The Effects of Allocation Strategies in Multi-nodal Large Scale Rainwater Harvesting Systems

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ABSTRACT

Rainwater harvesting (RWH) is a valuable technology that is most often seen applied on a small scale. Large scale rainwater harvesting (LSRWH) systems are potentially a more effective way to collect available rainwater and combat urban flooding. LSRWH systems can be considered to be multi-nodal networks comprising multiple rainwater demand and storage nodes. A key element of designing a network is the strategy used to allocate water between available storages and demands. Research has been undertaken to investigate four simple allocation strategies on a small scale network comprising 2 demands and 2 storages (D2S2), arranged in five different layouts. The aims were firstly to establish whether the effects of allocation strategy and layout on the network performance were significant and/or predictable, and secondly to explore whether an optimal layout/allocation strategy could be defined. System performance was measured in terms of total yield, spillage, mains top-up (or demand not met), pumping requirements, and number of days tanks are empty or full. Results showed that allocation strategy affected all of these outputs, in particular pumping requirements, which can be significantly reduced. An optimal layout can be defined by weighting the results, though the weighting scheme chosen will depend heavily upon local site conditions.

KEYWORDS

Rainwater harvesting, modelling, optimisation, water efficiency, energy savings

INTRODUCTION

Rainwater harvesting is a technology that has the potential to increase water security/efficiency, as well as helping to address issues related to urban flooding. However, it is typically understood in terms of small, self-contained systems, such as those used for single residences or commercial buildings. Spatial lumping can be employed to represent large areas using large numbers of similar small systems (Xu *et al* (2010)). However, this approach is not universally applicable, and for example would not be effective for industrial applications where water demand and building size can vary considerably on a single site.

Large scale rainwater harvesting (LSRWH) design aims to make maximum use of rainwater in a large catchment, such as an urban neighbourhood or factory complex, by managing it as a single large system or network instead of multiple small ones. A single system like this can be understood and modelled as multiple points requiring a water supply (i.e. demand nodes) and multiple storage locations (storage nodes).

There are not many examples of LSRWH systems in the literature. Hashim *et al.* (in press) presents a system with a single storage and a single point of demand, with the storage node fed by multiple collection areas that make up a large catchment. However it is not clear that a single storage is necessarily an optimal configuration for a large site, nor is it expected that it will be universally true of large sites that all of the demand can be met at a single point. A multi-nodal modelling approach could potentially be used to determine a more efficient system design, for example by minimising the pumping work, and therefore the energy use of a system. Figure 1 shows an example of the kind of comparitive study that could be performed with multi-nodal modelling.

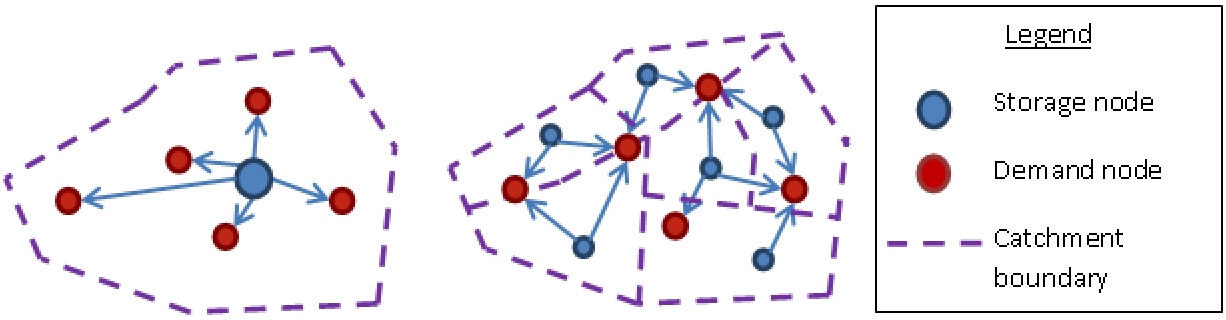

Figure 1. Large single storage versus multiple small storages.

In YAS or YBS modelling (yield after spillage/yield before spillage respectively), the order in which yield and spillage are deducted from available water in each time step impacts on the design outcomes (Jenkins & Pearson, 1978). Similarly, multiple storage and demand networks require an order of demand and storage node selection. Modelling therefore needs a means to differentiate between and prioritise individual demand/storage nodes within each model time step: referred to as the ‘allocation strategy’ in this paper.

It should be noted that system performance can be measured in a number of ways, such as the efficiency with which demand is met, and various cost factors. This paper aims to explore how different performance metrics are affected by the network layout and the allocation strategy.

Basic and complex multi-nodal modelling

Figure 2. D1S2 and D2S1 basic model layouts.

Figure 2 shows examples of the simplest multi-nodal layouts comprising 3-nodes only. The nomenclature employed is of the basic form DxSy, where x is the number of demand nodes and y is the number of storage nodes. For these simple models there are two scenarios: multiple storages per demand, and multiple demands per storage (D1S2 and D2S1 respectively), meaning that allocation is either based on storage selection or demand selection. In the D1S2 layout, for example, the allocation strategy might require the fullest storage to be utilized first, or the nearest storage, or an equal volume from both.

For more complex networks (D2S2 and above), the allocation strategy needs to determine priorities based on both demand and storage node characteristics. This is done by applying prioritization criteria to the storage-demand links, with different allocation strategies defined by applying different weightings to these criteria. In this study three prioritization criteria were used: link length, the fullness of the link's storage node, and the rate of demand at the link's demand node. Four allocation strategies were defined using these (Table 1):

Table 1: Example allocation strategies

Allocation strategy Name	Weighting applied to prioritisation criteria		
	Link length	Link demand rate	Link storage fullness
(1) 100% shorter links	1.0	0.0	0.0
(2) 100% fuller storages	0.0	1.0	0.0
(3) 100% higher demands	0.0	0.0	1.0
(4) Equal weighting	1.0	1.0	1.0

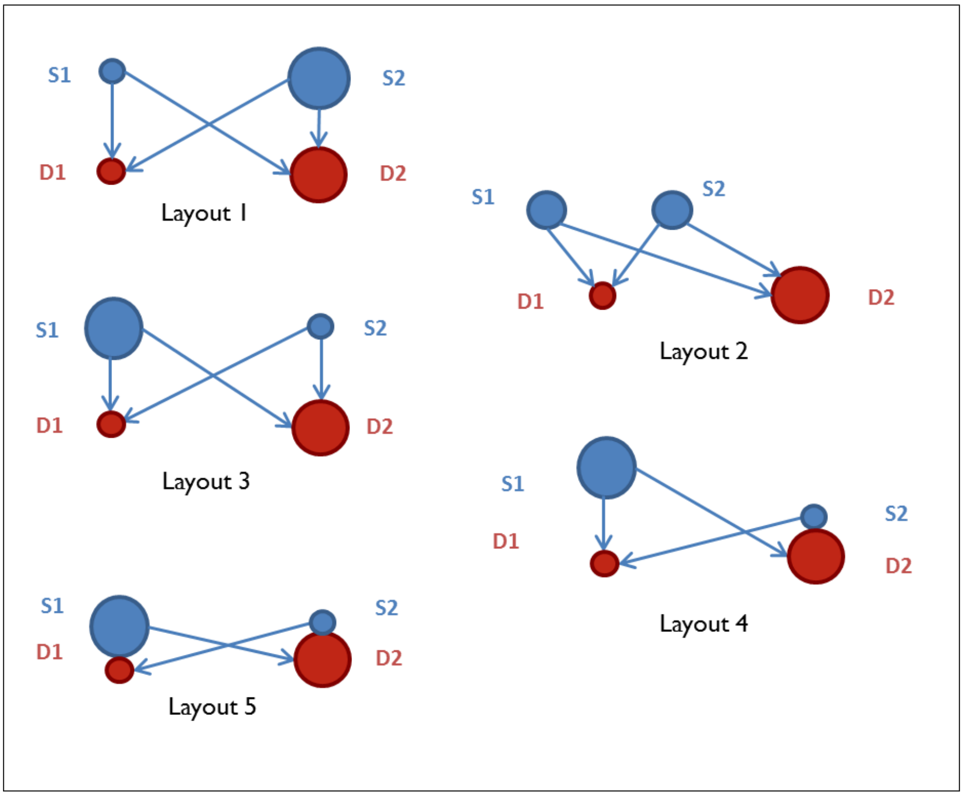

Figure 3. Example D2S2 layouts used in the modelling process

SCOPE OF STUDY

In this investigation, a small, representative range of allocation strategies and D2S2 layouts was modelled to develop an initial understanding of the effects of applying different allocation strategies. The layouts in Figure 3 and the allocation strategies in Table 1 were used, giving a total of 20 different model permutations. Each of these was then evaluated using a long-term simulation using a synthetic 30 year rainfall time series generated using the UKCP09 Weather Generator (UKCP09, http://ukclimateprojections.defra.gov.uk/)[1]. In all cases, it was assumed that each of the two storages had an effective collection area of 20,000 m^2 and that no losses occurred due to hydrological processes (infiltration, evapotranspiration etc.). Total demand was a constant rate (5 m^3/hr) for the whole duration, and total storage was set to ten days' demand (1,200 m^3).

The modelling process employed the YAS approach, i.e. within each time step, spillage is subtracted before yield is calculated (Jenkins *et al* (1978)). The approach was adapted to incorporate multiple nodes and the use of allocation strategies. YAS was used as it is well understood within the RWH systems literature, and is considered to give accurate, conservative results (Fewkes & Butler (2000), Schiller & Latham (1987), Roebuck & Ashley (2006)).

To classify the layouts used, they can be termed 'matched' and 'mismatched', where 'matched' has appropriately sized storages closer to their respectively sized demands (layout 1) and a mismatched layout is the opposite (layouts 3-5). Layout 2 fits neither category, with two equal storages a long distance from the largest demand.

Table 2. D2S2 Node Details

Layout No.	Storage volumes (m^3)		Demand rates (m^3/hr)	
	S1	S2	D1	D2
1	300	900	1.25	3.75
2	600	600	1.25	3.75
3	900	300	1.25	3.75
4	900	300	1.25	3.75
5	900	300	1.25	3.75

Table 3. D2S2 Link Details

Layout no.	Link length (m)				Total link length (m)
	D1 – S1	D1 – S2	D2 – S1	D2 – S2	
1	5.0	25.3	25.5	4.0	59.7
2	10.0	2.2	35.0	23.0	70.2
3	5.0	25.3	25.5	4.0	59.7
4	5.0	25.0	25.5	0.0	55.5
5	0.0	25.0	25.0	0.0	50.0

System performance was measured using six metrics: total rainwater yield (i.e. volume used to meet demand), total spillage, total mains top up (i.e. rainwater shortfall), total pumping work required (volume multiplied by distance between storage and demand), and the total number of days that either storage tank was empty or full (these can be useful for assessing the efficiency of storage tank size, and should ideally by minimised).

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[1] Data was generated for the Port Talbot location, as the ultimate focus of the research programme is to consider rainwater harvesting strategies for the Port Talbot steel plant.

Some predictions of the effects of altering the allocation strategy/layout were made before modelling:

(1) Of the allocation strategies (see Table 1), '100% shorter links' should minimise pumping work and '100% fuller storages' should minimise spillage. Clear predictions could not be made about '100% higher demands' and 'equal weighting'.

(2) Of the different layouts (see Fig 3), the 'matched' layout was expected to perform the best in all areas, but possibly requiring more pumping work than layouts 4 and 5 as they have shorter total link lengths. Layout 2 was expected to perform the poorest in all areas, especially in pumping requirements.

RESULTS OF THE MODELLING

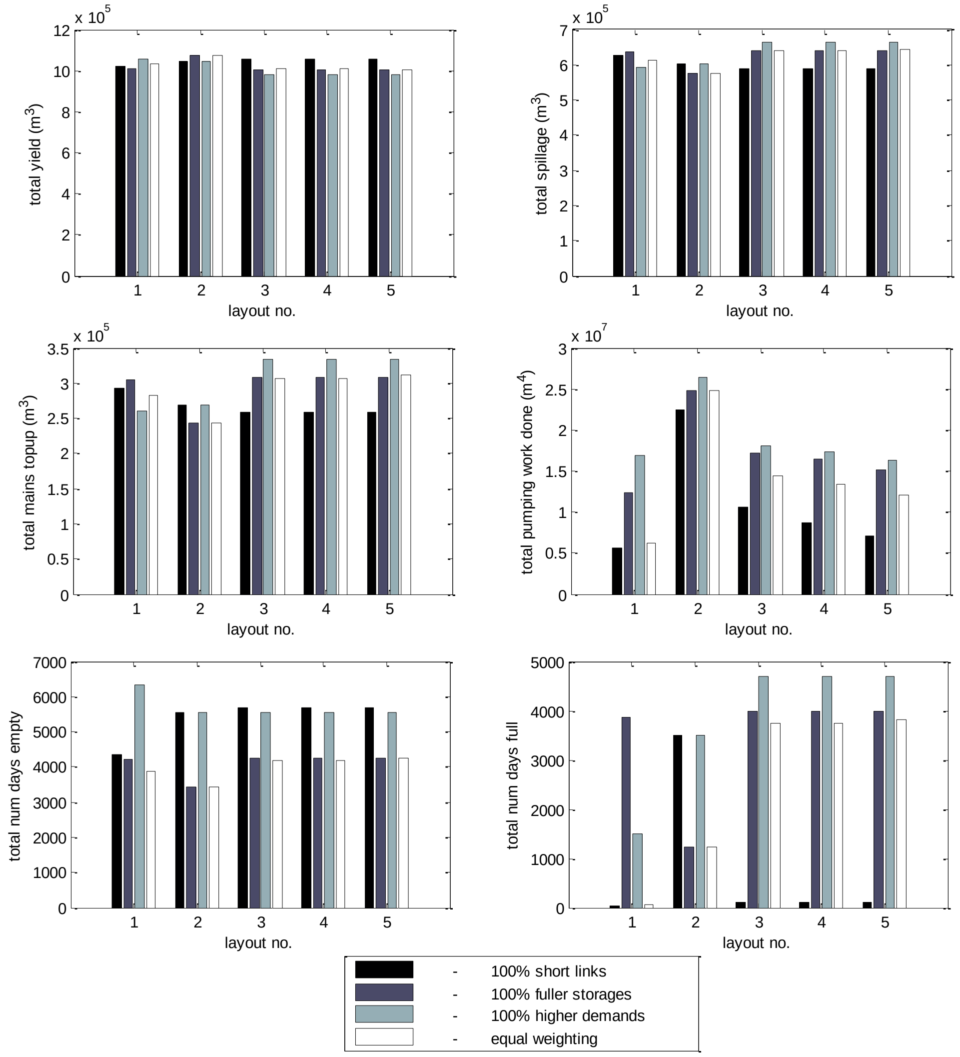

Figure 4. Model results.

The model results (Fig 4.) clearly show the impact that allocation strategy has on the performance of a RWH system. The variations in yield, spillage and mains top up are relatively low, but are not insignificant as the costs associated with small changes could be large in some situations e.g. a site where the cost of mains water supply may be heavily regulated. Pumping work and days full/empty results are greatly affected by allocation strategy, to the point where the allocation strategy choice could be considered more important even than layout design.

In terms of predictability, the hypothesis that ‘100% shorter links’ would result in the lowest pumping requirements was universally accurate. This is a useful outcome, as this metric has the most significant variation between allocation strategies.

Other predictions were not as accurate: firstly, use of ‘100% fuller storages’ didn’t give the expected lowest spillage results, except for layout 2. Secondly, layout 2 has the two highest yield results of the whole sample, despite it being expected to perform badly. However, in terms of pumping work, it is clearly outperformed by all other layouts, as hypothesised. The reason for the first discrepancy appears to be because ‘100% fuller storages’ is less effective at reducing spillage if the storages are not equally sized, the reasons for which require further investigation. This also helps to explain the high yield results for layout 2, which are achieved with this strategy (as less spillage means a higher yield). The sizing of storages is acknowledged as an important factor in RWH design, but the effects of storage sizes relative to one another have not been considered before. It seems likely that it only has an effect when allocating based on a factor related to storage.

The variability caused by allocation strategy supports further investigation into this aspect. Even though some of the variations are small e.g. total yield, these differences may be magnified by factors such as high local water costs. Pumping work, which is likely to be a significant cost factor for any large site, can be reduced by >50% in some cases, which has high cost saving implications.

Optimality

The multiple performance measures mean that it is not straightforward to define an optimal layout or allocation strategy. It is possible to define each system with a single performance value by first normalising all of the outputs, and then using the formula:

$$R = aY - bS - cM - dP - eD_{empty} - fD_{full}$$

Where:

- a, b, c, d, e and f are factors, which all sum to a constant (i.e. unity)
- Y = Normalised total yield
- S = Normalised total spillage
- M = Normalised mains top up amount
- P = Normalised total pumping work
- D_{empty} = Normalised total no. days empty
- D_{full} = Normalised total no. days full
- R = System performance

The negative signs indicate that these are outputs that should be minimised for an ideal system performance. The outputs are normalised using the approach:

$$X_n = \frac{(X_r - X_{min})}{(X_{max} - X_{min})}$$

Where:

- X_n = Normalised output

- X_r = Raw (unmodified) output
- X_{min} = Minimum value in sample of outputs
- X_{max} = Maximum value in sample of outputs

This normalises all outputs to the range 0-1 (lowest to highest respectively). Results obtained using this method cannot be compared with those obtained from a different sample of results, as X_{min} and X_{max} will usually be unique to their native sample.

The values of factors a-f will be heavily affected by local site conditions. To demonstrate this, Table 4 shows some synthetic scenarios with associated values for the weighting factors, and Table 5 shows the values for R generated using those scenarios.

Table 4. Theoretical scenarios and associated factors

	a	b	c	d	e	f
Scenario 1: High cost mains supply	0.4	0.05	0.4	0.05	0.05	0.05
Scenario 2: High costs associated with pumping	0.1	0.1	0.1	0.5	0.1	0.1
Scenario 3: Local flooding a key issue	0.1	0.5	0.1	0.1	0.1	0.1

Table 5. System performance results using theoretical scenarios (best performances highlighted)

Layout No.	Allocation Strategy No.	System Performance (R)		
		Scenario 1	Scenario 2	Scenario 3
1	1	-0.108	-0.139	-0.504
1	2	-0.180	-0.245	-0.128
1	3	0.107	-0.435	-0.555
1	4	-0.012	-0.125	-0.471
2	1	0.040	-0.542	-0.562
2	2	0.310	-0.450	-0.235
2	3	0.031	-0.636	-0.581
2	4	0.310	-0.450	-0.235
3	1	0.171	-0.224	-0.463
3	2	-0.236	-0.380	-0.177
3	3	-0.553	-0.645	-0.806
3	4	-0.217	-0.308	-0.165
4	1	0.176	-0.175	-0.454
4	2	-0.234	-0.360	-0.173
4	3	-0.551	-0.628	-0.802
4	4	-0.214	-0.281	-0.159
5	1	0.179	-0.139	-0.446
5	2	-0.231	-0.330	-0.167
5	3	-0.549	-0.601	-0.797
5	4	-0.222	-0.213	-0.091

Table 5 suggests that the best option (i.e. the highest value of R) for weighting scenario no. 3 is Layout no. 5 combined with allocation strategy no. 4. However, if the local site conditions require a solution that is heavily biased towards addressing a high cost mains supply, then weighting scenario 1 is more relevant and layout no. 2 emerges as the most preferable option. This simple example demonstrates the possibilities available for optimisation. The next investigative steps will include theoretical case studies of large sites with their own specific conditions.

CONCLUSIONS

It has been demonstrated that if a multi-nodal approach is employed when designing RWH systems at a small scale, the choice of how to manage that system i.e. the allocation strategy, is a key design decision. It is possible that a poorly designed layout with the right allocation strategy can perform better than an intuitively designed layout with the wrong one in some performance areas. If the effects are this visible on a small scale, then it is strongly implied that for large sites with potentially large numbers of demand and storage nodes the effects will be more demonstrable.

It is proposed therefore that for complex RWH design, allocation strategy is a key design factor. Further research and modelling is required to develop the approach, but in the form demonstrated in this paper it can still be considered an essential part of a RWH design toolkit.

The next step is to apply this methodology to real world case studies, or at least theoretical simulations that approach them. This is also likely to require the introduction of further complexity to the model, such as water quality and treatment (i.e. for demands that require particular levels of quality, for example) and the hydrology of the site catchment area as so far all rainfall is assumed to occur as collectable runoff.

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