An Evaluation of Water Treatment Technologies for Sustainable Rural Communities.

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Abstract
This paper presents the initial stages of research funded by the Scottish Government to enable an evaluation of the suitability of drinking water treatment technologies at small to medium scales to facilitate the application of the Scottish Government's Sustainable Rural Communities concept. The research included a technology scan to identify relevant drinking water treatment technologies suitable for small and medium sized rural communities in Scotland and an expert stakeholder workshop to verify and refine the technology inventory. The stakeholder workshop was also used to identify suitable selection criteria for Sustainable Rural Community drinking water projects. The criteria can be used in subsequent multi-stakeholder decision making for the most sustainable treatment options for specific communities. An explanation is provided on the methodology and the types of information that were collected and the outcomes of the research.

Keywords
Drinking water, treatment technology, rural communities, stakeholder engagement, sustainability

INTRODUCTION

In developed countries, the Millennium Development Goals (MDGs) for water have been largely achieved however there are still rural communities where drinking water treatment may be lacking or insufficient (Unicef and WHO 2015). In continuing to improve water quality, as well as addressing sustainable growth strategies such as the EU 2020 programme, strategic national objectives are seeking to go beyond MDGs to enable a transition to more resource efficient, greener and competitive economies (EC 2010). Water is seen to be an enabling factor within this programme, and hence evaluating options for improving sustainable and resource efficient collection, treatment and distribution of water to all areas including the most rural communities is needed. In Scotland, the Scottish Government Planning Policy (Scottish Government, 2014) identifies the need for the protection and development of "…remote and fragile areas and island areas outwith defined small towns…" and states that maintaining and growing communities should encourage "development that provides suitable sustainable economic activity, while preserving important environmental assets such as landscape and wildlife habitats that underpin continuing tourism visits and quality of place". The Scottish Government is funding capacity building research to help address water related challenges to rural communities through its Centre of Expertise for Waters (CREW), currently undertaking research related to the Sustainable Rural Communities (SRC) concept. The SRC approach aims to facilitate "a paradigm shift in delivery of affordable energy, treatment and disposal of waste and the provision of drinking water supplies" and "aims to deliver a closed loop system that is carbon and energy neutral, cost-effective and resilient".

There are some key challenges in the treatment of Scotland's rural water sources, particularly related to the higher concentration of private water supplies in rural areas. Private water supplies in Scotland are regulated by local authorities under the Private Water Supplies (Scotland) regulations, in place since 2006. Type A private supplies, which supply 50 or more persons or commercial or public buildings, are treated differently from Type B supplies, which only supply domestic premises. Type A supplies must be monitored by the local authority, and failures reported. The Water Quality (Scotland) Regulations 2010 also require the investigation of water quality issues and determination of the cause and extent of issues for Type A supplies. Discretionary powers for Type B supplies also exist where risks to health have been identified as non-trivial (DWQR 2015, Mercer and Bartram 2011) however there is no requirement for local authorities to monitor Type B supplies and hence Type B private supplies have a reduced coverage of monitoring compared to public supplies. The quality of drinking water provided by public supplies achieves greater compliance with drinking water quality criteria as compared to both Type A and Type B private supplies as shown in Table 1 (DWQR 2014a, DWQR 2014b). For private supplies, microbial failures represent the majority of non-compliance events, and more microbiological failures are observed for surface water sources as compared to ground water sources.

Table 1 Compliance with drinking water quality parameters in Scotland 2014

Parameter	Public supply (% compliance)	Type A – Private (% compliance)	Type B - Private (% compliance)
Overall compliance	99.89	93.97	87.86
Coliform bacteria	99.55	75.77	56.88
E. coli	99.99	86.62	78.37
Colour	100.00	82.03	83.18
pH	99.98	83.21	73.21
Iron	99.63	86.56	85.94
Manganese	99.70	92.70	87.73

Challenges for private drinking water treatment in Scotland include microbiological contamination (affected by onsite wastewater treatment, agricultural sources, wildlife) but also the effects of local conditions, for example peatland affected aesthetics and chemistry. A particular challenge is balancing the need for improved disinfection, with the risk of production of disinfection by-products, a key challenge that exists for water treatment across Europe (van der Hoek et al. 2014). Rural communities also face site specific challenges based upon the size and scale of water treatment infrastructure and the extent of treatment complexity required to achieve the desired water quality. Local demands and perceptions of water quality may also differ from one community to the next, with varying priorities and levels of capacity to manage water on a local level.

In general, the assessment of sustainable drinking water provision options, as with sustainable energy options, is increasingly focussing on whether large centralised systems or decentralised, locally managed systems provide the most sustainable option for communities. There are several identified barriers to delivery of decentralised treatment of drinking water, particularly for rural communities, many of which are socio-economic such as the local governance, resource and capacity to manage decentralised systems, and the financial costs of doing so (Quezada et al. 2016, Kot et al. 2011, Daniell et al. 2014, Hunter et al. 2009) as well as technical barriers related to the ability of technologies to provide the type and level of treatment and monitoring required for diverse decentralised source waters (Rowe and Sprigg 2014, Mercer and Bartram 2011). The lack of economies of scale on a decentralised system compared to large centralised supplies compounds these barriers. Additionally, households in developed countries generally have high expectations, but may place low value on the delivery of a clean water supply, and hence may be unwilling to pay more for innovations and technologies to treat water locally to a high level, or incorporate additional sustainability considerations to protect the environment (Libralato et al. 2012, Krozer et al. 2010).

Previous cost benefit analyses (CBA) by Hunter et al. (2009) for developed regions of the world (Americas, Europe, Oceania) found that in all scenarios the benefits of improving rural small and private water supplies (measured by direct and indirect costs of illness prevented) outweighed the costs of treatment. Potential added benefits of reduced impact on temporary users (tourists), chronic disease occurrence (IBS), livelihood benefits (house prices and tourism), and general impacts on well-being, predict that the CBA ratio is likely to be even more in favour of the benefits of treatment. However, the literature provides limited evidence of how sustainability considerations can be optimised within rural water treatment systems in developed countries, taking into account the specific treatment requirements alongside local economic, social and environmental concerns.

This paper describes research to review available drinking water treatment technologies, with a view to improving sustainable drinking water provision in rural areas of Scotland, taking into account the SRC concept. The research provides a technology scan of drinking water treatment technologies, a methodology for selection of suitable candidate technologies and identifies key sustainability criteria to be used in decision making for selection of drinking water treatment technologies for rural communities.

METHODOLOGY

Technology scan

The technology review was carried out in consideration of key challenges for drinking water treatment in Scotland, referring to academic literature and key documents from the government and regulators (Scottish Executive 2006, DWQR 2014a, DWQR 2014b, Reid et al. 2001, Reid et al. 2003, Grose et al. 1998. Academic and grey literature was consulted along with technical literature from water treatment technology providers to identify current treatments and trends in innovation. Recent water industry publications were reviewed to identify emerging treatment technologies. Websites and product offerings from key actors in Scotland and internationally were reviewed to identify additional candidate water treatment technologies. A number of online water technology expert forums were also consulted in order to identify emerging and novel technologies. These were compiled to establish a list of candidate technologies.

Expert workshop

In order to verify and shortlist appropriate technologies for further analysis, the support of key actors and experts in Scotland was sought. A one-day workshop was held to present the initial findings of the literature review, propose an appropriate technology inventory, and guide the selection of the most appropriate criteria to assess the technologies for Scottish rural communities. Key actors involved in Scotland’s water sector, and innovation in water treatment were invited to attend the workshop. These included representatives from a Scottish research body (CREW), the Drinking Water Quality Regulator (DWQR), Scotland’s primary water supplier (Scottish Water), a private environmental/water consultancy, the enterprise agency involved in Scotland’s Water Innovation Centres (Scottish Enterprise) and the Water Industry Commission for Scotland (WICS).
The workshop was used to evaluate and confirm a technology inventory suitable for Scottish rural communities and shortlist a selection of candidate technologies for a case study location. The workshop was also used to confirm a list of sustainability criteria to be used in decision making in the selection of treatment solutions for a specific community. The selection of criteria to assess the most sustainable water treatment options for rural communities was carried out using a combination of stakeholder input, confirmed against a review of criteria from the literature used to assess water treatment technology choices.

RESULTS AND DISCUSSION

The inventory of technologies

A broad review of technologies to address Scottish rural water treatment issues on small to medium scales was carried out, initially identifying large numbers of individual water treatment products. The large number of products resulted in the need to classify technologies by general types. Barrier technologies (filtration) and disinfection technologies provided the largest number of generic technologies. The review identified both conventional treatments (filtration, UV, chlorination, reverse osmosis), alongside more innovative and emerging technologies (ceramic membranes, ECAS, nano-technologies). Technologies deemed unsuitable or impractical were not added to the technology inventory. For example, technologies providing small scale mobile water treatment (e.g. personal use and field treatment) were excluded from the inventory. In addition, technologies only applicable to a single home scale (e.g. point of entry and point of use technologies) were generally excluded where scalability to a small or medium sized community scale would not be possible. The inventory was populated with additional information about each technology type including an outline description, references to literature and technical guidance, and information on example suppliers. The literature review identified a wide body of recent literature for some technologies such as membranes yet relatively little in the academic literature beyond company specifications for emerging technologies.

Workshop Outputs: Confirmation of the technology inventory

An initial technology list was presented to the expert stakeholders at a workshop for review of relevance, suitability, and completeness. The attendees were asked to individually indicate whether the technologies were suitable or not in the context of Scottish rural communities, or to indicate if they did not know. The definition of "suitable" was at the discretion of the expert based on their own knowledge and experience of drinking water treatment in the context of Scottish rural communities, and familiarity with the technology. After individual scoring, a discussion of each of the technologies was carried out in two groups. The initial scoring for the technologies is presented in Table 2. In order to rank the suitability based on the expert opinion, a net score of suitability was calculated (*suitable = 1, don't know = 0, unsuitable = -1*). All workshop participants agreed on the suitability for some technologies, whereas no technologies were unanimously unsuitable.

Table 2: Workshop Part 1. Individual Technology Review.

Technology	Suitable	Unsuitable	Don't know	Net Score of Suitable-Unsuitable
Activated carbon	8	0	0	8
Filter media	8	0	0	8
Ion exchange	8	0	0	8
Microfiltration	8	0	0	8
Nanofiltration	8	0	0	8
UV	8	0	0	8
UVC-LED disinfection	8	0	0	8
Advanced oxidation process	7	0	1	7
Ceramic membrane filtration	7	0	1	7
Ozonation	7	0	1	7
Particle filtration	7	0	1	7
pH correction technologies	7	0	1	7
Ultrafiltration	7	0	1	7
Chlorine dioxide disinfection	6	0	2	6
Reverse osmosis	7	1	0	6

Electrochlorination	4	0	4	4
Chemical disinfection (chlorine)	5	2	1	3
ECAS (Environmental water recycling)	4	1	3	3
Sand filtration	4	1	3	3
Distillation	3	1	4	2
Electrodialysis reversal (EDR)	2	0	6	2
Solar distillation	2	0	6	2
Nanotubes	2	1	5	1
Pulsed light technology	1	0	7	1
Activated alumina	4	4	0	0
Atmospheric water generators	2	2	4	0
Nanoparticles	1	1	6	0
Submerged membrane system	3	3	2	0
Coagulant addition	2	3	3	-1
Ballasted clarification	1	4	3	-3
Electrodionisation (EDI)	1	4	3	-3
Sedimentation	0	4	4	-4
Water softeners	1	6	1	-5

The group discussion confirmed that the lowest net scoring technologies were probably not appropriate in a Scottish SRC context due to the nature of the treatment they provide (e.g. arsenic removal or water softening, which have limited relevance Scottish rural communities), or, they generally did not represent realistic treatment options for rural communities. A deselection of all the technologies with a net score <0 was carried out with consensus. An additional discussion of the low scoring technologies resulted in removal of some that were not deemed to be sustainable due to high energy costs (e.g. distillation), or deemed unlikely to operate effectively in the Scottish climate (e.g. solar distillation). Some innovative and emerging technologies (e.g. nanotechnologies) were deselected by the group due to lack of market readiness, and lack of expert knowledge of technical performance and operational requirements for an adequate assessment to be made. The excluded technologies are listed in Table 3 with the reasons for their removal.

Table 3 Technologies removed from inventory and expert reasons for their removal

Technology excluded	Reason for exclusion
Activated alumina	Primarily for As removal, not relevant for Scottish rural communities
Atmospheric water generator	Limited application, temperature and dew point issues in Scotland
Ballasted clarification	Not suitable for small scale, too complex for community operation
Coagulant addition	Operator handling and high operation and maintenance requirements
Distillation (traditional)	Energy intensive and expensive
Electrodeionisation	Targeted removal of ions may be less applicable to rural water supplies, unnecessary, may be energy intensive
Nanoparticles	Limited application, high cost, may not be market ready
Nanotubes	Limited application, high cost, may not be market ready
Sedimentation (settling basins and clarifiers)	Old technology, process control varies, operational issues, additional treatment still required
Submerged membrane system	Not suitable for small scale, too complex for community operation
Water softeners	Not required in most areas of Scotland, mainly aesthetic
Solar distillation	Limited application, temperature and dew point issues in Scotland

The expert stakeholders were asked to suggest additional technologies for inclusion in the inventory that had not yet been included. These generally represented innovative or emerging technologies (Table 4).

Table 4 Additional technologies added to inventory based on expert recommendation

Suggested additional technologies	Reason for inclusion in inventory
Biological treatment	Emerging technology of potential use in Scotland for treatment of broad range of contaminants with non-chemical process
Electrocoagulation	Possible pre-treatment for poor quality source water
Vacuum distillation	Vacuum distillation at low temperature, potential to combine with renewable energy sources
Organics destruction cell	Emerging technology of potential relevance in Scotland for removal of organic compounds and colour

Workshop participants suggested the need to assess water treatment solutions with respect to different stages of treatment (e.g. barrier technologies or filtration, disinfection, and additional site specific treatments). A refined list of key technologies was thus produced following the workshop with the final list of technologies categorised into key treatment units of filtration, disinfection and alternative/additional treatment (removal of specific parameters or polishing). This provided a candidate list of 27 drinking water treatment processes (11 filtration or barrier technologies, 8 disinfection technologies, 8 additional post or pre-treatment technologies).

Workshop Output: Selection of shortlist of technologies for a case study location:
Due to the site specific nature of treatment needs in rural communities in Scotland, it was observed that a shortlist of key technologies from the main list would be required to allow for a multi-criteria decision analysis (MCDA) to take place for a given community. The workshop attendees therefore participated in a shortlisting exercise to provide a list of candidate technologies for a selected SRC pilot community. This shortlist would be used for evaluation by MCDA at a subsequent workshop with a wider range of stakeholders including community members (reported elsewhere by the project team). In the shortlisting exercise, the workshop participants were asked to repeat Part 1 of the workshop (technology evaluation), in the context of the selected SRC pilot community. The workshop participants were presented with basic information on the community size and composition, and the nature of the local water supply. The community provided an example location where multiple small private water supplies (approximately 100 homes) could potentially be replaced by a small community supply. The location had a major industrial water user locally (food and drink sector business) and was a popular tourist location, where protection of the nearby river from environmental harm was also of importance to regulators and the community. Data on the type of private water supply failures that had been measured within the catchment were made available, alongside information on the number and location of onsite wastewater treatment systems. The participants were again asked to review the main technology inventory and indicate whether a technology was suitable or unsuitable for water treatment at the location. The participants agreed that treatment of the water supply to achieve water quality standards would require barrier/filtration treatment, followed by disinfection and additional treatment in the form of pH correction. A shortlist of potentially suitable treatments in the categories of filtration, disinfection, and additional treatments was then agreed (Table 5).

Table 5. Shortlist of technologies for the case study location.

Filtration	Disinfection	Additional treatment
Ceramic membrane filtration	Chlorine disinfection	pH correction (limestone filter)
Sand filtration	UV disinfection	pH correction (chemical dosing)
Microfiltration	UV – LED disinfection	

Workshop Outputs: Selection of decision making criteria for selection of sustainable water treatment technologies for rural communities.

In order to evaluate technology choices using MCDA techniques at a later date, stakeholders were asked to participate in a criteria selection exercise. The participants were asked in a round-table discussion to propose generic selection criteria that would help decision makers choose between technology options. The delegates were also asked to consider the units of measurement that would allow evaluation of each of the criteria. The delegates were asked to debate and confirm the appropriateness of the criteria in the context of the SRC concept. After the delegates had proposed an initial list of the most important criteria, the workshop facilitators presented a summary of selection criteria found in the literature for comparison (Brikke and Bredero 2003, USEPA 2003, CDC 2008, NDWC 2009, Ray and Jain 2011, Vogt et al. 2014, DETR/DWI 2015), and asked the workshop attendees to debate the completeness of the final criteria list, and approve the addition of any missing criteria with relevance to water technology selection in Scottish rural communities. The criteria that were identified as important in decision making for sustainable water treatment technology selection in rural Scottish communities and proposed units of measure to assess each technology against are shown in Table 6, categorised according to sustainability themes.

Table 6. Finalised sustainability criteria to assist selection of sustainable drinking water treatments in rural communities

Sustainability theme	Criteria	Description	Units
Economic	Capital Cost	Capital cost of equipment and install	£
	Maintenance Cost	Maintenance costs per year	£/year
	Operational Cost	Operational cost (e.g. consumables, energy)	£/year
Social	Affordability	Ability of householders to pay for services delivered	% of household budget
	Willingness to pay	Willingness to pay for attributes covering environmental , safety and health factors	£/unit of reduced risk
Technological/ performance	Complexity (user input required)	Basic, intermediate or advanced skill or low medium or high frequency of input	basic/int/adv or low/med/high
	Adaptability	Level of accommodation in design: potential and ability to accommodate future changes (qualitative)	1-5
	Reliability, ability to achieve compliance	Ability to meet drinking water quality standards (parameter specific - no treatment, good, very good, excellent/complete treatment)	0, +, ++, +++
	Durability	Design life, years expected to operate successfully	years
Environmental	Water resource use	Consumption of raw water resources	% recovery
	Energy use	Energy required in process	kWh/m^3
	Chemical use	Chemical use (qualitative or quantitative)	yes/no or kg/m^3
	Chemical transport requirement	Impact on air quality (sulphur dioxide, nitrous oxide emissions) and climate change (CO_2	yes/no or $miles/m^3$

		emissions)	
	Impact on water environment	Discharge of waste water from process	low/med/high
	Solid waste produced	Sludge, chemical waste streams	low/med/high or tonnes/year
	Physical footprint	Size of treatment plant	m^2
	Visual impact	Local visual impact	low/med/high

DISCUSSION

The main objective of the work was to review available drinking water treatment technologies in order to propose a suitable inventory of treatment choices for small and medium supplies in rural areas of Scotland and to identify suitable sustainability criteria to be used in decision making on treatment options. The development of the technology inventory sought to include innovative and emerging technologies for small and medium scale drinking water treatment however some of these were deselected from the inventory at a later stage due to the lack of field testing and evidence that the technology was market ready. The experts generally took a conservative approach to technology selection, selecting "tried and tested" technologies over innovative or emerging ones. This was largely due to uncertainty over cost, compliance and ease of use for new technologies. This conservative approach to adoption of innovation in the water sector is seen elsewhere and may reflect the wider approach taken by regulators and water suppliers in the sector (Rowe and Sprigg 2014). While selection of technologies at this level did not consider local issues or stakeholder concerns directly, the use of expert opinions at the initial inventory selection stage may suitable for deselecting technologies that will not achieve the required regulatory standards, or provide practical solutions based upon expert knowledge. There is however a risk of excluding viable new technologies on the basis of lack of sufficient proven results or field testing.

In contrast to the general selection of the main technology inventory, the selection methodology at a community level may be improved by the input of local stakeholders in the shortlisting and selection of technologies. The technology shortlisting process used in this study was based on expert opinion (e.g. regulators and water supply companies). The technologies shortlisted by this group may differ for community members or local businesses. Consumer preference for treatment technology (e.g. aesthetic parameters) could be different from what the "experts" perceive to be important (e.g. compliance with parameters listed in regulation) (Hegger et al. 2011). In order to include community members in technology selection shortlisting, they may require a technical or performance briefing on each technology to assist the shortlisting process. Similarly, experts involved in the shortlisting exercise may benefit from a briefing by community members to understand the key issues of concern, or to confirm/dispel the perceived concerns and community capacity to adopt specific technologies. The inclusion of community members or local stakeholders in technology selection is explored in a follow up paper by the project team examining co-production and community engagement in the design of water treatment solutions.

The sustainability criteria identified in this study included a range of economic, technical, social and environmental criteria, with the largest number of identified criteria in the environmental category. Users of the criteria should assess how to balance the importance of the criteria in application to decision making processes. The sustainability criteria identified may potentially be ranked differently by the expert group as compared to community members and therefore any ranking exercise to classify criteria in a MCDA exercise should consider the make-up of the decision making group carefully. In addition, in order for decision makers to use the criteria effectively, they must be able to evaluate each technology against these criteria. This requires some effort to populate the technology inventory with data relevant to the location and size of the proposed treatment system. Some data can only be obtained from local users, such as “Willingness to pay” or “Affordability”, whereas others can be entered in the technology inventory in advance (e.g. economic and technical/performance data). Facilitators should also consider whether the “status quo” option should be included in the decision making process, and efforts made to populate a dataset for the relevant criteria if needed. The follow up paper to this one discusses the outcomes of a MCDA exercise carried out with a range of stakeholders to choose appropriate treatment technology for the SRC pilot community.

CONCLUSIONS

The research has provided a database of technologies and appropriate selection criteria required for carrying out an MCDA exercise with local stakeholders in order to evaluate drinking water treatment options for a given community. Both the inventory of candidate technologies, and criteria against which these can be evaluated are dynamic and should be reviewed in the future to allow emerging technologies to be added (where suitable), or additional sustainability criteria to be considered (if relevant). The decision making process should consider the views and priorities of local stakeholders alongside water treatment experts in order for complete information to be available to the decision makers and may benefit from inclusion of local stakeholders at the shortlisting stage. The application of the MCDA approach utilising the outputs of the current study are presented elsewhere by the project team.

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