Rainwater harvesting systems for stormwater management: Feasibility and sizing considerations for the UK

Utilisation des récupérateurs d'eaux de pluie pour le contrôle du ruissellement à la source: faisabilité et méthode de dimensionnement au Royaume-Uni

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RÉSUMÉ

L'eau de pluie peut être collectée et stockée pour des usages ultérieurs ne requérant pas l'utilisation d'eau potable. Les effets des cuves de récupération sur les réseaux d'assainissement lors de forts événements pluvieux n'ont fait l'objet que de peu d'études, notamment car stocker de l'eau pour des usages ultérieurs et maitriser le ruissellement lors de pluies exceptionnelles sont deux fonctions pouvant paraître contradictoires. Pour cette étude, des chroniques de pluie générées stochastiquement sont utilisées pour simuler le comportement des cuves à l'échelle de la parcelle lors d'événements extrêmes dans trois villes anglaises. Compte-tenu des hypothèses du modèle, les résultats soulignent que les volumes et débits de pointe rejetés dans les réseaux peuvent être fortement réduits lorsqu'en moyenne l'apport pluviométrique annuel est inferieur à la demande au sein du bâtiment. Les résultats de cette étude appuieront le développement d'une méthode de dimensionnement visant à intégrer les récupérateurs d'eaux de pluie dans les systèmes de gestion des eaux pluviales.

ABSTRACT

There has been growing interest in the use of rainwater harvesting systems in recent years. Rainwater can be collected and stored to supply a range of non potable domestic uses. Until recently, rainwater tanks were primarily considered as a solution to reduce potable water consumption. The impact of rainwater harvesting practices on drainage systems, mainly during extreme rainfall events, has been a secondary consideration, one reason being that these two functions, namely supplying water and managing stormwater runoff, appear to be contradictory. This study uses a time series modelling approach to assess the benefits achieved in runoff reduction at a plot scale during heavy rainfall events, across three locations in England. Considering the assumptions of the model, the results show that substantial reductions can be achieved in areas where, on average, the rainfall supply is smaller than the non potable domestic demand in the households. Further work is underway to factor the main conclusions of the study into design guidelines that can be applied in areas where stormwater management is needed.

KEYWORDS

Extreme events management, rainwater harvesting, runoff control, tank sizing, time series modelling

1 INTRODUCTION: THE CONSIDERATION OF RAINWATER HARVESTING FOR STORMWATER MANAGEMENT

1.1 A recent history of rainwater harvesting in the United Kingdom

There has been growing awareness of the importance of 'water conservation' in the UK in recent years. In this context, rainwater harvesting has been promoted as a means of conserving water, reducing bills and more generally 'helping the environment'. This message has been greeted with growing demand for such systems in the UK, in particular amongst 'eco-home' and 'self-build' property developers and organisations seeking to develop their 'green credentials', such as local authorities, educational establishments and environmental charities. As a result, a British Standard relating to rainwater harvesting has recently been produced (BSI, 2009). However, although water conservation is now actively encouraged in the UK e.g. through initiatives such as the Code for Sustainable Homes (DCLG, 2008), wide-scale uptake has not yet occurred. There is little incentive for 'conventional' house building organisations to install rainwater harvesting systems on new properties, with potable water costs being relatively low and hence payback times being relatively long. Questions also remain over the true environmental benefits of rainwater harvesting compared to the alternative of adopting water saving practices in buildings e.g. use of low-flush WC's, aerator taps, etc.

On the other hand, planning regulations, such as PPS25 (DCLG, 2006, 2008), now seek to tackle increasing incidences of flooding through requiring that pre-development run-off rates are maintained to post-development levels through the implementation of control measures. This has been coupled with the promotion of 'sustainable drainage systems' (SUDS) philosophy (CIRIA, 2007).

In the UK, although the potential stormwater management benefits of rainwater harvesting are alluded to in reference documentation (CIRIA, 2007; Environment Agency, 2008; BSI, 2009), this has not been formally proven and quantified. In drainage design, rainwater harvesting is still generally assumed as not providing stormwater management benefits, and until this is demonstrated otherwise and a suitable design methodology has been developed, engineers are unlikely to use this technique widely as the advantages of minimising water demand alone (from a developers perspective) do not provide sufficient incentive for implementing or using them.

It is anticipated that if it can be shown that rainwater harvesting has stormwater management capabilities, then the synergy of both saving water and the ability to use it to address stormwater control will result in widespread use of the technique in the UK.

1.2 Supplying water and managing extreme events: a paradox?

Until a few years ago, rainwater tanks were mainly considered as a solution to reduce potable water consumption. Their impact on drainage systems during extreme rainfall events has been a secondary consideration, one reason being that these two functions, namely supplying water and managing runoff, appear to be contradictory (Vaes & *al.*, 2001) since, on the one hand, the tank should be 'more full than empty' to meet the demand from the household on a regular basis and, on the other hand, it should be nearly empty to be able to store significant rainfall depths occurring during intense storm events.

The current sizing methods for rainwater tanks are essentially built on 'demand-based' approaches and aim at optimising the volume of the tank. Hence, when using the '5% rule' in the UK for instance (BSI, 2009), which involves sizing a tank based on the smallest value between 5% of the annual rainfall yield from the roof and 5% of the annual non potable water demand in the household, it can be noted that the volumes computed generally range between 0.5 to 0.9 m^3 of storage per person in the household. In some cases, this may correspond to relatively small tanks, and this storage is currently ignored with respect to possible stormwater management opportunities. However, previous exploratory works at a residential scale in the UK (Kellagher & *al.*, 2007) and in other regions (Hermann & *al.*, 1999; Coombes & *al.*, 2001; Hardy & *al.*, 2004; Tahir & *al.*, 2009; etc.) suggest that this approach could be reviewed. What is more, hydraulic constraints in residential developments have become stricter (planning requirements for on site stormwater management measures, limitation of discharges into the sewer systems, etc.) and the density of housing developments has increased, meaning that the additional runoff generated by roofs and other impervious areas presents significant cost and space challenges, when considering how to manage it. Storing a significant amount of runoff from the roof in 'bigger' rainwater tanks, when on site infiltration is not or is only partially feasible, can be considered as a means of reducing the impact of new housing and a means of assisting in meeting drainage planning regulations.

In this context, this study is aimed at showing the benefits of using rainwater harvesting as a source control measure for the hydrological conditions found throughout the United Kingdom. The objectives were as follows:

- To analyse the benefits provided by rainwater tanks during extreme rainfall events for a wide range of scenarios (roof area, size of the tank, demand) for different locations across England;
- To summarise the performance of the systems using simple characteristisation of the relevant parameters to determine the conditions for which stormwater management using rainwater harvesting is feasible;
- To provide a simple methodology to allow prediction of the storage performance of the tanks during high intensity storm events and develop these conclusions into design guidelines.

2 METHODOLOGY: ANALYSIS OF LONG-TERM SIMULATIONS

2.1 The need for long and continuous rainfall time series

To assess the behaviour of rainwater tanks under extreme conditions, the choice of the rainfall data to use is important. For modelling purposes in urban drainage, three ‘types’ of rainfall data are available:

- Design storms, which are widely used for the design of drainage/sewer systems,
- Historical records with different time-steps potentially available,
- Time series generated with a stochastic tool; these series need to be validated before being used.

When continuous rainfall series is not used, an assumption has to be made about the initial state of the system before running the model. This is the case when design storms are used. However, the spare volumes available in the tanks can be significantly different from one configuration to another. Moreover, as rainwater tanks are ‘capacitive’ facilities, which may require several days to drain, they are very sensitive to antecedent rainfall and its variability (Vaes & *al.*, 2001). This is why an approach using continuous rainfall series has been chosen for this study.

Then, to provide a sufficient number of extreme rainfall events and allow statistical analysis to be performed, long historical records are needed. Since controlling peak flows is also of possible interest, it is necessary to have data with a small time-step. Stochastic time series has been used, which provides 100 years of synthetic rainfall data for several locations across the United Kingdom.

The series have been generated with the software TSRsim®, first produced as a prototype by Imperial College London, and then developed as a tool and supplied by HR Wallingford Ltd.

Hourly data are first generated using a BArtlett-LEwis REctangular Pulse (BALEREP) model and then disaggregated into a 5-min time step using a CASCADE macro-disaggregator process. A full description and evaluation of these two models can be found in Onof & *al.* (2002) and Kellagher (2005).

The top 30 extreme rainfall series were found within the generated series for three locations (Birmingham, London and Manchester). These were used to test the retention effectiveness of the storage systems so as to determine a methodology for designing rainwater harvesting tank sizes.

2.2 Runoff and non potable water demand modelling

The runoff from the roof is controlled by several local parameters, which can be difficult to estimate accurately. As such, the relative importance of each of them needs to be justified. On the other hand, as stated by Vaes & *al.* (1999), Fewkes & *al.* (2000) and Mitchell & *al.* (2005), knowledge of the daily variation of the household’s water consumption is of little importance when long rainfall time series is used, allowing modelling of the demand as a constant drawdown. Another reason is that during extreme events the demand can be considered to be negligible compared to the inflow from the roof.

The model used is summarised in Figure 1.

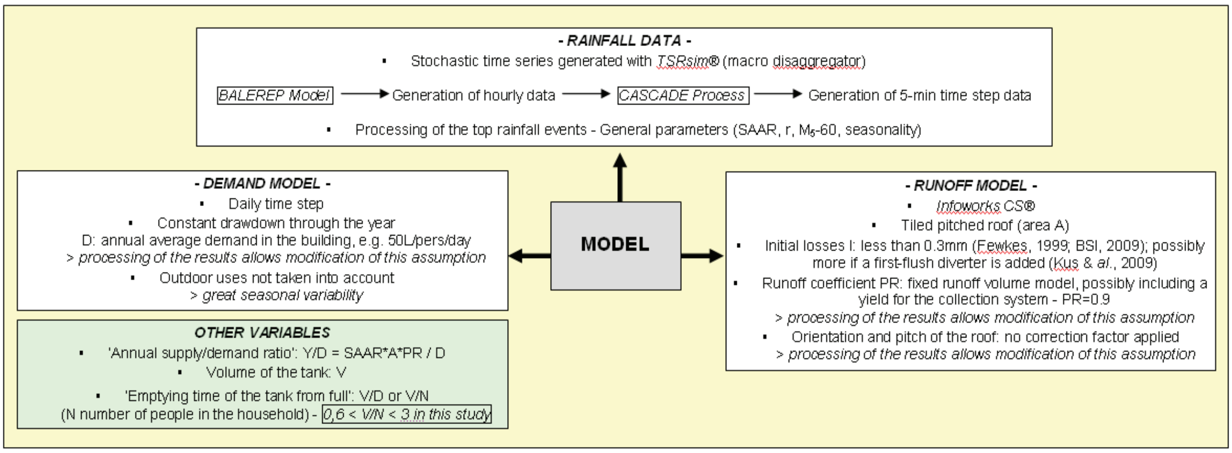


Figure 1 – Components of the model and assumptions

3 RESULTS

3.1 Benefits provided by rainwater tanks during extreme storm events

3.1.1 The relevance of the supply-demand ratio for the reduction in the volume of runoff

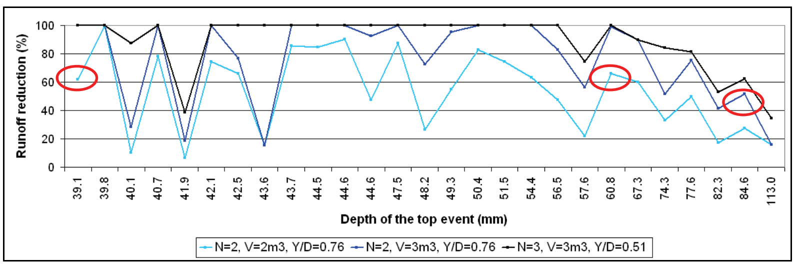
For the analysis of the performance of rainwater tanks for the extreme events identified from the 100-year time series, nearly 40 scenarios were analysed. The series generated were for the following three locations: Greenwich (London, average annual rainfall = 650mm (from TSRsim®), Ringway (Manchester, 860mm) and Elmdon (Birmingham, 710mm)). Although the annual rainfall depths are not dramatically different, Manchester in particular is very different from the other two in terms of seasonality and intensity of the rainfall.

The key fact that became evident was that where the average annual rainfall supply was smaller than the annual household demand (Y/D < 1), the performance of the rainwater harvesting systems in retaining runoff for extreme events was good. In all cases where the ratio is less than 1, an increase in the size of the tank leads to greater retention of runoff and reduction in the volume of runoff and peak flow.

Conversely, when Y/D ≥ 1, the benefit obtained in terms of runoff retention is usually quite small. For more than one third of the events, bigger tanks do not provide additional benefits in terms of runoff reduction or reduction of peak flow discharged into the sewer systems. An increase in the size of the tank becomes totally ineffective as Y/D increases above 1.5. This is discussed later in the paper.

3.1.2 Difficulties in assessing the reductions in peak flows

It is difficult to link the reduction achieved in the rate of runoff from the roof and the storage provided. This is due to the shape (skewness) of the storm. Figure 2 shows a plot of the reductions in runoff and peak flows for the 30 top events in Greenwich for 3 different scenarios. In some cases, the runoff volume can be reduced by up to 65% without any reduction in the peak discharge (red circles), because the peak rainfall intensity occurs after the tank is full. Thus, it has been decided for the sequel of the study that the assessment of the performance of the tanks for stormwater management will be based only on the volume of rainfall likely to be stored, potentially allowing the required capacity of downstream storage facilities (detention basins) to be reduced. But this also has the implication that pipes into which runoff from the tank overflow passes must be sized without any reduction.



What is also shown in Figure 2 is that there is no specific link between the return period of the event (represented here by the rainfall depth of the event) and the runoff volumes and peak flow reductions achieved.

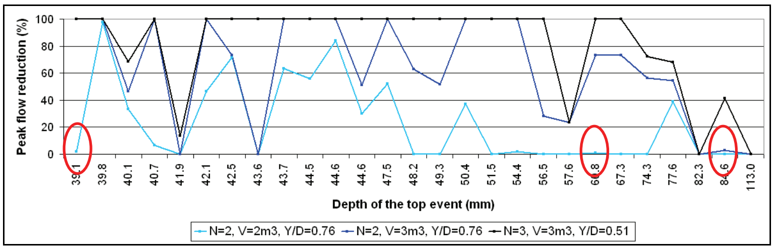


Figure 2 - Example of comparison between runoff and peak flow reductions

This is due to the fact that rainwater tanks are drained slowly (over many days) and therefore the tank performance is a function of the antecedent period of rainfall as well as the demand and the storm event itself.

3.2 A key parameter: the variability of the storage volume available in the tanks

3.2.1 Influence of the variables of the model

As antecedent rainfall is important, it is necessary for the analysis of the performances of the tanks during rainfall events to take into account the variability of the storage volumes available in the tanks and not the size of the largest rainfall event(s).

For each of the scenarios considered in this study, the spare volume in the tank before each of the top 30 large events of the 100-year time series was assessed. In line with the results from Section 3.1.1, it appeared that the supply/demand ratio (Y/D) was an important parameter to use as an indicator of the rainfall depth that could be stored in the tank.

However, the information given by the value of Y/D should not be misunderstood. If two configurations (A_1, D_1) and (A_2, D_2) with the same tank size (V_1) have the same ratio Y/D, it does not necessarily mean that the same amount of runoff will be stored during extreme events since the storage available in the tank, in equivalent mm of rainfall, is a function of $1/A_i$ (spare volume will always be expressed in equivalent mm of rainfall in this paper). This parameter is rather useful to assess the proportion, as a percentage, of the volume of the tank available before an event. Indeed, this value is all the more important as the ratio Y/D is small. Figures 3 and 4 illustrate this point for some scenarios run for Ringway and Greenwich. The results are not plotted against the return period or the depth of the event but against the month in which the top event occurs.

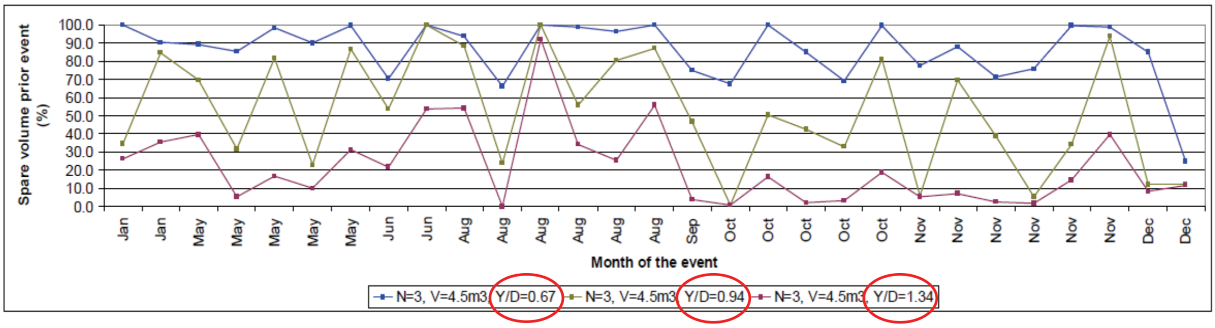


Figure 3 - Spare volumes available prior to extreme events as a proportion of the volume of the tank (Ringway)

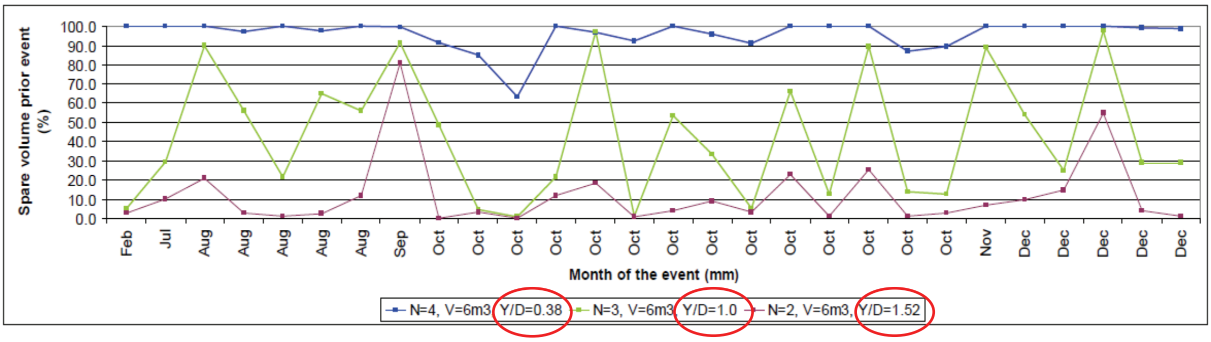


Figure 4 - Spare volumes available prior to extreme events as a proportion of the volume of the tank (Greenwich)

3.2.2 Seasonal variability of the storage volume available in the tanks

The previous figures also show that the storage volumes available in the tanks can vary significantly between events occurring in a given season (through the 100-year time series) e.g. autumn. However, as illustrated in Figure 4, this trend tends to be less varied in two cases:

- When the annual rainfall supply is much greater than the average non potable water demand in the household (practically when Y/D>1.5); here, the system is controlled by the rainfall: the drawdown from the household is too small to significantly reduce the amount of stored water in the tank before the next rainfall event occurs;
- When the annual rainfall supply is much smaller than the average demand (practically when Y/D<0.5); in this case, the system is controlled by the demand: the runoff from the roof is quickly used and the tank is usually nearly empty and is therefore less sensitive to the variability of the antecedent rainfall pattern.
- Between these values, the storage volumes available are more 'chaotic'. This can be seen from the green line (middle line) plotted in Figure 4 for Y/D=1.0.

3.2.3 So, when is stormwater management feasible?

It has been shown that the supply/demand ratio (Y/D) is a key parameter and it has been found to be sufficiently robust to use in the development of a methodology for sizing tanks for stormwater control. One explanation of the relevance of this parameter is that the rainfall at the locations used for the study is fairly evenly spread in terms of monthly depth throughout the year.

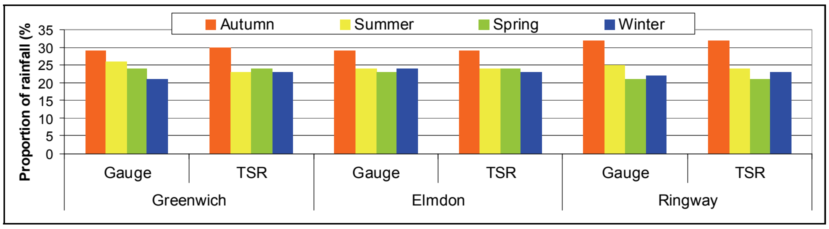


Figure 5 - Seasonal repartition of the average annual rainfall depths for the locations investigated

Figure 5 partitions the annual rainfall depths on a seasonal basis for Greenwich, Elmdon and Ringway, for the historical data (gauge) and the stochastic series.

The previous remark implies that the methodology developed following the results of this study will preferably have to be applied in geographical areas where rainfall patterns are quite evenly distributed around the year. Actually, it could theoretically be used everywhere but, in regions with strong seasonal discrepancies in the rainfall depths, the results may lead to oversized tanks, with poor technical and economic relevance. In those cases, it may be necessary to resort to 'dual tanks' providing specific stromwater control performances (Coombes & *al.,* 2001; Huang & *al.,* 2009) and which implies a different sizing approach. Other solutions, which are not 'technical' solutions, rely on real time control systems, such as experimented in Asia (Han, 2009; Dao & *al.,* 2009) but are not beyond the scope of this paper.

For each scenario investigated, the minimum value of the storage volume available for at least 80% of the extreme events has been evaluated. Provided that Y/D<1, the storage volume increases as Y/D decreases and as the size of the tank increases. As mentioned before, this is assessed as the proportion of storage volume. Conversely, for Y/D>1, extreme events can not be safely controlled using traditional rainwater harvesting tanks; only a few large events have significant runoff volumes retained.

To develop a sizing method based on the evaluation of the storage volume available in the tanks to provide a given level of stormwater retention, it is important that the technique provides a reasonable degree of confidence, that the design depth will be retained, but this should preferably be achieved without having to carry out a time series analysis each time (from a practical perspective).

3.3 How to estimate the storage volume available in the tanks before extreme events?

3.3.1 Reliability of the percentile values

A simple approach using easily available parameters should preferably be developed to switch from long-term simulations to a practical way of designing a tank sized for a specific level of flood prevention. The differences in using some percentile values instead of the observed values for the spare volumes available prior to the events have been assessed. This paper only presents the general results and conclusions that were obtained when considering the 50 percentile (P50) measure. P50 is the proportion of the tank that is available for storage for at least 50% of the time (median value). The following indicators have been computed for each scenario investigated:

- The mean error defined as $\frac{1}{N}\sum_i (V_{av}(i) - P50)$ where $V_{av}(i)$ is the storage available in the tank before the event i and N is the total number of events;
- The mean absolute error defined as $\frac{1}{N}\sum_i \left| V_{av}(i) - P50 \right|$.

Once again, some interesting trends appeared with the value of the supply/demand ratio Y/D. As can be seen on Figure 6, which shows the results from Greenwich, Ringway and a few points for Elmdon used as a ‘check’ location, the mean absolute error is highest when Y/D ranges roughly between 0.8 and 1.1, whereas it tends to be small when Y/D becomes respectively smaller or greater than 0.8 and 1.1. The mean error is used as a complement to the previous graph to determine whether the error in using the percentile P50 results in an overestimation (negative values) or an underestimation (positive values) of the volume available in the tank before an event. Figure 7 indicates that in scenarios where Y/D is smaller than 1, the use of P50 results in more over-estimation of the performance of the tank whereas it is the opposite when Y/D is greater than 1 (but for this value of Y/D, it has been shown that stormwater benefits are minimal and therefore stormwater management would not be considered.

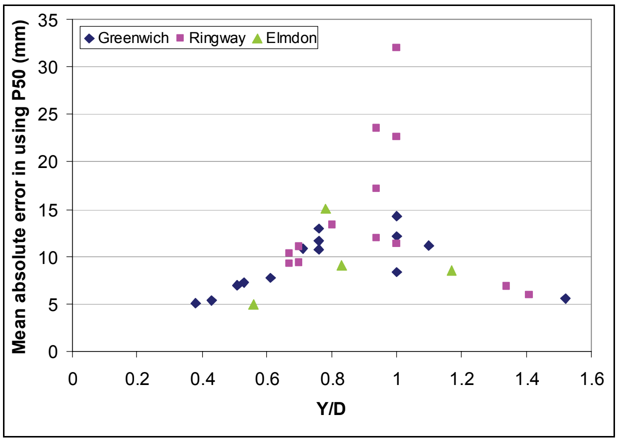


Figure 6 - Mean absolute error in using P50 to predict the volume available in the tanks before extreme events

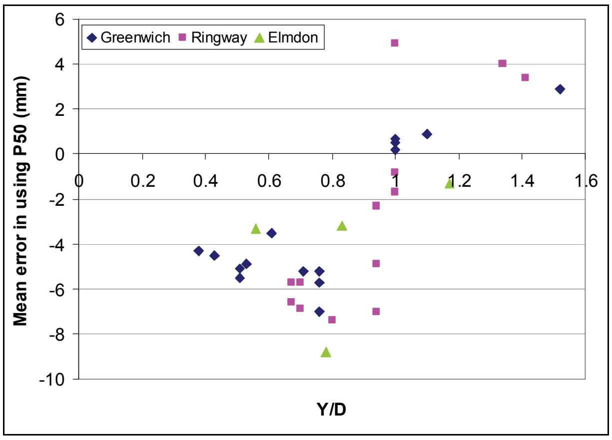


Figure 7 - Mean error in using P50 to predict the volume available in the tanks before extreme events

3.3.2 Definition of an allowance depth

It has been shown in this paper why sizing a tank based on the size of the event would not be applied to rainwater tanks. Since tanks drain more or less slowly, the available storage volume is very sensitive to the antecedent rainfall. This is why the study focuses on the variability of the spare volume available in the tank. The ‘allowance depth’ is a safety coefficient defined as the rainfall depth in mm to subtract from the percentile 50 (P50) of the storage volume available in the tank in order to achieve a safe level of confidence to store a given size of rainfall event. The following points can be made with regard to the allowance depth:

- Up to Y/D<1, the allowance depth increases as Y/D increases; this reflects the fact that the volume of water in the tank becomes more variable as the tank is more sensitive to the antecedent rainfall;
- For Y/D >1, the allowance depth decreases and tends to zero;
- The various scenario checks have also shown that a second relevant parameter, which has not proven to be a key element so far, was the emptying time of the tank from full, which can be represented by the ratio V/N or V/D (cf. Section 2.2); once again, the higher the ratio, the more significant the ‘memory’ of the system.

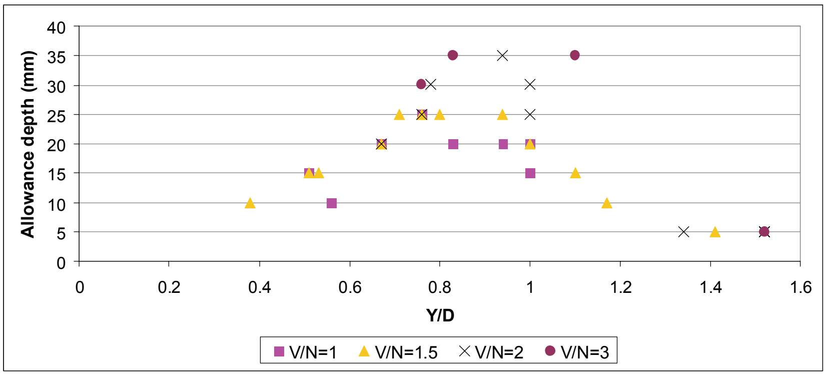


Figure 8 - Allowance depths to be subtracted from P50 to provide the required level of confidence for sizing of tanks

For the scenarios investigated across the three locations, the associated allowance depths have been plotted against Y/D in Figure 8. The results are presented for four different values of V/N.

The point which has not been discussed so far is the difference found between the locations. They were small, that is why only a 'worst state graph' is presented opposite.

The values of the allowance depth are slightly lower for Elmdon; and this is believed to be due to the fact that the predominance of extreme events occurring in summer is more significant for this location than the other two sites.

The P50 analysis was also evaluated for seasons and also the median value prior to the selected major events. However the results were not significantly different, while the annual P50 determination is very easily understood and the analysis achieved.

3.4 Quantification of the effects of an increase in the size of the tank

The methodology developed will enable the prediction of the storage volume available for a tank for any configuration. For runoff management, it is now necessary to be able to quantify, in a simple way, the effects of 'bigger' tanks.

As suggested in Section 3.1.1, an increase in the size of the tank does not necessarily lead to the same increase in the storage available in the tank.

To better understand the evolution of the percentile 50 (P50) according to the supply/demand ratio (Y/D), the volume of the tank (V) and possibly the location, the increases in P50 have been plotted against the increase in the size of the tanks, starting with $1m^3$, for a range of configurations in Elmdon (E), Greenwich (G) and Ringway (R). The results are presented in Figures 9 and 10. So as not to overload the graphs, only some of the results are plotted.

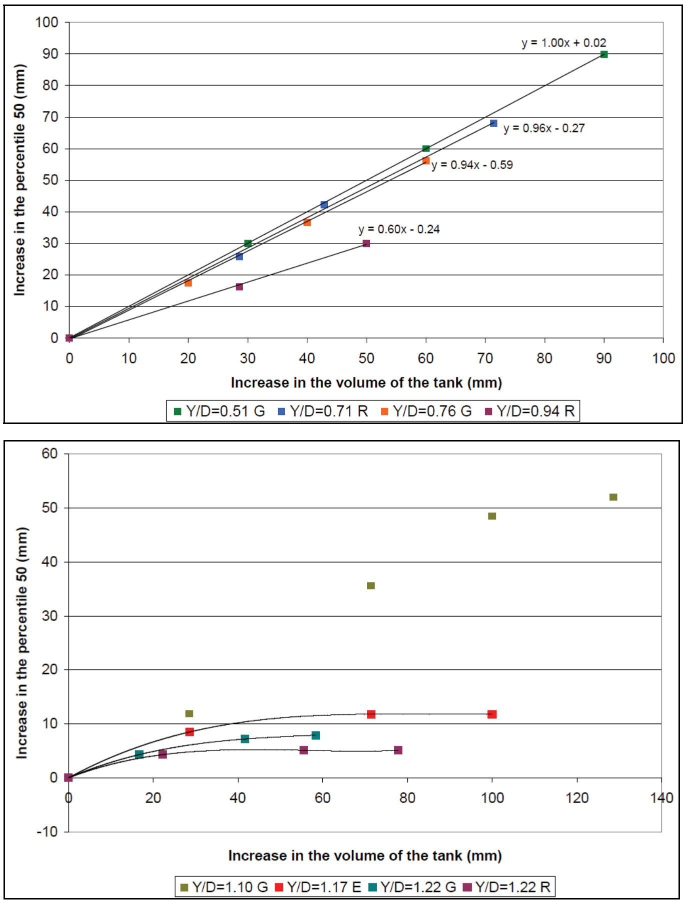


Figure 9 - Increase in the percentile 50 vs. increase in the size of the tank (a- Y/D<1, b- Y/D>1)

For stormwater management, the main conclusions to draw from these graphs are as follows:

<u>Where Y/D<1:</u>

- P50 increases linearly with an increase in the size of the tank (for every location);
- The gradient of the straight lines tends to one for values of Y/D <<1;
- However as Y/D approaches 1 the gradient reduces and it can be seen in Figure 9 that this is only 0.6 for a

Y/D value of 0.94. For a gradient equal to 0.6, this means that if the size of the tank is doubled, the storage volume available in the tank is multiplied by 1.6.

So increasing the size of the tank can offer significant benefits for stormwater management during extreme events where Y/D <1.

Where Y/D>1:

- The increase in the percentile 50 is not proportional to the size of the tank anymore;
- In the same way that we can identify a threshold for the volume of the tank above which there is no greater benefit for water supply (Fewkes & *al.*, 2000), we can identify a size of tank above which the benefits for stormwater management are also not effectively improved.

Where 0.95<Y/D<1.10:

Actually, depending on the locations, the increase may still be nearly linear up to a reasonably effective size of tank (Greenwich, Elmdon) or the threshold may be reached more quickly (Ringway). This difference in the result between the locations may be linked to the magnitude of annual rainfall (SAAR) or the parameter 'r', or to the number of events in a year (Manchester is a wetter location than London or Birmingham). 'r' is a parameter used in the Flood Studies methodology (NERC, 1975) which is the rainfall proportion of the 1 hour 5 year event compared to the 2 day 5 year event.

The results and conclusions of this study will allow the definition of a simple tank sizing method for stormwater management. This work is beyond the scope of this paper.

4 CONCLUSIONS

Rainwater tanks do not behave like any other drainage facility (proportional to the size of an event) as they are sensitive to antecedent rainfall. This study has shown the need for the emphasis being placed on understanding the variability of the storage available in the tanks for being able to develop a method for sizing them and assessing the benefits that can be provided in terms of managing urban runoff at a plot scale.

The supply/demand ratio has proved to be a vital parameter for assessing rainwater harvesting potential for extreme events management in the UK context and to assess the required tank sizes to control runoff from a specific storm event. The benefits of increasing the size of the tanks have also been quantified. The simple measure of Y/D has been shown to be an accurate assessment of when stormwater management benefits can be realised and conversely when tanks will not provide any stormwater benefits.

Further work is needed to check the reliability of the results across the United Kingdom and validate the sizing methodology. The possible application of this method in regions where the rainfall patterns are quite different from the UK, e.g. with strong seasonal variations in terms of rainfall depth, has also been discussed and are less relevant.

The additional cost compared to the added value of stormwater control associated with the increase in size over and above that needed for water supply needs to be investigated and compared to the other technical solutions such as dual tanks.

The reduced number of spills from the tanks may also have an impact on the quality of the water stored in the system and should be investigated.

In addition to stormwater management for extreme events, smaller tanks storing runoff from frequent events can also prove beneficial in reducing CSO spills. An alternative storage depth criterion may need to be developed.

Eventually, due to the importance of antecedent rainfall, it is likely that the use of green roofs and the reduced volume of runoff in conjunction with rainwater harvesting storage would make rainwater harvesting very effective for areas of high annual rainfall or buildings with relatively low demand compared to the roof area.

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