measure the nitrate-nitrogen (NO_3^-–N) and phosphate-phosphorus (PO_4^{3-}–P) concentration. These were estimated using a Griess based colorimetric method (Nelson et al. 1954), with the post-reaction sample colour matched to the provided ones. For the nitrate concentration, seven ranges were available, separated by values of 0.2, 0.5, 1, 2, 5 and 10 mg/l. The phosphate concentrations were similarly grouped into 7 ranges defined by values of 0.02, 0.05, 0.1, 0.2, 0.5, and 1 mg/l. These non-linear intervals are used in FWW projects (e.g., Scott and Frost 2017; Quinlivan et al. 2020), as they give equal weight to values in every order of magnitude. Participants could further comment on the land use setting and vegetation type, report an abnormal water colour, and comment on the presence of litter, algae, or other visible pollutants. The complete set of measured and observed parameters is given in Table 2. The data could be uploaded using the FWW mobile application or the online platform, and are freely accessible on the FWW website.

The collected data were subject to quality control by the staff of the University of Luxembourg. In several cases, the coordinates provided by the citizen scientists were incorrect, as they did not correspond to the location of a body of water, most likely due to uncalibrated GPS devices, or poor network coverage. As participants provided a brief site description, or a photograph, most of these points could be relocated to their likely correct location. In these cases, even a brief comment such as "bridge where cycle path crosses the river" was often sufficient. Only 4 data points had to be discarded owing to untraceable locations. Shortly after the closure of the 2021 event, participants were invited to take part in a survey about their motivation, experience in citizen science initiatives, impressions, and recommendations.

RESULTS

During the Water Blitz 2019 event, 132 samples were collected in Luxembourg in September 2019, providing a good geographic coverage of the country (Figure 1). The

PARAMETER	DESCRIPTION
Date	When sample was taken
Location	Coordinates and/or site description
Nitrate concentration	Match sample to one of 7 colorimetric ranges
Phosphate concentration	Match sample to one of 7 colorimetric ranges
Water body Type	Choose from: stream, river, pond, lake, wetland, source
Land use	Choose from: agriculture, forest, grassland/shrub, urban residential, urban park, industrial, other (specify)
Vegetation	Choose from (more than one possible): trees/shrubs, grass, other (specify)
Pollution	4 binary answers concerning presence of: foam, litter, algae, oily sheen
Colour	Choose from: colourless, yellow, green, brown, other (specify)

Table 2 Parameters required at each data point. While other parameters were optional (e.g., turbidity, water flow), for dataset completeness only the parameters listed here were used in this study.

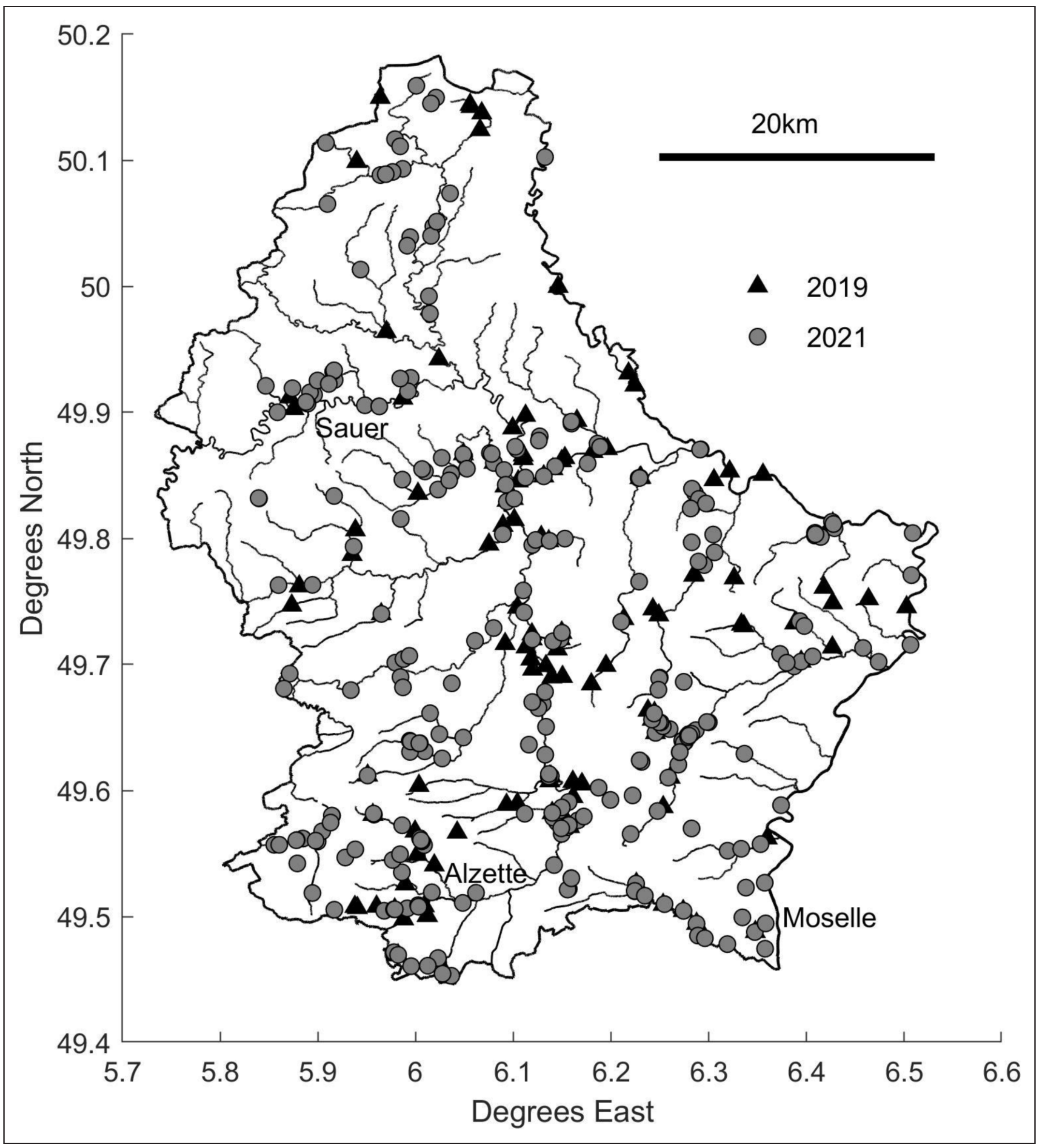

Figure 1 Location of sampling sites from the 2019 and 2021 Water Blitz events in Luxembourg.

2021 event received significantly more interest, with 296 data points collected in May 2021 (Figure 1). All these data are freely available on the FWW website. The distribution of measured nutrient concentration is shown in histograms in Figure 2, while the geographical locations are presented in Figure 3. To understand the relative values of these concentrations, one must refer to the guidelines established by the European Environment Agency. In following these,

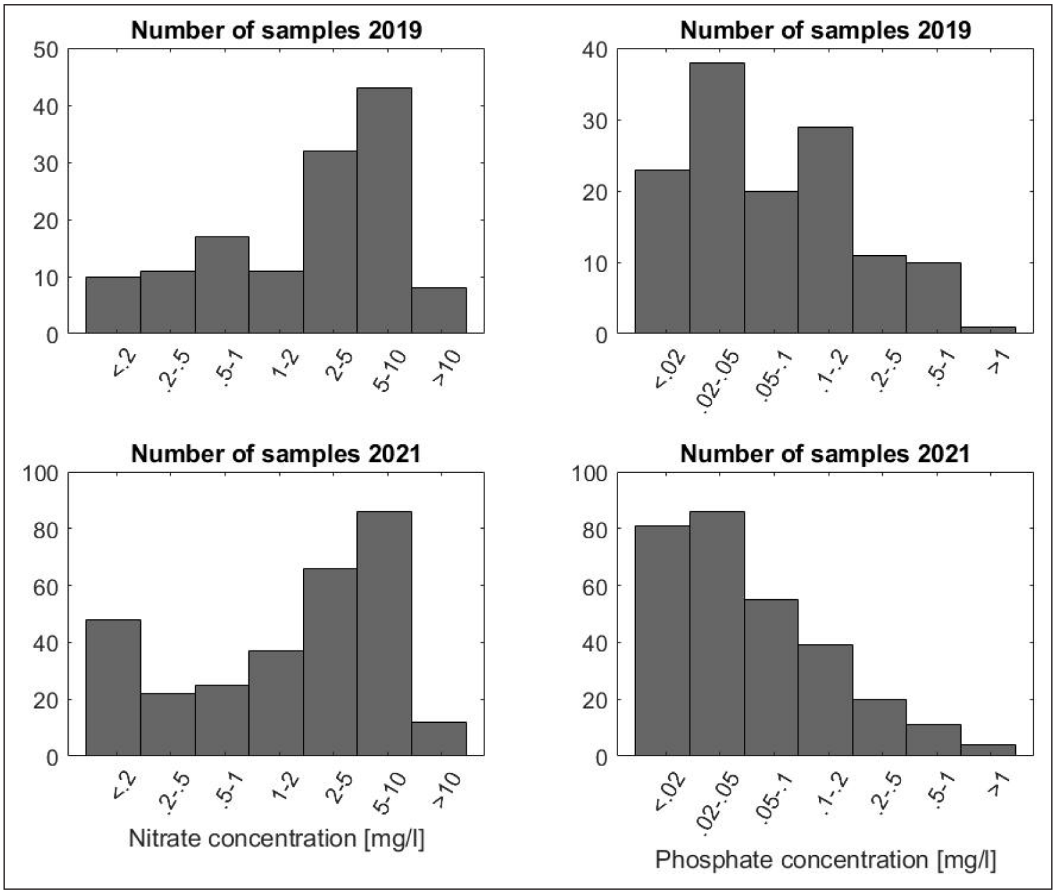

Figure 2 Distribution of observed nutrient concentrations.

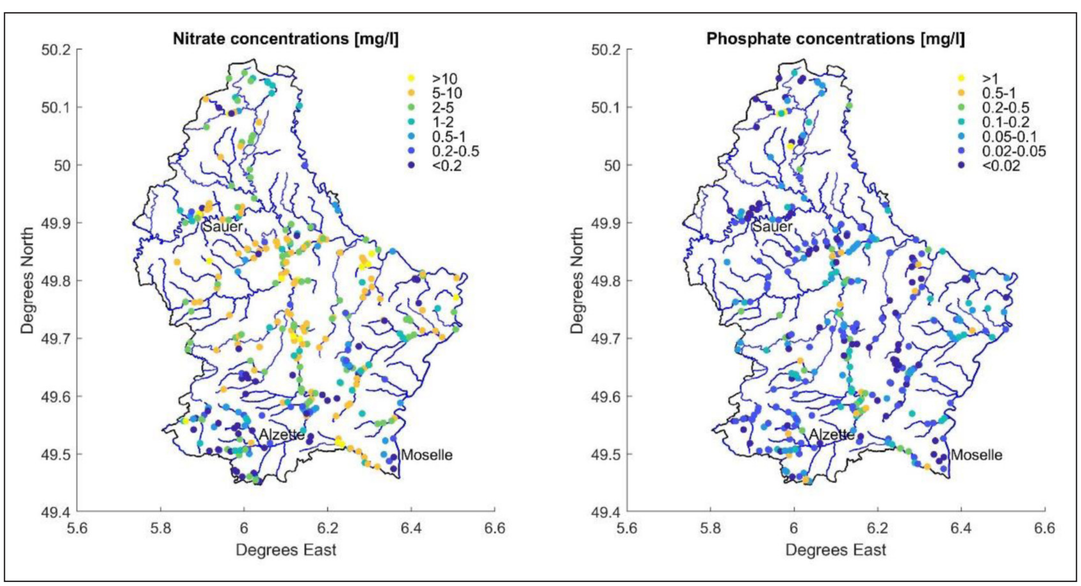

Figure 3 Geographical distribution of observed nutrient concentrations combined for the 2019 and 2021 events.

AGE (2009) established a scale to specify the water quality based on the nutrient concentration. The relevant sections of this scale are listed in Table 3.

Uncertainty, a key issue when presenting any data, has been put forward as one of the key obstacles to sustainable governance of freshwater (Pickar 2021). However, mere reference of uncertainty in sustainable governance can be confusing (Hasselman 2017; and references therein), without distinguishing types of uncertainty. Very broadly, uncertainty can be classed into reducible and irreducible (e.g. Ascough et al. 2008), entailing that some of it can be reduced or eliminated, such as by further research, and that some of it cannot be. How to even slightly broaden this classification is not trivial, with Walker et al. (2003) putting forward the location, level and nature of uncertainty as its three dimensions, while Hasselman (2017) identifies imperfect knowledge, incomplete knowledge, and unpredictability as three broadly recognised types. In yet another classification, numerical and social dimensions of uncertainty are distinguished (van der Sluijs et al. 2005).

Given the different nature of the two data sets, it is essential to define a framework in which data, along with associated uncertainties, will be interpreted. The European Statistical System lists 5 principles of the Code of Practice for statistical output (ESS 2012):

- Relevance
- Accuracy
- Timeliness
- Coherence and Comparability
- Accessibility and clarity

It is important to note that there is no such thing as a perfect data set for development of official statistics or indicators—the tool serves to make transparent limitations and trade-offs in relation to policy-relevant quantitative information. Assigning scores for each of these criteria allows for the assessment of a statistical set, including the identification of its shortcoming. Applying these criteria to evaluate the statistics behind the Ecological Footprint, Ravetz et al. (2018) found a favourable ranking for Relevance, but poor rankings for all other principles, leading them to propose NUSAP (Funtowicz and Ravetz 1990) as a powerful way to critically look at numbers where environmental indicators are concerned. The notational NUSAP system is based on five categories; the first three (Numeral, Unit, and Spread) convey traditional statistical information. The category Assessment represents a summary of qualitative judgements concerning the information.

An especially novel category is the Pedigree. This is an evaluative description of the mode of production (and anticipated use) of the information. Each sort of information has its own pedigree, the construction of which is a process that provides insight about the strengths, weaknesses, and uncertainties of the dataset. Pedigree is often calculated using a pedigree matrix (e.g., van der Sluijs et al. 2005; Kloprogge et al. 2011), where columns describe the different aspects of the information, with descending rows displaying weakening quality. For any data point, a score can be assigned for each column. To gauge of the strength of the information, these scores can then be averaged. A low Pedigree score does not automatically imply low quality, with the rating rather showing what can be accomplished in the given scientific context, within which research can then be done better or worse (Ravetz et al 2018).

A matrix constructed for the purposes of this study is shown in Table 4. The official AGE data provide "exact measures" done with "best available practice," and while

INDICATOR	VERY GOOD	GOOD	MODERATE	UNSATISFACTORY	BAD
Nitrate-nitrogen (NO_3^--N) [mg/l]	≤2.3	≤5.7	≤11.3	≤22.6	>22.6
Phosphate-phosphorus (PO_4^{3-}-P) [mg/l]	≤0.033	≤0.163	≤0.326	≤0.653	>0.653

Table 3 Scale of nitrate and phosphate concentrations in relation to surface water quality.

SCORE	PROXY	EMPIRICAL	METHOD	VALIDATION
4	Exact measure	Large sample set	Best available practice	Compared with independent measurements of same variable
3	Good fit	Small sample set	Reliable method	Compared with independent measurements of related variable
2	Well correlated	Modelled data	Acceptable method	Compared with measurements not independent
1	Poorly correlated	Educated guess	Unknown method	Indirect validation
0	No clear relation	Speculation	No rigor	No validation

Table 4 Pedigree matrix for nutrient data in fresh water.

the dataset is larger than required by EU regulations, some of the smaller streams are not regularly sampled—thus it would fall short of the perfect score in the "empirical" column. Furthermore, the matrix involves independent validation of data. While Luxembourgish communes and wastewater syndicates also perform measurements, the data landscape would be further improved by a completely independent dataset from regular citizen science measurements. While such crowd-sourced data would score lower, e.g. 3, in the "proxy" and "method" columns, a well-coordinated event has the potential for maximum scores in the "empirical" and "validation" categories.

With this pedigree matrix in mind, we present the Water Blitz results. The data set concerns water quality as well as factors determining human influence on it. The nutrient concentration data, collected in 7 non-linear intervals, need to be understood as ordinal data. Such data are in categories that can be ordered, but for which the distance from one category to another is not known and cannot be compared. A way to analyse ordinal data is by using medians. This is the reading that represents the middle-interval, for which the same amount of higher (or equal to) and lower (or equal to) readings exist in the dataset. A further analysis tool for ordinal data is assigning a threshold value, which corresponds to a value separating adjacent intervals. Using the AGE guidelines specifying that nitrate concentration below 5.7 mg/l classify the water body as "good" (Table 3), the highest two concentration intervals (5–10, and > 10 mg/l) could represent high concentration intervals. The relative number of such readings in a particular area, or at a specific water body, could be used to flag potential pollution hotspots. When the Water Blitz results are presented alongside official measurements of the AGE (Table 1), it is important to remember the latter are given as exact values.

LAND USE

The results for nutrient concentrations according to various land use types are summarised in Table 5. Across the two sampling events, only seven sites were classified as industrial and four as viticulture. These subsets do not allow for statistically viable analyses and are excluded from the table. As the AGE data are concentrated along major rivers, including it here would likely skew the analysis, no longer being just a function of land use. The presented data must thus be treated as unvalidated for the Pedigree calculation, though as mentioned earlier this does not automatically make it poor—however, for any future measurement campaign an independent validation set would be a recommendation.

For four of the five land use types, the median nitrate value was the 2–5 mg/l interval, which roughly corresponds to the "good but not very good" classification from Table 3. The exception is the urban park setting, where 1–2 mg/l represents the median. It is concerning to report that concentrations above 5 mg/l (no longer classified as good) are common throughout all settings, accounting for 35% all collected samples. These high values are less common in urban settings. The significant amount of these values on agricultural land might be a result of chemicals used in the fields. The percentage of concentrations above 5 mg/l has decreased slightly, from 48% in the 2019 measurements to 36% in 2021. This could be the result of Luxembourg becoming the first country in the European Union to ban the use of glyphosate in 2020 (Government GDL, 2020), with a clear link between glyphosate and the evolution of inorganic anions at the highest oxidation states, that is, phosphate and nitrate (e.g., Manassero et al. 2010). It is furthermore concerning to note that forest sites accounted for the highest fraction of high nitrate concentrations. Nitrate content in forests is a complex parameter, dependant on factors such as forest harvesting methods, forest composition, altitude, and environmental factors (e.g., Mupepele and Dormann 2017), and agroforestry is the subject of ongoing studies at the University of Luxembourg. The phosphate concentration had median values in the 0.05–0.1 mg/l interval in the two types of urban settings, and 0.02–0.05 mg/l in other setting. These all fall within the "very good" and "good" categories. High phosphate concentrations were rare (Figure 2), with 11 samples in 2019 and 15 in 2021 in the highest two intervals. These are discussed later in the manuscript.

LAND USE	#SAMPLES	MEDIAN NITRATE	# SAMPLES NITRATE ≥ 5 mg/l	% SAMPLES NITRATE ≥5 mg/l	MEDIAN PHOSPHATE
Urban residential	84	2–5	23	27	0.05–0.1
Urban park	56	1–2	13	23	0.05–0.1
Grassland/shrub	84	2–5	30	36	0.02–0.05
Agriculture	77	2–5	31	40	0.02–0.05
Forest	116	2–5	49	42	0.02–0.05

Table 5 Nutrient concentration summary for the combined data according to land use.

TYPES OF WATER BODIES

Different types of water bodies are associated with different biodiversity, and play different roles in processes such as the carbon cycle (e.g., Davies et al. 2008; Tranvik et al. 2009). The type of sampled body was therefore one of the parameters required to make up each data point, with the citizen scientists asked to choose from 6 options: stream, river, pond, lake, wetland, and source. With no definition distinguishing a stream from a river, or a pond from a lake, participants individually decided what they are sampling. These divisions thus cannot be considered exact. During the quality control, it was found that samples from similar locations at the same water body sometimes classified it differently. Nonetheless, all water body types were left as the participants defined them, and their summary is presented in Table 6. As with land use data, the results are not validated through an independent data set.

The data sets from both events were merged for this section, as there were no significant statistical differences between the events according to water body type. The observed nitrate concentration in streams and rivers follow similar distributions, with the median interval being 2–5 mg/l for both types. The percentage of measurements above 5 mg/l was 36% for streams, and 42% for rivers. Considering the non-exact definitions of these two water types, this difference is not statistically significant. However, for the phosphate concentration, there is a clear difference, with the median of the stream data being the 0.02–0.05 mg/l interval, and that of rivers significantly higher at 0.1–0.2 mg/l.

For ponds, the median interval for nitrate concentration was the lowest one available, with values not exceeding 0.2 mg/l. This value applied to 32 of the 52 data points. The median for the phosphate concentration was 0.02–0.05 mg/l, also representing very good water quality. As ponds can be highly susceptible to environmental change and urbanisation due to their small volume, making the effects of urbanisation more profound (e.g., Hassall 2014; Beklioglu et al. 2016), these results suggest the overall quality of ponds in Luxembourg is good, at least regarding nutrient content. Concerning algae on the surface, this was reported in 20 cases, giving a frequency of 38%. For streams and rivers, this value was significantly lower at 9%.

The data for lakes are limited, with just 12 data points. This is hardly surprising given that Luxembourg has no natural large lakes. From these points, four were at an artificial lake near Echternach in the east. Three of these recorded the nitrate concentration below 0.2 mg/l, with one reading in the 0.2–0.5 mg/l range. The phosphate readings were all under 0.1 mg/l. Five readings were in

TYPE	SAMPLES	MEDIAN NITRATE	MEDIAN PHOSPHATE
Stream	215	2–5	0.02–0.05
River	127	2–5	0.1–0.2
Pond	52	<0.2	0.02–0.05
Lake	12	0.5–1	0.02–0.05
Wetland	13	<0.2	0.02–0.05
Source	9	2–5	0.02–0.05

Table 6 Nutrient concentration summary for the combined data for different water body types.

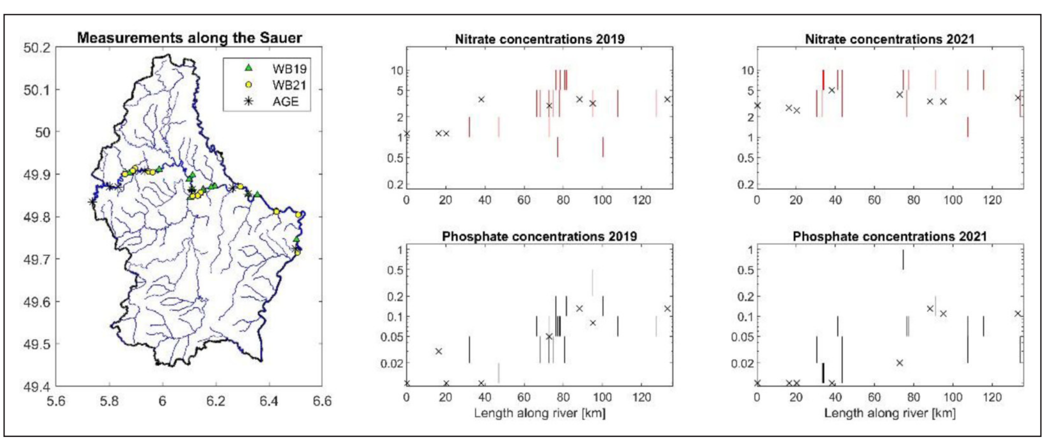

Figure 4 Results for the Sauer.

the lake upstream from the dam on the Sauer. While the phosphate concentrations were all low, the two readings reported nitrate levels above 5 mg/l. The Sauer is discussed in more detail in a further section. The remaining three lake readings corresponded to one measurement each in a recreational area in Weiswampach in the north, an urban park in Hesperange near Luxembourg City, and a small unnamed water body in the southwest, classified as a lake by a very generous participant. None of these observed values suggested pollution hotpots.

MAJOR RIVER CASE STUDY 1: SAUER

The Sauer, or Sûre, is one of the major rivers in Luxembourg (Figures 1 and 4). Its source is located in Belgium, about 30 km west of the border village of Martlenage, where it enters Luxembourg (km 0 in this study). Near the village of Bigonville, it transforms into a lake created artificially by the dam near Esch-sur-Sure at km 36. This is the biggest dammed lake in Luxembourg, with a surface area of up to 3.8 km^2, and it serves as the main drinking water source for the country. It also provides an environment for diverse recreational activities, as well as for hydroelectric power production. Further downstream, the Sauer passes the cities of Ettelbruck and Diekirch (~km 70–80), before reaching the German border at Wallendorf at km 90. It then forms the national border between the two countries, passing through the cities of Echternach and Wasserbillig, where it empties into the Moselle at km 135. The landscape of the Sauer is predominantly rural, mostly characterised by forest and agricultural areas.

The Sauer was well sampled during the Water Blitz events, with 19 samples in 2019 and 15 in 2021. The measured data are shown in Figure 4, using the river course length as the x-axis. The median values for nutrient concentration in 2019 were 2–5 mg/l for nitrates and 0.05–.1 mg/l for phosphates, and in 2021 5–10 mg/l for nitrates and 0.02–0.05 mg/l for phosphates. A direct comparison between the two events is, however, difficult, as in 2019, nine measurements were obtained in the Ettelbruck-Diekirch urban region, compared with just three in 2021. This could explain the drop in the phosphate values, where the higher readings between km 70–80 from 2019 are sparse in 2021. An analysis of the nitrate values presents a completely different picture. Whereas in 2019, the highest concentrations are all in the aforementioned urban region, in 2021 the 5–10 mg/l interval dominates the entire river course, with 9 of the 15 readings.

The Water Blitz results can be compared with official measurements of the AGE, which maintains eight sampling stations along the Sauer (Table 7; Figure 4), where among many other parameters, the nutrient content is measured every month. As discussed earlier, unlike the range estimates in Water Blitz data, these are given as exact values, thus the only tool used to compare the two data sets is visual comparison. While the geographical overlap between the two sets is not perfect, they do provide completely independent validation sets of the same parameters for each other, greatly improving the Pedigree score of both sets. The AGE data clearly show the increasing nutrient content near, and downstream from Ettelbruck. They also confirm the nitrate concentration increase from the September 2019 to May 2022. However, whether this represents a pollution event, possibly from outside of Luxembourg, a seasonal trend, or a weather-related result, cannot be answered with the presently available data.

MAJOR RIVER CASE STUDY 2: ALZETTE

Another prominent Luxembourgish river is the Alzette (Figures 1 and 5) with sources in France, a few kilometres from Luxembourg, and entering the country near the city of Esch-sur-Alzette (not to be confused with Esch-sur-Sure) in the south. A high proportion of the landscape it flows through is urban, including industrial regions near Esch, and the urban agglomerations of Luxembourg City, Mersch, and Ettelbruck, where it empties into the Sauer. As a result, many wastewater treatment plants direct their effluents into the Alzette. There are, however, also areas where agriculture dominates the landscape. The course of the Alzette inside Luxembourg is 68 km.

The Alzette was one of the best-sampled water bodies during both Water Blitz events, with 18 samples recorded in 2019, and 26 in 2021 (Figure 5). For the nitrate concentration, in 2019 the median interval was 5–10 mg/l, at which level the water condition can no longer be classed as good, with three samples between Walferdange and Shieren measured in the highest available interval, > 10 mg/l. That these three readings are not separated by any lower measurements strongly suggests the presence of a pollution hotspot. While many factors could have led to these measurements, the presented results certainly justify further investigation. As it is, a few days before the Water Blitz 19, the wastewater treatment plant of Beggen, located between Eich and Walferdange at ~km 35, was subject to a malfunction, with wastewater leaked from the plant to the river. The malfunctioning was only noticed 20 hours later as dead fish were spotted in the Alzette.

As with the Sauer, the Water Blitz results can be compared to official measurements of the AGE, which maintains nine sampling stations along the Alzette (Table 8; Figure 5). Unfortunately, only the 2019 AGE data were available. These show an increase in nitrate concentration around Luxembourg City, with the three stations upstream of it containing around 2 mg/l, increasing downstream to around 5 mg/l. While all measurements fall within the classification of "good," some of them are nonetheless very close to 5 mg/l,

STATION LOCATION	DIST. [KM]	MEASUREMENT DATE 2019	NITRATE [MG/L]	PHOSPHATE [MG/L]	MEASUREMENT DATE 2021	NITRATE [MG/L]	PHOSPHATE [MG/L]
Martelange	0	25.9	1.1	0.01	11.5	3.0	0.01
Bigonville	16	25.9	1.1	0.03	11.5	2.7	0.01
Miserbreck	20	26.9	1.1	0.01	12.5	2.5	0.01
Esch/Sauer	38	26.9	3.6	0.01	12.5	5.0	0.01
Erpeldange	73	16.9	3.0	0.05	25.5	4.3	0.02
Reisdorf	88	5.9	3.6	0.13	18.5	3.4	0.13
Dillingen	95	5.9	3.2	0.08	18.5	3.4	0.13
Wasserbillig	133	5.9	3.6	0.13	18.5	3.9	0.11

Table 7 List of nutrient concentrations measured at AGE stations on the Sauer in 2019 and 2021.

STATION LOCATION	DISTANCE [KM]	MEASUREMENT DATE	NITRATE [MG/L]	PHOSPHATE [MG/L]
Esch/Alzette	0	16.10	1.9	0.17
Schifflange	5	16.10	1.6	0.17
Huncherange	9	16.10	2.3	0.26
Hesperange	20	17.10	3.2	0.31
Eich	34	23.10	4.3	0.14
Walferdange	39	23.10	3.9	0.19
Mersch	50	17.9	4.1	0.27
Colmar Berg	62	23.10	4.8	0.15
Ettelbruck	66	16.9	4.3	0.19

Table 8 List of nutrient concentrations measured at AGE stations on the Alzette in 2019.

which separated intervals in the Water Blitz. In this case, it would have been nearly impossible for citizen scientists to match the colour correctly, which might explain the high frequency of 5–10 mg/l results. That none of the official stations picked up anomalously high values corresponding to the Beggen spill can be explained by the timing of the measurements (Table 8). It is not possible to attribute the high concentrations to the spill with absolute certainty; they could be the result of other, less significant, events, or even the result of the complex relation between leaching and rainfall (Wang et al. 2015). Furthermore, the signature of the spill would need to be confirmed by measuring other parameters, such as the full spectrum of data as measured by the AGE (Table 1; AGE 2015). Nonetheless, we put forward that this case study particularly strongly demonstrates how citizen science initiatives have the potential to complement official measurements in meaningful ways.

For the data collected during Water Blitz 2021, the median value of nitrate concentrations was the interval 2–5 mg/l. This was also the most commonly observed interval, with 11 from the 26 samples. While eight samples recorded values higher than the 5 mg/l corresponding to the reference threshold for eutrophication, none of the records were in the highest available interval, above 10 mg/l. All the readings above 5 mg/l are downstream from Luxembourg City (~km 30), suggesting that concentrations of nitrate are relatively high in this section. However, several lower measurements also exist, and when these are taken into account, the overall picture is not negative.

For the phosphate concentration, the median interval in the 2019 was 0.2–0.5 mg/l, and in 2021 0.1–0.2 mg/l. The 2019 AGE measurements varied from 0.14 to 0.31, with just two of the nine values classed as good, and the others fitting within the 0.326 mg/l threshold for "moderate." From the plot, there is no clear trend in either the Water Blitz or the AGE sets, suggesting that if pollution sources exist, they are very localised.

DETECTING POTENTIAL POLLUTION HOTSPOTS

The data collected during the Water Blitz events also provide insight into smaller water bodies, which often are not sampled for official statistics, even though they can

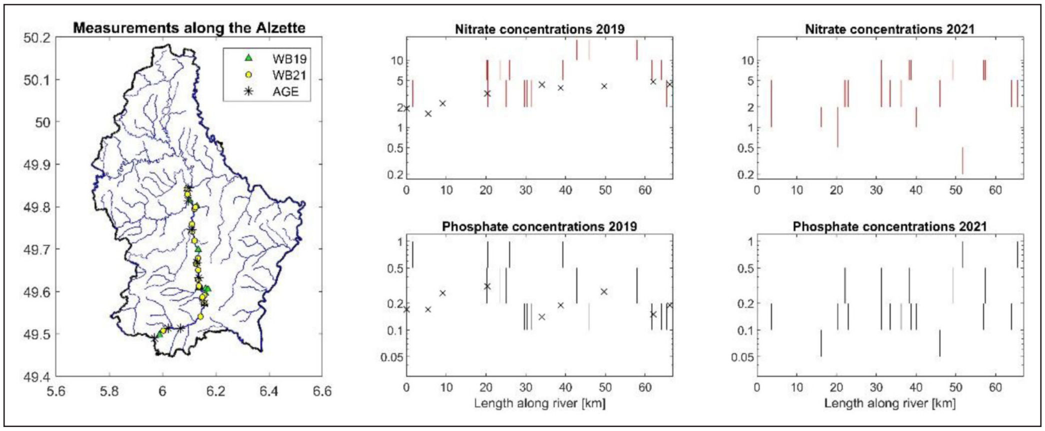

Figure 5 Results for the Alzette.

play an important role in catchment biodiversity. While a solitary high reading in a stream can be explained by measurement errors, especially when lower readings were recorded in the vicinity, multiple high readings do at least invite further investigation. One such stream is the Gander, a tributary of the Moselle in the southeast, partially forming the border between Luxembourg and France. From the 10 readings sampling it, three recorded nitrate concentration in the highest available interval, > 10 mg/l, and five further ones in the 5–10 mg/l interval. These readings were collected in both sampling events, and by several independent participants. Although errors in readings can never be completely ruled out, it is unlikely that different users obtained the same result by mistake. While the records do not conclusively illustrate the state of the Gander, they should be taken seriously, and warrant further investigation.

Another region demanding attention is the Mullerthal, just south of where the Sauer becomes the German border. In an area about 10 km across, four readings of nitrate above 10 mg/l and eight between 5–10 mg/l were observed, with just three readings in other intervals. These high concentrations were measured by different users in several different streams, very strongly suggesting the region should be investigated further.

Very high phosphate concentrations were much rarer than those for nitrate. From the 428 samples across the two sampling events, only five recorded the highest available interval, > 1 mg/l. One of these was in the Gander, where additionally two samples in the 0.5–1 mg/l interval were observed, strengthening the suggestion the stream should be investigated further. The Mullerthal region with high nitrate concentrations did not provide any extreme phosphate results, though 2 of the 15 measurements put it in the 0.5–1 mg/l range. Nonetheless, the nitrate concentrations are likely to be a more serious issue in the area than phosphates. Another high phosphate reading came from the Syre river at Munsbach in the east, though this reading represents an outlier for the river. In fact ,another user recorded a reading in the 0.02–0.05 mg/l at the same location two days earlier, suggesting that the anomalously high reading could be an error. Two high phosphate reading were taken in the small stream Tretterbaach in the north by one user. Other readings in the stream are not as high, though one put phosphate concentration in the 0.2–0–5 mg/l interval, where it could be classed as unsatisfactory. While these results are not conclusive, they do warrant investigation.

CONCLUSIONS

This study demonstrates the feasibility of citizen science to meaningfully contribute to monitoring activities to fulfil the requirements of the EU WFD and support SDG 6 to "Ensure availability and sustainable management of water and sanitation for all." In two public monitoring events, participants sampled water bodies at locations of their choice, using field kits to estimate nitrate and phosphate concentrations. Samples (428) were collected over two weekend events, providing snapshots in time with a good geographic coverage of the water bodies across Luxembourg. The analysis of these data demonstrated the strength of citizen science initiatives to complement data collected by national agencies.

More distributed and local approaches to water governance in the era of interconnected global and local change are vital for developing more resilience in the ways we interact with aquatic ecosystems and with the whole environment. Citizen science projects have the potential not just to complement official data sets, but to contribute to awareness raising and reflection and action in wider segments of the population, by building lasting relationships with local stakeholders. However, for citizen science to reach its full potential, there remain several challenges. We thus finish this paper by identifying some limitations and presenting recommendations to address them.

SCIENTIFIC COMMUNITY

Citizen science continues to face scepticism is some quarters, with its value sometimes poorly communicated. While not suggesting that the role of citizen science should be downplayed, we follow Buytaert et al. (2014) to suggest that limitations need to be clearly stated, and realistic goals need to be set. These limitations, and a clear representation of uncertainties, along with recommendations about which of them can be addressed and how, are critical when presenting results to policy- and decision-makers. Competing interests and apparent contradictions make environmental decision-making very complex, and different aspects of uncertainty will affect the decisions made. Furthermore, results of projects incorporating citizen science should, possibly in addition to scientific literature, be presented in ways that do not require expert technical knowledge, and data should be freely available (as is the case with Earthwatch and FWW initiatives).

PROJECT COORDINATION

While Earthwatch and FWW projects have successfully engaged volunteers in several countries, it is important to recognise the idiosyncrasy of individual water systems and regions, and accordingly adapt the sampling protocol. To this end, the University of Luxembourg is engaged in identifying relevant parameters to be collected through a citizen science app. When organising projects, it would also be beneficial to liaise with agencies responsible for water monitoring. This would allow determination of key parameters to monitor, identification of potential areas of interest, and decisions on the appropriate timing of the measurements. The parameters and areas of interest would be particularly relevant near possible pollution sources, as this would allow for flagging, or even identifying, potential events with more certainty than was possible for the Beggen plant in 2019. Appropriate timing, to stage the sampling events at times when other, independent datasets are collected, would allow for mutual validation, increasing the Pedigree score of all datasets, and improving the quality of the conducted research. More frequent, regular sampling events would furthermore allow for a study of trends in nutrient concentration. With the AGE data being collected at least quarterly, this would allow a glimpse at each season. While the responses to the participants' survey were not sufficient for a full analysis, respondents indicated an overwhelming interest to participate in further citizen science events, should these be organised more frequently. The onus on more frequent citizen science campaigns lies with the organisers, not the participants.

CITIZEN SCIENTISTS

It really is stating the obvious that there can be no citizen science without the citizens. By their active involvement, the public do, or should, assume a certain level of responsibility, whatever their level of involvement. The organisers have the right to expect that every participant collects data to the best of their ability. From the participation survey, it is clear that public are willing to invest extra time to achieve that.

OFFICIAL DATA

Public access to environmental information has been granted by the Aarhus Convention of the United Nations Economic Commission for Europe, applied in the EU in its legislation with the WFD. In Luxembourg, publicly accessible geospatial information shows the results of evaluations of water quality in a map of rivers subject to monitoring. However, a study interviewing officials found some of them voicing fears concerning the publication of these data (Pickar 2021). The interpretation of datasets is often complex even for specialists, and non-specialists may reach wrong conclusions if not informed accordingly—for example, high nitrate concentrations might lead to panic if the consequences are exaggerated. It is therefore critical that published data are accompanied by narrative reports to put data in the relevant context. These reports should also incorporate a discussion of uncertainty. While all AGE numbers were treated as exact measure, with the highest possible score in the "Empirical" column of the pedigree matrix (Table 4), there must be a level of uncertainty in each measurement. These become especially relevant given the quality regimes are separated by thresholds (Table 3). If a nitrate concentration of 11.2 is "good" while 11.3 only "moderate,"', it needs to be clearly stated how certain it is that a reading falls in the particular regime. The other pertinent column of the pedigree matrix is Validation. Even if a reading scores highly on being an "exact measure" in a "large sample set" collected with "best available practice," it would benefit from comparisons with independent measurements, which citizen science initiatives provide.

GOVERNANCE

Governance of natural resources is inherently poly-centric, with citizen science projects clearly demonstrating the shortcomings of the technocratic model of knowledge production. De-centering of the scientific knowledge process is required within the social process of co-creation of actionable knowledge that should form the basis for all actions associated with the adaptive and transformative governance of natural resources, such as fresh water.

ACKNOWLEDGEMENTS

We are grateful to all citizen scientists, whose participation in the Water Blitz events made this study possible. We are thankful to the FreshWater Watch team of the NGO Earthwatch for their coordination efforts and providing the test kits. We thank all our partners at AGE and Syre and Obersauer River Partnerships, Natur&Emwelt, members of the Reference Group of the Nexus Futures Project, and Jerome Ravetz. The manuscript benefited from three anonymous reviews.

FUNDING INFORMATION

The research was financed through the University of Luxembourg fund for interdisciplinary research (WATGOV project) and the Luxembourg Ministry for the Environment, Climate and Sustainable Development (NEXUS FUTURES Project).

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR AFFILIATIONS

Jacek Stankiewicz orcid.org/0000-0003-2848-4855
University of Luxembourg, LU
Ariane König orcid.org/0000-0002-5212-4668
University of Luxembourg, LU
Karl Pickar
Naturpark Our, LU
Stefan Weiss
University of Luxembourg, LU

REFERENCES

Administration de la gestion de l'eau (AGE). 2009. Umsetzung der EG-Wasserrahmenrichtlinie: Bewirtschaftungsplan für das Großherzogtum Luxemburg. Ministry of the Interior.

Administration de la gestion de l'eau (AGE). 2015. Entwurf des Bewirtschaftungsplans für die luxemburgischen Anteile an den internationalen Flussgebietseinheiten Rhein und Maas (2015–2021). Ministry of the Environment, Climate and Sustainable Development.

Ascough, JC, Maier, HR, Ravalico, JK and **Strudley, MW.** 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological Modelling*, 219(3–4), 383–399. DOI: https://doi.org/10.1016/j.ecolmodel.2008.07.015

Beklioglu, M, Meerhoff, M, Davidson, TA, Ger, KA, Havens, K and **Moss, B.** 2016. Preface: Shallow lakes in a fast changing world. *Hydrobiologia*, 778 9–11. DOI: https://doi.org/10.1007/s10750-016-2840-5

Bird, TJ, Bates, AE, Lefcheck, JS, Hill, NA, Thomson, RJ, Edgar, GJ, Stuart-Smith, RD, Wotherspoon, S, Krkosek, M, Stuart-Smith, JF, Pecl, GT, Barrett, N and **Frusher, S.** 2014. Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation*, 173: 144–154. DOI: https://doi.org/10.1016/j.biocon.2013.07.037

Bonter, DN and **Cooper, CB.** 2012. Data validation in citizen science: a case study from Project FeederWatch. *Frontiers in Ecology and the Environment*, 10(6): 305–307. DOI: https://doi.org/10.1890/110273

Buytaert, W, Baez, S, Bustamante, M and **Dewulf, A.** 2012. Web-Based Environmental Simulation: Bridging the Gap between Scientific Modeling and Decision-Making. *Environmental Science and Technology*, 46: 1971–1976. DOI: https://doi.org/10.1021/es2031278

Buytaert, W, Zulkafli, Z, Grainger, S, et al. 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, 2: 26. DOI: https://doi.org/10.3389/feart.2014.00026

Chapman, PM. 2012. Adaptive monitoring based on ecosystem services. *Science of the Total Environment*, 415: 56–60. DOI: https://doi.org/10.1016/j.scitotenv.2011.03.036

Chislock, MF, Doster, E, Zitomer, RA and **Wilson, AE.** 2013. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature Education Knowledge*, 4(4): 10.

Davies, B, Biggs, J, Williams, P, Whitfield, M, Nicolet, P, Sear, D, Bray, S and **Maund, S.** 2008. Comparative biodiversity of aquatic habitats in the European agricultural landscape. *Agriculture, Ecosystems and Environment*, 125: 1–8. DOI: https://doi.org/10.1016/j.agee.2007.10.006

Duit, A, Galaz, V, Eckerberg, K and **Ebbesson, J.** 2010. Governance, complexity, and resilience. *Global Environmental Change*. 20(3): 363–368. DOI: https://doi.org/10.1016/j.gloenvcha.2010.04.006

EU. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060.

European Statistical System. (2012). Quality Assurance framework of the European Statistical System, Eurostat. http://ec.europa.eu/eurostat/documents/64157/4392716/qaf_2012-en.pdf/8bcff303-68da-43d9-aa7d-325a5bf7fb42. (Accessed 28/09/2022).

Fraisl, D, Campbell, J, See, L, When, U, Wardlaw, J, Gold, M, Moorthy, I, Arias, R, Piera, J, Oliver, JJ, Maso, J, Penker, M and **Fritz, S.** 2020. Mapping citizen science contributions to the UN sustainable development goals. *Sustainability Science*, 15: 1735–1751 DOI: https://doi.org/10.1007/s11625-020-00833-7

Funtowicz, SO and **Ravetz, JR.** 1990. Uncertainty and Quality in Science for Policy. Dordrecht: Kluwer. DOI: https://doi.org/10.1007/978-94-009-0621-1

Funtowicz, SO and **Ravetz, JR.** 1993. Science for the post-normal age. *Futures*, 25(7): 739–755. DOI: https://doi.org/10.1016/0016-3287(93)90022-L

Government of the Grand Duchy of Luxembourg. 2020. Luxembourg, the first country in the European Union to ban the use of glyphosate. Press release https://agriculture.public.lu/content/dam/agriculture/publications/ma/dossier/glyphosat/20200116-Press-release-Luxembourg-bans-use-of-Glyphosate.pdf.

Hadj-Hammou, J, Loiselle, S, Ophof, D and **Thornhill, I.** 2017. Getting the full picture: assessing the complementarity of citizen science and agency monitoring data. *PLoS One*, 12(12): 1–18. DOI: https://doi.org/10.1371/journal.pone.0188507

Hajer, M, Nilsson, M, Raworth, K, Bakker, P, Berkhout, F, de Boer, Y, Rockström, J, Ludwig, K and **Kok, M.** 2015. Beyond cockpitism: four insights to enhance the transformative potential of the sustainable development goals. *Sustainability*, 7(2): 1651–1660. DOI: https://doi.org/10.3390/su7021651

Haklay, M. 2015. *Citizen Science and Policy: A European Perspective*. Washington, DC: Woodrow Wilson International Center for Scholars.

Hassall, C. 2014. The ecology and biodiversity of urban ponds. *Interdisciplinary Reviews: Water*, 1: 187–206. DOI: https://doi.org/10.1002/wat2.1014

Hasselman, L. 2017. Adaptive management; adaptive co-management; adaptive governance: What's the difference? *Australasian Journal of Environmental Management*, 24(1): 31–46. DOI: https://doi.org/10.1080/14486563.2016.1251857

Jasanoff, S. 1999. The Songlines of Risk. *Environmental Values*, 8(2): 135–152. DOI: https://doi.org/10.3197/096327199129341761

Khajwal, AB and **Noshadravan, A.** 2021. An uncertainty-aware framework for reliable disaster damage assessment via crowdsourcing. *International Journal of Disaster Risk Reduction*, 55: 102110. DOI: https://doi.org/10.1016/j.ijdrr.2021.102110

Kasperowski, D and **Haggen, N.** 2022. Making particularity travel: Trust and citizen science data in Swedish environmental governance. *Social Studies of Science*, 52(3): 447–462. DOI: https://doi.org/10.1177/03063127221085241

Kloprogge, P, van der Sluijs, JP and **Petersen, AC.** 2011. A method for the analysis of assumptions in model-based environmental assessments. *Environmental Modelling & Software*, 26: 289–301. DOI: https://doi.org/10.1016/j.envsoft.2009.06.009

König, A, Pickar, K, Stankiewicz, J and **Hondrila, K.** 2021. Can citizen science complement official data sources that serve as evidence-base for policies and practice to improve water quality? *Statistical Journal of the IAOS*, 37(1): 189–204. DOI: https://doi.org/10.3233/SJI-200737

Kremen, C, Ullmann, KS and **Thorp, RW.** 2011. Evaluating the Quality of Citizen-Scientist Data on Pollinator Communities. *Conservation Biology*, 25(3): 607–617. DOI: https://doi.org/10.1111/j.1523-1739.2011.01657.x

MacFeely, S and **Nastav, B.** 2019. "You say you want a [data] revolution": a proposal to use unofficial statistics for the SDG global indicator framework. *Statistical Journal of the IAOS*, 35: 309–327. DOI: https://doi.org/10.3233/SJI-180486

Malone, TC and **Newton, A.** 2020. The globalization of cultural eutrophication in the coastal ocean: causes and consequences. *Frontiers in Marine Science*, 7: 1–30. DOI: https://doi.org/10.3389/fmars.2020.00670

Manassero, A, Passalia, C, Negro, AC, Cassano, AE and **Zalazar, CS.** 2010. Glyphosate degradation in water employing the H2O2/UVC process. *Water Research*, 44(13): 3875–3882. DOI: https://doi.org/10.1016/j.watres.2010.05.004

Munson, MA, Caruana, R, Fink, D, Hochachka, WM, Iliff, M, Rosenberg, KV, Sheldon, D, Sullivan, BL, Wood, C and **Kelling, S.** 2010. A method for measuring the relative information content of data from different monitoring protocols. *Methods in Ecology and Evolution*, 1: 263–273. DOI: https://doi.org/10.1111/j.2041-210X.2010.00035.x

Mupepele, AC and **Dormann, CF.** 2017. Influence of Forest Harvest on Nitrate Concentration in Temperate Streams – A Meta-Analysis. *Forests*, 8(5). DOI: https://doi.org/10.3390/f8010005

Nelson, L, Kurtz, LT and **Bray, H.** 1954. Rapid determination of nitrates and nitrites. *Analytical Chemistry*, 26(6): 1081–1082. DOI: https://doi.org/10.1021/ac60090a041

Pickar, KA. 2021. *Exploring the potential of citizen science for more adaptive and sustainable surface water governance in Luxembourg*. PhD Thesis, University of Luxembourg. http://hdl.handle.net/10993/51867.

Quinlivan, L, Chapman, DV and **Sullivan, T.** 2020. Validating citizen science monitoring of ambient water quality for the United Nations sustainable development goals. *Science of the Total Environment*, 699: 134255. DOI: https://doi.org/10.1016/j.scitotenv.2019.134255

Ravetz, JR, Hild, P, Thunus, O and **Bollati, J.** 2018. Sustainability Indicators. In König, A (ed.), *Sustainability Science*. Routledge Publishing, pp 271–295. DOI: https://doi.org/10.9774/gleaf.9781315620329_16

Scott, AB and **Frost, PC.** 2017. Monitoring water quality in Toronto's urban stormwater ponds: Assessing participation rates and data quality of water sampling by citizen scientists in the FreshWater Watch. *Science of the Total Environment*, 592: 738–744. DOI: https://doi.org/10.1016/j.scitotenv.2017.01.201

Shirk, JL, Ballard, HL, Wilderman, CC, Phillips, T, Wiggins, A, Jordan, R, McCallie, E, Minarchek, M, Lewenstein, BV, Krasny, ME and **Bonney, R.** 2012. Public participation in scientific research: a framework for deliberate design. *Ecology and Society*, 17(2): 29. DOI: https://doi.org/10.5751/ES-04705-170229

Silvertown, J. 2009. A new dawn for citizen science. *Trends in Ecology and Evolution*, 24(9): 467–471. DOI: https://doi.org/10.1016/j.tree.2009.03.017

Thornhill, I, Loiselle, S, Clymans, W and **van Noordwijk, CGE.** 2019. How citizen scientists can enrich freshwater science as contributors, collaborators, and co-creators. *Freshwater Science*, 38(2): 231–235. DOI: https://doi.org/10.1086/703378

Topping, M and **Kolok, A.** 2021. Assessing the Accuracy of Nitrate Concentration Data for Water Quality Monitoring Using Visual and Cell Phone Quantification Methods. *Citizen Science: Theory and Practice*, 6(1): 5, pp. 1–9. DOI: https://doi.org/10.5334/cstp.346

Tranvik, LJ, Downing, JA, Cotner, JB, et al. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, 54(6.2): 2298–2314. DOI: https://doi.org/10.4319/lo.2009.54.6_part_2.2298

van der Sluijs, JP, Craye, M, Funtowicz, S, Kloprogge, P, Ravetz, JR and **Risbey, J.** 2005. Combining quantitative and qualitative measures of uncertainty in model-based environmental assessment: The NUSAP System. *Risk Analysis,* 25(2): 481–492. DOI: https://doi.org/10.1111/j.1539-6924.2005.00604.x

Vinke-de Kruijf, J, Kuks, SMM and **Augustijn, DCM.** 2015 Governance in support of integrated flood risk management? The case of Romania. *Environmental Development*, 16: 104–118. DOI: https://doi.org/10.1016/j.envdev.2015.04.003

Walker, D, Forsythe, N, Parkin, G and **Gowing, J.** 2016. Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. *Journal of Hydrology*, 538: 713–725. DOI: https://doi.org/10.1016/j.jhydrol.2016.04.062

Walker, WE, Harremoës, P, Rotmans, J, van der Sluijs, JP, van Asselt, MBA, Janssen, P and **Krayer von Krauss, MP.** 2003. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment,* 4: 5–17. DOI: https://doi.org/10.1076/iaij.4.1.5.16466

Wang, H, Gao, J-E, Li, X-H, Zhang, S-L and **Wang, H-J.** 2015. Nitrate Accumulation and Leaching in Surface and Ground Water Based on Simulated Rainfall Experiments. *PLoS ONE*, 10(8): e0136274. DOI: https://doi.org/10.1371/journal.pone.0136274

Waylen, KA, Blackstock, KL, van Hulst, FJ, Damian, C, Horvath, F, Johnson, RK, Kanka, R, Kulvik, M, Macleod, CJA, Meissner, K, Oprina-Pavelescu, MM, Pino, J, Primmer, E, Risnoveanu, G, Satalova, B, Silander, J, Spulerova, J, Suskevics, M and **Van Uytvanck, J.** 2019. Policy-driven monitoring and evaluation: Does it support adaptive management of socio-ecological systems? *Science of The Total Environment*, 662: 373–384. DOI: https://doi.org/10.1016/j.scitotenv.2018.12.462

Withers, PJA, Neal, C, Jarvie, HP and **Doody, DG.** 2014. Agriculture and Eutrophication: Where Do We Go from Here? *Sustainability*, 6: 5853–5875. DOI: https://doi.org/10.3390/su6095853

Wohl, E. 2017. Connectivity in Rivers. *Progress in Physical Geography*, 41(3): 345–362. DOI: https://doi.org/10.1177/0309133317714972

TO CITE THIS ARTICLE:
Stankiewicz, J, König, A, Pickar, K and Weiss, S. 2023. How Certain is Good Enough? Managing Data Quality and Uncertainty in Ordinal Citizen Science Data Sets for Evidence-Based Policies on Fresh Water. *Citizen Science: Theory and Practice,* 8(1): 39, pp. 1–15. DOI: https://doi.org/10.5334/cstp.592

Submitted: 03 October 2022 **Accepted:** 24 April 2023 **Published:** 27 June 2023