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Innovative solutions for sustainable drinking water treatment at small to medium scales

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1.0 Executive Summary

Aim of the project

This project surveys the drinking water treatment technology landscape (national and international) and develops a rational for assessing the technology across a range of operational scenarios.

Main findings

The main outcome of the project is a generic four stage decision support process for the selection of appropriate drinking water treatment for sustainable rural communities. This is based on, and is comprised of, the three key project deliverables:

1. An inventory of technologies from which to choose candidate technologies for further evaluation,
2. A set of SRC drinking water technology selection criteria to be applied to each decision making process,
3. A recommended MCDA tool to be populated for future decision making.

Background

Within the EU Horizon 20/20 program and The Hydro Nation Agenda water is seen as a significant enabling factor in the transition towards a resource efficiency and regenerative circular economy. While major urban managed water systems have seen much improvement in performance, small to medium supplies still require optimisation.

The research undertaken addressed the need to optimise the overall sustainability of small to medium sized water treatment processes.

Research undertaken

Initial work on the project consisted of a review of technologies, contact with suppliers of water treatment technologies and engagement with the Sustainable Rural Communities (SRC) Steering Group, which resulted in the creation of an inventory of appropriate technologies. Initial work confirmed the appropriateness of the planned methodology and programme of work and identified a need to have workshops at two stages, the first being a workshop to confirm and verify the list of candidate technologies, typologies, criteria and key actors. A second workshop confirmed the proposed criteria and allowed a range of stakeholders to participate in a Multi Criteria Decision Analysis (MCDA) of appropriate technologies for the test catchment, which was one of the priority SRC Community Pilot site case study sites. A decision support process and tool was developed that uses data from the Technology Inventory to enable a group of stakeholders to rank potential technologies and hence to recommend the most appropriate technologies for Sustainable Rural Communities. A spreadsheet based MCDA tool was created that included two analytical methods. These are (i) a Simple Multi Attribute Rating Technique tool and communication, and (ii) a TOPIS based model to allow further analysis of the data to support the final decisions.

Recommendations

1. The inclusion of community actors in the decision making process is essential to allow the local context and local issues to be identified and this must be maintained in the application of the approach. Facilitators may wish to consider whether there may be value in also including community members at the technology shortlisting stage.

2. The approach should be applied to a number of catchments with differing characteristics. Further application may build up a portfolio of suitable technologies that can be linked to catchment typologies and lead to the production of a more generic technology selection matrix for Sustainable Rural Communities.

3. A mechanism should be established to maintain the Technology Inventory to ensure the inclusion of emerging technologies in the future. This should be carried out annually through literature review and by establishing a robust means of communication with the Hydro Nation Water Innovation Services (HNWiS).

Type of Information	Details and Link
Tools and associated data collection worksheet	Technology Inventory
	MCDA Criteria
	MCDA Tool
	Worksheets 2A, 2B, 3A, 3B, 4A, 4B, 5A, 5B
Case Study Information	Catchment Data Sheet for Cragganmore
	Table of Candidate Technologies for Cragganmore
	Criteria Weighting Data from Cragganmore
	Candidate Technology general information sheet
	Candidate Technology Data Sheets
	Scoring Data from Cragganmore Workshop
	Initial SMART MCDA Output for Cragganmore
	TOPSIS Output for Cragganmore
	Sensitivity Testing for Cragganmore
Supporting Information	Workshop 1 Report
	Workshop 2 Report

Contents

1.0 Introduction

This project surveys the drinking water treatment technology landscape (national and international) and develops a rational approach for assessing the technology across a range of operational scenarios.

1.1 Project Objectives and Deliverables

The project objectives were to:

1. Review drinking water treatment innovation and the use of MCDA
2. Compile a list of technologies to assess their sustainability in the context of rural communities
3. Identify, develop and populate an appropriate set of sustainability assessment criteria
4. Develop a comprehensive MCDA model that includes uncertainty
5. Identify an appropriate range of typologies
6. Review regulatory impacts
7. Develop a decision support tool (DST) and apply it to the typologies to rank technologies and recommend innovations on the basis of best value

The principal deliverables are:

- An inventory of small to medium sized water treatment technologies that are appropriate for rural communities (the Technology Inventory)
- A set of drinking water technology selection criteria to support the Sustainable Rural Communities initiative (CRW2014_12)
- A decision support process and tool that utilises data from the Technology Inventory to enable stakeholders to rank potential technologies and hence to recommend the most appropriate for Sustainable Rural Communities

1.2 Methodology

1.2.1 Literature Review

A literature review of academic and grey literature, including technical literature from water technology companies was undertaken to:

- Identify trends in innovation in small to medium sized water treatment technologies to:
  (i) identify candidate innovative technologies,
  (ii) identify key actors in Scotland and internationally in water treatment innovation and
  (iii) guide the selection of the most appropriate approach to assess the technologies.
- Identify potential assessment criteria related to the sustainability of the technology and its applicability to Sustainable Rural Communities (SRC).
- Confirm our understanding of the use of MCDA in technology assessment as reported in published work in the area and facilitate the selection of the most appropriate MCDA technique; this will be affected by the nature of the assessment criteria, e.g. independence, number of criteria etc.

1.2.2 Confirmation of Key Actors

A list of key actors who would be involved as participants in decision making workshops was collated and agreed with the project manager. The list of actors, which included the identification of companies involved in innovation of water treatment, combined knowledge of actors in the James Hutton Institute with those identified by Abertay University through the literature review and previous work on the CREW Scotland's Water Map project.

1.2.3 Compilation of the Technology Inventory

An inventory of innovative and appropriate technologies was created. The inventory includes an outline description of each of the technologies, references to literature and technical guidance, and information on example suppliers. The technologies were initially grouped in the inventory by treatment process typology such as conventional treatments (filtration, UV, chlorination, reverse osmosis), innovative technologies (ceramic membranes, ECAS, nanotechnologies) and combination technologies (multiple combinations). Available data on the technologies were assembled, categorised by the MCDA selection criteria and presented for each technology. These included data on economic value, scalability and the applicability of technologies to SRC. The inventory was reviewed for completeness by the stakeholders at **Workshop 1** and data from the Inventory were then used in a case study application in **Workshop 2**. The feedback from workshop 1 identified that grouping technologies by application, rather than by stage of innovation would be a more useful approach. As such, Workshop 2 presented technologies to stakeholders by stage of treatment (filtration, disinfection, and additional treatment).

1.2.4 Confirmation of technologies, typologies, assessment criteria and MCDA data

The literature review identified the catchment specific nature of decisions related to water treatment technologies. It was evident that technology selection decisions for individual catchments would be heavily influenced by the nature of the catchment. Issues such as location, geography, land use, water source type etc. would influence both the appropriateness of the criteria and values that would be attributed to the MCDA criteria.

Therefore, two workshops, each involving a range of stakeholders were required. Workshop 1 confirmed and verified the list of generic candidate technologies, treatment process typologies and key actors, and identified potential generic MCDA criteria. The delegates were able to debate and confirm the appropriateness of the candidate technologies that had been obtained from the literature and to propose generic selection criteria.

Workshop 2 confirmed the applicability of the proposed set of generic MCDA criteria in the context of a study catchment. It also allowed a range of stakeholders to participate in a case study application of the MCDA approach for the selection of appropriate technologies in the context of a catchment specific case study. The Cragganmore catchment, which was one of the priority SRC Community Pilot site case study sites (CRW2014_12), was selected for this process at a SRC steering group meeting. Workshop 2 allowed for collection of data (weights and scores) for the MCDA analysis of the Craggamore catchment including the determination of relative scores for the criteria and an assessment of their value functions and their weightings.

1.2.5 Modelling and communication of results

A final decision on the nature of the MCDA model was taken in conjunction with the project manager on completion of the literature review and in response to the nature of the selected criteria. A spreadsheet based MCDA tool was created that included two analytical methods. These were (i) a Simple Multi Attribute Rating Technique tool (used in Workshop 2 as it offers considerable advantages in terms of stakeholder engagement and communication) and (ii) a TOPIS based model to allow further analysis of the data to support the final decisions. ANP/AHP techniques or outranking techniques such as Electre were discounted because of concerns on their practicality due to the

large number of assessment criteria. Uncertainty in the weights and scores of MCDA criteria was addressed by incorporating risk modelling, using sensitivity analysis, in the MCDA tool. The data output from the MCDA tool ,which includes the results of the risk analysis, has been designed to be engaging and communicative to the range of stakeholders who would be involved in the final decision making stage.

2.0 Results

2.1 Literature Review

The literature review established that in Scotland in 2014, the quality of drinking water provided to households from public supplies achieved greater compliance with drinking water quality criteria (99.89% overall) as compared to private supplies (DWQR 2014a, DWQR 2014b). In 2014, Type A private supplies (≥50 population equivalent (pe) and 10m^3/day or commercial or public building) achieved 94% compliance and Type B private supplies (all other private supplies e.g. households) achieved 88% compliance for key water quality parameters overall but with a high degree of variation. The lowest levels of compliance were observed for:

- Coliform bacteria (76% Type A, 57% Type B)
- Colour (82% Type A, 83% Type B)
- pH (83% Type A, 73% Type B)
- Iron (87% Type A, 86% Type B)
- Manganese (93% Type A, 88% Type B)
- E. coli (87% Type A, 78% Type B).

Challenges for drinking water treatment in Scotland are site specific and will vary significantly based on the source raw water and characteristics of the catchments. 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).

A broad review of literature was carried out initially identifying large numbers of individual water treatment products. These were then grouped into treatment type categories that included conventional treatments (filtration, UV, chlorination, reverse osmosis), innovative technologies (ceramic membranes, ECAS, nanotechnologies) and combination technologies (multiple combinations). 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 community scale would not be possible.

In addition, the literature review guided the identification of selection criteria for choosing the most appropriate water technology for a specific treatment scenario. Final criteria selection agreed with other technology selection guidance documents (Brikke and Bredero 2003, USEPA 2003, CDC 2008, NDWC 2009, Ray and Jain 2011, Vogt et al. 2014, DETR/DWI 2015). This guidance material, along with additional supplementary material was consulted when populating the technology inventory with criteria data for each technology. A detailed list of supporting references is provided in the Technology Inventory. Reliable data were not found for all technology types for all selection criteria, or were found to be limited. Many of the selection criteria require site specific data to be collected (e.g. affordability, willingness to pay, visual impact), and costs and effectiveness of treatment can be linked to source water, scale, and local conditions. The practical use of the inventory is detailed in the Workshop 2 report.
The literature review also guided the selection of MCDA approaches. The selection of an appropriate MCDA methodology is a key decision in any multi-objective modelling problem. A number of methods were ruled out due to the number of criteria and solution technologies that may be appropriate for a rural catchment. The methods ruled out included AHP and ANP where pairwise comparisons are needed. One of the major limitations of ANP and AHP approaches is that if the number of criteria and alternatives increases, one has to perform several pair-wise comparisons, which increases the effort (Guitouni and Martel, 1998). Given the decision making groups varied in composition and to avoid fatigue amongst the decision makers (Gasiea et al, 2010) it was agreed by the steering group to adopt a simple SMART approach at the workshop. These results are validated using an objective MCDA method such as TOPSIS (technique for order by similarity to ideal solution) that can use both real data and preference data (in the absences of real data). TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative solution.

2.2 The Technology Inventory

2.2.1 Inventory Development

An initial technology list was presented to key stakeholders at Workshop 1 for review of completeness. Table 1 shows technologies (e.g. nanotechnologies) that were excluded together with the reasons for their exclusion. Some of these may be included in future updates of the Inventory. Additional technologies for inclusion in the inventory were suggested by Workshop 1 participants. Workshop 1 participants also noted the need to assess technologies with respect to different stages of treatment (e.g. barrier technologies or filtration, disinfection, and additional treatments that may be site specific). A refined list of technologies was produced following this workshop and is provided as an electronic annex to this report, with the final list of technologies categorised into treatment units of filtration, disinfection and alternative/additional treatment (specific parameters or polishing). Combination technologies were not included in the final inventory, as it was found that multiple technologies (2, 3 or more) could be combined in a large number of combinations, making assessment of all possible combinations impractical. However, the approach to evaluating technologies at treatment stages may allow for enhanced comparison of combination technologies.

The Inventory has been populated with data and references (where available) pertaining to each criterionfor each technology where possible. This workbook presents the amended finalised inventory as of January 2016, as agreed by stakeholders. It is noted that most technologies will be used in combination with other technologies. The technologies are categorised according to treatment type (Filtration, Disinfection, Alternative/Additional). A brief description of each technology type is provided, along with relevant data pertaining to each selection criteria.

2.2.2 Limitations in Inventory Data

Firstly, data are not available for all criteria for all available products for all technologies and may be based on limited available references. Where no reliable data was found for a specific criteria/technology combination, "ND" (no data) is noted.

Secondly, data for each criteria (e.g. cost, footprint of system, etc.) may be very site, and product, specific. Some cost data in literature is based on large scale plants. Not all data in literature is scalable down to community size.

Thirdly, criteria categories of "Affordability" and "Willingness to Pay" can only be determined by site specific users. The calculation

of affordability based on cost per household may differ based on the site specific scenario. Affordability thresholds for water identified by USEPA (2003) states 2.5% of median household income or less is "affordable". In the test example, "affordability" included operation and maintenance cost, but did not include capital cost.

Fourthly, cost figures (capital, maintenance and operational, where available) have been converted to GB pounds, using December 2015 exchange rates ($US 1.51: £1GB; 1.42: £1GB). Capital cost figures do not include costs of distribution systems and community infrastructure. Separate "maintenance" and "operational" costs were not always available, with many reference providing a combined "operation and maintenance cost".

2.3 The Decision Support Tool

The decision support process and tool uses data from the Technology Inventory to enable a group of stakeholders to rank potential technologies and hence to recommend the most appropriate for Sustainable Rural Communities. The catchment specific nature of technologies was identified by the literature review and confirmed by interaction with the stakeholders. This is reflected in the design of the process and tool, which can only be applied at an individual catchment level. This catchment specific application is exemplified in this report in the context of the Cragganmore catchment.

The decision support tool can be accessed here.

In future applications the decision support process would be led by a facilitator who has knowledge of the selection and operation of drinking water treatment technologies.

The decision support process involves four stages:

1. An initial decision on the required stages of drinking water treatment and the appropriate candidate technologies to allow a compilation of an inventory shortlist and data set to guide Criteria Ranking, Weighting and Scoring.
2. A multi-stakeholder workshop to decide on Criteria Ranking, Weighting and Scoring, which includes a provisional decision using a Simple Multi Attribute Rating Technique
3. Further MCDA analysis of the workshop data to allow verification and risk analysis of the provisional decision.
4. Final Decision

The decision support key process steps are shown in Figure 1 alongside an indication of lead actors at each stage.

Figure 1 Stages in the decision support process and actors

At each stage, information from the previous activity will be used to inform the decision process. Table 2 describes each stage in the process and the information required at that stage, together with links to further guidance and supporting material. A worked example of Cragganmore has been used to illustrate the generic and catchment specific material required at each stage and the likely outputs/inputs to the next stage in the process.

Table 1 List of Excluded Technologies

Technology	Comments
Activated Alumina	Primarily relevant for Arsenic removal, which is not an issue in Scotland
Atmospheric Water Generator	Limited application, temperature and dew point issues in Scotland
Ballasted Clarification	Not suitable for small scale, too complex
Coagulant addition	Operator handling and operation and maintenance may be complex and difficult to manage
Distillation (traditional)	Energy intensive and expensive
Electrodeionisation	Targeted removal of ions may be of limited application 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
Water softeners	Not required in most areas of Scotland, mainly aesthetic
Solar distillation	Limited application, temperature and dew point issues in Scotland

Table 2

Stage Activity	Brief Description	Further Guidance
Stage 1. Initial Decision and Data Compilation	(i) The facilitator will assemble summary information on the catchment and prepare an information sheet. (ii) The facilitator will issue information sheets to stakeholders together with the Technology Inventory. Stakeholders will be dependent on the specific case but are likely to include DWQR, Local Authority, Scottish Water, Water Innovation specialists, Community Representatives and SEPA (iii) The facilitator will compile a table of potential treatment stages and technologies	Example: Catchment Data Sheet for Cragganmore Example: Table of Candidate Technologies - Cragganmore
Stage 2. Criteria Ranking, Weighting and Scoring	(i) Criteria Ranking and Weighting (a) Delegates are briefed on the characteristics of the catchment and the list of MCDA criteria to compare each option. (b) Delegates are invited to record individual rankings and weightings of criteria on Data Sheets 2A and 2B (c) The stakeholder group is required to reach -a consensus through discussion on weights and to record this on a group version of Data Sheets 2A and 2B.	Input: Catchment Data Sheet for Cragganmore List of MCDA Criteria Blank Worksheet Templates Output: Group weightings used in initial MCDA for each treatment stage at the workshop and in subsequent full MCDA analysis Example: Criteria Weighting Data from Cragganmore
Stage 2.	ii) Scoring Technologies Scoring is done sequentially for the appropriate technologies that were suitable for each stage of the treatment process as identified in Stage 1. Once the data are compiled for each stage, an initial MCDA analysis is undertaken for that stage to provide a further context for evaluation of the subsequent stage e.g. the assessment of the technologies for a Disinfection stage could be influenced by the nature of the selected technology at a Filtration stage (a) Delegates are reminded of the characteristics	Input

Stage Activity	Brief Description	Further Guidance
Scoring Criteria (Continued)	(a) Delegates are reminded of the characteristics of the catchment and briefed on the list of candidate technologies that had been identified in Stage 1. (b) The following information is issued and discussed by delegates for, initially, the first stage of the treatment process: • information sheet on the general features of each of the candidate technologies. • Data sheet 3A, providing data for each candidate technologies drawn from the Technology Inventory. • Data Sheet 3B on which each delegate records their own opinions on the rank order and hence and score for each of the technologies against each of the criteria. (c) Each group is then required to reach a consensus on weights and scores for each technology and record this on a group version of Data Sheets 3B. (d) An initial MCDA is then undertaken for first stage technologies (e) The results from (d) are then presented to the delegates and steps (b) to (e) are repeated for further stage technologies (Data Sheets 4A, 4B, 5A, 5B).	**Example:** Catchment Data Sheet for Cragganmore **Example:** Candidate Technology general information sheet **Example:** Candidate Technology Data sheets **Input:** Blank Worksheet Templates **Output** Group scoring used in initial SMART MCDA for each treatment stage at the workshop and in subsequent full MCDA analysis **Output** Initial SMART MCDA analysis for the first stage. Initial SMART MCDA analysis for each stage **Example:** Scoring Data from Cragganmore Workshop **Example:** Initial SMART MCDA Output for Cragganmore
Stage 3 Further Analysis	Stage 3 Further analysis involving verification of the Initial SMART analysis using TOPSIS and Risk Analysis using sensitivity testing are undertaken following the workshop. The procedure is as follows: **(i) Verification of the Initial SMART analysis using TOPSIS** **(ii) Risk analysis using sensitivity testing**	**Input:** Weighing, scoring or, where available, qualitative data from stage 2. **Example:** TOPSIS Output for Cragganmore **Example:** Sensitivity Testing for Cragganmore
Stage 4. Final Decision	(i) Facilitator will assemble MCDA results, recommend the appropriate solution and circulate a brief summary to stakeholders (list as stage 1) for comments and/or confirmation of agreement (ii) Final Decision based on feedback.	**Example:** Summary output from MCDA

3.0 Conclusions and Recommendations

3.1 Decision Support Tool

Section 2 presents the decision support process for Sustainable Rural Communities in the selection of the most appropriate water treatment technologies. It provides a worked example and blank templates for Stages 1-3. The case study highlights the catchment specific nature of the decision process. This stems from the fact that the characteristics of the catchment dictate the mix of candidate solutions, dictating in turn the data required for the decision making process. Each decision, driven by these factors, will therefore be unique.
A generic four stage process can however be applied to support decisions. This includes the three deliverables from this project. Firstly an inventory of technologies from which to choose candidates for further evaluation, secondly a set of drinking water selection criteria to be applied to each decision making process, and thirdly a recommended MCDA tool to be populated for a future decision.

As noted, the Technology Inventory presents an overview of technologies currently available, and data currently accessible for populating the criteria. This inventory will require updating from time to time to ensure emerging and innovative technologies are included, and that up to date data for each criteria are added. An annual literature review could be carried out to update the technology list and data.

3.2 Community Input and Perspective

Workshop 1 did not include community members in the selection of candidate technologies, relying solely on technology and drinking water treatment experts to provide a shortlist of technologies for further assessment. At Workshop 2, the involvement of community participants provided site specific knowledge of current levels and types of water treatment, common issues related to water supply and demand, and local issues that may not have been apparent to outside actors. For instance, for some community members the decision was being considered in the context of the current levels of treatment at the site, which for some may have been no present treatment at all, and possibly no perceived need for additional treatment. The inclusion of community actors in the decision making process is therefore essential to allow the local context and local issues to be identified. Facilitators may wish to consider whether there may be value in including community members at the technology shortlisting stage.

3.3 Quality of Dialogue and Usefulness

The process of reaching consensus amongst delegates at the decision making workshop identified the range of priorities and values different stakeholders place on different criteria with relation to drinking water criteria. All delegates found that discussion of the technologies assisted in enhancing knowledge about technologies' application, but also in recognising issues that they may previously have discounted as unimportant.

3.4 Further Development of the tool

To further develop the tool, it is recommended that the approach should be applied to a number of catchments with differing characteristics. Further application may build up a portfolio of suitable technologies that can be linked to catchment typologies and lead to the production of a more generic technology selection matrix for Sustainable Rural Communities.

Additionally, a mechanism should be established to maintain the Technology Inventory to ensure the inclusion of emerging technologies in the future. This should be done through a literature review and by establishing a robust means of communication with the Hydro Nation Water Innovation Services (HNWiS).

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