The University Of Sheffield.

MPhil Thesis

ASSESSING THE PERFORMANCE OF MULTI-NODAL RAINWATER MANAGEMENT SYSTEMS

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Abstract

Rainwater Management Systems (RMS) is a term that describes the decentralisation and management of rainfall at source for multiple purposes. Many studies have focused on the water saving potential of RMS at a small single storage single demand (S-D) scale, but research into the stormwater management potential of a multi-nodal network scale is lacking. Multi-nodal rainwater management systems comprise numerous storage and demand nodes (nSnD) and are hypothesised to be a more effective way of improving water supply and stormwater management performance of RMS in a domestic network.

This MPhil evaluates the performance of multi-nodal RMS for the water supply and stormwater management potential compared to a conventional S-D system. To achieve this, S-D and nSnD models were created and performance metrics have been developed to enable comparison analysis for the water supply and stormwater management potential. The five identified metrics are water supply efficiency, water supply frequency, stormwater retention efficiency, peak outflow and time above greenfield runoff rate. The feasibility comparison of the model showed that the model was capable of simulating results comparable to monitored RMS data and that the performance metrics developed efficiently analysed RMS performance. The model sensitivity analysis explored the effects of behavioural model, time step and the demand profile on model accuracy. The findings of the sensitivity analysis highlighted that time-step had a high impact upon accuracy, whilst behavioural model and demand profile had a reduced impact on the accuracy.

The nSnD to S-D comparison has shown that the stormwater management and water supply potential of a RMS can both be enhanced through the introduction of a multi-nodal network. nSnD systems are capable of producing a reduced peak outflow, reduction to the time outflow exceeds greenfield runoff rate and an increased water supply efficiency, water supply frequency and stormwater retention efficiency when compared to that of an S-D system.

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List of Symbols and Abbreviations:

A Roof Area (m^2)

D Demand (m^3/5 min)

D/AR Demand ratio calculated from the demand, roof area and rainfall

GRR Greenfield Runoff Rate (m^3/5 min)

I Roof runoff/tank inflow (m^3/5 min)

n Total number of time steps in the time series

nSnD n-storage n-demand

N_t Number of time steps

nt Nodal time series (m^3/timeseries)

O Outflow or Spill (m^3/5 min)

OPeak Peak Outflow (m^3/5 min)

R Rainfall (mm)

RMS Rainwater management system

RWH Rainwater harvesting

S Storage capacity (m^3)

S-D Single storage single demand

SGRR Stormwater that exceeds greenfield runoff rate (-)

SRE Stormwater Retention Efficiency (-)

SWM Stormwater management

t Time series (m^3/timestep)

TAG Time above greenfield runoff rate (hours)

V Stored volume (m^3/5 min)

WSE Water Supply Efficiency (-)

WSF Water Supply Frequency (-)

Y Yield (m^3/5 min)

1SnD 1 storage n-demand

2S2D 2 storage 2 demand

Model inputs:

Rainfall time-series, R_t

Roof Area, A

Storage capacity, S

Demand time-series, D_t

Greenfield Runoff Rate, GRR

Model outputs:

Roof runoff/tank inflow time-series, I_t

Yield time-series, Y_t

Outflow time-series, O_t

Stored volume time-series, V_t

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1 Introduction

1.1 Background

A rainwater management system (RMS) at its most basic is a storage tank used to collect and store rainwater at the collection location to supply a range of non-potable domestic uses. Until recently, the collection and storage of rainwater was primarily referred to as rainwater harvesting systems (RWH). RWH primarily focused on reducing potable water consumption by the provision of an alternative water source. The impact RWH had upon reducing the flow in drainage systems, primarily during extreme rain events, highlighted a secondary function to the conventional RWH system. The water supply and stormwater management (SWM) benefits of a RWH became identified as dual-objective capabilities or a dual-function RWH system. However, the literature soon identified that the term RWH did not suitably describe the additional functions and complexity of a rainwater system. Rainwater management systems (RMS) is a term identified by Butler (2018) to describe the decentralisation and management of rainfall at a source for multiple purposes.

RMS and RWH systems are commonly understood and implemented as a single storage single demand system (S-D). Modelling tools and methodologies regarding RMS have been developed over the last 30 years to facilitate the design of RMS. Previous research on domestic RMS has primarily focused on the RMS ability to provide a reliable water supply (Dixon et al., 1999; Melville-Shreeve et al., 2016; Roebuck et al. 2011). More recently, literature has acknowledged the RMS capacity to provide additional stormwater management benefits and consequently RMS evaluation techniques have been extended to enable the measurement of stormwater management performance. Currently RMS modelling for stormwater and water supply performance is simulated through behavioural simulations which refer to the water balance of a system (Campisano and Modica, 2012; Melville-Shreeve et al., 2016; Roebuck, 2007; Zhang et al., 2010). Previous literature relating to a performance evaluation of RMS often document water supply assessment metrics well. However, the performance metrics that regard the stormwater management benefits of a RMS are often an average value of the system performance and are not capable of indicating a RMS behaviour during a storm event. Xu et al. (2018) for example analysed the RMS efficiency and frequency for stormwater retention, water supply and base-flow restoration. Whilst the findings of the study highlight that stormwater retention can be achieved by a RMS, it is not understood how the stormwater management benefits are achieved during specified storm events.

Campisano et al. (2017) recognised that a shortage of high-quality datasets relating to the dual benefit performance of RMS was still present within current literature and identified an improvement in modelling performance of the RMS and evaluation performance metrics was required to accurately assess the dual-benefit RMS performance.

System performance measures of a RMS are often calculated based upon key assumptions and parameters. Performance measures are normally used as a base structure for determining the feasibility for a RMS for economic, water saving and stormwater management benefits. Variations to the key parameters on performance measures of a RMS are assessed via a sensitivity analysis. Sensitivity analysis is required when behavioural models are based on limited, low resolution or uncertain data to assure accurate modelled outputs (Fewkes and Butler, 2000; Campisano and Modica, 2014). The identification and understanding of model sensitivities in a RMS have been briefly assessed within previous RMS research (Campisano and Modica, 2014). Mun and Han (2012) identified 6 important parameters that are to be considered in the modelling of a RMS: model algorithm, rainfall time step, catchment area, water demand, storage volume and collection efficiency. Despite the understanding that sensitivity does occur in the modelling of RMS and will compromise the modelled outputs often a lack of available high-quality datasets limits the reliability of system performance assumptions (Campisano et al. 2014).

It has been previously hypothesised that the system performance of a RMS could be further enhanced through the interconnectedness of a multi-nodal network (nSnD) (HR Wallingford, 2012; Farahbakhsh et al.,2007). Balhatchet et al. (2014) introduced a simplified multi-nodal RMS that had 2 storage and 2 demand nodes (2S2D) using a simple configuration. An example of Balhatchet et al. (2014) 2S2D network design can be seen compared to the conventional S-D design in figure 1-1. Further examples of interconnected multi-nodal RMS networks have not been assessed and therefore the viability of a multi-nodal RMS is only understood on a small scale 2S2D or 1SnD scenario using a simple system configuration. Further to this the current literature has failed to assess if a nSnD system is capable of enhancing RMS performance when compared to the conventional S-D RMS.

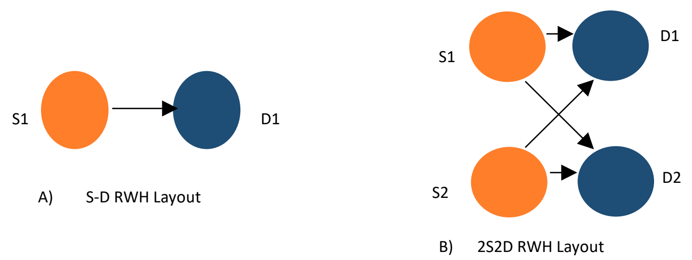


FIGURE 1-1- RMS DESIGN S-D COMPARED TO 2S2D DESIGN (BALHATCHET ET AL., 2014)

This MPhil addresses some of the most relevant issues suggested above including, evaluation of RMS performance metrics for water supply and stormwater management performance evaluation, analysis of model sensitivity for a domestic S-D RMS and investigation of the system performance impact for a nSnD RMS compared to a traditional S-D RMS. This document aims to compile previous RMS research to address the key knowledge gaps highlighting how a nSnD RMS would alter performance when compared to the conventional S-D system. Understanding will be gained from the research to create a concise list of performance evaluation metrics used to highlight if a nSnD system could be a viable option when designing for RMS in the future. This work will develop from work undertaken by Balhatchet et al. (2014) and HR Wallingford (2012) to ultimately present and analyse a series of novel multi-nodal RMS designs to that of a traditional S-D RMS design understanding the effects a nSnD RMS will have upon stormwater management performance and water supply performance.

1.2 Overall aims of the MPhil

1) Identify existing rainwater harvesting and stormwater management assessment criteria and performance metrics to propose appropriate performance metrics to be used when referring to the dual-objective capabilities of a rainwater management system (RMS)
2) Understand factors that influence the simulation of performance for RMS, specifically sensitivities in the model algorithm, time step and demand fluctuations.
3) Evaluate the performance of multi-nodal (nSnD) systems compared with conventional single storage single demand (S-D) systems.

1.3 Outline of the thesis

- Section 2 presents a literature review of a RMS
- Section 3 presents the generation of an outflow equation and performance metrics required for the future of RMS research
- Section 4 illustrates a basic S-D study, to analyse performance metrics, model performance and the feasibility comparison of the model to an RMS case study
- Section 5 analyses model sensitivity to model algorithm, time step and demand pattern
- Section 6 presents the next step in the model development introducing the nSnD RMS. Additional metrics are introduced, applied and analysed to a 1S2D system.
- Section 7 analyses the importance allocation strategies have upon the performance of a nSnD RMS scenario

- Section 8 progresses the ideas seen in section 6 and 7 comparing a nSnD to a typical S-D scenario using a British standard sized tank and a smaller DIY Store sized storage capacity for a 10-demand node scenario.
- Section 9 concludes the research undertaken for this thesis and suggestions for future research.

2 Literature Review

2.1 What a rainwater management system/rainwater harvesting system is

Previous literature has identified that the term rainwater harvesting (RWH) that was previously used to identify a RMS does not suitably describe a dual/multiple purpose system. A rainwater management system (RMS) is a term identified by Butler (2018) to easily distinguish the multiple benefits of a system and move away from the previous single-use RWH. The multiple benefits addressed when using a RMS are the ability to collect and store rainfall for water supply usage and to act as a stormwater retention volume to prevent stormwater runoff during a rainfall event.

A RMS is often defined under a larger umbrella term of sustainable drainage systems, more commonly known as SuDS (Woods-Ballard et al., 2015). Other terms are used, such as best management practices and low impact developments, to define a similar subset of systems, these terms identify the movement away from more traditional drainage systems into more sustainable systems that promote reuse and additional environmental benefits. Rozos and Makropoulos (2010), identified that the introduction of SuDS and rainwater harvesting schemes can considerably reduce the adverse effects increased water pressures are causing on the urban water cycle.

Previous research regarding RMS has focused primarily on a traditional domestic, single storage single demand (S-D) RMS design, ability to supply a reliable water supply and, more recently, their ability to provide additional SWM benefits (Campisano et al., 2014; Roebuck et al. 2011). The implementation of RMS is commonly at a S-D scale due to the lack of availability of additional research, literature and guidelines. However, HR Wallingford (2012) previously hypothesised that the system performance of a RMS could be further enhanced through the interconnectedness of a multi-nodal network (nSnD). A multi-nodal network is an umbrella term that refers to a number (n) greater than 1 of RMS storage (S) facilities and/or demand (D) nodes within a system. Balhatchet et al. (2014) introduced a simplified multi-nodal RMS that had 2 storage and 2 demand nodes (2S2D) using a simple configuration as shown in figure 1-1. Previous to Balhatchet et al. (2014), SR 736 (H R Wallingford, 2012), Kellagher suggests the idea of a communal storage node (1S) feeding multiple demand nodes (nD), at a neighbourhood house scale. Further examples of interconnected multi-nodal RMS networks have not been assessed and therefore there is a limitation to the assessment of benefits a nSnD RMS can achieve compared to that of a S-D RMS.

2.1.1 The need for a rainwater management system

In the past, rainwater management systems were commonly used across the globe as a main water source supply, with some stone rubble structures dating back to the third millennium BC (Agarwal and Narain, 1997). More recently rainwater management systems have seen a steady decline of uptake with many higher economic countries relying on centralised water supply sources.

The understanding of the multiple purposes generated from an RMS system are a relatively recent discovery. Qualities such as stormwater management and ecosystem improvements through decreasing rainwater runoff, the addition of sustainability of additional water sources, base flow restoration and water supply enable much lower secondary economic costs and higher benefits than a traditional singular function RWH system have increased the research and implementation of RMS (Butler, 2018; Xu et al., 2018).

Rainwater management systems have the potential to achieve both water conservation and allow alleviation and mitigation of flooding similar to that of conventional stormwater management (Fletcher et al., 2007; Xu et al., 2018). Further to these benefits, A RMS is also capable of restoring the predevelopment flow regime and urban water cycle by alleviating surface runoff rates, thus reducing the level of polluted water entering the river/ocean (Xu et al., 2018). Steffen et al. (2013) identified that a RMS implemented in an urban environment can reduce the annual stormwater runoff volume by up to 20% whilst also cutting imported potable water supply by up to 50%.

A study undertaken by Coombes et al. (2002) illustrates the conservation a RMS would have upon a central supply explaining that the usage of such alternative water sources could delay construction of a new water supply by up to 34 years and present up to $67 million worth savings to the study area despite the anticipated increase in population. Further research regarding the water supply benefits undertaken by Campisano et al. (2017) suggested that the use of decentralised water supplies such as that harvested from a RMS in urban areas could reduce the non-potable water demand on central reservoirs by around 80-90%. However, the key findings of the Campisano et al. (2017) research highlight that despite the water supply benefits of a RMS many implementation limitations restrict the use of RMS, often these limitations are regarding economic restraints.

A steady increase of non-potable RMS is being implemented at small scale across Europe and the UK due to the multitude of benefits highlighted above and issues arising within the private sector company such as reduced supply during droughts. Despite this increase, the majority of RWH research and implementation at the present time occurs outside of Europe in places like Australia, Africa and America. The majority of identifiable RWH/RMS in the UK is in the format of household scale rainwater collection systems or single demand single storage systems used for irrigation and toilet flushing purposes.

However, due to environmentally focussed policies increasing the need for sustainable and decentralised water solutions decentralised management systems are steadily increasing in the UK and elsewhere (Burns et al., 2014; Herrmann and Schmida 1999). The capture, storage and use of rainwater are now promoted in many policies as a priority drainage method for new development sites due to the dual purpose of stormwater reductions during rainfall events (Melville-Shreeve and Butler, 2018).

To conclude, previous literature has identified, that a rainwater management system could offer several benefits both to the user, the environment and the urban catchment; such as a reduced demand upon potable (centralised) water whilst still meeting water demand with filtered rainwater runoff for non-potable usage, which in turn will reduce water bills and energy consumption (Walsh, Pomeroy and Burian, 2014). Further advantages of such a system would be that it enables a community of people to develop sustainably and effectively with a technological improvement that meets water demand. This type of system could also provide potential to mitigate several detrimental impacts on the hydrology and water quality of the waterways. If stormwater is to be captured, polluted runoff water entering the river's catchment is reduced. With the addition of a rainwater harvesting system, the combined sewer system is less likely to become overloaded thus reduced flooding and meaning untreated water should not enter a watercourse from the sewerage system. By reducing the number of flooding events caused by a combined sewer system overflow this, in turn, reduces the detrimental impacts to the water quality of a waterway, the waterway and the habitats that are based upon, near or use the waterway. Overall, reducing urban stormwater runoff as well as aiding urban areas to meet water supply demands could reduce damage and degradation to the ecological condition of the original water supply whilst also preventing flooding (Fletcher et al., 2007; Burns et al., 2014).

2.2 S-D to multi-nodal RMS

2.2.1 Motivation

RMS is traditionally understood at the small, domestic scale with a single storage and a single demand. The potential interest of how smaller systems can be scaled up to meet the needs for larger applications has been hypothesised in previous literature. H R Walligford (2012) previously hypothesised that the system performance of a RMS could be further enhanced through the interconnectedness of a multi-nodal network (nSnD). Balhatchet et al. (2014) introduced a simplified multi-nodal RMS that had 2 storage and 2 demand nodes (2S2D) using a simple configuration. An example of Balhatchet et al. (2014) 2S2D network design can be seen compared to the conventional S-D design in figure 1-1. Balhatchet et al. (2014) hypothesised that a multi-nodal network comprising of multiple storage and demand nodes may provide a more effective way to collect available rainwater and combat urban flooding. However, there is no evidence within the literature, research and studies to compare if a nSnD system is more effective at increasing RMS performance when compared to a S-D RMS.

2.2.2 Previous nSnD research

Previous literature have conceptualised a RMS performance through modelling at a S-D, neighbourhood or catchment scale. Models, such as Jamali et al., (2020) and HR Wallingford (2012) analysed a large catchment area that consisted of a number of buildings equipped with a RMS to supply the numerous demand nodes. The study identified that the water saving benefits and flood saving benefits (a reduction of around 25-50% of total flood saving benefits was recorded in Jamali et al. (2020)) of a 1SnD RMS showed it to be economically feasible. Balhatchet et al. (2014) identified similar findings to Jamali et al. (2020) and HR Wallingford (2012) portraying evidence of nSnD scenarios enabling a good level of performance benefits. However, Balhatchet et al. (2014) highlighted the complexities of modelling a 1SnD RMS layout design suggesting that allocation strategies would be required to allocate water between the nodal demands. Previous literature has identified that nSnD systems require additional understanding compared to a S-D RMS to understand and model RMS performance (Balhatchet et al., 2014; HR Wallingford, 2012; Jamali et al., 2020). Previous literature has identified that modelling of a 1SnD and 1S2D system is feasible. However, the complexity of nSnD systems has often restricted the literature to these scales and many limitations and additional complexities occur within the results and modelling techniques identified within the previous literature (Balhatchet et al., 2014; HR Wallingford, 2012; Yannopoulus et al., 2019). The main complexity introduced in a multi nodal network is how the available water is to be distributed between the different demand nodes, if one supply is connected to more than one demand or one demand is connected to more than one supply in a multi nodal network there is a need to choose between how to prioritise nodes (Balhatchet et al., 2014). Further to this complexity, most urban water use require high quality potable water and therefore for RMS to be used at an increased scale to that of an individual house this means that the quality requirements of the water produced would be of a raw to non-potable water scale. In addition to these complexities large-scale storage systems within an urban setting will produce additional cost complexities in retrofit and new build SuDS scenarios. In addition to these logistic complexities the main limitations identified with the 2 previous nSnD research is the temporal resolution is identified to be too low with an hourly time step used thus producing modelling reliability issues within the results generated) Balhatchet et al., 2014; HR Wallingford, 2012).

Balhatchet et al. (2014) introduced a simplified multi-nodal RMS that had 2 storage and 2 demand nodes (2S2D), through the 2S2D research Balhatchet et al. (2014) identified the need to define how storage or demand nodes are prioritised within each time step. The approach that was used within Balhatchet et al. (2014) is defined as an 'allocation strategy'. An allocation strategy enables characterisation of each storage/demand node based upon specific criteria which enables node allocation priority at any given time e.g. D1 could be supplied by S1 or S2 or a combination of both and therefore a decision is made within the model as to which storage would be used to feed the demand node. Balhatchet et al, (2014) proposed 3 prioritisation criteria in order to create the 3 allocation strategies analysed against the 2S2D design, the prioritisation criteria included 'fullest storage first', 'highest demand first' and 'shortest links first'. The findings of the research highlight the importance allocation strategy has upon water supply, pumping costs and the total overflow of a RWH system when analysing performance for a 2S2D network. The research concluded that an equal priority of the 3 prioritisation criteria was the most effective allocation strategy for the combination of performance metrics. However, when analysing for a total overflow performance Balhatchet et al. (2014) highlighted that layout designs that have a 'higher demand' allocation strategy performed better to reduce the quantity of overflow. The shortcomings of this research are identified in a significant lack of additional stormwater management performance metrics, for example the use of a retention efficiency and overflow frequency would have enabled an increased understanding of stormwater management within a multi-nodal RMS enabling more accurate assumptions on an optimal configuration. In addition to this the model time step selected throughout Balhatchet et al., (2014) research was of a low temporal resolution. Therefore, due to the temporal resolution of the data set inaccuracies to the modelling performance will be visible throughout the research. Further to this shortcoming further research limitations are identified in a lack of comparison to a S-D performance for a similar scenario and a lack of follow up for a larger multi-nodal network that has numerous storage and demand nodes (nSnD). If these shortcomings and limitations had been incorporated within the work a better understanding upon the effects of allocation strategy and multi-nodal systems would have been gained, enabling a justified reasoning as to why multi-nodal and one allocation strategy is more optimal for RWH performance.

Previous to Balhatchet et al. (2014), SR 736 (H R Wallingford, 2012), Kellagher suggests the idea of communal storage feeding multiple demand nodes, at a neighbourhood house scale to enable more reliable runoff control. A study was undertaken to test how a communal storage facility used to feed 55 demand nodes would perform with regards to water supply when compared to multiple conventional S-D systems. Findings of the study highlighted that a 10% reduction in storage volume was required when a communal approach was used over the traditional S-D approach and demand in the communal approach was still being met at a similar efficiency and frequency as that seen in a S-D approach. Limitations of this study are identified in a lack of clarification as to model assumptions made and if/what allocation/prioritisation strategy was used to meet the demand of the nodes. Further to these limitations a suggestion made within the study states that fewer overflow events occurred within the communal storage facility, but no stormwater management performance metrics were identified to enable an understanding upon how the communal approach performed to reduce overflow runoff.

The basic framework for nSnD viability has partially been established in previous research (Balhatchet et al., 2014; H R Wallingford, 2012). The results of the previous literature are only a guidance on what affects a nSnD RMS and the assessment on improved RMS performance due to the sensitivities seen in temporal resolution. However, with reasonable assumption the enhancements of performance derive from the fact that a nSnD scenario can average out any differences in demand that would naturally occur between the individual users and with respect to time. A reasonable enhancement in performance is hypothesised to be reflected in water supply and stormwater management performance metrics when comparing a nSnD to a S-D RMS.

2.3 System design for a simplified S-D RMS

The basic components of a RMS are a catchment area (A), Rainfall (R) which falls across the catchment area to create roof runoff (the total amount of available inflow), a storage tank (also referred to as a cistern in some literature) (S), that harvests the roof runoff to a temporary storage facility, a filter that filters water to remove contaminants and removes the initial fraction of roof runoff (this is mainly seen in more advanced systems and removes around 5% of the initial runoff), yield (Y) is withdrawn as an outflow from the available water stored to fulfil the quantity of demand (D). If the storage capacity is exceeded, outflow (O) (also referred to as runoff, overflow, or spillage in previous literature) will occur. If the storage capacity is depleted (no available water) yield will not be withdrawn until inflow occurs.

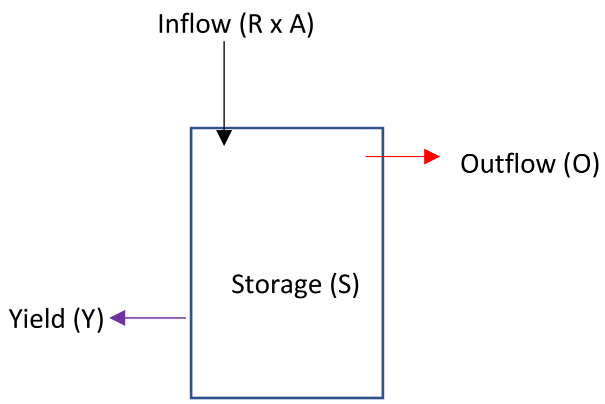


FIGURE 2-1 - BASIC HOUSEHOLD SETUP FOR A SIMPLE SINGLE DEMAND SINGLE STORAGE RMS

The system design parameters of a RMS are with regards to location, storage volume and system configurations. The basic parameters that relate to performance alterations are incoming rainfall (R), outflow (O), storage (S), and yield (Y).

The design of the system does not assume any rainfall loss occur, this is because the rainfall data used within the model set-up is used to understand the impact of multi-nodal network arrangements on the potential performance with no accurate quantification of expected performance for a specific system in a specific location/climate being necessary to the research findings.

In a RMS system the inclusion of previous literature modelled rainfall losses could have caused a large assumption to have been made up on the system. Previous assumptions regarding the measurement of rainfall loses have varied dramatically from a timed quantity to a percentage quantity or actual proportion of rainfall determined to have been lost prior to input into the RMS storage. The assumption regarding the inclusion of losses in this scenario would in some rainfall events categorise a reduced capacity of inflow to no inflow which would have created a lag time between input to output/supply performance of the RMS. However, it was decided through subjective judgement that the inclusion of rainfall losses to create and absolute inflow quantity was not justified for this preliminary research regarding the performance of a multi-nodal multi-objective RMS given that the same inflow input would be used when comparing two alternative arrangements.

2.3.1 Simplified model structure of a RMS

Ward et al (2008) identified that 10 detailed models currently exist for the analysis of RMS system design and/or performance with 5 specifically designed for RWH modelling. The main findings of modelling RMS literature have identified that a YAS or YBS based continuous simulation approach provides the most conservative and reliable results for RMS modelling (Ward et al. 2008; Fewkes and Butler 1999).

2.3.2 How a RMS has been modelled in previous studies

Once an approach to modelling is assumed, a computational based program will be used e.g. MATLAB to create a RMS simulation. The simulation will use a series of input parameters to model inflows and system design characteristics to generate a results time series and a series of outflows. The model inputs for a RMS will relate to the quantity of inflow/ roof runoff, roof runoff is calculated as the quantity of input Rainfall (R) that falls over a catchment area (A). Storage capacity is a volume that is available to store and capture roof runoff in the storage tank (S). Demand (D) is a desired quantity of water needed to supply the individual or network node. Further to these inputs;

- An initial storage quantity may be required to identify if a storage capacity is empty, full, or at partial capacity at the beginning of the model.
- The quantity of demand/storage nodes in a nSnD scenario to identify numerous nodal demand patterns
- Allocation strategy in a nSnD strategy to identify nodal prioritisation

Roof runoff is the quantity of rainfall that occurs across the catchment area recorded for a specific time step (e.g. Daily, Hourly or in Minutes).

Two outflows are designed in a S-D RMS design: outflow through exceedance of storage capacity and yield to fulfil demand (D). If the tank fills to the maximum capacity, any of the collected water that exceeds the maximum capacity will cause outflow; outflow cannot be used and is therefore wasted but also contributes to the localised flood risk. Water is withdrawn from the tank up to the amount required (demand) unless the tank is empty, and no demand can be withdrawn.

Generally, outflow is spilt via an overflow pipe or discharge orifice. The timing of outflow and demand withdrawal within a model time-step is dependent upon the model approach taken (generally the model used is the behavioural model of yield after spillage or yield before spillage as suggested by Jenkins (1978) and analysed by Fewkes and Butler (2000) in which yield after spillage was preferred).

2.4 Modelling RMS

The key aspect when designing a RMS is deciding an appropriate storage volume. The optimal storage volume is related to the demand and the supply of water. The simplest and earliest design methods within the literature are based upon a critical event such as the mass curve analysis (Handia et al., 2003). Various authors have used a model defined as the critical period model in which the system is designed for the most extreme events in historic data and the mass curve method is included (Chow, 1964) alongside the statistical methods designed by Perrens (1982), Rippl (1883), Ree et al. (1971) and Latham (1983). However, this design aspect has disadvantages that have often led to overdesign and uneconomically large storage volumes and is no longer recommended within the literature (Butler and Memon, 2005). A newer simple design that is used within dual function RMS research uses the ratio of annual Yield/Demand (Y/D) to evaluate the design requirements for effective stormwater management. If the Y/D exceeds 0.9 the tank is only suitable for water supply and interception storage. However, if the Y/D is less than 0.9 then the tank storage size is likely to be compliant with stormwater control criteria and can be calculated by the

‘Kellagher and Gerolin Methodology’ (Kellagher, 2012) in which case the tank size is calculated to 5% of the annual yield or annual demand. These two methods are deemed to be much quicker than the more complex methods available and are easily used as a preliminary assessment tool.

Previously, RWH systems that asses stormwater management and water supply performance have been simulated using behavioural approaches (Liaw and Tsai, 2004), probabilistic or stochastic approaches (Coombes and Barry, 2007; Su et al., 2009) or an extension to the behavioural approach known as the ‘knee of the curve’ approach, as described in work by Sample and Liu (2014), in which the tank size is balanced with regards to the probability of overflow and water supply deficits. Coombes and Barry (2008) researched the ‘Knee of the curve approach’ and developed duration curves for the retention storage in which it was found to increase with tank capacity, decreased roof sizes, household population size and event return periods. Further conclusions similar to this have been identified in work by Herrmann and Schmida (1999). Further design approach methods have made use of balance models, combined with probabilistic functions to estimate overflow to enable an estimation of reduction for stormwater management purposes. Again, this function is likely to be most useful as a preliminary assessment tool (Kim et al., 2012).

2.4.1 Behavioural simulation introduction

The behavioural model approach of a system is based upon one of two operating algorithms; ‘yield after spillage’ (YAS) which is an assumption that demand is withdrawn after the spillage has been determined. In contrast, ‘yield before spillage’ (YBS) is an assumption that demand is withdrawn before spillage has been determined (Lade, 2013).

More advanced to these are the behavioural models in which a simulation of the behaviour a RMS produces is generated on a time series basis (Jenkins et al., 1978). Early analyses using behavioural models made use of monthly time step data, but more recent studies have highlighted time step influence with hourly, 15-minute and 5-minute data being more preferable (Campisano and Modica, 2014; Fewkes and Butler 2000; Fewkes and Warm 2000). Behavioural models attempt to model water influxes in response to a realistic rainfall data set and demand time series. These types of models are often preferred within the literature as they are easy to develop and understand having been built upon simple mass balance equations.

The yield after spillage (YAS) algorithm is:

$$[1] \quad Y_t = \min \quad \begin{cases} D_t \\ V_{t-1} \end{cases}$$

EQUATION 1 - YAS YIELD

$$[2] \quad V_t = \min \begin{cases} V_{t-1} + I_t - Y_t \\ S - I_t \end{cases}$$

EQUATION 2 – YAS VOLUME

Where:

I_t = Rainwater runoff (m^3) during a time interval, Δt

V_t = Volume in store (m^3) at time t

Y_t = Non-potable Yield from store (m^3) during a time interval, Δt

D_t = Non-potable Demand (m^3) during a time interval, Δt

S = Store Capacity (m^3)

The yield before spillage (YBS) algorithm is:

$$[3] \quad Y_t = \min \begin{cases} D_t \\ V_{t-1} + I_t \end{cases}$$

EQUATION 3 - YBS YIELD

$$[4] \quad V_t = \min \begin{cases} V_{t-1} + I_t - Y_t \\ S \end{cases}$$

EQUATION 4 - YBS VOLUME

2.4.2 YAS vs YBS

Previous literature has indicated that a YBS algorithm usually overestimates the performance of a RMS whilst a YAS algorithm underestimates performance (Fewkes and Butler, 2000; Liaw and Tsai, 2004). Analysis of the two approaches, findings by Fewkes and Butler (2000) identified the YAS algorithm to be more conservative resulting in more literature and storage designs using this algorithm when compared to that of the YBS algorithm. However, this assumption was based upon a model using a low temporal resolution (monthly time step), input data set which will have affected the accuracy of the results generated and therefore the assumptions made regarding YAS and YBS model performance.

2.4.3 The importance of time step on the behavioural simulation approach

The loss of accuracy with an increase in time step is a well-known problem for discrete time step models as the whole rainfall event might enter the barrel in a single time step. If the simulation add all of the flow to the barrel in a rainfall event, there is likely to be insufficient storage capacity, and overflow/outflow will be modelled to occur. Whereas with a smaller time step, the filling and emptying processes are more gradual occurrences, demand will slowly reduce the volume in storage between time steps, and therefore less of the total inflow becomes outflow. The consequences of large computational time steps, such as that of a daily timestep in a RMS, result in the addition and subtraction of large volumes of water instantaneously and the simulations are far more sensitive to the ordering of calculation steps (e.g. YAS or YBS) than when smaller time steps (reduced flow volumes) are involved.

The time-step used in the modelling process has been previously highlighted to be an important design factor. Latham (1983), Fewkes and Butler (2000), and later Campisano and Modica (2014), have analysed the use of differing time steps had upon the respective model accuracies and concluded that large time-steps can underestimate RMS water supply performance and overestimate the required storage. Previously, time step studies undertaken by Campisano and Modica (2014) and Fewkes and Butler (2000) suggest that a daily time step could be reliably chosen for an accurate evaluation of a rainwater harvesting system's performance. However, it has not been analysed what effect time step will have upon the model simulation with regards to RMS stormwater management performance. Whilst high resolution data in theory would be the most preferable option for modelling, historic data at most sites is restricted in the UK and often lacks temporal resolution in detail. Therefore, it is important that research highlights these issues accurately, analyses a reliable time-step to model simulations at and evaluates any inaccuracies caused due to time-step discrepancies.

2.4.4 Modelling outflow

The YAS and YBS behavioural model highlighted in equations 1-4 measure the volume of yield and volume of water in storage but do not provide the volume of outflow that occurs during the model simulation period. This highlights that previous research relating to RMS has focused upon the water supply performance. However, to effectively analyse the stormwater management performance of the RMS a volumetric quantity of outflow will be required. To effectively measure the quantity of outflow that occurs a further mass balance equation will be required to enable stormwater management analysis.

2.5 Model performance evaluation

In analysing whether or not a dual function system will perform efficiently, the system must initially be modelled to identify its performance e.g. the total volume over a given time period, demand capacity, outflow occurrence and stormwater capture efficiency alongside other performance metrics (Lade, 2013).

Previous research on rainwater management systems has primarily focused upon the ability of the RMS to conserve a considerable quantity of water and deliver a reliable water supply with little consideration to further RMS benefits (Campisano et al., 2017; Campisano and Modica, 2014; Fewkes and Warm, 2000; Xu et al., 2018). The water saving capabilities of a RMS are commonly understood and highlighted frequently in the evaluation of a RMS.

Xu et al. (2018) and Ward et al. (2008) both measure the performance of a RMS by the quantity of water conserved in a RMS scenario for a S-D RMS at a small occupancy scale and large occupancy scale respectively. The literature found that the use of a water saving efficiency which enabled a volumetric performance metric was a reliable indicator to measure the water conserved by the RMS. Further to the water saving/supply efficiency Xu et al. (2018) suggested a water supply frequency to characterise the frequency in which water is supplied by the RMS. However, as the demand was constant in Xu et al. (2018), the water supply efficiency and frequency were shown to be comparable. Xu et al. (2018) modelled at a S-D scale to analyse water conservation and stormwater retention alongside baseflow restoration. Using an 11-year rainfall dataset 2 performance metrics specifically analysed the stormwater management benefits a RMS to quantify system performance. The retention efficiency enabled a volumetric indicator of the RMS capability to retain stormwater whilst the overflow frequency defined the frequency of outflow events of the system. The indicators used in Xu et al. (2018) work comprised average values and therefore did not indicate behaviour during storm events which Poff et al. (1977) and Walsh et al., (2005;2012) previously highlighted as a key criteria for stormwater management performance assessment.

It has previously been identified the low impact stormwater management systems such as RMS are now no longer only required to alleviate and mitigate flooding to an urban area but are more recently required to aim towards restoring the pre-development flow regime and urban water cycle (Walsh et al., 2005;2012). Stormwater event flow reductions has previously been analysed by Gerolin et al. (2010). Gerolin et al. (2010) analysed the benefits provided by RMS during extreme storm events through 2 performance metrics: stormwater retention and peak flow. The findings of Gerolin et al. (2010) research highlighted that up to 65% of stormwater can be retained within a RMS without any reduction to the peak outflow due to the timing of peak rainfall occurring once the storage capacity is full. The performance work undertaken by Gerolin et al. (2010) has highlighted how stormwater management performance metrics can often conceal the performance during stormwater event periods due to the use of average performance values. The findings of Gerolin et al. (2010) highlighted the importance of additional performance metrics being required to enable performance representation during storm event periods.

Poff et al. (1977) proposed a natural flow paradigm in which it is implied that simply reducing a peak flow from urban runoff through a detention and or retention system is not sufficient enough to protect or restore the proposed ecological function. To aid the restoration of ecological function the magnitude, duration and timing of all overflows need to be maintained close to their natural levels prior to development which is commonly referred to as the greenfield runoff rate in the SuDS manual. Previous stormwater management performance evaluation of RMS has failed to compar3e outflow to the greenfield runoff rate or peak outflow. Therefore, within the previous multiple-benefit RMS literature there is a limited comprehension of how a RMS can alleviate stormwater runoff to that of the pre-development and natural flow regime. If in the future of RMS research, it is capable to evaluate the magnitude, duration and timing of outflow events a better evaluation of stormwater management performance will be achieved.

2.6 Factors to consider when modelling for a RMS

2.6.1 Precipitation

Precipitation will vary with season, location, topography and year (Apaydin et al., 2010). Factors such as local topography, distance from the coast, East or West facing or North or South location in the UK will strongly influence the precipitation. The population of the UK is highest in areas with low rainfall e.g. the south of England, compared to areas with high rainfall e.g. the Northwest of England and Scotland. For a model to function, an area/study site must first be selected to efficiently model the actual rainfall profile. There are two ways of incorporating this data into the analysis and these are stochastic and historic.

In the UK seasonality, locality and intensity of the rainfall will alter, as it has done previously, this will alter the amount of rainfall a tank/reservoir will receive over a given time period. Therefore, the storage size will alter, in particular, in regions that suffer strong seasonal discrepancies. For example, if East Anglia is to use RMS it could be suggested or assumed that oversized tanks or smart system tanks may work better in order to ensure water demands and supply remain at a similar level throughout the year thus meeting water demands of the user (Gerolin et al., 2010).

Similarly, if the impact of climate changes are taken into consideration this could also have a considerable effect upon the tank size required. Youn et al. (2012), UKCP (2009) and IPCC have suggested that precipitation patterns have already altered due to climate change and it is expected further changes will occur.

In the UK rainfall data is available from several sources e.g. Met Office, CEH, universities and research etc. Most commonly rainfall data is collected in hourly time intervals or at a daily scale, the collection of very short duration rainfall e.g. 15-minutes is only collected and reported by the environment agency whilst 5 minutes time steps are rare and only usually found in research data (Kellagher and Franco, 2007).

2.6.2 Time step

The selection of a time step in the input data and analysis when modelling for a RMS is important; finer time steps may limit the availability of data and larger time steps may cause inflow and outflow inaccuracies to the results generated. Research undertaken by Burian and Jones (2010) suggests using a continuous simulation on a sub-daily temporal scale. A variety of time steps have previously been used in literature from 5 minutes to daily (Coombes et al., 2002; Herrmann and Schmida, 1999; Mitchell et al., 2008; Palla et al., 2011). Previous research has identified that when measuring performance with regards to water supply a daily time step is acceptable (Fewkes and Butler, 2000). However, when regarding stormwater management and runoff capture performance a much smaller time step of around 15 minutes is required (Campisano and Modica, 2014). Coombes and Barry (2008) identified that time steps with a larger time step are less accurate and tend to overestimate yield, due to overestimating inflow and underestimating spillage outflow.

2.6.3 Demand fluctuations

Demand fluctuations occur at any scale as expected but are more important when dealing with fluctuations that cause large peaks in flow to occur and fluctuations that may cause days of little to no demand. Very little research has been undertaken with regards to demand fluctuations with most previous literature opting to use a uniform demand rate throughout the time period or increasing/ decreasing demand at the weekends with regards to the building use (Fewkes and Butler, 2000; Campisano and Modica, 2014; Ward et al., 2008). Blokker et al. (2017) evaluated that the use of a stochastic demand fluctuation modelling tool (SIMDEUM) has enabled more realistic input data to be used when modelling. Therefore, the use of stochastic demand fluctuation will enable additional value and understanding to be seen when modelling for a current and future water demand due to a better of understanding upon performance of RMS with regards to demand fluctuations. Currently, there is no available literature regarding the benefits of using a stochastic demand fluctuation input when modelling for a RMS. However, since a RMS is modelled often to be used in a real-life case study scenario it should be a component that is considered to enable a simulation that predicts real life demand patterns within the results. The benefits of using a real-life demand pattern when compared to that of a uniform demand rate would include a more realistic RMS hydraulic model with a possibility of gaining a better understanding of water supply and stormwater management benefits due to the alteration of a more realistic demand pattern.

2.6.4 Allocation strategies

Balhatchet et al. (2014) introduced the concept of multi-nodal RMS and with-it modelling factors that are associated with multi-nodal RMS. An allocation strategy is required when modelling a multi-nodal RMS and is defined in Balhatchet et al (2014) as a means to differentiate and prioritise individual demand/storage nodes within each model time step. Balhatchet et al. (2014) had only 4 proposed allocation strategies, *Shortest links, fullest storage, highest demand and equal weighting*. Balhatchet et al. (2014) suggested that, under the tested parameters, the allocation strategies that provided the better water supply efficiencies for a simple multi-nodal RWH system are fullest storage and an equal weighting strategy. However, it is noted that Balhatchet et al. (2014) researched at a low temporal scale and inaccuracies to the importance of allocation strategies on RMS performance may have been introduced through this modelling discrepancy.

2.7 Summary

RMS are a valuable SuDS approach for water supply and stormwater management. From the literature analysed, there is an opportunity to develop a mass balance equation and a series of performance metrics to reliably evaluate stormwater management performance. There is a further opportunity to evaluate whether a nSnD RMS has a comparable performance to a RMS with regards to water supply and stormwater management metrics.

3 Creation of appropriate RMS outflow equation and performance metrics

3.1 Introduction

This section details the initial steps undertaken in the development of the RMS modelling approach. The main objective of this section is to produce a feasible outflow equation that can be inputted alongside a behavioural approach model (equations 1,2,3 and 4) and a series of performance metrics to evaluate the system performance. The literature review has highlighted that modelling approaches and performance evaluation of S-D RMS for water supply purposes is well documented. However, the performance measures and modelling approaches used when modelling for the multiple-benefits of a RMS are not as well documented (Ossa-Moreno et al., 2017). The main aims of this part of the research are to:

1) Evaluate the documented research in relation to performance metrics
2) Produce an outflow mass balance equation that can be inputted into a behavioural approach RMS model
3) Develop a set of performance metrics that can be used to assess the model performance

3.2 The need for an outflow equation

As detailed in section 2.4.4 The YAS and YBS behavioural model approach measure the volume of yield (equation 1 and 3) and volume of water in storage (equation 2 and 4) but do not provide the volume of outflow that occurs during the model simulation period. However, to effectively analyse the stormwater management of the RMS a volumetric quantity of outflow will be required.

3.3 Identified outflow and inflow equation

[5] $O_t = \max \begin{cases} V_{t-1} + I_t - S \\ \emptyset \end{cases}$

Equation 5 - Outflow equation

[6] $I_t = R_t * A$

Equation 6 - Inflow equation

I_t = Rainwater runoff (m^3) during a time interval, Δt

O_t = Outflow from store (m^3) during a time interval, Δt

V_t = Volume in store (m^3) at time t

S = Store Capacity (m^3)

R_t = Rainfall at time t

A = Catchment area

3.4 Proposed YAS and YBS model with the additional water balance equations

As detailed in section 2.4.1, the ordering of water balance calculations differs between the YAS and YBS behavioural model approaches. The models outlined in section 2.4.1 were modified as follows to incorporate the calculation of inflow and outflow:

- YAS: Determine I_t (equation 6); Determine V_t (equation 2); Determine O_t (equation 5); Determine Y_t (equation 1)
- YBS: Determine I_t (equation 6); Determine V_t (equation 2); Determine Y_t (equation 3); Determine Y_t (equation 5)

3.5 The need for a concise list of performance metrics

A number of performance metrics have been proposed for analysing the performance of a RMS. These have included previously used rainwater harvesting and stormwater management metrics from the accessible literature (Gerolin et al., 2010; Ward et al., 2008; Xu et al. 2018). A review of these studies is shown in section 2.5.

Previous literature has many knowledge gaps regarding how the performance of a RMS should be measured for stormwater management and water supply benefits. It is therefore crucial to the understanding of this research that a series of performance metrics are generated that can reliably assess model performance.

3.6 Identified performance metrics

The metrics chosen for performance analysis of a RMS evaluate both water supply and stormwater management objectives. Relevant water supply and stormwater retention efficiency and water supply frequency metrics have been taken from Xu et al. (2018), in addition a peak outflow, and a quantification of time outflow exceeds the greenfield runoff rate will be reported. The water supply and stormwater management metrics are as follows:

TABLE 3-1 - PERFORMANCE METRICS FOR RMS PERFORMANCE EVALUATION

Metric	Equations	Abbreviations/Symbols
EQUATION 7 - WATER SUPPLY EFFICIENCY (WSE) (-)	$WSE = \frac{\sum Y_t}{\sum D_t}$	Y_t – Non-potable Yield time series (m^3/timestep) D_t – Non-potable Demand time series (m^3/timestep) e.g. the quantity of demand

[7]		required for toilet flushing and or garden irrigation for the time series
EQUATION 8 - WATER SUPPLY FREQUENCY (WSF) (-) [8]	$N_t = \begin{cases} 1, & Y_t = D_t \\ 0, & else \end{cases}$ $WSF = \frac{\sum N_t}{n}$	N_t- Number of time steps (count function) Y_t – Non-potable Yield time series (m^3/timestep) D_t – Non-potable Demand time series (m^3/timestep) e.g. the quantity of demand for toilet flushing and or garden irrigation for the time series n - Total number of time steps in the time series
EQUATION 9 - STORMWATER RETENTION EFFICIENCY (SRE) (-) [9]	$SRE = 1 - \frac{\sum O_t}{\sum I_t}$	O_t - Outflow (m^3/timestep) I_t Roof runoff/tank inflow time series (m^3/timestep)
EQUATION 10 - ANNUAL TIME ABOVE GREENFIELD RUNOFF RATE (TAG) (MINUTES/ANNUAL) [10]	$N_t = \begin{cases} 1, & O_t > GRR \\ 0, & else \end{cases}$ $TAG = \sum N_t \times T$	O_t - Outflow (m^3/timestep) GRR - Greenfield Runoff Rate (m^3/timestep) assumed to be 5l /s/ha equivalent to a 1:1 year return period to enable controlled assessment of outflow N_t- Number of time steps (count function) T - Minutes within the timestep
EQUATION 11 – PEAK OUTFLOW (OPEAK) (M^3/5 MIN) [11]	$OPeak = \max(O_t)$	$OPeak$ - Peak Outflow (m^3/5 min)

The water supply frequency, water supply efficiency and stormwater retention efficiency metrics have previously been used in Xu et al. (2018) and enable a good understanding of water supply and stormwater retention capabilities of the RMS. Whilst, the peak outflow and time above greenfield runoff rate metrics represent a new proposal that addresses the noted deficiencies associated with previously utilized volumetric metrics for stormwater management. In a parallel study, Quinn et al. (2020) have also determined outflow rates and compared them with greenfield runoff rates.

The WSE and WSF metrics in this scenario are used to enable analysis of water supply for non-potable demand sources such as toilet flushing and or garden irrigation only resulting in a reduced water supply capacity of 40-120 litres per person per day for the analysis of this research but the metrics can be used to measure the water supply performance in a potable scenario if desired. The SRE has been designed to enable good analysis of stormwater retention performance of the RMS and was previously analysed in research by Xu et al. (2018). The time above greenfield runoff rate is an annual metric that relates the quantity of outflow that exceeds that of a 1:1 year return period (5l/s/ha greenfield runoff rate) this metric was used to assess the number of times the system exceeded the proposed outflow rate for an annual time series. Time above greenfield runoff rate was assessed rather than the volume that exceeded greenfield runoff rate for this analysis but in future work both metrics would complement each other well and enable additional analysis for the volumetric quantity of outflow that exceeds alongside the quantity of time exceeded. However, for this research an additional annual metric specifically relating to the volume of outflow that exceeded greenfield runoff rate was not deemed necessary within the analysis for stormwater management performance and instead a total outflow volume could easily be accessible for analysis review. The peak outflow metric as suggested asses the volumetric peak outflow for the time series to enable an understanding of the largest event to occur throughout the time series. However, unlike the other metrics suggested the peak outflow will analyse for the largest outflow event to occur for the full time series (e.g. 1 year or 30 years) and this metrics dependence upon the time series could cause limitations to smaller events being misrepresented when the time series exceeds a yearly time scale. However, this misrepresentation of outflow could be analysed by using a yearly peak outflow or analysing using other stormwater metrics. Overall, the metrics as suggested will enable constructive analysis of performance for stormwater management and water supply purposes of a RMS.

3.7 Conclusion

Section 3 has successfully addressed the initial key knowledge gaps identified within the literature and has presented an outflow equation and concise list of performance metrics that will be used in the future of modelling work.

4 Model feasibility and analysis of the performance metrics for S-D RMS

4.1 Introduction

This section details the initial steps undertaken in the development of the nSnD RMS modelling approach, beginning at the most basic level of a single storage single demand (S-D) system in a hypothetical real-world RMS scenario. This section details how the modelling foundation of the S-D system provides a basis for the following sections of this report.

The main aims of this section are to:

1) Begin development of a hypothetical real-world S-D simple RMS in MATLAB which can later be scaled up for nSnD application
2) Evaluate the relevance of the performance metric results
3) Analyse the modelled behaviour against a case study RMS

4.2 Illustration of model performance and analysis of performance metrics

4.2.1 Introduction

Rainwater management systems will contribute to water supply whilst a volume of water is retained in the storage capacity. However, a RMS will only contribute to stormwater reductions during the period where inflow can be captured and stored. Once the tank storage is full, there will be no reduction in flow rates, and it should be assumed that outflow will pass to the site's original drainage system. Unless the RMS can be designed to capture all events (unlikely to occur due to costs, implementation and other key design factors), RMS cannot be assumed to reduce the stormwater outflow on a consistent basis. An increase to the stormwater management benefits may be gained by altering system configurations to increase storage capacity prior to an inflow event (Gerolin et al., 2010; Xu et al., 2018).

This study explores the behaviour of a S-D conventional RMS using a deterministic demand pattern quantity over a short-period of time. The water yield of the system for non-potable domestic supply and the stormwater retention behaviour will be assessed against 5 performance metrics as stated in section 3.5 for a 14-day period in which the system will experience depleted and exceeded volumetric capabilities to enable periods of time with outflow and water availability shortages. The use of 14-day period enables a concise dataset on the RMS model behaviour emphasising quick succession between storm events to highlight any areas where the model works as expected or may fail to follow expectations. This section aims to illustrate that the model has been correctly conceptualised to analyse a S-D RMS and the performance of the system can be accurately and reliably represented using a series of performance metrics.

4.2.2 Methods

In MATLAB a single demand single storage (S-D) conventional RMS was created using equations 1, 2, 5 and 6 to represent a YAS model approach (Fewkes and Butler, 2000). Rainfall (R) is a University of Sheffield dataset collected during a 1-year period of 2007 at a 5-minute timestep (Stovin et al. 2012), the rainfall event used here is a 14-day period from June 1st to June 14th, catchment area (A) simulates an area of 40 m^2 representative of 1 terraced house. Demand (D) is withdrawn at a constant rate at a set demand fraction (D/AR) of 0.65 (0.08 m^3/5min). The demand fraction or D/AR is calculated as the quantity of demand divided by the calculated model area and total yearly rainfall. Storage (S) was estimated based on a simple approach as highlighted in the British Standards providing a storage of 3.5 m^3 ((BS 8515)-2009 + A1-2013), initial storage volume (V) is modelled to be half full. The sizing of the storage facility is intended to provide effective stormwater management based on retention of a 1 in 100 year event and is therefore notably larger than a typical domestic rainwater tank. It should be noted that regional geographical variation of design storm depth is not taken into account for these simulations but a base geographical variation for the UK is considered for the design storm depth of 1 in 100 year event. The British Standard guidelines often oversize the storage capacity to enable a more reliable water supply and reduce outflow capacity to a minimum. Whilst the BS guidelines on storage sizing is a desired RMS combination it is realistically often not feasible in practice given cost, time and available area for RMS storage limiting the desired storage capacity to a much smaller quantity and therefore much smaller RMS storage capacities are preferred in practice. Outflow (O) occurs when the storage capacity is exceeded. Performance of the modelled RMS will be measured using five performance metrics shown as equations 7 through to 11. The greenfield runoff rate modelled was assumed to be 5 l/s/ha in line with sustainable drainage guidance (H R Wallingford, 2012).

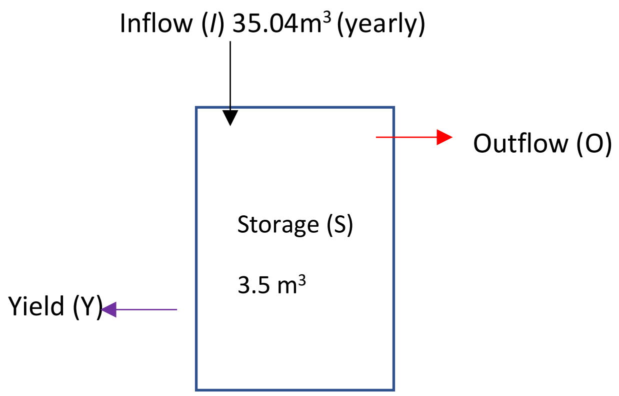


FIGURE 4-1 - HOUSEHOLD SET UP FOR A 1 IN 100 YEAR EVENT AS SUGGESTED IN METHODOLOGY

4.2.3 Results and Discussion

Initial Analysis:

Figure 4-2 provides a series of time series plots for the 14 day time period for a YAS model showing the yield (Y), outflow (O), Rainfall (R), and Storage (S) results.

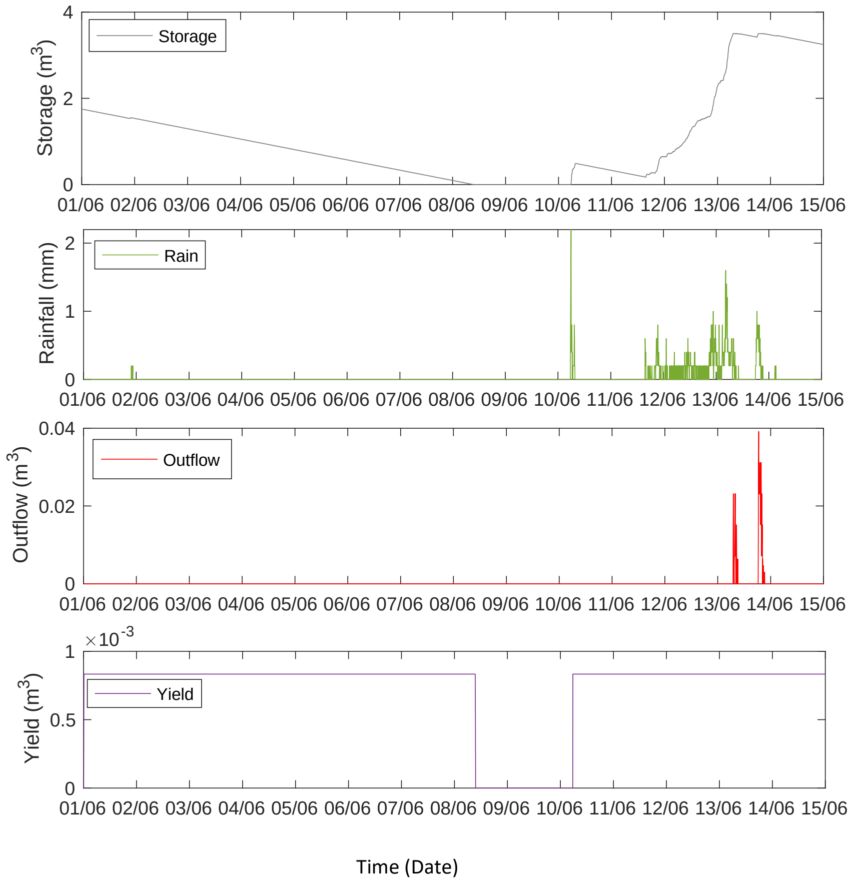


FIGURE 4-2 - STORAGE, RAINFALL, OUTFLOW AND YIELD RECORDED DURING THE SIMULATION

The model was assessed using a check sum error (the total inflow minus the total yield, total outflow and volume at the end time step is equal). A check sum analysis enables an overall assessment of the RMS model water balance loop. For the analysis the model ran at a check sum of 1.03 e-19.

The results show that the RMS is following the expected behaviour i.e. when the storage is empty no outflow or yield occurs and when the storage reaches maximum capacity whilst rainfall is occurring yield and outflow will occur simultaneously. Table 4-1 highlights the results of the 5-performance metrics analysed.

TABLE 4-1 - PERFORMANCE METRICS RESULTS THAT RELATE TO TANK PERFORMANCE FROM THE METRICS AND WILL BE COMPARED TO THAT OF THE MODEL RESULTS

WSE	0.8685
WSF	0.8685
SRE	0.8545
TAG	235 minutes
OPeak	0.0392 m^3/5min

With a quality of model assurance throughout the model simulation (model checksum) showing at 1.02925 e-16.

Analysis of water supply efficiency and frequency metrics:

Figure 4-3 provides a comparison of the yield and demand time series for the model simulation.

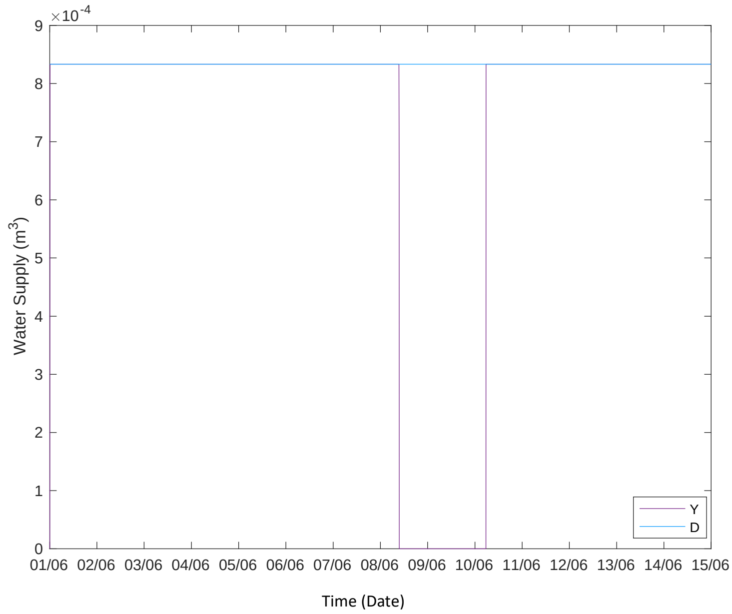


FIGURE 4-3 - WATER SUPPLY - YIELD COMPARED TO DEMAND

The water supply efficiency performance metric suggested that the yield of the S-D system met the required demand 86.85% of the time. From figure 4-3 it can be shown that failure for yield to meet demand was noted for 2,650 minutes out of the 20,160 minutes modelled, creating a 13.15% failure for yield withdrawal and a system water supply efficiency of 86.85%.

The water supply frequency performance metric for a constant demand is expected to equal that of the WSE. Figure 4-3 provides evidence of the water supply efficiency and frequency under these circumstances being equal through analysis of the yield flow meeting the required water supply quantity. Further analysis shows that water supply was met for 3501 time step intervals out of the total 4032 timesteps and the system failed to meet water supply for 531 time step periods creating a WSF of 86.85%. Overall, figure 4-3 confirms that the water supply frequency and water supply efficiency performance metrics are reasonable in providing the desired flow frequency of the system.

Analysis of stormwater retention efficiency metric:

Figure 4-4 presents the cumulative inflow and outflow for the time series to enable an evaluation of how the outflow and inflow rate are comparable to the SRE performance metric.

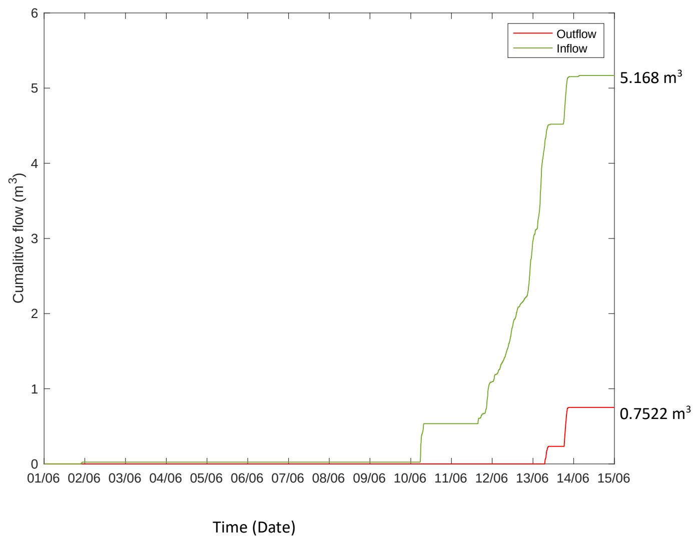


FIGURE 4-4 - CUMULATIVE INFLOW AND OUTFLOW

The performance metric for stormwater retention efficiency suggested that from the model results a total inflow of 85.45% could be retained and reused whilst a modelled outflow of 14.55% would be overflowed. The SRE metric has provided a reliable representation of the overall retention efficiency of the system as concluded in the results shown in Figure 4-4.

Analysis of time above greenfield runoff rate and peak outflow metric:

Figure 4-5 presents an outflow flow frequency diagram for the simulation time series with a zoomed in frequency profile of the main events that exceed greenfield runoff rate.

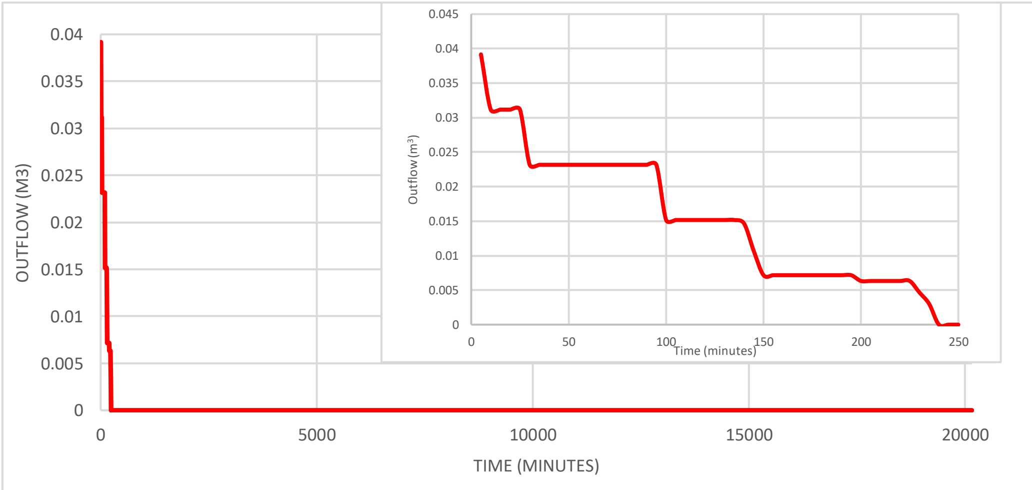


FIGURE 4-5 - OUTFLOW FREQUENCY DIAGRAM FOR 14 DAYS AND ZOOMED IN VIEW OF THE TIME ABOVE GREENFIELD RUNOFF RATE

Figure 4-5 highlights a frequency of outflow in cubic metres generated in excel for the 14 day period as highlighted in minutes and a zoomed in view of the outflow events is shown to the right of the diagram to aid in assessment of performance metrics. Figure 4-5 is identified as a flow frequency diagram for outflow with a zoomed in view of the event only periods. From the modelled performance metrics time above greenfield runoff rate was recorded as 235 minutes whilst peak outflow was recorded at 0.0392 m^3/5min. From the flow frequency diagram shown in figure 4-5 outflow that occurs above greenfield runoff rate occurs for 235 minutes out of a total 20,160 minutes (14-day period) with a peak outflow of 0.0392 m^3/5min. The results from figure 4-5 are therefore consistent in providing feasibility of the OPeak and TAG performance metrics.

4.2.4 Conclusion

Overall, the preliminary modelling exercise has illustrated that the performance metrics used within this study provide a reliable representation of the RMS performance with the system configurations following all the expected and desired outcomes.

4.3 Model comparison using Broadhempston S-D RMS data

4.3.1 Introduction/Background

The main aim of this section is to emphasise that a conceptualised RMS model is capable of providing comparable results to a case study site. Through achieving this aim the S-D RMS model used in this study will demonstrate the modelling tool used is valid for future work within this document.

The RMS model used will be a YAS algorithm as used in section 4.2, whilst the case study site will be comprised of monitored data from a household domestic RMS at the Broadhempston site. The Broadhempston site data has previously been analysed by Quinn et al. (2020) in published literature.

The Broadhempston site is located in Broadhempston, Devon, UK and consists of 6 RMS to supply six demand nodes (S-D layout). The Broadhempston site is a unique community that relies upon non-centralised water supplies for six families. RMS have proved to be capable of supplying a proportion of their water supply whilst the borehole provides the rest. Each RMS storage tank of the same simple configuration and size (800 litres) was installed in May 2018, with monitoring of the inflows, outflows and tank level occurring between June 2018 and August 2019.

The aim of this research is to assess a known simple configuration non-potable S-D case study data set at the Broadhempston site, as seen for a small section in Quinn et al. (2020), for a small period of time and compare the results to that of the coded computational model previously used in earlier sections. From the results of the study a calibration of my S-D computational model will be achieved through a close replication of the real-life RMS scenario at Broadhempston. Through achieving a close replication from computational model to case study results this will enable the research of this thesis to move towards multi-nodal networks, whilst that of Quinn et al., (2020) has focused upon barrel configuration adjustments.

4.3.2 Methodology

The validation study compared a 800-litre single demand single storage (S-D), simple, rainwater management system (RMS) located in Broadhempston, England to the modelling code. The data collected comprised of the inflows, outflows and tank levels for one household (approximately a 41.5 m^3 catchment area) RMS at the Broadhempston site. The RMS at the Broadhempston site comprised 1 storage tank per 1 demand node that supplied water for non-potable, toilet flushing, usage. For the Broadhempston site 2 inflows where possible, roof runoff (not measured at the site) and water top-up from the borehole (measured using a flow meter). During the monitored collection period only an estimated roof runoff inflow was present as displayed in figure 4-6. The storage level of the tank was measured using a pressure sensor. Two possible outflows occurred during the monitored data period, the yield quantity was measured with a flow meter whilst spillage outflow was not measured. The sensors of the RMS were connected to a data-logger that saved data at 1-minute intervals.

The model was configured with data comparable to the results from the Broadhempston RMS; the catchment area was 41.5 m^2, storage capacity of 800 litres, rainfall data was an estimation of site rainfall, displayed in figure 4-6 is the rainfall pattern collected from a site 4 miles away, demand was a uniform demand pattern, of 0.0495 m^3 daily. A uniform demand pattern was applied in the computational model to highlight the impact of assuming a constant demand pattern (previously used in RMS computational modelling literature) when compared to that of the real-life Broadhempston data. Figure 4.7 displays the comparison of the results from the validation study.

4.3.3 Results and Discussion

Figure 4-6 presents the rainfall profile from the collection site close to Broadhempston for the time series. whilst figure 4-7 presents the modelled storage volume results compared to the Broadhempston collected results and a squared error.

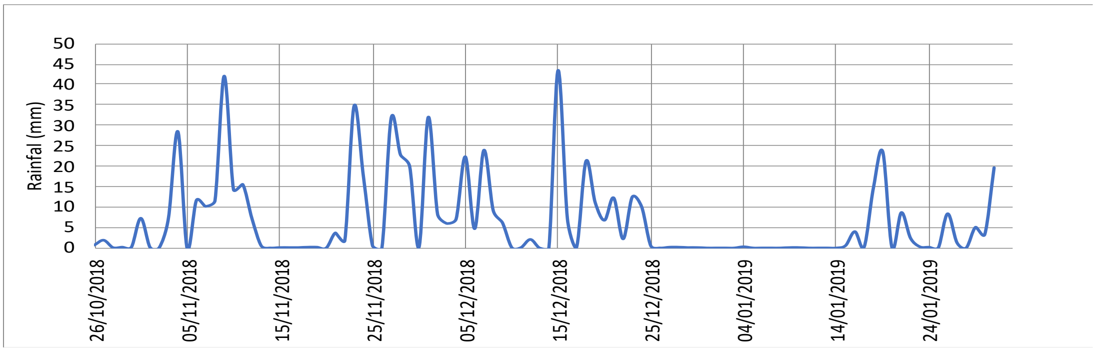


FIGURE 4-6 - RAINFALL INPUT AT A DAILY TIME-STEP (GENERATED FROM A SITE 4 MILES AWAY FROM BROADHEMPSTON)

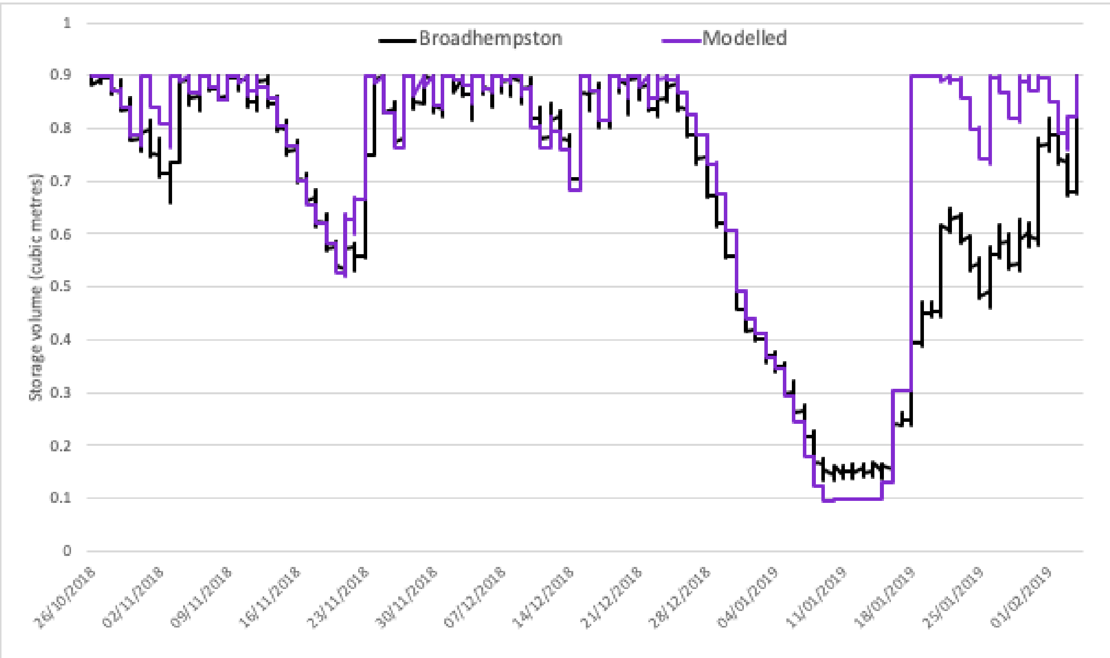


FIGURE 4-7 - STORAGE VOLUME FOR BROADHEMPSTON SITE AND MODELLED RESULTS

The model comparison study results highlight that the model was capable of following a similar pattern to the data previously collected at Broadhempston, with the most noticeable difference between the model and Broadhempston data being shown on the 18/01/19 when the difference in squared error peaked at 0.29 m^3. The model overall provided reliable results with a root mean squared error of 0.016.

Overall, the modelled results simulated at a 5 minute timestep highlight a similar pattern to Broadhempston up until the 18/01/19 when an event occurred in which the Broadhempston data recorded a reduced storage volume compared to the modelled data. It is hypothesised that the differences within the modelled results and the collected data could be due to a variation in the rainfall input data or the output water demand data not being accurately correlated with that of the uniform demand pattern as used in the computational model. The rainfall data used within the model is collected from a site 4 miles away from the RMS site and therefore differences in rainfall pattern may be highlighted during an event period. The demand pattern highlighted in the computational model scenario is a uniform continuous demand pattern and therefore may not have taken into account the slight increase in demand that occurred on the 18/01/19 for the Broadhempston site. Overall, the validation data shows that computational errors, and model discrepancies are reduced to a minimum and when modelling for a RMS with the model used within this simulation providing reliable results.

The Broadhempston data seen in this validation study was used in a research article by Quinn et al. (2020) shown as 'House A'. Quinn et al. (2020) validated a YAS model to 3 RMS tanks from the Broadhempston site. The results of Quinn et al. (2020) showed that a YAS model was capable of representing the monitored data well with little differentiation between a constant and measured demand pattern. The results shown here are consistent with Quinn et al. (2020). Quinn et al. (2020) research has enabled further confidence with the reliability of the model that has been used to represent a S-D RMS within this document so far.

However, in the future undertaking a model comparison study alongside the simulated results may not be possible. The study site at Broadhempston is a single demand single storage RMS comprising of a simple system configuration. The planned work aims to model the performance of a multi-nodal system. Unfortunately, there are no known multi-nodal RMS systems that are implemented and collecting results currently. Therefore, if a model correlation study like that shown in figure 4-7 cannot be undertaken, model reliability will be checked using mass balance checks and analysing against previous data where possible.

4.3.4 Conclusion

To conclude, the model replicated the model calibration and short term assessment results of 'House A' in Quinn et al. (2020) and confidently showed that the model used is capable of producing results comparable to a real-life RMS scenario. The monitored data shown in section 4 reasonably evaluated performance accurately until the 18/01/19 when the model predicated a larger tank level than the recorded data this discrepancy is also shown in Quinn et al. (2020) research. The differences between the model and recorded data is assumed to have occurred due to discrepancies in the input inflow (rainfall) and the use of a uniform constant demand profile in the computational model results.

Overall, section 4.3 has shown that the conceptualised RMS is capable of providing comparable results to that of the Broadhempston case study site. Future work will not require modelled to monitored data validity analysis due to the comparison checks undertaken on a S-D model in section 4.3 and the evolution of the project to nSnD from S-D using similar modelling techniques.

4.4 Conclusion for S-D model feasibility

As discussed in section 4.2 and 4.3 relative confidence in the model of a S-D RMS and reliability in the analysis of performance has been achieved. The S-D model has shown that all results analysed have been capable of providing an accurate representation of a RMS performance. Section 4.3 compared the model to a case study example with the findings highlighting that the S-D RMS model provides representative results to the case study site. To conclude section 4.2 and 4.3 have provided evidence to show that the S-D model used throughout section 4 has provided feasible RMS results.

5 Model sensitivity analysis

5.1 Introduction and background

Section 5 aims to understand how time step, demand pattern and the algorithm used to model affect the simulated performance of a S-D RMS. To begin with, the model algorithms chosen to model the RMS studies were analysed and the results are discussed as part of section 5.2. Shown as part of section 5.3 is a concise report documenting the time step sensitivity analysis findings. Section 5.4 analyses how demand fluctuations can alter the performance result in a S-D RMS. The results of this section will create an understanding of what the RMS model is sensitive to which will determine an appropriate model set-up for following RMS analysis. Reduced model sensitivity in the future nSnD work will enable more reliable performance results to be generated.

Previous RMS research has modeled mainly using a YAS algorithm for a set continuous demand at a sub-daily time-step of 30minutes and higher. However, with the inclusion of stormwater management performance in other water management systems such as sewer and flood modelling suggesting a 5-6-minute step should be used and no higher it is critical to model for sensitivity analysis and reduce this sensitivity prior to research. In previous literature Campisano and Modica (2014) highlighted the importance of time-step sensitivity when modelling for stormwater management performance for a RMS but unfortunately no conclusion upon a critical time-step to model at was generated as part of this research. This section of research will aim to analyse and evaluate model algorithm, time step and demand sensitivities for a dual-function RMS

5.2 Analysis of sensitivity to model algorithm

5.2.1 Introduction/Background

Previous literature has identified that when analysing RMS performance, using a continuous simulation approach, it is crucial to correctly input the hydrological operations of the system into the modelling code (Fewkes and Butler, 2000; Campisano and Modica, 2014). A minimum of 3 input factors should be determined prior to the model simulation. The simulation time period, the operating algorithm (the determination of the order of outflow within the computational time step usually a YAS or YBS approach), and the computational time step. The YAS operating algorithm assumes that demand is withdrawn after spillage (outflow) has been determined, while the YBS operating algorithm assumes that demand is withdrawn before spillage (outflow) is determined. Previous literature has indicated that a YBS algorithm usually overestimates the performance of a

RMS, whilst a YAS algorithm underestimates performance (Fewkes and Butler, 2000; Liaw and Tsai, 2004).

This section aims to investigate the influence of operating algorithms on the assessment of yield and outflow performance of the RMS. The conclusions of this research will identify if one algorithm is capable of providing more conservative results than the other and therefore should be used in future RMS modelling work.

5.2.2 Methods

Model structure:

In MATLAB a single demand single storage (S-D) conventional RMS was created using equations 1 and 2 to represent a YAS model approach and equations 3 and 4 for a YBS model approach (Fewkes and Butler, 2000). Rainfall (R) is a University of Sheffield dataset collected during a 1-year period of 2007 at a 5-minute timestep (Stovin et al. 2012), which was disaggregated into 1-minute time steps through division of the 5-minute profile into 1-minute sections, catchment area (A) simulates an area of 10 m^2. Demand (D) is withdrawn at a D/AR (set demand fraction) of 0.42 (Low demand) and 2.5 (High demand), Storage (S) was estimated at 0.5 m^3, initial storage volume (V) is modelled to be half full. The sizing of the storage facility is intended to provide a typical domestic rainwater tank. Outflow (O) calculated using equation 5 occurs when the storage capacity is exceeded (simple system configuration). Performance of the modelled RMS will be assessed against the cumulative outflow and yield.

5.2.3 Results and discussion

Figure 5-1 highlights model sensitivity in a YAS and YBS algorithm through analysis of cumulative outflow and yield for 5 time series.

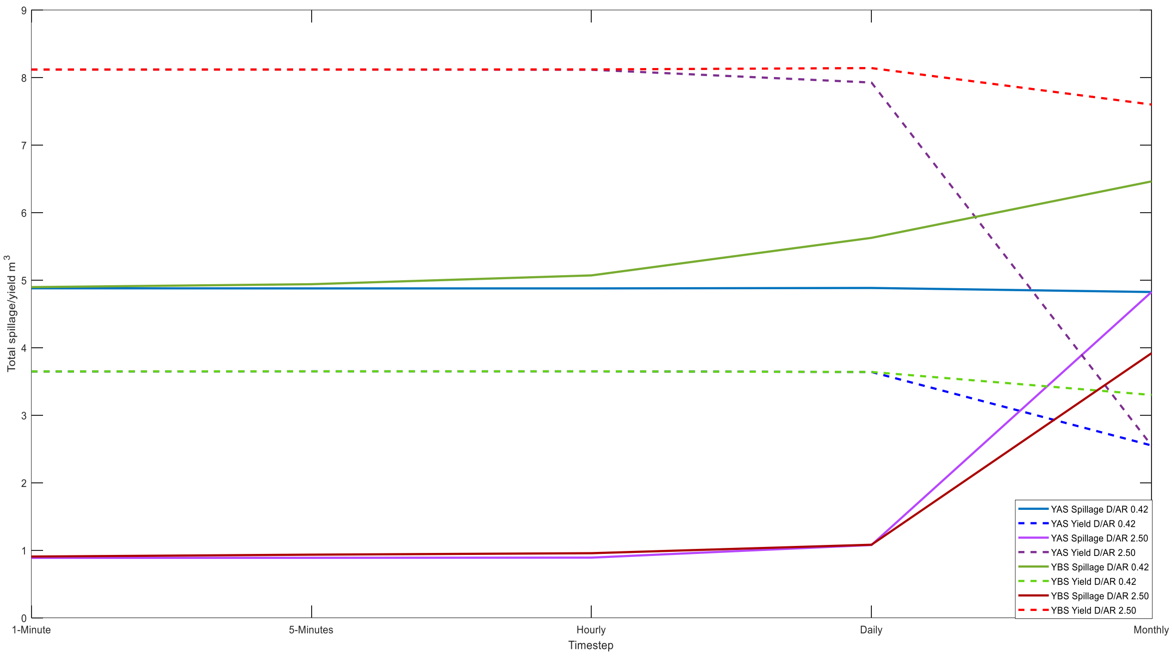


FIGURE 5-1 - MODELLING ALGORITHM SENSITIVITY ANALYSIS YIELD AND SPILLAGE RESULTS

The YBS and YAS results shown in figure 5-1 are consistent with previous literature findings highlighting that when using a large time-step YBS overestimates yield compared with a YAS model. The evidence of divergence to the results are compared against a 1-minute time step which is assumed to be correct. As show by figure 5-1 the biggest divergence for both algorithms is seen at the monthly time-step. Differences between the YAS and YBS results decrease as the time-step changes from monthly to 5-minutes, and as the D/AR decreases. The results of this section have identified that sensitivity to the model algorithm is apparent, thus, providing supporting evidence of previous literature. The YAS model is a more conservative model when estimating spillage results compared to that of the YBS model with results remaining consistent when a daily timestep or smaller is used.

The yield results obtained using a daily time series are close to those generated using an hourly time series for a low D/AR. However, the yield results presented when the D/AR is increased to 2.5, highlights a 3.5% variation from a daily to hourly time step result. The use of a monthly time series has generated inaccurate results in both operating algorithms with a large divergence being present.

When the time step is reduced to 5-minute or 1-minute, the YBS model provides more accurate results than previously seen at a daily or hourly time step. The YBS algorithm results for spillage and yield have shown to be more sensitive to time step when compared to the YAS model. A YBS model has tended to overestimate yield and spillage by a much larger divergence throughout the results shown and even when the temporal scale is reduced to that of 5-minutes a 0.56% and 0.23% divergence is seen between the algorithms.

The overestimation in Yield for a YBS algorithm and spillage (outflow) is due to the temporary storage for inflow being in excess of the maximum storage capacity of the RMS which is created when yield is withdrawn before spillage (outflow). Whilst, the underestimation in a YAS yield and spillage (outflow) is due to a reduction of the effective storage capacity in a RMS due to spillage (outflow) occurring before yield is to be withdrawn. The computational time-steps impact the accuracy of the YAS and YBS operating algorithm as a shorter time-step will increase the frequency of inflow, withdrawal and outflow causing a smaller divergence between a YAS and YBS result. Whilst a larger computational time step is shown to increase the divergence between a YAS and YBS result.

5.2.4 Conclusion

To conclude, the overestimation of YBS and the underestimation of the YAS algorithm with regards to yield is consistent with previous studies (Fewkes and Butler, 2000; Mitchell, 2007). The YBS and YAS models have shown high sensitivity to timestep and that a YAS algorithm provides more conservative results compared to the YBS algorithm. It can be identified from the results shown in figure 5-1 that the difference in the results obtained when using the two algorithms (YAS and YBS) can be reduced through the use of smaller simulation time steps. In future research both a YAS and YBS modelling approach is capable of providing reliable and accurate results at a small time-step. However, in the follow on sections of this report a YAS behavioural approach will be selected for modelling purposes.

5.3 Analysis of sensitivity to time step when modelling a dual function rainwater management system

5.3.1 Introduction and background

The time step sensitivity study was initially touched upon when analysing for sensitivities to model algorithm shown in section 5.2. The findings of the initial research were consistent with previous research (Fewkes and Butler, 2000) in that a YAS algorithm shows little sensitivity to time step. It was therefore decided that for the future of the research a YAS algorithm was to be used.

Previously, time step studies had been undertaken by Campisano and Modica (2014) who suggested that a daily time step could be reliably chosen for an accurate evaluation of a rainwater harvesting system's water saving and stormwater retention efficiency. However, Campisano and Modica failed to evaluate how time step would affect the peak overflow rate and overflow frequency, both of which would affect the system's stormwater management capabilities from a modelling perspective. The use of additional performance metrics to those used in the Campisano and Modica (2014) research will be included to identify an accurate representation of the stormwater evaluation for a RMS when analysing for sensitivity to timestep.

This section aims to further the time-step research of section 5.2 and Campisano and Modica (2014) by identifying the importance computational time step has on measuring the stormwater management and water supply performance of a RMS. The findings of this section will highlight a computational time-step that is capable of generating reliable and accurate results for RMS research.

5.3.2 Methodology

The time step sensitivity study undertaken developed from the previous model algorithm study time-steps to incorporate time step suggestions made by Campisano and Modica's (2014) research, suggestions of 1-minute, 5-minutes, 15-minutes, 30-minutes, 1-hour, 1-day and 1-month were used.

In MATLAB a single demand single storage (S-D) conventional RMS was created using equation 1 and 2 representative of a YAS model approach (Fewkes and Butler, 2000) and the additional equations 4 and 5. Rainfall (R) is a 12 hour period from the University of Sheffield dataset collected during a 1-year period of 2007 at a 5-minute timestep (Stovin et al. 2012), this is then disaggregated down into 1-minute time steps. Catchment area (A) simulates an area of 10 m^2. Demand (D) is withdrawn at a D/AR (set demand fraction) of 0.42 (Low demand), Storage (S) was estimated at 0.5 m^3, initial storage volume (V) is modelled to be half full. Outflow (O) calculated using equation 5 occurs when the storage capacity is exceeded. Performance of the modelled RMS will be assessed using equations 9 and 11 alongside analysis of the total yield and total outflow. The greenfield runoff rate modelled was assumed to be 5l/s/ha in line with sustainable drainage guidance (HR Wallingford, 2012). A small selection of performance metrics have been assessed from chapter 3 to create a more concise analysis of the RMS response to stormwater management performance as previously assessed in Campisano and Modica (2014) research. Stormwater retention efficiency, Peak outflow and time above greenfield runoff rate alongside total outflow and yield have been selected as performance indicators in this section. The aim of this research was to analyse how timestep affects the stormwater management performance of a RMS and therefore water supply performance metrics as previously shown in chapter 3 where not required within the analysis stages and therefore where omitted from the analysis.

5.3.3 Results

Table 5-1 provides performance metric analysis with regards to time-step sensitivity. Whilst figure 5-2 analysis the event time series outflow for time sensitivity analysis.

Table 5-1 - Performance metrics for a 1-year period

Timestep	SRE	Total Outflow	Total Yield
1-minute	0.557	4.8793	3.6477
5-minutes	0.557	4.8773	3.6497
15-minutes	0.557	4.8774	3.6497
30-minutes	0.557	4.8774	3.6496
1-hour	0.557	4.8774	3.6495
Daily	0.556	4.884	3.64
Monthly	0.551	4.824	2.552

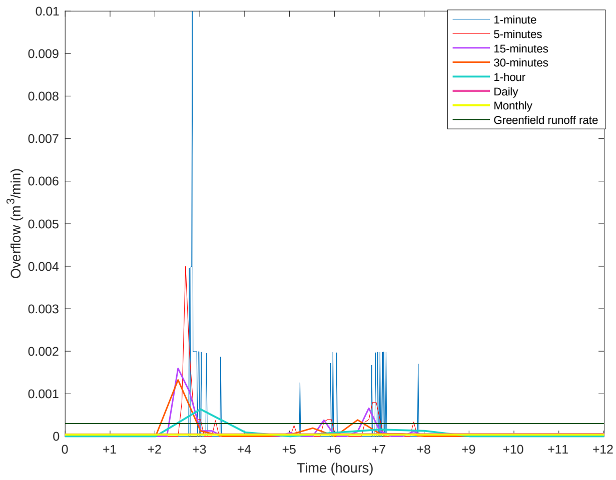


Figure 5-2 - Overflow vs Greenfield runoff event period time step analysis

It is argued from the results in figure 5-2 that the use of a daily and sub-daily time step, as suggested was reliable in previous research (Campisano and Modica, 2014), provides false confidence in a system's stormwater management capability. A monthly and daily time step have shown model sensitives to stormwater retention efficiency, peak outflow, total outflow and total yield when compared to that of the results provided by much smaller time-step increments. The additional performance indicators, total outflow and total yield introduced in this section in addition to the SRE and Peak outflow as previously assessed, enable an understanding of the total outflows modelled by the system during the time period with regards to assessing sensitivities occurred through time-step alterations.

The total outflow indicator has highlighted an increase of 1% outflow when modelling at a daily or larger time step and a small deviation of 0.01% change identified when modelling at the time-steps between 1-hour and 1-minute. The total outflow metric has identified that with a very small proportional decrease (0.04%) a 5-minute time step increment is capable of replicating outflow results closer to that of a 1-minute time-step. Whilst the total outflow has shown very limited sensitivity to time-step alterations, the total yield indicator has emphasised that up to a 30% decrease in the total yield performance can be assumed should a monthly time-step be used in the modelling process. However, the total yield is relatively unaffected to time-step alterations from a daily to 1-minute result with sensitivity showing results of 0.2% to 0.05%.

The SRE performance indicator highlighted that at a time step of hourly and smaller the systems retention efficiency was not sensitive to time-step alterations. However, when time-step was increased to that of daily and monthly increments the retention efficiency showed a small deviation of 0.2% and 1%. The stormwater retention efficiency, total outflow and total yield result follow the expected pattern and guidance on time-step as suggested by Campisano and Modica (2014) with time-steps of larger than sub-daily highlighting an increase in model sensitivity. Therefore, when measuring for these metrics alone time step provides no discrepancies of daily to sub-daily increments to the results and would be deemed adequate. However, Campisano and Modica (2014) failed to asses peak outflow and overflow frequency when assessing time-step sensitivity in a dual function RMS which has been assessed in this section.

It was previously assumed that peak outflow and overflow frequency will show the highest sensitivity to time-step alterations which can be seen to be correctly assumed as shown in figure 5-2. Figure 5-2 highlights that a daily time step is incapable of predicting peak outflow and overflow frequency when compared to that of a smaller time step e.g. 1-minute and 5-minutes. Peak outflow from a 1-minute time step is shown to exceed up to 10x that of a daily spillage. Increases to the volumetric peak outflow was expected due to the larger time-steps averaging the peak outflow across the time-step period resulting in a much smaller peak when compared to that of a 1-minute timestep. Whilst it is known that peak flow is not independent of time step, it should be noted that during the event period shown a 5-minute time-step is the closest time-step increment to predicting peak outflow with an estimation of OPeak at 0.004 m^3/min compared to that of OPeak at 0.01 m^3/min as seen at a 1-minute time step. However, when comparing the results from a 1-hour, 30-minute or 15-minute time-step to that of the 1-minute time step results we see that the simulated peak flows show a much larger significance with peak flow being underestimated by up to 100%.

Since rainfall data at 5-minute increments is more readily available than that at a 1-minute time-step (because of the use in stormwater management designs) a 5-minute time step will enable a reduced quantity in data input uncertainties and computational errors along with reducing the average time volumetric outflows occur to enable a more reliable peak outflow result. Clearly, to achieve a credible level of accuracy with regards to the performance and feasibility of the input data in an RMS simulation, a rainfall data at no greater than 5-minute increments are required, and the model should use a YAS simulation as suggested in section 5.2.

5.3.4 Conclusion

To conclude the use of sub-daily time step as previously suggested by Campisano and Modica (2014) provides an understanding that time step affects the stormwater management peak outflow of a RMS. This research has enhanced the understanding of Campisano and Modica (2014) research and has analysed the timestep increments required for RMS modelling accuracy for stormwater management performance benefits with the findings of this section highlighting that some metrics conceal sensitivities that would affect performance and that when analysing for SWM reliability and both a volumetric and flow performance metric should be used in future research. It can therefore be suggested from this research that any future research regarding the stormwater management capabilities of a rainwater management system models at a 5-minute time step, in a YAS algorithm.

5.4 Demand sensitivity analysis

5.4.1 Demand fluctuation sensitivity analysis for a dual function rainwater management system comparing constant vs diurnal pattern

5.4.1.1 Introduction

Previous research has often opted to use a set continuous daily demand withdrawal instead of a varied real-life demand withdrawal pattern, for example, Fewkes and Butler (2000); Campisano and Modica (2014); Ward et al. (2008) etc. Whilst it has been noted in previous findings, that demand does need to be capable of fitting an average real-life daily scenario, it has not been investigated if a set-continuous demand is capable of predicting the same results as that of a real-life demand fluctuation scenario.

The main aim of this section is to investigate to what extent simple representations of demand (continuous demand patterns) are adequate enough to represent a real-life scenario in RMS modelling. This section will begin investigations by identifying how diurnal demand fluctuations affect the spillage generated from a dual function rainwater management system when compared to a set continuous (simple representation) daily demand during a 1-year period.

5.4.1.2 Methods

Research has been undertaken to establish how fluctuations within a demand pattern alter spillage in a dual function rainwater management system, this is tested using a set demand and a varying demand that has previously been simulated in a SIMDEUM program (Blokker et al., 2017). A generalised 1 demand 1 storage model was created in MATLAB with a YAS algorithm. Rainfall (R) data has been collected from prior research at the University of Sheffield with a 1-year period of rainfall during 2007 being used within this report. The model hypothetically harvests over the 1-year period, assuming a 2700 m^2 catchment area (A) (based upon previously implemented RWH tank at the Imperial Tobacco head office, Bristol (Stormsaver, 2019)). The water is then collected and stored in a tank of 32 m^3 (S). The initial storage level of the tank is assumed to be half full at 16 m^3. Demand (D) is withdrawn at a fluctuating rate (a weekly demand profile that varies in order to represent a commercial diurnal scenario, in which demand is withdrawn during the day only at a commercial demand rate, with 1 day of no demand, simulated using SIMDEUM software (Blokker et al., 2017). The demand is withdrawn using either the original demand pattern, a 12–hour offset to the original demand pattern or a set continuous demand (demand that is continuously withdrawn at a volume equal to that of the fluctuating demand). The inclusion of a 12-hour offset pattern enables the demand to be withdrawn at the opposite time scale to that of the original demand pattern which will enable justification on the alterations in performance identified due to the withdrawal of a varying demand pattern. Mean demand is 20.6 m^3/day. Demand is withdrawn to meet a D/AR of 3.18 and an S/AR of 0.014 (Fewkes and Butler, 2000). The demand profiles are shown in figure 5-3. A 5-minute time step has been chosen for this scenario. If the tank reaches maximum capacity, spillage is modelled to occur. Any water not overflowing or withdrawn for demand purposes remains within the modelled tank until used or spilt. The parameters of this scenario have been selected to magnify the impact of demand on a RMS to enable justification and analysis for demand sensitivity analysis. System performance has been measured with regards to spillage (outflow quantity) solely for each of the generated results. The justification to the use of measuring solely based upon outflow quantiy comes from simply analysing the affects demand alterations have upon the total volumetric outflow rather than stormwater retention, supply and peak outflow performance as seen in the previous metrics which in this assesment where not necessary to make a judgment upon demand representation.

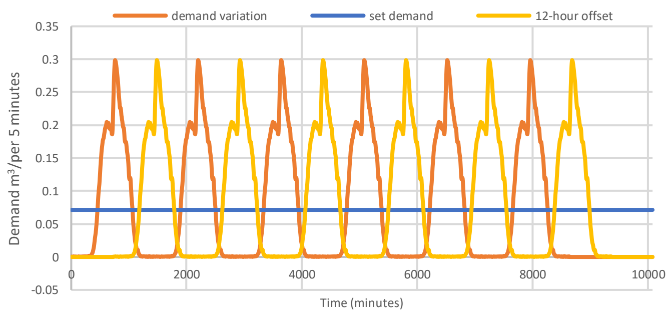


FIGURE 5-3 - THE CHARACTERISTICS OF THE DEMAND PROFILES OVER A 7-DAY CYCLE

5.4.1.3 Results

Figure 5-4 to 5-9 the performance indicators of the system with regards to the spillage generated over the 1-year period for a set demand, fluctuating demand at an original and offset of 12 hours and a greenfield runoff rate.

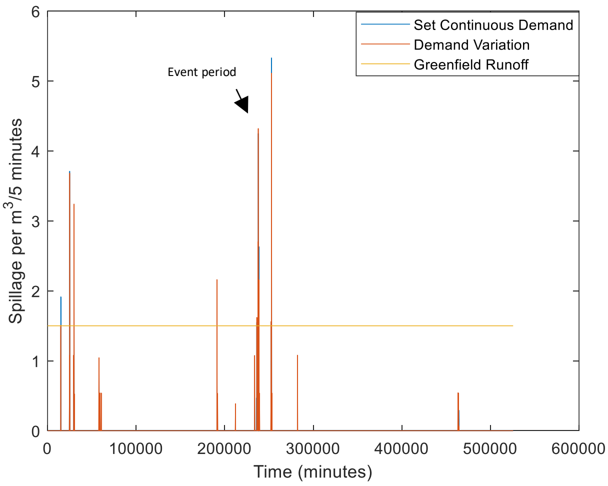


FIGURE 5-4 - MODELLED SPILL VS GREENFIELD RUNOFF RATE FOR A 1-YEAR PERIOD

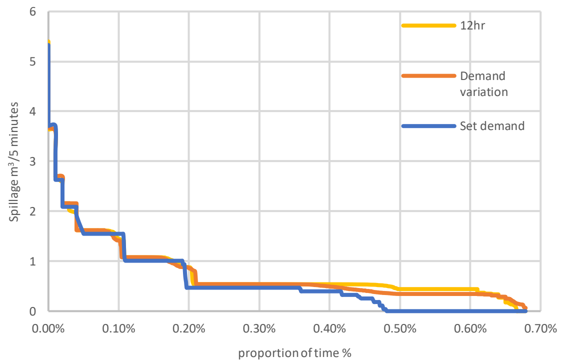


FIGURE 5-5 - FLOW DURATION CURVE FOR A 1-YEAR PERIOD

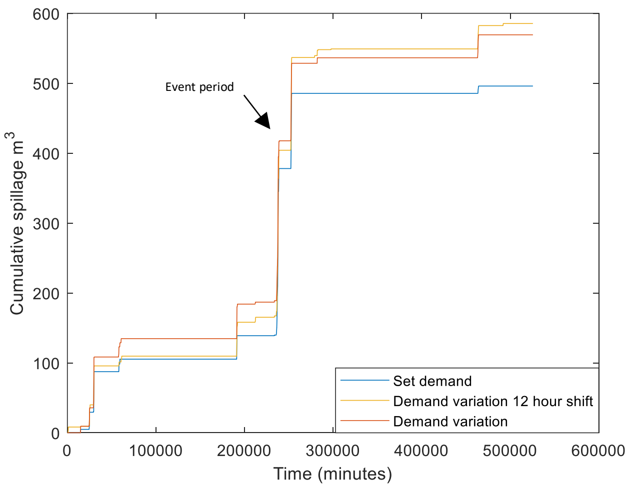


FIGURE 5-6 – PERCENTAGE DIFFERENCE BETWEEN SET AND VARIABLE DEMAND FOR A 1-YEAR PERIOD

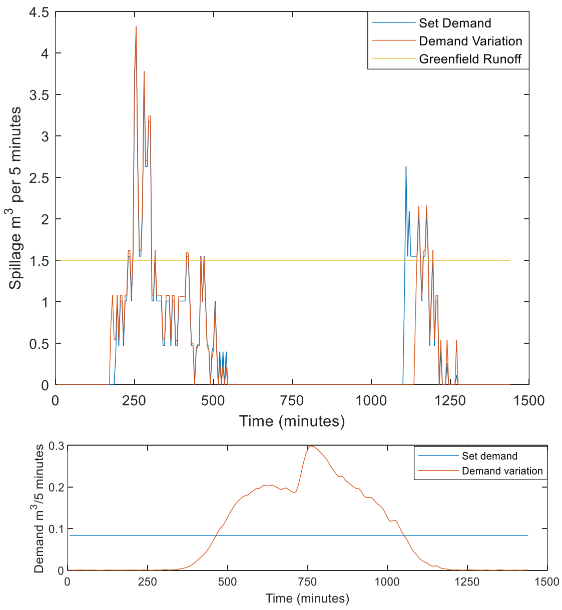


FIGURE 5-7 – EVENT PERIOD FROM DAY 166 MODELLED OUTFLOW VS GREENFIELD RUNOFF RATE

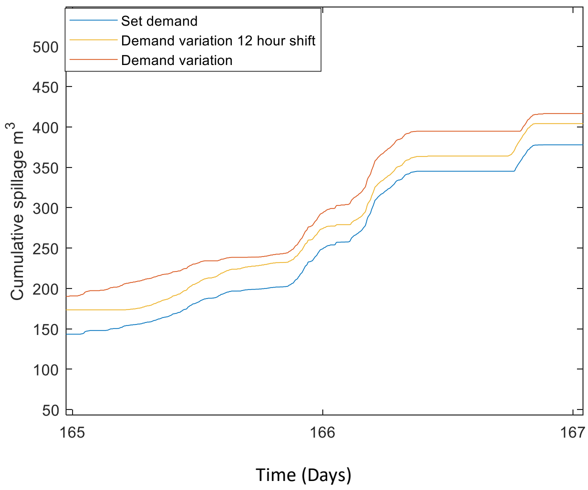


FIGURE 5-8 - EVENT PERIOD FROM DAY 166 CUMULATIVE SPILLAGE

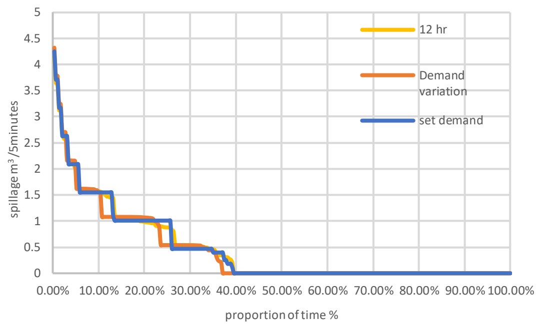


FIGURE 5-9 - FLOW DURATION CURVE FOR EVENT PERIOD OF DAY 166

5.4.1.4 Discussion

In figure 5-4 the peak outflow can be identified at approximately 260,000 minutes, showing that difference is seen between a set demand and a fluctuating demand. Whilst outflow at this time occurs at the same time step, a peak outflow rate of 5.329 m^3 is identified for a continuous set demand and 5.109 m^3 for a varying demand. This variation in the volume of spillage identifies a 4.3% increase in peak spillage from a varying demand to a set continuous demand. However, a significant variation in spillage is seen previous to this with spillage flow at 239,050 minutes (Day 166) with around a 27% peak difference identified. Figure 5-4 shows that during the 1-year period, spillage from the demand variation pattern exceeds the greenfield runoff rate for 7 event periods whilst a set demand is only seen to generate spillage above the greenfield runoff rate for 5 event periods.

Figure 5-6 shows the cumulative spillage that was generated in figure 5-4. It can be highlighted from the results shown in figure 5-5 that 14.8% more spillage is generated over the total 1-year period when using the original demand variation compared to that of a continuous set demand. Whereas up to an 18% increase in the total spillage is identified should the demand variation be offset by 12 hours. The addition of the offset demand pattern has overall caused an increase of 2.8% more spillage to be generated from the original demand pattern. Whilst there is a difference in spillage volume that has been identified, this alteration is mainly due to the demand pattern used causing larger spillage events to be simulated to occur due to high-intensity rainfall events.

Figures 5-7 and 5-8 show a zoomed-in view of the large rainfall event that occurred at day 166 as shown in figures 5-4 and 5-6. From figure 5-7 it can be seen that the second spill event that occurs at around 1100 minutes (approx. 18 hours later), in which spill is generated initially in a set demand and around 40 minutes later spill is generated in a fluctuating demand, this offset in spill generation causes a large difference in the volume and peak flow of spill to be generated with regards to the two demand patterns. During this event period, there is a difference of 22% and a 40-minute delay between the peak flow rate from a set demand to that of a demand variation. The difference seen in the spillage here is triggered due to a higher demand withdrawal in the fluctuating demand at this time period enabling more retention room for stormwater management purposes to be used during the initial rainfall period, thus causing less spillage initially.

From figure 5-8 it can be identified that the large rainfall event that occurred during the time period of day 166 has caused a set demand to continue to underestimate the spillage whilst the addition of the 12-hour offset generates less spillage compared to the demand variation pattern. The addition of the 12-hour shift has seen an overall reduction of 9% spillage from the original varying demand pattern on the 166th day. However, the 12-hour shift still remains to cause an increase of spillage at around 10% from the original set continuous demand pattern. It can be concluded that the 12-hour offset to the varying demand pattern has altered when spillage is generated and the volume of spillage that is modelled to occur within this example as previously hypothesised. With the results generated in figure 5-8 further concluding previous findings in that the timing of the demand withdrawal patterns does affect the volume of spillage mostly due to the volume of water in the storage tank prior to an event period alongside the previously identified sensitivities to fluctuating the demand pattern.

The flow duration curves identified in figure 5-5 and 5-9 portray the spillage generated for each of the demand patterns for the 1-year period and event period. Figures 5-5 and 5-9 further confirm previous findings e.g. the difference seen when using a set continuous demand to that of a demand variation pattern is relatively small and is usually caused due to a few event periods throughout the time period analysed.

5.4.1.5 Conclusion

To conclude, the addition of the demand variation in this example is seen to have increased the volume of spillage that is modelled to occur during the year-long period due to the timing of the rainfall events with regards to the demand withdrawal. Considering the percentage difference in the overall total volume of spillage, differences identified to peak flow, and frequency of spill events, alongside the uncertainties with regards to a fluctuating the demand, it is suggested that using a set continuous demand under these circumstances is sufficient.

5.4.2 Demand fluctuation sensitivity analysis for a dual function rainwater management system with regards to D/AR changes

5.4.2.1 Introduction

Previous research regarding demand fraction and storage fraction sensitivity to demand fluctuations does not exist and therefore demand fraction will be considered here whilst S/AR is to remain at a constant value.

Previous research in section 5.4.1 has used a D/AR of 3.18 which is seen as a relatively high demand fraction. However, it is yet to be identified as to when the sensitivity to demand fluctuations is increased to a level in which it is no longer viable to use a set continuous demand and at what demand fraction it is accurate to begin using a set continuous demand. The hypothesis of this research is that at lower D/AR values, the sensitivity of spill to demand fluctuations will be reduced, whereas at high D/AR values sensitivity will be increased.

5.4.2.2 Methods

Research has been undertaken to establish how demand representation is capable of altering spillage in a dual function rainwater management system for a residential to commercial scale, this is tested using a set demand and a varying demand that has previously been simulated in a SIMDEUM program (Blokker et al., 2017) as seen in section 5.4.1. A generalised 1 demand 1 storage model was created in MATLAB with a YAS algorithm. Rainfall (R) data has been collected from prior research at the University of Sheffield with a 1-year period of rainfall during 2007 being used within this report. The model hypothetically harvests over the 1-year period, assuming a 2700 m^2 catchment area (A) (based upon previously implemented RWH tank at the Imperial Tobacco head office, Bristol (Stormsaver, 2019)). Storage (S) remains at 32 m^3, rainfall (R) remains at 0.876 m, area (A) remains at 2700 m^2. S/AR ratio remains constant at 0.013, storage at the beginning of the simulation is always half full of the storage size allocated. The D/AR ratio is altered with regards to dividing the original demand in order to generate the selected D/AR ratios which in turn will alter the S/AR to D/AR ratio despite storage capacity remaining consistent at 32 m^3 to enable analysis of RMS at a commercial and residential RMS scale. The D/AR values have been chosen with regards to the D/AR values previously used within work undertaken by Fewkes and Butler (2000). Demand (D) was divided by average daily demand by 1.5, 2.55 and 11.5 in order to generate D/AR ratios of 2.1, 1.25 and 0.27. For figure 5-10, demand (D) was divided and multiplied at 0.1 intervals to generate a series of D/AR results ranging from 0.1-10. A 5-minute time step has been chosen for this scenario. If the tank reaches maximum capacity, spillage is modelled to occur. Any water not overflowing or withdrawn for demand purposes remains within the modelled tank until used or spilt. The parameters of this scenario have been selected to magnify the impact of demand on a RMS to enable justification and analysis for comparison of demand representation analysis at a residential and commercial scale (represented by D/AR changes). System performance has been measured with regards to spillage (outflow quantity) solely for each of the generated results. The justification to the use of measuring solely based upon outflow quantiy comes from simply analysing the affects demand alterations have upon the total volumetric outflow rather than stormwater retention, supply and peak outflow performance as seen in the previous metrics which in this assesment where not necessary to make a judgment upon demand representation.

5.4.2.3 Results

Figure 5-10 identifies the total spillage generated over the 1-year period for various demand fractions between 0.1 and 10. Whilst figure 5-11 displays how the cumulative spillage is altered with regards to alterations in D/AR.

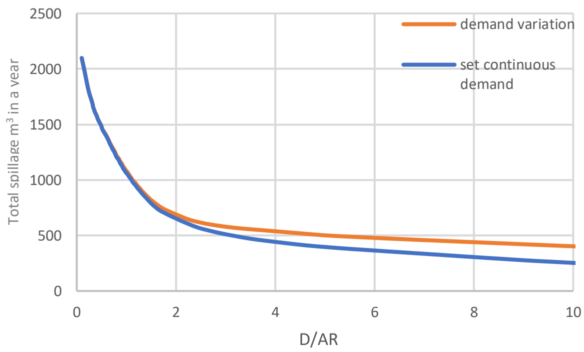


Figure 5-10 - Total spillage for a D/AR between 1 and 10 calculated using an average D/AR representation

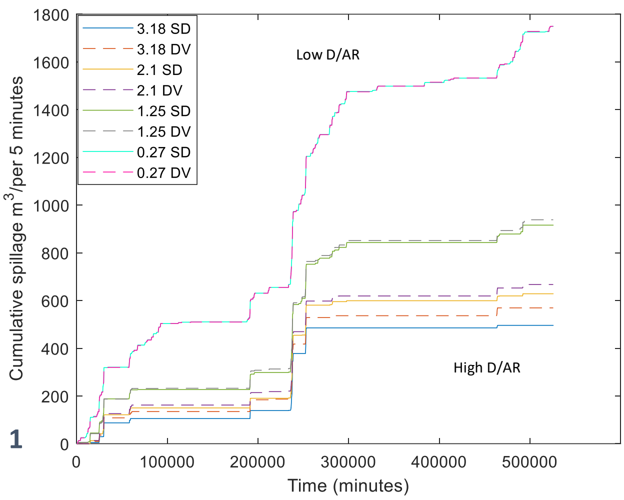


Figure 5-11 - Cumulative spillage for a D/AR of 3.18, 2.1, 1.25 and 0.27

5.4.2.4 Discussion

It can be seen from figure 5-10 that as the D/AR increases, sensitivity to demand profile increases, with a 59% increase in spillage being simulated from a set demand to a demand variation pattern at a demand fraction of 10. However, when the demand fraction is reduced to 0.5 and below then the difference simulated is 0%. The findings of this study show that when a low D/AR, of 3.5 and below (equivalent to that of a residential RMS) is used the sensitivity to demand profile is reduced, therefore, a set continuous demand is capable of generating similar results to that of fluctuating demand. However, when a demand profile of greater than 3.5 (equivalent to a commercial RMS) is used sensitivity to demand profile is increased and more caution should be taken when regarding the volume of spillage should a set continuous demand be used.

Figure 5-11 further confirms the findings identified in figure 5-10, with a 14.8% difference in the cumulative spillage being generated between a set demand and a varying demand at a D/AR of 3.18 whilst at a low D/AR the sensitivity is reduced to 0.011%.

These results show that the hypothesis has been proven correct with a smaller demand fraction showing smaller sensitivity to demand fluctuations and higher demand fractions showing higher sensitivity. The reasoning for this is due to the lower demands causing less fluctuation to the storage capacity whereas at the larger demand sizes more fluctuation to the storage capacity is identifiable and therefore timing for withdrawal becomes more important.

The findings of this study identified that spill levels are more sensitive to the demand pattern when the demand fraction is high. However, when the demand fraction is low, a D/AR of 3 and below, then the sensitivity to demand profile is reduced to a point in which a set continuous demand is capable of generating similar results to that of fluctuating demand. Therefore, moving forward a set continuous demand can be used if the demand fraction is at 3 and below but should not be used when the demand fraction is greater than 3 dues to a larger uncertainty in the results generated.

5.4.2.5 Conclusion of demand sensitivity analysis

To conclude, these findings have highlighted that demand representation in residential RMS storage sizes (D/AR of below 3) is not as significant as in commercial RMS storage sizes (D/AR of above 3). Figure 5-10 and 5-11 have shown that at residential D/AR scale significance to the demand pattern is reduced to less than 1% due to a smaller variation in demand fluctuations when compared to that of a commercial scale which can cause a significant variation of up to 15% difference between the demand representation. Therefore, future work that is scaled at a residential scale can assume a set continuous demand pattern but more consideration to a variable pattern should be taken when analysing RMS for a commercial setting.

It should be noted that since demand is going to be a relatively unknown varying parameter that can change on a daily basis there is always going to be a degree of inaccuracy when attempting to model this parameter even when using a fluctuating demand pattern in either a commercial or residential RMS model. However, the use of a set continuous demand in a residential (D/AR of below 3) under these model parameters has shown to be an accurate and realistic assumption when compared to that of the varying (realistic) demand pattern. Therefore, judgment can be assured that if a residential RMS setting with a D/AR of less than 3 is to be modelled accuracy can be gained in using a set-continuous demand or a more realistic demand pattern.

5.5 Conclusion regarding model sensitivity

This section systematically investigated the influence of model algorithm, time-step and demand pattern for the assessment of stormwater management (SWM) and water supply performance. Results showed findings consistent with previous research and highlighted sensitivities for a RMS designed for water supply and stormwater management benefits (Fewkes and Butler, 2000; Campisano and Modica 2014).

- The YBS operating algorithm highlighted an overestimation for water supply and stormwater management performance, whereas the YAS algorithm showed to provide more conservative performance estimates.
- Computational time steps impact the accuracy of the modelled RMS. Previous studies indicated a sub-daily or hourly time step could lead to sufficient model accuracy. However, when modelling SWM performance, sub-daily and hourly time-steps can lead to a decreased accuracy. Smaller computational time-steps analysed as part of this research enable an increased frequency of inflow, withdrawal and outflow causing a smaller divergence in the obtained model result. When a 15-minute time series or below is used, as shown in section 5.3, the differences between the performance results are negligible with the main difference being identified in the peak outflow. When analysing RMS performance for stormwater management a 5-minute time-step or below should be applied to provide confidence of the RMS stormwater management performance.
- Demand variation analysed as part of this research enabled confidence in modelling for a set continuous demand pattern as long as the D/AR remained below 3 which is equivalent to residential RMS scale. However, more consideration into demand representation should be required if a commercial scale RMS is to be considered with a D/AR of above 3.

To conclude, section 5 has enabled a conclusion on the operating algorithm, time-step, and demand pattern to be selected that minimizes the risk of error and inaccuracy to the modelled results. The future of this research will use a YAS operating algorithm, at a 5-minute computational time step, for a set continuous demand pattern to enable confidence in the model results.

6 1SnD RMS model development

6.1 Introduction and aims

A nSnD system refers to a rainwater management system that is comprised of numerous storage nodes that feed numerous demand nodes. Most RMS are currently understood on a S-D RMS scale as analysed in the previous sections of this research. However, it has previously been hypothesised that the performance of an RMS could be further enhanced through the interconnectedness of a multi-nodal network (nSnD or 1SnD) (HR Wallingford, 2012). A multi-nodal (nSnD) network for example would connect multiple demand nodes from differing houses of the same street to 1 or more storage tanks which harvest rain to be later used for non-potable uses. A nSnD network may be a reasonable adjustment in new and retrofit sustainable drainage systems (SuDS) designs to enable an increased RMS performance.

The S-D model presented in previous sections of this research provided foundation to progress to the 1SnD RMS scenario. This section details the first steps used in the development of a nSnD modelling approach; beginning with the most basic upscale from the conventional single storage single demand (S-D) RMS to a 1S2D RMS design. The modelling of the single-demand single storage (S-D) RMS is well documented in sections 4 and 5, the aim of this section is to introduce and develop a 1SnD RMS and assess if the metrics highlighted in section 3 are feasible for a nSnD RMS model. The following section of this MPhil will detail the complexities of upscaling the conventional S-D RMS to a 1SnD RMS.

6.2 Analysis of 1SnD nodal water supply efficiency and frequency performance metric

6.2.1 Introduction

A series of performance metrics have been identified in section 3 to evaluate the system performance of a S-D RMS. The performance metrics were evaluated in section 4 for a S-D RMS scenario and provided feasible analysis of performance.

In 1SnD networks, there is a single storage, and therefore a single outflow time-series. This means that all the stormwater management metrics are unchanged from those defined in Section 3. However, the yield associated with each of the multiple demand nodes may vary. It is therefore of interest to consider water supply performance at each individual node, as this may highlight inequalities or inefficiencies in supply. Two new terms are introduced to designate nodal demand and nodal yield, Dnodal and Ynodal. The Water Supply Efficiency in a 1SnD network is therefore now defined as the ratio of the sum of n nodal yields to the sum of n nodal demands, and a specific WSEnodal is also determined for each node *i* in the network. This is a similar scenario in the WSF with a specific WSFnodal result being determined for each node *i* in the network. The range of the individual nodal values is also considered in the subsequent analysis.

From the metrics highlighted in section 3 and explained in the above paragraph only the water supply metrics will require alterations for the nSnD scenarios. Water supply efficiency and water supply frequency are performance metrics as analysed in section 3 to evaluate the RMS efficiency to meet water demand. The water supply efficiency and water supply frequency will include a network water supply efficiency/frequency result (a total network performance) as defined in equation7 and 8 alongside an additional nodal water supply efficiency/frequency result (individual nodal performance) as defined by the new equation 12 and 13. The nodal water supply efficiency/frequency results will reflect upon the variation within the nodal performance that may otherwise be concealed within the network performance metrics. Whereas the water supply efficiency and frequency network will provide an overall result on the network performance to supply water. However, the WSE and WSF network result is not representative of the water supply efficiency for each node. The WSE and WSF will be comparable with no changes within the results to be anticipated as each node will alter dependent upon the quantity of yield the node is supplied thus meaning the frequency and efficiency should remain consistent. It is important to note that the system water supply efficiency in a nSnD scenario will be calculated by summing the total network yield and dividing by the total network demand rather than a mean network WSE. Whilst the nodal WSE will be calculated based upon the quantity of yield supplied divided by the total network demand for each storage node scenario. A collection of the 1SnD performance metrics to be used in this section can be seen in table 6.1 with additional nSnD metrics identified using equation 12 and 13.

TABLE 6-1 - PERFORMANCE METRICS TO BE USED IN A NSND SCENARIO

	1SnD Metrics
WATER SUPPLY EFFICIENCY (WSE)	[7] $WSE = \frac{\sum Y_t}{\sum D_t}$ [12] $WSEnodal(i) = \frac{\sum_{i=1}^{n} \sum Ynodal_t}{\sum_{i=1}^{n} \sum Dnodal_t}$
WATER SUPPLY FREQUENCY (WSF)	[8] $\mathrm{WSF} = N_t = \begin{cases} 1, & Y_t = D_t \\ 0, & else \end{cases}$ $WSF = \frac{\sum N_t}{n}$ [13] $\mathrm{WSFnodal(i)} = N_t = \begin{cases} 1, & Ynodal_t = Dnodal_t \\ 0, & else \end{cases}$ $WSF = \frac{\sum N_t}{n}$
STORMWATER RETENTION EFFICIENCY (SRE)	[9] $SRE = 1 - \frac{\sum O_t}{\sum I_t}$
TIME ABOVE GREENFIELD RUNOFF RATE (TAG)	[10] $N_t = \begin{cases} 1, & O_t > GRR \\ 0, & else \end{cases}$ $TAG = \sum N_t \times T$
PEAK OUTFLOW (OPEAK)	[11] $OPeak = \max(O_t)$

In order to evaluate the water supply performance metric for a nSnD scenario it has been identified by Balhatchet et al. (2014) that an allocation strategy will be required. An allocation strategy is a way of altering the prioritisation of water supply to meet demand in a multi-nodal RMS. An allocation strategy is required in theory to represent that of a necessary choice a system such as that of a 1SnD system would need to take should supply be depleted in a real life scenario. In order to represent and analyse the effects an allocation strategy has upon performance a number of allocations strategies that are assumed to affect the performance result should be analysed in the given scenario. Previous work by Balhatchet et al. (2014) identified a few allocation strategies mainly relating to the cost implication of a prioritisation strategy. However, this research will mainly identify prioritisation strategies solely focusing on the water supply and stormwater performance advantages.

A total of 3 allocation strategies for this research have been hypothesised by myself to alter nSnD performance alongside the additional 'highest demand first' strategy as suggested by Balhatchet et.al (2014); '*equal supply*', '*predetermined order*', '*highest demand first*' and '*lowest demand first*'. A '*predetermined order*' allocation strategy works by meeting demand based upon an inputted number prioritisation system. An *'equal supply'* strategy will alter the simulation to supply all demand nodes a percentage of the requested nodal demand from the available total water, thus meaning each demand node will not have the required water supply when the tank is at a reduced volume. A *'highest demand first'* and '*lowest demand first*' are two allocation strategies that will only work when the demand in a multi-nodal system is not equal and works to allocate demand to either the highest or lowest demand first until all demand is met of there is no available water for that time step.

The research of the nSnD RMS will upscale the storage capacity dependent upon the number of demand nodes included to that of an equal S-D storage quantity. Therefore, throughout the nSnD research storage capacity will be determined based upon the quantity of demand nodes and will be comparable in a S-D and nSnD scenario due to a direct upscale.

The main aim of the study is to generate the mass balance equation for the 4 allocation strategies so they can be implemented when analysing for a nSnD model scenario. Alter the water supply efficiency metric from section 3 to incorporate nSnD model changes. Finally, the overall aim of this section is to confirm that the nSnD model used to analyse 4 differing allocation strategies is simulating the desired water supply performance response to allocation effectively and accurately.

6.2.2 Methods

This section will analyse the water supply performance as a network and nodal metric using a 1 storage 2 demand node scenario (**Demand 1** will be a higher demand and **Demand 2** will be a lower demand).

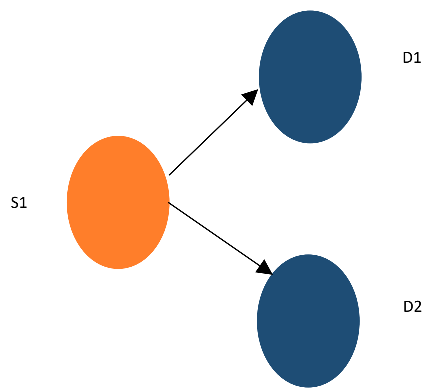


FIGURE 6-1 - 1S2D LAYOUT DESIGN

In MATLAB a 1S2D RMS design was created using the fundamental operating rules of equation 1, 2, 5 and 6 alongside 4 allocation strategies. Rainfall (R) is a synthetic 6-hour rainfall period. The model is designed to hypothetically harvest rainfall for a 5-minute time step over a 6-hour period, assuming each demand node has a catchment area (A) of 30 m^2. The water is collected into a storage tank (S), the tank has been designed to offer 1.8 m^3 of storage per 30 m^2 catchment area. Demand is withdrawn at a set demand fraction with **Demand 1** having a higher demand fraction with a D/AR 1.1 and **Demand 2** having a lower demand fraction with a D/AR 0.56, If the tank reaches maximum capacity, outflow (O) is modelled to occur, any water that does not outflow from the tank is to remain within the modelled tank until used or spilt. Yield is supplied in relation to the allocation strategy selected ('equal supply', 'predetermined order', 'highest demand first', and 'lowest demand first'). System performance has been measured using 4 performance measures (Yield, system water supply efficiency (equation 7) , water supply frequency (equation 8) and nodal water supply efficiency and frequency (represented by equations 12 and 13).

Currently, for this study the nSnD code is modelled to have 2 demand nodes to 1 storage node. However, it has been simulated such that the code can be altered to incorporate multiple demand nodes as desired.

6.2.3 Generation of allocation strategy

EQUATION 14 - EQUAL SUPPLY ALLOCATION STRATEGY:

If the volume in store (V) is equal to or greater than the total network demand (D), nodal yield (Ynodal) is equal to nodal demand (Ynodal) for all nodes. Otherwise, the yield at each node (Ynodal) is determined as a fixed proportion (V/D) of the nodal demand. For example, if the network demand is 100 litres and the volume in store is only 75 litres, each node receives 0.75 of its nodal demand.

[14] $$Ynodal_t = \begin{cases} Dnodal_t, \; V_{t-1} \geq D_t \\ Dnodal_t \frac{V_{t-1}}{D_t}, \; V_{t-1} < D_t \end{cases}$$

EQUATION 15 - ORDERED ALLOCATION STRATEGY:

If the volume in store (V) is equal to or greater than the total network demand (D), yield is equal to demand for all nodes. Otherwise, the yield at each node is determined for each node according to a predetermined order/ highest/lowest demand first scenario using equation [15]. The model uses a loop structure to allocate yield to each demand (i) in turn. The loop structure determined by (i) will alter based upon the predetermined order, highest or lowest demand strategy implemented.

[15] $$Ynodal_t(i) = min \begin{cases} Dnodal_t(i) \\ V_{t-1} \end{cases}$$

In the case of a predetermined order allocation strategy the ordered equation shown in 15 is intended to be ordered based on e.g. the physical location of the house, rather than on demand. Demand no. 1 will be prioritised over Demand 2 etc.

In the case of the Highest demand first allocation strategy order is intended to be based on e.g. on the demand proportions. E.g. Demand no. 1 with a higher demand will be prioritised over Demand 2 etc.

In the case of the Lowest demand first allocation strategy order is intended to be based on e.g. on the demand proportions. E.g. Demand no. 2 with a lower demand will be prioritised over Demand 1 etc.

6.2.4 Results and Discussion

The mass balance error for each allocation strategy remained constant throughout the allocation strategy model alterations at 2.7e-17. A mass balance error of 2.7e-17 enables confidence that the simulation can provide the desired degree of accuracy from the model. However, mass balance alone may not provide a valid indicator of simulation accuracy when analysing for the allocation strategies used within the nSnD model. To analyse simulation accuracy for the allocation strategies used a more manual approach was also necessary, this approach used a visual and performance metric check to analyse results against a previously hypothesised estimation.

From the 4 allocation strategies tested all the simulations are modelled to withdraw the same quantity of combined yield which is equivalent to the total tank inflow during this period (0.1416 m^3). Therefore, when analysing the performance metrics all the simulations tested if working accurately should provide the same network water supply efficiency (WSE **network**). The WSE **network** is an indication of how the system overall is capable of supplying water to meet the requested demand. All the results provided from the model simulations provided a WSE **network** of 2.14. The WSE **network** provides a further indication of simulation accuracy with the same quantity of yield being available and hypothetically supplied to the demand nodes. However, the WSE **network** is incapable of truly highlighting if the allocation strategies are working as expected as the results conceal nodal yield changes.

The nodal water supply efficiency and frequency (WSE **nodal** and WSF **nodal**) refers to the efficiency of water supplied to each demand node and is dependent upon the allocation strategy used. The nWSE and nWSF is capable of indicating if the system allocation strategies are performing effectively and as anticipated. From the results generated no difference was noted between the WSE and WSF results with each metric highlighting the same findings and therefore in this section WSE will be focused upon as a performance assurance result of the nSnD and allocation strategy results.

Figure 6-2 shows the results of the WSE **nodal** for the 4 allocation strategies analysed as part of the 2-demand node scenario. In an *'equal supply'* (ES) *allocation* strategy the WSE **nodal** must be equal between the nodes, in a '*highest demand first'* (HD) and '*predetermined order'* (PO) strategy **Demand 1** would have a higher WSE **nodal** and in a *'lowest demand first strategy'* (LD) **Demand 2** would have a higher nWSE. Figure 6-2 shows that the simulated results follow the anticipated results based upon the allocation strategy selected.

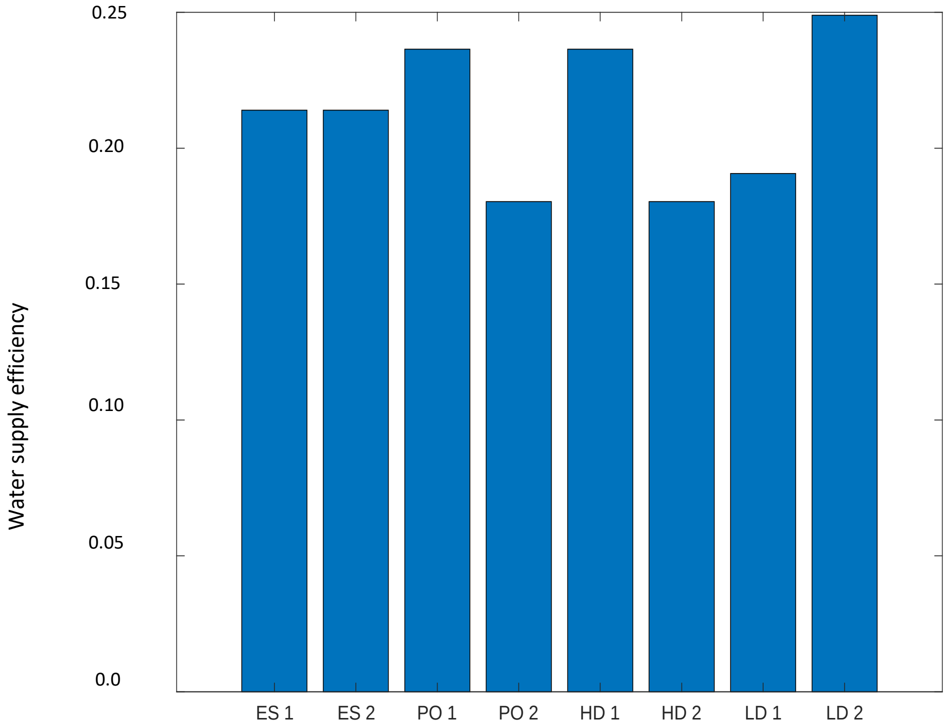


FIGURE 6-2 - SIMULATED NETWORK WATER SUPPLY EFFICIENCY

Figures 6-3 to 6-6 provide time series plots to further assess that the allocation strategies are working as expected over the full timeseries tested.

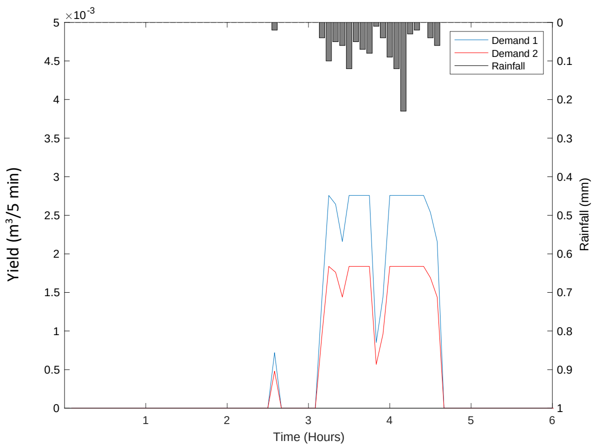


FIGURE 6-3 - EQUAL SUPPLY

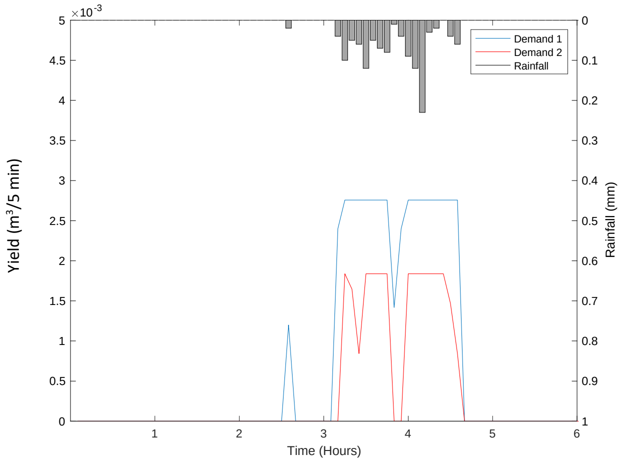


FIGURE 6-4 - PREDETERMINED ORDER

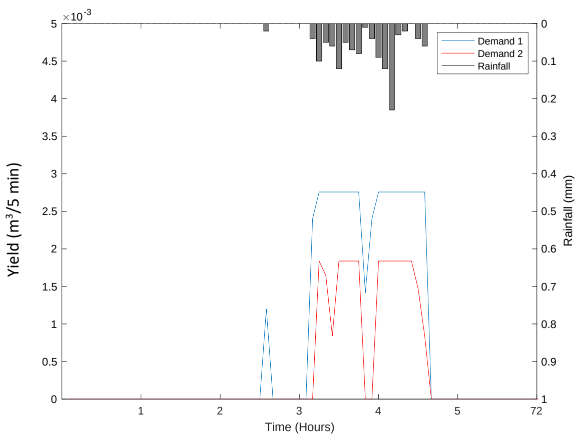


FIGURE 6-5 - HIGHEST DEMAND FIRST

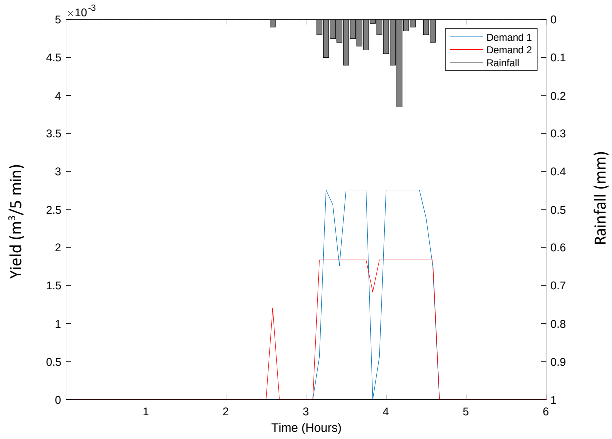


FIGURE 6-4 - LOWEST DEMAND FIRST

An '*equal supply*' allocation strategy, shown in figure 6-3, is seen to follow the desired strategy with a 50% difference between the yield withdrawn at **Demand 1** compared to **Demand 2** been seen continuously throughout the simulation even when water supply is reduced below that of the desired demand quantity.

A *'predetermined order'* allocation strategy and *'highest demand first'*, seen in figure 6-4 and figure 6-5, follow the same pattern with **Demand 1** being prioritised over **Demand 2.** Therefore, under these circumstances both a predetermined order and highest demand first have provided the same results. A '*predetermined order'* and '*highest demand first'* allocation strategy have shown to follow the desired allocation strategy with **Demand 1** being a prioritised node and therefore when supply is reduced, as seen at 2.5 hours, **Demand 1** receives some of its demand but **Demand 2** receives none due to the reduced quantity of water within the storage tank. This provides evidence that when the tank has a reduced capacity, lower than that of 1 demand node, the model behaves as expected. A further example of the strategy working is seen at 3.5 hours when **Demand 1** has all its demand fulfilled but **Demand 2** (the non- prioritised/lower quantity demand) has a 54% decrease in yield

A '*lowest demand first*' allocation strategy, highlighted in figure 6-5, provides evidence that the strategy is working as anticipated with **Demand 2** receiving yield much more frequently than **Demand 1**. At 2.5 hours figure 6-5 shows that the yield provided to **Demand 2** is reduced by 34% of its desired demand whilst **Demand 1** receives no desired yield. Once again, this provides evidence that when the tank has a reduced capacity, lower than that of 1 demand node, the model behaves as expected. At 3.5 hours when demand is lower than the demand of both nodes, **Demand 2** receives all the desired yield whilst **Demand 1** receives only 64% of the desired yield.

6.2.5 Conclusion

To conclude, a nSnD RMS scenario has been simulated for 4 allocation and the water supply efficiency metric altered for a nSnD RMS scenario. It can be shown from the results that a multi-nodal RMS model simulation has been generated and the model simulations are working accurately with each allocation strategy providing the expected outcomes. From the water supply results provided, the simulation can be said to be accurate in modelling an RMS simulation at a 2 demand 1 storage approach and the water supply performance metrics analysed capable of representing nSnD model performance. Therefore, in the future of this research the multi-nodal model used will be able to increase the number of demand nodes whilst still providing reliable and accurate water supply performance results.

7 The effect of allocation strategy on the performance of a multi-nodal rainwater management system

7.1 Introduction

The section aims to build upon the research of section 6 and Balhatchet et al. (2014) by analysing whether the effects of allocation strategies in a small scale multi-nodal (nSnD) rainwater management system are as significant when time step is reduced to 5-minutes. Balhatchet et al. (2014) research modelled previously on a larger timestep of 1-hourly intervals which have previously shown modelling reliability concerns with an underestimation of water supply performance and an overestimation in stormwater/ outflow quantities. It is anticipated that this research will highlight that at the smaller timestep of 5-minutes a nSnD will provide a more reliable performance with allocation showing little to no change in the performance of the network and nodes simulated. Further to this aim the results of this study will highlight if an optimal allocation configuration is apparent for water supply and stormwater management benefits of a RMS. The layout selected in Balhatchet et al. (2014) research is a simplified version of a nSnD RMS modelled to follow a 1 storage node to 2 demand nodes (1S2D) design as shown in figure 7-1. From the original allocation strategies Balhatchet et al. (2014) highlighted 1 optimal allocation strategy for water supply and stormwater management purposes. Therefore, 1 original Balhatchet at al. (2014) allocation strategy ('highest demand first') and three further allocation strategies have been selected ***'predetermined order', 'equal supply', 'highest demand first', 'lowest demand first'***. Furthering the existing literature this scenario will include a mismatched demand scenario in which ***'Demand 1'*** will represent a daily demand for 3 people and **'Demand 2'** will represent a 2-person daily demand. The nSnD will be split into 2 subcategories when analysing results and performance; these are referred to as the ***network*** and ***nodal***. The ***network*** is the overall RMS and includes the results of all the demand nodes to create the desired output, whilst the ***nodal*** refers to individual node results.

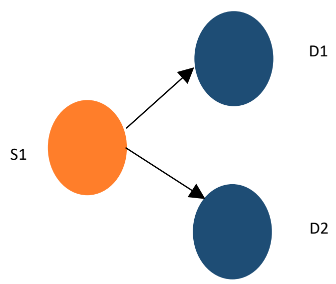


FIGURE 7-1 - RMS 1S2D DESIGN

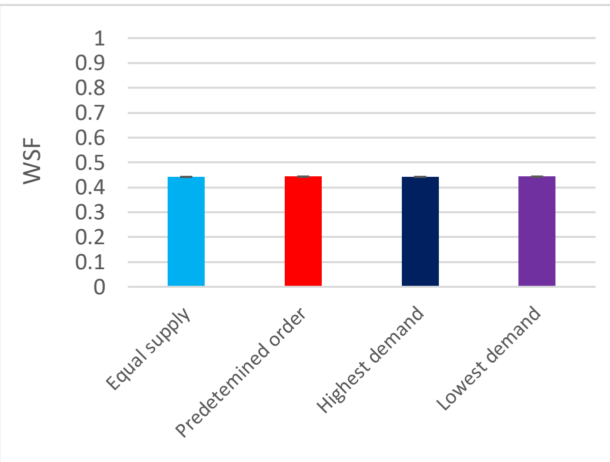
It is hypothesised that the allocation strategy will have little effect upon the nSnD network performance and a slight impact upon the nSnD nodal outputs. This hypothesis has been made as for the vast majority of the timesteps analysed there will be enough water available for all demands or no water for any of the demands.

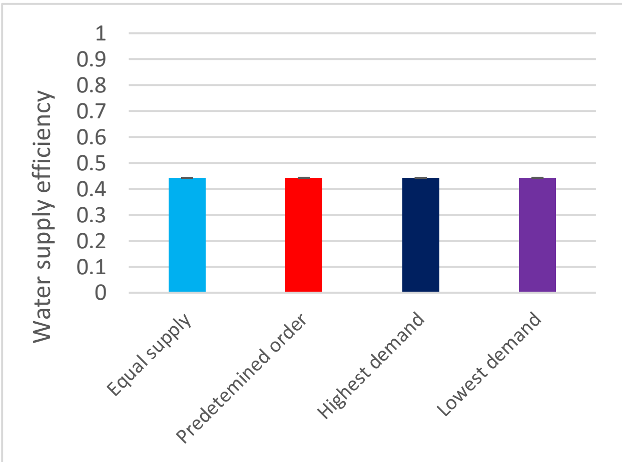
7.2 Methodology

In MATLAB a single storage 2 demand (1S2D) conventional RMS was created using equation 1, 2, 5 and 6 to represent a YAS model approach (Fewkes and Butler, 2000). The model simulation is programmed to follow one of 4 allocation strategies per scenario (*'predetermined order', 'equal supply', 'highest demand first', 'lowest demand first').* Rainfall (R) is a University of Sheffield dataset collected during a 1-year period of 2007 at a 5-minute timestep (Stovin et al. 2012), catchment area (A) simulates an area of 30 m^2 representative of 1 roof side for a terraced house. Demand (D) will be approximated to the national average for non-potable demand at 60 l/person/day on a 2.5 person per household basis providing an overall total network daily demand of 0.3 m^3. Storage (S) was estimated based on a simple approach as highlighted in the British Standards providing a storage of 2.6 m^3 per roof catchment ((BS 8515)-2009 + A1-2013), initial storage volume (V) is modelled to be half full. The sizing of the storage facility is intended to provide effective stormwater management based on retention of a 1 in 100 year event and is therefore notably larger than a typical domestic rainwater tank. Outflow (O) occurs when the storage capacity is exceeded. Performance of the modelled RMS will be measured using five performance metrics shown as equations 7 through to 11. The greenfield runoff rate was assumed to be 5 l/s/ha in line with sustainable drainage guidance (H R Wallingford, 2012).

7.3 Performance metric results

Figure 7-2 presents 5 performance metric graphs displaying the effects allocation strategy has upon performance in a 1S2D multi-nodal network.





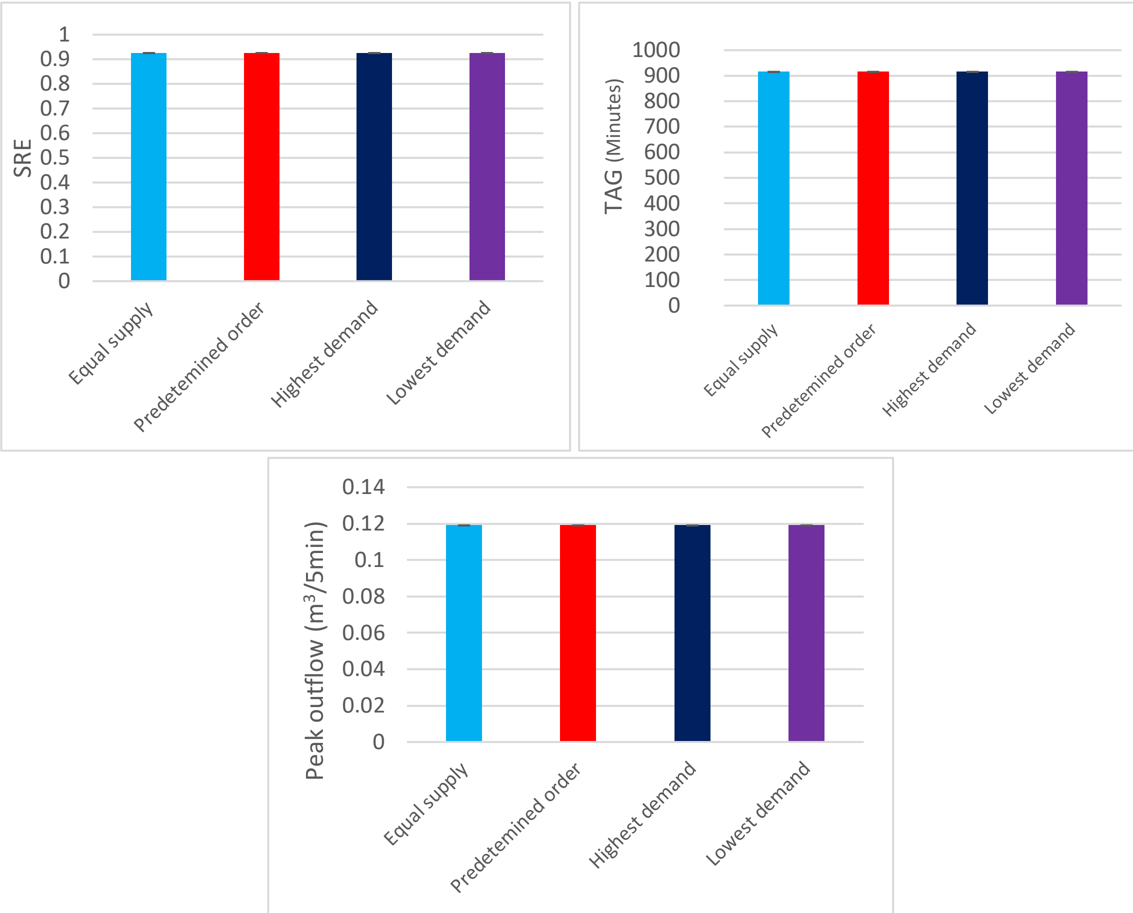


FIGURE 7-2 - MODELLED PERFORMANCE RESULTS FOR THE ALLOCATION STRATEGIES ANALYSED

7.4 Discussion

The modelled results in this study have highlighted that the impact an allocation strategy can have upon a multi-nodal RMS when using a decreased time-step is less significant than previously understood. In this study allocation strategies have been shown to have had no effect on the 3 stormwater management performance metrics (time above greenfield runoff rate, stormwater retention efficiency, and peak outflow) and a minimal effect upon the supply performance metrics (water supply efficiency and water supply frequency).

The water supply frequency is slightly influenced by the allocation strategy selected. A 'lowest demand first' and 'predetermined order' allocation have provided a WSF increase of 0.2% compared to an 'equal supply' and 'highest demand first' strategy. This result has occurred due to alterations caused within the yield to demand ratio thorough the introduction of the allocation strategy and was hypothesised to occur even under the small model time step. A lowest demand first and predetermined order have meant that under this allocation strategy 1 node has received 1 time step in which all of the yield was met for the lowest demand node and has caused the slight increase in

WSF which isn't identified in an equal supply or highest demand first scenario. Whilst there is a visible change in the water supply frequency results, this change is minimal under a 1-year time period and would be much smaller over an even longer modelled period of time. Therefore, the water supply frequency has proven to be insensitive to allocation strategy alterations with the only noticeable difference being accounted to occur when under the model circumstances at 1 time step the demand proportion was fulfilled for the lowest demand node and causing a slight increase in the WSF percentage.

Whilst the alterations seen in water supply efficiency as a network is unaffected by allocation strategy. The water supply efficiency and WSF between nodes (WSE nodal and WSF nodal) has shown performance difference as anticipated. An alteration in WSE and WSF nodal of 0.15% is recorded in a 'highest demand first' and 0.18% in a 'lowest demand first' and 'predetermined order' whilst an 'equal supply' strategy presents no change between the demand nodes. The variations visible within the water supply efficiency and frequency performance metrics are due to changes within the nodal water supply, this is shown with the error bars providing a nodal minimum and nodal maximum output. The variations identified where expected to occur due to demand quantity changes within the nodes but have shown a reduced significance to that previously hypothesised by Balhatchet et al. (2014) which is assumed to have been caused through the reduced time-step.

Whilst the network water supply efficiency remains consistent throughout the study and small changes in water supply frequency are noted these changes are not significant enough to identify an optimal configuration or a proffered performance outcome. It is understood that the importance of water supply may have a higher impact in some situations e.g. an area that has a higher scarcity of water may need to regulate an allocation strategy to enable a more reliable nodal water supply. However, from the perspective of this study allocation strategy has proven to have had a minimal effect upon the performance of a nSnD RMS with no apparent optimal allocation configuration being present.

7.5 Conclusion

To conclude, Balhatchet et al. (2014) results have shown sensitivity in the results regarding the importance of allocation strategy which is assumed to have occurred due to time step sensitivity. This study has provided evidence that the importance of allocation strategy is reduced when using a smaller time step. The results within Balhatchet et al. (2014) suggested an optimal allocation strategy for certain performance metrics. However, from this study all allocation strategies appear to provide similar and fair results with regards to all the performance metrics analysed and therefore no optimal configuration can be suggested. From this study it can be said that allocation strategy is no longer a ‘key decision’ in the nSnD modelling process.

Therefore, in future research, allocation strategy and tank performance are topics that can be handled separately with differences in allocation being visible to users should one strategy be more viable under specific circumstances. In the future of this nSnD research allocation will be used to characterise demand nodes based upon an ‘equal supply’ allocation priority at any given time. ‘Equal supply’ has been considered the preferred allocation strategy for any future work as in theory the strategy will enable the fairest option for nSnD water supply performance.

8 nSnD hypothetical study

8.1 Background

The nSnD previously considered in this research comprised 1 storage node to 2 demand nodes. This section aims to upscale the quantity of demand nodes to 10 to represent a 10 housed terraced street, with the quantity of storage nodes varying to represent a S-D or nSnD scenario. The nSnD model presented in previous sections has provided the fundamental foundation to progress to a 10 demand node RMS scenario. This section aims to address the most pertinent issues regarding current nSnD RMS research by addressing the comparison of RMS performance between a S-D RMS and a nSnD RMS to evaluate the additional benefits for a nSnD RMS. The comparison of a S-D to nSnD RMS design will, enable an evaluation on the importance of layout design, highlight any advantages or disadvantages to RMS performance through interconnecting demand nodes, and assess whether demand uncertainties can be reduced through the introduction of interconnected nSnD RMS.

Balhatchet et al. (2014) assumed that all houses have the same quantity of demand ('matched' scenario) in S-D and 1S2D scenarios. Quinn et al. (2020) emphasised that the findings from the Broadhempston case study site show that households comprised of similar demographics can have substantially different usage rates. From the demand sensitivity study shown in section 5.4 and Quinn et al. (2020) no significant decrease in accuracy has been identified when an average constant demand profile was used at an S-D scale. Since a nSnD scale RMS will include a series of households comprising of mixed demographics and differing usage rates, consideration to modelling different usage rates needs to be accounted for to adequately represent a realistic variation in usage rates between households. In this research, demand demographic uncertainties will be represented through 'matched' and 'mismatched' demand profiles. A 'matched' demand scenario will consist of each demand node having an averaged demand quantity where as a 'mismatched' scenario will have a demand profile representative for the individual nodes within the network.

The optimum storage capacity for RMS is a function of the availability of inflow and the quantity of demand. The storage capacity is known to have a direct influence on the performance of a RMS. When modelling for the performance of a RMS a series of factors should be evaluated initially to identify a correctly sized storage capacity. These factors include the catchment area, the quantity of inflow and demand outflow. In the UK the British standards ((BS 8515)-2009 + A1-2013), suggest 3 approaches to be used when sizing the storage capacity of a RMS; simplified approach for residential properties that have a consistent daily demand, intermediate approach for a more accurate estimation at the residential scale, and the detailed approach for non-standard RMS e.g. commercial implementation. Each of the British standard sizing approaches estimate storage capacity to retain stormwater for a minimum of a 1 in 50 year event which often leads to large storage capacity sizes when compared to standard DIY sized RMS storage approaches. However, for the majority of residential RMS that are implemented in the UK a DIY store sized approach is used. This research will initially compare a nSnD to S-D RMS evaluation for a British standard sized approach with an additional section evaluating whether a DIY sized storage capacity that reduces the storage capacity by around 10x would alter the initial nSnD to S-D RMS research findings.

8.2 Objective of the research

The overall aim of this research is to understand whether the performance of a nSnD system is superior to that of a S-D system. This research will analyse the performance of a S-D RMS for 10 hypothetical terraced houses compared to a 1SnD RMS. The main objective of this research is to identify whether through the introduction of a nSnD RMS, performance, seen as the water supplied by the RMS and stormwater management benefits, can be enhanced. To evaluate whether the performance of a RMS is greater in a S-D or nSnD scenario, a 10S10D (S-D), 2S10D (1S5D) and 1S10D layout design will be analysed for the 10 house scenario. HR Wallingford (2012) suggested that through the introduction of 1SnD assumptions to household demographics across the network could be made as demand sensitivities are reduced. This hypothesis will be analysed using a 'matched' (continuous set average network demand) and 'mismatched' (different set continuous nodal demand) demand scenario. Storage capacity of the model scenario will be estimated on a British standard simple sizing approach and a simple DIY store water butt.

8.3 Methodology

In MATLAB 3 nSnD conventional RMS were created using equation 1, 2, 5 and 6 to represent a YAS model approach (Fewkes and Butler, 2000). Figure 8-1 displays 3 nSnD layout designs that are modelled to alter the available demand to storage ratio to analyse S-D and nSnD performance (S-D, 1S5D and 1S10D). The model simulation is programmed to follow an *'equal supply'* allocation strategy. Rainfall (R) is the UKCP09 data set as used in Stovin et al. (2017), the data set consists of data for a 30-year time period at a disaggregated timestep of 5-minutes producing an average yearly rainfall of 838mm. Catchment area (A) is 40 m^2 per demand node representative of a terraced house roof area. Demand (D) was estimated based on 22 people living across 10 houses, which is approximated to the national average for non-potable demand on a 2.2 person per household estimation for a 'matched' demand scenario (best case scenario where all nodes are receiving the same quantity of demand) creating a D/AR of 1.3. In contrast, the number of person(s) per household is varied in an 'unmatched' demand scenario (worst case scenario where each node is receiving a different or variable demand) to equal that of the 22 people across 10 houses (demand profile shown in figure 8-1) creating a nodal D/AR varying from 0.59 to 2.4. Both the 'matched' and 'unmatched' demand scenario provide a total network D/AR of 1.3. The 'matched' scenario is equivalent to a best case scenario in a S-D RMS situation and will have an identical performance to that of a 1SnD layout whilst the 'unmatched' scenario is a worst case scenario and will show nodal differences and altered performance in a S-D scenario. Storage (S) for a British standard sizing approach was estimated based on a simple approach as highlighted in the British Standards providing a storage of 3.5 m^3 per roof catchment ((BS 8515)-2009 + A1-2013). This would equate to storage in a British standards sized approach being 3.5 m^3 in a S-D scenario, 17.5 m^3 in a 1S5D and 35 m^3 in a 1S10D scenario. Whilst storage (S) for a DIY store sizing approach was based on the most common water butt size of 210 litres per roof catchment (0.21 m^3 for S-D, 1.05 m^3 for 1S5D and 2.1 m^3 for 1S10D). Initial storage volume (V) is modelled to be half full. Outflow (O) occurs when the storage capacity is exceeded. Performance of the modelled RMS will be measured using five performance metrics shown as equations 7 through to 11. The greenfield runoff rate was assumed to be 5 l/s/ha in line with sustainable drainage guidance (HR Wallingford, 2012)

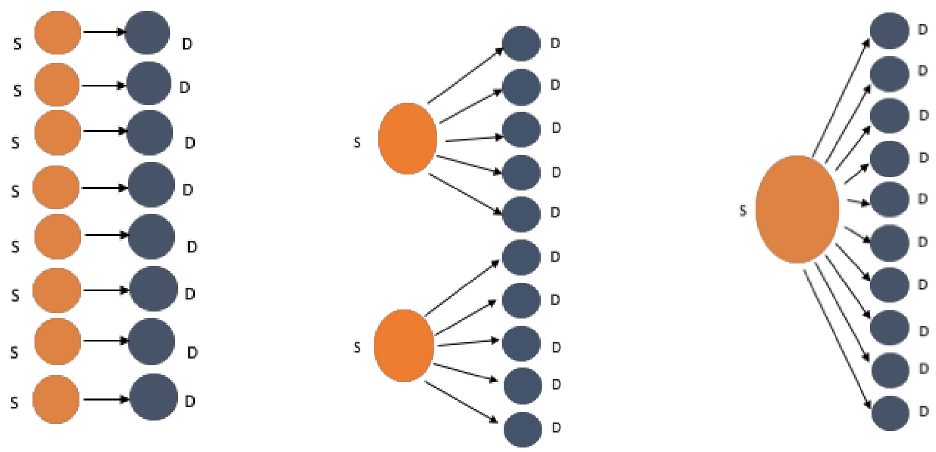


FIGURE 8-1 - LAYOUT DESIGN CONCEPTS FOR SUPPLYING 10 DEMAND NODES AT S-D AND 1SND SCALE

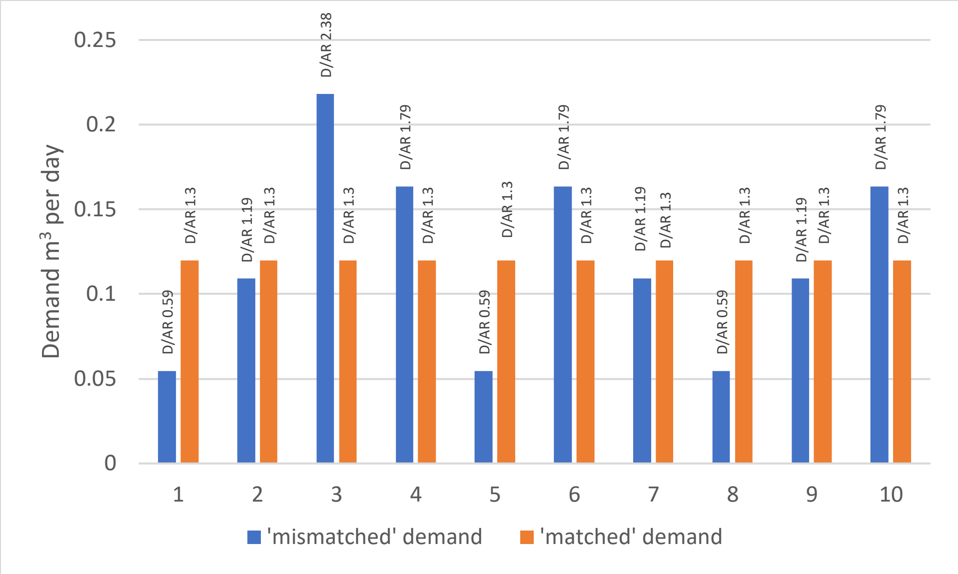


FIGURE 8-2 - DEMAND PROFILE AND D/AR FOR 10 HOUSES SIMULATED IN THE STUDY

8.4 British standard sizing results and discussion

8.4.1 Water Supply Performance

8.4.1.1 Section overview

Section 8.4.1 aims to evaluate the alterations in water supply performance that occur when altering the layout design of a RMS from S-D to 1SnD for a British standard sized storage RMS simulation.

The results of the simulation in this section are analysed in order to evaluate the water saving efficiency and frequency. If the demand is constant (network demand) in a best case scenario situation then the overall water supply efficiency and water supply frequency results should be comparable, if a nodal demand scenario is evaluated then the network water supply efficiency and frequency should be equivalent to the node.

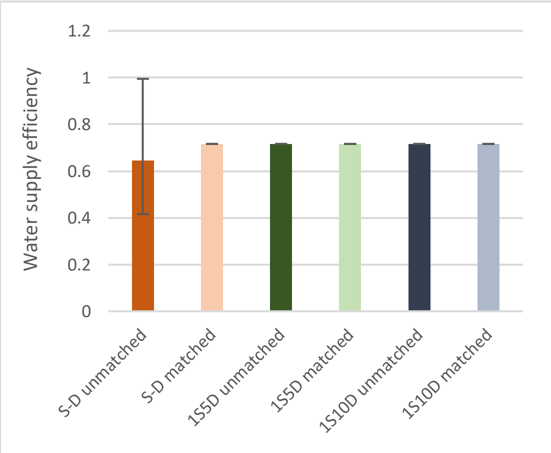
8.4.1.2 Hypothesis

Hypothesis for WSE: water supply efficiency will increase in a 1SnD scenario compared to a S-D. A 1sSnD scenario has a storage capacity sized to be n times larger than a S-D scenario therefore when calculating WSE the 1SnD scenario should average out differences in low and high demand nodes to create an increase in the overall network water supply.

Hypothesis for WSF: water supply frequency (counted based on '1 – the failure to supply *any* demand') will decrease in a 1SnD network compared to a S-D system.

8.4.1.3 Results for WSE and WSF in a British standard sized storage approach:

The water supply efficiency and frequency shown in figure 8-3 and 8-4 respectively highlight the quantity of water supplied across the network. Further to this figure 8-5 details evidence of why 'mismatched' demand scenarios lead to a reduced overall performance in S-D scenarios. Whilst figure 8-6 details nodal water supply efficiency performance.



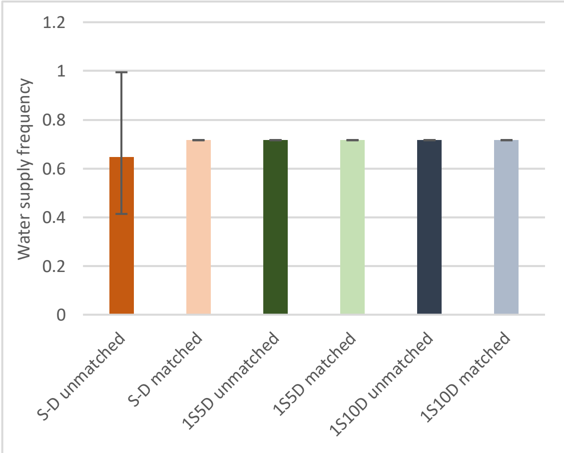


FIGURE 8-4 - WSE (NETWORK)

FIGURE 8-5 - WSF (NETWORK)

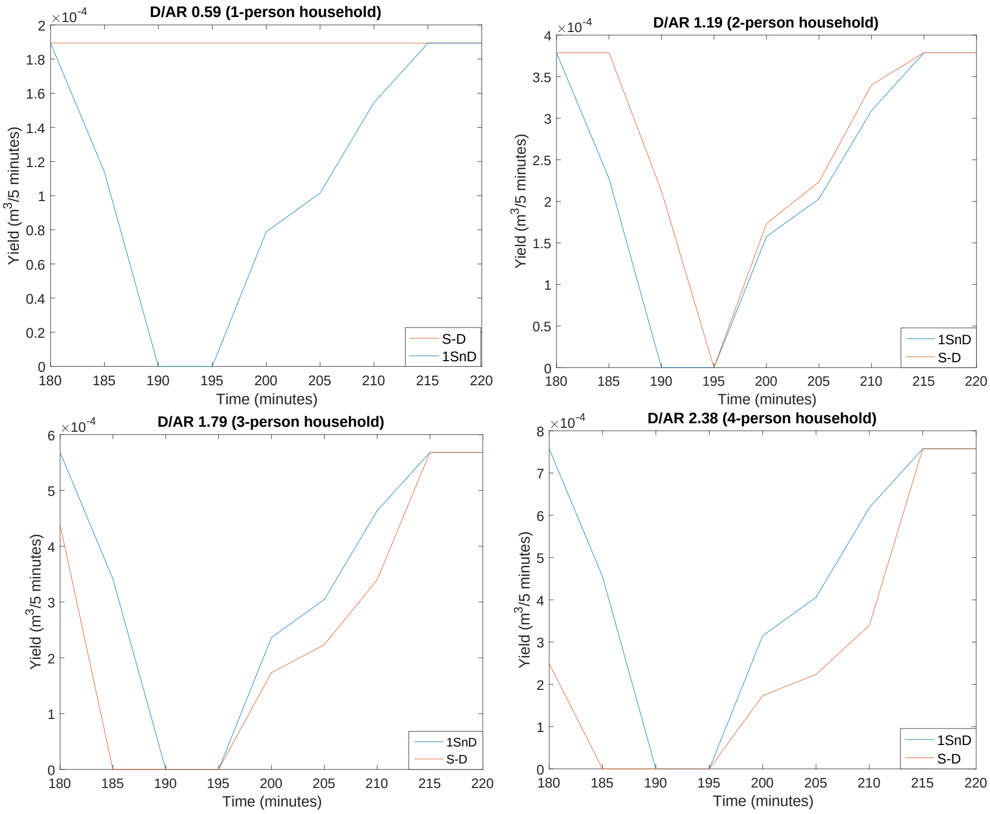


FIGURE 8-3 - EVIDENCE OF YIELD ALTERATIONS DUE TO D/AR CHANGES IN AN 'UNMATCHED' SCENARIO (WHY IS THE WSE LOWER IN A S-D SCENARIO)

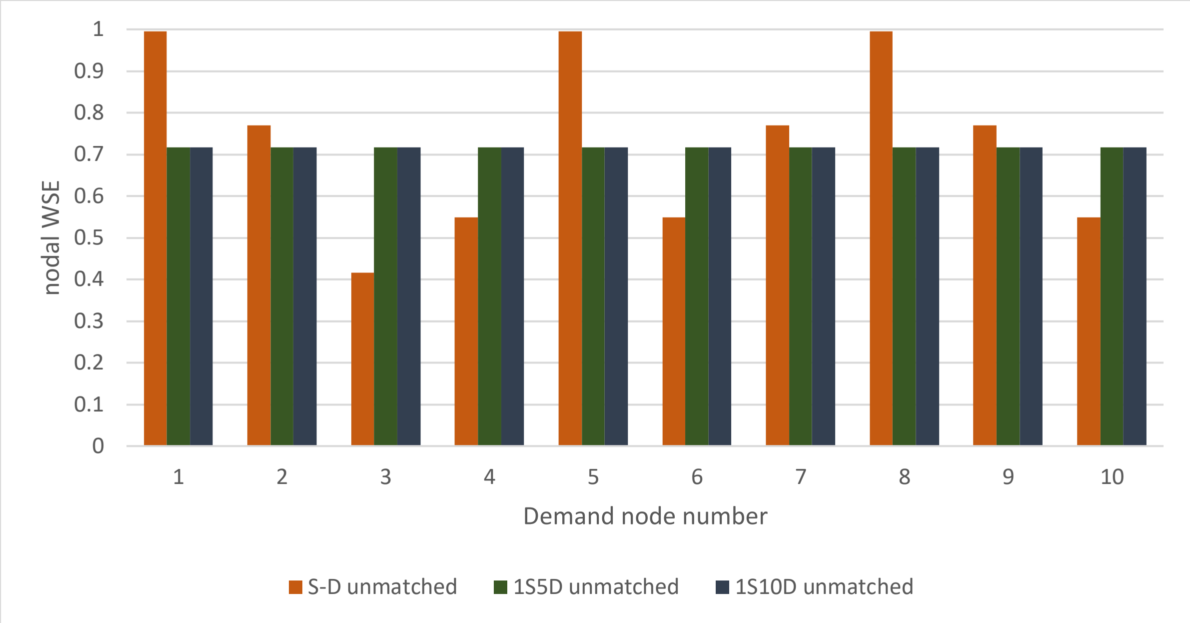


Figure 8-6 - nodal WSE

8.4.1.4 The impact of nSnD on Water supply performance as a network in a British standard sized approach

The results show that water supply of the RMS when using a British standard sized storage capacity is met over 64% of the time in a S-D scenario and over 71% in a 1SnD scenario resulting in a correct hypothesis. These results indicate that over the 30 year period the network D/AR of 1.3 has generated a required demand that is higher than the quantity of rainfall captured. The higher D/AR has been chosen in this experiment to optimise the stormwater management benefits. However, the results have shown that the storage capacity has provided an adequate percentage of the overall requirement for non-potable demand in a S-D and 1SnD scenario. The 1SnD scenario under the model scenario has proven the hypothesis correctly assumed that a 1SnD scenario would enhance network water supply performance.

Figure 8-3 and 8-4 have highlighted a 7% deviation in water supply performance for a 'matched' (best case scenario) to 'mismatched' (worst case scenario) S-D scenario. The higher network water supply performance calculated from the results in a 1SnD scenario suggest that the implementation of multi-nodal has enabled D/AR to become averaged throughout the network and reduce nodal demand fluxes to generate an increased water supply performance for the network. When the D/AR is non-linear shown in an 'unmatched' demand profile the network flux of yield outgoing is hypothesised to show a small fraction of variation when compared to a linear 'matched' or averaged 1SnD demand profile. Figure 8-5 displays how the outgoing yield correlates in a S-D and 1SnD scenario when the D/AR is between 1 and 2, whilst the main fluctuations to outgoing yield occur when the D/AR is reduced below 1 (1-person household) and above 2 (4-person household). The results of figure 8-5 display how the 1SnD and S-D scenario could provide an increased water supply performance dependent upon the household configuration for example a S-D scenario would provide enhanced water supply performance in a 1 person household but a 1SnD in a 4-person household.

Further to the previous findings, figure 8-5 shows the outgoing Yield which explains the effects D/AR alterations have upon the WSE and WSF for a zoomed in small event period. For the lowest demand configuration (D/AR of 0.59 and representative of a 1 person-household) water supply was significantly better in a S-D scenario compared to that of a 1SnD scenario. The results during the zoomed in period recorded a period of time in which a S-D scenario was capable of fulfilling the required demand proportion whilst a nSnD could only fulfil 42% of the required demand in a 1-person household configuration (D/AR of 0.59). For the D/AR configuration of 1.19 and 1.79 representative of a 2 and 3 person household configuration there is a reduced fulfilment of the demand with less than 7% and 15% deviation being noted in yield supply between a 1SnD and S-D configuration. It can be seen in figure 8-5 that a S-D scenario has a slightly improved water supply in a reduced D/AR scenario of 1.19 whilst a nSnD provides an improved water supply in an increased D/AR configuration. For the highest demand configuration (D/AR of 2.38 and representative of a 4-person household) water supply shows a deviation of 38% between a 1SnD scenario compared to that of the S-D scenario. The results provided from figure 8-5 highlight how WSE and WSF is reduced in a S-D unmatched scenario when compared to that of a 1SnD scenario due to the D/AR in a 1SnD scenario becoming averaged to that of the network and creating a lowered flux in D/AR alterations this creates an increased water supply for the 1SnD scenario. This correlates to HR Wallingford's (2012) assumption that through the introduction of multi-nodal RMS networks demand can become averaged across the network and increase water supply performance.

It is assumed that if the demographics of the model set up had been slightly increased to that of slightly higher network D/AR then a nSnD system would achieve a further increased water supply performance than that of the 7% recorded. However, it should be noted that the increased water supply performance noted in a 1SnD system is generated due to the D/AR flux alterations in a S-D scenario causing enhanced periods where water supply is reduced in larger D/AR capacities whilst a 1SnD scenario averages these D/AR fluxes to create a more sustained water supply across the network catchment. It is assumed from the results that should a network D/AR of 0.9 and above be obtained a nSnD will provide an increased water supply efficiency compared to the S-D system as highlighted from the results.

8.4.1.5 *The impact of nSnD nodal water supply performance in a British standard sized approach*

The nodal variation represents the quantity of water supplied to meet the demand of 10 individual nodes within the network system. Figure 8-6 identifies how the water supply efficiency varies between the demand nodes in an 'unmatched' (worst-case) scenario. It can be identified from figure 8-6 that in 6 S-D scenarios the WSE is higher than that in a nSnD scenario. This correlates with the demand profile, 6 of the S-D scenarios with a higher WSE have a D/AR of 1.2 or below whilst the remaining 4 households have a higher D/AR.

A maximum variation of 58.2% is recorded in the nodal WSE metrics for a S-D scenario. Whilst no variation in nodal water supply is recorded in a 1SnD scenario. Figure 8-6 further emphasises how the variation in nodal WSE shows how alteration in D/AR can impact the uncertainties in yield outgoing and highlight the impact household demographics have on a S-D system is much greater than the impact seen at a nSnD scale. The introduction of a 1SnD scenario has reduced the water supply variability seen across the S-D network creating a more reliable water supply across the 10 houses in the network.

8.4.1.6 *Conclusion for water supply*

To conclude, the results show that a S-D RMS is comparable to a nSnD RMS. The results have highlighted that the water supply performance of a RMS can be increased by 7% through the introduction of multi-nodal RMS when compared to the conventional S-D RMS. The results have also shown that when including very low D/AR ratios a S-D scenario may provide an increased water supply performance due to small event periods in which a S-D scenario is capable of supplying a proportion of demand greater than that of a 1SnD scenario. Further to this, the results have displayed that the 1SnD scenarios create a fairer assumption and feasibility on the regularity of water supplied to the 10 demand nodes as a network through averaging the D/AR.

HR Wallingford correctly assumed that nSnD irregularity in demand, shown when comparing 'unmatched' to 'matched' demand results, can be averaged out when assessing for water supply performance. The results of this section have identified that a 5 demand node to 1 storage node scenario can even out differing constant demand rates the same as a 10 demand node to 1 storage node for the water supply metrics shown.

8.4.2 Stormwater Management Performance

8.4.2.1 Peak outflow:

8.4.2.1.1 Section overview

Section 8.5.1 aims to analyse the alterations to peak outflow that occur when altering the layout design of a RMS from S-D to 1SnD for the 10 terraced house scenario.

The results of the simulations in this subsection are analysed in order to evaluate the peak outflow reduction, a stormwater management benefit. Peak outflow will be measured in m^3/5-minutes to enable comparison with greenfield runoff rate. Nodal minimum and maximum peak outflow rates will be displayed on error bars.

8.4.2.1.2 Hypothesis

Hypothesis for Peak outflow: If a large storm event peaks when the storage node(s) are full, all of the inflow will cause outflow. This will therefore not make a difference whether it's from a S-D or 1SnD. However, since there is more likelihood of less available storage for inflow when a rainfall event occurs in a S-D scenario it could be that a peak outflow decrease will occur when analysing for a nSnD network. Therefore, the hypothesis for this section with regards to peak outflow is that in nSnD scenario peak outflow will be reduced compared to that of an S-D scenario.

8.4.2.1.3 Results and discussion for peak outflow

This analysis was undertaken for the entire 30-year simulation period and the effect of peak reduction observed for a number of rainfall events. The peak outflow rate shown in figure 8-7 highlights the largest outflow rate that occurred during the 30-year simulation. Table 8-1 highlights the top 30 peak outflow events that occurred throughout the 30-year simulation.

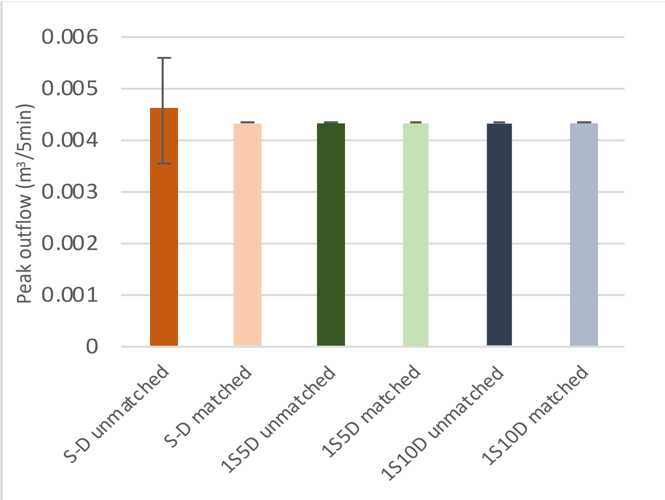


FIGURE 8-7 - PEAK OUTFLOW (NETWORK)

TABLE 8-1 - TOP 30 PEAK OUTFLOW EVENTS RECORDED FROM THE MODELLED SIMULATION

Day of simulation	1S10D	1S5D	1S1D
6419.489583	0.004317984	0.004317984	0.004461557
200.9444444	0.004290384	0.004290384	0.00443304
6419.961806	0.003564884	0.003564884	0.003683417
6419.958333	0.003548084	0.003548084	0.003666058
6419.434028	0.003405984	0.003405984	0.003519233
201.0208333	0.003393084	0.003393084	0.003505904
3727.5	0.003242384	0.003242384	0.003350194
10003.82986	0.002895084	0.002895084	0.002991346
10003.83333	0.002895084	0.002895084	0.002991346
3061.763889	0.002781784	0.002781784	0.002874279
10250.07986	0.00274634	0.00274634	0.002837656
5639.208333	0.002668284	0.002668284	0.002757005
6419.829861	0.002664084	0.002664084	0.002752665
4849.520833	0.002635584	0.002635584	0.002723218
3061.767361	0.002629184	0.002629184	0.002716605
2285.208333	0.002610484	0.002610484	0.002697283
4849.517361	0.002595829	0.002595829	0.002682141
6419.430556	0.002578142	0.002578142	0.002663866
6419.350694	0.002570384	0.002570384	0.00265585
6419.347222	0.002531884	0.002531884	0.00261607
4849.524306	0.002506384	0.002506384	0.002589722
201.0243056	0.002478484	0.002478484	0.002560894
2285.204861	0.002473938	0.002473938	0.002556196
8597.868056	0.002449784	0.002449784	0.00253124
3061.736111	0.002443938	0.002443938	0.002525199
6419.826389	0.002369346	0.002369346	0.002448127
6419.954861	0.002325184	0.002325184	0.002402497
3061.770833	0.002256584	0.002256584	0.002331616
6419.642361	0.002202784	0.002202784	0.002276027
6419.645833	0.002202784	0.002202784	0.002276027

Table 8-1 highlights that the 6419th day of the simulation was a particularly bad event that simulated 12 of the top 30 peak outflow discharges with the largest simulated event in all S-D and 1SnD scenarios occurring on the 6419th day of simulation. The peak inflow was 0.0055 m^3/5mins for the network catchment. Whilst the maximum network outflow is recorded and shown on figure 8-7. An 11 hour lag time was identified after the peak inflow to the maximum peak outflow for each scenario analysed. The lag time under these circumstances highlights the period in which inflow couldn't be retained in the RMS network and the inflow rate equalled that of the outflow due to a lack of rainwater demand. This result highlights that under an extreme inflow event if the storage capacity is below maximum some of the stormwater can be retained to reduce peak outflow until inflow exceeds the available capacity and demand withdrawal.

The results show that a nSnD system is capable of reducing the network peak outflow by up to 3.35% from that of the conventional S-D RMS. The higher peak outflow modelled in a S-D scenario network has occurred due to a number of houses within the scenario having a low D/AR thus creating a higher volume within the storage and reducing the retention volume available for stormwater prior to a rainfall event. The network reduction in peak outflow shown in a nSnD scenario has been caused by the D/AR being averaged out creating an even usage rate across the network scenario enabling a larger proportion of retention available prior to inflow events.

The 'mismatched' results have further emphasised that D/AR differences observed in the S-D scenario cause an alteration to the peak outflow performance. Through the introduction of a multi-nodal network the differing constant demand rates shown in D/AR of the nodes have become averaged and the results provide a significantly lower peak outflow rate with no significance in difference being observed in a 'matched' to a 'mismatched' scenario.

8.4.2.1.4 Conclusion

To conclude the results have highlighted that peak outflow can be reduced in a nSnD scenario by up to 3.35%. The results of the peak outflow analysis further emphasise that irregularity in demand has been averaged out when introducing the nSnD scenario, shown by the 'matched' to 'mismatched' results. A 1S5D has shown some sensitivity (0.1%) to different constant demand rates but is a lot closer to the 1S10D water supply metrics than that of the S-D analysis.

8.4.2.2 Time above greenfield runoff rate:

8.4.2.2.1 Section overview

Section 8.5.2 aims to analyse the alterations to the period of time outflow occurs above the greenfield runoff rate when altering the layout design of a RMS from S-D to nSnD for the 10 terraced house scenario. The greenfield runoff rate is an estimation of the surface water regime from a site prior to development. In this section to maintain the natural equilibrium of the modelled site the outflow discharge from the RMS should not exceed the natural greenfield runoff rate. Typical greenfield runoff rates for the UK are between 1.5 l/s/ha and 5 l/s/ha for a 1 in 1 year event and 5 l/s/ha to 16 l/s/ha for a 1 in 100 year event (Kellagher, 2002). The results of this simulation in this subsection are analysed for the period of time outflow occurs above the greenfield runoff rate, a stormwater management metric as expressed by equation 10. The greenfield runoff rate for this section is measured to be 5l/s/ha and the period of modelled time outflow exceeds this rate is counted. Nodal minimum and maximum time above greenfield runoff rates will be displayed on error bars.

8.4.2.2.2 Hypothesis

Hypothesis for TAG: Time above greenfield runoff rate will decrease in a nSnD network. In a S-D system one barrel attached to a low demand will result in lots more small spills from the network as a whole compared to 1 larger barrel attached to the whole network.

8.4.2.2.3 Results and discussion for TAG

Figure 8-8 shows the recorded time above greenfield runoff rate during the 30-year model period for the network.

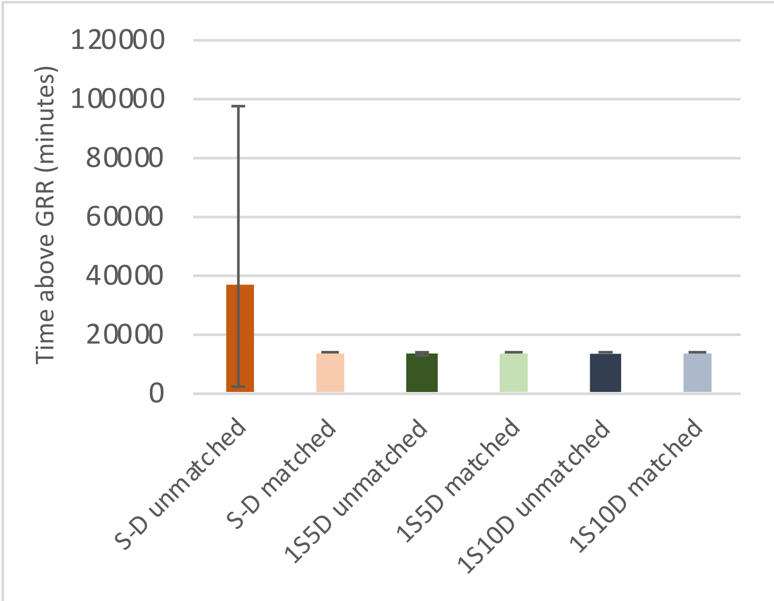


FIGURE 8-8 - TIME ABOVE GREENFIELD RUNOFF RATE (NETWORK)

Figure 8-8 displays the largest differences in performance to occur between a S-D and nSnD RMS design. The total period of time outflow occurs above greenfield runoff rate for the whole model simulation is 0.23% in a S-D scenario whilst only 0.09% in a 1SnD. A total network reduction of 22744.5 minutes over the 30-year period was observed by the introduction of a 1SnD scenario. This introduction of the 1SnD averages to an approximation of 758 minutes per year less time spent above the greenfield runoff rate when compared to the S-D scenario. The TAG metric highlights that the implementation of a 1SnD system has reduced the period of time outflow occurs above greenfield runoff rate across the 30 year-period by 62.5% compared to the conventional S-D system.

This result was highly anticipated as suggested by H R Walligford (2012) and previous performance analysis in section 8.4 the introduction of an interconnected multi-nodal network reduces the uncertainties associated with D/AR and as such reduces the quantity of outflow events that occur. It is anticipated that the time above greenfield runoff rate is highly dependent upon the quantity of retention storage prior to a rainfall event. In a S-D scenario the available storage volume for stormwater retention is highly likely to be reduced compared to a 1SnD scenario.

The inclusion of the 1SnD network has portrayed that a lower time above greenfield runoff rate for the network catchment can be achieved compared to a S-D network. The 'mismatched' results have shown findings similar to previous metric results once again emphasising that different constant demand rates observed in the S-D scenario cause a greater significance to the time outflow exceeds greenfield runoff rate performance whilst in a multi-nodal network the different constant demand rates become averaged and the results provide a significantly lower performance result.

8.4.2.3 Stormwater retention efficiency:

8.4.2.3.1 Section overview

Section 8.4.2.3 is the final section in nSnD to S-D RMS comparison for a British Standard storage sized guideline and aims to analyse the effects altering the layout design of a RMS from S-D to 1SnD for the 10 terraced house scenario has to the stormwater retention efficiency. The results of the simulations in this subsection are analysed in order to evaluate the stormwater retention efficiency, a stormwater management metric, expressed by equation 9.

8.4.2.3.2 Hypothesis

Hypothesis for SRE: Stormwater retention efficiency will increase in a nSnD network. In a nSnD spill volume will decrease due to a reduction in spill events.

8.4.2.3.3 Results and discussion for SRE:

Figure 8-8 displays the stormwater retention efficiency for the 30-year simulation period with nodal minimum and maximum SRE rates displayed on error bars.

The result of the SRE metric was anticipated to follow a similar pattern as the previous stormwater

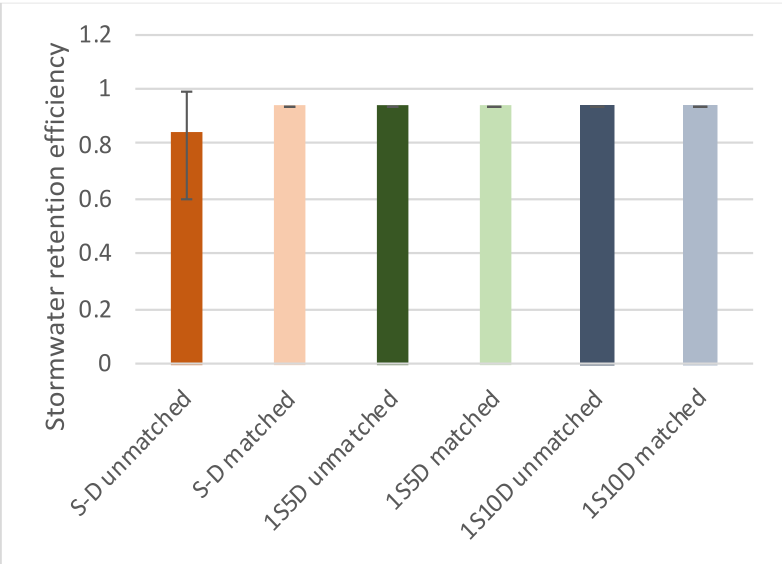


FIGURE 8-9 - STORMWATER RETENTION EFFICIENCY (NETWORK)

management and water supply metrics in that through the introduction of nSnD SWM performance will be increased and D/AR will be averaged therefore improving the stormwater retention efficiency for a 1SnD scenario. The introduction of an interconnected multi-nodal network has once again shown to reduce the uncertainties associated with occupancy rates (D/AR).

The introduction of 1SnD system has enabled an increase to the stormwater retention efficiency compared to the traditional S-D system. A 10.2% increase has been highlighted in SRE through the introduction of 1SnD compared to the traditional S-D scenario. The 1SnD is capable of retaining 93.8% of inflow compared to a S-D network that is capable of only 84% retention.

However, the stormwater retention variation in a S-D scenario has shown significant variation of up to 40% to the RMS stormwater retention capability as shown in figure 8-9. It is anticipated once again that the lower SRE value is due to the inclusion of lower D/AR nodes that result in a lower outgoing yield.

8.4.2.3.4 Conclusion

To conclude the 1SnD has portrayed a similar pattern as previous stormwater management metrics highlighting that a greater SWM performance is identified through the introduction of a interconnected 1SnD RMS. It can be clarified from the SWM results in section 8.4 that the 1SnD is more capable of providing available storage capacity for stormwater and therefore a greater SRE is achieved in a nSnD scenario.

8.5 DIY storage size approach results and discussion

Often in the UK RMS is limited in the area allocated for storage capacity and or the initial costs. Therefore, would the same results be shown should a smaller storage system be allocated instead of the British guidance sized storage capacity. For example, the typical water butt size sold in B&Q would provide a much smaller storage capacity than that of the British standard guideline but is a much more economically feasible way of implementing RMS.

Section 8.5 has been designed to analyse whether a smaller storage capacity will follow a similar pattern to that seen in the prior sections. Section 8.6 will identify a comparison between a 1SnD and S-D scenario is visible once the storage capacity is reduced, to that of a DIY store sized capacity. It is hypothesised that the layout design in a smaller storage capacity scenario will show a reduced significance to the water supply and stormwater management performance of the RMS. This hypothesis has been drawn due to the reduced volumetric capability for retention and detention in all of the layout designs.

Figure 8-10 shows the recorded performance analysis for a 30 year simulation period using a DIY store sized storage approach.

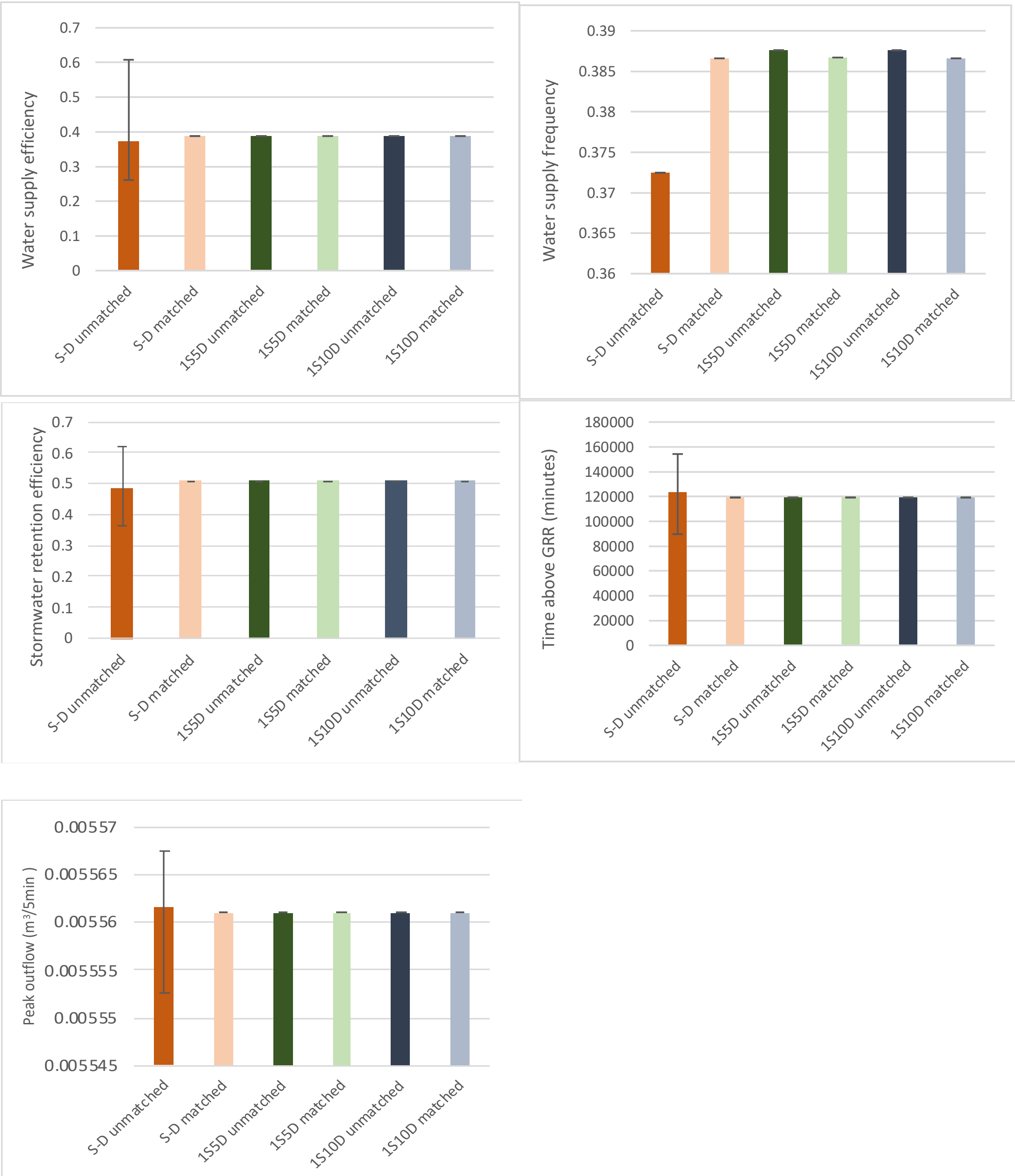


FIGURE 8-10 - DIY STORE(S) MODELLED RESULTS

The results of this research have shown general findings consistent with the previous research shown in section 8.5.

The results show that water supply of the RMS network, when using a DIY store standard 210 litre storage capacity, is met over 30% of the time and is capable of retaining more than 48% of stormwater flow. The present data has highlighted that layout design has a reduced influence on stormwater management and water supply performance when the storage capacity is reduced.

The overall variation in water supply metrics have suggested that a 1.6% increase to supply have occurred through the introduction of a nSnD system. The water supply results identified in this section show findings consistent with section 8-4. The alteration in water supply variation between a DIY store and British Standards sized approach has occurred due to the reduced storage capacity.

The performance analysis regarding stormwater management are analysed through stormwater retention efficiency, time above greenfield runoff and peak outflow. The SRE and TAG performance results have highlighted an improvement in performance correlated to the introduction of nSnD. Overall, the results in this section have shown an improved stormwater management performance in a nSnD design with a 2% increase in retention efficiency and a decrease of 3.5% less time outflow exceeds greenfield runoff rate. Whilst the peak outflow shows no significant difference that can be correlated to the change in layout configurations. Whilst the 1SnD has under these model circumstances highlighted a slight advantage to the water supply of the RMS, at around a 4% increase alongside an increased stormwater retention performance by an increase of 2%. Further stormwater management benefits have highlighted a reduced time in which outflow exceeds greenfield runoff rate by the introduction of the nSnD scenario.

Overall, the findings of the DIY store sized analysis have shown general findings consistent with the hypothesis and section 8-4. The results have highlighted that when reducing the storage capacity size, the advantages previously seen in nSnD stormwater management and water supply performance are reduced.

8.6 Is it worth it: S-D to nSnD overview

- Better stormwater retention efficiency – 10% increase in SRE for a 1SnD compared to S-D RMS scenario
- Reduced time above GRR in 1SnD
- Reduced peak outflow by more than 3.35% in a 1SnD scenario when compared to a S-D scenario
- Increased water supply efficiency and water supply frequency – 7% increase in a British standard approach and 1.6% in a DIY store approach.
- Different constant demand rates across the network become less significant in a nSnD layout design

8.7 Conclusion

The main aim of this section was to evaluate whether a nSnD RMS is comparable to a S-D RMS. This research has generated a series of results that provide comparison of a 1SnD scenario to the conventional S-D scenario. The findings have provided evidence to suggest that a RMS can provide an additional water supply whilst providing stormwater management benefits in both a S-D and 1SnD scenario. The key findings of this research have concluded that in a 1SnD scenario under these model circumstances highlighted an advantage to the water supply of the RMS and the stormwater retention performance has significantly been improved through the introduction of 1SnD. Further stormwater management benefits are a decrease to the peak outflow and time outflow exceeds greenfield runoff rate performance by the introduction of the 1SnD scenario. Further to these findings the results provided throughout this section show that HR Wallingford correctly assumed that nSnD irregularity in demand, shown when comparing 'unmatched' to 'matched' demand results, can be averaged out when assessing for all of the performance metrics analysed (HR Wallingford, 2012). The results of the 1SnD research have shown that when multiple demand nodes performance are assessed the irregularity in demand can be averaged out at a much smaller increment, such as 5 demand nodes, than previously suggested by HR Wallingford of 10 demand nodes.

Since the benefits of a 1SnD system to that of the conventional S-D system at modelling level are relatively comparable it's important to regard the intentions for RMS. If the main intentions for implementing RMS are to provide water supply at a low network scale D/AR (averaged D/AR of below 0.9) network scale then a greater reliability in water supply can be assumed by the implementation of a S-D network. However, if a higher network D/AR (averaged D/AR of above 0.9) network scale is to be considered then a greater water supply performance can be assumed in a nSnD scenario. Further to this, it should be noted that should a lower network D/AR of below 1 be considered then a significant decrease in SWM performance can be assumed. When stormwater management intentions are also evaluated then a strong recommendation could be regarded for a nSnD network since a greater performance can be achieved compared to the S-D system. A 1SnD design has shown in this study to be more capable in increasing water supply, retaining inflow, reducing peak outflow and reducing the time the outflow exceeds greenfield runoff rate. However, the S-D scenario could still provide to be more feasible for implementation due to conflict of interest, initial costs, and demographics.

It is suggested that more research should be undertaken to determine if the results of this scenario provides an accurate representation of 1SnD to S-D RMS or if the results produced as part of this research are due to an off chance in the model set up generating a varied D/AR pattern.

In the future of RMS research, it would be interesting to identify if multi nodal networks that have increased storage and demand nodes would further enhance RMS performance. Further to this it would be interesting to identify how through the introduction of system configurations (passive or advanced/smart) to the RMS would affect performance in a nSnD scenario.

9 Conclusions

The aim of the work presented in this thesis was to explore the potential for understanding RMS at a nSnD scale and assess the performance of a nSnD layout configuration compared to a conventional S-D configuration. This section will summarise the primary conclusions of the study and the main outcomes of this research.

9.1 Performance metrics

The modelling of performance in RMS has often focused upon water supply benefits. During the development of this research a concise list of performance metrics has been proposed for the water supply and stormwater management benefits of a RMS at a S-D and nSnD scale. The five metrics are: water supply efficiency, water supply frequency, stormwater retention efficiency, peak outflow and time above greenfield runoff rate.

9.2 Model sensitivity

During the development of this research the sensitivity of model results to model algorithm, time-step and demand has been analysed. The main findings of the model algorithm sensitivity analysis were consistent with previous research, emphasising the YAS algorithm to be the more reliable operating algorithm to be used in RMS model research. The data presented in the time step sensitivity and model algorithm highlighted that a temporal scale of larger than hourly intervals creates a significant divergence in the modelled results. The time-step sensitivity analysis showed that to reduce the sensitivity due to time-step, a time step of 5-minutes or lower should be used in future RMS research. The 5-minute time-step increments coincide with current stormwater management practice, and therefore data is easily accessed at this temporal scale. Finally, from the results generated in the demand sensitivity analysis and earlier findings in model feasibility (section 2) suggested that the use of a set continuous demand at a household scale for future research is feasible should the D/AR be below 3.

9.3 Allocation strategy

Balhatchet et al. (2014) identified the significant impact that allocation strategies had on the modelled performance of large-scale RMS. During the development of the nSnD research four allocation strategies were analysed for their impacts on performance. Of the four allocation strategies evaluated, 'Equal supply', 'predetermined order', 'highest demand first', and 'lowest demand first' no allocation strategy resulted in higher performance efficiency. The significance of allocation strategy in Balhatchet et al. (2014) research is assumed to be a direct result of the one day time step used generating time-step sensitivity. In the findings of this research there is no impact on performance of a nSnD achieved as a result of altering the allocation strategy. Therefore, in the future of nSnD RMS research, any allocation strategy can be reliably chosen given the fact a lower temporal-scale is selected initially.

9.4 Viability of nSnD as stormwater management approach

The modelling of RMS that has multiple demands to 1 or more storage nodes has a broad generic application. The concept of a nSnD RMS is scalable to any size desired for residential or commercial developments. During this research the model developed a 10 terraced house RMS concept at a S-D, 1S5D and 1S10D level.

The research has generated a series of results that provide comparison of a 1SnD scenario to the conventional S-D scenario. The results have provided evidence to suggest that a RMS can provide an additional water supply whilst providing stormwater management benefits in both a S-D and 1SnD scenario. It has been demonstrated that a 1SnD RMS is more effective at increasing water supply benefits and enhancing stormwater management performance when compared to that of a S-D RMS. Overall, a nSnD network can be shown to provide a comparable performance to that of the S-D scenario with some advantages being highlighted.

The findings of the nSnD research were consistent with HR Wallingford (2012) who correctly assumed that in nSnD irregularity in demand, shown when comparing 'unmatched' to 'matched' demand results, can be averaged out. The nSnD research undertaken during this study enables a good platform to develop upon in future research for nSnD RMS.

Overall, the nSnD system under the model circumstances has provided evidence of increasing water supply performance by up to 7% and enhancing stormwater management performance with a 10% increase in stormwater retention efficiency, reduced time above greenfield runoff rate and a reduction in peak outflow by 3.35% being observed. The results have shown that a small D/AR node would provide better water supply potential in a S-D scenario compared to a nSnD. Whilst, the nSnD scenario has provided evidence of enhancing network water supply efficiency and frequency by more than 1.6%.

9.5 Suggestions for future research

- Optimisation of 1SnD networks – this would enable a greater understanding to the capabilities of 1SnD networks and possible pose an improvement to the RMS research. It is hypothesised that should the D/AR of the network be varied further or the network D/AR be between 1 and 2 the water supply potential of a nSnD scenario would be increased and provide a more optimal RMS configuration scenario to that of the S-D scenario.
- nSnD networks – nSnD networks have only been researched briefly by Balhatchet et al. (2014). Therefore, the potential of nSnD is relatively unknown. However, from the research undertaken I believe that the nSnD network would provide an increased performance to that of the 1SnD in particular when regarding SWM benefits. Further to this it would be informative to know how upscaling the RMS design could influence stormwater reduction and the decentralisation of water supply systems.
- The inclusion of active and passive release systems – these system configurations are implemented/modelled at an S-D scale to provide increased stormwater management performance. Therefore, in the future of 1SnD and nSnD research the implementation of system configurations to this design may provide further enhancement to system performance.

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