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Rainwater Harvesting Typologies for UK Houses: A Multi Criteria Analysis of System Configurations

Peter Melville-Shreeve *, Sarah Ward and David Butler

Centre for Water Systems, University of Exeter, Exeter EX4 4QF, UK; sarah.ward@exeter.ac.uk (S.W.); d.butler@exeter.ac.uk (D.B.)
* Correspondence: pm277@exeter.ac.uk; Tel.: +44-1392-723600

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Abstract: Academic research and technological innovation associated with rainwater harvesting (RWH) systems in the UK has seen a shift of emphasis in recent years. Traditional design approaches use whole life cost assessments that prioritise financial savings associated with the provision of an alternative water supply. However, researchers and practitioners are increasingly recognising broader benefits associated with rainwater reuse, such as stormwater attenuation benefits. This paper identifies and describes a set of novel RWH system configurations that have potential for deployment in UK houses. Conceptual schematics are provided to define these innovations alongside traditional configurations. Discussion of the drivers supporting these configurations illustrates the opportunities for RWH deployment in a wide range of settings. A quantitative multi criteria analysis was used to evaluate and score the configurations under a range of emerging criteria. The work identifies several RWH system configurations that can outperform traditional ones in terms of specified cost and benefits. Selection of a specific RWH technology is shown to be highly dependent on user priorities. It is proposed that the system configurations highlighted could enable RWH to be cost-effectively installed in a broad set of contexts that have experienced minimal exploitation to date.

Keywords: configurations; decision support; multi criteria analysis; product innovation; rainwater harvesting; sustainable drainage systems; source control

1. Introduction

1.1. Rainwater Harvesting at UK Houses

Rainwater harvesting (RWH) systems in the UK have traditionally been installed at domestic residences for the single objective of providing a non-potable water supply for use in toilets, laundry facilities and for garden irrigation [1,2]. Unlike some fully off-grid configurations implemented elsewhere [3,4], system configurations in the UK are supplemented by mains water supplies for potable water applications such as drinking, bathing and dishwashing. Germany has seen strong uptake of RWH technologies as reported by Partzsch [5] with 80,000 installations per annum and a total industry value of 340 million Euros. With successful growth in that market driven by policies that seek to (financially) support green technologies, one in three houses constructed in 2005 installed a rainwater tank. However, the nascent UK RWH installation market has developed with early-adopters purchasing well-established technologies that directly derive from installations found in countries where RWH is now mainstream, such as Germany [6] and Australia [7].

In fact, a review of three leading RWH system providers in the UK illustrates that they either license products from European manufacturers or have mimicked such configurations [8–10]. Whilst suitable for some sites, the direct transplantation of these off-the-shelf, traditional RWH system configurations into the UK marketplace could prevent optimal RWH solutions from being installed, as the current market-place only offers a limited range of technologies to potential purchasers. Additionally, these traditional RWH systems are best suited to new build houses with large gardens or driveways (under which tanks can be placed) with high non-potable water consumption. They can be difficult and costly to retrofit and may have high maintenance requirements [11]. House building trends in the UK are for smaller properties with low-flush toilets and less garden space. Recent research on water using practices revealed that 62% of the sample had some garden applications for which rainwater could be used (plants, flowers, lawn). However, 26% of this subset did not irrigate or water their gardens, but simply waited for rain [12]. In combination, this means that there is a growing need for retrofitable RWH systems, which utilise smaller rainwater tanks. However, there are few commercially-available systems to address this opportunity. Furthermore, optimal RWH systems might be designed to respond to a wider set of drivers than simply achieving (non-potable) water supply, such as reducing total water related energy consumption and improving stormwater control.

Minimal government incentives, subsidy or support for RWH means the UK market remains nascent. At the residential property scale, installation rates remain low with the market reportedly worth just £8 million in 2009 [13]. This is no doubt due to the whole life cost benefits of traditional technologies resulting in long payback periods to individual purchasers [14]. There is therefore a compelling case to develop an affordable, retrofittable and multi-benefit range of RWH system configurations and options to respond to these property and regime level drivers.

In this paper, traditional and innovative RWH systems have been identified and their configurations described. Secondly, a set of criteria are defined that enable RWH system configurations to be evaluated using multi criteria analysis (MCA). The outputs from the research illustrate the ability of RWH systems to achieve a number of objectives and the methods are intended to support designers, householders, water companies and installers in understanding the broader opportunities presented by emerging innovative RWH technologies.

1.2. Existing Cost–Benefit Approaches to RWH Assessment

A straightforward method of financial appraisal can be achieved by evaluating the payback period for a RWH system. This sets the capital cost against the long-term savings generated from the reduced water supply and associated sewerage costs. Contemporary RWH studies and modelling tools also integrate the operational costs and planned maintenance costs (for example pump replacement and tank cleaning) [15]. Such an approach was demonstrated by Roebuck *et al.* [14], who concluded that a whole life cost (WLC) approach is most appropriate for undertaking financial appraisal of RWH systems in the UK. This work advocated the need to include capital, maintenance, operational and decommissioning costs while attributing financial benefits to the savings linked to water and sewerage tariff reductions. Ward *et al.* [11] agree that WLC approaches represent best practice and propose that daily rainfall datasets should be deployed to enable more accurate modelling of RWH systems [16]. Roebuck and colleagues' later work [17] also illustrated that use of simplified tools (for example those that do not account for WLC) can result in designs that have hypothetically viable payback periods but cost more to maintain and operate than they save when whole lifecycle costs are included.

A wider review of literature and RWH system design tools illustrates that appraisal beyond financial benefit is lacking [18–20]. An appraisal under a single objective "maximise whole-life financial benefit of water reuse" omits many of the nuanced benefits offered by RWH systems. Consequently, examination of novel RWH system configurations benchmarked against a wider set of criteria is warranted.

1.3. A Framework for RWH Evaluation under a Range of Criteria

Following Coombes [21], the work set out in this paper develops a decision space that trades off whole life benefits and whole life costs. This concept neatly frames the need for innovation in the context of the UK's RWH industry through visualizing system configurations using a Pareto front. The delivery of optimal water management is currently constrained by the size and variety of the original set of solutions at the designer's disposal. For example, if the designer of a new housing development seeks to install a water reuse system, they might reasonably investigate the relevant British Standards; BS8595:2013 Code of practice for the selection of water reuse systems [22] and BS8515:2009+A1:2013 Rainwater Harvesting Systems—Code of practice [2]. The components and configurations included within the standards might be extracted and evaluated on a case-by-case basis using a handful of cost benefit metrics. These designs represent the total set of potential design solutions. The designer may conclude that RWH is not a cost effective option, as no solutions evaluated met the designer's budgetary constraints. Consequently, the initial target to incorporate water reuse into the development remains unmet. In graphical form, this is conceptualised in Figure 1. It is evident from this graphic that expanding the original set of solutions can increase the likelihood that suitable RWH system configurations can be identified. In this example, Figure 1 identifies that two previously "unseen" solutions are available to the designer that are within budget but were not considered in the previously limited decision space. It is proposed that the development of a quantitative RWH assessment tool that incorporates a range of criteria will enable practitioners to widen the decision space and implement RWH systems in locations where single objective benefit appraisals fail to satisfy cost benefit criteria.

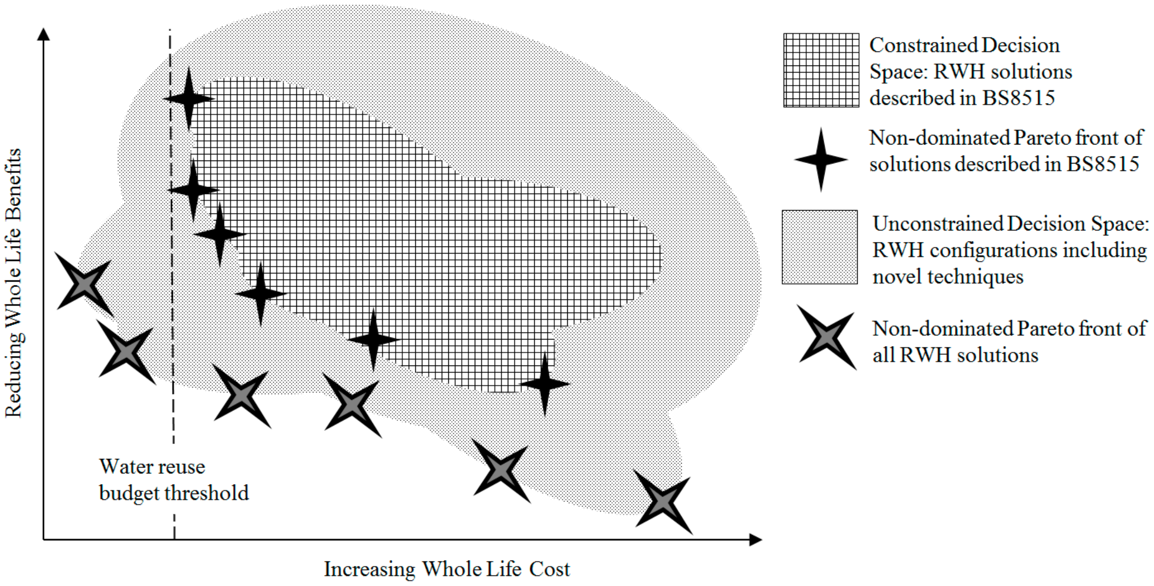

Figure 1. Conceptualising the benefits of innovative design of novel RWH system configurations (adapted from Coombes [21]).

1.4. Multi Criteria Analysis

Multi criteria analysis (MCA) methods are frequently used in the field of integrated water management to support decision makers who wish to differentiate between options with complex, multi-faceted characteristics [23–26]. The methods typically follow a structure as follows [27]: define the problem, identify alternative options, define criteria and associated objectives, populate performance matrix and evaluate performance against criteria. With values for each criteria defined, previous studies have deployed a range of methods such as weighted summation or range of value methods [25]. These techniques add a final tier of expert judgement to enable the preferred option to be selected from those which perform strongly. The MCA method used in this paper describes innovative systems and identifies a process for differentiating between them. In a final step, three scenarios are defined to assess technology selection based on user preferences.

2. Method

The method adopted in this paper is a simple linear weighted MCA based on the following 6 steps, adapted from [27].

Step 1—Define the problem and associated parameters. A well-defined problem statement was needed to enable the MCA to be developed.

Step 2—Identify alternative options. A comprehensive literature review of existing and emerging RWH system configurations was conducted to identify and define their characteristics.

Step 3—Define criteria and associated objectives. The literature review identified a number of drivers (objectives) which have enabled five criteria to be defined for RWH implementation at a household level in the UK. Details of technologies and criteria were established from a broad range of sources, which included: patent searches, meetings with industry suppliers, site visits, conference attendance, facilitating workshops, innovation events with rainwater practitioners, collaborative design partnerships and reviews of industry texts and the peer-reviewed literature.

Step 4—Populate performance matrix. With system configurations and criteria defined, quantitative methods were used to evaluate each configuration.

Step 5—Evaluate performance against criteria. Results were generated to benchmark the configurations against one another to demonstrate how they perform when each criteria is considered as the sole objective in selecting a RWH configuration.

Step 6—Scenario Testing. Three hypothetical scenarios were defined and weightings allocated to the MCA in order to illustrate the effectiveness of the MCA approach as a decision support tool.

The UK has seen many developments and innovations in RWH design configurations, both within the RWH industry and within the academic research community [28–32]. The identification of details of these systems form the basis of Step 2. A summary of traditional and innovative RWH configurations is described in Section 3.2. A matrix was constructed to allow values for each configuration to be derived from literature or calculated against the five criteria determined in Section 3.3. The criteria were utilised to evaluate the configurations against each objective. To achieve this, a fixed set of parameters was used to define a case study house against which each RWH system could be assessed using a time-series model. For simplicity, the paper illustrates how the systems compare when assessed against a single house. The intention is that the method can be further utilised in order to allow decision makers to assess the range of RWH systems against any site.

3. RWH System Configurations and Drivers

This section describes the process of applying the previously described 6 MCA steps using the RWH industry as its focus.

3.1. Step 1—Define the Problem and Associated Parameters

The method set out in this paper seeks to answer the following problem statement:

"Identify a quantitative method to evaluate the broad benefits of a range of traditional and novel RWH technologies at a given location."

A set of fixed parameters was generated to enable comparison of RWH technologies to be undertaken at a domestic property. Parameters for a typical UK house are described in Table 1. The property is assumed to have: a pitched roof with a plan area of 60 m^2, four occupants utilising 150 L/person/day (with a usage ratio based on existing literature [33]), space and structural capacity for up to 2 No. 0.25 m^3 loft or wall mounted header tanks, and can accommodate up to 5 m^3 of above ground or below ground storage.

Table 1. Defining the characteristics for a typical UK house.

Model Parameter	Reference	Value
Roof Area (m^2)	User Selected	60
Roof Runoff Coefficient	User Selected	0.9
First-Flush Losses (L/day)	User Selected	5
Usage Ratio (WC:Laundry:Potable:Other)	[33]	30:20:5:45
Tank storage size	User Selected	• 0.5 m^3 if located in loft • 0.5 m^3 if located externally for gravity feed • 5 m^3 if located at or below ground level. (Storage volume reduced to 4.5 m^3 where mains top up also enters storage tank)
Time-series rainfall data	Exeter, UK	Daily rainfall (mm) records for Exeter, UK

3.2. *Step 2—Identifying Alternative Options: RWH System Configurations*

RWH systems comprise a number of components, which typically include: gutter systems, filters, storage tanks, tank overflows, pumps, pressure vessels, pipework, valves, backup supply systems, sensors/float switches and electronic controllers. Details of these components can be identified through grey-literature available from RWH providers [8–10] and are described in BS8515:2009+A1:2013 [2]. Detailed descriptions of well-defined components are not included here as they are already suitably described in existing texts [34]. Existing literature describing RWH typologies chiefly focuses on a small number of potential configurations [6]. Furthermore, some terminology used does not match terms used by current UK RWH suppliers. The following typologies aim to extend and clarify these terminologies.

3.2.1. Best Practice in the UK: Traditional RWH System Configurations

In the UK, residential RWH systems typically utilise buried tanks although above ground tanks are also sometimes installed. Pumped flows are delivered via direct-feed or header tank systems. Consequently, four traditional RWH system configurations were identified as representing current best practice for household installations as described in Figure 2 [8–10]. The systems illustrated in Figure 2 each capture rainfall from the roof and store the filtered water in below ground (Figure 2a,c) or above ground (Figure 2b,d) tanks. Rainwater is then delivered by a submersible pump to non-potable applications either by direct-feed (Figure 2a,b) or via a header tank (Figure 2c,d). For the purposes of clarity, the overflow outlet from the system is described as a sewer (for example a combined sewer network) although RWH systems can also discharge to an infiltration device, surface water sewer or watercourse, depending on the site setting.

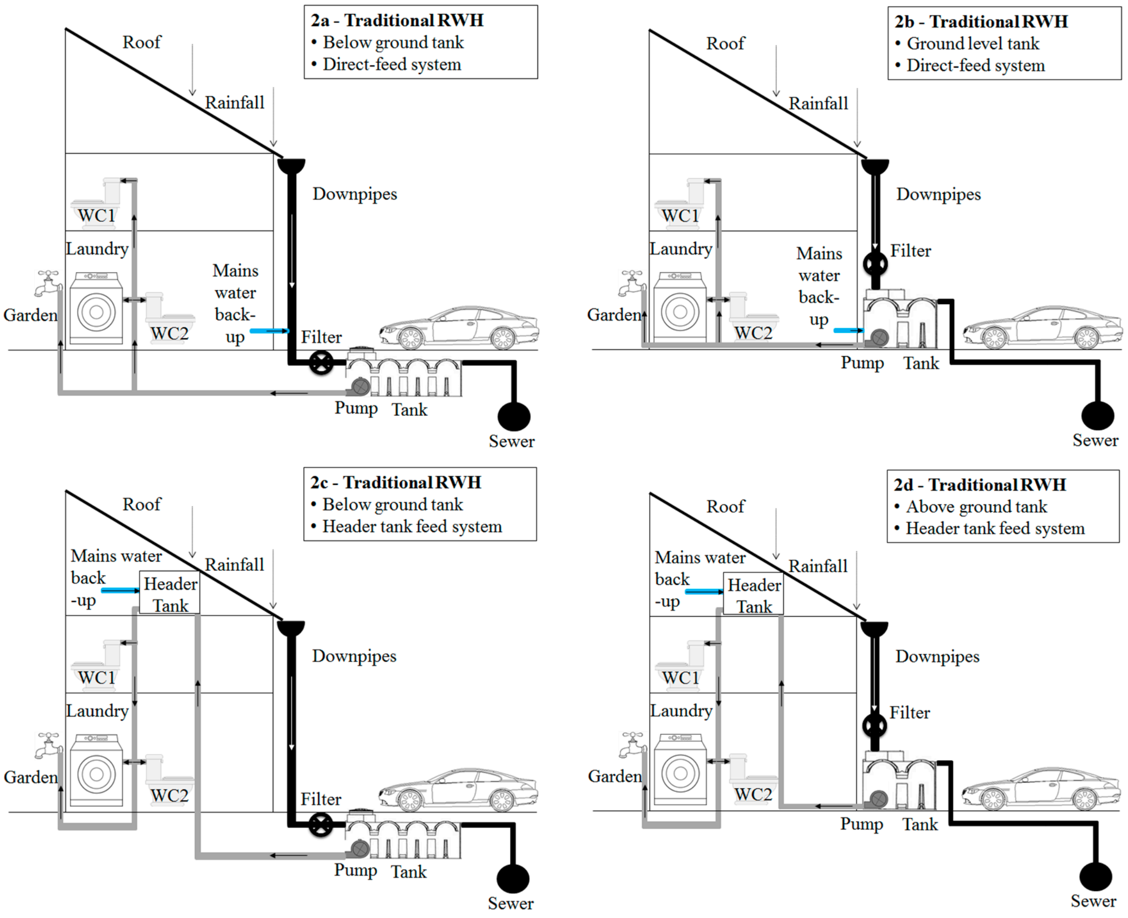

Figure 2. Conceptual schematics for four traditional rainwater harvesting RWH configurations used in the UK. (**a**) below ground, direct-feed ;(**b**) above ground, direct-feed ;(**c**)below ground, header tank feed ;(**d**) above ground, header tank feed.

3.2.2. Emerging Practice in UK: Innovative RWH System Configurations

In addition to the traditional RWH system configurations set out in Figure 2, a series of RWH innovations were identified. Through the collection of evidence, as described in Table 2, it is apparent that stormwater control potentially represents an additional key driver for innovation of RWH technologies. A summary of the innovations identified is set out in Table 2 and the configurations are diagrammatically illustrated in Figure 3.

Table 2. Innovative RWH system configurations.

System Provider and Patent No.	Description	Country	References
FlushRain Ltd., Farnham Common, UK. Patent: GB2449534	A patented suction pump system that captures rainwater from downpipes and stores rainwater in large header tanks. Easily retrofitted, with no external tanks.	UK	[35,36]
Aqua Harvest and Save Patent: GB2480834	A patented gutter-located pump system lifts rainwater into large header tanks. Easily retrofitted, with no external tanks.	UK	[36,37]
Atlas Water Harvesting Patent: GB2496729 and Rooftop Rain Patent:GB2475924 and GB2228521	A gravity-fed inlet is installed within the roof to enable ~50% of the roof to flow under gravity into large header tanks within the loft.	UK	[38–41]
Aqualogic (ARC); Rainbeetle GB2501313-B	An externally mounted tank, located near the roofline is installed to store rainwater and deliver flows by gravity.	UK	[42]
Hydromentum, Water Powered Technologies Ltd., Bude, UK.	An externally mounted header tank, drives a passively powered (zero electricity) pump to lift flows to a header tank.	UK	[43]
RainActiv, Rainwater Harvesting Ltd., Peterborough UK.	A passive rainwater discharge control (flow attenuation system) for inclusion within RWH tanks to ensure some storage is always maintained to attenuate extreme storm events.	Germany, USA, UK	[44–46]
KloudKeeper Ltd., Exeter, UK.	An active rainwater discharge control (flow attenuation system) for inclusion within RWH tanks to ensure some storage is always maintained to attenuate extreme storm events.	UK	[2]
IOTA,Melbourne South East Water (Aus) and Geosyntec, Boca Raton, FL, (USA)	A real-time control system that enables weather forecast data to support a decision maker to empty a RWH tank in a controlled way before a storm, thus ensuring capacity is available to capture extreme storm events.	Australia, Korea, USA	[47,48]
RainSafe, Newtown Mt Kennedy, Ireland	Rainwater treatment system that enables harvested rainwater to meet potable water standards.	UK	[49]

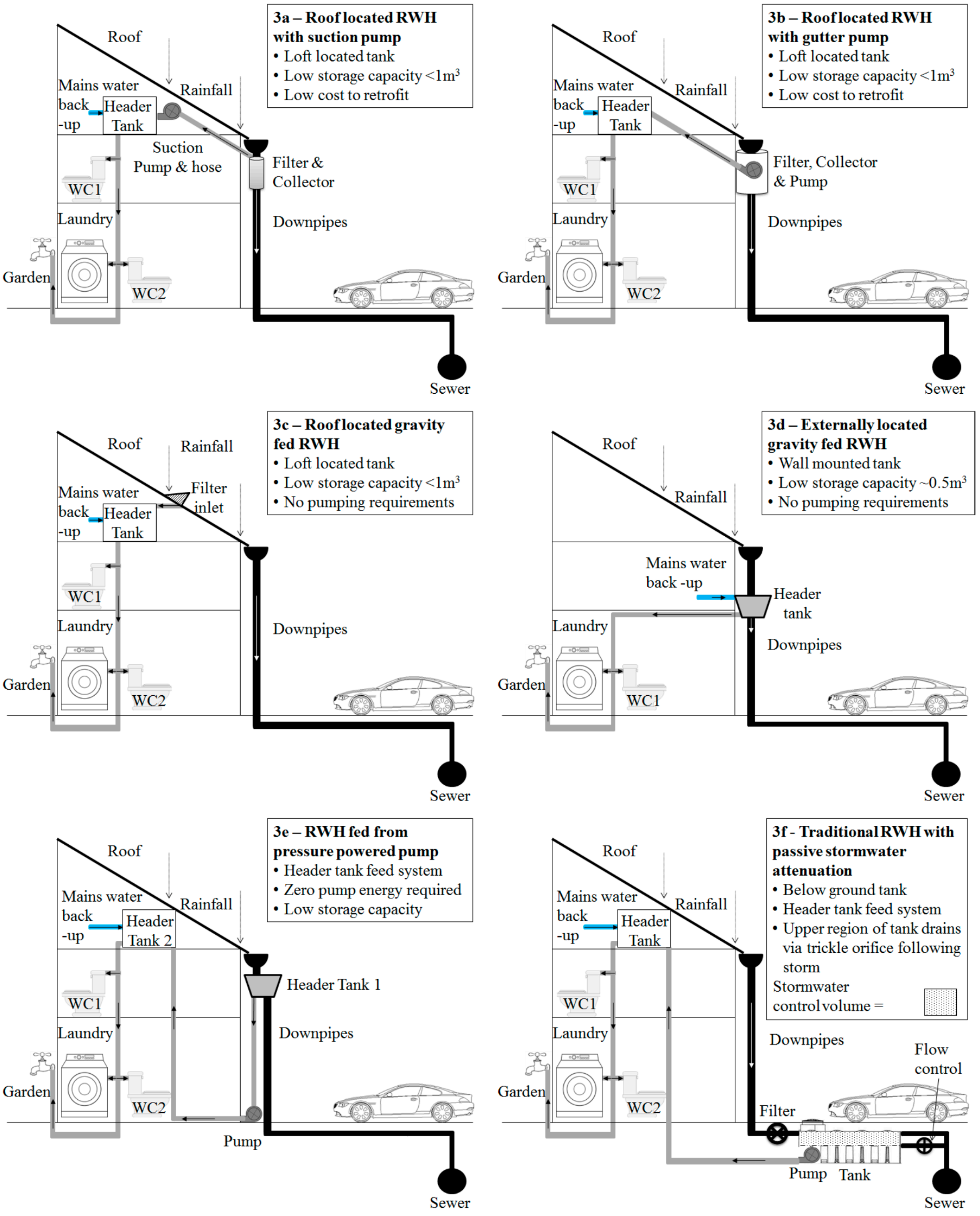

Figure 3. *Cont.*

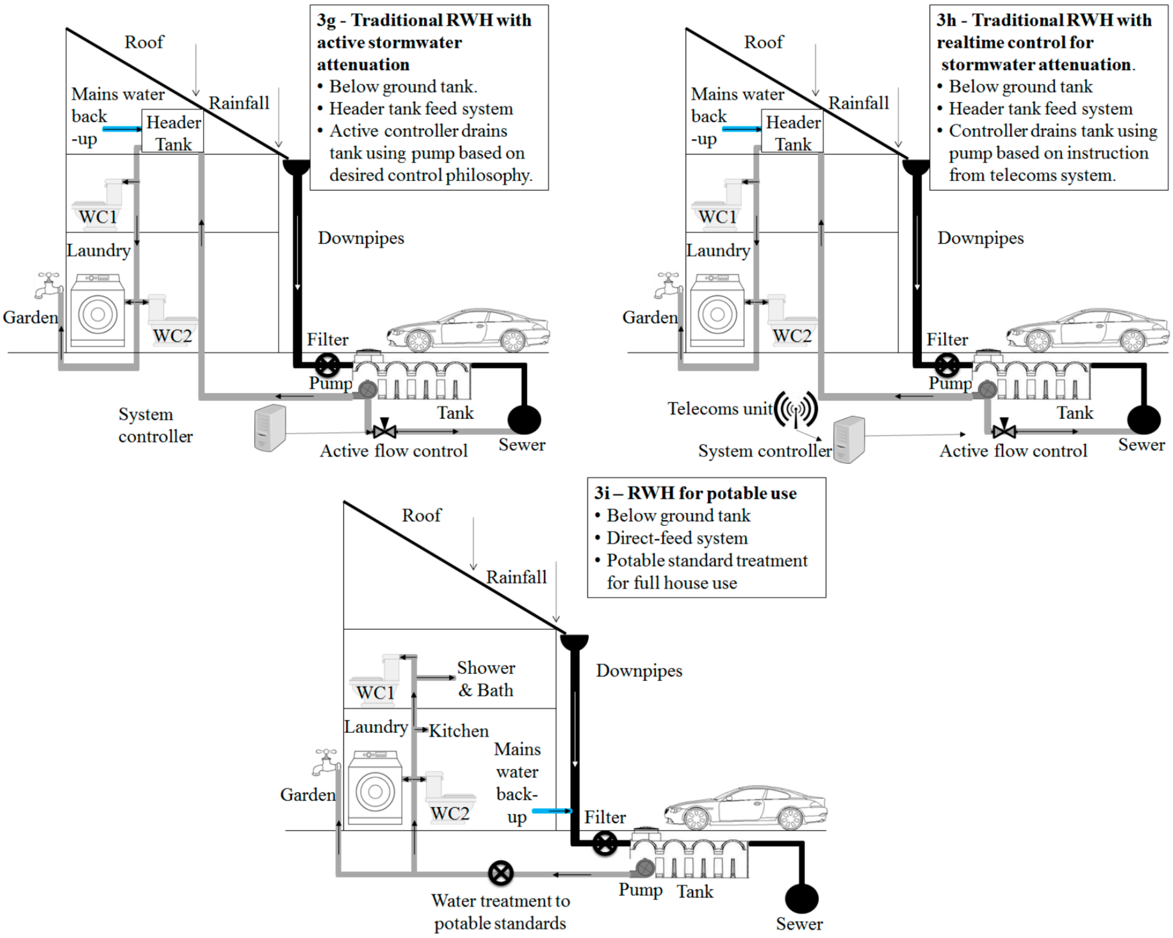

Figure 3. Innovative RWH system configurations emerging in the UK market. (**a**) Flushrain ; (**b**)Aqua Harvest and Save; (**c**) Atlas Water Harvesting / Rooftop Rain; (**d**) Rainbeetle / Aqualogic Rain Catcher; (**e**) Hydromentum;(**f**) RainActiv; (**g**) KloudKeeper; (**h**) Real time control RWH; (**i**) RainSafe.

A common theme with the first five of these innovative RWH system configurations is a high-level roof-runoff inlet, which facilitates the replacement of the large ground-level tank with wall-mounted or internal header tanks. This enables rainwater to be propelled by low energy pumps or flow under gravity into header tanks, which in turn feed appliances by gravity. A second common theme with the next three innovative RWH system configurations (Figure 3f-h) is the inclusion of a "sacrificial" amount of storage that is utilised for stormwater control. These dual-purpose RWH systems enable flow to be released from storage either passively, using an orifice at a specifically designed height in the tank, or actively through a release valve. Figure 3h describes a system that includes functionality to enable a central authority (for example the water service provider (WSP) to control tank levels based on predictive rainfall, to enable real time control of rainwater discharges to a sewer network. The final innovative RWH system is a treatment train consisting of filtration, UV and ozonation, which is designed to enable harvested rainwater to be treated to potable standards.

3.3. Step 3—Define Criteria and Associated Objectives

Previous RWH evaluation studies have focused on analyses using a traditional set of criteria (capital costs, water saving and energy consumption). In addition to these traditional criteria, this work seeks to investigate emerging criteria associated with stormwater management.

3.3.1. Traditional Criteria: Capital Costs, Water Savings and Energy Consumption

RWH systems are currently installed in the UK to provide alternative water supplies to displace reliance on potable water. Cash savings are generated for homeowners as metered water charges are reduced accordingly [1]. Minimising the capital cost of a system represents the first driver for consideration when appraising RWH configurations. Re-configuring RWH systems to minimise the capital cost could enable the market to further develop by increasing affordability to a larger number of consumer segments. A RWH system's ability to reduce water demand (*i.e.*, contribute to water efficiency) represents the second key criteria when assessing configurations. Reducing the cost of the configuration (perhaps by reducing the tank size and thus storage volume) may reduce the water savings associated with the installation, so assessment of this criterion enables the traditional assessment of RWH benefits to be evaluated. Detailed price comparison information was made available by a UK provider [50]. Where cost data have not been available (for example where prototype systems were identified that have yet to reach the marketplace), estimates were compiled based on component costs and anticipated labour requirements.

Energy consumption associated with the operation of RWH systems has been comprehensively investigated [51]. Roebuck *et al.* [14,17], illustrates the need to monitor and plan for operational energy consumption associated with pumping rainwater in RWH systems. Vieira *et al.* [51], published an extended review of power consumption for RWH systems and drew comparisons against a range of alternative water resources. This research confirmed that theoretical data for median energy consumption (0.20 kWh/m^3) typically underestimate the data from empirical studies (1.40 kWh/m^3). Viera *et al.* [51] also exemplified the challenges associated with generalisations in energy consumption. Factors such as pump efficiency, pipe friction, fittings (e.g., controls such as ball valves), usage rates, pump start-up factors and control systems all have a role to play. In the UK, Ward *et al.* [52], showed that electricity use for a traditional RWH system installed at an office building was 0.54 kWh/m^3. Raw data were also provided by a supplier who monitored their traditional household-scale RWH system (RainDirector) with a header tank feed. This illustrated that it achieved an energy consumption of 0.68 kWh/m^3 in a laboratory setting and that fewer pump starts were needed than for equivalent direct feed systems [53], which would therefore be expected to have a higher consumption.

The mean energy consumption for UK municipal water supply has been reported as 0.60 kWh/m^3 [54]. European average municipal water supplies are also quoted at a similar level of 0.46 kWh/m^3 [54]. RWH configurations that are able to provide water at a lower energy consumption than the municipal supply could therefore be supported on energy/carbon emission reduction grounds. Consequently, the energy consumption of each RWH configuration represents a suitable criterion to review in terms of kWh/m^3 of water delivered [51]. Where possible, energy costs allocated to each RWH system were taken from literature, although some first principles assumptions were necessary (for example RWH systems with lower total head are likely to have a lower energy consumption than those which pump against a higher head).

3.3.2. Emerging Criteria: Stormwater Management and Reducing Combined Sewer Overflows

Through intercepting and using rainwater where it falls (source control), stormwater discharges to sewer systems are reduced as less rainwater enters the sewer network during a storm. Gerolin *et al.* [30], illustrated that RWH can reduce stormwater discharges successfully when the non-potable demand of a property exceeds the rainwater yield. Supporting this, a number of modelling studies on RWH systems have demonstrated their ability to reduce stormwater runoff volumes and rates [55–58]. However, none of the traditional systems outlined in Figure 2 is designed to focus on this functionality.

Variability in extreme rainfall events has been evaluated by Lash *et al.* [59]. This study incorporated modelling approaches (via a probabilistic tank-sizing tool) applied to case study locations in the UK using UK Climate Projections 2009 data. Analysis revealed tank sizes would need to be larger in order to accommodate the increased likelihood of periods with no rainfall. This approach would add support to historic stormwater control approaches set out in Gerolin *et al.* [30], which calls for intentionally oversized RWH tanks to minimise stormwater discharges. The original British Standard for RWH, BS8515:2009 [60], included an approach that encouraged users to size storage tanks to supply a household's non-potable water demand for 18 days. The Standard's "design methods" did not include parameters relating to stormwater control. This single objective approach potentially discouraged technological innovation from RWH system suppliers. Despite this, some technological innovation has been achieved as systems have become increasingly easy to install due to the "plug and play" nature of the components provided [9]. The original Standard also suggests that designers can implement systems that achieve stormwater control by including: "*green roofs; a tank which attenuates flows with an outlet throttle to discharge excess flows; a large tank which is sized for stormwater storage and automatically pumped out or otherwise drained; a tank which is connected to an infiltration system for excess flows*." [60] (p. 32). A recent update to the British Standard [2] now includes an additional technical annex that encourages the design of source control benefits when sizing RWH. However, the stormwater control objective remains outside the scope of the Standard's core tank-sizing calculations. The UK's incumbent RWH system providers do not currently produce systems that provide source control in line with UK guidance. However, it is anticipated that novel configurations that achieve this will be available in the near future as development is underway and products are beginning to be launched [44].

Controlling stormwater discharges to combined sewer networks can mitigate the risks of pollution events from sewage spills during intense rainfall. Reducing combined sewer overflow discharges (in terms of frequency and volume) represents a key area of Asset Management Plan (AMP) investment for a number of UK WSPs [61]. WSP projects such as RainScape, WaterShed and the Urban Demonstrator are underway, which seek to deliver and monitor pilot studies where retrofit stormwater management solutions are being trialled to reduce sewer flooding and associated pollution of watercourses from spills at combined sewer overflows [61–63]. RWH systems that are configured to satisfy the stormwater reductions targeted by WSPs could potentially see them become a viable option alongside other retrofit SuDS approaches over the next decade.

RWH systems evaluated in this study were appraised against two stormwater-related criteria: (1) The reduction in peak daily stormwater discharge volumes; and (2) The reduction in annual average stormwater discharge volumes.

3.3.3. Summarising Criteria for Evaluating RWH Design Configurations

The discussion presented in the previous sections enabled a range of criteria (and associated objectives) to be defined. These are summarised in Table 3 and can be used to evaluate the RWH configurations outlined in Figures 2 and 3. Other criteria, such as the ease of retrofitability, end-user acceptability and lifetime maintenance requirements, have not been considered in the present analysis, but are the subject of on-going research.

Table 3. Criteria for evaluation of RWH system configurations.

Criteria	Objective
C_1 Capital cost of RWH system (£/installation)	O_1 Minimise capital cost of system
C_2 Water Efficiency (m^3/annum potable saved)	O_2 Maximise water saving of system
C_3 Change in operational energy consumption for water supply (kWh/annum)	O_3 Minimise energy required to supply household water
C_4 Reduction in stormwater flow during extreme events (m^3/day)	O_4 Minimise discharge volume of rainwater during largest 24 h storm in 20 year time-series
C_5 Reduction in annual stormwater discharge to sewer (m^3/annum)	O_5 Minimise annual average discharge volume to sewer network

3.4. Step 4—Populating Assessment Matrix: Details of Quantitative Assessment Methods and Criteria for Calculation

In order to populate the assessment matrix, an input/output flow balance model was developed as a VBA spreadsheet tool, based on earlier RWH studies [2,34,64], but here incorporating additional stormwater related outputs. The model uses the "Yield After Spillage" algorithm whereby rainwater is added to the storage volume recorded for the previous time step. Next excess flows are overflowed prior to extracting demand at that time step [64]. Where intentional stormwater discharges are released from either passive or active controls, these also occur prior to demand being extracted [34]. A runoff factor of 0.9 is assumed. A daily time step was used, which matched the 20-year input rainfall time series for Exeter, UK. The model parameters used to define the property and system simulated are given in Table 1. Criteria C_2 (water saving), C_4 (reduction in maximum daily stormwater discharged) and C_5 (reduction in average annual stormwater discharged) were calculated from the flow balance for each RWH system. C_1 (capital cost) and C_3 (change in operational energy consumption) were calculated as explained in the next section. The model enables outputs to be derived from an annual simulation with rainfall, demand and stormwater spill volumes calculated at the daily time step. Outputs were generated for each day of the year, and the simulation was repeated using 20 annual rainfall files.

C_1 Capital cost of RWH system: Values for this criterion were derived outside the flow balance model. They were based on best available information on material costs and labour costs required to install each RWH system evaluated. Costs are defined in terms of £/installation and as a percentage of the highest cost option.

C_2 Water efficiency: Water efficiency was taken as the average non-potable water demand satisfied by the RWH system over the 20-year simulation period and is given in m^3/annum. The house's remaining potable water demand and the reduction in potable water usage were calculated.

C_3 Change in operational energy consumption for water supply: Operational power consumption for each configuration was taken from the literature with first principles used to differentiate between novel systems where empirical data were not available. Power consumption increases and decreases for annual water supply were recorded as a percentage of the baseline scenario (*i.e.*, a house without RWH receiving only municipal water).

C_4 Reduction in stormwater flow during extreme events: The largest 24 h storm event recorded over the 20-year period was used to evaluate each RWH system's ability to reduce the discharge volume. The difference between the volume controlled when each RWH system was modelled compared with the volume spilled without RWH was used to define these values. The percentage change between the scenarios was also calculated (*i.e.*, the percentage of stormwater successfully controlled by each RWH system during the largest storm event).

C_5 Reduction in annual stormwater discharge to sewer: The annual average reduction in stormwater discharges to the sewer was derived as the difference between uncontrolled overflows to the sewer when RWH is included *vs.* the annual volume spilled without RWH installed. The percentage change between the scenarios was also calculated (*i.e.*, the percentage of annual stormwater successfully controlled by each RWH system).

With simulations completed and outputs derived for the range of options tested, the performance matrix was populated and an analysis conducted as described in Section 4.1.

4. Results and Discussion

4.1. Step 5—Evaluate Performance of RWH Configurations against Criteria

Using the quantitative assessment methods described, an evaluation matrix was defined (Table 4) to summarise simulated performance of the RWH configurations under each criteria.

Table 4. Populated Evaluation Matrix for Criteria Associated With 13 RWH Configurations.

Criteria	**RWH System (Reference Figure)**													
	No RWH	**2a**	**2b**	**2c**	**2d**	**3a**	**3b**	**3c**	**3d**	**3e**	**3f**	**3g**	**3h**	**3i**
C_1 Capital cost of RWH system (£)	0	4300	3800	4800	4300	1050	1030	1000	1000	2000	5300	5550	6300	6100
C_1 Capex relative to highest cost option (%)	0	68	60	76	68	17	16	16	16	32	84	88	100	97
C_2 Water Saved (m^3/annum)	0	34	34	34	34	23	23	16	23	7	32	34	34	40
C_2 Mains water consumed (m^3/annum)	219	185	185	185	185	196	196	202	196	212	187	185	185	179
C_2 Water Efficiency: Change in mains water use/annum (%)	100	84	84	84	84	89	89	92	89	97	85	84	84	82
C_3 Energy cost for RWH system (kWh/m^3)	0.0	1.1	1.0	0.8	0.7	0.1	0.1	0.0	0.0	0.0	0.7	0.8	0.9	2.0
C_3 Energy cost of rainwater delivered per annum (kWh)	0	38	35	28	24	3	3	0	0	0	22	28	31	80
C_3 Energy cost of mains water used per annum (kWh)	131	111	111	111	111	117	117	121	117	127	112	111	111	107
C_3 Total energy cost per annum (kWh)	131	148	145	138	134	120	120	121	117	127	135	138	142	187
C_3 Change in operational energy (kWh/annum)	0	17	14	7	3	−11	−11	−9	−13	−4	3	7	10	56
C_3 Change in operational energy (%)	100	113	110	105	103	92	92	92	89	97	102	105	108	143
C_4 Reduction in stormwater flow during extreme event (m^3)	0	3.3	3.3	3.3	3.3	0.5	0.5	0.5	0.5	0.5	2.5	3.3	4.9	4.5
C_4 Change in stormwater flow during extreme event (%)	0	67	67	67	67	10	10	10	10	10	51	67	100	92
C_5 Reduction in annual stormwater discharge to sewer (m^3/annum)	0	37	37	37	37	22	22	17	22	8	33	37	40	40
C_5 Change in annual stormwater discharge to sewer (%)	0	91	91	93	93	56	56	43	56	20	82	93	100	100

Figure 4 illustrates the ability of each system to perform when plotted against the five criteria. This figure describes the data in a normalised format. For C_1–C_5, each value is divided by the maximum score to give output values between 0 and 1. For C_4 and C_5, this value is subtracted from 1. Hence, the system with a value closest to 0 is the best performing under that criterion. When a single criterion is selected, the results show that there is always at least one novel configuration available that outperforms the four traditional systems (Systems 2a-d). This illustrates that the current RWH configurations deployed in the UK do not necessarily represent the optimal design when broader criteria are included in their evaluation. The traditional RWH systems are outscored by a number of novel RWH system configurations in relation to a number of criteria (for example System 3b and System 3d have lowest cost (C_1) and lowest energy (C_3) ranks). The real time control strategy associated with System 3h was able to fully prevent uncontrolled stormwater spills for every storm in the 20-year study period. In addition, the high demand (600 L/day) associated with System 3.i's potable use ensured this system was also able to reduce the largest storm event in 20 years by 92%. The passive stormwater controls associated with System 3g reduced the extreme storm event by 67% and limited total stormwater discharge volumes to just 7% of the "No RWH" scenario. Evidence from this analysis suggests that the current RWH systems being implemented in the UK can be improved to better satisfy the criteria highlighted in this paper.

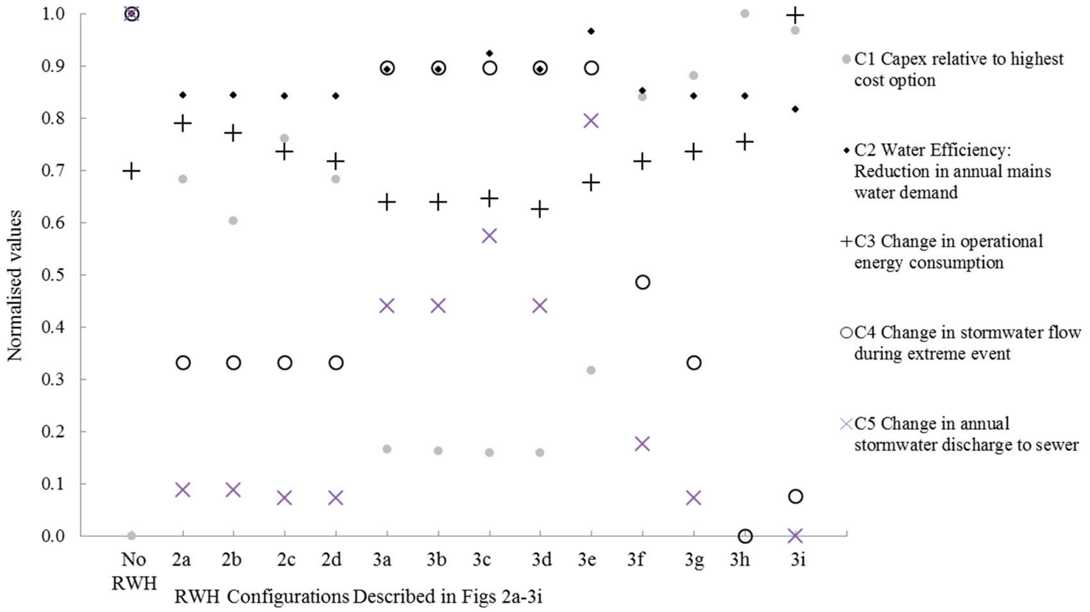

Figure 4. Normalised performance of RWH configurations against a range of design criteria (best scoring systems have lowest values for each criteria).

4.2. Step 6—Scenario Testing

The MCA developed in this paper can be deployed as a method for selecting a configuration for a specific site by adding user-based weightings to define the relative importance of each criterion. Such an approach could be deployed by decision makers to test how different weightings affect the selection of a RWH system. To enable this, the decision maker allocates weightings across each criterion that total 1 unit. Three scenarios are defined below to illustrate in outline how the preferred configuration might be defined by differing decision makers. The assumptions made in the scenarios are based on the authors' knowledge.

Scenario A—A RWH designer concludes that all criteria have equal weight and 0.2 units are applied to each. The MCA suggests that system 3h (traditional RWH with RTC) is the preferred option as it has the lowest total score across all criteria.

Scenario B—A householder wishes to retrofit a RWH system at the lowest possible capital cost. No other criteria hold importance in the system selection process. A weighting of 1 unit is applied to the C_1 *Capex relative to highest cost option* and all other weights set to zero. The MCA selects system 3c3 (roof located, gravity fed gravity RWH) or 3d4 (externally located, gravity fed gravity RWH).

Scenario C—A WSP plans to retrofit houses with RWH as a water demand reduction measure. They also have a secondary objective to reduce peak stormwater flows at a local pumping station. Costs are not an important factor as no alternative solutions have been identified by the WSP. A weighting of 0.75 units is applied to C_2 *Water Efficiency* and 0.25 units allocated to C_4 *Change in stormwater flow during extreme event* to ensure these dominate the remaining criteria. System 3i (RWH for potable use) is identified as dominating other options as this configuration scores best in terms of water demand reduction and is also able to mitigate 92% of the peak storm discharge during the largest storm event tested.

The three scenarios considered above each illustrate the ability of the MCA method to readily offer a high level focus for a designer to identify suitable RWH options under a range of settings/ site objectives.

5. Conclusions

This paper presented the identification, description and multi-criteria analysis of existing and novel RWH configurations that could be adopted at UK households to satisfy a broad range of property and regime level drivers. The evaluation criteria were defined as follows: reduce capital costs, maximise water saving efficiency, minimise operational energy consumption associated with water supply, minimise peak stormwater discharges, and minimise annual stormwater discharges. A broad range of RWH configurations are emerging in the UK marketplace. Through benchmarking each configuration using the MCA, it was possible to score each system's ability to satisfy a number of key RWH criteria. Evidence from the MCA illustrates that the traditional RWH configurations are not necessarily the optimum solutions when broader criteria are considered. However, the specific technology selected will depend on the preferences of the decision maker or user, as illustrated by the three scenarios. Based on these results, it is suggested that minor alterations to existing RWH technologies, such as integration with real time stormwater control devices, could see demand for RWH systems grow in the years ahead. This may be the case where stormwater control is desirable to meet drainage design criteria at new developments, or to reduce sewer flooding and spills in existing combined sewer catchments. The identification of RWH systems as a multi-functional technology is exemplified in this paper. Further empirical studies are now underway to enable novel benefits of emerging RWH system configurations to be further quantified, understood and exploited by a range of decision makers.

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Conflicts of Interest: The work reported here builds upon a series of research and development projects that have been undertaken in collaboration with Severn Trent Water and a number of the RWH system providers referenced in this paper. The authors have sought to balance input from a range of these sources and to minimise the reliance on grey literature when opportunities have permitted.

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