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Review

Economic Analysis and Feasibility of Rainwater Harvesting Systems in Urban and Peri-Urban Environments: A Review of the Global Situation with a Special Focus on Australia and Kenya

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Abstract: Rainwater harvesting (RWH) plays an important role in increasing water security for individuals and governments. The demand for tools to enable technical and economic analysis of RWH systems has led to a substantial body of research in the recent past. This paper focuses on the economic aspects of domestic RWH in urban and peri-urban environments. In this regard, key issues are identified and discussed including quality and quantity of harvested water, the water demand profile, the scale of installation, interest rates, the period of analysis, real estate value, and the water-energy-food nexus. Kenya and Australia are used as reference points having different economies and opposing RWH policies. It has been found that the previous studies on financial aspects of RWH systems often had conflicting results. Most of the economic analyses have ignored the full benefits that a RWH system can offer. In view of the varying and conflicting results, there is a need to standardize the methods of economic analysis of RWH systems.

Keywords: rainwater tank; rainwater harvesting; economic analysis; urban; peri-urban; Kenya; Australia

1. Introduction

"Is there anything that thou hast seen under the heavens that is better than water?" Solomon said to the Queen of Sheba [1]. Ancient cultures realized the value of water to the extent of covering cisterns to reduce evaporation [2]. In modern times, with increasing concerns about water security, the rainwater harvesting (RWH) system, with its high water saving potential, is an important area of research. There is a growing international interest particularly in the more water-stressed countries, resulting in a significant body of research on RWH in recent years. The purpose of this paper is to review the economic aspects of the RWH system and identify key issues and areas requiring further research. While research from all over the world has been considered, Australia and Kenya are used as reference points, having similar average annual rainfall variety, but different economies [3–5], levels of urbanization, and existing uptake of RWH systems.

Economic analysis is defined as a "systematic approach to determining the optimum use of scarce resources, involving comparison of two or more alternatives in achieving a specific objective under the given assumptions and constraints" [6]. Economic analysis attempts to "measure in monetary terms the private and social costs and benefits of a project to the community or economy". Therefore, the economic analysis of the RWH system must have a broad perspective. Research about the quality and quantity of water harvested from a RWH system focuses on a particular issue, while the economic analysis needs to consider the cost implications of a whole range of issues considering also, for example, environmental benefits, the cost of alternative water supplies [7,8], water saving options [9,10], and, particularly in foreign aid projects, the cost of training individuals and of ongoing maintenance of RWH systems [11,12].

The RWH system has the potential to alleviate the increased water demand caused by urbanization [13,14]. This has been a key issue in Australia, which is "the most urbanized country in the world" [15] with over 75% of people living in only 20 cities [16] and a total urban population of 89.4%, increasing at 1.47% annually. Kenya's urban population which stands at 25.6% is considerably less but is increasing much faster with an annual rate of change of 4.34% [17]. Sub-Saharan Africa in general has a level of urbanization nearly as low as India [18]. In India, water security issues due to population growth have already led to the RWH system's being made mandatory in several cities, e.g., Delhi and Chennai [19]. Globally, urban population exceeded rural in 2009 [20]. There are already 1039 cities with over half a million people worldwide [21], and extensive urban systems called Megalopolises are emerging, such as the region between London and the Midland cities in Great Britain and the "Tokyo-Ōsaka-Kyōto complex" in Japan [22]. Peri-urban areas are also developing as a consequence of urbanization and a desire for a more ambient lifestyle [18,20]. In Australia, these may extend up to 100 km [23]. The RWH system in peri-urban, as in rural areas, often represents the only water available [24], so reliability is a high priority in these areas [25].

Changing and unpredictable climates and droughts, regardless of what the cause may be [26,27], compound the water stress caused by increased urbanization. As a result of Australia's "Millennium Drought" and government incentives, 34% of households have adopted RWH systems. This is the highest adoption rate in the world [28]. Review of this implementation therefore holds many lessons for the international community [29]. However, many urban planners in Australia still see a need to address issues of water quality and safety in response to climate change [30]. Their integrated water resources planning has been criticized for not being mature enough to provide future water security [31], and Asia's water problems are expected to produce water refugees directly affecting Australia in the near future [32]. The importance of water and food security, as well as energy security in relation to economic growth, has increased internationally. The water-energy-food nexus aims at the relationship between these three [33].

In Kenya, there is inadequate access to sustainable safe drinking water (62%) and water for basic sanitation (30%) [34–36]. Target 10 of the Millennium Development Goals (MDG) adopted in 2000 by the UN, the IMF, the OECD, and the World Bank aimed to halve the proportion of people worldwide by 2015 that do not have this access [37]. Based on the first author's personal experience, while living in a suburb of Nairobi Kenya mid 2015, water was only available through the centralized pipe system for one day each week. On the other days, water stored in tanks or bought at high prices, e.g., 10–20 Ksh (AU$ 0.14–0.28) for 25 L, are the only alternatives. These problems throughout Kenya's urban areas are well-known [38–41]. Ndola, Zambia has experienced progress towards MDG through informal water supply systems where the formal sector has failed. Research has shown that there are "simple and cost-effective" alternatives to the centralized piped network which the formal sector should embrace [42]. Economic analysis of the RWH system plays an important role in the search for cost-effective solutions to water security and in developing countries particularly. However, economic analysis of RWH systems has a limited presence in scientific literature. Moreover, the limited amount of studies focusing mainly on financial aspects of RWH systems has often reported conflicting results.

This paper presents a review of economic analysis and feasibility of RWH systems with special focus on Australia and Kenya. At the beginning, various aspects of economic analysis of RWH are discussed such as life cycle cost analysis, water price, interest and inflation rates, costs, and benefits. Thereafter, the impacts of modeling and design of a RWH system on economic analysis are reviewed.

The feasibility of adopting a RWH system, particularly in developing countries such as Kenya, is then discussed. Finally, a number of important conclusions are drawn from this review. It is expected that this paper will serve as a key reference on economic aspects of RWH to researchers, water engineers, environmentalists, town planners, and policy makers dealing with water issues in urban and peri-urban environments.

2. Economic Analysis

2.1. Life Cycle Cost Analysis

Informed economic decision about the installation of RWH systems includes detailed analysis of its Life Cycle Cost (LCC). The Australian/New Zealand Standard AS/NZS 4536:1999 defines LCC as "the sum of acquisition cost and ownership cost of a product over its life cycle" [43]. This method is commonly used in the water and energy sector, e.g., in the US [44]. It involves comparing the flow of costs and benefits from a project or investment, where the flows are discounted to net present equivalent values: Results are then expressed in a variety of ways. For example, Morales-Pinzón *et al.* [45] used net present value (NPV), return on investment (ROI), benefit-cost ratio (BCR) and payback period (PP) as financial indicators in their model. Matos *et al.* [46] used similar indicators, as well as internal rate of return (IRR). Khastagir *et al.* [47] and Hall [48] used the levelized cost (LC), also called "amortized cost", following the approach outlined for Australia's water and energy sectors. Zhang *et al.* [49] used the hedonic price method to assess the real-estate value of a RWH system.

For a comparison, Table 1 presents economic inputs and results from a selection of journal articles and technical reports. The scenarios used to produce these results are given later in Table 2. The large variety in results can be seen particularly by comparing the payback periods (PP) column. The payback period is defined as "the time required to recover an investment or loan" [50,51]. In this paper, currency has been standardized to the Australian dollar (AU$) [40] to compare economic aspects of RWH systems among different countries. The NPV is the sum of present values (PV) over the project life. Present values are calculated by multiplying cash flows (CF) by the discount rate, which is a function of the interest rate (i) and the year in which the cash flow occurred (t), as shown below:

$$\text{Discount rate} = \frac{1}{(1+i)^n}\; PV = \frac{CF}{(1+i)^n} \tag{1}$$

The net present value (NPV) is then calculated as:

$$NPV\,(i,N) = \sum_{t=0}^{N} \frac{CF_t}{(1+i)^t} \tag{2}$$

where N is number of years the life cycle is considered over, noting that CF is the difference between cash out flow and inflow, each reduced by the discount rate appropriate to the time of cash flow. The benefit-cost ratio (BCR) is also calculated using discounted rates. It is simply the sum of discounted costs (C) divided by the sum of discounted benefits (B) as they occur at time t over the lifetime of the project N:

$$BCR = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{B_t}{(1+i)^t}} \tag{3}$$

The levelized cost involves multiplying cash flow by the discount rate, but is formulated to give the equivalent cost of water [48]. It is calculated as the NPV cost of a scheme divided by the PV of the water saved:

$$\text{Levelized cost}\left(\frac{\$}{\text{kL}}\right) = \frac{\text{NPV(of \$ costs of scheme)}}{\text{PV (of savings ie amount of water saved in kL)}} \tag{4}$$

Further information on these can be found in financial dictionaries [50,51].

Table 1. RWH System Economics.

Location (Reference)	Water Price ^{*1} AU\$/m^3	Water Price Increase Annual % Increase	Inflation %	Interest (i) %	Life Cycle Years	PP * Years	NPV * AU\$ Over Project Life	LC * AU\$/m^3	BCR *
Sydney, Australia [52]	1.48	3	1	5–15	60	None	–	–	0.15–1.01
Perth, Australia [49]	2.76–5.22	–	–	5, 7, 9	15	None ^{*1}	–	–	–
Melbourne, Australia [53]	1.5–2.7	6	–	–	20	1–12, 12–47 ^{*2}	191760–980566	0.09–0.71	–
Brisbane, Australia [48]	–	–	–	3, 6, 9	25,50	–	–	7.62–11.17	–
Brisbane, Australia [54]	used to calculate yield for financial analysis in Hall [48] *cf.* Table 2								
Kenya [55]	"Nomographs" of roof area-tank size for financial decisions. No LCC analysis done.								
Nairobi, Kenya [56]	0.3–0.8, 6.3	–	–	–	25	25 ^{*3}	139, 236	–	–
Spain [45]	1.3–4.2	–	3	–	50	5.5–204 ^{*4}	–	−6.9 to 2.4	>1 ^{*4}
Yorkshire, UK [57]	5.1	–	–	3.5–15	50	None	–	–	–

* PP = payback period, NPV = net present value, LC = levelized cost BCR = benefit-cost ratio. ^{*1} Unless the real estate value is included. ^{*2} Government 1–12 years and the Householder 12–47 years. ^{*3} The PP was set to the lifespan of a tank, and the water prices that gave that lifespan were calculated. ^{*4} Apartments scale only.

Table 2. RWH system installation scenarios corresponding to Table 1.

Location (Reference)	Annual Rainfall mm	Roof Area m^2	Tank Size m^3	Usages ^{*1} –	Water Use m^3/p/d ^{*2}	Reliability %	Water Savings m^3/hh/yr ^{*2}	Costs ^{*3} –
Sydney, Australia [52]	–	4000	75	O, L, T	–	70, 99	45	C, M, I
Perth, Australia [49]	826	125, 250	2, 5	O	–	–	–	C, M
Melbourne, Australia [53]	550–900	–	0.6–5+	O, T, L	0.26	–	105	–
Brisbane, Australia [48]	–	100	5	–	–	–	–	–
Brisbane, Australia [54]	–	98–117	4.4–6.7	O, L, T	0.11–0.16	68–80	43	–
Kenya [55]	454–1296	160, 220	12, 6	–	–		110	–
Nairobi, Kenya [56]	938	15	48.8	All	0.03–0.05	30–65	–	C, M
Spain [45]	284–1794	80–4580	3–125	L	–	8–96	1–12	–
West Yorkshire, UK [57]	–	76	1.2, 2.4	–	–	58–65	–	C, M
Jordan [58]	42–582	100–500+	20	All	0.07–0.4	0.27–19.7	0.3%–20% ^{*4}	C

^{*1} Usages: O = outdoor, T = toilet, L= laundry. ^{*2} p/d person per day hh/yr = household per year. ^{*3} Costs included in economic analysis: C = construction, M = maintenance, I = infrastructure savings. ^{*4} Percentage of total domestic water use.

Gato-Trinidad *et al.* [53] noted that the PP method is simple to understand but ignores the benefit that accrues after the payback period. Roebuck *et al.* [59], however, found that RWH systems in the UK are not likely to present any payback period and concluded that any research that finds they can should be thoroughly examined. It appears that the majority of researchers have found that RWH systems are not financially viable [19,52,57,59–61]. Conflicting results may be affected by a number of financial assumptions and modeling parameters, as discussed later.

2.2. Water Price, Interest, Inflation, and Period of Analysis

Firstly, since water savings are the primary benefit of the RWH System, the water price is a key factor in its economic analysis [45,62,63]. A number of authors represented financial viability in terms of the water price required to make the installation of a rainwater tank able to recover the investment costs [56,62]. Predictions about future water prices are frequently used to calculate the payback periods. The price of water is often expected to increase at a higher rate than the general interest rate [62,64]. For example, Melbourne's potable water price is expected to increase by 100% in the next five years [47]. Gato-Trinidad *et al.* [53] (see Table 1) used a price increase of 6%, which is conservative considering that the Melbourne Metropolitan water retailers increased the price by 14% in January 2009 [65]. For comparison, Australia's annual average GDP real growth rate was 3% between 2000 and 2010 [66]. Sydney Water, however, has proposed a reduced water price over the coming years [67]. The Water Framework Directive of the European Union is expected to increase the price of water due to a cost-recovery principle and the need to accommodate the higher production costs of desalination [64].

The cost of water in Kenya, and Sub-Saharan Africa generally, is often higher than in developed countries, and considerably more when measured against the average wage. For example, water from Nairobi Water, despite being heavily subsidized, costs between 19–54 Kshs/m^3 (0.26–0.76 AU$). However, people are often forced to buy from one of the following three options: from a motorized tanker at 450 Kshs/m^3 (6.3 AU$), in 20L Jerry Cans from stand pipes at 500 Ksh/m^3 (AU$ 6.8), which is the most popular, or bottled at 50 Kshs/L (700 AU$/$m^3$) or more [56]. Meanwhile, in developed countries, there is open access to drinking quality water. These prices are even higher when we compare them to the average Kenyan wage. The country's consumer price index (CPI) was 149.74 in 2014 according to an economic survey done by the Kenyan Bureau of Statistics (KBS) in 2015. KBS reported the average wage in the modern sector as 555,117 Ksh [65] equivalent to only AU$ 7540 [68] in 2015. However, in the authors experience, many people in Kayole earn considerably less, not having work every day, perhaps 1500 Ksh in a good week (approx. AU$ 1000 per year). A laborer might earn 500 Ksh for a day's labor, and a tradesman 1500 Ksh.

The state of a country's economy affects the results of economic analysis. Low inflation and high discount rates (a function of interest rate) have been found to result in a shorter payback period [47]. The consumer price index and also the relationship between labor and material costs may also affect results, but there seems to be little research on this issue with respect to RWH systems, as most research has been done locally.

The period of analysis has also been found to reduce the effect of discounting the operating costs and yields relative to the capital costs. Hall [48] found that halving the analysis period from 25 to 50 years increased average levelized cost from AU$ 9.22/m^3 to AU$ 9.54/m^3.

2.3. Costs

Melville-Shreeve *et al.* [69] found that innovative RWH systems, located via the UK patent office, have the potential to reduce capital costs and environmental impacts. Preece [70] concluded that it is the capital cost of the plumbing that makes the RWH system economically nonviable. Therefore, the installation method that requires the least plumbing may be the best option economically, e.g., outdoor use only [52].

Roebuck *et al.* [59] propose that, if the owner is only responsible for the operational and maintenance costs, and not the capital costs, then any financial loss will be minimal and there is a chance of a financial benefit from a RWH system. Rebate schemes in Australia have been used to help cover capital costs and encourage the use of RWH systems [63]. User reactions in Barcelona, Spain and their level of satisfaction towards RWH systems suggest that both regulations and subsidies are good strategies to advocate and expand RWH technologies in residential areas. A review of sustainable building policies in Kenya suggested the same [64,71]. Gato-Trinidad *et al.* [53] in their review of the rebate scheme in Greater Melbourne considered the cost-effectiveness of installation from both the government's and the owner's perspective and found them to be cost-effective to both. Financial analysis should consider the various stakeholders.

Improper consideration of maintenance and operational costs are responsible for many of the conflicting conclusions on the economic viability of a RWH system [52,57]. Ongoing maintenance expenses have often been identified as a primary reason for RWH system costs outweighing the benefits [59,60]. Hall [48] found that the variation in yield, along with pump and tank life and maintenance, had the largest effect on cost-effectiveness. Maintenance of a RWH system also requires adequate asset management to achieve water saving targets and to minimize health risks [72]. Financing the long-term operation and maintenance is a key issue. Financing with minimal external assistance is an important consideration for non-government organizations (NGOs) hoping to provide sustainable solutions to developing countries. Lessons can be learned from a review of sustainable handpump projects in Africa that found that there are hundreds of non-functioning village handpumps and that many projects are still failing to address basic issues such as training communities, establishing cost recovery mechanisms, and supply of spares [12].

Energy use as an operational cost is often not considered. Vieira *et al.* [73] found that RWH systems with pumps installed are less energy-efficient than conventional systems and closer to recycled water energy use, while without pumps they are competitive. The median energy intensity of their research was 0.20 and 1.40 kWh/m^3 [73]. They also found that the median energy intensity of theoretical studies was much less than in empirical studies and concluded that the theoretical studies had neglected some of the energy used, e.g., pump start up. It is noted that the difference may be due to lack of optimization in the empirical studies. Ward *et al.* [74] also noticed the same lack and, using an improved method, found that simple methods underestimated the energy consumption by 60% but still concluded that the energy consumption associated with RWH systems is minor, being only 0.07% of the office building they modeled. Their findings were confirmed by comparison to real life data.

2.4. Benefits

The primary economic benefit used in the literature is a function of the amount of water saved and the price one would have otherwise paid for it. Put simply: the more water saved, the more money saved. Issues with calculating water savings are discussed in Section 3, "Modeling and Design". There are also several other potential benefits, some of which have been economically quantified by researchers.

The quality of rainwater may represent a benefit in terms of power for heating and treatment when using it in the laundry and in hot water systems [45,75]. In contrast to RWH systems, Willis *et al.* [76] noted that water saving devices that save hot water also save energy because the water saved would also have been heated. However, the fact that rainwater is soft and also of a reasonable quality may give it an economic advantage over other water sources if they are hard. The economic and environmental advantage of replacing water mains when it is hard with rainwater in the laundry has been quantified by Morales-Pinzón *et al.* [45] by calculating power savings. The soft rainwater requires a lower washing temperature than hard tap water resulting in up to 0.84 kWh/cycle of power savings (at 0.22 AU$/kWh). They could also have calculated it using saved washing powder. The environmental benefits were also found to outweigh costs representing a carbon saving. The South Australian Appendix of the Building Code of Australia (ABCB, 2012) provisioned for a combined solar hot water and rainwater harvesting system. Chao *et al.* [75] analyzed the installations of the system at Lochiel Park, SA and found that it contributed up to 40% of the total hot water use. An added advantage of using rainwater in hot water systems is that it is heated to a minimum of 60 °C, as required by the Australian standards for water storage [77], killing harmful bacteria and saving the need for, and cost of, additional treatment.

There is concern that water from RWH systems may not be of high enough quality for certain applications [78]. This needs to be considered case by case and will depend on a comparison between the quality required for the intended use and the quality of the water collected from RWH system. In urban environments, it may be of lower quality than in rural or peri-urban. Roof type and system maintenance also affect the quality of harvested rainwater. EnHealth [79] acknowledges that rainwater is being used for almost all uses in Australia with relatively low risk, but mentions possible risks from microbiological activity and, in some areas, major industrial emissions, such as lead in Port Pirie, also compromise quality. In urban areas, it is common to use rainwater for a combination of outdoor, toilet, and laundry use (see Table 2 in Section 3).

Infrastructure savings may also represent another benefit. Coombes *et al.* [80] argued that delaying the water main's supply headworks by the widespread installation of RWH systems represents an economic benefit. They also noted that a lower rate of absorption of the roof catchment area compared to a dam's catchment makes the RWH system more efficient per unit volume of water. The cost of a particular dam and associated headworks depend upon a number of local factors such as geography and economics. In 2003, the ACT Government estimated that, by deferring a new dam worth AU$ 100 million for 3 years, which could be achieved by increasing water efficiency by 3%, would save AU$ 1 million/year. White [81] stated that rainwater systems are the most cost-effective means for increasing the security of urban water supplies. Two desalination plants are now a significant part of Perth's water, and their cost of water has increased considerably over the last 10 years [49]. Marsden *et al.* [82], in a report prepared for the Department of the Prime Minister and Cabinet in Australia, stated that urban centers reducing their use of water mains by 20% or more is equivalent to the water savings major projects such as desalination can supply. They concluded that water conservation measures are superior to desalination and are therefore a key strategy. Ishida *et al.* [61] recognized the potential benefit of RWH systems in stormwater management and combined sewer overflow control. Gwenzi *et al.* [83] found that urban RWH systems reduced downstream peak and total discharge, baseflow, and flow velocity. DeBusk *et al.* [84] in a comprehensive review found very little research on the stormwater management benefits of RWH systems.

Using a RWH system for irrigation also has the potential to improve food security [85–88], and particularly nutrition among women and children via small-scale domestic gardens [1,83]. Ngigi *et al.* [89] investigated $50 m^3$ of water storage used in conjunction with drip irrigation kits over 0.2 ha of cropped land, where cash flow was calculated from the improved yield of 4000–5000 kg/ha, showing an increase of 1000 kg/ha.

Many other indirect benefits from RWH systems may not be measured financially due to data limitations and difficulty in quantifying value. For example, in Sydney there is the privilege of being able to freely use water from a RWH system not connected to the mains, while others are restricted by the "water wise rules" that have replaced water restrictions [90]. There may be an increase in the real estate value of the homeowner's property, as quantified by Zhang *et al.* [49] using the hedonic price method. This method is commonly used to estimate the extent that price and demand can be affected by "scenic views, house appearance, and neighborhood demand" [50]. RWH systems are listed by the real estate agents as an "eco-friendly feature", and were found to represent a premium of AU$18,000 in Perth, Australia. One problem with this method is the complexity of knowing what attributes of the house are truly responsible for the increased value. Another is that not everyone is concerned with the value of his house on the property market. Zhang *et al.* [49] suggested that rebates might be unnecessary because of the increased real estate value, while stating that people installing RWH systems are generally unlikely to place their house on the market shortly after installing one.

Using a multiple criteria analysis (MCA) [91] may reveal more benefits. A simplified version was used by Melville-Shreeve *et al.* [69] to assess traditional and innovative RWH systems. As a result, they proposed several other potential energy savings and environmental benefits (which in turn relate to monetary savings) such as reduced raw water abstraction, pumping, and treatment. They also noted that, by reducing the peak demand, it might be possible to reduce the design capacities and delay a necessary upgrade of not only storm water infrastructure but also the water main's supply infrastructure. Savings on wastewater treatment could also be relevant where there are combined sewer and storm water systems in place. Thus, if all the potential savings and benefits are considered in a LCC analysis, RWH systems may be found to be more economically favorable.

The potential benefit in building up the economy of a nation is considered in Section 4.

3. Modeling and Design

The more water you save, the more money you save; hence, the quantity of water harvested from a RWH system is the predominant factor used in the literature to calculate financial benefit. This section specifically reviews in detail the factors involved in quantifying water savings for economic analysis. Table 2 presents a summary of the scenarios used to produce the financial results presented earlier in Table 1. It reflects the wide variety of inputs and corresponding water saving results in the literature.

The costs considered give an important indication of how well the economic aspects have been analyzed. Few have considered benefits from infrastructure savings, and some have ignored maintenance costs. Of particular interest for modeling water savings are type of installation, (often a combination of outdoor use, laundry, and toilets), the amount of water saved per household, and, in the peri-urban environment, the reliability. Difficulties in modeling and design are discussed below.

3.1. The Water Demand Profile

A major finding of investigations by Coombes *et al.* [92] was that using average water demands instead of spatial and temporal information produces large uncertainty in performance. Water use is a highly variable factor; for example, Australia has one of the highest levels of potable water consumption in the world, while in developing countries such as Kenya daily consumption may be considerably lower [93]. A comprehensive report on small community water supply states that domestic water use can vary from 5 L/p/d–250 L/p/d. People that have to walk more than 1 km to collect water use considerably less than those in houses with multiple tap connections [94]. On the basis of the International Reference Centre for Community Supply and Sanitation (IRC) report [94] Wanyonyi [95] considered the rainwater tank connection in Kenyan rural areas to be similar to a yard connection at 20 L/p/d–80 L/p/d, noting that 3–10 L/p/d is required for drinking water alone. Essendi [56], analyzing Nairobi County, used a daily threshold of 50 L/p/d for higher income households and 25 L for low-income households based on the United Nations recommendation of 20 L–50 L. A study of the Obunga Slums in Kisumu, Kenya [38] found that their water security was compromised by poor water-user preferences, including lack of conservation and use of low-quality water due to ease of access. Preferences were compared to United Nations World Water Assessment Programme UN-WWAP [93] recommendations for proportions of water use for personal washing, gardens, laundry, toilets, car washing, dishes, cooking, and drinking. It was concluded that water conservation and better water use preferences could help improve the water security of the slum. In the wealthier areas of Nairobi, GIS-based analysis revealed that water demand is associated with land value as well as population and building density [96].

Consumption may also be affected by water restrictions and other water saving initiatives. For example, the Millennium Drought in Australia saw all its capital cities imposing water restrictions with the exception of Darwin and Hobart [97]. Converting to water efficient devices also reduces consumption. Gato-Trinidad *et al.* [9] reported that annually up to 66 m^3 per household can be saved through water efficient appliances such as "front loaders, dual flush toilets, and AAA shower heads". However, the paper did not discuss some of the modern innovations such as the Caroma high efficiency duel flush toilet [98], which combines the toilet and hand basin, encouraging sanitation and saving water, or the AQUS greywater toilet, which recycles greywater from the sink. Various forms of greywater reuse are coming into focus in both developing and developed countries. In Kenya, as elsewhere, it is more perception than practicality that hinders its uptake [99].

Lochiel Park, South Australia has mains water supply consumption 29% lower than the national average. This is assumed to be due to a combination of RWH systems, water saving devices and other factors. The total water consumption on site is 16% lower than the national average. The 13% difference between the mains consumption and total onsite water use is assumed to be due to the RWH systems which are estimated to contribute 6%–10% of the total water use in summer and up to 26% in winter [75].

The rainwater is estimated to contribute 6%–10% of the total water use in summer and up to 26% in winter [75]. Gato-Trinidad *et al.* [53], using data provided by Yarra Valley Water in Australia for households that installed rainwater tanks, estimated savings of 105 m^3 annually per household (*i.e.*, from 247 m^3 to 142 m^3 after installation). However, while acknowledging the potential of water saving devices and strong water saving campaigns to reduce consumption, due to limited information they did not include them in their water saving calculations but assumed that the whole amount was due to RWH systems. As a result, the financial benefit of the rainwater tank in terms of water saved may be overestimated. Mayer *et al.* [100] found that retrofit water efficient devices can represent a 49.7% saving in water use per capita, while Inman *et al.* [101] reported 35%–50%. Willis *et al.* [76] noted that accurate assessment required high-resolution data for all the end uses, namely, "disaggregating water use for showers, toilets, clothes washers and garden irrigation *etc.*" However, they calculated a two-year payback period for showerheads, which could be reduced to one year if the energy savings were included (the water saved would also have been heated). Washing machines yielded a seven-year payback, while RWH systems required 23 years for the capital costs alone. Water efficient devices by reducing consumption also reduced the cost of water supply and treatment [76]. Given the option then, it may be more financially viable to reduce consumption rather than increase supply using a RWH system. Additionally, it appears that there may be some kind of conflict of interest in financial calculation as to which option should be credited for the reduction in reticulated water supply use, as noted by Gato-Trinidad *et al.* [53].

Composting toilets, especially in peri-urban and rural areas may be another alternative to using rainwater for toilets. Devkota *et al.* [10] developed a life cycle model, "EEAST", for analyzing the economic and environmental impact of RWH systems and composting toilets. Simulations so far favor composting toilets being used in conjunction with rainwater for irrigation to maximize water saving. Their model does not consider the solid waste management aspect of the composting toilets, so results are preliminary. In Nairobi, communal pit toilets are common among people with low income, whereas the middle-income bracket more commonly have flush toilets [56]. Composting toilets can produce good soil valuable as fertilizer, e.g., the "Clivus Multrum" [102], which, particularly in peri-urban and rural areas of developing countries, can produce an income or enhance crop production [85].

Outdoor water use probably represents the greatest variety in use including irrigation, washing hard surfaces, and cars. Apartments are likely to have low outdoor water usage compared to peri-urban areas or suburban detached houses with back yards, although research in Hong Kong has studied the use of RWH systems for rooftop rain gardens in highly urbanized areas. These rain gardens have the added benefit of producing a cooling effect of 1.3 °C, reducing the urban heat island and air-conditioning costs [91]. Improving water management methods has a direct impact on the water demand profile, which in turn has its financial effect. In other words, the financial research on RWH systems is dependent upon the technical research. A review paper on "Garden Kits" in Africa found that there has been little research on the economic outcomes and sustainability of water management technologies used in home gardens, such as use of greywater or clay pots, bag gardens, keyhole gardens, and trench gardens, although there has been a limited amount on the outcomes of programs promoting the use of RWH systems [103]. Although it is outside the scope of this paper, this area of research merges with that done on diverting roof and ground water runoff into ponds and dams. For example, unplanned land sub-division in Kenya has resulted in uneconomical small plots (<2 ha), leading to intensive agriculture and high risks of crop failures. The effectiveness of RWH systems also depends on soil characteristics and types of crops. A study of the Kieni East region of Kenya showed that one reason for RWH systems not being commonly practiced is the lack of capital for constructing the system [88].

3.2. Quantity of Rainwater Harvested

Rainfall patterns are highly variable, not only between countries but also within a country, and even from one part of a city to another, as well as from season to season. For example, in Australia from December to February, Perth has less than 6 days with more than 1mm of rainfall [49]. In Sydney, Mean Annual Rainfall (MAR) varies from 743 mm in Campbelltown to 1325 mm in Hornsby [24], only about 50 km away. In Kenya MAR ranges from 760 mm+ on the coast to 1780 mm+ in the highlands and less than 250 mm in the northern desert areas [104]. Khastagir *et al.* [47] investigated installing a RWH system in a variety of geographical locations around Melbourne with significantly varying MAR and found that the higher rainfall locations represented the more favorable financial scenarios for the RWH systems.

Design for optimum tank size is often based on the MAR of the location and yield calculated in conjunction with the roof area, tank size, installation method and demand profile [48]. Daily or even hourly rainfall data is often preferred by researchers. For example, Maheepala *et al.* [54], in a stochastic simulation, found that a daily time-step overestimated the yield by about 2% when compared to an hourly time-step. Devkota *et al.* [10], in their life cycle-based model "EEAST", used a monthly method which they found overestimated the size of tank required, and hence payback period, relative to a daily time-step. Londra *et al.* [105] made a comparison between the daily water balance method and the dry period demand method, which is based on meeting demand for the longest annual average dry period, and found that in all cases studied, the dry period demand method leads to a smaller tank. Hajani *et al.* [25] used a daily time step to build a water balance simulation model and noted that the type of behavioral model used could also affect yield-*i.e.*, that the yield-before-spillage (YBS) could overestimate the water savings by 10%–15% in comparison to a yield-after-spillage. After detailed behavioral analysis Fewkes *et al.* [106] advised using the Yield-After-Spillage (YAS) model for design because it gives a conservative estimate. They also proposed constraints for the use of hourly, daily and monthly time intervals based on the storage fraction of the RWH system (a function of roof area, tank size and annual rainfall). Daily, let alone hourly data, however, is not always available, and for ease of calculation Hajani *et al.* [25] developed a set of regression equations using MAR data to estimate reliability and water savings anywhere in the peri-urban regions of Greater Sydney, Australia. Developments in satellite estimation of rainfall data where there is little or no ground data available [107–110] may also become a powerful tool in estimating potential yield, water savings and hence financial viability of a RWH system.

3.3. Design Methods

In 2005 the Kenyan government in conjunction with a cross-section of the key stakeholders and in particular the Kenya-Belgium Study and Consultancy Fund, undertook a study for investigating various ways of securing water autonomy which resulted in the Practice Manual for Water Supply Services [111]. Several simple formulas are recommended in the Manual for Rainwater Harvesting, which included: (a) how to calculate rainfall yield; (b) how to calculate monthly demand for a given number of people, and c) how to calculate minimum tank storage. These methods, however, are similar to those criticized by Roebuck *et al.* [57] who found that simplified methods of RWH system analysis such as those presented in British Standards [112], Code for Sustainable Homes (UK) [113] and the Building Regulations (UK) [114], when compared to a more detailed analysis led to wrong financial & reliability claims.

Further work has been done by Gathenya *et al.* [55] who developed "nomographs" for a predetermined reliability of 67% for 50 towns in Kenya. The nomographs plot tank size against roof area making it easy to see what combinations will give a reliability of 67%. A decision can then be made between increasing tank size or roof area and the cheapest option can then be chosen. The reliability values were calculated using long-term rainfall data and various system configurations. They were put into the "JKUAT-RWH Performance Calculator" developed at Jomo Kenyatta University of Agriculture & Technology and compared to the "Warwick Calculator" developed by Warwick University in the UK [115]. There is, however, limited research on the financial viability of RWH systems in Kenya.

In Kenya, Andersen [116] focused on developing RWH system products for marginalized communities, and was able to develop an innovative and cost-effective RWH system for the Village Ngumbulu. Cost was of high concern due to poverty. By working alongside the villagers in conjunction with other stakeholders, he was able to develop a realistic solution using local materials and labor to minimize costs. In the UK, innovative design of RWH systems is being researched for potential improvement of their economic viability. Melville-Shreeve *et al.* [69] assessed traditional as well as innovative RWH systems gleaned from the UK Patent Office, expecting that with improved innovation their capital costs and environmental impacts may be reduced further. In this way, economic research needs to move with the technology.

The idea that RWH systems are best suited for individual homes was challenged by Morales-Pinzón *et al.* [117], who found that the neighborhood scale was the optimal scale for large-scale and high-density developments. Morales-Pinzón *et al.* [45] studied five spatial scales of installation of RWH systems: two single houses, eight single houses, one apartment building, groups of houses, and groups of apartment buildings. They found that the groups of houses and the groups of apartments resulted in the "highest profitability". Later, Morales-Pinzón *et al.* [62], having developed the software program "Plugrisost," found that the apartment-building scale is financially preferable to single-house scale, becoming viable for apartment buildings at a water price >2.2 AU$/m^3 compared to >6.28 AU$/m^3 for single houses.

Coombes *et al.* [92] recommend that regional water source analysis needs to be done using detailed local inputs, such as "demographic profiles, human behavior and climate dependent water demands, and linked systems that account for water supply, sewerage, storm water and environmental considerations" so that the full potential of Water Sensitive Urban Design (WSUD) can be realized. To design RWH systems more accurately, researchers in South Africa defined regions in terms of "ecotopes" (areas with same physical and socio-economic characteristics) [87]. They also concluded that only an integrated system approach is likely to be successful in improving water supply. Ward *et al.* [118] also highlighted the importance of a detailed method to avoid the over-sizing of the RWH system. The relationship between the water energy and food sectors, commonly called the water-energy-food nexus has been increasingly acknowledged as a key principal for water planning. With two related conventions having come into force globally in 2014, it is expected to become an increasing area of research [119].

3.4. Real-Life RWH System Studies

While there are plenty of studies based on hypothetical situations, there are a few studies of multiple RWH system installation economics using actual water consumption data from real life situations [120]. These studies, such as those by Chao *et al.* [75], are valuable but do have their limitations due to the large amount of data collection required. Limitations in the analysis of The Water Smart Gardens and Homes Rebate Scheme Melbourne [53] identified several problems in regards to water savings (the main factor in calculating financial benefit):

1. contribution of water efficient devices;
2. the effect of imposed water restrictions;
3. the effect of other water conservation programs; and
4. Information such as lawn/garden size, roof size, and household size.

Additionally, the costs, including installation and maintenance, were not based on data collected from actual money spent but were assumed based on academic research [121], reports by economists Marsden Jacob Associates prepared for the Nature Conservation Council [122] as well as information gleaned from retailers. Most of the assumed details could be collected via surveys, but that would require a substantial amount of data collection.

Ward *et al.* [118] compared a real life installation RWH system using a model-based approach with a theoretical design approach and found that the modeled system gave a higher reliability than the theoretical design, and concluded that this was due to the system being oversized. The RWH system malfunctioned during the analysis, which highlights the need to factor in malfunction and maintenance issues into theoretical design.

4. Feasibility of RWH Systems

4.1. Implementation in Developing Countries

Many Australian states have policies promoting uptake of RWH systems [49], which have been successful in achieving water saving targets. For example, a review of Queensland's mandate showed that many areas have reached their water saving targets and that adopting a RWH system beyond the mandate may significantly exceed the target [123]. The potential of RWH systems to also reduce water and food crises in developing countries and water-scarce urban and peri-urban areas like Sub-Saharan Africa is recognized by several authors [1,83,86–88,124]. Some governments are offering financial assistance in an effort to achieve Millennium Development Goals (MDG) [125]. In South Africa, despite this assistance, domestic RWH systems are technically illegal [87]. In Namibia, it is neither encouraged nor supported financially by the government [126] despite the fact that RWH system-based small-scale gardening in Namibia could improve daily meals and income in poor peri-urban and urban areas. However, due to high material costs relative to income they are unaffordable, and it is recommended that the government funds the RWH system infrastructure while the individual looks after the gardening and maintenance costs [126]. International institutions such as the Organization for Economic Co-operation and Development (OECD) and The World Bank argue that it is unrealistic to base financial planning of water services on full cost recovery of investment costs, proposing sustainable cost recovery instead [127,128]. A number of NGOs are addressing this issue and are focusing on using RWH systems, e.g., Africa Now, World Vision, and CARE Kenya [129].

Income inequality in Kenya, South Africa, and Mozambique is among the largest in the world; in all three countries, equity struggles related to water are growing in social, political, and ecological significance. Kenya as a country lacks mechanisms that will cushion it from the imminent scarcity that is recorded in, among other documents, the Kenya Vision 2030 [56,130]. Population in Kenya using improved drinking water sources is only about 60%, and improved sanitation is as low as 30% [34]. Shortage of domestic water is reported by residents as a key problem in Nairobi [40]. The RWH system holds a potential benefit for Kenya and much of Sub-Saharan Africa, but uptake will require a policy shift, as in some areas it is illegal [131]. For example, in Kenya the Public Health Act [132] legally prohibits it. Existing laws that were mainly developed by the British are outdated and neither encourage sustainability in construction nor take local conditions into account adequately: Presently, the building codes do not encourage and even prohibit RWH systems. There are, however, proposals to make it a requirement for new buildings, along with solar heating [71,133–135]. The reviewing of laws and sorting out of conflicts of interest, e.g., between the health act and sustainable development, is a substantial hidden cost. Awareness campaigns [136], and in many cases finance [71], will also be necessary, as the initial costs of developing green buildings is too expensive for most existing households. Additionally, there is a lack of cost-benefit analysis of building projects in Kenya [71]. However, it is expected that Kenya's legal framework will soon actively promote and support the adoption of RWH systems [137]. A recent study focusing on underserved households in urban and rural Kenya, investigating the viability of decentralized models, such as the Safe Water Enterprise (SWE), reports that a maximum of 2% of their water supply presently comes from RWH systems [138].

One reason for the insufficient impact of Water, Sanitation and Hygiene (WASH) programs, despite receiving financial support from NGOs in 76% of schools, including RWH systems and other components, is a lack of funds from the government to cover maintenance, repairs, and other recurrent costs (60% of these schools had hand-washing water, 13% had washing water in latrines for menstruating girls, and 2% had soap). Sub-optimal WASH conditions in schools may hinder girls' ability to concentrate in class or attend school when menstruating, leading to, at worst, a greater likelihood that girls will drop out of school completely [139].

Water scarcity is also a real problem in arid and semi-arid (ASAL) regions of Kenya [88,138]. A review of the Australian Centre for International Agricultural Research (ACIAR) activities in Africa concerned with agricultural advances suggest that new skills should be developed through training and longer-term involvement with Australian scientists, implying that information alone is not sufficient and that some projects have been unsuccessful as a result of a lack of underlying skills, the long time taken to learn new techniques, and high turnover of personnel [140].

A study of the innovations in Mathare Valley Slums, a peri-urban settlement in Nairobi, argues that urban slums are ideal places to consider adaptation because they offer examples of extreme social-ecological stress and find that people are already using RWH systems [41]. The fact that many of the occupants are financially challenged is an indication that RWH systems can be financially viable. The Kenya Debt Relief Network (KENDREN) surveyed water services in Kibera, Mathare, and Huruma slums and found community organizations capturing and using rainwater in gardens, for washing cars and/ or selling it and putting profits back into the community [130].

4.2. Individuals, NGOs, and Policy Makers

Ryan *et al.* [97] saw increasing water efficiency via RWH systems as a cost shifting exercise, finding that water from RWH systems costs the individual AU\$6/m^3. In many respects, and particularly in the urban environment, adoption of privately owned RWH systems takes the responsibility of water supply out of the hands of the public sector and into the private. The benefit of private RWH systems to the government has been recognized in India where national and state governments have framed rules and policies supporting the installation of RWH systems [13]. In Huruma Estate, an uncontrolled residential development area in Nairobi, Kahariri [39] found that successful water and sanitation supply is dependent upon the involvement of all the stakeholders, suggesting actions for government, the private sector, NGOs, community members, the Nairobi Water Services Board, the Nairobi Water and Sewerage Company, and the Nairobi County Council.

Although questions about the job creation potential with the RWH systems are outside the scope of this review, effects on the society as a whole; for example, the Snowy Mountains Hydroelectric scheme in Australia was used to build up the Australian nation [141] and other socio-economic considerations [142], present important questions for policy makers. Herrmann et al. [143] found that the RWH system market in Germany contributed to the country's economy, stating: "The market for rainwater usage related products is booming and of increasing economical importance".

5. Conclusions

In this paper, issues concerning the economic analysis of RWH systems are reviewed with a special focus to Australia and Kenya. The following important points are highlighted from this review.

RWH systems can save a large quantity of relatively high quality water at a reasonable cost. The dominant factor in assessing the economic benefit of a RWH system is the price of water saved. This is largely dependent upon future predictions of water price, which are expected to increase substantially in future, and accurate modeling of the RWH system. Higher water price, lower interest rate, higher rainfall, and proper tank sizing relative to demand profile contribute towards making RWH systems more economically favorable. The majority of research in Australia and other countries with strong economies have shown that water from RWH systems is generally more expensive than tap water at current water price. The studies on financial aspects of RWH systems often had conflicting results. Misrepresentation of operational costs of RWH systems particularly has led to misleading conclusions in many cases. In view of the varying and conflicting results, there is a need to standardize the methods of economic analysis for RWH systems.

Most of the studies on economic analysis of RWH systems have ignored subsidiary benefits that a RWH system can offer, such as the flexibility offered by a RWH system during water restriction period and intermittent presence of water in the mains particularly in developing countries like Kenya, the creation of additional jobs, and environmental benefits. Regarding laundry, there are potential energy savings from using rainwater, which is soft, in exchange for water main supply when it is hard. Replacing treated water mains by water from RWH systems in hot water systems can save the energy used in treatment. However, most of the previous studies have ignored these benefits offered by a RWH system.

There is a growing awareness that concepts such as water-sensitive urban design, multiple criteria analysis, and consideration of the water-energy-food nexus is necessary for effective design and appraisal of the full range of benefits that a RWH system offers. Infrastructure savings are a potential benefit to the government in delaying large-scale infrastructure for increasing water supply to a growing population and possibly reducing the size of stormwater infrastructure when RWH systems are installed across entire suburbs.

Kenya and other developing countries can learn from Australia where RWH systems have been quite successful. Kenya has undertaken limited economic analysis of RWH systems, and this should be a priority for the government and NGOs in Kenya. Rebate schemes in Australia have been successful. Research suggests that, if capital costs are excluded, the owner of a RWH system has a reasonable opportunity to make a financial benefit when paying for the ongoing costs alone. Therefore, a rebate scheme for RWH systems should be a preferred option for policy makers in Kenya and other developing countries. There is also an indication that funding tank installations in Kenya will be successful if adequate training for maintenance is also organized. The use of RWH systems in water management strategies for small-scale domestic gardens and their financial benefit through crop production also warrant further research. Barriers to installation of RWH systems such as legal issues embedded in the government policies in Kenya should be removed to encourage a wider adoption of RWH.

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