The spatial and temporal variation of water quality at a community garden site in an urban setting: citizen science in action

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Abstract: Interest in urban agriculture has increased rapidly in recent decades, but little is known about the effect of potential contaminants, such as groundwater pollution, in urban areas. Furthermore, local and timely science necessary for developing place-based solutions and management plans are lacking. We present a citizen-science-driven case study of water quality in a large urban community garden in southwestern London that was initiated in response to the concerns of members about the effect of inorganic compounds in the water supply on organic produce. The 5.6-ha community garden has been cultivated for fruit and vegetables since 1921 and hand-pumped boreholes drawing water from an underlying shallow aquifer provide the only source of irrigation. We assessed the spatial and temporal distributions of specific conductance and tryptophan-like fluorescence to explore the dynamics of inorganic and organic pollution based on water drawn from the boreholes. A trained citizen scientist made measurements with a calibrated Manta II probe over a 28-mo period from 2014 to 2016. We also surveyed >80 members of the community garden to gain insight into cultivation practices. Results indicate that the concerns about external sources of pollution were unfounded. We found little evidence of the effect of potential adjacent sources of contamination or of changes in water quality in time. Distinct trends were absent, and evidence of poorer water quality close to possible sources of urban contamination was not apparent. However, significant interborehole variations in water quality were directly associated with the storage and use of manure on the site and local geological conditions. The study demonstrates the potential of citizen science to respond to community concerns and generate new and novel information when participants are engaged, trained, and equipped over longer periods of time.
Key words: citizen science, water quality, groundwater, shallow aquifer, geostatistics, urban agriculture

Urban agriculture is expanding rapidly, but little is known about potential threats arising from groundwater contamination in urban areas. Furthermore, local and timely science necessary for developing place-based solutions and management plans is lacking. We present a citizen-science-driven case study of water quality in a large, by UK standards, urban community garden near Kingston Upon Thames, southwestern London (Fig. S1). The members have a strong preference for organic cultivation, and our study arose from questions by members about the possible presence of inorganic compounds from the water supply on produce. In contrast to other community gardens in the region, the water is drawn with handpumps from an underlying aquifer. The effect of sources of pollution on such aquifers has been widely described in relation to general urban development (Eisen and Anderson 1979, Kelly 2008, Foppen et al. 2008, Takem et al. 2010, Mohamed and Hassane 2016) and more specific sources, such as unconstrained landfill (Han et al. 2014) or animal manure application (Pedersen et al. 1991, Krapac et al 2002, Harter et al. 2002). Questions about the quality of water in shallow aquifers has general significance on a global basis and within the Thames Basin. Younger et al. (1993) noted that 10% of the public water supply in the Thames Basin comes from boreholes <500 m of a river.

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Community gardens (allotments) were first established >200 y ago in the UK (Savill 2009). The requirement for local authorities to provide land for community gardens was codified in law in 1908 and by subsequent acts of Parliament in 1922 and 1950. Each plot cannot exceed 1000 m^2 (40 square rods) and must be used to produce fruit, flowers, or vegetables for use by the plot-holder and their family. Community gardens were used traditionally to supplement food supplies during periods of austerity, but interest in these gardens had increased in the last 30 y in conjunction with a greater demand for organic produce cultivated in a sustainable way (Pavord 2008, Smithers 2009, GetSurrey 2013). A substantial increase in demand for access to community gardens at local and national levels has led to waiting lists >40 y at some locations (Wallop 2009).

We identified several potential sources of contamination of the groundwater supply at the study location. These sources included road salt used on the adjacent major highway and inorganic (e.g., PO_4^{3-}-based detergents) and organic contaminants from leaking sewage systems in the adjacent, mixed-use urban area (Fig. 1). A sports field to the west of the site was also considered a possible polluting source because inorganic fertilizer is applied as part of the maintenance of a heavily used cricket pitch.

The initial stages of the analysis were designed to answer 2 questions about water quality at the site: 1) Does water quality vary systematically in time at a site level (possible indicator of deterioration in quality or seasonal variability), and 2) Does water quality vary spatially across the site (possible indicator of localized sources of contamination). The a priori hypothesis was that variation in water quality across the site in time and space should be nonsignificant given the relatively uniform geology and land use without significant new development in the area. As the study developed and data highlighting local variation in the markers of organic and inorganic pollution became available, in-person stakeholder interactions and survey responses provided additional questions: 1) Do more heavily used pumps yield cleaner water? 2) Do wells of different age and depth have different water qualities? 3) Does the storage and application of animal manure in large quantities at specific locations on the site affect groundwater quality?

Figure 1. Detailed plan of the Royal Paddocks Allotments showing major features, pump locations, plot boundaries, and plots for which we received questionnaire responses. Includes content Copyright: OpenStreetMap contributors or use supplied substitute diagram

We considered 2 primary measures of water quality, specific conductance and tryptophan-like fluorescence (TLF). Previous investigators of groundwater pollution have primarily used direct analysis of inorganic components, such as Cl^{-}, PO_4^{3-}, or NO_3^{-} concentrations, whether considering contamination in urban (Eisen and Anderson 1979, Kelly 2008, Foppen et al. 2008, Takem et al. 2010, Mohamed and Hassane 2016) or agricultural settings (Pedersen et al. 1991, Krapac et al. 2002, Harter et al. 2002). In some cases, researchers measured fecal coliforms, such as *Escherichia coli*, as a measure of sewage contamination (Foppen et al. 2008, Takem et al. 2010). We used specific conductance and TLF as surrogates for these direct measures to enable us to sample without further analysis. The utility of TLF in assessments of organic contamination in groundwater was highlighted by Baker and Lamont-Black (2001) and Sorensen et al. (2015), who argued that TLF may be a more sensitive indicator than fecal coliforms of some forms of contamination (e.g., viruses) because it is more easily transported in aquifers of limited permeability.

Role of citizen science

In proposing the concept of citizen science, Irwin (1995) sought to define a new relationship between citizens and science and argued that science should incorporate citizens' concerns and interests and that citizens themselves could produce reliable scientific knowledge. Since this early work, the concept of a citizen scientist has become more widely understood. The definition encompasses scientists as either those whose work is characterized by a sense of responsibility for the interests of the wider community or as members of the general public who engage in scientific work. Citizen science has been recognized as supporting public policy in Europe and the USA as a way to develop scientific skills in the wider community and to encourage more direct involvement in the formulation of public policy (EC 2014, OSTP 2015).

Here, we document the process and scientific outcomes associated with engagement of a citizen scientist in exploring the environmental concerns raised by members of the nonscientific community. Our study is a direct example of the type of engagement proposed by Irwin (1995). This kind of end-user-directed citizen science has a high potential for long-term engagement, a common challenge in citizen science (Rotman et al. 2012, Thornhill et al. 2016). A catalyst was the participation of Royal Dutch Shell plc employees (including the Citizen Scientist, via the global FreshWater Watch program) in gathering data for the Pollution Change in Urbanisation (POLLCURB) project led by the UK Centre for Ecology and Hydrology (CEH) and funded through the UK Natural Environment Research Council, Changing Water Cycle program. A general principle of POLLCURB was to engage a community to participate in research led by professional scientists. The purpose of the POLLCURB project was to identify the effect of urbanization on water quality, and the specific involvement of Royal Dutch Shell plc employees was to monitor water quality in the Rivers Thames and Mole near the study site. Community engagement was manifested in a variety of ways including the creation of new studies directly conducted by trained citizen scientists. This principle was realized by the Citizen Scientist in this study who took the opportunity to use equipment made available to Royal Dutch Shell plc employees.

METHODS

The Royal Paddocks Allotments are situated on a 5.6-ha site to the east of Bushy Park in the Borough of Richmond upon Thames, UK (Fig. 1). The Allotments have been on their present site for >90 y. The land was granted by Royal Warrant in the 12th year of the reign of King George V, on 30 June 1921, for use as allotments by "the labouring classes of Hampton Wick and South Teddington" ("Royal Warrant 1921", Royal Paddocks Allotments 2017). The area had been used as a grazing and stabling area for horses since the 18th century. The site has been divided into 210 plots, which are cultivated for vegetables and fruit. The site is bounded on its west and south sides by areas in Bushy Park given over to sports fields. The northern and eastern boundary is a major road, beyond which is the urban, mainly residential area of Hampton Wick. The Thames flows south to north in the vicinity, the closest point being ~250 m east of the southeastern corner of the site (Fig. S1). The site lies in an area potentially at risk from a 100-y flood event and a former channel runs southwest–northeast across the site (EA 2017). The site is not supplied from the public water supply, and water is drawn from a shallow aquifer that underlies the site.

Geologically the site lies on the sand and gravel of the Kempton Park Member, overlying London Clay and consists of postglacial fluvial sediments deposited by the Thames in the last 20,000 y (Gibbard et al. 1982, Bowen 1999). A borehole recorded 600 m northwest of the site showed 2.5 m of sand overlying 4 m of interbedded sand and coarse gravel sitting above the clay (British Grid Reference: TQ17SE187; Fig S1). The lower layers have a high degree of connectivity (Gibbard et al 1982) and form an extensive aquifer across the site. A commercial borehole sunk 200 m south of the site in 1991 struck water 2.8 m below the surface and yielded 5700 L/h. Drawdown in the test well was restored in 10 min (British Grid Reference: TQ16NE70) and indicates a highly permeable, interconnected, and freely following aquifer.

On the allotment site, the aquifer has been exploited by a series of 27 shallow boreholes, of which 23 were sampled, distributed across the site (Fig. 1). These cased boreholes extend 3 to 4 m into the gravels, and water is raised using hand pumps. The actual dates when individual pumps were commissioned have not been recorded, but installation occurred during 2 periods. The first pumps were constructed during the 1950s, and further pumps were established in 2004–2005. The methods of construction differed between periods. The earlier boreholes were created by deep excavation, whereas the more recent boreholes were installed by ram-driving the pipework into the gravels. Oral histories suggest that the older, excavated boreholes reach greater depths in the aquifer than the more recent boreholes. Both methods of well installation would have disturbed the stratigraphy of the gravels, but disturbance would have been more extensive where the wells were created by excavation (potentially several square meters).

Mean annual rainfall in the area is 591 mm (Met Office 2012) with peak rainfall falling in the months October to January (Fig. S2A). Peak discharges in the adjacent River Thames typically occur in November to April, but these peaks are not accompanied by large variations in stage because the river is heavily controlled through sluices (Fig. S2B). This aquifer is thought to be charged through vertical infiltration with contributions from the southeast from the Thames and from a minor stream lying to the west within Bushy Park. During periods of drought water levels fall in the pump boreholes even through river levels have been maintained (Plotholders, personal observation) suggesting that infiltration of rainfall is the main recharge mechanism.

Water sampling

The Citizen Scientist took water samples on a periodic basis during summer from 23 pitcher-style hand pumps distributed across the site. In total, 13 sampling runs occurred between 2014 and 2016 (Table S1). Sampling was restricted to the period between March and October because the pumps are decommissioned in the winter. On some occasions, water could not be drawn water from specific pumps because of mechanical failure or a low water table in periods of restricted rainfall. At each pump, the Citizen Scientist drew ~8 L of water into a container to allow measurement. Care was taken to follow the same sampling protocol at each pump, such that ~5 L of water were allowed to flow after priming the pump and were discarded before collection to ensure that the water was drawn from the borehole itself.

We considered 4 variables measured with a Manta 2 multiparameter sonde (Eureka Water Probes, Austin, Texas), including temperature (°C), specific conductance (μS/m), TLF (μg/L), and turbidity (nephelometric turbidity units [NTU] estimated by the measuring light scattering at 90°). We used specific conductance and TLF as markers of water quality. Specific conductance is a measure of the ability of water to pass electric current and is affected by the presence of dissolved salts (e.g., Cl^-, NO_3^-, PO_4^{3-}), and we used it as an indicator of inorganic inputs (e.g., road salt, PO_4^{3-}-based fertilizers) affecting the site.

The Manta 2 system used included a fluorometer (Cyclops 7™; Turner Designs, Sunnyvale, California) with specific wavelengths for excitation (285 ± 10 nm) and emission (350 ± 55 nm) to measure TLF. Amino acids, synthesised by microbes when breaking down more reactive organic matter, such as that found in sewage, are represented by TLF. TLF was considered initially as an indicator of possible contamination from the aging sewerage system in the area, but during the study, it became apparent that TLF could be applied to trace the usage of horse manure on the site. TLF can be affected by sample turbidity and water temperature. Particulates cause an increased scattering and attenuation of emitted light, and elevated temperatures increase the quenching effect on the TLF signal. Both effects can necessitate corrections to the data. Turbidity correction has been deemed unnecessary for groundwater studies (Khamis et al. 2015), but we applied a correction (J. Sorenson, British Geological Survey, personal communication) to all data (river and groundwater) captured by the TLF sensor in our study to enable comparisons with sampling elsewhere. Khamis et al. (2015) found that the influence of temperature on TLF was small. Given the limited range of temperature in the boreholes, a correction was not applied.

Specific conductance and TLF measures made at the boreholes were comparable to the freshwater samples obtained as part of the parallel POLLCURB project at closely located sites on the Rivers Thames and Mole (Fig. S1).

Plotholder survey

We undertook an online and paper survey of the plotholders (Appendix S1) in year 3 of the study as part of a process of engagement with a wider group of stakeholders at the Gardens. The objectives were to obtain: 1) information regarding usage of the pumps during the summer and 2) an indication of the types of fertilizer being used. We deliberately limited the survey to a number of simple questions with the intention of encouraging a high response rate. We asked questions regarding which pumps were used by individual plotholders and what fertilizer (organic, inorganic) they applied to their plots. Answers to questions about the frequency with which each plotholder irrigated their plot and how often they applied fertilizer provided an approximate indication of which were the most heavily used pumps and where fertilizer was most regularly used. We received 86 responses, representing ~50% of the cultivated plots distributed widely across the site (Fig. 1).

Statistical analysis

We assessed systematic variation among sampling runs on both a site-wide and borehole-specific basis. We tested site-wide, time-related variation with a 1-way analysis of variance (ANOVA) with sampling run as the independent variable. We analyzed the spatial variation in the variables with deterministic (inverse distance weighted [IDW]) and geostatistical (kriging) interpolation techniques in ARCGIS (version 10.5; Environmental Systems Research Institute, Redlands, California), SAGA (version 6.2; SAGA User Group Association, Hamburg), and QGIS (version 2.18; QGIS Open Source Consortium). The geostatistical techniques followed the approaches described by Bjerg and Christensen (1992), Hassan (2014), Marko et al. (2014), and Gharbia et al. (2016). We undertook separate analyses for each sampling run and for the average values of each variable across the 13 sampling runs. IDW is a deterministic interpolation technique that explicitly assumes that each measured point has a local influence that diminishes with distance. As an exact interpolator, it is particularly sensitive to the presence of outliers and is poor in describing regional trends, but it is of value in highlighting significant local variation in parameters (Johnston et al. 2001).

We used kriging to examine systematic site wide variation (Davis 1986, Johnston et al 2001). Kriging assumes that measurements represent regionalized (site-wide) variables that are continuous in nature and spatially correlated over short distances and, thus, have properties intermediate between a random variable and one that is completely deterministic. The degree and form of the variation in the variable can be described by an empirical semivariogram (Davis 1986, Cressie 1993). To derive an interpolated surface, we fitted an experimental semivariogram to the measured data to derive weights, which we used to predict values at unmeasured locations. We used empirical Bayesian kriging (EBK) to build a valid kriging model (ESRI 2013) after testing various kriging models and semivariogram forms on a limited number of example surfaces.

As the study progressed, we noticed that variation in water quality occurred at relatively local scales both spatially and temporally. We tested for the presence of statistically significant clusters of high and low values in the measured variables across all sampling runs with Getis–Ord Gi* Hotspot analysis (Getis and Ord 1992, Ord and Getis 1995) as implemented by Oxoli (2016) in the QGIS software. Based on inspection of the data and earlier analysis of variation at specific clusters of boreholes, we gave slightly different treatment to specific conductance and TLF data in that we set the minimum distance band applied to the TLF data at 5 m rather than the default minimum (0 m) to ensure ensured that repeated measures at each borehole were excluded from the analysis, thereby eliminating time-based variation and focussing on spatial clustering. The default minimum of 0 m was used for the specific conductance data because time-based variation was limited at individual boreholes.

Survey data Data gathered from the survey of plotholders (Appendix S1) allowed us to estimate the intensity of use of individual pumps. The relative usage of the pumps was estimated from the questionnaire responses by multiplying the count of usage by the frequency of usage/wk reported by each plotholder (Fig. S3). This approach allowed us to test a hypothesis by one of the plotholders that the more heavily used pumps seemed to produce visually cleaner water. Information gained from the survey also provided a circumstantial indication of areas of high manure application. A more direct source of evidence was the records of the Citizen Scientist in relation to the delivery of large quantities of farmyard manure to his plot. We also tested a hypothesis suggested by another plotholder that was related to oral histories about the installation of the pumps. This hypothesis was that the older, deeper pumps (pre-1950) have water quality different from that of the more recent shallower pumps. A similar effect was observed by Bjerg and Christensen (1992) in a comparable shallow aquifer.

RESULTS

Plotholder survey

A total of 86 responses was received for the plotholder survey. Several plotholders cultivate >1 plot, so this response rate represented ~50% of the cultivated plots (Fig. 1). Overall, 66% of the respondents used the pumps ≥3 times/wk, and 97% used some form of additional fertilizer, predominantly stable manure or plant compost (86%). In some cases, respondents provided supplementary information as to the storage of stable manure on their plots. This information proved to be significant in the subsequent interpretation of TLF hotspots.

Regional comparison

We undertook an assessment of the measured values at the site relative to a regional average by comparing the site-wide, time-averaged values for specific conductance and TLF with measurements taken from 2 local rivers, the Thames and its tributary, the River Mole, over the same period as part of the POLLCURB study. The POLLCURB measurements were obtained with the same equipment as used for our study and represent aggregated contributions of surface water, groundwater, and treated effluents. The mean values of specific conductance (573 μS/cm) and TLF (23 μg/L) at the site were below the range of mean values obtained from 4 sampling sites (Fig. S1) on the 2 rivers (TLF: 33.2–40.8 μg/L, specific conductance: 586–629 μS/cm). However, at specific locations, maximum values of both variables on the site (TLF: 420 μg/L, specific conductance: 837 μS/cm) were significantly higher than the regional average.

Site-wide temporal variation

Site-wide specific conductance did not vary significantly over time ($F = 1.076$, $p = 0.38$; Table 1, Fig. 2). Specific conductance did not appear to be related to environmental factors, such as rainfall levels (Fig. S2A). Site-wide TLF also did not very significantly over time ($F = 1.748$, $p = 0.056$;

Table 1. Analysis of variance tables for dependent variables specific conductance and tryptophan-like fluorescence (TLF) as functions of the independent variable, sampling run.

Source	Sum of squares	df	Mean square	F	p	F_{crit}
Specific conductance						
Between groups	133085.56	12	11090.46	1.076	0.38	1.79
Within groups	2813052.11	273	10304.22			
Total	2946137.67	285				
TLF						
Between groups	28875.024	12	2406.25	1.748	0.056	1.787
Within groups	375727.71	273	20451376.29			
Total	404602.7338	285				

Fig. 3). However, notable differences in the interquartile range of values between some time-adjacent sampling runs seem to reflect localized variation in the TLF values around specific clusters of pumps.

Site-wide spatial variation

The lack of temporal trends in the data and consistent differences between closely spaced sampling points led us to examine the spatial variation in specific conductance for each sampling run and in relation to the mean across all sampling runs. We detected an apparent trend across the site, with higher values of specific conductance occurring to the north of the site adjacent to the Hampton Wick urban area and lower values to the southwest of the site. This trend was consistent among individual sampling runs. However, once this trend was accounted for in the analysis, the theoretical semivariogram functions fitted by the EBK models and inspection of the empirical data indicated limited spatial structure to the data (Fig. S4). The fitted semivariograms showed a horizontal form that would be produced by a random variable with little or no spatial autocorrelation. Any kriging surface would reflect only an apparent underlying linear trend in the data. We tested the significance of the trend in the data by calculating a linear trend surface for the mean specific conductance values. The goodness of fit (R^2) of the surface to the data was poor, and the relationship was not statistically significant (Table 2). The lack of spatial autocorrelation and the non-significant nature of the trend indicates that no single factor influenced these points.

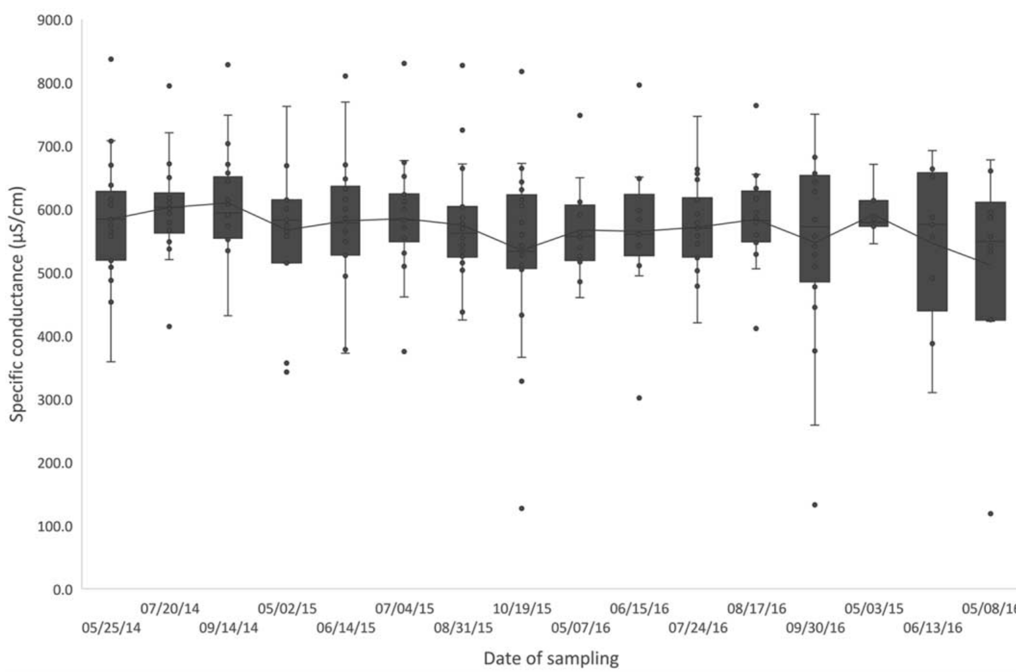

Figure 2. Box-and-whisker plots of specific conductance values on each sampling date. Lines connect medians between boxes, box ends are quartiles, whiskers indicate variability outside the upper and lower quartiles, and any point outside those lines or whiskers is considered an outlier. Circles show actual data points. Dates are formatted mm/dd/yy.

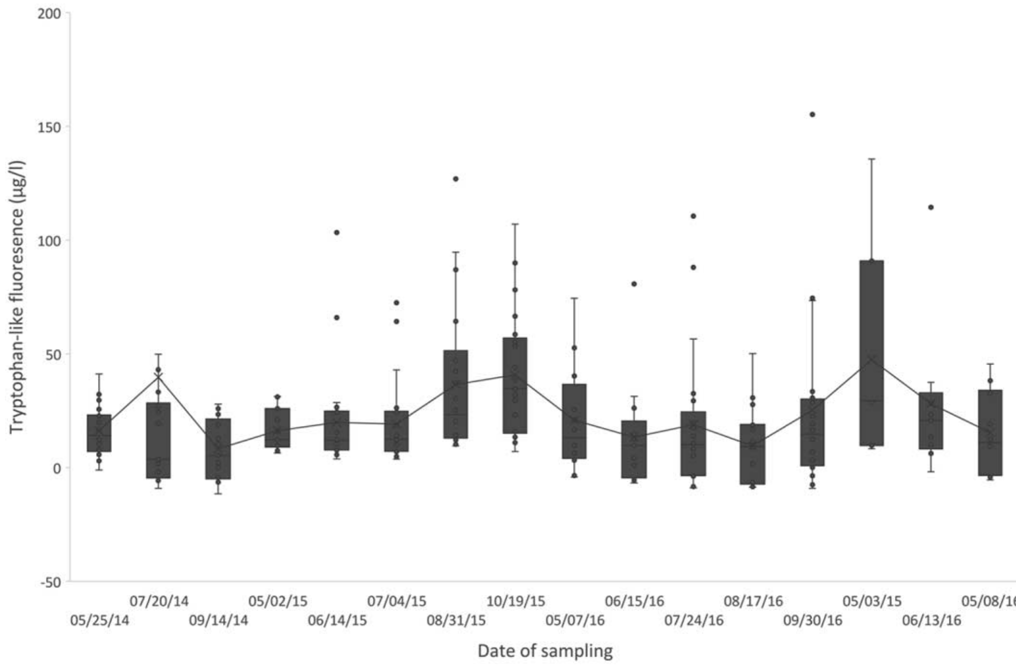

Figure 3. Box-and-whisker plots of tryptophan-like fluorescence (TLF) measurements values on each sampling date. Lines connect medians between boxes, box ends are quartiles, whiskers indicate variability outside the upper and lower quartiles, and any point outside those lines or whiskers is considered an outlier. Circles show actual data points. Dates are formatted mm/dd/yy.

We detected hotspots where specific conductance was significantly higher or lower than elsewhere on the site (Getis-Ord Gi* analysis; Fig. 4). Pump 133 showed particularly high values and was an anomaly relative to other wells. Other notable hotspots included 2 wells with high values adjacent to the highway east of the site (pumps 94 and 180), and several wells (pumps 10, 25, 130) with significantly low values in the southwestern corner of the site. The combined effect of these outliers seemed to be the cause of the nonsignificant trend in specific conductance across the site, and their presence was closely reflected in the IDW interpolation (Fig. S4). This resulted highlighted very marked differences in specific conductance over short distances (for instance between Pumps 130 and 133) and reinforced the impression of highly localized controlling factors.

Site-wide variation in the TLF data showed little evidence of distinct patterns on an averaged basis or in relation to individual sampling runs. Inspection of the empirical semivariogram data indicated limited spatial structure to the data (Fig. S5). The kriging surface for the mean values of TLF across sampling runs showed a slight nonsignificant trend from the northwest to southeast of the site. This trend was not repeated on a consistent basis among individual sampling runs. However, we identified specific pumps where values of TLF were significantly and consistently high when considering the data as a whole (hotspot analysis; Fig. 5). The IDW interpolation (Fig. 5) of the average TLF values highlighted locations with relatively high concentrations that corresponded with these hotspots. In some cases, incidental comments volunteered in the plotholder survey provided supporting information regarding the origin of the hotspot (e.g., pumps 148 and 167).

Inspection of the interpolated IDW surfaces for time-adjacent sampling runs (Fig. 6) around specific clusters of pumps showed that the pattern was not consistent in time and that the spatial extent of higher values differed between successive sampling runs. This effect was not statistically significant in the analysis of the temporal variation in TLF on a site-wide basis, but the significantly high measurements occurred during sampling runs when the range of values was particularly high (Fig. 3) indicating a local effect.

Table 2. Linear trend surface results for mean specific conductance. RSME = root mean square error.

Variable	R^2	RSME	F	F_{crit}	p
Specific conductance	0.130	115.11	1.50	5.66	0.25

Local variation

The hotspot analysis and examination of the interpolated IDW plots highlighted locations where marked differences in specific conductance were recorded at adjacent pumps <20 m apart. We selected 2 pairs of pumps (165/188 and 130/133) for more detailed examination. An analysis of variance carried out on both pairs of sample sets indicated that

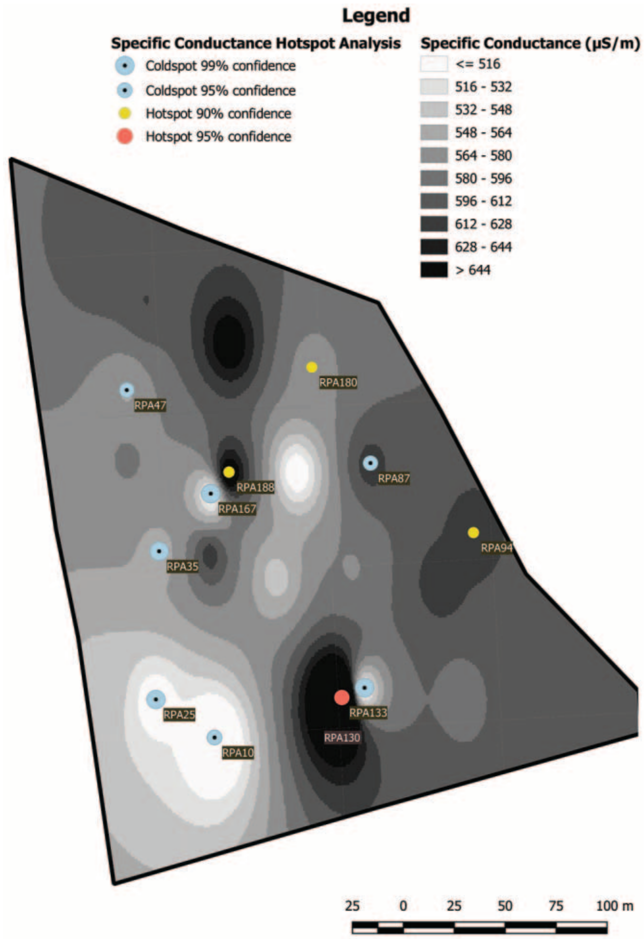

Figure 4. Interpolated distribution of mean specific conductance and Getis-Ord Gi * hotspot analysis.

the differences in values were significant ($p < 0.05$; Table 3, Fig. 7A, B). The pairing of these pumps was important because individual pumps in each pair were of different ages and, therefore, thought to be sunk to different depths in the aquifer. Bjerg and Christensen (1992) reported significant vertical variations in inorganic markers over short vertical distances, so we considered the hypothesis that the borehole depth and specific conductance values might be related. However, examination of the data for all pumps classified by pump age indicated no significant difference in the means (*t*-test, $p > 0.05$), and therefore, we were unable to infer a generalized relationship between pump age (and implicitly depth) and specific conductance.

Anecdotal evidence suggested that the water from the more heavily used pumps was cleaner than the water from the other pumps, so we used information gathered from the plotholder survey (Appendix S1) to examine whether pump usage (Fig. S3) affected values of specific conductance and TLF. However, neither the relationship between specific conductance ($R^2 = 0.0194$) nor TLF ($R^2 = 0.0031$) and pump usage estimated from the survey were significant.

Water from pumps 148, 167, and 180 had significantly higher TLF values than water from other pumps (Getis-Ord Gi*; Fig. 5), a pattern that closely corresponds with that demonstrated by the interpolated IDW plots for the averaged TLF values. Inspection of interpolated (IDW) TLF surfaces for successive months between June 2015 and May 2016 (Fig. 6) showed persistently high values adjacent to pump 167 in the center of the site and some elevation in the measurements taken at adjacent pumps (165, 188) after delivery of ~3 m^3 of stable waste to plot 166 in late April 2015 (Fig. 1). The manure was distributed more widely over 3 adjacent plots over the subsequent 3 mo.

A plot of TLF values for pump 167 and 4 nearby pumps (165, 188, 35, 42; Fig. 8) confirmed an increase in TLF concentrations subsequent to the manure delivery in April 2015 followed by a decline. The peak values were of a lower magnitude and occurred at a later date as the distance from the location where the manure was initially stored increased. The timing and distribution of the maximum TLF values suggests the spread of an input related to the delivery of manure that dissipated over time. High TLF values close to other pumps, such as pump 180 in the northeastern part

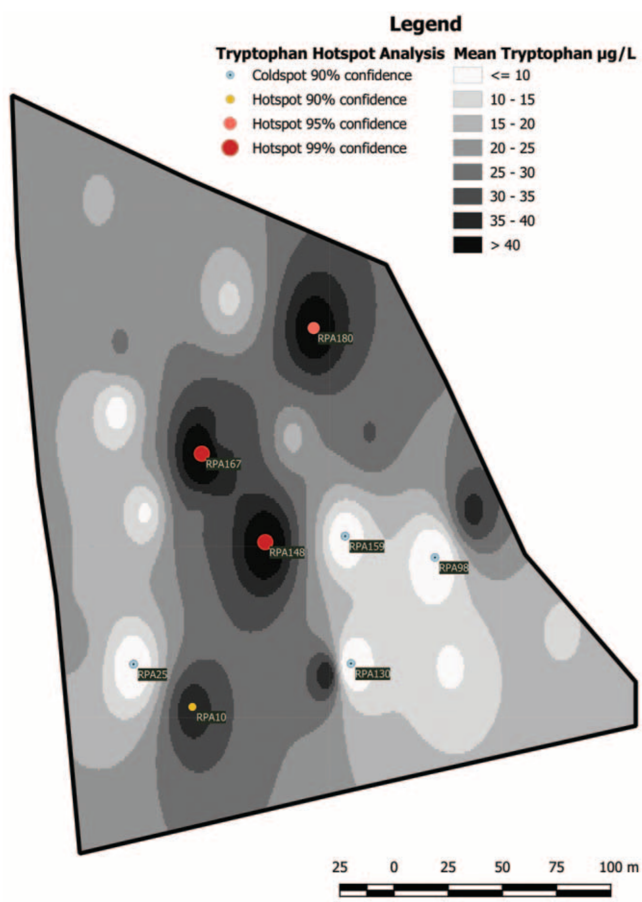

Figure 5. Interpolated distribution of tryptophan-like fluorescence (TLF) and Getis-Ord Gi* hotspot analysis.

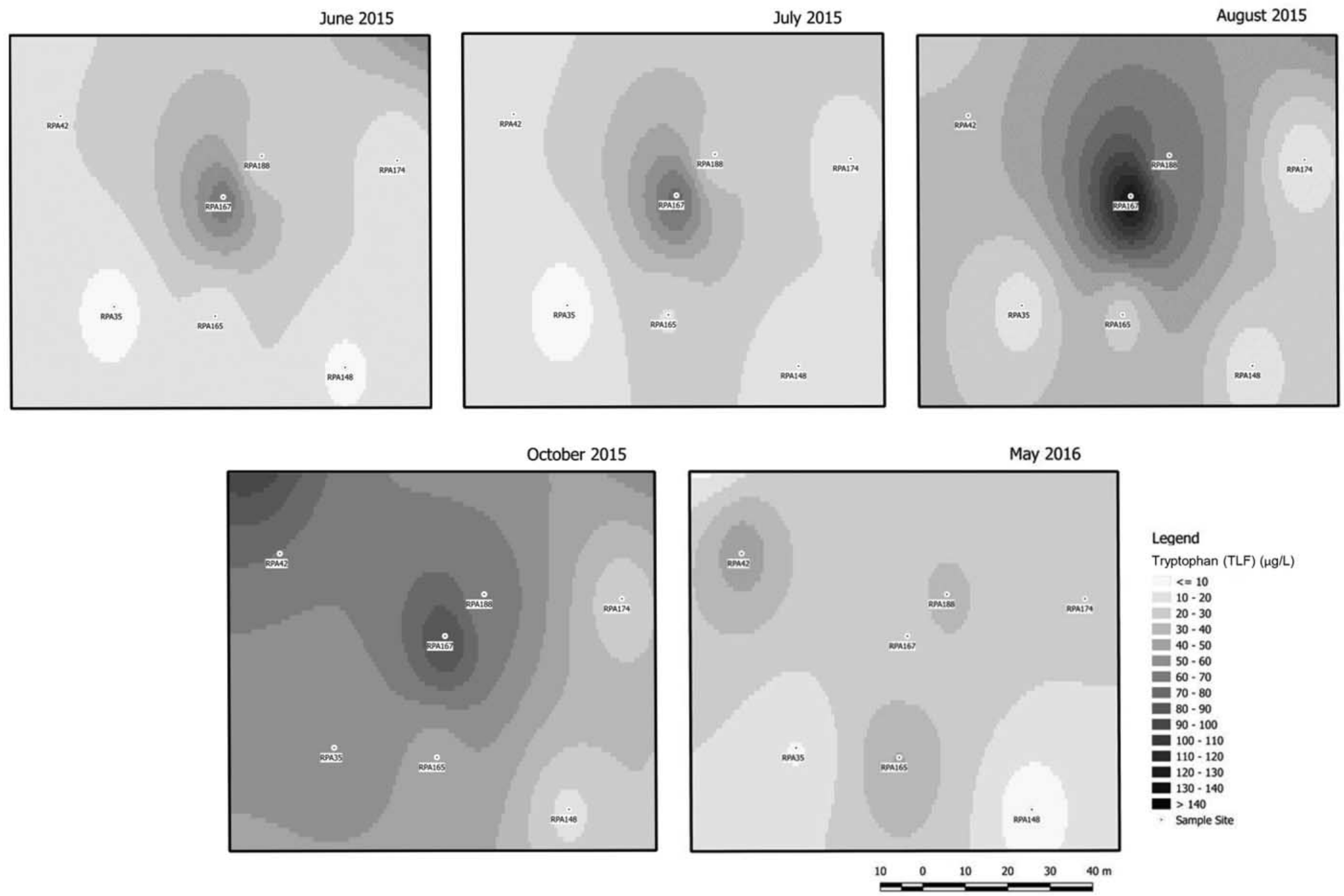

Figure 6. Variation in tryptophan-like fluorescence (TLF) in June 2015 to May 2016 after manure application to plot 166.

of the allotment, also might reflect storage and application of manure in the vicinity. Pump 180 is close to a frequently used delivery point for stable waste (Fig. 1), but we were unable to identify a direct relationship between specific deliveries and the recorded high values. We were able to identify a more direct relationship between a hotspot apparent at pump 148 and information provided in a response to the plotholder survey that identified the presence of a large amount of composted manure on the plot close to the pump.

DISCUSSION

The initial concern of the members of the community garden was that significant outside influences affected water quality on the site given its location adjacent to a major

Table 3. Analysis of variance results for the dependent variable specific conductance at pumps 130/133 and 167/188 over all sampling runs.

Source	Sum of squares	df	Mean square	F	p	F_{crit}
Pumps 130 and 133						
Between groups	543276.88	1	543276.88	151.18	3.40726×10^{-10}	4.414
Within groups	64683.34	18	3593.52			
Total	607960.2268	19				
Pumps 167 and 188						
Between groups	278048.23	1	278048.23	12.73	0.002	4.35
Within groups	436833.88	20	21841.69			
Total	714882.11	21				

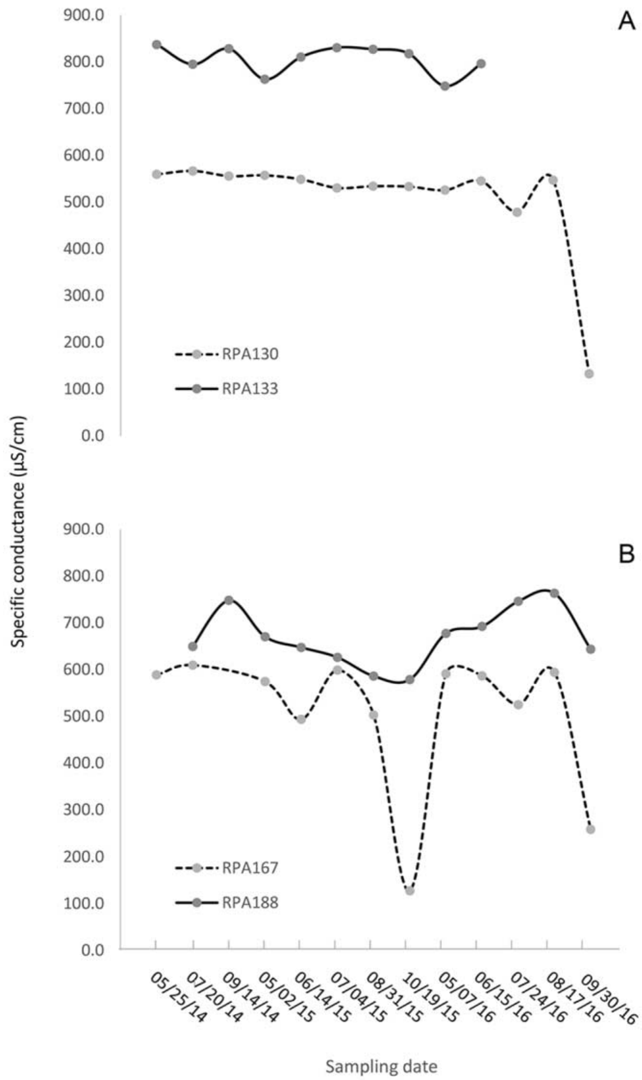

Figure 7. Variation in specific conductance at adjacent pumps 130/133 (A) and 167/188 (B). Dates are formatted mm/dd/yy.

highway and urban area on the eastern side of the perimeter and its proximity to a sports field on the western side. The variables we selected did not display strong temporal or spatial evidence of contamination. We found no evidence of elevated values of specific conductance adjacent to the sports field as might be expected from excessive application of NO_3^- or PO_4^{3-}-based fertilizers, nor did we find consistent evidence of elevated levels of specific conductance or TLF in the wells adjacent to the northeastern perimeter of the site that would indicate widespread contamination from common urban point sources, such as leaking sewage infrastructure. The presence of some higher values of specific conductance in specific wells close to the perimeter (e.g., pump 94) might reflect contamination from sources, such as road salting on the secondary highway and bus route that runs along the east and northeastern boundary (Kelly 2008).

The absence of statistically significant trends in specific conductance and TLF across the site support the view that any variation in water quality reflects controls or influences that are relatively local and intrinsic to the site. The semivariograms for the TLF and specific conductance data show no evidence of a spatial structure to the data (Davis 1986) with limited covariance with distance. Similar patterns for specific conductance were observed by Bjerg and Christensen (1992) who suggested that the variation for some inorganic indicators (e.g., NO_3^-) occurred at less than the distance between sampling points. Given the relatively sparse number of irregularly spaced samples at our site, the absence of a spatial structure to the data may be, in part, an artifact of the necessarily constrained sampling design. This explanation is particularly likely to be the case with respect to the TLF measurements that show some relationship between values at adjacent boreholes (Fig. 8).

Values of specific conductance and TLF were lower than the average values measured in the adjacent River Thames and tributaries. This result supports the hypotheses that water quality and its variation on the site were locally controlled or that, if the river were a major source of recharge, bed sediments acted as a filter as observed elsewhere in the Thames basin (Younger et al. 1993). Our analysis indicates relatively limited directional flow in the aquifer and that rainfall-related vertical infiltration is a more important driver than recharge from adjacent rivers. This conclusion is supported by the observation that water levels fall in the aquifer despite maintenance of adjacent river levels and is in accor-

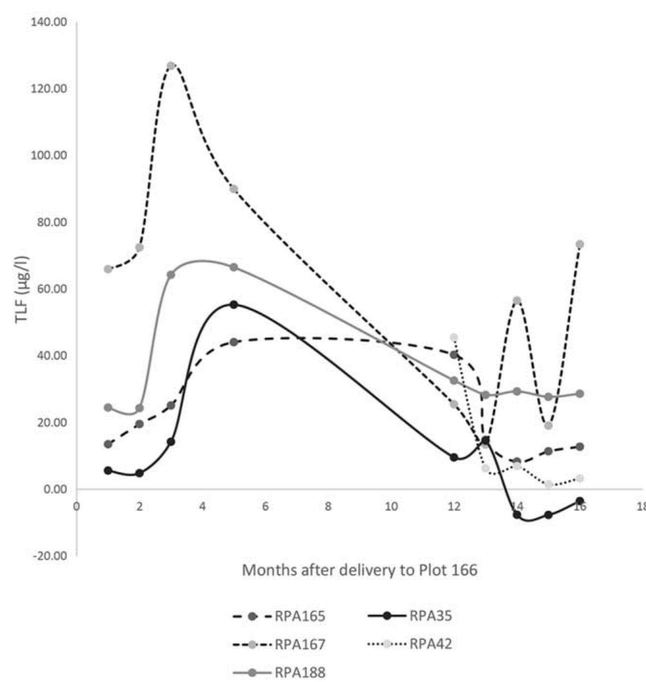

Figure 8. Variation in tryptophan-like florescence (TLF) at on pumps adjacent to plot 166 after manure delivery.

dance with the finding of Younger et al. (1993) from similar sediments elsewhere in the Thames Basin.

Variations in water quality on the site as evidenced by inorganic and organic markers seem to be driven by local but unrelated factors because the spatial and temporal patterns of specific conductance and TLF are distinctly different. The pattern shown by the TLF can be attributed to the application of organic fertilizer. In theory, a commensurate increase in specific conductance could occur in response to K^+ and NO_3^- derived from the manure (Bjerg and Christensen 1992). However, examination of the data indicated no correlation between the data sets. Therefore, the factors influencing the observed variation in both data sets seem to be operating independently. The potential for the variability of water quality in shallow aquifers in the absence of polluting sources was noted by Bjerg and Christensen (1992), who described marked horizontal and vertical variations in groundwater quality as measured by NO_3^- and PO_4^{3-} concentrations over short (<10 m) distances. An alternative explanation of the causes for this variation requires further investigation.

The consistent temporal, but spatially variable, differences in the values of specific conductance seem to be driven by influences that are local to individual pumps. In the absence of definitive anthropogenic influences or other environment factors, the physical and chemical heterogeneity of the aquifer in terms of porosity, permeability, and sediment mineral composition is thought to be the main control on local values of specific conductance (Back and Baedecker 1989). For instance, some evidence exists that lower values of specific conductance occur in conjunction with topography that reflects the presence of a former river channel trending southeast to northwest across the site.

In contrast, the spatial and temporal variability of TLF values at individual pumps (Fig. 8) can be directly attributed to the storage of stable manure and its subsequent usage as a fertilizer on the site. This inference was derived from information gained from the plotholder survey. At one of these locations, we were able to examine the dispersal of the TLF over a period of weeks through repeated measurements. In circumstances where such a water supply was to be used for human consumption, the apparent contamination and dispersal of organic pollutants would be a significant issue. At this location, the water supply is only used for irrigation and, given the preference of the plotholders on the site to cultivate organically, the presence and dispersal of organic contamination does not represent a concern, but produce should be washed adequately to remove possible pathogens.

Overall reflection on the contribution of citizen science

Our study was initiated by allotment users and citizen scientists based on their desire to discover more about their local environmental conditions. Data gathering, both measurements and contextual information, was supported by >80 users of the site including the principal researcher. This work is a good example of citizen science in action and demonstrates what can be achieved when resources and facilities are made available to a wider group of people outside mainstream scientific institutions. In many ways, our study reflects the attributes of the commonly accepted definition of citizen science in that it: 1) addressed concerns raised by a citizen group that might otherwise not have been considered by the established scientific community, and 2) was undertaken by people not normally engaged in environmental research supported by experts in the field.

Our study also provides grounds to challenge the assumption that the role of the citizen scientist is limited to that of providing and processing data under the guidance of others enabled by access to equipment (Anon 2014). As Mills (2015) argued, this definition of a citizen scientist discounts the ability of citizen scientists to inform study design, conduct data analysis and interpretation, or use skills transferable from other domains to undertake the analysis and interpretation themselves. Institutional support for research remains important, particularly with regard to access to instrumentation and specialist facilities for analysis and to peer-reviewed scientific journals often locked behind paywalls, but the scope and availability of ‘open data’ (data.gov.uk, Lammerhirt 2017), has increasingly allowed researchers to work independently. In our study, collection of the water-quality measurements relied on the use, after training, of institutionally provided equipment, but much (but not all) of the analysis was done using ‘open-source’ GIS packages, such as QGIS and Saga. Such tools could increase the prevalence and, in some fields, significance of citizen science, which perhaps is limited only by the time and motivation of the individuals involved. Encouraging growth in citizen science will require institutional support for individuals through training, equipment, and involvement in projects, but also guidance as to the norms and protocols of scientific practice (e.g., peer review and presentation of data).

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LITERATURE CITED

Anon (Anonymous). 2014. Citizen science. *In* Oxford Living Dictionaries. 1st online edition. (Available from: http://www.oxforddictionaries.com/definition/english/CitizenScience)

Back, W., and M. J. Baedecker. 1989. Chemical hydrogeology in natural and contaminated environments. Journal of Hydrology 106:1–28.

Baker, A., and J. Lamont-Black. 2001. Fluorescence of dissolved organic matter as a natural tracer of groundwater. Groundwater 39:745–750.

Bjerg, P. L., and T. H. Christensen. 1992. Spatial and temporal small-scale variation in groundwater quality of a shallow sandy aquifer. Journal of Hydrology 131:133–149.

Bowen, D. Q. 1999. A revised correlation of Quaternary deposits in the British Isles. Special Geological Society Special Report 23. Geological Society, London, UK.

Cressie, N. 1993. Statistics for spatial data. Wiley, New York.

Davis, J. C. 1986. Statistics and data analysis in geology. Wiley, New York.

Eisen, C., and M. P. Anderson. 1979. The effects of urbanization on ground-water quality—a case study. Ground Water 17:456–462.

EA (Environment Agency). 2017. Flood map for planning. Gov.UK, London, UK. (Available from: https://flood-map-for-planning.service.gov.uk/)

EC (European Commission). 2014. Green paper on citizen science for Europe: towards a society of empowered citizens and enhanced research. European Commission, Brussels, Belgium. (Available from: https://ec.europa.eu/digital-single-market/en/news/green-paper-citizen-science-europe-towards-society-empowered-citizens-and-enhanced-research)

ESRI (Environmental Systems Research Institute). 2013. ARCGIS resources: what is empirical Bayesian kriging? Environmental Systems Research Institute, Redlands, California. (Available from: http://resources.arcgis.com/en/help/main/10.1/index.html#//0031000000q9000000)

Foppen, J. W. A., M. van Herwerden, M. Kebtie, A. Noman, J. F. Schijven, P. J. Stuyfzand, and S. Uhlenbrook. 2008. Transport of *Escherichia coli* and solutes during waste water infiltration in an urban alluvial aquifer. Journal of Contaminant Hydrology 95:1–16.

GetSurrey. 2013. Growing interest in allotments is sparked by food concerns. Surrey Live, Guildford, UK. (Available from: http://www.getsurrey.co.uk/whats-on/find-things-to-do/growing-interest-allotments-sparked-food-4850224)

Getis, A., and J. K. Ord. 1992. The analysis of spatial association by use of distance statistics. Geographical Analysis 24:189–206.

Gharbia, A. S., S. Salem, S. S. Gharbia, T. Abushbak, H. Wafi, A. Aish, M. Zelenakova, and F. Pilla. 2016. groundwater quality evaluation using gis based geostatistical algorithms. Journal of Geoscience and Environment Protection 4:89–103.

Gibbard, P. L., G. R. Coope, A. R. Hall, R. C. Preece, and J. E. Robinson. 1982. Middle Devensian river deposits beneath the 'Upper Floodplain' terrace of the River Thames at Kempton Park, Sunbury, Surrey. Proceedings of the Geologists' Association 93:275–290.

Han, D., X. Tong, M. J. Currell, G. Cao, M. Jin, and C. Tong. 2014. Evaluation of the impact of an uncontrolled landfill on surrounding groundwater quality, Zhoukou, China. Journal of Geochemical Exploration 136:24–39.

Harter, T., H. Davis, M. C. Mathews, and R. Meyer. 2002. Shallow groundwater quality on dairy farms with irrigated forage crops. Journal of Contaminant Hydrology 55:287–315.

Hassan, J. 2014. A geostatistical approach for mapping groundwater quality (case study: Tehsil Sheikhupura). International Journal of Science and Research 3:2319–7064.

Irwin, A. 1995. Citizen science: a study of people, expertise and sustainable development. Routledge, London, UK.

Kelly, W. R. 2008. Long-term trends in chloride concentrations in shallow aquifers near Chicago. Groundwater 46:772–781.

Khamis, K., J. P. R. Sorensen, C. Bradley, D. M. Hannah, D. J. Lapworth, and R. Stevens. 2015. In situ tryptophan-like fluorimeters: assessing turbidity and temperature effects for freshwater applications. Environmental Science Processes and Impacts 17:740–752.

Krapac, I. G., W. S. Dey, W. R. Roy, C. A. Smyth, E. Storment, S. L. Sargenta, and J. D. Steele. 2002. Impacts of swine manure pits on groundwater quality. Environmental Pollution 120:475–492.

Johnston, K., J. M. Ver Hoef, K. Krivoruchko, and N. Lucas. 2001. Using ARCGIS geostatistical analyst. Environmental Systems Research Institute, Redlands, California.

Lämmerhirt, D. 2017.; The state of open licensing in 2017. Open Knowledge International Blog. Available from: https://blog.okfn.org)

Marko, K., N. S. Al-Amri, and A. M. M. Elfeki. 2014. Geostatistical analysis using GIS for mapping groundwater quality: case study in the recharge area of Wadi Usfan, western Saudi Arabia. Arabian Journal of Geoscience 7:5239–5252.

Met Office (Meteorological Office). 2012. Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current). NCAS British Atmospheric Data Centre, Leeds, UK. (Available from: http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0)

Mills, K. 2015. Only scientists can do science. *In* J. Brockman (editor). This idea must die: scientific theories that are blocking progress. Harper Perennial, New York.

Mohamed, M. A., and A. B. Hassane. 2016. Hydrochemistry assessment of groundwater quality in Al-Ain city, UAE. Environmental Earth Sciences 75:353.

Ord, J. K., and A. Getis. 1995. Local spatial autocorrelation statistics: distributional issues and an application. Geographical Analysis 27:286–306.

OSTP (Office of Science and Technology Policy). 2015. Fact sheet: Empowering students and others through citizen science and crowdsourcing. The White House, Washington, DC. (Available from: https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/citizen_science_backgrounder_03-23-15.pdf)

Oxoli, D. 2016. Hotspot analysis with QGIS. QGIS Development Team, Boston, Massachusetts. (Available from: https://github.com/danioxoli/HotSpotAnalysis_Plugin/blob/master/test_data/Hotspot_Analysis_UserGuide.pdf)

Pavord, A. 2008. Gardens: growth industry. The Independent, London, UK. (Available from: http://www.independent.co.uk/property/gardening/gardens-growth-industry-888017.html)

Pedersen, J. K., P. L. Bjerg, and T. H. Christensen. 1991. Correlation of nitrate profiles with groundwater and sediment characteristics in a shallow sandy aquifer. Journal of Hydrology 124:263–277.

Rotman, D., J. Preece, J. Hammock, K. Procita, D. Hansen, C. Parr, D. Lewis, and D. Jacobs. 2012. Dynamic changes in motivation in collaborative citizen-science projects. Pages 217–226 *in* Proceedings of the ACM 2012 conference on computer supported cooperative work, Seattle, Washington, February 11–15, 2012. ACM, New York.

Royal Paddocks Allotments. 2017. Royal Paddocks Allotment, Hampton Wicks, UK. (Available from: http://www.paddocks-allotments.org.uk/about/history.htm)

Savill, R. 2009. England's oldest allotments celebrate 200 years. The Daily Telegraph, London, UK. (Available from: http://www.telegraph.co.uk/gardening/4967971/Englands-oldest-allotments-celebrate-200-years.html)

Smithers, R. 2009. Dig for recovery: allotments boom as thousands go to ground in recession. The Guardian, London, UK. (Available from: https://www.theguardian.com/lifeandstyle/2009/feb/19/national-trust-allotments)

Sorensen, J. P. R., D. J. Lapworth, B. P. Marchant, D. C.W. Nkhuwa, S. Pedley, M. E Stuart, R. A. Bell, M. Chirwa, J. Kabika, M. Liemisa, and M. Chibesa. 2015. In-situ tryptophan-like fluorescence: a real-time indicator of faecal contamination in drinking water supplies. Water Research 81:38–46.

Takem, G. E., D. Chandrasekharam, S. N. Ayonghe, and P. Thambidurai. 2010. Pollution characteristics of alluvial groundwater from springs and bore wells in semi-urban informal settlements of Douala, Cameroon, Western Africa. Environmental Earth Sciences 61:287–298.

Thornhill, I., S. Loiselle, K. Lind, and D. Ophof. 2016. The citizen science opportunity for researchers and agencies. BioScience 66:720–721.

Wallop, H. 2009. Allotment waiting lists reach up to 40 years. The Telegraph, London, UK. (Available from: http://www.telegraph.co.uk/foodanddrink/5422485/Allotment-waiting-lists-reach-up-to-40-years.html)

Younger, P. L., R. Mackay, and B.J. Connorton. 1993. Streambed sediment as a barrier to groundwater pollution from fieldwork and modelling in the River Thames Basin. Journal of the Institute of Water and Environmental Management 7:577–585.