Life cycle water, energy and cost analysis of multiple water harvesting and management measures for apartment buildings in a Mediterranean climate

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Abstract

Local water harvesting, demand reduction and wastewater treatment measures at a building scale can help manage water resources around the Mediterranean.

This study conducts a life cycle water, energy and cost analysis of rainwater and condensate water harvesting, water conservation, wastewater treatment and three combinations of these measures over 50 years, using an apartment building in Sehaileh, Lebanon. The measures' performance is further investigated through a comprehensive sensitivity analysis that extends the applicability of findings.

Reducing water demand in the building through efficient water fixtures and appliances can decrease annual water and primary energy use by 1 534 kL and 130 GJ, respectively, while saving 530 USD every year. Wastewater treatment requires 230 MJ and costs 0.97 USD per kL of water saved, necessitating subsidies to be competitive. Rainwater and condensate water harvesting cover 4.8% and 1% of the total demand, respectively, but can reduce infrastructure spending, avoid water leakage and reduce urban run-off. Combining all measures reduces mains water supply by up to 75% for 1 MJ/kL saved and no cost. Finally, a

metered, seasonal and demand-driven water pricing scheme is recommended to better relate building occupants with the intermittent and scarce nature of water around the Mediterranean.

Keywords: Life cycle water analysis; life cycle cost analysis; sustainable urban water management; rainwater; condensate water; Lebanon.

1 Introduction

Water is essential for life on earth but is becoming increasingly scarce in some areas, notably due to increased urbanisation and surface run-off as well as reduced access to water (Bourne & Wouters, 1997). As urban populations are expected to represent 60-67% of the world population over the coming decades (U.N., 2012), and a number of major cities are expected to be subject to more frequent droughts due to climate change (IPCC, 2013), it is critical to better manage urban water resources. This is aligned with the United Nations sustainable development goals (U.N., 2015) number six (clean water and sanitation) and eleven (sustainable cities and communities) and is supported by recent studies in the field that highlight the importance of sustainable urban water management (Jimenez Cisneros & Rose, 2009; Marlow, Moglia, Cook, & Beale, 2013).

Based on Marlow et al. (2013), sustainable urban water management cannot be simply defined but comprises a range of concepts such a decentralising water infrastructure to avoid delivery losses, differentiating water uses by required water quality to avoid wasting potable water, harvesting stormwater and increasing the resilience of urban water systems by relying on multiple sources of water, among others. These themes are also highlighted by other studies such as Agudelo-Vera, Keesman, Mels, and Rijnaarts (2013). Buildings have a key role to play in sustainable urban water management as they constitute the bulk of the direct urban water demand (e.g. residential buildings alone represent 65% of the total water demand of Melbourne, Australia (Melbourne Water, 2016)). Furthermore, building roofs represent around 40-50% of impervious areas in urban settings (Dunnett & Kingsbury, 2008), offering great opportunities for rainwater harvesting, reducing runoff and saving costs on drainage infrastructure (Speers & Mitchell, 2000).

A large number of studies has focused on water conservation at the building scale, including sizing systems (notably water tanks), estimating the so-called 'water saving efficiency' (or the amount of mains water reduction) and calculating the cost-benefit of harvesting or conservation measures (inter alia Agudelo-Vera et al., 2013; Beal, Sharma, Gardner, & Chong, 2012; Eroksuz & Rahman, 2010; Santos & Taveira-Pinto, 2013; Villarreal & Dixon, 2005; Ward, Memon, & Butler, 2012). Several of these studies have adopted a life cycle approach in quantifying the benefits of water conservation measures.

Loubet, Roux, Loiseau, and Bellon-Maurel (2014) have reviewed life cycle studies on urban water systems and identified 24 papers out of which 18 were selected for review. They find that studies relying on multiple indicators can better inform policy-making. The reviewed studies focus on precincts or cities of 14 300 – 20 000 000 inhabitants and their water distribution system at a macro scale rather than on strategies at the building scale.

Multiple studies have quantified the life cycle performance of water harvesting and management systems. These include, *inter alia,* Devkota, Burian, Tavakol-Davani, and Apul (In Press), Devkota, Schlachter, and Apul (2015), Wang and Zimmerman (2015), Ghimire, Johnston, Ingwersen, and Hawkins (2014), Devkota, Schlachter, Anand, Phillips, and Apul (2013), Vargas-Parra, Villalba, and Gabarrell (2013), Morales-Pinzón, Lurueña, Rieradevall, Gasol, and Gabarrell (2012), Ward et al. (2012) (financial cost only), Rahman, Keane, and Imteaz (2012), Angrill et al. (2011), Anand and Apul (2011), Racoviceanu and Karney (2010), and Crettaz, Jolliet, Cuanillon, and Orlando (1999). These studies and others are reviewed in more detail in Section 2. However, the majority of existing studies do not take into account embodied water requirements when quantifying life cycle environmental requirements. In addition, most studies typically focus on rainwater harvesting, excluding other sources, such as condensate water. Furthermore, existing studies on residential water harvesting and management tend to target detached dwellings, with very few studies considering apartment buildings. In the review conducted by Vieira, Beal, Ghisi, and Stewart (2014), only 1/7 of the reviewed theoretical studies and 0/9 of the empirical studies investigated multi-storey residential buildings.

Apartment buildings represented the largest single housing type (compared to semi-detached and detached housing) in Europe in 2015 (Eurostat, 2017a) and are dominating the new construction market in other regions, such as Australia (ABS, 2016). In most European Mediterranean countries, i.e. Greece, Italy, Malta and Spain, more than 50% of the population lives in apartment units (Eurostat, 2017a). From a water harvesting perspective, apartment buildings present challenges compared to detached and semi-detached housing as the ratio of roof to habitable surface area for each unit is reduced. In addition, they can offer economies of scale for the installation of particular systems, such as wastewater treatment.

Among the different climatic regions, the Mediterranean climate is worthy of investigation as it is expected to suffer from reduced precipitations and increased levels of droughts (Dai, 2011; Iglesias, Garrote, Flores, & Moneo, 2006; IPCC, 2013; Parish, Kodra, Steinhaeuser, & Ganguly, 2012). Furthermore, coastal areas around the Mediterranean sea accommodated more than 143 million people in 2000 with a projected population of 174 million in 2025 (UNEP/MAP/BP/RAC, 2005). Most of this population is urban and resides in less developed economies (UNEP/MAP, 2012) with less efficient water infrastructure, less rainfall

(UNEP/MAP/ MED POL, 2003) and less data and knowledge for policy-making (World Bank, 2010). For these reasons, it is critical to conduct studies that help inform policies in data-poor countries where most of the population typically live in high density urban centres (UNEP/MAP, 2012).

While the studies of Angrill et al. (2011), Morales-Pinzón et al. (2012) and Angrill et al. (2017) provide insights into the life cycle energy performance of rainwater harvesting systems of apartment buildings in a Mediterranean climate, they cover a limited scope of either indicators or end-uses (see Table 1) and are conducted in a Spanish context of a developed economy. There is therefore a need to investigate the life cycle water, energy and cost requirements of multiple water harvesting and management measures for apartment buildings in a Mediterranean climate and a developing economy in order to provide a more comprehensive understanding of their potential. This will inform policies that can help preserve this precious resource.

1.1 Aim and scope

The aim of this paper is to quantify the life cycle water, energy and cost requirements of different water harvesting and management measures for apartment buildings in a Mediterranean climate, over 50 years. The study uses a case study apartment building located in Sehaileh, Lebanon (see Section 3.1 for more details on the choice of the location). It focuses on rainwater harvesting techniques and on collecting condensate water from air-conditioning units in summer. From a water management perspective, the study considers the installation of water efficient fixtures (demand-side management) and wastewater treatment systems (waste minimisation). The scope of the study is depicted in Figure 1. The system boundary includes quantifying the initial and recurrent embodied energy and water requirements, operational energy and water requirements and capital, operational energy and water and material/component replacement costs.

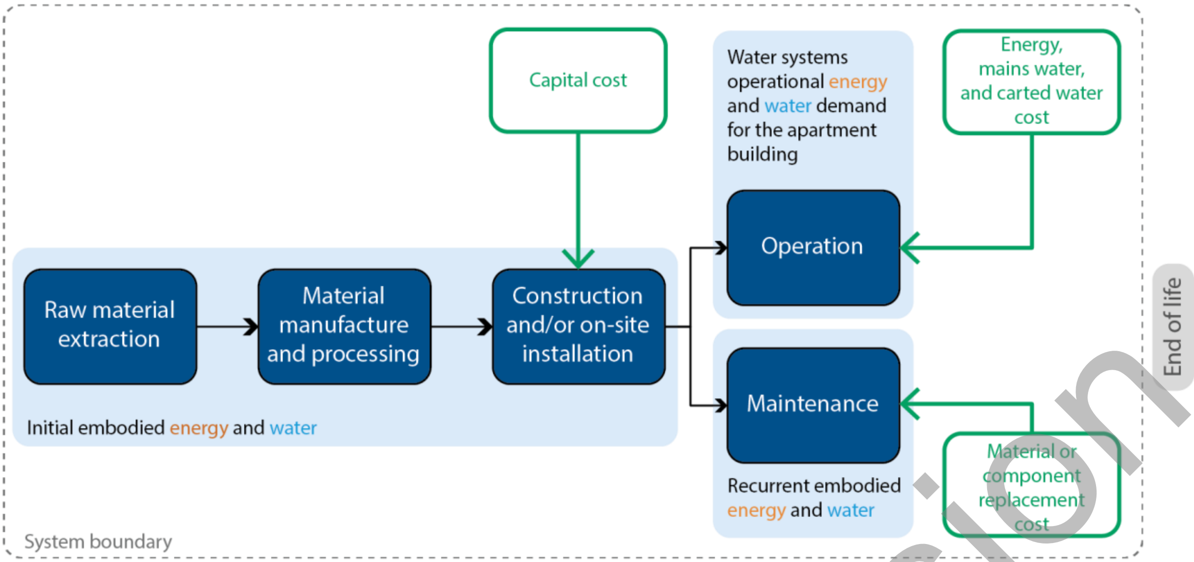

Figure 1: System boundary of the study.

1.2 Structure

This paper is structured into six sections. Section 2 briefly reviews some of the existing studies that use a life cycle approach to quantify the environmental and/or cost requirements of sustainable water harvesting and management. Section 3 details the method used while the results and sensitivity analysis are presented in Section 4. Section 5 discusses the contribution of the study, its implications and limitations before concluding in Section 6.

2 Existing life cycle assessment studies on water harvesting and management systems

Most life cycle studies applied to water harvesting and management systems have been conducted in the last 5-10 years, highlighting the recent interest in the topic. Table 1 summarises a number of these studies and compares their scope to this one, depicting the lack of studies on apartment buildings that consider both the environmental and financial performance of water harvesting and management measures. It is important to note that Table 1 does not intend to reflect an exhaustive review of the literature. Selected studies are commented on below.

Table 1: Summary of existing literature showing a lack of studies using an integrated approach to assess the environmental and financial performance of water harvesting and management measures for apartment buildings.

Study	Scale	Building type	Water harvesting source	Water management aspect(s)	End-uses	Life cycle energy	Embodied water	Life cycle cost
Crettaz et al. (1999)	Building	Detached residential	RW	Low-flow toilets	Toilet flushing	✓		
Sharma et al. (2009)	Precinct water servicing	Mixed	RW, GW, SW	Reduced demand	Toilets; Bathroom; Kitchen; Laundry; Outdoor; Commercial; Industrial	✓		✓
Racoviceanu and Karney (2010)	Urban residential distribution network	Residential buildings	RW	Reduced demand	Toilet flushing; Toilet faucets; Kitchen tap; Showers; Washing machine and Dishwasher	✓		
Anand and Apul (2011)	Building	University building	RW	Standard toilets; low-flow toilets; composting toilets.	Toilet flushing	✓		✓
Angrill et al. (2011)	Building	Apartment building	RW		Laundry	✓		
Roebuck et al. (2011)	Building	Detached residential	RW		Toilet flushing; Laundry; Outdoor			✓
Rahman et al. (2012)	Metropolitan	Detached residential	RW		Toilet flushing; Laundry; Outdoor			✓
Ward et al. (2012)	Building	Office building	RW		Toilet flushing			Not NPV
Morales-Pinzón (2012)	Building	Detached residential; Apartment building	RW		Laundry	✓		✓
Vargas-Parra et al. (2013)	Metropolitan	Detached residential; Apartment building	RW		Laundry	✓		
Devkota et al. (2013)	Building	Office building	RW	Low-flow toilets; Composting toilets	Toilet flushing; Outdoor	✓		✓
Ghimire et al. (2014)	Building	Detached residential	RW		Toilet flushing	✓	✓	
Devkota et al. (2015)	Building	University dorms building	RW		Toilet flushing; Outdoor	✓		✓
Wang and Zimmerman (2015)	City	Office buildings	RW		Toilet flushing	✓		✓
Devkota et al. (In Press)	Building	Office building	RW		Toilet flushing	✓		

Study	Scale	Building type	Water harvesting source	Water management aspect(s)	End-uses	Life cycle energy	Embodied water	Life cycle cost
This paper	**Building**	**Apartment building**	**RW, CW, GW (treated)**	**Reduced demand (including low-flow toilets, aerated showers and taps, and efficient appliances)**	**Toilet flushing; Toilet faucets; Showers; Kitchen tap; Washing machine; Dishwasher**	✓	✓	✓

Note: RW: rainwater; CW: condensate water; GW: greywater; SW: stormwater; NPV: net present value;

One of the most comprehensive life cycle cost analyses of rainwater harvesting systems was performed by Roebuck, Oltean-Dumbrava, and Tait (2011). In their study, they use the net present value method to evaluate 3 840 different rainwater system configurations covering four different discount rates, four discount periods, three combinations of water use, five occupancy rates and sixteen tank sizes. They find that, at the building-scale, and in the context of the United Kingdom, rainwater harvesting systems are not cost effective compared to using mains water, due mainly to the ongoing maintenance costs. However, their study does not consider the potential environmental benefits associated with rainwater harvesting.

Angrill et al. (2011) have conducted one of the rare life cycle assessment studies on rainwater harvesting systems in a Mediterranean climate, focusing on different tank designs. They compared the life cycle environmental performance of different designs for rainwater harvesting systems in Barcelona using both a diffuse urban layout (houses) and a compact urban design (apartment buildings). Their study found that using storage tanks distributed over the roof result in the best environmental performance. This is mainly due to the absence of pumps that would otherwise be required to pump water from an underground storage tank and the associated energy and greenhouse gas emissions. This study, along with Angrill et al. (2017) focus on rainwater harvesting systems for apartment buildings in the Mediterranean but they do not consider embodied water nor financial costs.

In their life cycle assessment of domestic and agricultural rainwater harvesting systems, Ghimire et al. (2014) quantified a range of endpoint environmental indicators, including blue and green water use. They highlight the blue water savings associated with rainwater harvesting systems as these avoid leakage on the mains distribution system. However, they do not include financial costs in their evaluation and use a detached case study house for the domestic scenario, which provides a high roof area per capita compared to apartment buildings.

One of the studies combining environmental and financial life cycle assessment of rainwater harvesting systems has been conducted by Devkota et al. (2015) using university buildings in Toledo, United States of

America. Among their many results, they found that the payback time for a rainwater system for toilet flushing in a new building is 17 years and that low mains water prices penalised rainwater systems. They also found that pumps and wastewater treatment systems represented the large majority of life cycle energy use and greenhouse gas emissions. However, reviewed studies that combine environmental and cost performance (*inter alia* Anand and Apul (2011), Morales-Pinzón et al. (2012), Devkota et al. (2013), Wang and Zimmerman (2015) and Devkota et al. (In Press)) did not, however, consider embodied water requirements, and typically focus on one or two end-uses.

While existing studies have analysed the life cycle financial cost, life cycle energy demand and life cycle water requirements of rainwater harvesting systems, there is no study on apartment buildings that combines all three aspects while simultaneously covering water management measures and multiple end-uses. This study fills this gap and will help inform relevant policies to reduce mains water use.

3 Quantifying life cycle water and cost requirements of sustainable water harvesting and management measures

The case study building, overall research strategy, quantification algorithms and the various water harvesting and management measures considered are presented in this section. The base case apartment building scenario is referred to as BC throughout the text.

3.1 Case study: climate, water distribution and building characteristics

Lebanon is one of the Mediterranean countries facing a drying climate (MOA, 2003) and lacks data on its water harvesting and management potential (World Bank, 2010). It lies on the eastern shore of the Mediterranean, and covers an area of 10 452 km², has a shoreline of ~210 km and two mountain ranges that run parallel to its length and reach the altitudes of 3 086 m and 2 814 m. This topography explains the wide variation in precipitation on such a small territory, ranging from 200 mm to 1 200 mm, on average (UNDP/GEF/MPWT/DGU, 2005). However, most of the Lebanese population lives in the so-called 'Mount-Lebanon and Beirut' area, where rainfall varies between 750-1 000 mm. According to the second report of Lebanon to the United Nations Framework Convention on Climate Change (MOE, 2011), rainfall is expected to drop by 10-20% by 2040 and by 25-45% by 2090. This is more than the expected reductions around the Mediterranean (IPCC, 2013) and it further justifies the need for reducing mains water use.

Lebanon is one of the most urbanised countries on the Mediterranean with more than 85% of its population living in cities (UNEP/MAP, 2012). Apartment buildings dominate the residential building stock with an estimated 67% of the total floor area (Mourtada, 2010). This explains the use of an apartment building as a case study.

Water distribution in Lebanon is managed by the Ministry of Energy and Water. It is characterised by an inefficient grid with 20-40% leakage (Comair, 2011), intermittent water supply with less than 3 hours in summer in Mount-Lebanon and Beirut where 60% of connected households are located (World Bank, 2010) and deteriorating water quality. For these reasons, households typically rely on water cartage by private companies to ensure the continuity of water supply. The market price for carted water is ~3.74 USD/kL compared to an average mains water price of 0.73 USD/kL. The ratio of carted to mains water price is therefore 512% and much lower than the average figure of 1 083% in Victoria, Australia, based on data collected in 2007 during the Australian Millennium Drought (Hurlimann, 2009). This might be due to the fact that water cartage is widely available and common in Lebanon and there are many competitors on an established market compared to the more mushrooming nature of the Australian drought market. The non-continuous nature of water supply in Lebanon has led to the systematic installation of storage tanks in the basement of dwellings from which water is pumped to header tanks on the roofs. This existing water infrastructure at the building level supports the consideration of rainwater harvesting as most of the needed equipment is already in place, contrarily to the situation in most developed economies.

The case study is a recent four-storey apartment building located in the residential town of Sehaileh, on the western side of the Mount-Lebanon ranges in Lebanon, 25 km North of the capital Beirut, at 515 m above sea level. Each storey comprises two apartments of 154 m^2 gross floor area and 113 m^2 of usable floor area (see Figure 2). This apartment size is very close to the average national dwelling size which is 129.3 m^2 according to Mourtada (2010). The building accommodates eight households of four persons or a total of 32 occupants. It uses a conventional Lebanese water system as depicted in Figure 4. The case study is used as a representative sample of new apartment buildings in Lebanon. As such, all measures are considered to be implemented upon construction. Costs associated with retrofitting or installing systems in an existing building are not considered.

Figure 2: South elevation and floor plan of case study apartment building in Sehaileh, Lebanon. Note:GFA = Gross floor area. Based on Technical Enterprises Co. (2017)

Detailed information about the case study building can be found in Stephan and Stephan (2014). It is important to note that all information on the building was sourced directly from the construction company (Technical Enterprises Co., 2017), resulting in reliable data for many significant variables such as the bill of material quantities for plumbing, water pumps installed and their power rating, the replacement frequency of certain systems and assemblies and others. The main characteristics of the base case study building are summarised in Table 2.

Table 2: Main characteristics of the case study apartment building in Sehaileh, Lebanon.

Characteristic	Value
Period of analysis	50 years
Gross and (useful) floor area per apartment	154 m² (113 m²)
Number of apartments	8
Number of occupants per apartment	4
Basement storage tank material	Polyethylene
Basement storage tank volume	8 000 L
Header tanks material	Polyethylene
Header tanks volume (individual/total)	1 000 L / 9 000 L (including one distribution tank)
Water pump power rating	0.56 kW
Carted water as percentage of total water supply	32%[a]
Average mains water leakage	40%[a]
Primary energy conversion factor for electricity	3.8[b]

Note:

[a]from World Bank (2010); and

[b]from Stephan and Stephan (2014).

3.2 Overall research strategy

Figure 3 depicts the overall research strategy and data required at each step. The operational water demand of the case study building, which is supplied by a mix of mains and carted water, is first quantified. This is used to identify the main areas to reduce water use and to propose relevant water harvesting and management measures. For each of these measures, the life cycle water, energy and cost are quantified. Measures are also combined and their associated life cycle requirements are quantified. Finally, a sensitivity analysis is run to broaden the applicability of results and account for potential variability and uncertainty. The following sections describe how life cycle requirements are quantified before defining the various water harvesting and management strategies investigated.

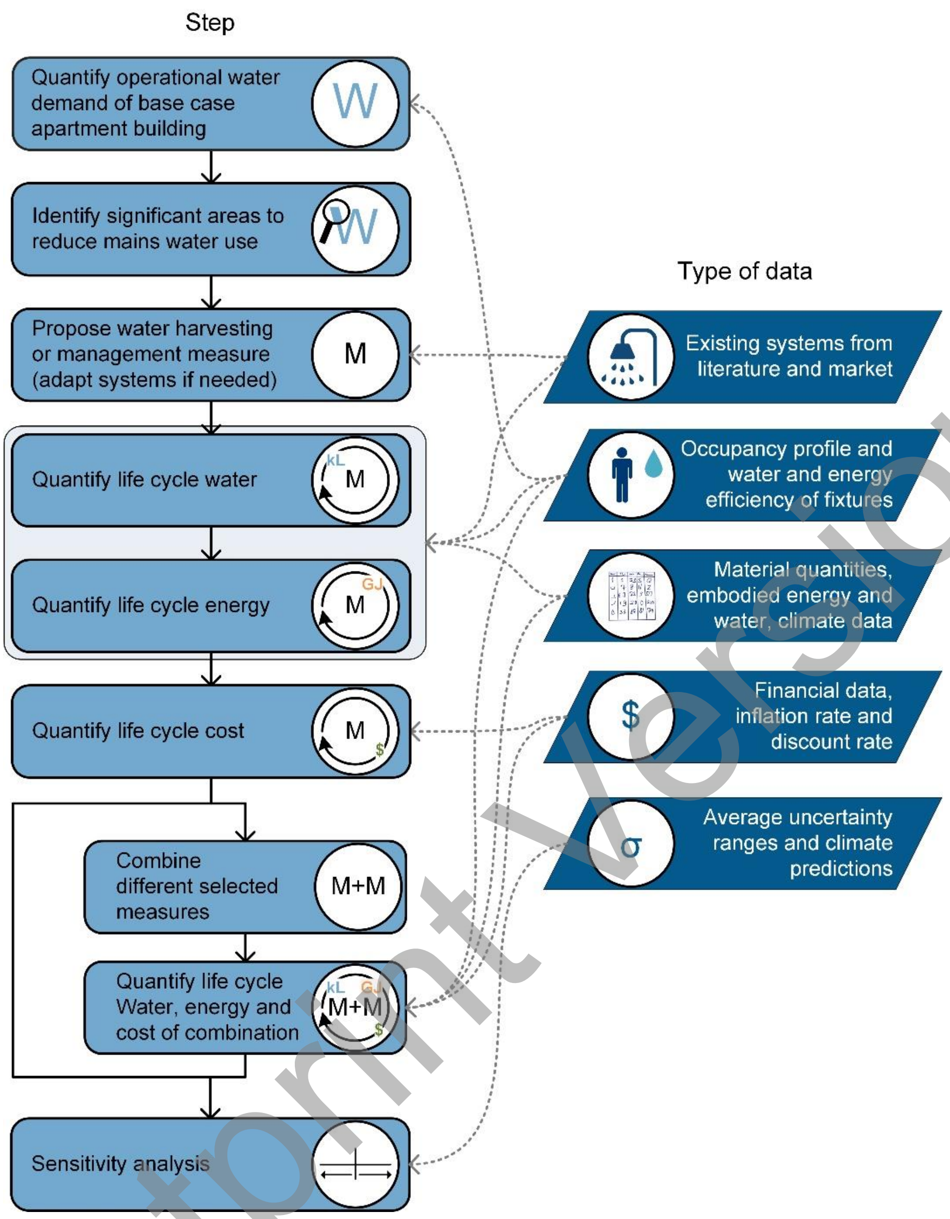

Figure 3: Overall research strategy and data requirements.

3.3 Life cycle water and energy demands

A life cycle assessment framework (International Standard 14040, 2006) is applied to the water system of the case study house. This takes into account water and energy inputs for raw material extraction, material manufacture, processing and transport, on-site installation, operation and maintenance. The end-of-life stage of different water system components, such as pumps or pipes is not taken into account because of the huge uncertainties regarding the fate of the systems and recycling technology, decades into the future (Angrill et al., 2011; Angrill et al., 2017). As noted in the aim and in Table 2, a period of analysis of 50 years is chosen for this study. This is based on previous life cycle assessment studies of rainwater harvesting systems (e.g.

Angrill et al. (2011) and Ghimire et al. (2014)) and to provide consistency with the previous life cycle assessment studies of the authors (Stephan & Stephan, 2014, 2016) on the same case study building.

Life cycle water requirements are calculated as the sum of embodied water (needed for raw material extraction, processing, manufacturing, construction and replacement of components and systems), operational water (delivered through mains by the central public supplier or by private carted water suppliers) and operational harvested water (harvested within the building, either from rainwater, condensate water or waste water treatment) requirements over 50 years. The net life cycle water difference between a water harvesting or management measure *M* and the BC is given by Equation 1.

$$\Delta LCW_M^{\mathrm{BC}} = \left(LCEW_M - LCEW^{\mathrm{BC}}\right) + \left(LCOPMCW_M - LCOPMCW^{\mathrm{BC}}\right) + \left(LCOPHW^{\mathrm{BC}} - LCOPHW_M\right) \quad (1)$$

Where: ΔLCW^{BC}_M = the difference in life cycle water demand between a water harvesting or management measure *M* and the base case scenario *BC*, in kL; *LCEW* = life cycle embodied water, in kL; *LCOPMCW* = life cycle operational mains/carted water demand, in kL; and *LCOPHW* = life cycle operational harvested water demand, in kL.

The net life cycle energy difference between a scenario and the BC is calculated as per Equation 2.

$$\Delta LCE_M^{\mathrm{BC}} = \left(LCEE_M - LCEE^{\mathrm{BC}}\right) + \left(LCOPE_M - LCOPE^{\mathrm{BC}}\right) \quad (2)$$

Where: ΔLCE^{BC}_M = the difference in life cycle energy demand between a water harvesting or management measure *M* and the base case scenario *BC*, in GJ; *LCEE* = life cycle embodied energy, in GJ and *LCOPE* = life cycle operational primary energy demand, in GJ.

The sections below describe the methods used to quantify each of the embodied and operational water and energy requirements.

3.3.1 Embodied water and energy

Embodied water and energy are quantified using the comprehensive input-output-based hybrid analysis technique developed by Graham J. Treloar (1997) and validated by Crawford (2008), compiled into a database of coefficients (G. J. Treloar & Crawford, 2010) and described in Stephan and Crawford (2014a) and Stephan and Crawford (2014b). This approach combines bottom-up process data and top-down economic input-output data to provide the most comprehensive system boundaries possible in terms of embodied requirements. It also takes into account capital investments in its input-output model, as described in Lenzen and Treloar (2004). For more details on hybrid life cycle inventories, please refer to Suh et al. (2004). The database and input-output-based hybrid analysis approach are chosen for two main reasons. Firstly, most existing inventory data typically rely on process analysis which is known to underestimate embodied requirements (Crawford, 2008, 2011; Dixit, Culp, & Fernández-Solís, 2013; Majeau-Bettez, Strømman, & Hertwich, 2011). Secondly, previous studies by the authors within a Lebanese context (Stephan & Stephan, 2014, 2016) have used the same hybrid database and it is important to ensure that the method is consistent between studies. Regardless, the potential uncertainty in embodied water and energy figures is discussed in the limitations.

Recurrent embodied water and energy, associated with the replacement of systems and materials, is also taken into account. This is done by using average material and system service lives, which are given for each component and measure in Appendix A.

3.3.2 Operational water

The common aspects related to the calculation of operational water are given below. For details related to a particular water harvesting or management measure, please refer to the relevant paragraph in Section 3.5 and to Appendix A.

WATER DEMAND

The average daily mains household water demand per capita in Lebanon has been estimated at 187 L and ~200 L by World Bank (2010) and Comair (2011), respectively. This is higher than in many countries such as Belgium (107 L/(capita·day) (Statistics Belgium, 2013)) or the Netherlands (118.9 L/(capita·day) (Van Thiel, 2014)), but lower than in Australia (219 L/(capita·day) (ABS, 2015)), Canada (251 L/(capita·day) (ECCC, 2016)) and the United States of America (379 L/(capita·day) (EPA, 2016)). Ideally, statistical data on the average water demand for each end-use, e.g. laundry or flushing, would be used to obtain specific water demands but these are not available for Lebanon, unlike in the developed economies mentioned above. Instead, the average daily water demands are used as target values and the operating schedules of the fixtures are adapted to reach this value, while relying on realistic estimates. Specific water requirements in terms of flow, flush volume or laundry requirements are based on installed fixtures and corresponding data from the comprehensive database of the water efficiency and labelling standards (WELS scheme, 2016), developed under AS/NZS 6400:2016 (2016). The water demand is assumed constant throughout the 50 years of analysis, within each measure, as is the case in most previous studies (inter alia Angrill et al., 2011; Devkota et al., 2015; Ghimire et al., 2014). The average daily water demand for a household of four is 754.6

L (see Table A.2, Appendix A for detailed water requirements per water fixture, for the BC) or 6 029 L/day for the entire building.

TANK SIZING

Typical tank sizes of 8 000 L and 1 000 L are used for the storage (one in common for all apartments) and header tanks (one for each apartment), respectively. These tanks are installed in the BC apartment building and are very representative of water distribution systems in Lebanese apartment buildings. Three additional tank sizes are used for the rainwater harvesting measure (4 000 L, 6 000 L and 8 000 L). These tank sizes are determined using the RainCycle software (readers are referred to Roebuck and Ashley (2007) for details) as in Angrill et al. (2011) and are determined based on both their efficiency (share of water demand covered) and the net present value of the measure, over 50 years. The software relies on a daily water balance throughout the year and 50 years of simulations were used. Tank efficiencies are reported in Section 4 but do not exceed 7%, notably due to the very high water demand. Please refer to Appendix A.2 for more details on tank sizing. While more detailed hourly software can provide more accurate results (e.g. Villarreal and Dixon (2005) or Agudelo-Vera et al. (2013)), a daily balance model is ideal for Lebanese conditions as water supply is intermittent and often random throughout the day.

3.3.3 Operational energy

The life cycle operational energy demand is calculated as per Equation (3), by multiplying the power rating of each system (e.g. pump or greywater treatment system) by its operation time over a year and by the primary energy factor associated with the energy vector used by the system (e.g. electricity). The resulting annual primary energy demand is assumed constant and is multiplied by the period of analysis.

$$LCOPE_M = POA \times \sum_{s=1}^{S} \underbrace{\underbrace{PR_{s,M} \times DOPT_{s,M} \times 3.6 \times 10^{-6} \times 365}_{ADE_{s,M}} \times PEF_s}_{APE_{s,M}} \tag{3}$$

Where: $LCOPE_M$ = Life cycle operational energy demand of measure M, in GJ; POA = period of analysis, in years; $PR_{s,M}$ = power rating of system s considered in measure M, in W; $DOPT_{s,M}$ = daily operational time of system s considered in measure M, in hours; PEF_s = primary energy conversion factor of the energy source associated with system s considered in measure M; $ADE_{s,M}$ = annual delivered energy demand of system s considered in measure M, in GJ; and $APE_{s,M}$ = annual primary energy demand of system s considered in measure M, in GJ.

This section has described the method used to quantify life cycle water and energy requirements. The next presents the calculation of life cycle cost requirements.

3.4 Life cycle cost requirements

The life cycle cost requirements are calculated in net present value (NPV) terms. For each water harvesting or management measure considered, the NPV is computed over 50 years, as per Equation (4), based on Berk and DeMarzo (2010). The NPV of each measure is calculated as the net difference with the base case scenario. A positive NPV means that the measure is economically worth pursuing.

$$NPV_M = \sum_{y=1}^{50} \frac{\left(\Delta Capex_{M,y} + ES_{M,y} + MWS_{M,y} + CWS_{M,y}\right) \times \left(1 + CPI\right)^y}{\left(1+r\right)^y} \quad (4)$$

Where:

NPV_M = The net present value of measure *M* compared to the base case BC over 50 years, in USD; *y* = a specific year; $\Delta Capex_{M,y}$ = the capital expenditure in year *y,* which is the difference between the investment for the considered measure *M* minus the investment for the base case *BC* on that specific year *y*, in USD; $ES_{M,y}$ = the delivered electricity savings in year *y,* which are the difference between the electricity spending for the considered measure *M* minus the electricity spending for the base case on that specific year *y*, in USD; $MWS_{M,y}$ = the mains water savings in year *y,* which are the difference between the mains water spending for the considered measure *M* minus the mains water spending for the base case on that specific year *y*, in USD; $CWS_{M,y}$ = carted water savings in year *y,* which are the difference between carted water spending for the considered measure *M* minus the carted water spending for the base case on that specific year *y*, in USD; *CPI* = the considered inflation rate (3.9%), which is computed as the average of the consumer price index (CPI) over the last 20 years, after the end of the civil war and return to normality, based on data from International Monetary Fund and the Central Administration of Statistics; and r = the discount rate. It is calculated as described in Appendix A of Stephan and Stephan (2016) and has a value of 12.2%.

It is assumed that the residual value of all plumbing material, systems, tanks, etc. is nil after 50 years, at the end of the period of analysis. The last replacement of any item is performed so that the end of its service life coincides with the end of the period of analysis.

Prices of plumbing components, tanks, water fixtures and systems are sourced from a market study conducted in November 2016 in Lebanon and are based on average retail prices from major suppliers. Tanks and plumbing material (pipes and accessories) are made in Lebanon, pumps are made in Italy, the greywater treatment system is made in China and water fixtures are made in Italy or China. However, the supply chains providing raw materials or processed components for manufacturing the systems and fixtures above are often and increasingly global (Wiedmann, Wilting, Lenzen, Lutter, & Palm, 2011) This makes the very concept of ‘made in “country X”’ obsolete as highlighted by the recent ‘made in the world’ campaign of the World Trade Organisation (2016).

Electricity tariffs for the state owned Electricité du Liban (EdL) are based on current official figures which are given in Table 3. Since the state electricity supply is also intermittent and covers only 75% of the demand (MEW, 2010). Private neighbourhood generators are widespread in Lebanon. The average generator fee for a standard connection (5 Amperes) is calculated as the average of monthly figures over three years (2014-2016) in the Zouk-Mosbeh area, Mount-Lebanon. These are presented in Table 4.

All prices include tax and are corrected for inflation over 50 years. The price of components replaced over the period of analysis is also indexed based on the year of replacement. For instance, the life cycle cost of a pump replaced every 10 years is the sum of its current price, its price in 2027, 2037, 2047 and 2057 as well as the associated electricity use.

Table 3: Average monthly electricity prices in Lebanon as of 2016, in USD/kWh.

Electricity demand (kWh/month)	Cost (USD/kWh)
0-100	0.0255
100-300	0.0401
300-400	0.0584
400-500	0.0876
>500	0.146

Table 4: Average generator monthly tariff for a 5 A connection in Zouk-Mosbeh, Lebanon for 2014-2016, in USD

Average price for a 5 A connection (USD)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average
2014	66	67	67	47	47	84	93	97	90	90	66	57	72.6
2015	62	62	45	45	50	50	73	70	79	54	40	46	56.3
2016	53	37	33	30	30	44	54	63	43	40	40	57	43.7
Average	57.53 USD												
Specific price[a]	0.218 USD/kWh												

Note: [a]The specific price is based on the assumption of full capacity use (5 A ≡ 1.1 kW) for the entire time the generator is on over 30 days (8 h/day as in Stephan and Stephan (2014)). This gives: 1.1 × 8 × 30 = 264 kWh of generator energy per month. The price is therefore: 57.53/264 = 0.218 USD/kWh, which is 20.8% lower than what was used in Stephan and Stephan (2016) based on 2014 data only, revealing significant variation in private generator tariffs over the course of 3 years. This reduction in prices is largely due to the worldwide drop in oil prices which drive the price of diesel used to operate private generators.

3.5 Selected sustainable water harvesting and management strategies

Four main water harvesting and management measures are considered in this paper (see Figure 4 which is inspired by Legget, Brown, Brewer, Stanfield, and Holliday (2001, p. 38) and Roebuck et al. (2011, p. 356)) along with three of their combinations. The main measures are categorised into harvesting water locally (two measures), minimising the demand flow (one measure) and minimising the waste flow (one measure). This categorisation follows the metabolic approach of Agudelo-Vera et al. (2013). This section describes all measures considered for the entire apartment building. Measures are based on available technologies. Redesigns to the building floor plan to increase the catchment area are not considered to maintain a representative case study building and to maintain comparability. Details for each measure are provided in Appendix A.

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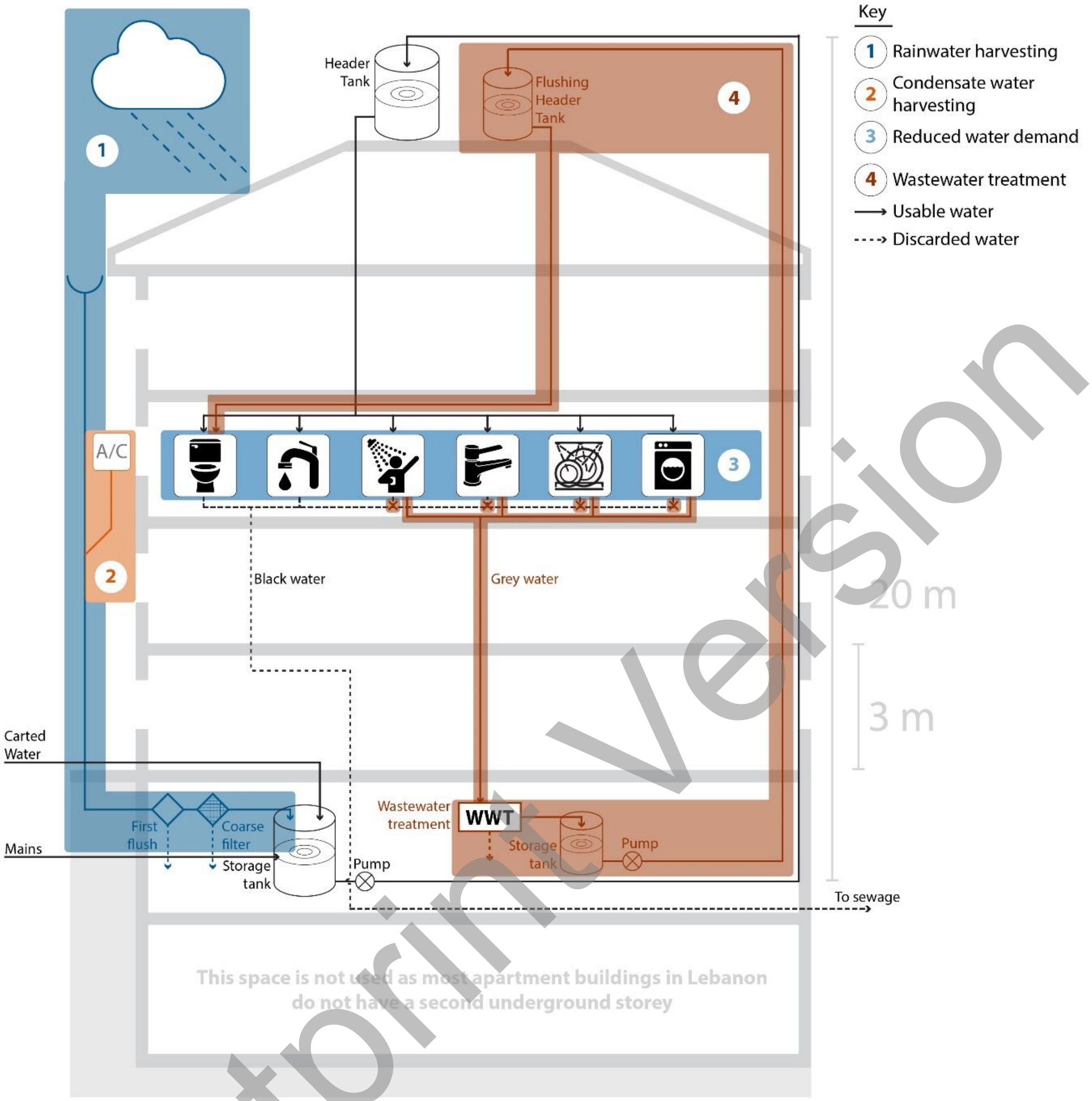

385 *Figure 4: Base case water system (in black) and considered water harvesting and management measures.*
386 *Note: A/C: air conditioning; systems are not to scale; original in colour. Inspired by Legget et al. (2001, p. 38)*
387 *and Roebuck et al. (2011, p. 356).*

388 ### 3.5.1 Rainwater harvesting

389 The first measure *RWH* consists of rainwater harvesting. This is the focus of most existing studies on the
390 topic of efficient water use in buildings. Rainwater harvesting (from roads and greenhouses) has been
391 identified as the most relevant technology to improve water use patterns in light of climate change in Lebanon
392 (MOE/UNEP/UNDP, 2012). Furthermore, rainwater harvesting at the building scale is particularly attractive
393 in a Lebanese context as most of the required additional systems are already installed, namely a storage
394 tank connected to a header tank through a pump and a piping system.

The *RWH* measure consists of deviating the roof drainage pipes to a first flush system and through a coarse filter to improve water quality (see Figure 4→①). The first flush and filtration are adopted as they significantly improve water quality as demonstrated in Mendez et al. (2011). The same authors show that tiles are good candidates as a roofing material in terms of resulting harvested rainwater quality. Harvested rainwater is not treated any further as by this stage, its water quality is expected to probably exceed that of mains water or private carted water in Lebanon which is not treated at all. More information about this measure can be found in Section A.2, Appendix A.

3.5.2 Condensate water harvesting

The second measure *CWH* also focuses on locally sourcing water by capturing condensate water from air conditioning units in summer (see Figure 4→②). This measure is highly complementary to rainwater harvesting as there is no rain during all summer months in the Lebanese climate and many other Mediterranean climates. With high relative humidity, significant amounts of condensate water can be harvested (Loveless, Farooq, & Ghaffour, 2012). For instance, Mahvi, Alipour, and Rezaei (2013) reported that home air conditioners in Bandar Abbas, Iran, on the Persian Gulf, generated on average 36 L/day of water that is suitable for non-potable domestic use. The high quality of condensate water is further confirmed by Loveless et al. (2012) who studied harvested condensate water across different sites in Saudi Arabia. They found that the quality of condensate water 'is close to that of distilled water'.

With the large majority of new apartment buildings equipped with air conditioning units in Lebanon, and a high relative humidity throughout summer in the Beirut and Mount Lebanon area (70-75% (UNDP/GEF/MPWT/DGU, 2005)), there is a local water harvesting potential in collecting condensate water.

The daily volume of condensate water is calculated as per Equation (5), by multiplying the average condensate water production per hour of an air conditioning compressor by its operating hours during the summer months, for every air conditioning unit.

$$DCWV_b = \sum_{ac=1}^{AC} CWP_{ac,b} \times OPH_{ac,b} \quad (5)$$

Where $DCWV_b$ = Daily condensate water volume for building *b*, in L; *ac* = an air conditioning unit that is switched on; $CWP_{ac,b}$ = condensate water production of air conditioning unit *ac* installed in building *b*, in L/hour; and $OPH_{ac,b}$ = number of operating hours of air conditioning unit *ac* installed in building *b*, in hours.

Data regarding the number of air conditioning units installed in every apartment and their operating time were sourced directly from Technical Enterprises Co. which designed, built and manages the building. The condensate water production rate was measured by the authors over a period of two weeks on typical air conditioning units (9 000 British Thermal Units or ~2.64 kW). The average production rate was 1.23 L/h with an average humidity of 64%, an average outdoor temperature of 29.5°C and a set temperature of 21°C. The standard deviation of the generation rate was ±0.22 L/h. For this reason, a lower boundary value of 1 L/h is used in this study. This is in line with values suggested by the Alliance for Water Efficiency (2016). The details of this measure can be found in Section A.3, Appendix A.

3.5.3 Reducing the water demand of households

The third investigated measure *RWD* consists of reducing the water demand of households by installing water efficient fixtures such as dual flush toilets, aerated flow taps, efficient washing machines and dishwashers and low-flow shower heads (see Figure 4→③). The operation schedules are left untouched as consistently modifying the behaviour of all occupants is considered unrealistic within the scope of this study. The replacement rate of water efficient fixtures is considered the same as for typical fixtures and aligned with the considered replacement rate for pipes, i.e. 25 years. Additional information about the data used for this measure is in Section A.4, Appendix A.

3.5.4 Treating wastewater

The fourth measure *WWT* separates and recycles greywater and uses it for flushing. A separate water system is installed with one extra storage and one header tank for all apartments (see Figure 4→④). The wastewater treatment plant contains an ultraviolet lamp for sterilisation and disinfection, rendering the recycled water suitable for toilet flushing. An additional chlorination process through in-tank chlorine tablets is also considered to ensure that the water is safe to use. Such tablets are already often used in Lebanon for household water storage tanks.

The material composition of the wastewater treatment plant was obtained from the manufacturer, along with the average service life of subcomponents such as filters, membranes and others, providing reliable data. All material quantities and other information can be found in Section A.5, Appendix A.

3.5.5 Combining multiple measures

Three different combinations of the four aforementioned measures are tested in order to investigate potential synergies and resulting life cycle benefits. The investigated combinations consider rainwater and condensate water harvesting (*RWH+CWH*), rainwater, condensate water harvesting and a reduced water demand (*RWH+CWH+RWD*) and all measures (*ALL*). The supporting information for these combinations is provided in Sections A.6, A.7 and A.8, Appendix A, respectively.

4 Results

This section presents the results of the study. All figures are quantified for the entire apartment building (8 apartment units and 32 occupants) over 50 years. Results are expressed in kL (or m^3) of water, GJ of primary energy and in USD for cost. All quantities are in comparison to the base case which is referred to as *BC*.

Figure 5 represents the life cycle water, energy and cost of each investigated measure. Negative life cycle water or energy demands represent water and energy savings while a negative net present value represents a cost. Therefore, measures that results in the largest water saving and the highest net present value (while ideally also saving energy) provide both environmental and financial benefits. In addition, Figure 6 displays the average energy intensity and financial value of each kL of water saved, for all investigated measures. This improves the comparability of measures by normalising the results per unit of water saved.

A common observation for all measures is the relative insignificance of embodied water and energy requirements in comparison to operational requirements. In terms of life cycle water balance, all measures pay back their embodied water extremely quickly, regardless of the high leakage volume on the Lebanese water network.

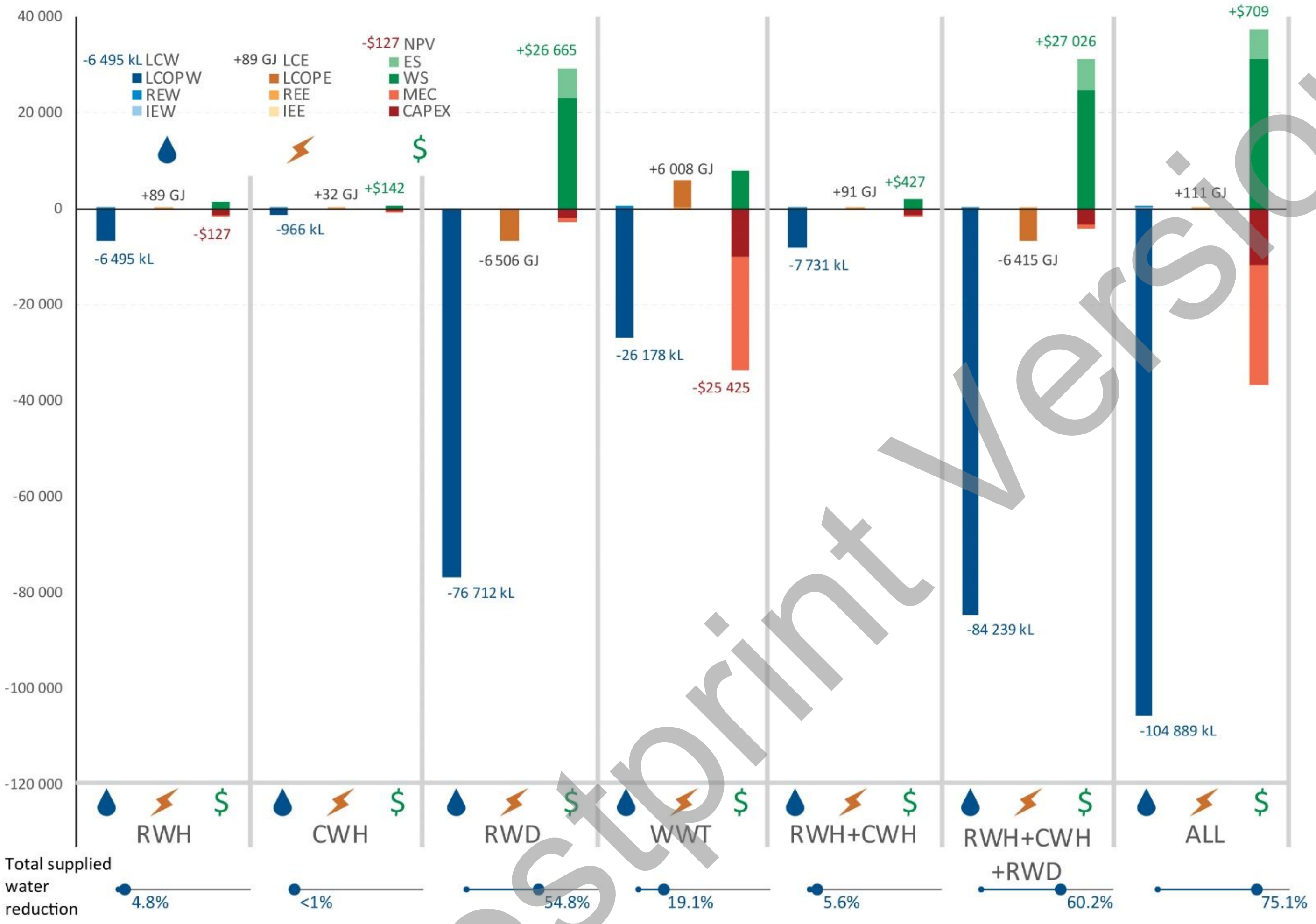

Figure 5: Life cycle water, energy and cost analysis of investigated measures over 50 years. Note: IE = Initial embodied; RE = recurrent embodied; OP = operational; LC= life cycle; W = water in kL; E = energy in GJ; CAPEX = capital expenditure; MEC = Maintenance (and electricity) costs; WS = water cost savings; ES = energy cost savings; and NPV = net present value in USD. A negative life cycle water or energy balance represents savings while a positive NPV reflects financial savings.

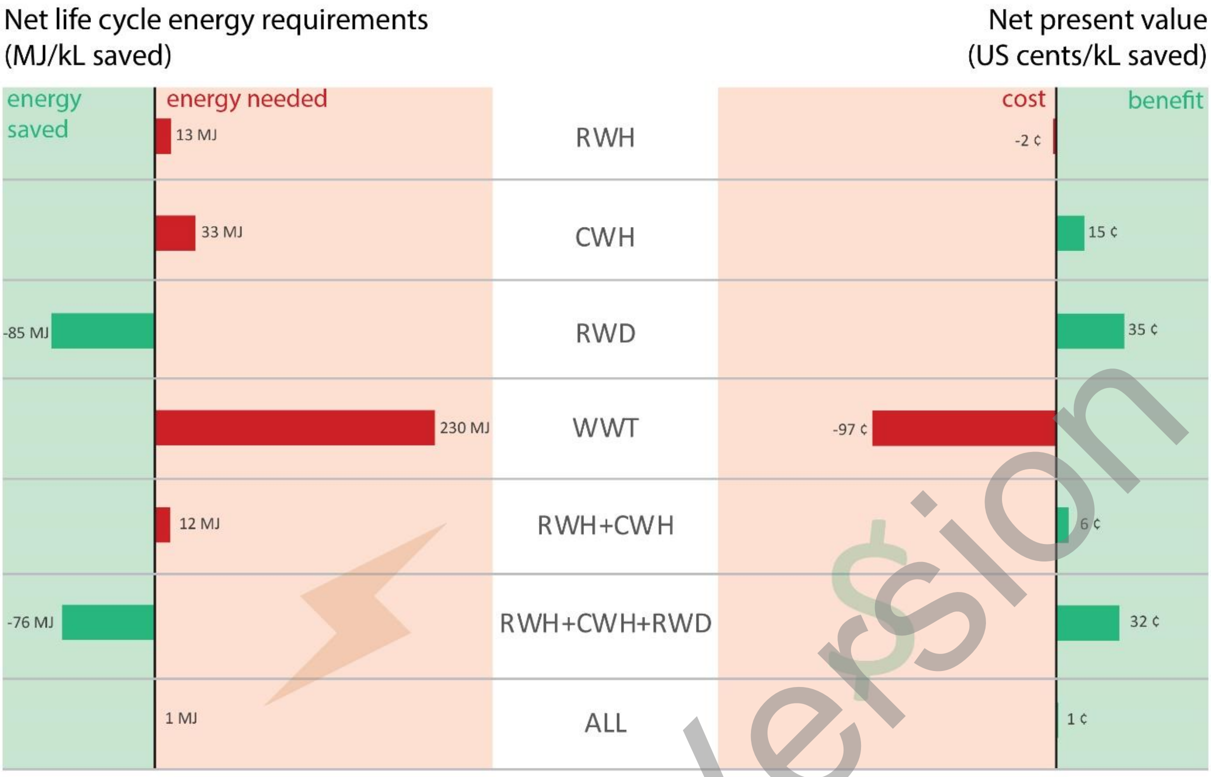

Figure 6: Net life cycle energy requirements and net present value per kilolitre of saved supply water over 50 years, by measure.

The rainwater (*RWH*) and condensate water harvesting (*CWH*) measures can cover only a small share of the water demand, i.e. 4.8% and less than 1%, respectively. Even when increasing the tank size from 4 000 L to 6 000 L and 8 000 L, the share of water demand covered by rainwater increases only to 5.8% and 6.4%, respectively. If only toilet flushing and laundry were considered, the share of water demand covered by rainwater would rise to 24%, 29% and 31%, for the 4 000 L, 6 000 L and 8 000 L tanks, respectively. It is interesting to note that *RWH* does not result in net financial savings (regardless of the rainwater tank size) despite the fact that most of the system (collector and header tanks, pump and piping) is already installed (see Section 3.1). This can be explained by two main factors: (1) the inadequate fixed fee pricing for the mains water in Lebanon which translates in a very low price per litre; and (2) because rainwater harvesting tends to replace mostly cheap mains water, when it is available in winter rainy months. Conversely, *CWH* replaces mostly costly carted water in the dry summer months and is therefore more valuable. It is ranked second among measures in terms of financial savings (15 ¢/kL).

The most cost-effective measure is to reduce the water demand (*RWD*) through the installation of efficient fixtures. This reduces the need for supplied water by 54.8% compared to the *BC*, saves 6 506 GJ in primary energy and associated emissions over 50 years and saves 26 665 USD. *RWD* is also the most cost-effective (35 ¢ saved/kL saved) and energy saving (85 MJ saved/kL saved).

The wastewater treatment measure (*WWT*) is the costliest and most energy intensive. While it can reduce the supplied water demand by up to 19.1%, its associated capital and maintenance costs are very high and result in a net present value of -25 425 USD over 50 years compared to the *BC*. On a per kL basis, *WWT* has the lowest performance. It costs 95 ¢ per kL of water saved and requires 225 MJ/kL, 95% of this in terms of operational energy for the plant and the pump.

However, while assessing single measures allow a systematic evaluation, the combination of measures can provide compounding effects and result in higher water savings. Combining the two water harvesting measures in *RWH+CWH* covers 5.8% of the *BC* water demand, saves 6 ¢/kL saved and requires only 12 MJ/kL saved (compared to 13 MJ and 33 MJ for *RWH* and *CWH*, respectively). Using the same piping system for both measures saves on materials, capital expenditure and embodied energy. There is arguably more value to local water harvesting measures as the widespread development of these systems can reduce infrastructure costs and maintenance. This is discussed in Section 5.

The most effective combination consists of harvesting water locally while reducing the water demand (*RWH+CWH+RWD*). This reduces the supplied water demand by 60.2% compared to the *BC* and saves 84 239 kL of water over 50 years (1 685 kL/year). This means that two apartment buildings that implement these measures use, together, less than the *BC* building. Furthermore, this combination results in significant net energy savings through a reduced electricity demand for appliances and also for pumping water from the storage to the header tank (see Figure 4). The 6 415 GJ of primary energy saved represents 14.7% of the life cycle operational household energy demand of the entire building (43 615 GJ) as calculated in Stephan and Stephan (2014). Finally, *RWH+CWH+RWD* saves 27 206 USD over 50 years or 32 ¢/kL saved.

Combining all measures together can reduce the supplied water demand by up to 75% compared to the BC. This equates to 104 889 kL over 50 years or enough water to fill 42 Olympic swimming pools. By combining all measures, the costs and energy needs associated with *WWT* are counter-balanced by the benefits and energy savings of the other measures. This results in negligible energy requirements (1 MJ/kL saved) and a very small benefit of 1¢/kL saved.

4.1 Sensitivity analysis

Any model suffers from uncertainty, and notably life cycle cost assessments. This is due to the unforeseeable nature of financial indicators (Berk & DeMarzo, 2010). This study relies on a high discount rate of 12.2%, as calculated in Stephan and Stephan (2016). This matches the risk profile of Lebanon. Previous studies that focus on the life cycle costing of water harvesting and management measures typically use a much lower discount rate, e.g. 2.7% (Devkota et al., 2015). Among the investigated studies, only Roebuck et al. (2011) and Anand and Apul (2011) use a range of different discount rates. In this study, two other inflation (CPI) and discount (r) rates pairs are evaluated, namely CPI=2% and r=3% and CPI=4.1% and r=15%. These values are the same as in Stephan and Stephan (2016) for consistency.

Another main parameter varied is the ratio of mains water to the total. This ratio affects the price of water as mains water is much cheaper than carted water. In addition to the base ratio of 68% mains, two other ratios are considered: 50% and 100%. While the 50% figure represents a worst case scenario, the 100% scenario simulates the conventional situation in most developed economies. In addition, this scenario tests a recently rolled out water pricing scheme in Lebanon that meters water use and charges 0.55 USD/kL.

The sensitivity analysis also tests the influence of rainfall on the results. Three variations are considered: a dry year with 600 mm of rainfall, a wet year with 1 000 mm of rainfall and a so-called 'climate change' annual rainfall of 450 mm. The dry and wet year rainfall are based on longitudinal data over 75 years from MOA (2003). The climate change rainfall is based on a 40% reduction in rainfall based on MOE (2011).

In addition, the variability in the base case water demand is taken into account. A ±30% deviation in the water demand schedule, that is the operation time of appliances and the number of uses per day, is tested. This is to represent the wide variability that is present between households of the same size.

Finally, these sensitivity analysis variations are combined into four different scenarios in order to explore the entire variability and uncertainty space. These are chosen to result in the highest and lowest net present value and the highest and lowest water savings.

Figure 7 represents the sensitivity of results to the investigated parametric variations. Each measure is depicted by a central black dot which represents its base net present value (NPV) and life cycle water saving potential (LCWS). All variations spring from this central black dot and radiate in various directions. The estimated deviation space is then depicted as a shaded area that connects the most spread modelled deviations. Note that the graph is zoomed in on the *RWH*, *CWH* and *RWH+CWH* measures for clarity. Figure 7 contains a significant amount of information and only the three major observations are discussed below.

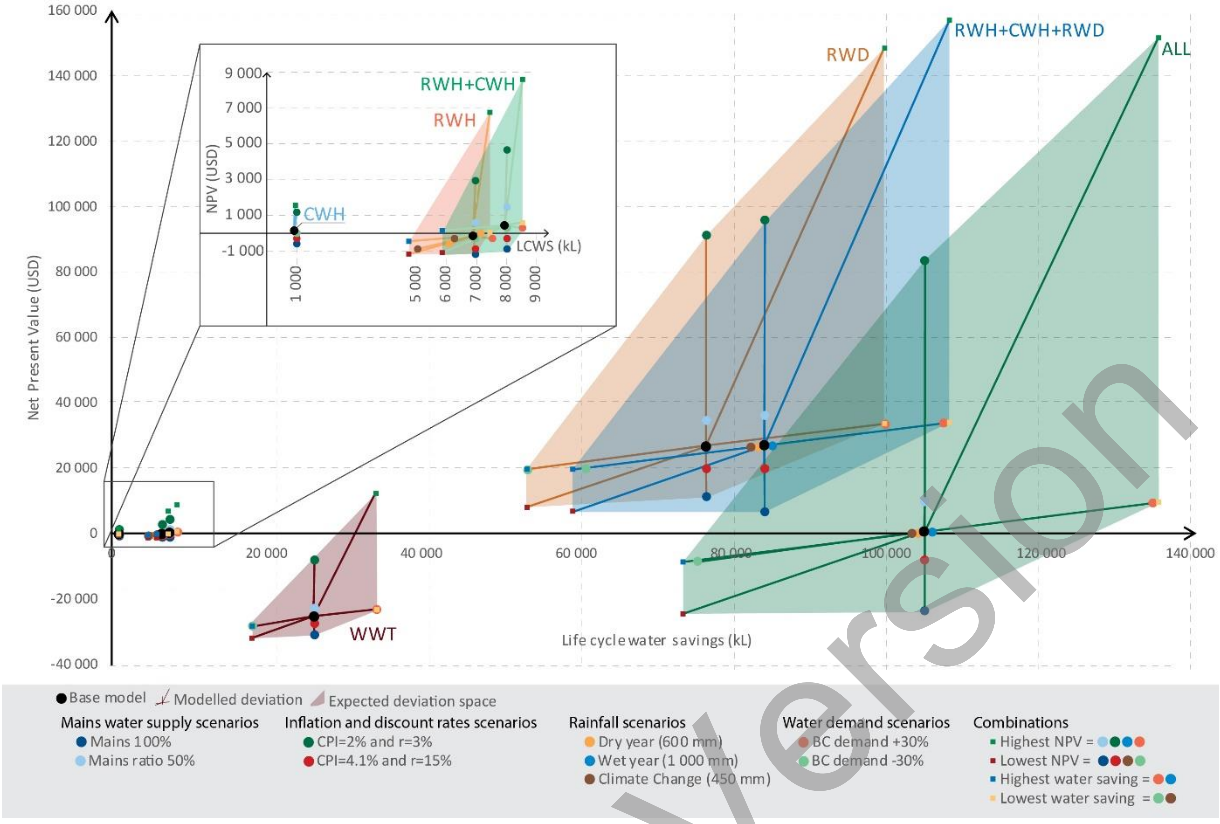

Figure 7: Sensitivity analysis of the results to variations in in the share of mains water supply, inflation and discount rates, rainfall and water demand. Note: NPV = net present value, in USD, LCWS = life cycle water savings, in kL; BC = base case. All other acronyms refer to the investigated measures, see Section 3.5. Original in colour.

Firstly, the *RWD* and *RWH+CWH+RWD* measures save water and are profitable regardless of the uncertainty and variability in water prices, inflation and discount rates, rainfall and water demand. This clearly reveals that water conservation should be favoured as a top priority to reduce water demand and energy use while saving money for users.

Secondly, the *WWT* measure remains unprofitable in all variations except in the most financially favourable environment. This means that this measure, which can yield significant water savings should be either subsidised or deployed at a larger scale to benefit from economies of scale. Increasing the price of water can help improve financial performance but not enough to make the measure profitable. The average water price would need to reach ~6.5 USD/kL for this measure to have an NPV of 0 USD.

Thirdly, it is important to note that the variations investigated do not consider feedback effects between parameters. For example, the climate change rainfall variation does not factor in the probable increase in water prices that would result from a significant reduction in rainfall. Further analysis, such as separating the water price inflation from the general inflation rate (taken from the consumer price index) would help better inform decisions around water pricing. This would however need to be quantified using a model that accounts for supply and demand linkages. A scarcity-driven increase in the price of water would tend to result in a reduced demand and vice versa. This reveals the complexity of forecasting such parameters, notably due to large uncertainty in quantifying these linkages. This forecasting is not considered because it is out of the scope of this paper, but would constitute a relevant research endeavour in the Eastern Mediterranean context and beyond.

Interestingly, the newly adopted pricing scheme that is being rolled out in Lebanon, and which comprises one fixed connection fee and a consumption-related component based on a water price of 0.55 USD/kL results in the lowest NPV (bottom blue dot of all measures). This means that this scheme is inadequate and the water price should be increased to incentivise water saving measures.

5 Discussion

The discussion section is divided into four parts. Section 5.1 presents the contribution of this paper in light of previous studies combining life cycle assessment and life cycle cost analysis of water harvesting and management measures in buildings. Section 5.2 discusses the practical implications of the findings in terms of policy and guidelines. Section 5.3 discusses the applicability of the results in other countries. Section 5.4 presents the limitations of this study and outlines future research directions.

5.1 Contribution

This study provides one of the most comprehensive life cycle assessments of water harvesting and conservation measures, covering water, energy and financial requirements over 50 years. The use of detailed bill of material quantities, including piping accessories and filters, as well as the consideration of material replacement, maintenance and labour costs provides a very detailed modelling, as recommended in Roebuck et al. (2011). All supporting data is included for transparency as advocated for by Säynäjoki, Heinonen, Junnila, and Horvath (2017). The breadth of measures considered, the depth of the analysis and the multiple life cycle indicators considered contribute to a more integrated approach to reducing life cycle water use in buildings, compared to most existing studies (see Section 2), e.g. Villarreal and Dixon (2005), Angrill et al. (2011), Ward et al. (2012), Ghimire et al. (2014) and Devkota et al. (2015). The use of a case study apartment building also provides complementary insights to the typical focus on either detached houses or office buildings (see Table 1).

Results reveal that life cycle embodied water requirements are insignificant in comparison to the water savings that rainwater systems and water efficient fixtures and appliances provide. Embodied energy requirements are also very small in comparison to operational requirements, as shown for greenhouse gas emissions by Sharma, Grant, Grant, Pamminger, and Opray (2009), at the urban water service level. This is despite using comprehensive system boundaries through hybrid analysis (Majeau-Bettez et al., 2011; Suh et al., 2004) in the life cycle inventory. However, when expressing results on a per kL of water saved basis, embodied energy requirements should be considered as evidenced by the 13 MJ, 33 MJ and 12 MJ per kilolitre of water saved in the rainwater harvesting (*RWH*), condensate water harvesting (*CWH*), and waste water treatment (*WWT*) measures, respectively. These figures are larger than the 5.8 MJ/kL reported by Ghimire et al. (2014) for a domestic rainwater harvesting system for a detached family home in Virginia, USA. When including operational energy, they are also larger than the 4 kWh/m³ (14.4 MJ/kL) reported by Morales-Pinzón et al. (2012), in a Spanish context, or the average energy intensities (0.8-5 MJ/kL) reported for conventional and recycled water supply in the review conducted by Vieira et al. (2014). The more comprehensive hybrid life cycle inventory data as well as the use of the actual pump and waste water treatment plant energy ratings are likely to cause these higher energy intensities.

From a financial perspective, the price of water is the major determinant regarding the performance of water harvesting and conservation measures. Results show that rainwater harvesting is not cost effective in most cases (see Figure 7) because of the low price of water. This is further discussed in the policy recommendations below.

It is important to highlight that the *CWH* and *RWH+CWH* measures result in cost savings while requiring energy for every kL saved, all of which is embodied energy. A decision maker would have to priorities between either embodied energy use, or water and money savings. From a life cycle assessment perspective, weighting would intervene in this situation (Finnveden et al., 2009) and this would depend on the goal of the measure. The fact that embodied energy is used across a global supply chain makes it very hard to integrate in a decision making process at a local level. There is a need for more integrated carbon taxing schemes that are capable of capturing embodied energy and associated emissions (Bordigoni, Hita, & Le Blanc, 2012). This will increase the complexity of decision-making and shifting impacts (e.g. trading water savings for energy and emissions) but would also better reflect reality.

In addition to the above, this study contributes to building knowledge within the Eastern Mediterranean region which is expected to be severely hit by climate change and a reduction in rainfall (MOA, 2003; MOE, 2011; MOE/UNEP/UNDP, 2012). By focusing on reducing the water demand at an apartment building scale, this study complements the analysis conducted by the World Bank (2010) at the public sector scale and recommends measures such as reducing water leakage on distribution networks and increasing the reservoir capacity. It also answers the call for *'improving the availability of accurate and consistent information* […]' (World Bank, 2010, p. 52). The findings of this study are translated into policy recommendations below.

5.2 Policy recommendations

Four main recommendations can be drawn from the findings of this study, including incentivising water conservation, revising water pricing, supporting rainwater harvesting and its multiple benefits and further investigating wastewater treatment plants.

Firstly, reducing the water demand through water conservation is the single most cost-effective and energy saving measure, regardless of uncertainty and variability in a range of parameters and despite the low water price in Lebanon. Saving more than 50% of the base case water demand, the *RWD* measure should be the top priority of water policy, in Lebanon and potentially elsewhere. More importantly, the modelled water conservation measure in this study does not rely on any behavioural change and is achieved through more efficient fixtures and appliances only. Authorities are highly encouraged to phase out inefficient water fixtures and appliances from the market. New buildings should be systematically equipped with water efficient fixtures and appliances as theses come at a minor additional capital cost and very quickly payback the extra investment through reduced water and energy bills. The cost-effectiveness of this measure increases if water is correctly priced.

Secondly, the current water pricing scheme in Lebanon is disconnected from its water supply and demand profile, infrastructure and forecasted climate. The fixed fee and unlimited water use scheme, when mains water is available, does not reflect the dwindling availability of the resource in light of the increasing demand (World Bank, 2010) and does not incentivise water savings. The recent move to metered water use is a very positive step in addressing this issue but the set price of 0.55 USD/kL is too low to incentivise water savings.

Under this scheme, all rainwater harvesting measures, regardless of tank size, result in financial losses. A higher price of mains water, with a minimum of 1.2 USD/kL is needed to make the *RWH* and *CWH* measures financially attractive (in case the availability of mains water increases to cover 100% of water requirements and no carted water is used). Using higher water prices can be an effective mechanism to reduce demand (Dinar, Pochat, & Albiac-Murillo, 2015; Grafton, Chu, & Kompas, 2015; Molinos-Senante & Donoso, 2016). However, we argue for a varied water price based on both season and demand. Seasonal water pricing has been discussed by many scholars, such as Sibly (2006), Grafton and Peterson (2007) and Grafton and Kompas (2007) in an Australian context. It is highly relevant for the climatic conditions of Lebanon, the Eastern Mediterranean and the entire Mediterranean basin which is typically characterised by highly differentiated rainfall between the winter (wet) and summer months (dry) as well as many microclimates (UNEP/MAP/ MED POL, 2003). By adopting two seasonal price tags that reflect the availability of water, a more environmentally-conscious water use can be promoted and the water scarcity aspect will be valued and captured in the price. Taking a thirty-minutes shower has much less impact on water reserves if it is raining outside compared to doing so in the middle of a three-month dry period. This is further exacerbated by the typical influx of tourists in summer months around the Mediterranean (Eurostat, 2017c), which imposes an additional water demand during the dry period. Although this influx has been affected by conflict in the East Mediterranean and North Africa from 2011 to date (2017) (Eurostat, 2017b), its contribution to GDP (gross domestic product) is projected to increase across the basin by more than 25% by 2026 (WTTC, 2016), highlighting the significance of seasonal water management and pricing schemes. Furthermore, in order to incentivise water saving measures, the price of water could also be incremented based on demand. The effectiveness of an incremental pricing scheme has already been demonstrated (see Molinos-Senante and Donoso (2016) for an example from Chile). Incremental pricing is already used for electricity in Lebanon (see Table 3) and the scheme could be easily replicated for water. A metered, seasonal and demand-driven water pricing scheme would significantly improve the financial benefits of water harvesting and conservation measures (this corresponds to moving upwards on the NPV axis in Figure 7). Out of the investigated measures, rainwater harvesting benefits most from a revised water price, moving its NPV from negative to highly positive. However, the benefits of rainwater harvesting span well beyond the financial performance of apartment buildings.

Rainwater harvesting should be incentivised by the authorities, as highlighted in most existing studies on the topic (e.g. Zhang, Chen, Chen, and Ashbolt (2009)), not only because of mains (and potentially carted) water savings at the household level, but most importantly because of its additional benefits. These include mitigating stormwater floods and runoff and potentially downsizing water distribution networks if widely deployed ((Marlow et al., 2013)). These co-benefits are significant in the Lebanese context which is characterised by widespread impervious surfaces due to uncontrolled urbanisation, steep sloping mountains that channel water towards the sea and the lack of water reservoirs (World Bank, 2010). It is common to observe 40 cm deep stormwater channels on the roads, draining towards the sea during heavy rain. Capturing a large share of this water would help reduce flood risks, infrastructure degradation and cover a share of the household water use. For these reasons, rainwater harvesting could be subsidised as it provides significant public value. Installing a wastewater treatment plant can help reduce the mains water demand even more than rainwater harvesting, but it is still currently very expensive.

As shown in Figures 4, 5 and 6, a greywater treatment plant for an apartment building of four storeys does not seem to be cost-effective. This is in contrast to the findings of Stec and Kordana (2015) in a Polish context. Furthermore, it requires up to 8 353 kWh of delivered electricity or 112.3 GJ of primary energy per year for its operation. Knowing that electricity in Lebanon is generated mostly with heavy fuel oil and diesel generators (MEW, 2010) which result in significant amounts of greenhouse gas emissions and the release of pollutants (MOE, 2011), this additional operational energy use needs to be weighed against water savings. A potential solution would be to install a solar photovoltaic array that powers the wastewater treatment system but further studies on the life cycle environmental and financial performance of this alternative need to be conducted as non-subsidised photovoltaic systems might not be cost-effective in a Lebanese context (Stephan & Stephan, 2016). Furthermore, the expected reduction in rainfall due to climate change can significantly modify the price of water and the value of water recycling in coming years. Although the benefits of installing wastewater treatment plants in apartment buildings are currently mitigated by low water prices, polluting electricity generation and economic considerations, separating grey and black water in new apartment buildings should still be considered. It comes at a low capital cost (~1 000 USD for the entire building) and allows for the subsequent installation of a wastewater treatment plant in the building or at the precinct level, should conditions become favourable.

Finally, these policy recommendations can also be translated into guidelines for developers of new apartment buildings. Based on results depicted in Figure 5, developers are encouraged to:

1. Systematically install the most water efficient fixtures and potentially appliances;
2. Install rainwater and condensate water harvesting collection systems; and
3. Make provisions for the installation of wastewater treatment plants by separating black and grey water collection.

5.3 Applicability of results in other countries

This study is applied to the Lebanese context and is therefore relevant to its particular economy, its rainfall pattern, its water distribution network and water pricing. However, a number of findings can be applied to different countries.

The cost-effectiveness of the water conservation measure and the limited fraction of water demand covered by rainwater harvesting are two aspects that are expected to hold true in many other countries with a similar rainfall pattern and apartment building typology such as parts of Cyprus, Greece, Israel, Italy, Jordan, Spain, Syria, Tunisia and Turkey. The consideration of different annual rainfall levels also improves the applicability of findings in these contexts. For these reasons, the proposed seasonal water pricing scheme would be relevant across the Mediterranean basin and can contribute to reconnecting people with their water cycle and reserves.

Furthermore, the sensitivity analysis conducted significantly extends the applicability of the results as it covers a broad range of economic contexts and water demands. For instance, the low inflation and discount rates result in a positive net present value for the greywater treatment plant (*WWT*) measure. Similarly, the potential variation in the initial base case water demand of ±30% spans a daily water demand of 135-245 L/capita, covering a range of different potential water demands in neighbouring countries.

5.4 Limitations and future research

As any scientific endeavour, this study suffers from a number of limitations. Firstly, results are relevant for the case study building only, although it is representative of typical apartment buildings in Lebanon and the region. Secondly, potential technological breakthroughs within a 50 years timeframe are not considered. This could be modelled using projection scenarios as detailed in Pesonen et al. (2000) but it falls outside the scope of this paper. Thirdly, the recurrent costs and embodied requirements are based on current figures and therefore suffer from a high level of uncertainty. This limitation is systematic in life cycle cost analysis. Fourthly, this study relies on Australian hybrid data for the quantification of embodied water and energy. By applying an uncertainty range of ±40% to embodied energy figures (as is typical for hybrid life cycle inventories based on Crawford (2011)), the embodied energy intensity of *RWH* and *CWH* varies between 7.8-18.2 MJ/kL saved and 19.8-46.2 MJ/kL saved, respectively. Where a measure involves additional or reduced operational energy use, the effect of uncertainty in embodied energy figures is minimal. For example, the energy intensity of the *WWT* measure varies between 225-234 MJ/kL saved (±2%) as embodied requirements are dwarfed by operational requirements. Regardless of uncertainty in embodied energy figures, the ranking of measures by energy intensity is not affected. A more detailed discussion on the implications of using Australian data in a Lebanese context can be found in Stephan and Stephan (2014), who highlight the difficulties of quantifying embodied requirements in the highly import-focused Lebanese economy. Fifthly, energy savings resulting from a reduced hot water demand have not been taken into account in the *RWD*, *RWH+CWH+RWD* and *ALL* measures. The financial and energy performance of these measures are therefore expected to be slightly underestimated. In addition to the above, the water demand profile has been determined based on the average daily water demand per capita. A more detailed demand profile by fixture and appliance would improve the reliability of the results. However, these data are not available for Lebanon, as mentioned in Section 3.3.2. Sixthly, this research investigates the implementation of water harvesting and management measures in new buildings. Additional research is required to quantify the costs associated with retrofitting existing buildings to accommodate these measures. Finally, further research could consist of broadening the system boundaries as to reduce the embodied water of the entire building, including all its materials, as well as the indirect transport requirements of its occupants. This would mirror the life cycle energy and cost analysis conducted in Stephan and Stephan (2016) based on the life cycle water framework for residential buildings described in Stephan and Crawford (2014a). Despite these limitations, the sensitivity analysis conducted shows that the main findings still hold, regardless of potential variability and uncertainty in certain variables.

6 Conclusion

This study has quantified the life cycle water, energy and cost of various water harvesting and conservation measures for apartment buildings in a Mediterranean climate. The comprehensive approach and the breadth of the sensitivity analysis ensure that multiple solutions are explored simultaneously, across the 50-year period of analysis, and made relevant for a range of different economic and climatic contexts. Results show that water conservation is cost-effective, saving 0.35 USD/kL saved and reducing primary energy use by 85 MJ/kL. Regardless of uncertainty in the results, water conservation results in energy and cost savings. Combining rainwater and condensate water harvesting results in cost savings of 0.06 USD/kL but requires 12 MJ of energy. Wastewater treatment was found to be very energy intensive and not cost-effective at a building level. Combining rainwater and condensate water harvesting with water conservation and wastewater treatment can reduce the mains water demand of the building by up to 75% at virtually zero cost and life cycle energy use. Findings also support a metered, seasonal and demand-driven water price that incentivises local water harvesting and conservation measures. These measures will ultimately help reduce the demand for mains (and carted) water, reduce spending on centralised infrastructure, improve resilience and help save water, energy and money.

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Appendix A Calculation details

This appendix contains the supporting information for all investigated measures. Each section covers a particular measure.

Embodied water and energy coefficients were taken from G. J. Treloar and Crawford (2010). These are given in Table A.1 below. When no material breakdown for a particular component was available, e.g. water pump or wastewater treatment plant, the total water or energy intensity of the corresponding input-output sector was used and multiplied by the unit price. This is based on the same input-output data that was used to derive the coefficients, for consistency.

Table A.1: Embodied water and energy coefficients used

Item	Embodied Water coefficient	Embodied Energy coefficient
Polyvinyl chloride pipe (~20-70 mm)	0.452 kL/m	0.212 GJ/m
Polyvinyl chloride pressure pipe (~100mm)	0.568 kL/m	0.266 GJ/m
General plastics (used for polyethylene and polyvinyl chloride)	0.366 kL/kg	0.157 GJ/kg

Material service lives for pipes (25 years) and tanks (50 years) are based on previous studies (Angrill et al., 2011; Ghimire et al., 2014) to ensure consistency and improve the comparability of results. The service life of other materials and/or components is provided in each scenario.

A.1 Base water demand

The base water demand was estimated using a typical household water usage within each apartment unit. The total daily demand per capita, obtained from World Bank (2010) and Comair (2011) was used to calibrate the demand profile which is provided in Table A.2. The resulting daily and annual water demands for the whole building are 6 029 L and 2 200 kL, respectively.

Table A.2: Typical daily water demand for a single apartment unit in the base case scenario

Water fixture	Flow (L/min) or Operational volume (L/use)	Minutes or number of uses per day	Water use per day (L)	Share of total	Comment
Guest WC faucet	10	2	20	2.7%	Based on manufacturer specifications
Guest WC toilet	12	4	48	6.4%	Measured

Water fixture	Flow (L/min) or Operational volume (L/use)	Minutes or number of uses per day	Water use per day (L)	Share of total	Comment
Master Bathroom faucet	10	6	60	8%	Based on manufacturer specifications
Master Bathroom toilet	12	4	48	6.4%	Measured
Master Bathroom shower	12	10	120	15.9%	Based on manufacturer specifications
Bathroom faucet	10	6	60	8%	Based on manufacturer specifications
Bathroom toilet	12	4	48	6.4%	Measured
Bathroom shower	12	10	120	15.9%	Based on manufacturer specifications
Kitchen faucet	15	10	150	19.9%	Based on manufacturer specifications
Dishwasher	19	0.429	8.1	1.1%	3 washes per week
Washing machine	100	0.714	71.4	9.5%	5 washes per week
Total			753.6	100%	This equates to 188 L/capita

Note: WC: water closet.

A.2 Rainwater harvesting measure

The rainwater harvesting measure is modelled using a roof floor area of 278 m² with a slope of 25° as per the planning regulations in force in the locality of Sehaileh, Lebanon. The roof is covered by fired clay tiles for which a runoff coefficient of 0.84 was used based on the study of Farreny et al. (2011) who analysed the runoff coefficients and water quality of various roof types in the Mediterranean climate of Spain. The first flush volume was calculated using a ratio of 0.41 L/m² of roof catchment area based on the same study. Rainfall data is extracted from Meteonorm (MeteoTest, 2012).

The rainwater harvesting system consists of five extra risers made of PVC pipes of 3 inches in diameter (76.2mm). The net vertical elevation is 20 m and each riser runs horizontally for 10 m for a total of 30 m of pipes for each riser. The required piping accessories, such as tees, elbows and holders are all taken into account. All quantities and weights are based on actual measurements on site, on the manufacturer's specifications and on actual weighing of accessories.

Three rainwater tank sizes were investigated, including 4 000 L, 6 000 L and 8 000 L. The first tank size does not require additional materials as the inlet level of the mains water is lowered in the existing 8 000 L tank to provide space for rainwater reducing the non-rainwater capacity to 4 000 L. This corresponds to the case presented in the results. The other two tank sizes are used for the discussion. These tanks sizes were determined using the RainCycles software and are optimised for both their coverage of the water demand as well as the resulting total net present value. Figure A.1, depicts the tank efficiency and net present value for different underground storage tanks. While the tank efficiency plateaus after a tank size of 16 000 L, the net present value is the highest for tanks of 4 000, 6 000 and 8 000 L, after which it decreases linearly until the 16 000 L capacity. From there, it decreases at a faster rate since no operational water is saved any further. For these reasons, these three tank sizes were selected (see shaded area in Figure A.1). Table A.3 summarises the quantities, weights, current prices and service lives of the additional materials used for rainwater harvesting.

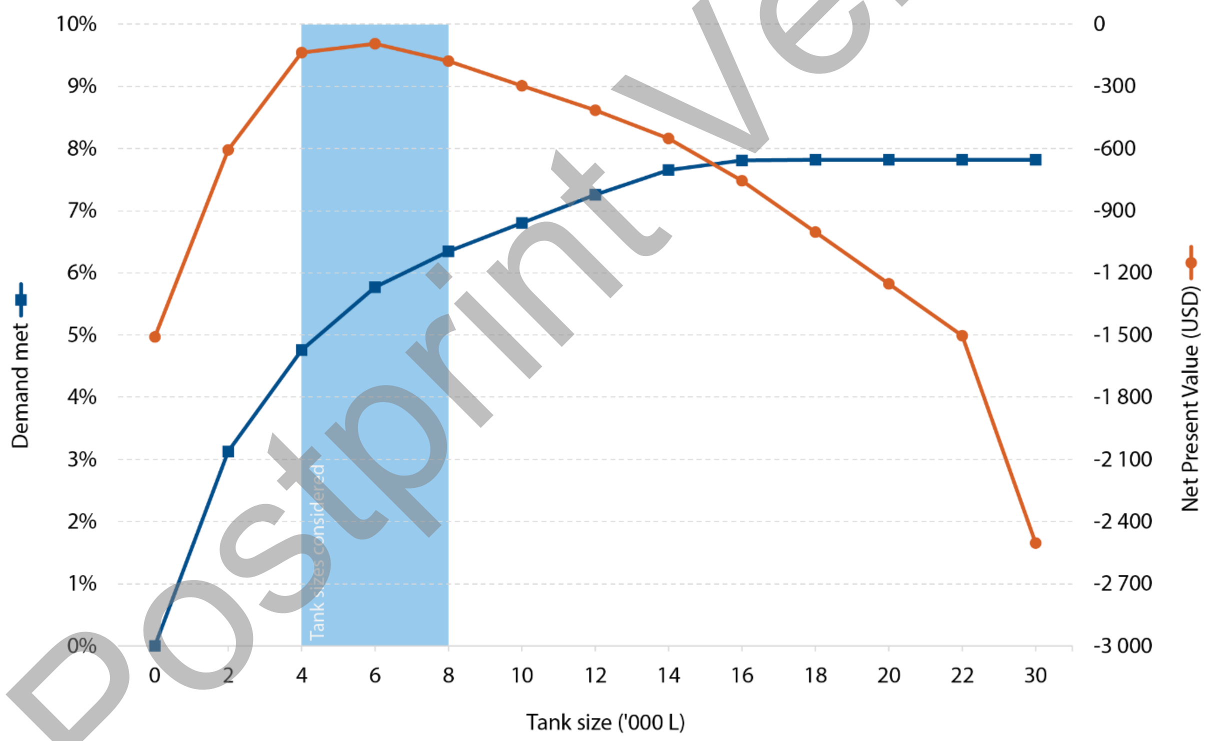

Figure A.1: Relationship between tank size, operational water demand met by rainwater harvesting and net present value, over 50 years.

Table A.3: Details of piping system data used for the rainwater harvesting measure. Note: additional 2 000 L tanks are added to increase the storage tank capacity.

Item	Quantity	Unit	Service life (years)	Weight (kg/unit)	Unit price (USD/unit)

Pipes	168	m	25	1	1.23
T connector	11	no	25	0.15	0.7
Holders	79	no	25	0.1	0.15
Elbows	2	no	25	0.15	0.7
Valve	1	no	25	0.5	5
Diverter	1	no	25	30	130
Coarse filter	1	no	10	0.3	50
Manpower	N/A	N/A	N/A	N/A	368
Tank 2 000 L	1	no	50	50	250

A.3 Condensate water harvesting measure

The condensate water harvesting is based on two units in each apartment unit, operating for 12 hours from July to August and for 3 hours in September. The average condensate water generation is 1 L/(unit·hour) as per Section 3.5.2, resulting in 192 L of daily condensate water during June-August and 48 L during September.

The condensate water harvesting measure consists of installing two risers to collect condensate water from the air conditioning compressors, located in the flower trays (see Figure 2). The drains from the units are directly connected to the risers. In addition, a collector is installed in the basement to connect the two risers to the underground tank. More details on quantities can be found in Table A.4.

Table A.4: Details of piping system data used for the condensate water harvesting measure

Item	Quantity	Unit	Service life (years)	Weight (kg/unit)	Unit price (USD/unit)
Pipes	66	m	25	1	1.23
T connector	11	no	25	0.225	1.1
Adaptor	10	no	25	0.1	2
Elbow	2	no	25	0.15	0.7
Holder	32	no	25	0.1	0.15
Manpower	N/A	N/A	N/A	N/A	120

A.4 Reduced water demand measure

The reduced water demand measure consists of replacing the base case fixtures, dishwasher and washing machine by the most efficient models on the market. The reduced water demand is detailed in Table A.5. One of the main advantages of the reduced water demand measure is that more water efficient appliances are also energy efficient, saving electricity. Furthermore, the reduced water demand results in less operating time for the pump since less water needs to be moved to the header tank.

Table A.5: Daily water demand for a single apartment unit within the reduced water demand measure

Water fixture	Flow (L/min) or Operational volume (L/use)	Minutes or number of uses per day	Water use per day (L)	Share of total	Comment
Guest WC faucet (efficient tap)	2	2	4	1.2%	Based on manufacturer specifications
Guest WC toilet (dual flush large)	12	1	12	3.5%	Measured
Guest WC toilet (dual flush small)	6	3	18	5.3%	Measured
Master Bathroom faucet (efficient tap)	2	6	12	3.5%	Based on manufacturer specifications
Master Bathroom toilet (dual flush large)	12	2	24	7%	Measured
Master Bathroom toilet (dual flush small)	6	3	18	5.3%	Measured
Master Bathroom shower (low-flow shower)	5	10	50	14.7%	Based on manufacturer specifications
Bathroom faucet (efficient tap)	2	6	12	3.5%	Based on manufacturer specifications
Bathroom toilet (dual flush large)	12	2	24	7.0%	Measured
Bathroom toilet (dual flush small)	6	3	18	5.3%	Measured
Bathroom shower (low-flow shower)	5	10	50	14.7%	Based on manufacturer specifications
Kitchen faucet (efficient tap)	6	10	60	17.6%	Based on manufacturer specifications
Dishwasher (EU A+++ water/energy)	6.5	0.429	2.8	0.8%	3 washes per week
Washing machine (EU A+++ water/energy)	50	0.714	35.7	10.5%	5 washes per week
Total			340.5	100%	This equates to 85 L/capita

Note: WC: water closet, EU: European Union and A+++: highest water and energy rating.

The average delivered annual electricity demands of the efficient dishwasher and washing machine are 137 kWh and 189 kWh, respectively. These are significantly lower than the standard inefficient appliances. Note that the average operational time of the dishwasher is a cycle of two hours. A cycle of 55 minutes is used for the washing machine and the replacement rate of both appliances is 15 years as per Stephan and Stephan (2016). The reduced water demand results in a shorter operation time for the pump. Based on the pump power rating of 0.56 kW and nominal flow of 30 L/hour, the annual delivered energy savings are 402 kWh.

A.5 Wastewater treatment measure

The wastewater treatment measure involves the largest modifications to the base case system by installing a separate collection system for greywater, a new storage tank, pump, riser, header tank and separate distribution pipes dedicated for flushing as well as the wastewater plant itself. The service lives of the latter and its components are based on data from the manufacturer. The water pump was considered to last 10 years based on data collected at Technical Enterprises Company on more than 20 buildings operated for more than 30 years. Table A.6 details the quantities and prices of the piping system needed for the wastewater treatment measure.

Table A.6: Details of piping system data used for the wastewater treatment measure

Item	Quantity	Unit	Service life (years)	Weight (kg/unit)	Unit Price (USD)
Pipes 4 inches	72	m	25	1.325	1.93
Pipes 3 inches	6	m	25	1.193	1.23
Pressure pipe 0.5 inches	76	m	25	0.159	0.68
Pressure pipe 1 inch	32	m	25	0.553	1.82
Elbows	4	no	25	0.2	0.95
T connectors	17	no	25	0.3	2.05
Holders	32	no	25	0.1	0.20
Waste water plant (SWCM-15)	1	no	25		7 500
Waste water plant O'ring	1	no	2		50
Waste water plant membranes	3	no	5		66.67
Pump 0.75 horsepower (0.56 kW)	1	no	10		85
Storage Tank 2 000 L (basement)	1	no	50	65	135
Header tank 1 000 L (roof)	1	no	50	50	85
Automatic controls	2	no	5		20
Other piping accessories			25		35
Manpower	N/A	N/A	N/A	N/A	1 672

In addition, the wastewater treatment measure introduces two new electricity demands, one for the additional pump and one for the plant itself. The power rating of the pump is 0.56 kW and it is assumed to operate 40 minutes per day (based on a flow rate of 30 L/min and a total flushing volume of 1 152 L per day as per the base case demand, see Table A.2). The power rating of the plant is 2.25 kW based on the manufacturer's specifications. It is operated 10 hours per day based on an average load of 119L/hour (80% capacity).

A.6 Rainwater and condensate water harvesting

The combination of the rainwater and condensate water harvesting measures results in savings on the piping system since the same risers can be used by both systems. Therefore, the piping system required is the same as for the rainwater harvesting measure with minor additional connections of the air conditioning units to the risers. For each storey, three T connectors and adaptors are needed to connect the compressors to three of the five rainwater harvesting risers. This results in an additional 12 T connectors and adaptors (see Table A.4 for their service life, weight and unit price).

A.7 Rainwater and condensate water harvesting with a reduced water demand

The combination of rainwater and condensate water harvesting as well as a reduced water demand (*RWH+CWH+RWD*) consists of adding all the requirements for each measure. The only compounding effect is the economy of pipes resulting from the combination of rainwater and condensate water harvesting, as explained in Section A.6. The storage tank size is not affected.

A.8 All measures combined

The *ALL* combination implements all measures. Resulting compounding effects include:

1. Using the same risers for rainwater and condensate water harvesting as in Section A.6; and
2. Downsizing the waste water treatment plant (6 000 USD instead of 7 500 USD) which results in one extra plant operating hour (11 hours instead of 10 hours) and an associated increase in electricity demand. This increase largely exceeds the reduced energy demand for the pump resulting from a 20% shorter operating time as the water demand is reduced; and
3. Piping installations are not affected.

References

ABS. (2015, 25/11/2015). Water account Australia 2012-13. Retrieved from http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/4610.0Main%20Features32012-13?opendocument&tabname=Summary&prodno=4610.0&issue=2012-13&num=&view=

ABS. (2016). 8752.0 - Building Activity, Australia, Jun 2016. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8752.0Jun%202016?OpenDocument#Time

Agudelo-Vera, C. M., Keesman, K. J., Mels, A. R., & Rijnaarts, H. H. (2013). Evaluating the potential of improving residential water balance at building scale. *Water Res, 47*(20), 7287-7299. doi:10.1016/j.watres.2013.10.040

Alliance for Water Efficiency. (2016, 2016). Condensate Water Introduction. Retrieved from http://www.allianceforwaterefficiency.org/Condensate_Water_Introduction.aspx

Anand, C., & Apul, D. S. (2011). Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets. *Journal of Environmental Management, 92*(3), 419-428. doi:10.1016/j.jenvman.2010.08.005

Angrill, S., Farreny, R., Gasol, C. M., Gabarrell, X., Viñolas, B., Josa, A., & Rieradevall, J. (2011). Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. *The International Journal of Life Cycle Assessment, 17*(1), 25-42. doi:10.1007/s11367-011-0330-6

Angrill, S., Segura-Castillo, L., Petit-Boix, A., Rieradevall, J., Gabarrell, X., & Josa, A. (2017). Environmental performance of rainwater harvesting strategies in Mediterranean buildings. *The International Journal of Life Cycle Assessment, 22*(3), 398-409. doi:10.1007/s11367-016-1174-x

AS/NZS 6400:2016. (2016). Water efficient products—Rating and labelling (pp. 85). Wellington: Standards Australia Limited/Standards New Zealand.

Beal, C. D., Sharma, A., Gardner, T., & Chong, M. (2012). A Desktop Analysis of Potable Water Savings from Internally Plumbed Rainwater Tanks in South-East Queensland, Australia. *Water Resources Management, 26*(6), 1577-1590. doi:10.1007/s11269-011-9973-0

Berk, J. B., & DeMarzo, P. M. (2010). *Corporate finance* (2nd edition ed.). Boston: Pearson Education.

Bordigoni, M., Hita, A., & Le Blanc, G. (2012). Role of embodied energy in the European manufacturing industry: Application to short-term impacts of a carbon tax. *Energy Policy, 43*, 335-350. doi:http://dx.doi.org/10.1016/j.enpol.2012.01.011

Bourne, C. B., & Wouters, P. (1997). *International Water Law: Selected Writings of Professor Charles B. Bourne*. London: Kluwer Law International.

Comair, F. (2011). *L'efficience d'utilisation de l'eau et approche économique. Etude nationale, Liban*. Retrieved from

Crawford, R. H. (2008). Validation of a hybrid life-cycle inventory analysis method. *Journal of Environmental Management, 88*(3), 496-506. doi:DOI 10.1016/j.jenvman.2007.03.024

Crawford, R. H. (2011). *Life cycle assessment in the built environment*. London: Spon Press.

Crettaz, Jolliet, Cuanillon, & Orlando. (1999). Life cycle assessment of drinking water and rain water for toilets flushing. *Aqua, 48*(3), 73-83. doi:10.1046/j.1365-2087.1999.00134.x

Dai, A. (2011). Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change, 2*(1), 45-65. doi:10.1002/wcc.81

Devkota, J. P., Burian, S. J., Tavakol-Davani, H., & Apul, D. S. (In Press). Introducing demand to supply ratio as a new metric for understanding life cycle greenhouse gas (GHG) emissions from rainwater harvesting systems. *Journal of Cleaner Production*. doi:http://dx.doi.org/10.1016/j.jclepro.2015.10.073

Devkota, J. P., Schlachter, H., Anand, C., Phillips, R., & Apul, D. S. (2013). Development and application of EEAST: A life cycle based model for use of harvested rainwater and composting toilets in buildings. *Journal of Environmental Management, 130*, 397-404. doi:http://dx.doi.org/10.1016/j.jenvman.2013.09.015

Devkota, J. P., Schlachter, H., & Apul, D. S. (2015). Life cycle based evaluation of harvested rainwater use in toilets and for irrigation. *Journal of Cleaner Production, 95*, 311-321. doi:10.1016/j.jclepro.2015.02.021

Dinar, A., Pochat, V., & Albiac-Murillo, J. (2015). Introduction. In A. Dinar, V. Pochat, & J. Albiac-Murillo (Eds.), *Water pricing experiences and innovations* (Vol. 9, pp. 485). Cham: Springer.

Dixit, M. K., Culp, C. H., & Fernández-Solís, J. L. (2013). System boundary for embodied energy in buildings: A conceptual model for definition. *Renewable and Sustainable Energy Reviews, 21*(0), 153-164. doi:http://dx.doi.org/10.1016/j.rser.2012.12.037

Dunnett, N., & Kingsbury, N. (2008). *Planting green roofs and living walls*: Portland, Or. : Timber Press, 2008.

2nd ed.

ECCC. (2016, 02/17/2016). Residential Water Use in Canada. Retrieved from https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=7E808512-1

EPA. (2016, 09/03/2016). Watersense - Statistics and Facts. Retrieved from https://www3.epa.gov/watersense/about_us/facts.html

Eroksuz, E., & Rahman, A. (2010). Rainwater tanks in multi-unit buildings: A case study for three Australian cities. *Resources, Conservation and Recycling, 54*(12), 1449-1452. doi:http://dx.doi.org/10.1016/j.resconrec.2010.06.010

Eurostat. (2017a). Housing Statistics. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Housing_statistics#Type_of_dwelling

Eurostat. (2017b, 2014). Tourism statistics - North Africa and Eastern Mediterranean. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Tourism_statistics_-_North_Africa_and_Eastern_Mediterranean

Eurostat. (2017c, 2014). Tourism statistics - top destinations. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Tourism_statistics_-_top_destinations

Farreny, R., Morales-Pinzon, T., Guisasola, A., Taya, C., Rieradevall, J., & Gabarrell, X. (2011). Roof selection for rainwater harvesting: quantity and quality assessments in Spain. *Water Res, 45*(10), 3245-3254. doi:10.1016/j.watres.2011.03.036

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., . . . Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management, 91*(1), 1-21. doi:10.1016/j.jenvman.2009.06.018

Ghimire, S. R., Johnston, J. M., Ingwersen, W. W., & Hawkins, T. R. (2014). Life cycle assessment of domestic and agricultural rainwater harvesting systems. *Environmental Science & Technology, 48*(7), 4069-4077. doi:10.1021/es500189f

Grafton, R. Q., Chu, L., & Kompas, T. (2015). Optimal water tariffs and supply augmentation for cost-of-service regulated water utilities. *Utilities Policy, 34*, 54-62. doi:http://dx.doi.org/10.1016/j.jup.2015.02.003

Grafton, R. Q., & Kompas, T. (2007). Pricing Sydney water. *Australian Journal of Agricultural and Resource Economics, 51*(3), 227-241. doi:10.1111/j.1467-8489.2007.00390.x

Grafton, R. Q., & Peterson, D. (2007). Water Trading and Pricing. In K. Hussey & S. Dovers (Eds.), *Managing Water for Australia* (pp. 73-84). Collingwood, VIC: CSIRO Publishing.

Hurlimann, A. C. (2009). Water supply in regional Victoria Australia: A review of the water cartage industry and willingness to pay for recycled water. *Resources, Conservation and Recycling, 53*(5), 262-268. doi:10.1016/j.resconrec.2008.12.005

Iglesias, A., Garrote, L., Flores, F., & Moneo, M. (2006). Challenges to Manage the Risk of Water Scarcity and Climate Change in the Mediterranean. *Water Resources Management, 21*(5), 775-788. doi:10.1007/s11269-006-9111-6

International Standard 14040. (2006). Environmental management - life cycle assessment - principles and framework. Geneva: International Organization for Standardization (ISO).

IPCC. (2013). *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Retrieved from Cambridge:

Jimenez Cisneros, B., & Rose, J. B. (2009). *Urban Water Security: Managing Risks: UNESCO-IHP*. Hoboken: CRC Press.

Legget, D. J., Brown, R., Brewer, D., Stanfield, G., & Holliday, E. (2001). *Rainwater and greywater use in buildings: best practice guidance*. Retrieved from London: https://www.thenbs.com/PublicationIndex/documents/details?Pub=CIRIA&DocID=262178

Lenzen, M., & Treloar, G. J. (2004). Endogenising capital: a comparison of two methods. *Journal of Applied Input-Output Analysis, 10*, 10.

Loubet, P., Roux, P., Loiseau, E., & Bellon-Maurel, V. (2014). Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature. *Water Res, 67*, 187-202. doi:10.1016/j.watres.2014.08.048

Loveless, K. J., Farooq, A., & Ghaffour, N. (2012). Collection of Condensate Water: Global Potential and Water Quality Impacts. *Water Resources Management, 27*(5), 1351-1361. doi:10.1007/s11269-012-0241-8

Mahvi, A. H., Alipour, V., & Rezaei, L. (2013). Atmospheric moisture condensation to water recovery by home air conditioners. *American Journal of Applied Sciences, 10*(8), 917-923. doi:10.3844/ajassp.2013.917.923

Majeau-Bettez, G., Strømman, A. H., & Hertwich, E. G. (2011). Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental Science & Technology, 45*(23), 10170-10177.

Marlow, D. R., Moglia, M., Cook, S., & Beale, D. J. (2013). Towards sustainable urban water management: a critical reassessment. *Water Res, 47*(20), 7150-7161. doi:10.1016/j.watres.2013.07.046

Melbourne Water. (2016, 2016). Water use data. Retrieved from http://www.melbournewater.com.au/waterdata/wateruse/pages/default.aspx

Mendez, C. B., Klenzendorf, J. B., Afshar, B. R., Simmons, M. T., Barrett, M. E., Kinney, K. A., & Kirisits, M. J. (2011). The effect of roofing material on the quality of harvested rainwater. *Water Res, 45*(5), 2049-2059. doi:10.1016/j.watres.2010.12.015

MeteoTest. (2012). Meteonorm 7.1.3. Bern.

MEW. (2010). *Policy Paper for the Electricity Sector - (COM#1-21/06/2010)*. Retrieved from Beirut:

MOA. (2003). *National Action Plan to Combat Desertification*. Retrieved from Beirut: http://www.unccd.int/ActionProgrammes/lebanon-eng2003.pdf

MOE. (2011). *Lebanon's Second National Communication to the United Nations Framework Convention on Climate Change*. Retrieved from Beirut:

MOE/UNEP/UNDP. (2012). *Lebanon Technology Needs Assessment Report for Climate Change*. Retrieved from Beirut:

Molinos-Senante, M., & Donoso, G. (2016). Water scarcity and affordability in urban water pricing: A case study of Chile. *Utilities Policy, 43, Part A*, 107-116. doi:http://dx.doi.org/10.1016/j.jup.2016.04.014

Morales-Pinzón, T., Lurueña, R., Rieradevall, J., Gasol, C. M., & Gabarrell, X. (2012). Financial feasibility and environmental analysis of potential rainwater harvesting systems: A case study in Spain. *Resources, Conservation and Recycling, 69*, 130-140. doi:http://dx.doi.org/10.1016/j.resconrec.2012.09.014

Mourtada, A. (2010). *Energie, changement climatique et bâtiment en Méditerranée. Etude nationale Liban*. Retrieved from Paris:

Parish, E. S., Kodra, E., Steinhaeuser, K., & Ganguly, A. R. (2012). Estimating future global per capita water availability based on changes in climate and population. *Computers & Geosciences, 42*(0), 79-86. doi:http://dx.doi.org/10.1016/j.cageo.2012.01.019

Pesonen, H., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z., . . . Wenzel, H. (2000). Framework for scenario development in LCA. *The International Journal of Life Cycle Assessment, 5*(1), 21-30. doi:10.1007/bf02978555

Racoviceanu, A. I., & Karney, B. W. (2010). Life-Cycle Perspective on Residential Water Conservation Strategies. doi:10.1061/(ASCE)1076-0342(2010)16:1(40)

Rahman, A., Keane, J., & Imteaz, M. A. (2012). Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits. *Resources, Conservation and Recycling, 61*, 16-21. doi:http://dx.doi.org/10.1016/j.resconrec.2011.12.002

Roebuck, R. M., & Ashley, R. M. (2007). Predicting the hydraulic and life-cycle cost performance of rainwater harvesting systems using a computer based modelling tool. *Water Practice and Technology, 2*(2). doi:10.2166/wpt.2007.046

Roebuck, R. M., Oltean-Dumbrava, C., & Tait, S. (2011). Whole life cost performance of domestic rainwater harvesting systems in the United Kingdom. *Water and Environment Journal, 25*(3), 355-365. doi:10.1111/j.1747-6593.2010.00230.x

Santos, C., & Taveira-Pinto, F. (2013). Analysis of different criteria to size rainwater storage tanks using detailed methods. *Resources, Conservation and Recycling, 71*(0), 1-6. doi:http://dx.doi.org/10.1016/j.resconrec.2012.11.004

Säynäjoki, A., Heinonen, J., Junnila, S., & Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environmental Research Letters, 12*(1), 013001.

Sharma, A. K., Grant, A. L., Grant, T., Pamminger, F., & Opray, L. (2009). Environmental and Economic Assessment of Urban Water Services for a Greenfield Development. *Environmental Engineering Science, 26*(5), 921-934. doi:10.1089/ees.2008.0063

Sibly, H. (2006). Urban Water Pricing. *Agenda, 13*(1), 13.

Speers, A., & Mitchell, G. (2000, 30-31/08). *Integrated urban water cycle.* Paper presented at the National Conference on Water Sensitive Urban Design–Sustainable Drainage Systems for Urban Areas, Melbourne.

Statistics Belgium. (2013, 2007). Disponibilité de l'eau et consommation. Retrieved from http://statbel.fgov.be/fr/statistiques/chiffres/environnement/eau/dispo/#5

Stec, A., & Kordana, S. (2015). Analysis of profitability of rainwater harvesting, gray water recycling and drain water heat recovery systems. *Resources, Conservation and Recycling, 105, Part A*, 84-94. doi:http://dx.doi.org/10.1016/j.resconrec.2015.10.006

Stephan, A., & Crawford, R. H. (2014a). A comprehensive life cycle water analysis framework for residential buildings. *Building Research & Information, 42*(6), 685-695. doi:10.1080/09613218.2014.921764

Stephan, A., & Crawford, R. H. (2014b). A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings. *Architectural Science Review, 57*(1), 39-48. doi:10.1080/00038628.2013.837814

Stephan, A., & Stephan, L. (2014). Reducing the total life cycle energy demand of recent residential buildings in Lebanon. *Energy, 74*(0), 618-637. doi:http://dx.doi.org/10.1016/j.energy.2014.07.028

Stephan, A., & Stephan, L. (2016). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Applied Energy, 161*, 445-464. doi:http://dx.doi.org/10.1016/j.apenergy.2015.10.023

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., . . . Norris, G. (2004). System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science & Technology, 38*(3), 657-664.

Technical Enterprises Co. (2017). Le Peuplier - New Sehaileh. Retrieved from www.tecentlb.com

Treloar, G. J. (1997). Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. *Economic Systems Research, 9*(4), 375-391.

Treloar, G. J., & Crawford, R. H. (2010). *Database of embodied energy and water values for materials*.

U.N. (2012). *World urbanization prospects: the 2011 revision* (ST/ESA/SER.A/322). Retrieved from New York:

U.N. (2015). *Transforming Our World: the 2030 Agenda for Sustainable Development*. Retrieved from New York: https://sustainabledevelopment.un.org/post2015/transformingourworld

UNDP/GEF/MPWT/DGU. (2005). *Climatic Zoning for Buildings in Lebanon*. Retrieved from

UNEP/MAP. (2012). *State of the Mediterranean Marine and Coastal Environment*. Retrieved from Athens:

UNEP/MAP/ MED POL. (2003). *Riverine Transport of Water, Sediments and Pollutants to the Mediterranean Sea* (10117148). Retrieved from Athens:

UNEP/MAP/BP/RAC. (2005). *A sustainable future for the Mediterranean : the Blue Plan's environment and development outlook*: Earthscan.

Van Thiel, L. (2014). *Watergebruik Thuis 2013*. Retrieved from Amsterdam: http://www.vewin.nl/SiteCollectionDocuments/Publicaties/Watergebruik_Thuis_2013.pdf

Vargas-Parra, M. V., Villalba, G., & Gabarrell, X. (2013). Applying exergy analysis to rainwater harvesting systems to assess resource efficiency. *Resources, Conservation and Recycling, 72*, 50-59. doi:http://dx.doi.org/10.1016/j.resconrec.2012.12.008

Vieira, A. S., Beal, C. D., Ghisi, E., & Stewart, R. A. (2014). Energy intensity of rainwater harvesting systems: A review. *Renewable and Sustainable Energy Reviews, 34*, 225-242. doi:http://dx.doi.org/10.1016/j.rser.2014.03.012

Villarreal, E. L., & Dixon, A. (2005). Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrköping, Sweden. *Building and Environment, 40*(9), 1174-1184. doi:http://dx.doi.org/10.1016/j.buildenv.2004.10.018

Wang, R., & Zimmerman, J. B. (2015). Economic and Environmental Assessment of Office Building Rainwater Harvesting Systems in Various U.S. Cities. *Environmental Science & Technology, 49*(3), 1768-1778. doi:10.1021/es5046887

Ward, S., Memon, F. A., & Butler, D. (2012). Performance of a large building rainwater harvesting system. *Water Research, 46*(16), 5127-5134. doi:http://dx.doi.org/10.1016/j.watres.2012.06.043

WELS scheme. (2016, 15/11/2016). Water Efficiency Labelling and Standards (WELS) scheme. Retrieved from http://www.waterrating.gov.au/

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecological Economics, 70*(11), 1937-1945. doi:http://dx.doi.org/10.1016/j.ecolecon.2011.06.014

World Bank. (2010). *Republic of Lebanon Water Sector: Public Expenditure Review*. Retrieved from

WTO. (2016, 28/01/2016). Global Value Chains. Retrieved from https://www.wto.org/english/res_e/statis_e/miwi_e/miwi_e.htm

WTTC. (2016). *Mediterranean 2016*. Retrieved from London, UK: https://www.wttc.org/research/economic-research/economic-impact-analysis/regional-reports

Zhang, Y., Chen, D., Chen, L., & Ashbolt, S. (2009). Potential for rainwater use in high-rise buildings in Australian cities. *Journal of Environmental Management, 91*(1), 222-226. doi:http://dx.doi.org/10.1016/j.jenvman.2009.08.008