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Water chemistry and endangered white-clawed Crayfish: a literature review and field study of water chemistry association in *Austropotamobius pallipes*

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ABSTRACT

Key-words: *freshwater, aquatic, conservation, water quality, habitat requirements*

Populations of the endangered white-clawed crayfish (*Austropotamobius pallipes*) have rapidly declined in distribution and density in recent decades as a result of invasive crayfish, disease and habitat degradation. The species is thought to be particularly sensitive to water chemistry, and has been proposed as a bio-indicator of water quality. Here we detail the results of a systematic review of the literature regarding the chemistry of waterbodies inhabited by white-clawed crayfish, along with a wide-scale field study of the chemistry of crayfish-inhabited waterbodies in the UK. We use these data to examine potentially significant variables influencing crayfish distribution. Several variables appear to have thresholds that affect crayfish distribution; crayfish presence was associated with high dissolved oxygen, low conductivity, ammonium, sodium, and phosphate, and to a lesser extent low sulphate, nitrate, and total suspended solids. Some variables (magnesium, potassium, sodium, sulphate, nitrate, and total suspended solids) may be tolerated at moderate to high concentrations in isolation (indicated by the presence of some populations in high levels of these variables), but suites of chemical conditions may act synergistically *in situ* and must be considered together. Recent efforts to conserve white-clawed crayfish have included relocations to *Ark Sites*; novel protected habitats with reduced risk of the introduction of disease, invasive crayfish and habitat degradation. We use our findings to propose the first detailed guidelines for common water chemistry variables of potential *Ark Sites* for the conservation of the species throughout its European range.

RÉSUMÉ

Chimie de l'eau et écrevisse à pattes blanches en voie de disparition : une revue de la littérature et une étude sur le terrain de la chimie de l'eau associée à *Austropotamobius pallipes*

Mots-clés : *eau douce, aquatique,*

Les populations de l'écrevisse à pattes blanches (*Austropotamobius pallipes*) en voie de disparition, ont rapidement décliné dans leur distribution et leur densité au cours des dernières décennies à cause d'écrevisses invasives, de maladie et de la dégradation de l'habitat. L'espèce est supposée être particulièrement sensible à

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conservation, qualité de l'eau, besoins en habitat

la chimie de l'eau, et a été proposée comme un bio-indicateur de la qualité de l'eau. Ici, nous détaillons les résultats d'une revue systématique de la littérature concernant la chimie des masses d'eau habitées par des écrevisses à pattes blanches, avec une étude de terrain à grande échelle de la chimie des masses d'eau abritant des écrevisses au Royaume-Uni. Nous utilisons ces données pour identifier les variables potentiellement importantes qui influent sur la distribution des écrevisses. Plusieurs variables semblent avoir des seuils qui affectent la distribution des écrevisses ; la présence d'écrevisses a été associée à de l'oxygène dissous élevé, une faible conductivité, une faible concentration d'ammonium, de sodium et de phosphate, et dans une moindre mesure à une faible concentration en sulfate, nitrate, et matières en suspension. Certaines variables (le magnésium, le potassium, le sodium, le sulfate, le nitrate, et les matières en suspension) peuvent être tolérées à des concentrations modérées à élevées quand il n'y en a qu'une seule en concentration forte (indiqué par la présence de certaines populations à des niveaux élevés de ces variables), mais les conséquences de conditions chimiques peuvent agir en synergie *in situ* et l'ensemble de ces conséquences doit être considéré. Les récents efforts pour conserver l'écrevisse à pattes blanches comprennent les délocalisations vers des sites *Ark* ; nouveaux habitats protégés avec un risque réduit d'introduction de maladie et d'écrevisses invasives et de dégradation de l'habitat. Nous utilisons nos résultats pour proposer les premières lignes directrices détaillées pour les variables de chimie de l'eau communes de sites *Ark* potentiels pour la conservation de l'espèce dans son aire européenne.

INTRODUCTION

The white-clawed crayfish (*Austropotamobius pallipes*) has a widespread distribution throughout Western Europe, with significant numbers found in Britain (Holdich *et al.*, 1999; Kouba *et al.*, 2014). Despite its wide range, many populations have been lost or dramatically reduced in size in recent decades as a result of crayfish plague, competitive exclusion by invasive non-native crayfish, and habitat degradation (*e.g.* Gherardi and Holdich, 1999; Holdich *et al.*, 2009). Whilst some populations of *A. pallipes* have been found in relatively low quality water bodies (Holdich *et al.*, 1999), presence of the species is generally reported to be associated with water of 'good' quality; typically, moderately alkaline, low in pollutants, and non-eutrophic waters (*e.g.* Holdich and Reeve, 1991). The use of *A. pallipes* as a bioindicator species, however, has been debated, since some tolerance to pollutants may exist (see Füreder *et al.*, 2003; Füreder and Reynolds, 2003; Talley and Dagget, 2006).

A. pallipes has been included in the IUCN Red Data List, and is currently listed as endangered (IUCN, 2011). It is also included in Annexes II and V of the European Habitats Directive (Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora), with an implicit requirement for the establishment of protected areas for their protection (Special Areas of Conservation), and Appendix 2 of the Bern Convention. Various forms of Environment Agency and Natural England licensing exist in the UK to protect the species from detriment. Conservation efforts to maintain populations of *A. pallipes* in the wild in Britain have recently focussed on relocation of threatened populations. The species is threatened from crayfish plague (*Aphanomyces astaci*), which has caused the loss of numerous populations, and also from habitat degradation and competition with invasive, non-native crayfish. Animals are removed from areas where risk of infection by crayfish plague, competitive exclusion by invasive non-native crayfish, and population decline due to habitat degradation are high, and placed into habitats that are assessed to have minimal risks from these factors. Such relocation has been termed *Ark Site* conservation and has undergone substantial public review to produce management guidelines for *Ark Site* conservation in the UK (Kemp *et al.*, 2000; Peay, 2003, 2009; Whitehouse *et al.*, 2009). However, water chemistry guidelines would be strengthened considerably by a detailed examination of typical water chemistry conditions for the species in its European and British ranges. This has yet to be undertaken beyond a regional scale (*e.g.* Smith *et al.*, 1996; Favaro *et al.*, 2010). Such analysis would allow conservation managers to assess the suitability of potential *Ark Site*s by relating their water chemistry to the known range of variables from the species' natural range. A degree of suitability can then be attached to these *Ark Site* water chemistry variables based on their frequency of occurrence in the wild.

Until recently, *Austropotamobius pallipes* was referred to as a species complex, consisteing of several subspecies in Western Europe. It has now, however, been reclassified as two distinct species (Grandjean *et al.*, 2002); *A. pallipes* in the British Isles and France, and several subspecies of *A. italicus* in the rest of its range (including Spain and Italy). Since the species are similar in their morphology and habitat requirements and only genetic analysis has shown them to be separate, we include *A. italicus* in this review (clearly stated as a different species where referenced) to make the best use of limited evidence.

Other recent work has been published which aims to link crayfish distributions to the macroinvertebrates on which they feed (*e.g.* Grandjean *et al.*, 2011; Trouilhé *et al.*, 2012; Jandy *et al.*, 2014). We have chosen to focus instead on water chemistry variables due to the ease with which water samples can be taken and the high level of measurement accuracy attainable. We recognise the merits of studies examining macroinvertebrate prey species distributions with respect to crayfish presence, however.

Herein, we present the findings of an analysis of the evidence regarding water chemistry in sites inhabited by *A. pallipes* in Europe. We also present results of an observational field study of water chemistry in 18 sites inhabited by the species in Britain. We identify variables that may be affecting the distribution of *A. pallipes* and suggest guidelines for the selection of potential *Ark Site*s for conservation of the species in Britain.

METHODS

> *SYSTEMATIC LITERATURE REVIEW*

Literature searches were carried out using *Web of Science* (including Web of Science Core Collections, Biosis Previews, MEDLINE, SciELO Citation Index, and Zoological Record) on 13/09/14 for water chemistry associations of *A. pallipes*.

The following search string was used for *A. pallipes* water chemistry associations: ("austropotamobius pallipes" OR white-claw* OR "white claw*" OR whiteclaw*) AND (chemistry OR conductivity OR ammoni* OR nitrate OR nitrite OR phosphate OR chloride OR magnesium OR calcium OR conduct* OR potassium OR sodium OR sulphate OR "dissolved oxygen" OR pH OR TSS OR "total suspended solid"). These water chemistry variables were chosen from an initial assessment of commonly examined variables in the literature. Search results were assessed for relevance in a three-tier approach; title, abstract, and full text. Potentially relevant references were also assessed from within identified articles. Additional relevant articles not found through searches were added using a "snowballing" technique (Jalali and Wohlin, 2012), whereby the reference lists of relevant articles were scanned for further relevant studies.

In order to produce values with which to compare waters inhabited by *A. pallipes*, mean values reported for major global and European rivers were collated from the literature. The following water chemistry variables for global and European rivers were obtained from Berner and Berner (1996); calcium, magnesium, sodium, potassium, chloride, and sulphate. Values for conductivity, dissolved oxygen, ammonium, nitrate, total dissolved solids, pH, and phosphate were obtained from an independent review of the literature on 24/08/2012. Twenty-two additional articles (see Appendix 1 for details) were identified from a search of the literature on global and European rivers using Web of Science. These articles were reviewed and data on the water chemistry variables described above were extracted to generate means and ranges. In addition, representative values for rivers in the United Kingdom were obtained from the Harmonised Monitoring Scheme, a Defra and CEH initiative to monitor water chemistry. 15 regions across England and Wales were chosen as representative regions also currently/previously inhabited by *A. pallipes* (see Appendix 2 for details of data and their sources).

Table I
Sites inhabited by white-clawed crayfish (A. pallipes) that were sampled for water chemistry.

Site	Location	Latitude (WGS84)	Longitude (WGS84)	Type
Adel Beck	Leeds, West Yorkshire	52°42′33.47″N	2°27′58.01″W	Lotic
Brasside Pond	Durham, County Durham	54°48′29.10″N	1°33′00.91″W	Lentic
Broomlee Lough	Hexham, Northumberland	55°01′18.48″N	2°19′49.34″W	Lentic
Coppice Pond	Bingley, West Yorkshire	53° 50′47.06″N	1° 51′54.77″W	Lentic
Cound Brook	Condover, Shropshire	52°39′24.17″N	2°43′00.22″W	Lotic
Crook Burn	Hexham, Northumberland	55°02′06.98″N	2°17′53.71″W	Lotic
Dean Brook	Huddersfield, West Yorkshire	53°37′04.53″N	1°47′55.76″W	Lotic
Halleypike Lough	Hexham, Northumberland	55°02′28.66″N	2°17′50.49″W	Lentic
Meanwood Beck	Leeds, West Yorkshire	53°52′18.71″N	1°37′21.75″W	Lotic
Pinfold Dam	Huddersfield, West Yorkshire	53°38′18.09″N	1°49′02.92″W	Lentic
River Derwent	Scarborough, North Yorkshire	54°11′50.63″N	0°30′08.29″W	Lotic
River Kent	Kendal, Cumbria	54°19′46.69″N	2°45′09.32″W	Lotic
River Redlake	New Invention, Shropshire	52°23′07.86″N	3°02′56.20″W	Lotic
River Wansbeck	Rothley, Northumberland	55°08′54.89″N	1°56′53.18″W	Lotic
Robsheugh Burn	Milbourne, Northumberland	55° 03′46.96″N	1° 50′59.05″W	Lotic
Simpson's Pool	Horsehay, Shropshire	52°39′48.06″N	2°29′26.74″W	Lentic
Trench Pool	Telford, Shropshire	52°42′33.47″N	2°27′58.01″W	Lentic
Wyke Beck	Leeds, West Yorkshire	53°46′58.85″N	1°29′19.45″W	Lotic

Reported water chemistry variables have been converted to $mg \cdot L^{-1}$, with the exception of conductivity ($\mu S \cdot cm^{-1}$). Most authors have provided a mean, and a maximum and minimum (range) for the rivers examined, whilst some have presented only means or ranges. Graphed global, European and UK values are presented as ranges of means (mean mean, minimum mean, and maximum mean), rather than ranges in absolute values. This method allows discriminatory ability between these values and those for crayfish-inhabited waters. Since global and European values presented are ranges of means, some concentrations for crayfish-inhabited waters may therefore exceed these ranges.

> *WATER CHEMISTRY ANALYSIS OF UK POPULATIONS*

Water chemistry was recorded at 18 sites known to be inhabited by *A. pallipes* (see Table I) throughout the Midlands and North England between May and October 2009. Potassium, magnesium, calcium, sodium, chloride, nitrate, sulphate, and phosphate were measured from water samples analysed at the University of Leeds. Dissolved oxygen was measured on-site. Samples of filtered (0.45 μm) water were frozen and run through a Dionex ion chromatograph (ICS-90 machine) and gas diffusion flow injection analysis on FIA (ammonium only). Integration was then examined for each sample, and peaks adjusted if necessary to increase accuracy.

Without detailed long-term study, it is impossible to identify whether the absence of *A. pallipes* from a water body is due to local extinction or to historical absence. For this reason, presence/absence comparisons were not carried out in this study. Descriptive statistics (means and ranges) were produced and used to compare with European and global means in order to identify potential patterns in *A. pallipes*-inhabited waters.

RESULTS

Searches in Web of Science using the crayfish and water chemistry search string resulted in 155 hits. Thirty-two results remained after title- and abstract- level screening, and 23 following full text screening. A total of 23 articles were found to present water chemistry data for at least one variable in waters inhabited by *A. pallipes* across Europe (Wales, England,

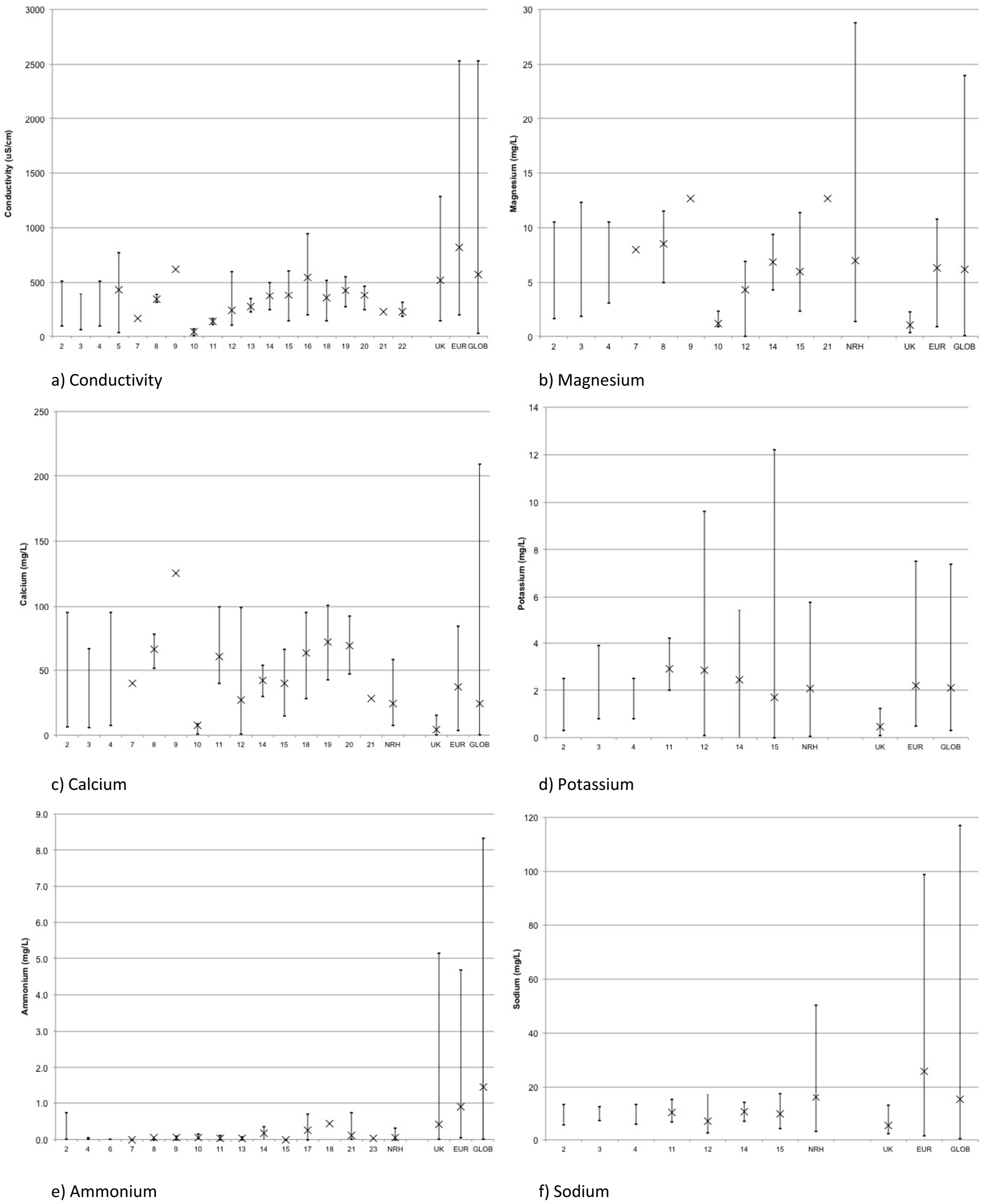


Figure 1

a-f. Cited levels (mean and range) of major water chemistry variables in waters inhabited by A. pallipes, along with means for European (ER) and worldwide (WR) rivers obtained from Berner and Berner (1996) and an independent review of the literature. See Figure 1m for author codes.

Ireland, France, Germany, Spain, Italy, Bosnia and Herzegovina and Croatia). Three studies referred to the species *Austropotamobius italicus*, which was reclassified from *Austropotamobius pallipes italicus* (Grandjean *et al.*, 2002). These studies have been included here because of the species' significant phylogenetic similarities (Grandjean *et al.*, 2002). One article modelled water chemistry variables in waters inhabited by *A. pallipes* but did not present the data or summary statistics and could therefore not be included (Favaro *et al.*, 2011). Means and/or maxima and minima were extracted from sources and are presented in Figure 1 (see Appendix 3 for summary data used in these figures).

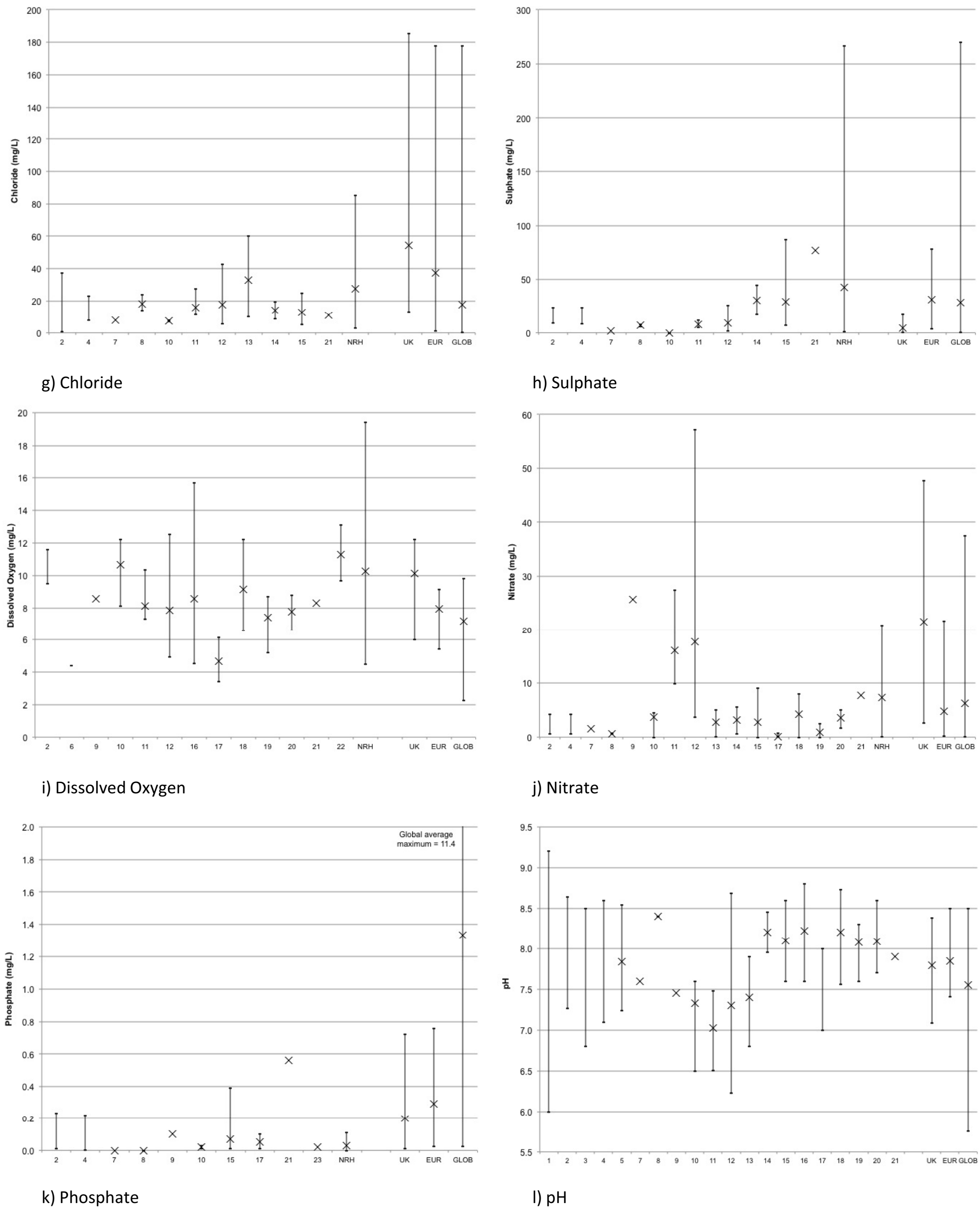
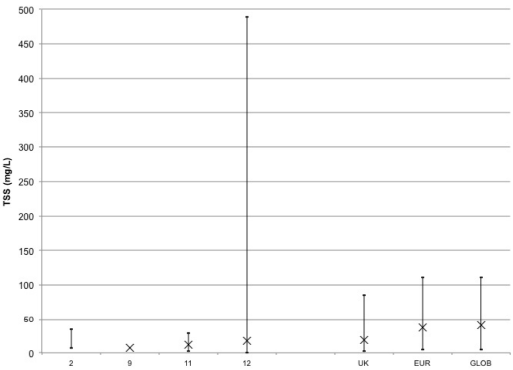


Figure 1
Continued. g-l. Cited levels (mean and range) of major water chemistry variables in waters inhabited by A. pallipes, along with means for European (ER) and worldwide (WR) rivers obtained from Berner and Berner (1996) and an independent review of the literature. See Figure 1m for author codes.

The data from the review of water chemistry for waters inhabited by *A. pallipes* are presented in Figure 1 and results of the water chemistry analysis of UK waters are presented in Table II.

> CONDUCTIVITY

All populations of *A. pallipes* reported in the literature lie in the lower range of conductivity reported for UK, global and European rivers (Figure 1a). Waters with conductivity above 700 $\mu S \cdot cm^{-1}$ are typically polluted or brackish/saline. Two studies reported levels in excess of



m) Total Suspended Solids (TSS)

Code	Author	Year	Country	Notes
1	Jay and Holdich	1981	Wales	
2	Foster	1995	Wales	
3	Lilley et al.	1979	England	
4	Smith et al.	1996	England	
5	Demers and Reynolds	2002	Ireland	
6	Lyons and Kelly-Quinn	2003	Ireland	
7	Arrignon and Roché	1983	France	
8	Arrignon et al.	1993	France	
9	Broquet et al.	2002	France	
10	Reyjol and Roquelpo	2002	France	
11	Trouilhé et al.	2003	France	
12	Trouilhé et al.	2007	France	
13	Troschel	1997	Germany	
14	Garcia-Arberas and Rallo	2000	Spain	Standard deviations instead of min/max
15	Rallo and Garcia-Arberas	2002	Spain	
16	Nardi et al.	2005	Italy	Austropotamobius italicus
17	Scalici and Gibertini	2005	Italy	
18	Renai et al.	2006	Italy	
19	Barbaresi et al.	2007	Italy	
20	Brusconi et al.	2008	Italy	Austropotamobius italicus
21	Favaro et al.	2010	Italy	
22	Trožic -Borovac	2011	Bosnia and Herzegovina	
23	Gottstein	1999	Croatia	Austropotamobius italicus
NRH	This study	2009	England	

Figure 1

Continued. m. Cited levels (mean and range) of major total suspended solids (TSS) in waters inhabited by A. pallipes, along with means for European (ER) and worldwide (WR) rivers obtained from Berner and Berner (1996) and an independent review of the literature. Author codes, years, and locations presented for preceding graphs.

this threshold; Demers and Reynolds (2002) in Ireland, and Nardi *et al.* (2005) in Italy (although, this was *A. italicus*).

> MAGNESIUM [Mg^{2+}]

The wide range of values of magnesium concentration in rivers inhabited by the white-clawed crayfish suggests little association with waters of specific magnesium concentration (*i.e.* high or low) (Figure 1b). For example, Broquet *et al.* (2002), Smith *et al.* (1996), and Favaro *et al.* (2010) found populations in waters of higher magnesium concentration than the ranges reported for European river means. These higher values lie within the range of global means for magnesium concentration, however. The results from our field survey concur with this lack of association, with minimum and mean values falling well within cited levels and major European river ranges. One site, Trench Pool, had extremely high magnesium (28.8 mg·L^{-1}). This site is known to suffer from urban pollution, despite possessing a substantial population of *A. pallipes* (pers. obs.). The site is an actively used fishing reservoir in an urban area of Trench, Shropshire. An old noticeboard at the entrance to the site warns users of the risks of blue-green algal blooms, but it is unknown whether this is a current or historic concern. However, other sites did not exceed 12 mg·L^{-1}.

> CALCIUM [Ca^{2+}]

A. pallipes populations have been found across the range of European means of calcium concentration. Some authors suggested that the species is associated with concentrations in the lower range of European means (Rallo and Garcia-Arberas, 2002; Reyjol and Roqueplo, 2002). Others, for example Broquet *et al.* (2002), noted crayfish in higher concentrations than the range of European means, but with values that fell within the range of global means.
It has been suggested that a lower limit of 5 mg·L^{-1} calcium concentration restricts the presence of *A. pallipes* (Greenaway, 1974), as supported by observations of Jay and Holdich (1981) and Smith *et al.* (1996) in the British Isles, and Trouilhé *et al.* (2007) in France. Furthermore, laboratory manipulations involving *Astacus astacus* by Rukke (2002) showed stunted

Table II
Results of water chemistry analysis for sites inhabited by A. pallipes in England (n.a. signifies concentrations below the minimum level of detection).

Site	Location	Type	Date	Chloride mg·L^{-1}	Nitrate mg·L^{-1}	Phosphate mg·L^{-1}	Sulphate mg·L^{-1}	Ammonium mg·L^{-1}	Sodium mg·L^{-1}	Potassium mg·L^{-1}	Magnesium mg·L^{-1}	Calcium mg·L^{-1}	DO mg·L^{-1}
Adel Beck	Leeds, West Yorkshire	Lotic	08/10/2009	33.70	13.85	0.032	92.26	0.023	17.09	2.90	9.94	30.37	8.58
Brasside Pond	Durham, County Durham	Lentic	28/07/2009	29.52	n.a.	0.012	54.25	0.005	17.79	4.97	10.01	25.80	
Broomlee Lough	Hexham, Northumberland	Lentic	30/07/2009	3.45	n.a.	0.006	2.07	0.023	3.10	0.14	1.38	12.86	
Coppice Pond	Bingley, West Yorkshire	Lentic	11/06/2009	16.85	0.24	0.006	24.60	0.013	12.17	1.04	3.35	7.71	
Cound Brook	Condover, Shropshire	Lotic	09/09/2009	20.20	14.77	0.110	21.74	0.035	13.34	2.89	7.80	30.91	11.97
Crook Burn	Hexham, Northumberland	Lotic	29/07/2009	3.98	0.66	0.009	3.35	0.080	4.05	0.15	2.92	21.29	
Dean Brook	Huddersfield, West Yorkshire	Lotic	18/07/2009	45.39	18.73	0.083	40.84	0.038	23.89	2.74	9.06	20.96	9.32
Halleypike Lough	Hexham, Northumberland	Lentic	28/07/2009	4.33	0.11	0.009	1.96	0.044	4.54	0.30	1.60	9.33	
Meanwood Beck	Leeds, West Yorkshire	Lotic	16/07/2009	37.14	5.39	0.046	69.78	0.033	24.35	2.85	10.44	34.56	8.40
Pinfold Dam	Huddersfield, West Yorkshire	Lentic	27/06/2009	29.69	16.63	0.013	109.54	0.096	17.11	2.54	8.03	23.98	19.40
River Derwent	Scarborough, North Yorkshire	Lotic	18/07/2009	20.36	11.56	0.026	35.88	0.235	13.91	2.71	2.99	30.70	4.49
River Kent	Kendal, Cumbria	Lotic	08/06/2009	12.81	5.15	0.022	12.41	0.036	8.52	1.07	3.08	23.50	9.97
River Redlake	New Invention, Shropshire	Lotic	10/09/2009	7.74	5.53	0.036	7.07	0.027	7.16	0.98	4.59	16.03	9.69
River Wansbeck	Rothley, Northumberland	Lotic	28/07/2009	17.69	3.45	0.070	19.28	0.043	10.58	1.04	7.79	37.43	
Robsheugh Burn	Milbourne, Northumberland	Lotic	27/07/2009	25.86	3.45	0.023	44.03	0.029	14.10	3.88	10.97	47.41	12.94
Simpson's Pool	Horsehay, Shropshire	Lentic	09/09/2009	10.06	n.a.	0.045	0.88	0.010	5.41	2.85	8.03	19.85	7.56
Trench Pool	Telford, Shropshire	Lentic	10/09/2009	53.54	n.a.	0.025	355.99	0.029	50.30	5.78	28.78	58.31	13.41
Wyke Beck	Leeds, West Yorkshire	Lotic	06/06/2009	49.81	5.41	0.017	47.08	0.050	27.51	2.48	10.53	27.11	7.57

growth and reduced survival below 5 mg·L^{-1} calcium compared to that at 10 mg·L^{-1}. However, one study found populations inhabiting rivers with calcium concentrations below 2.5 mg·L^{-1} (Reyjol and Roqueplo, 2002) and one as low as 1 mg·L^{-1} (Trouilhé *et al.*, 2003). Crayfish can, therefore, evidently survive below the proposed 5 mg·L^{-1} threshold. However, the majority of populations have been found at calcium concentrations greater than 5 mg·L^{-1} (Figure 1c) and lie close to the range of cited means for European rivers. Our results also show little evidence of association, being similar to major European rivers and many of the cited studies. The minimum calcium concentration found in the UK *A. pallipes*-inhabited sites in our study was 7.4 mg·L^{-1}, in accord with a lower limit of 5 mg·L^{-1}.

> POTASSIUM [K^+]

Populations of *A. pallipes* have been found in water with potassium concentrations similar to those of mean global and European waters (Figure 1d) with two studies finding populations associated with concentrations in the lower ranges of global and European means (Rallo and Garcia-Arberas, 2002; Trouilhé *et al.*, 2007). Given the wide range of potassium concentrations found in waters inhabited by *A. pallipes*, no association for specific potassium concentrations can be identified. Similarly, our field results found no evidence for an association of *A. pallipes* with specific potassium concentration, and resemble both major European and global rivers.

> AMMONIUM [NH_4^+]

A. pallipes populations have all been found in rivers containing low concentrations of ammonium relative to cited means for UK, European and global rivers (Figure 1e), although three studies reported much higher ranges than the others (Foster, 1995; Rallo and Garcia-Arberas, 2002; Favaro *et al.*, 2010). This may indicate an intolerance to high ammonium levels in accordance with known toxicity of the ion to aquatic organisms. However, the toxicity study of Meade and Watts (1995) suggests that crayfish may not be so sensitive to ammonium alone, but to the combined effects of ammonium and nitrate or nitrite. Our field study also found ammonium concentrations in crayfish-inhabited waters to lie in the lower range of UK, European and global rivers. Our mean ammonium concentration was highly influenced by one site, the River Derwent, with relatively elevated ammonium. However, this site was suffering from seasonal flooding, with rotting leaf litter the likely cause of raised ammonium concentrations (Baldy *et al.*, 2007).

> SODIUM [Na^+]

Populations of *A. pallipes* reported in the literate have only been found in the lower range values for European and global river means for sodium, as shown in Figure 1f. This may indicate a low tolerance for elevated sodium concentrations. However, UK river sodium levels reported by the Harmonised Monitoring Scheme are very similar to those reported for crayfish in the literature. Surprisingly, our field study found levels of sodium at 5/18 of the sites to be higher than previously cited levels for *A. pallipes*, and one site, Trench Pool, had levels well above the mean values for major European and global rivers.

> CHLORIDE [Cl^-]

Figure 1g shows that reported chloride concentrations of waters inhabited by *A. pallipes* in the literature lie around the average cited European and global river means, with no populations found in higher concentrations than 60 mg·L^{-1}. No clear patterns in association are obvious, other than a lack of populations in high chloride concentrations typical of polluted water. Our field results concur with this finding despite some populations occurring in concentrations above other published studies. Nevertheless, we found crayfish populations in waters with low chloride concentration relative to UK, European and global rivers.

> SULPHATE [SO_4^{2-}]

The majority of *A. pallipes* populations have been found inhabiting waters with sulphate concentrations lower than those reported for major European rivers (Figure 1h), with two notable exceptions; in Italy (Favaro *et al.*, 2010) and Spain (Rallo and Garcia-Arberas, 2002). Other studies appear to have found an association of the species with low concentrations of sulphate relative to European and global rivers, however (but similar to values reported in the Harmonised Monitoring Scheme). This suggests an association with low levels, but tolerance to moderately elevated sulphate concentrations. Our study found extremely high levels of sulphate in one site, Trench Pool, which has been shown to suffer from significant urban pollution. Another site, Pinfold Dam, also showed very high concentrations of sulphate (maximum of 113.9 $mg{\cdot}L^{-1}$).

> OXYGEN (DO)

Some populations of *A. pallipes* are found in waters of high oxygen levels (Figure 1i). However, several studies (*e.g.* Trouilhé *et al.*, 2007) also found populations to persist at concentrations lower than the means cited for European rivers. It appears that there may be a lower threshold for dissolved oxygen concentration below which crayfish are not found (*i.e.* c. 3–3.5 $mg{\cdot}L^{-1}$). Some sites within our study might suggest that *A. pallipes* is associated with elevated dissolved oxygen, but we also recorded low DO in some sites (*e.g.* 4.5 $mg{\cdot}L^{-1}$ in the River Derwent, which was flooded at the time, suggesting that low DO may have been temporary).

> NITRATE [NO_3^-]

The majority of *A. pallipes* populations have been found in waters below or close to the average UK, European and global river means for nitrate (Figure 1j). Three notable exceptions relative to European rivers have been documented, however. Broquet *et al.* (2002), Trouilhé *et al.* (2003) and Trouilhé *et al.* (2007) have reported some French populations of *A. pallipes* to inhabit waters with substantially higher nitrate concentrations than other authors. Our field survey found a range of nitrate concentrations in waters inhabited by *A. pallipes* very similar to those of European rivers. Five sites had nitrate concentrations greater than 10 $mg{\cdot}L^{-1}$, with three of these exceeding 15 $mg{\cdot}L^{-1}$.

> PHOSPHATE [PO_4^{3-}]

Figure 1k displays phosphate concentrations of waters inhabited by *A. pallipes*. Most populations have been found at low phosphate concentrations relative to UK and European rivers, but one study has found the species in concentrations at the higher end of UK and European river means in Italy (Favaro *et al.* , 2010). Our study found English populations in water with low phosphate concentration. Populations were found in a narrow range that lies below those found in some published studies.

> PH

A. pallipes populations are found in the literature across a range of pH values (*e.g.* pH 6.0 to 9.2 in Britain; Jay and Holdich, 1981) (Figure 1l). These values lie around the range of cited means for UK and European rivers, but lie in the higher range of means for global rivers. Populations were not found to occur in water of pH below 6.0.

> TOTAL SUSPENDED SOLIDS (TSS) AND SILTATION

Only four studies have investigated total suspended solids (TSS) levels in waters inhabited by *A. pallipes* (Figure 1m). Whilst three of these reported populations in levels lower than the average of European and global river means (Foster, 1995; Broquet *et al.*, 2002; Trouilhé *et al.*, 2003), one study found populations persisting in water with concentrations of TSS up to 489.3 mg·L^{-1} (Trouilhé *et al.*, 2007), far higher than the means found in a review of European and global river chemistry. This maximum refers to one site inhabited by crayfish. No information exists regarding the long term status of this population, and this level of TSS may be a result of habitat degradation. A laboratory study by Rosewarne *et al.* (2014) found that levels above 500 mg·L^{-1} resulted in gill fouling in all exposed crayfish (*A. pallipes*), whilst 250 mg·L^{-1} was associated with fouling in 92% of exposed individuals. However, the same study did not find any reduction in survival over 45 days in concentrations up to 1000 mg·L^{-1}, indicative of at least short-term tolerance for extremely high levels. The other six sites in the study lie well within the range of European river means. It therefore seems apparent that crayfish can persist in waters with a range of TSS. No conclusions, however, can be made about the adverse effects of siltation on *A. pallipes* distribution. Elevated TSS levels in waters inhabited by crayfish populations in France (Trouilhé *et al.* , 2007) are associated with elevated nitrate and potassium concentrations, and a lower range of pH values. This is indicative of more polluted waters, and lends support for some populations of *A. pallipes* persisting in lower water quality for certain variables.

DISCUSSION

A summary of the conclusions from the review and water chemistry analysis is shown in Table III. *A. pallipes* appears to be fairly tolerant to a range of conditions for of a number of water chemistry variables. Rallo and Garcia-Arberas (2002) carried out multivariate analyses of a variety of variables for waters inhabited and uninhabited by crayfish in Spain. From their analysis sulphate and magnesium ions were the only factors that discriminated between crayfish presence/absence. In contrast, the current study indicates that the magnesium concentration of waters inhabited by crayfish is similar to the range of European means, and is unlikely to influence the distribution of crayfish populations. Similarly, *A. pallipes* does appear to associate with lower sulphate values than those reported for major European rivers. From our review of the literature and our field study, some factors that may be associated with crayfish presence relative to European and global means are: low conductivity; low ammonium; low sodium; low sulphate; low nitrate; low phosphate; and high dissolved oxygen. These variables can be grouped into those relating to anthropogenic inputs and those important for ecdysis and the production of the crustacean exoskeleton.

> HUMAN-INFLUENCED WATER CHEMISTRY

Conductivity is a correlate for nutrient load, and can indicate geology, watershed size, and the presence of mine waste or waste water (Goldenberg *et al.*, 1984; García-Criado *et al.*, 1999; Gucht *et al.*, 2005). *A. pallipes* populations appear to be associated with low values of conductivity relative to European and global means. It is likely that the observed association

Table III
Summary of conclusions from review of literature regarding waters inhabited by A. pallipes and analysis of water samples from UK populations of the species.

Variable	Conclusion
Conductivity	Association with low levels (<500 $\mu S \cdot cm^{-1}$). Upper threshold of 945 $\mu S \cdot cm^{-1}$.
Magnesium	No clear association. Tolerance of high concentration (28.8 $mg \cdot L^{-1}$).
Calcium	No clear association. Populations present at low levels (1.0 $mg \cdot L^{-1}$).
Potassium	No clear association. Tolerance of high concentration (12.2 $mg \cdot L^{-1}$).
Ammonium	Association with low levels (<0.15 $mg \cdot L^{-1}$). Upper threshold of 0.74 $mg \cdot L^{-1}$.
Sodium	Association with low levels (<18 $mg \cdot L^{-1}$). Tolerance of high concentration (50.3 $mg \cdot L^{-1}$).
Chloride	No clear association. Upper threshold of 85.2 $mg \cdot L^{-1}$.
Sulphate	Possible association with low levels (<25 $mg \cdot L^{-1}$). Tolerance of high concentration (266.8 $mg \cdot L^{-1}$).
Dissolved Oxygen	Association with high levels. Lower threshold of 3.4 $mg \cdot L^{-1}$ plausible.
Nitrate	Possible association with low levels (<9 $mg \cdot L^{-1}$). Tolerance of high concentration (57.2 $mg \cdot L^{-1}$).
Phosphate	Association with low levels (<0.22 $mg \cdot L^{-1}$). Tolerance of moderate concentration (0.39 $mg \cdot L^{-1}$).
pH	No clear association. Only found between pH 6.0 and 9.2.
TSS	Possible association with low levels (<34 $mg \cdot L^{-1}$). Tolerance of high concentration (489 $mg \cdot L^{-1}$).

patterns reflect pollution, and that crayfish presence is also associated with low levels of other pollution-indicators.

Ammonium, a waste product of animal metabolism, is indicative of agricultural pollution resulting from fertiliser runoff and sewage and is toxic in high concentrations (Berner and Berner, 1996). *A. pallipes* is associated in general with low ammonium concentrations: 8 of 10 studies found populations restricted to concentrations below 0.15 $mg \cdot L^{-1}$.

The primary source of nitrate in freshwater ecosystems is surface runoff; from the application of fertilisers in agriculture, and runoff from waste disposal sites and industrial practices (Camargo *et al.*, 2005). Between one third (Meybeck, 1982) and two thirds (Wollast, 1993) of all riverine total dissolved nitrogen (NO_3^- and NH^{4+}) results from pollution. It is also generated *in situ via* the nitrification of ammonia in sewage (Abeliovich, 1985). Toxicity of nitrate ions has been shown to occur *via* the conversion of oxygen carrying pigments (haemoglobin and haemocyanin) to forms that are unable to carry oxygen (methaemoglobin and methaemocyanin) (Camargo *et al.* , 2005). Nitrate is less toxic to aquatic organisms than ammonia or nitrite (Romano and Zeng, 2007). Nevertheless, nitrate concentrations of 10 $mg \cdot L^{-1}$ are detrimental to some freshwater invertebrates, fish, and amphibians (reviewed by Camargo *et al.*, 2005). Laboratory studies of tolerance demonstrate the ability of crayfish to withstand short-term exposure to nitrate levels as high as 1000 $mg \cdot L^{-1}$ (Meade and Watts, 1995), but these findings to not directly relate to long term tolerance in the wild. Whilst some studies have found *A. pallipes* to be associated with low concentrations of nitrate in the wild, three published studies along with the results herein show that populations can persist in very high nitrate levels.

Phosphorus, in the form of the inorganic phosphate ion, plays a vital role in the structure of DNA/RNA, the structure of cells (as phospholipids), and in energy transfer (as adenosine triphosphate or ATP), and is often a limiting nutrient in rivers and lakes (Elser *et al.*, 2007). On the other hand, elevated phosphorous as a result of fertilisers, industrial pollution, and deforestation may lead to eutrophication, particularly in lentic waters (Schindler, 1971). *A. pallipes* populations are generally found in waters of low phosphate concentration relative to European river means and our field survey data concur with the majority of the literature to suggest that white-clawed crayfish are associated with low phosphate concentrations.

Chloride is linked with ammonium and sodium; elevated levels of all three variables are associated with polluted waters. Sodium is a vital component of all animal cells, being the primary cation of extracellular fluids. High sodium concentration, however, can cause elevated mortality and limit growth (Hamilton *et al.*, 1975; Heath, 1977). Sodium enters rivers *via* the weathering of halite (NaCl) and plagioclase ($NaAlSi_3O_8$) rocks, from cyclic (sea) salt, and a substantial amount from pollution, such as domestic and industrial sewage and road salt (Meybeck, 1979). Elevated sodium concentrations are associated with elevated chloride and ammonium levels, and are typical of polluted or saline waters. Chloride originates from a range of sources; (i) sea salt; (ii) halite (NaCl) weathering and subsequent dissolution; (iii) volcanic springs; (iv) saline crust dissolution in deserts; (v) pollution. It has been estimated that around 30% of chloride in the world's rivers is the result of pollution (Meybeck, 1979). Populations of *A. pallipes* appear to be correlated with low concentrations of both sodium and chloride; these observations are in accord with work suggesting that the species may be sensitive to pollution from sewage or industrial effluent (*e.g.* Reynolds *et al.*, 2002).

Sulphate is a common ion in freshwater environments, but is generally found at low concentrations. There are two major sources of sulphate in rivers; weathering of rocks produces approximately 33 percent (Berner and Berner, 1996) and pollution produces approximately 54 percent (Meybeck, 1979) of global sulphate. Sources of sulphate pollution include acid rain, dry fallout, and fertilisers, particularly in European rivers (Oden and Ahl, 1978). The majority of *A. pallipes* populations in Europe are found in waters with relatively low sulphate concentration relative to European and global means. Rallo and Garcia-Arberas (2002), however, found populations associated with a wider range of sulphate concentrations, similar to those of European river means. Similarly, our field study found populations of *A. pallipes* in urban areas in relatively high concentrations of sodium, suggesting that the species is not particularly sensitive to sodium pollution alone. However, the species is associated with lower sulphate levels, and hence lower pollution, but does not indicate intolerance for levels typically observed in rivers throughout Europe.

A number of crayfish species (for example, *Parastacus defossus* and *Procambarus clarkii*) have been observed living in the very low or anoxic conditions associated with muddy habitats and are, to an extent, physiologically adapted to low dissolved oxygen (DO) conditions (reviewed by McMahon, 2002). Relatively few studies have examined dissolved oxygen levels in waters inhabited by *A. pallipes*. Three studies found the species associated with high levels relative to European and global means, whilst Trouilhé *et al.* (2007) found crayfish across a wide range of DO concentrations. Our field results similarly demonstrate a wide range, but also support an association with elevated DO. The results of our review, however, may challenge the theoretical minimum dissolved oxygen tolerance of around 5 $mg \cdot L^{-1}$ (Trouilhé *et al.*, 2007). This suggests that whilst an association with raised DO may exist, the species is tolerant, to a certain degree, of lower values.

Elevated hydrogen ion concentration (*i.e.* low pH) is toxic to many freshwater invertebrates (*e.g.* Bell, 1970). Low pH is believed to result in reduced growth by impairing the conversion efficiency of food energy for use in growth (Lee *et al.*, 1983), and Seiler and Turner (2004) found growth rates of the North American crayfish *Cambarus bartonii* to be higher in neutral than in acidic waters. In laboratory studies, *C. bartonii* adults were found to have an LD50 at pH 2.43 (Distefano *et al.*, 1991). *A. pallipes* were shown in laboratory studies to suffer high mortality at pH less than 6.0 in long-term studies (Jay and Holdich, 1977). The studies reviewed herein indicate that *A. pallipes* is tolerant of pH from 6 to 9.2, although populations are generally associated with pH from 7.5 to 8.5.

In nature, higher levels of individual variables may be associated with other variables that together result in toxicity and elevated mortality. For example, crayfish may be tolerant of high concentrations of ammonium alone, but in rivers, elevated ammonium may be associated with raised levels of other pollutants such as heavy metals, nitrate, sulphate, sodium, and chloride, and with low levels of dissolved oxygen. Therefore, whilst some studies have found an association of *A. pallipes* with low values of certain water chemistry variables, it may be a combination of several pollution-indicating variables that limit the distribution of the species.

> EXOSKELETONS AND ECDYSIS

Magnesium is an essential element required in crustacean integuments, and is required for successful *ecdysis* (moulting) (Jussila *et al.*, 1995). The crustacean exoskeleton is composed of chitin encrusted with calcium carbonate, making calcium another important metal ion in crayfish development (Roer and Dillaman, 1984). Potassium is also used in animal physiology, including action potentials of neurons and membrane polarisation (Roer and Dillaman, 1984). Comparing magnesium values for waters inhabited by *A. pallipes* with those for European and global means suggests no discernable pattern. Whilst crustaceans have a requirement for magnesium, it is unlikely to be limiting in these environments. This is particularly indicated by the presence of crayfish in water with very low magnesium concentration.

Various authors have suggested a lower limit of 5 mg·L^{-1} calcium concentration (Greenaway, 1974), as supported by observations of Jay and Holdich (1981) in the British Isles, and Trouilhé *et al.* (2007) in France. Furthermore, laboratory manipulations involving *Astacus astacus* by Rukke (2002) showed stunted growth and reduced survival below 5 mg·L^{-1} calcium compared to that at 10 mg·L^{-1}. Survival of the Parastacid crayfish *Paranephrops zealandicus* was increased as the concentration of calcium in laboratory investigations exceeded 10 mg·L^{-1} (Hammond *et al.* , 2006). However, survival of crayfish has been observed in waters with calcium concentrations as low as 2 mg·L^{-1} for *Orconectes virilis* (France, 1987), and *A. astacus* (*e.g.* Jussila *et al.*, 1995). These observations suggest that calcium is not limiting crayfish distribution. Crayfish are found over a wide range of potassium concentrations and their distribution is therefore unlikely to be affected by potassium concentration within the rivers examined. However, extreme levels of potassium caused by pollution may still adversely affect crayfish. Further research is needed to rule this possibility out.

> RECOMMENDATIONS FOR CRAYFISH CONSERVATION

In general our results suggest that *A. pallipes* populations are restricted to habitats that do not receive significant sewage effluent or contamination: typically, waters low in conductivity, sodium, chloride, nitrate, ammonium, to a lesser extent sulphate, and high dissolved oxygen concentration. The water chemistry data reviewed and analysed in this study form only a snapshot of the chemical conditions. Whilst these data are likely to give an indication of long term conditions, water chemistry will vary over time. Caution must therefore be exercised when making conclusions from single time point measurements of both water chemistry and crayfish presence. Long term studies of chemical conditions and crayfish abundance are necessary to allow for conclusions to be made regarding suitable conditions for the maintenance of wild populations. Such studies have not been well documented in the literature, but they are of great importance. We strongly recommend that these records be established and made available for the wider conservation audience. Water chemistry is not the only factor affecting the distribution of *A. pallipes* populations, which has also become restricted in because of invasive crayfish and crayfish plague. An understanding of the association of white-clawed crayfish with specific water chemistry variables, however, can assist in locating suitable *Ark Site*s for the relocation of threatened populations.

At present, the conservation of endangered populations of *A. pallipes* in the UK is believed to heavily depend upon the success of relocation to *Ark Site*s (*e.g.* Kemp *et al.*, 2000; Whitehouse *et al.*, 2009; Haddaway, 2010). Based on the analysis of the papers reviewed here, we propose guidelines for suitable water chemistry of *Ark Site*s (Figure 3). Ideally, these recommendations should be supported by manipulation studies to investigate the impact of different water chemistry on crayfish survival, growth, and reproduction. This may not be easy, however, since the toxicity of single water chemistry variables may not relate to habitat associations in practice. For example, Figure 2 demonstrates how concentrations of variables are often linked in rivers, in this case in the River Wharfe. Sources of agricultural (site 3) and industrial/urban runoff (sites 14 and 15) are evidenced in all three variables shown. Furthermore, the need to identify suitable *Ark Sites* is pressing due to the rapid migration of invasive

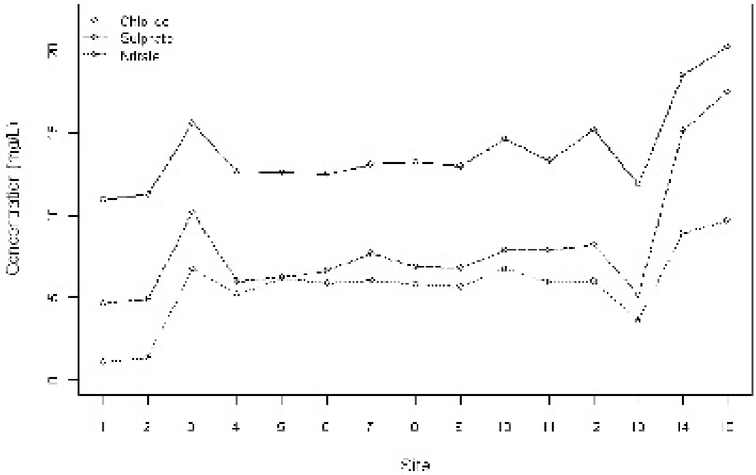


Figure 2
Concentration of chloride, sulphate, and nitrate in the River Wharfe from upstream (site 1) to 676 downstream (site 15) (E. Imhoff, R. Mortimer, and A. Dunn unpublished data).

crayfish and Chinese mitten crab, which has also recently been suggested as a possible vector for crayfish plague (*Aphanomyces astaci*) (Svoboda *et al.*, 2014), and on-going habitat degradation. In practice, it is often necessary to relocate threatened populations over short timescales.

In order to make recommendations to identify *Ark Site*s where water chemistry is suitable, data in this review and the results of field measurements were used to plot ranges of variables where crayfish occur and provide baselines that may form guidelines for water quality. Figure 3 displays these guidelines for water quality of *Ark Site*s by presenting variable ranges, grand means (means of study means), and the minima and maxima for study means (minimum mean and maximum mean). In order to be certain that water chemistry of an *Ark Site* is suitable, water chemistry should be measured and variables should fall within the narrower buffer zone, corresponding to the range of study means for variables measured within the literature. We believe that this represents a reliable buffer zone for acceptable water quality, since populations of *A. pallipes* have been recorded within these values.

CONCLUSIONS

This review and empirical study highlights several variables that may have thresholds dictating crayfish distribution. These variables are; conductivity, ammonium, sodium, dissolved oxygen and phosphate, and to a lesser extent sulphate, nitrate, and total suspended solids. There is substantial variability in many variables between studies and between sites in the same study. The presence of populations in the extremes of some variables may demonstrate a tolerance for certain types of pollution, for example urban pollution, but further investigation of these populations is paramount. Investigations of the water chemistry associations of *A. pallipes* populations have successfully characterised many waters containing the species. However, such studies are now highly unlikely to find water chemistry as a causative factor discriminating the presence and absence of crayfish. Population losses due to crayfish plague and competition with invasive non-native crayfish will overshadow all but drastic pollution events.

Whilst some populations of *A. pallipes* may persist over a wide range of certain variables, recommendations can be made for habitat restoration and relocation programs allowing the identification of habitats that are likely to be within acceptable ranges for threatened populations of white-clawed crayfish. The recommendations included herein are intended as a starting point for the selection of *Ark Site*s for relocation conservation.

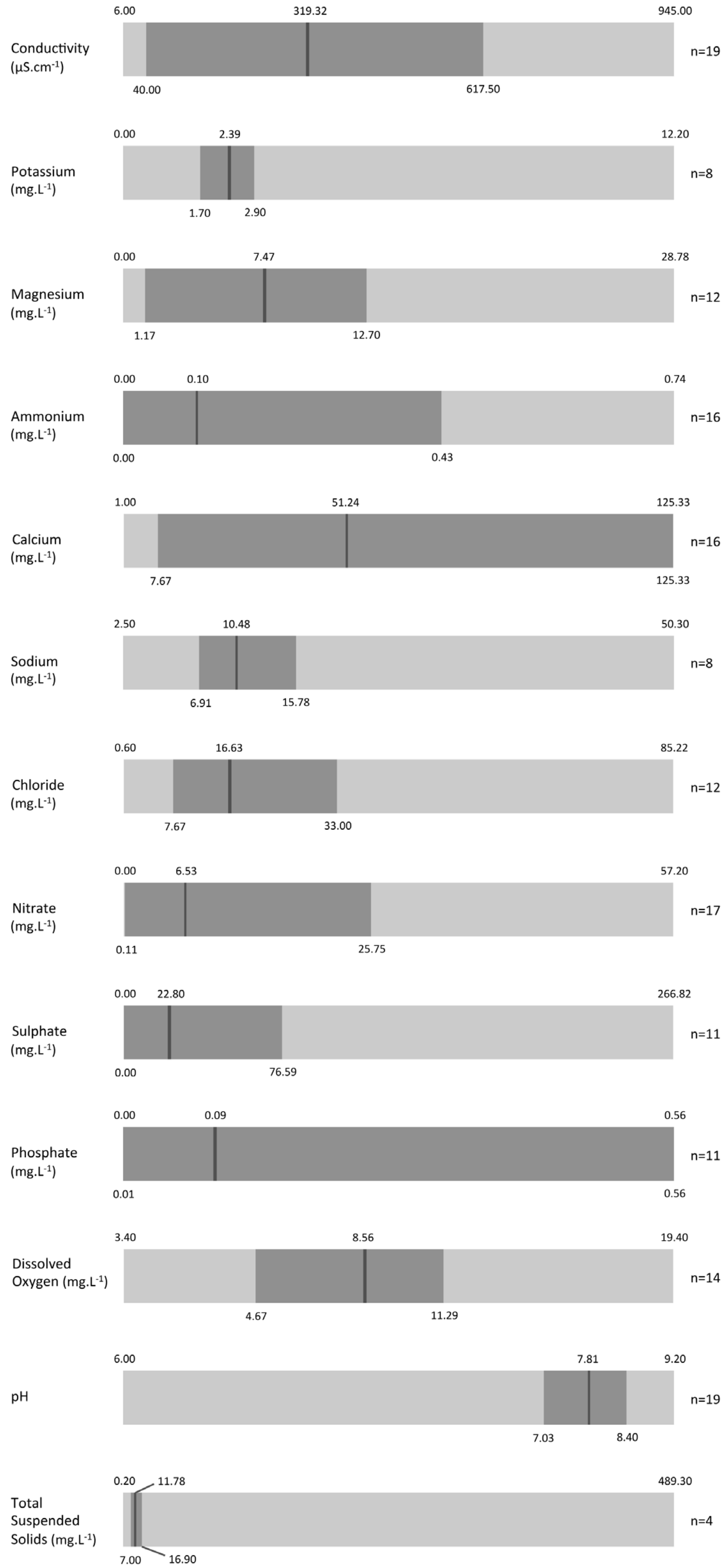


Figure 3

Recommended water quality guidelines for A. pallipes within the literature and from the study herein. The extremities (upper left and upper right numbers) represent the absolute ranges, the black bar (upper middle number) represent the mean mean values, and the intermediate values (lower left and lower right numbers) represent the mean minimum and mean maximum values respectively. All values are in mg·L^{-1} with the exception of conductivity (µS·cm^{-1}) and pH.

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Appendix 1.

	Ca++	Mg++	Na+	K+	Cl-	SO4--			my data	Reference	Citation	Cond. uS/cm	DO mg/L	Ammon. mg/L	Nitra. mg/L	TSS mg/L	pH	Phosph. mg/L
North America										Reference	Citation							
Colorado 1960s	83.0	24.0	95.0	5.0	82.0	270.0		W	Piracicaba River Basin streams, Brazil	Ometo et al. (2000)	Ometo, J. P. H., Martinelli, L.	124.36	6.87	0.294	2.15	43.83		
Columbia	19.0	5.1	6.2	1.6	3.5	17.1		W	Sierra Nevada streams, USA	Rehn (2009)	Rehn, A. C. (2009). Benthic m	27.16	7.625		0.046			
Mackenzie	33.0	10.4	7.0	1.1	8.9	36.1		E	Guadiana River, Spain	Urrea & Sabater (2009)	Urrea, G., & Sabater, S. (2009	702.92		0.85	5.49		7.98	
St. Lawrence 1870	25.0	3.5	5.3	1.0	6.6	14.2		W	Urauchi River, Japan	Ishiki et al. (2009)	Ishiki, M., Sakihama, H., Agat	98.4	9.8	0.0175	6.324			0.135
Yukon	31.0	5.5	2.7	1.4	0.7	22.0		W	Orinoco River, Venezuela	Mora et al. (2009)	Mora, A., Alfonso, J. A., Sánc	33.7				91.6	5.76	
Mississipi 1905	34.0	8.9	11.0	2.8	10.3	22.5		W	Nile, Egypt	Abdelhamid et al. (1992)	Abdel-Hamid, M. I., Shaaban-Dessouki, S. A., & Skulb			1.65				0.05612
Mississipi 1965-1967	39.0	20.7	17.0	2.8	19.3	50.3		W	Yamuna River, India	Kumar et al. (2009)	Kumar, M., Ramanathan, A. L., & Keshari, A. K. (2009). Understanding				37.56		7.36	11.38
Frazer	16.0	2.2	1.6	0.8	0.1	8.0		E	Reconquista River, Argentina	Olguin et al. (2004)	Olguín, H. F., Puig, A., Loez, C. R., Salibián, A., Topaliá			8.32				
Nelson	33.0	13.6	24.0	2.4	30.2	31.4		W	Adyar River, India	Venugopal et al. (2009)	Venugopal, T., Giridharan, L., Jayaprakash, M., & Velmurugan, P. M. (2009). A comprehensiv						7.735	
Rio Grande: Laredo	109.0	24.0	117.0	6.7	171.0	238.0		E	Aliakmon River, Greece	Gikas et al. (2009)	Gikas, G. D., Tsihrintzis, V. A.	371.7	5.4			108	8.5	
Ohio	33.0	7.7	15.0	3.6	19.0	69.0		E	Vatinsky River catchment, West Siberia	Moskovchenko et al. (2009)	Moskovchenko, D. V., Babushkin, A. G., & A		4.67	1.07	0.41	6.13	6.57	0.25
								E	North-Rhine Westphalia Rivers, Germany									
Europe								E	Ruhr	Stogbauer et al. (2008)	Stögbauer, A., Strauss, H., Ar	415.32	8.84		0.165	4.53	7.78	
Danube	49.0	9.0	(9)	(1)	19.5	24.0		W	Lippe			1354.14	8.59		0.315	5.35	7.97	
Upper Rhine: unpollu	41.0	7.2	1.4	1.2	1.1	36.0		E	Ems			2534.8	7.077		0.248	110.69	7.75	
Lower Rhine: pollute	84.0	10.8	99.0	7.4	178.0	78.0		E	River Hindon, India	Jain et al. (2008)	Jain, C. K., Gupta, H., & Chakrapani, G. J. (2		2.24		5.05		7.8	1.085
Norwegian Rivers	3.6	0.9	2.8	0.7	4.2	3.6		E	Douro River, Portugal	Azevedo et al. (2008)	Azevedo, I. C., Duarte, P. M.,	287.67	8.706	0.27		12.48	7.72	
Black Sea Rivers	43.0	8.6	17.1	1.3	16.5	42.0		E	Spanish Rivers	Moreno et al. (2006)	Moreno, J. L., Navarro, C., & I	671.9	9.125	0.059	1.64	8.675		0.024
Icelandic Rivers	3.9	1.5	8.8	0.5	4.4	4.8		E	UK Rivers	Neal et al. (2006)	Neal, C., Jarvie, H. P., Neal, M., Hill, L., & Wickham, H. (2006). Nitrate				21.69			
									Danube	Winter et al. (2007)	Winter, C., Hein, T., Kavka, G., Mach, R. L., & Farnleitn			0.0488	1.22		7.89	0.05167
South America									Adour River, France	Point et al. (2007)	Point, D., Bareille, G., Amouroux, D., Etcheber, H., & Donard, O. F. (2007). Reactivity, intera						7.41	
Upper Amazon:Peru	19.0	2.3	6.4	1.1	6.5	7.0			Upper Oder River, Poland (mg/L)	Absalon & Matysik (2007)	Absalon, D., & Matysik, M. (2007). Changes in water q			4.6875	3.4			0.6
Lower Amazon: Brazil	5.2	1.0	1.5	0.8	1.1	1.2			Irish Rivers n=273	Dodkins et al. (2005)	Dodkins, I. A. N., Rippey, B.,	196			0.42	6.15	7.6	0.03
Lower Negro	0.2	0.1	0.4	0.3	0.3	0.2			Seinne, Somme, Scheldt Rivers (France)	Thieu et al. (2009)	Thieu, V., Billen, G., & Garnier, J. (2009). Nutrient trar			0.112	13.67			0.3007
Madeira	5.6	0.2	2.6	1.6	0.8	5.6			Axios/Vardar River (SE Europe)	Milovanovic (2007)	Milovanovic, M. (2007). Water quality assessment an			0.24				0.7554
Parana	5.4	2.4	5.5	1.8	5.9	3.2												
Magdalene	15.0	3.3	8.3	1.9	(13.4)	14.4			Global									
Guyana Rivers	2.6	1.1	2.6	0.8	3.9	2.0			Mean	568.17		7.18	1.47	6.24	39.74	7.56	1.333	
Orinoco	3.3	1.0	(1.5)	(0.65)	2.9	3.4			Minimum	27.16		2.24	0.02	0.05	4.53	5.76	0.024	
									Maximum	2534.80		9.80	8.32	37.56	110.69	8.50	11.380	
Africa									n	12		11	10	16	10	14	11	
Zambeze	9.7	2.2	4.0	1.2	1.0	3.0			SE	219.49		0.77	0.83	2.69	15.32	0.18	1.010	
Congo (Zaire)	2.4	1.4	2.0	1.4	1.4	1.2												
Ubangui	3.3	1.4	2.1	1.6	0.8	0.8			European									
Niger	4.1	2.6	3.5	2.4	1.3	(1)			Mean	816.81		7.96	0.90	4.83	36.55	7.84	0.29	
Nile	25.0	7.0	17.0	4.0	7.7	9.0			Minimum	196		5.4	0.04878	0.165	4.53	7.41	0.024	
Orange	18.0	7.8	13.4	2.3	10.6	7.2			Maximum	2534.8		9.125	4.6875	21.69	110.69	8.5	0.7554	
									n	8		6	6	10	7	9	6	
Asia									SE	419.25		1.37	0.83	2.57	20.28	0.25	0.17	
Brahmaputra	14.0	3.8	2.1	1.9	1.1	10.2												
Ganges	25.4	6.9	10.1	2.7	5.0	8.5												
Indus	26.4	5.6	9.0	2.0	7.1	26.4												
Mekong	14.2	3.2	3.6	2.0	(5.3)	3.8												
Japanese Rivers	8.8	1.9	6.7	2.2	5.8	10.6												
Indonesian Rivers	5.2	2.5	3.8	1.0	3.9	5.8												
New Zealand Rivers	8.2	4.6	5.6	0.7	5.8	6.2												
Yangtze (Changjiang)	30.2	7.4	7.6	1.5	9.1	11.5												
Yellow (Hwanghe)	42.0	17.7	55.6	2.9	46.9	71.7												
Ob	21.0	5.0	4.0	3.0	10.0	9.0												
Yenisei	21.0	4.1	2.3	w.Na	9.0	8.6												
Lena	17.1	5.1	5.2	w.Na	12.0	13.6												
Philippines	31.0	6.6	10.4	1.7	2.9	13.6												
European																		
Mean	37.4	6.3	25.8	2.2	37.3	31.4												
Minimum	3.6	0.9	1.4	0.5	1.1	3.6												
Maximum	84.0	10.8	99.0	7.4	178.0	78.0												
n	6.0	6.0	6.0	6.0	6.0	6.0												
SE	13.6	1.8	16.9	1.2	31.4	12.5												
Worldwide																		
Mean	24.2	6.2	14.9	2.1	17.6	28.5												
Minimum	0.2	0.1	0.4	0.3	0.1	0.2												
Maximum	109.0	24.0	117.0	7.4	178.0	270.0												
n	44.0	44.0	44.0	44.0	44.0	44.0												
SE	3.2	0.8	3.6	0.2	5.6	5.9												

Appendix 2.

Annual average concentrations of selected determinands of river water quality, by river location: 1980, 1990 and 1995 - 2005

		pH	Cond	TSS	D.O.	Amm	Nitrate	Chloride	Sodium	Magnesi	Potassiu	Phospha	Calcium	Sulphate
Great Britain		Average levels 1980, 1990, and 1995-2005												
Region														
	North West; Mersey, Howle	**7.3**	**602.3**	**19.3**	**8.0**	**2.5**	**21.4**	**74.4**			available from; http://maps.environment-agency.gov.uk			
	North West; Ribble, Samle	**8.1**	**490.8**	**19.4**	**11.1**	**0.1**	**24.3**	**61.5**			See Sheet 2 for details			
	North East; Tees, Low Wo	**7.8**	**359.5**	**10.4**	**9.7**	**0.1**	**14.8**	**30.0**						
	North East; Tyne, Wylam	**7.8**	**214.0**	**9.2**	**11.1**	**0.2**	**3.8**	**18.4**						
	North East; Aire, Beal Wei	**7.5**	**813.7**	**19.0**	**9.1**	**1.1**	**27.3**	**115.1**						
	North East; Don, Doncaste	**7.6**	**953.7**	**20.1**	**9.5**	**1.3**	**33.8**	**125.0**						
	Midlands; Trent, Yoxall	**8.0**	**929.2**	**15.7**	**10.0**	**0.2**	**40.3**	**105.8**						
	Midlands; Severn, Haw Bri	**8.0**	**573.1**	**49.3**	**10.3**	**0.1**	**28.4**	**57.0**						
	Anglian; Bedford Ouse, Ea	**8.3**	**896.7**	**17.0**	**10.7**	**0.1**	**35.2**	**74.0**						
	Thames; Thames, Tedding	**8.0**	**597.6**	**16.8**	**10.3**	**0.2**	**31.6**	**50.4**						
	Southern; Medway, Upstre	**7.8**	**477.3**	**21.2**	**9.5**	**0.1**	**23.2**	**45.7**						
	South West; Tamar, Gunni	**7.6**	**188.4**	**19.1**	**10.5**	**0.1**	**12.6**	**23.0**						
	South West; Exe, Thorvert	**7.7**	**160.3**	**9.9**	**10.9**	**0.0**	**11.4**	**15.9**						
	Welsh; Dee, Iron Bridge	**7.6**	**259.2**	**9.8**	**10.3**	**0.1**	**9.4**	**30.3**						
	Welsh; Taff, Llandaff North	**7.9**	**303.6**	**14.2**	**11.1**	**0.1**	**6.4**	**20.5**						
		pH	Cond	TSS	D.O.	Amm	Nitrate	Chloride	Sodium	Magnesi	Potassiu	Phospha	Calcium	Sulphate
	Mean	**7.79**	**515.74**	**18.03**	**10.13**	**0.42**	**21.57**	**54.49**	5.25	0.99	0.46	**0.20**	4.32	4.33
		7.09	142.83	2.72	6.01	0.02	2.68	13.35	2.38	0.32	0.11	**0.01**	0.44	0.41
	max	8.38	1289.04	85.70	12.20	5.14	47.64	185.33	12.79	2.20	1.25	**0.72**	15.48	17.13
Source: Harmonised Monitoring S		from DEFRA	DEFRA	DEFRA	DEFRA	DEFRA	DEFRA	DEFRA	from CE	from CE	from CE	from Env	from CE	from CEH

1 Annual mean concentrations. Values below the limit of detection have been equated to one half the detection limit.

Table nomencla	**Full name of determinanc**	**Units**	**Full name of determinand**
Temp	Temperature	Degrees C	Ammoniacal nitrogen
pH	pH	pH Units	Nitrite
Cond	Conductivity	US/cm	Nitrate
S.S.	Suspended solids	mg/l	Chloride
Ash	(from suspended solids)	mg/l	Total alkalinity
D.O.	Dissolved oxygen	mg/l O	Chlorophyll alpha
BOD	Biochemical Oxygen Dema	mg/l O	Orthophosphate
	(Allythiourea)		Anionic detergent as
			manoxol OT

Source publication: e-Digest of Environmental Statistics, Published January 2007
Department for Environment, Food and Rural Affairs
http://www.defra.gov.uk/environment/statistics/index.htm

Appendix 2. Continued.

SITENAME	SDATE	pH	TSS	Conductivity	DO	Ammonium	Nitrate	Chloride	Phosphate	Sulphate	Sodium	Potassium	Calcium	Magnesium
Esthwaite	2004-01-01	7.58			10.78	0.02	0.48		0.01					
Windermere	2001-01-01	7.43		65.06	10.63	0.01	0.40	6.58	0.00	4.06	4.18	0.49	5.31	0.87
Llyn Llagi	2003-01-01	5.80		25.65			0.05	5.90	0.00	2.05	3.58	0.14	0.91	0.51
Esthwaite	2002-01-01	7.52		98.50	10.34	0.03	0.49	10.03	0.01	0.56	5.94	0.97	10.39	1.35
Windermere	2003-01-01	7.70			10.97	0.01	0.29	6.60	0.00	0.44	4.52	0.50	6.25	1.01
Llyn Llagi	2002-01-01	5.72		27.00			0.06	7.48	0.00	1.93	4.00	0.16	0.86	0.56
Windermere	1997-01-01	7.45		70.36	10.10	0.03	0.47	7.98	0.02	4.90	4.36	0.72	5.58	0.89
Windermere	1996-01-01	7.27		72.25	10.59	0.05	0.61	7.67	0.03	5.32	4.71	0.56	6.08	0.94
Esthwaite	1996-01-01	7.30		113.42	10.61	0.06	0.79	11.27	0.00	7.94	7.13	1.11	10.76	1.40
Llyn Llagi	1994-01-01	5.23		23.93			0.09	4.83	0.01	2.65	2.93	0.36	0.77	0.40
Bush	1994-01-01	8.08	5.01	329.24	10.27	0.06	1.79	23.73	0.09	14.24				
Old Lodge	2002-01-01	5.05		86.50			0.27	17.87	0.01	6.78	9.37	0.79	2.70	1.48
Bush	1996-01-01	7.91	7.16	322.43	11.18	0.11	2.83	24.51	0.09	17.10				
Old Lodge	1998-01-01	4.63		90.42			0.11	18.63	0.00	8.79	9.83	0.66	2.53	1.41
Nant Teyrn	1998-01-01	4.91		22.62		0.02	0.14	5.36	0.00	0.76	3.17	0.19	0.63	0.41
Trout Beck	2002-01-01	6.96	2.68	72.39		0.04	0.06	3.46	0.00	1.35	2.98	0.33	11.35	0.93
Trout Beck	2003-01-01	6.94	1.43	94.96		0.05	0.11	4.12	0.00	2.17	3.03	0.40	15.48	1.26
Scoat Tarn	2000-01-01	5.08		29.25			0.20	5.55	0.00	2.38	3.20	0.23	0.47	0.48
Llyn Llagi	2001-01-01	6.05		14.50			0.05	3.80	0.00	1.83	2.60	0.13	0.75	0.40
Windermere	1998-01-01	7.20		68.84	10.49	0.05	0.51	7.25	0.03	4.38	4.75	0.57	5.48	0.94
Esthwaite	1998-01-01	7.48		107.58	10.25	0.03	0.68	10.30	0.01	6.33	6.25	0.99	10.16	1.35
Llyn Llagi	1997-01-01	5.52		25.25			0.09	5.93	0.00	2.55	3.43	0.13	0.94	0.50
Scoat Tarn	1989-01-01	5.01		33.75			0.26	6.58	0.00	2.75	3.78	0.38	0.66	0.55
Scoat Tarn	1991-01-01	4.85		40.33			0.41	8.10	0.00	3.23	4.53	0.34	0.85	0.68
Scoat Tarn	2001-01-01													
Scoat Tarn	2002-01-01	5.06		28.75			0.24	5.30	0.00	2.38	2.85	0.24	0.47	0.47
Esthwaite	2001-01-01	7.66		102.19	10.50	0.03	0.42	9.31	0.01	5.76	5.68	0.94	9.38	1.24
Windermere	2000-01-01	7.50		64.85	11.01	0.14	0.32	7.30	0.03	3.92	4.31	0.45	5.46	0.91
Scoat Tarn	2004-01-01	5.15		26.75			0.20	4.83	0.00	2.40	2.63	0.20	0.46	0.43
Windermere	1999-01-01	7.39		65.70	10.82	0.05	0.46	7.31	0.04	4.76	4.45	0.52	5.53	0.94
Llyn Llagi	1996-01-01	5.53		24.50			0.25	5.75	0.00	3.28	3.53	0.13	1.11	0.58
Scoat Tarn	1996-01-01	5.04		32.25			0.46	5.10	0.00	2.93	3.25	0.26	0.62	0.53
Llyn Llagi	2004-01-01	5.86		25.00			0.09	5.48	0.01	1.78	2.85	0.11	0.82	0.44
Esthwaite	1995-01-01	7.23		103.18	9.91	0.05	0.68	11.32	0.00	7.10	6.02	0.94	10.12	1.29
Llyn Llagi	1998-01-01	5.52		22.75			0.12	6.95	0.00	2.38	3.65	0.13	0.90	0.53
Llyn Llagi	1999-01-01	5.62		27.75			0.12	7.45	0.00	2.38	4.08	0.16	0.98	0.58
Scoat Tarn	1993-01-01	5.01		31.50			0.19	5.90	0.00	3.10	3.45	0.23	0.57	0.53
Scoat Tarn	1992-01-01	5.02		33.05			0.27	6.13	0.00	2.93	3.50	0.25	0.62	0.55
Scoat Tarn	1998-01-01	5.02		31.75			0.26	6.18	0.00	2.88	3.43	0.27	0.57	0.50
Llyn Llagi	2006-01-01	5.81		25.00			0.11	5.53	0.01	1.96	3.10	0.13	0.88	0.48
Llyn Llagi	2005-01-01	5.75		27.00			0.06	6.40	0.01	1.93	3.40	0.11	0.86	0.49
Windermere	1994-01-01	7.12		67.30	10.67	0.00	0.50	7.57	0.04	5.28	4.51	0.53	5.74	0.91
Scoat Tarn	1995-01-01	5.03		35.50			0.36	6.38	0.00	2.78	3.70	0.32	0.64	0.60
Llyn Llagi	1990-01-01	5.20		46.25			0.18	10.73	0.03	3.18	5.55	0.38	1.49	0.75
Scoat Tarn	1994-01-01	5.09		31.50			0.21	5.63	0.00	3.00	3.33	0.35	0.56	0.50
Windermere	2004-01-01	7.41			10.68	0.01	0.40		0.00					
Esthwaite	2003-01-01	7.58		101.25	10.71	0.03	0.38	9.62	0.01	0.67	6.46	0.96	11.12	1.44
Esthwaite	2000-01-01	7.56		99.28	10.72	0.04	0.32	10.09	0.05	5.66	5.78	0.88	9.70	1.30
Scoat Tarn	2003-01-01	5.22		26.50			0.22	4.78	0.00	2.48	2.83	0.24	0.54	0.49
Esthwaite	1994-01-01	7.27		112.63	10.38	0.06	0.43	10.21	0.00	6.88	5.83	0.89	9.94	1.30
Scoat Tarn	1999-01-01	5.07		30.75			0.25	6.03	0.00	2.53	3.38	0.22	0.52	0.50
Scoat Tarn	1990-01-01	4.91		44.08			0.27	9.45	0.00	3.20	5.05	0.38	0.82	0.73
Llyn Llagi	1992-01-01	5.17		30.08			0.19	6.43	0.01	2.90	3.70	0.15	0.96	0.53
Llyn Llagi	1989-01-01	5.40		35.75			0.16	7.30	0.03	2.93	4.08	0.47	1.06	0.60
Llyn Llagi	1993-01-01	5.28		28.30			0.11	5.68	0.02	3.15	3.43	0.15	1.00	0.53
Scoat Tarn	1997-01-01	5.07		32.25			0.25	6.18	0.00	2.88	3.53	0.25	0.45	0.60
Scoat Tarn	2006-01-01	5.16		27.00			0.19	4.70	0.00	2.37	2.65	0.20	0.44	0.43
Windermere	2002-01-01	7.44		63.35	10.68	0.01	0.37	6.55	0.00	0.41	4.20	0.47	5.73	0.91
Scoat Tarn	2005-01-01	5.12		33.00			0.20	6.35	0.00	2.23	3.40	0.22	0.52	0.52
Llyn Llagi	2000-01-01	5.59		26.00			0.05	5.10	0.00	1.98	3.03	0.13	0.75	0.50
Esthwaite	1999-01-01	7.63		104.12	10.33	0.02	0.44	10.64	0.01	6.13	6.40	0.97	10.19	1.37
Windermere	1995-01-01	7.16		69.91	9.98	0.02	0.36	8.10	0.03	5.10	4.75	0.60	5.88	0.96
Llyn Llagi	1995-01-01	5.60		32.00			0.11	7.23	0.00	2.80	4.10	0.15	1.06	0.58
Llyn Llagi	1991-01-01	5.16		39.23			0.11	8.65	0.01	3.35	4.63	0.19	2.15	0.65
Old Lodge	2003-01-01	5.13		92.75			0.11	18.44	0.01	9.78	10.47	0.91	3.07	1.65
Old Lodge	1991-01-01	4.56		116.68			0.08	21.50	0.00	14.29	10.77	0.79	3.24	1.84
Nant Teyrn	2002-01-01	5.38		24.43		0.07	0.10	6.08	0.00	0.70	3.47	0.19	0.67	0.45

Appendix 2. Continued.

SITENAME	SDATE	pH	TSS	Conductivity	DO	Ammonium	Nitrate	Chloride	Phosphate	Sulphate	Sodium	Potassium	Calcium	Magnesium
Nant Teyrn	2007-01-01	5.41	1.69	22.70					0.01	2.00				
Bimie Burn	1994-01-01	6.69		63.07		0.02	0.10	7.99	0.01	2.11	6.89	0.68	5.08	1.56
Bimie Burn	1997-01-01	6.87		60.68		0.03	0.14	8.63	0.01	1.82	6.81	0.48	4.59	1.44
Bimie Burn	2001-01-01	6.80		70.92		0.01	0.14	7.29	0.01	1.79	6.20	0.47	4.32	1.36
Old Lodge	1999-01-01	4.83		90.75			0.09	18.50	0.00	8.56	9.67	0.60	2.76	1.54
Trout Beck	2005-01-01	7.31	2.81	80.13		0.03	0.10	3.98	0.00	1.31	2.60	0.34	12.16	0.96
Nant Teyrn	2001-01-01	5.44		19.51		0.03	0.12	4.16	0.00	0.67	2.59	0.18	0.59	0.34
Trout Beck	1995-01-01	6.09		86.63		0.02	0.15	4.18	0.00	1.98	2.87	0.37	13.29	1.13
Nant Teyrn	2003-01-01	5.56		26.63		0.04	0.10	5.06	0.01	0.71	2.86	0.21	0.63	0.38
Nant Teyrn	2004-01-01	5.55		23.94		0.03	0.09	4.68	0.02	0.66	2.64	0.17	0.56	0.35
Nant Teyrn	2005-01-01	5.41		25.80		0.04	0.10	5.19	0.01	0.69	2.83	0.19	0.57	0.37
Bimie Burn	2006-01-01	7.05		66.52	11.22	0.02	0.20	6.85	0.01	1.86	6.38	0.48	4.35	1.36
Bimie Burn	2007-01-01	7.01		63.13		0.02	0.19	6.37	0.01	1.52	6.67	0.44	4.28	1.34
Trout Beck	1994-01-01	6.09		75.57		0.01	0.11	4.34	0.00	1.56	2.49	0.34	10.89	0.83
Nant Teyrn	1999-01-01	4.98		20.97		0.02	0.15	5.17	0.00	0.68	2.86	0.20	0.58	0.37
Old Lodge	2005-01-01	5.16		92.00			0.10	19.52	0.00	7.64	10.23	0.86	2.85	1.57
Old Lodge	1988-01-01	4.52		77.17				20.17	0.01	9.30	10.43	0.46	2.76	1.68
Old Lodge	1993-01-01	4.60		91.83			0.10	17.40	0.00	11.02	9.46	0.74	2.71	1.49
Old Lodge	1994-01-01	4.66		87.50			0.06	17.39	0.00	8.87	9.23	0.68	2.44	1.34
Bush	1995-01-01	7.93	7.40	309.25	10.85	0.13	1.93	24.99	0.09	15.57				
Old Lodge	1996-01-01	4.60		108.33			0.14	19.51	0.00	12.10	10.68	1.02	3.00	1.78
Bimie Burn	2005-01-01	7.01		66.89	10.49	0.02	0.17	6.80	0.01	1.61	6.22	0.41	4.22	1.34
Trout Beck	2000-01-01	6.78	1.94	69.44		0.01	0.08	3.50	0.00	1.07	2.74	0.28	10.20	0.85
Nant Teyrn	2006-01-01	5.48	1.50	22.49					0.01	1.87				
Trout Beck	2006-01-01	7.15	1.63	76.22		0.02	0.09	3.60	0.00	1.33	2.46	0.30	11.40	0.91
Bimie Burn	1998-01-01	6.95		46.00		0.04	0.16	8.45	0.03	1.77	6.27	0.49	3.65	1.25
Trout Beck	1993-01-01	6.93		44.48		0.00	0.13	4.93	0.00	1.65	2.80	0.35	10.65	0.94
Bimie Burn	1999-01-01	7.05		51.65		0.02	0.15	8.07	0.00	1.78	6.56	0.49	4.23	1.37
Bush	1998-01-01	7.83	7.14	314.12	11.59	0.10	3.19	25.82	0.10	14.57				
Old Lodge	1997-01-01	4.57		102.17			0.12	19.43	0.00	10.05	9.86	0.85	2.65	1.55
Bimie Burn	1993-01-01	6.58		65.71		0.02	0.11	7.86	0.01	1.85	6.10	0.70	3.94	1.29
Bimie Burn	2003-01-01	6.94		76.98		0.01	0.17	7.59	0.01	1.97	6.67	0.45	5.12	1.51
Bush	1997-01-01	8.02	6.71	318.28	11.60	0.07	2.77	27.05	0.10	17.11				
Old Lodge	2006-01-01	5.02		113.55			0.11	26.33	0.00	8.20	12.22	1.04	2.87	1.63
Bimie Burn	2004-01-01	6.72		63.04		0.01	0.14	7.12	0.00	1.75	6.15	0.35	3.89	1.25
Old Lodge	1992-01-01	4.54		102.42			0.10	19.74	0.00	11.29	9.93	0.78	2.84	1.58
Old Lodge	2001-01-01	5.13		84.18			0.10	17.08	0.01	6.66	9.45	0.76	2.66	1.35
Trout Beck	2007-01-01	6.88		74.84		0.02	0.08	4.27	0.00	1.05	2.83	0.29	10.97	0.87
Bimie Burn	1996-01-01	6.77		58.12		0.01	0.16	8.33	0.00	2.03	6.75	0.47	4.36	1.47
Bimie Burn	2000-01-01	6.69		53.36		0.02	0.11	7.25	0.00	1.61	5.95	0.45	3.81	1.25
Trout Beck	1996-01-01	5.95		89.21		0.03	0.24	4.53	0.00	1.79	3.06	0.38	12.34	1.11
Bimie Burn	2002-01-01	6.73		58.83		0.01	0.12	6.73	0.01	1.65	5.68	0.35	3.91	1.20
Old Lodge	1990-01-01	4.45		128.51				23.85	0.01	17.13	12.79	0.73	3.94	2.20
Old Lodge	1995-01-01	4.62		112.67			0.09	20.52	0.00	11.64	11.38	0.75	3.10	1.78
Trout Beck	2004-01-01	6.78	3.73	64.69		0.03	0.07	3.44	0.00	1.07	2.38	0.30	10.26	0.80
Trout Beck	2001-01-01	7.18	2.36	78.65		0.03	0.08	3.30	0.00	1.25	2.84	0.33	11.76	0.96
Old Lodge	2000-01-01	4.90		84.25			0.11	17.87	0.00	8.07	9.36	0.80	2.80	1.75
Old Lodge	2004-01-01	5.00		97.08			0.11	19.80	0.00	9.75	9.54	0.80	2.95	1.59
Old Lodge	1989-01-01	4.55		104.36				24.06	0.01	15.00	12.49	0.76	3.76	2.14
Nant Teyrn	2000-01-01	5.25		19.79		0.02	0.12	4.26	0.00	0.67	2.47	0.18	0.52	0.32
Trout Beck	1997-01-01	6.11	2.29	84.07		0.02	0.16	4.17	0.00	1.40	2.87	0.34	12.36	1.05
Trout Beck	1999-01-01	7.03	1.63	75.42		0.02	0.09	4.44	0.00	1.21	2.90	0.35	10.88	0.93
Trout Beck	1998-01-01	6.14	1.61	61.33		0.02	0.11	4.18	0.00	1.14	2.59	0.27	9.07	0.79
Bimie Burn	1995-01-01	6.81		60.61		0.02	0.10	7.69	0.01	2.07	6.71	0.53	4.55	1.45
Esthwaite	1997-01-01	7.45		108.33	10.41	0.05	0.66	11.40	0.01	7.25	6.17	1.25	9.90	1.32
		pH	TSS	Conductivity	DO	Ammonium	Nitrate	Chloride	Phosphate	Sulphate	Sodium	Potassium	Calcium	Magnesium
1988-2007	**mean**	6.08	3.46	71.62	10.65	0.03	0.31	9.52	0.01	4.33	5.25	0.46	4.32	0.99
NI and Sco	**min**	4.45	1.43	14.50	9.91	0.00	0.05	3.30	0.00	0.41	2.38	0.11	0.44	0.32
9 lakes and	**max**	8.08	7.40	329.24	11.60	0.14	3.19	27.05	0.10	17.13	12.79	1.25	15.48	2.20

Appendix 3.

Conductivity	UK	Jay and	Foster (	Lilley e	Smith	Demers	Lyons a	Arrign	Arrign	Brogu	Reviol a	Trouilh	Trouill	Troschel (	Garcia-/	Rallo a	Nardi e	Scalici	Renai et al.	Barba	Brusco	Favaro	Trožic	Gottste	This stu n
Minimum	142.83		93	60	93	37			310		6	110	101	225	245	144	197		141	271	245.4		180		
Mean	**515.74**					427		160	335	618	40	138.5	233	272	372	376	540.8		350	424	373.3	225	225.4		
Maximum	1289.04		507	390	507	772			385		66	161	596	345	499	607	945		514	552	466		310		
Potassium	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	0.11		0.3	0.8	0.8							2	0.1		0	0.01									0.067
Mean	0.46											2.9	2.8		2.44	1.7									2.062
Maximum	1.25		2.5	3.9	2.5							4.2	9.6		5.4	12.2									5.784
Magnesium	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	0.32		1.6	1.8	3				5		0.9		0		4.31	2.3									1.381
Mean	0.99							8	8.5	12.7	1.2		4.3		6.84	6						12.7			6.976
Maximum	2.20		10.5	12.3	10.5				11.5		2.3		6.9		9.37	11.4									28.779
Ammonium	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	0.02		0.01		0.01			0	0	0	0.028	0.002		0.001	0	0		0				0.01			0.001
Mean	**0.42**							0	0.06	0.06	0.055	0.039		0.03	0.17	0		0.25	0.427			0.12		0.04	0.058
Maximum	5.14		0.74		0.05		0.004	0	0	0.1	0.148	0.114		0.07	0.36	0		0.7				0.73			0.305
Calcium	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	0.44		6.5	6.1	7.9				52		1.2	40	1		29.79	15			28.3	43.0	47.1				7.437
Mean	4.32							40	66	125	7.67	60.75	27.2		42.02	40			63.5	71.7	69	28.4			24.557
Maximum	15.48		94.7	66.8	94.7				78		8.5	100	99.3		54.25	66			94.5	100.8	92.2				58.306
Sodium	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	2.38		5.6	7	5.7							6.7	2.5		6.81	4.3									3.103
Mean	5.25											9.95	6.91		10.34	9.4									15.779
Maximum	12.79		13	12.1	13							14.8	17		13.87	17.5									50.300
Chloride	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	13.35		0.6		8				14		7.2	11.3	5.7	10	8.9	5									2.951
Mean	**54.49**							8	18		7.67	16.06	17.7	33	14.3	13						11.2			27.363
Maximum	185.33		37.3		23				24		8.1	27.6	42.7	60	19.7	25									85.218
Nitrate	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	2.68		0.6		0.6				0.6		0	9.88	3.7	0.05	0.6	0.01		0.01	0	0	1.7				0.107
Mean	**21.57**							1.6	0.6	25.8	3.67	16.01	17.7	2.8	3.12	2.7		0.11	4.3	0.94	3.578	7.7			7.362
Maximum	47.64		4.2		4.2				0.8		4.5	27.47	57.2	5	5.64	9.1		0.78	8	2.5	5				20.897
Sulphate	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	0.41		8.8		8.4				6		0	5.2	1.7		17.1	7									0.881
Mean	4.33							2	7		0	8.08	9.33		30.8	29						76.6			42.411
Maximum	17.13		23.6		23.6				8		0	11.51	26.2		44.5	87									#####
Phosphate	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	**0.01**		0.01		0				0		0.01					0.01		0.01							0
Mean	**0.20**							0	0	0.1	0.02					0.07		0.05				0.56		0.02	0.029
Maximum	**0.72**		0.236		0.22				0		0.03					0.39		0.1							0.11
DO	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	6.01		9.5				4.4				8.1	7.32	4.93				4.5	3.4	6.57	5.2	6.6		9.7		4.490
Mean	**10.13**									8.58	10.67	8.115	7.84				8.56	4.67	9.16	7.43	7.778	8.30	11.29		10.275
Maximum	12.20		11.6								12.2	10.35	12.5				15.7	6.1	12.21	8.7	8.8		13.1		19.400
pH	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	7.09	6	7.27	6.8	7.1	7.24			8.4		6.5	6.51	6.23	6.8	7.95	7.6	7.6	7	7.56	7.6	7.7				
Mean	**7.79**					7.84		7.6	8.4	7.45	7.33	7.025	7.3	7.4	8.2	8.1	8.22		8.2	8.08	8.089	7.9			
Maximum	8.38	9.2	8.64	8.5	8.6	8.54			8.4		7.6	7.48	8.69	7.9	8.45	8.6	8.8	8	8.73	8.3	8.6				
TSS	UK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	NRH
Minimum	2.72		7.5									2.8	0.2												
Mean	**18.03**									7		11.45	16.9												
Maximum	85.70		33.6									28	489												

Appendix 3. Continued.

Mean	Range	Min mean	Max mean
153.65	6		
319.3162		40	617.5
476.375	945		
0.509625	0		
2.386318		1.7	2.9
5.760513	12.2		
2.254511	0		
7.465149		1.17	12.7
11.50541	28.7787		
0.004379	0		
0.100929		0	0.427
0.237169	0.74		
21.94823	1		
51.23824		7.67	125.33
77.54278	100.8		
5.214113	2.5		
10.47583		6.91	15.77914
18.94621	50.2997		
7.36505	0.6		
16.6268		7.67	33
35.2618	85.218		
1.2758	0		
6.526785		0.114	25.75
11.09193	57.2		
6.120144	0		
22.80122		0	76.59
54.58122	266.821		
0.005857	0		
0.094667		0	0.56
0.155143	0.39		
6.225833	3.4		
8.556019		4.67	11.29444
11.88	19.4		
7.168235	6		
7.808926		7.025	8.4
8.413529	9.2		
3.5	0.2		
11.78333		7	16.9
183.6333	489.3		

Mean	Range	Min mean	Max mean
0.162593	0		
0.337901		0.042328	0.653439
0.504101	1		
0.041773	0		
0.1956		0.139344	0.237705
0.472173	1		
0.07834	0		
0.259398		0.040655	0.441299
0.399789	1		
0.005917	0		
0.136391		0	0.577027
0.320499	1		
0.21774	0		
0.508316		0.076091	1.243353
0.769274	1		
0.103661	0		
0.208268		0.137377	0.313702
0.376667	1		
0.086426	0		
0.195109		0.090004	0.387242
0.413783	1		
0.022304	0		
0.114105		0.001993	0.450175
0.193915	1		
0.022937	0		
0.085455		0	0.287046
0.204561	1		
0.015018	0		
0.242735		0	1.435897
0.397802	1		
0.320919	0		
0.441032		0.240722	0.582188
0.612371	1		
0.779156	0		
0.848796		0.763587	0.913043
0.914514	1		
0.007153	0		
0.024082		0.014306	0.034539
0.375298	1		

Conductivity	Min range	Mean min	Min mean	Mean mea	Max mean	Mean max	Max range
Minimum	0	0.162593	0.042328	0.337901	0.653439	0.504101	1
Mean							
Maximum							
1							
Potassium							
Minimum	0	0.041773	0.139344	0.1956	0.237705	0.472173	1
Mean							
Maximum							
Magnesium							
Minimum	0	0.07834	0.040655	0.259398	0.441299	0.399789	1
Mean							
Maximum							
Ammonium							
Minimum	0	0.005917	0	0.136391	0.577027	0.320499	1
Mean							
Maximum							
Calcium							
Minimum	0	0.21774	0.076091	0.508316	1.243353	0.769274	1
Mean							
Maximum							
Sodium							
Minimum	0	0.103661	0.137377	0.208268	0.313702	0.376667	1
Mean							
Maximum							
Chloride							
Minimum	0	0.086426	0.090004	0.195109	0.387242	0.413783	1
Mean							
Maximum							
Nitrate							
Minimum	0	0.022304	0.001993	0.114105	0.450175	0.193915	1
Mean							
Maximum							
Sulphate							
Minimum	0	0.022937	0	0.085455	0.287046	0.204561	1
Mean							
Maximum							
Phosphate							
Minimum	0	0.015018	0	0.242735	1.435897	0.397802	1
Mean							
Maximum							
DO							
Minimum	0	0.320919	0.240722	0.441032	0.582188	0.612371	1
Mean							
Maximum							
pH							
Minimum	0	0.779156	0.763587	0.848796	0.913043	0.914514	1
Mean							
Maximum							
TSS							
Minimum	0	0.007153	0.014306	0.024082	0.034539	0.375298	1
Mean							
Maximum							