

1.0 Introduction

1.1 Background

Rainwater harvesting is an ancient technology that has been used throughout history to supply water to human settlements and, more recently, to buildings in urbanised areas (Gould & Nissen-Peterson, 1999). Globally, millions of systems are currently in use (Lye, 1992; ABS, 1994; Heggen, 2000) and a wide variety of both potable and non-potable applications are evident (Fewkes, 1999a; Gould & Nissen-Peterson, 1999; Coombes *et al*, 2000c; Cooper, 2001; Leggett *et al*, 2001b; Ratcliffe, 2002; Weiner, 2003). The use of rainwater harvesting has declined in much of the developed world as a result of the introduction of centralised large-scale water treatment and distribution systems (Gould & Nissen-Peterson, 1999). However, there is growing concern that this approach may be unsustainable as the available resources that they primarily depend upon (ground and surface waters) are becoming progressively more expensive and difficult to develop (Hiesl *et al*, 2001). In many parts of the world traditional water resources are also becoming increasingly polluted, largely due to man's activities (e.g. Sayers, 1999).

Many countries have begun to show a resurgent interest in the use of rainwater harvesting techniques (Herrmann & Schmida, 1999; Argue, 2001; Konig, 2001; Villarreal & Dixon, 2005). Although not a panacea in itself, it is widely believed that these systems can form part of a new urban water management paradigm that is more sustainable than the traditional methods. In the UK this approach has become known as "Sustainable Drainage Systems", or SUDS. A more

holistic view of the urban water cycle is advocated and consideration should be given to 'source control' techniques rather than a complete reliance on large-scale piped solutions. Source control techniques attempt to deal with rainfall where it lands, or as close to the point of origin as possible. Examples of SUDS techniques include overland flow channels, filter drains, infiltration devices, permeable surfaces, green roofs, detention basins, ponds and wetlands. These generally operate by attenuating the peak stormwater runoff conveyed from the urban catchment to the sewer system or watercourse, thereby reducing the risk of flooding (Woods-Ballard *et al*, 2007).

Rainwater harvesting systems are also a part of the SUDS approach. Runoff arising from impervious surfaces (principally roofs) can be stored in rainwater tanks for subsequent potable and non-potable use. Providing that storage is available at the beginning of a storm event, these systems can act as attenuation devices, reducing both peak flow rates and effective runoff volumes under favourable conditions (Coombes *et al*, 2001; Vaes & Berlamont, 2001). In the UK, domestic rainwater harvesting systems are predominantly used for non-potable applications such as WC flushing, garden irrigation and laundry washing (Brewer *et al*, 2001; Leggett *et al*, 2001a,b). Mains supply water is to some degree substituted by harvested rainwater and so these systems are also a way of reducing pressure on the centralised water supply and distribution infrastructure (Schilling & Mantoglou, 1999; Coombes & Kuczera, 2003a).

In the UK, research has tended to focus on the potential to reduce reliance on potable mains supply at the single building scale (e.g. Dixon, 1999; Dixon *et al*,

1999; Fewkes, 1999a; Brewer *et al*, 2001). To date there have been few rigorous studies concerning the *financial* aspects. If these are considered at all then it is often done poorly, using sparse data, rules of thumb and unrealistic assumptions. There are claims that rainwater systems can offer financial benefits. Conversely, the opposite may be true and they may not be financial effective, or may be so only under certain circumstances. However, there is currently insufficient detailed research with which to support any of these conclusions (see chapter four).

1.2 Aims and objectives

This thesis aims to investigate the financial performance of rainwater harvesting systems for *new-build* developments in the UK. Particular attention will be given to the use of domestic systems for non-potable applications such as WC flushing, garden irrigation and laundry cleaning. The aims and objectives of this thesis are therefore to:

- Review the literature and determine the state of the art with regards to contemporary RWH in the UK, principally in relation to the prediction of financial performance, and to identify gaps in existing knowledge.
- Develop a computer-based modelling tool for the hydrological and financial assessment of RWH systems for non-potable uses at the single-building scale.
- Gather relevant data with which to populate the new model.
- Use the model to conduct a detailed financial analysis of a range of theoretical but realistic RWH systems for new-build developments, with

an emphasis on domestic installations. A system designed for a new communal (school) building will also be assessed.

- Evaluate the model outputs and draw a number of conclusions regarding the long-term financial performance and viability of RWH systems for new-build developments.

1.3 Thesis structure

The structure of the thesis reflects the stated aims and objectives and logically progresses through the steps required to meet them. The following subsections provide a brief description of each chapter (excluding chapter 1).

Chapter 2: rainwater harvesting literature review

The thesis starts with a general review of the literature considered relevant to this research area. The review explores:

- Different types and configurations of rainwater harvesting systems commonly employed in developed countries and an overview of the key drivers for their use.
- The key components that modern systems comprise of.
- Water quality issues.
- Contemporary rainwater harvesting in the UK including barriers to uptake and public perception.
- Potential benefits, including the possibility of financial savings.
- Relevant policies, regulations and design guidance.

Chapter 3: methods of modelling the hydrological performance of rainwater harvesting systems

Chapter three consists of a detailed literature review of the existing methods for modelling the hydrological performance of RWH systems at the single building scale. Topics that are covered include:

- An overview of modelling concepts including different types, general considerations and reasons for modelling rainwater harvesting systems.
- Key system components that require inclusion in any comprehensive model and an overview of the different ways in which their physical behaviour can be simulated.
- A detailed investigation into methods for modelling the behaviour of rainwater storage tanks and the selection of an appropriate approach.
- Methods for predicting future non-potable water demand, including how to account for the possible impacts of climate change and selection of an appropriate demand prediction approach.

Chapter 4: financial assessment of rainwater harvesting systems

Chapter four investigates existing research concerned with the financial assessment of rainwater harvesting systems at the single building scale. This chapter looks at:

- Financial assessment techniques that are applicable to the water industry in general, and identifies Whole Life Costing (WLC) as a suitable approach for assessing the financial performance of RWH systems.

- How to apply a WLC approach to rainwater harvesting systems including identification of relevant costs and data requirements.
- Existing 'rule-of-thumb' design and assessment approaches. The accuracy of these approaches is questioned and several methods are selected for a more detailed investigation later in the thesis.

Chapter 5: rainwater harvesting model development

Chapter five builds on the information presented previously in chapters two, three and four and details the creation of a new modelling tool for predicting the water saving efficiency and financial performance of contemporary rainwater harvesting systems. Model scope, structure and limitations are discussed, as are the main features and data requirements. Details are given of the underlying algorithms and assumptions.

Chapter 6: assessment of rainwater harvesting systems for new-build domestic dwellings

Chapter six reports on the application of the new model for predicting the water saving efficiency and financial performance of rainwater harvesting systems in new-build houses. The study area is the West Yorkshire region. A wide range of possible systems are investigated and financial performance results presented from different stakeholder perspectives. The key factors affecting the performance of domestic rainwater harvesting systems are identified. A sensitivity analysis of the financial model is also conducted. Finally, results predicted by several commonly applied 'rule-of-thumb' design and assessment

approaches are compared against those generated by the more rigorous thesis model.

Chapter 7: rainwater harvesting systems for communal buildings

Chapter 7 investigates the performance of a proposed RWH system for a new-build school facility. The water saving efficiency and financial aspects are investigated and a sensitivity analysis of the results conducted. The outcomes are used to draw conclusions about the cost effectiveness of RWH systems installed in such buildings. The RWH system supplier's own design and assessment methods are compared against those of the more rigorous thesis model.

Chapter 8: conclusions and recommendations for further work

Chapter 8 summarises the research undertaken in this thesis, draws a number of conclusions, states the contributions to knowledge and highlights the potential for further work.