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Rainwater Harvesting Impacts on Environment

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There are 6 aspects of impact analysis available on rainwater harvesting (RWH), which can be identified as: water savings, energy savings, life cycle analysis (LCA), life cycle costing (LCC), runoff reduction and pollutant load reduction. So far, all of these aspects have been neither considered fully nor analysed rigorously to evaluate the net environmental impacts of RWH on a catchment-scale. Particularly, direct impacts of runoff and pollutant load reductions on the environment were not evaluated. In this research, runoff and pollutant load reductions are estimated through simulation using storm water management model (SWMM). Water and energy savings, and runoff and pollutant reductions in LCA are used to estimate the net impacts on environment. Findings of this study are: i) RWH (with pump) have more negative environmental impacts than the system without RWH in all the considered impacts categories; ii) system with RWH (without pump) of 2KL, 3KL, 6.5KL and 9KL tank sizes have less negative environmental impacts than the system without RWH in all the impact categories, except ozone layer depletion; iii) higher non-potable demand met by RWH (without pump) showing less environmental impact; iv) annual rainfall amount has no effect on the considered impact categories, except eutrophication and freshwater eco-toxicity; however, these categories exhibit less negative impacts in dry years; and v) recycling of RWH system components contribute positively to the net environmental impact. This study would help to remove uncertainty related to performances of RWH in Australia and elsewhere on a catchment-scale.

1. INTRODUCTION

Rainwater is one of the most easily and freely available sources of water that can be used for non-potable purposes (Devkota et al., 2015). According to an Australian Bureau of Statistics (ABS) survey conducted in March 2013, about 34% of Australian households had a rainwater tank, increasing from 32% and 26% in 2010 and 2007 respectively. The ABS survey suggested that this increment between 2007 and 2013 might be due to one or more of: water restrictions, a government rebate scheme, water regulation and pricing. RWH has wide-spread perceptions of being environmentally friendly initiative in terms of potable water saving, mitigation of flooding in urban catchments and measures against extensive growth of impervious surfaces. It also reduces nutrient loads to waterways and increases the lifespan of centralized water distribution infrastructure, due to demand reduction (Vieira et al. 2014). However, the data and information required to verify these perceptions are not adequate as discussed by Stillwell & Webber (2010), Urmee et al. (2012), Vieira et al. (2014) and Devkota et al. (2015). Current literature shows that there are 6 aspects of RWH impact analysis available, which can be identified as: water saving, energy saving, LCA, LCC, runoff and pollutant load reductions. Some major studies have been discussed here in the light of above mentioned 6 aspects.

Rahman et al. (2010) developed a water balance model to estimate water savings of a multistoried building, considering various scenarios in relation to location and number of inhabitants in the building. Application of LCC showed that water savings and financial benefits are related to area of the roof available for RWH. Reasonable payback was possible under some scenarios and favorable conditions. Another study by Rahman et al. (2012) found that the average annual water savings from rainwater tanks were strongly correlated with annual rainfall quantity and pattern. However, its benefit/cost ratio was found to be greater than 1 only with the government rebate applied. Ward et al. (2012) estimated that about 87% of water saving efficiency of an office-based RWH system was possible over an 8 month period. Ghisi & Schondermark (2013) found that RWH is economically feasible only where higher
rainwater demand exists. Sample & Liu (2014) did not get net positive benefits for RWH. All these papers discussed primary benefits that would be expected to result in real cash savings to individual property owners. Government rebate is only? given to individual owners of RWH schemes that anticipate a notable reduction of demand on water mains, and thus have positive environmental impacts. That is why RWH, especially through rain water tanks, has become popular in Australia. With the increase in use of RWH, it is imperative that the net environmental impacts due to construction, operation & maintenance and disposal of the system are studied thoroughly.

It is obvious that the water saving is highly correlated to energy saving (Stokes, 2011). Jiang et al. (2013) found that RWH can save 139.8% of energy compared to a mains water supply system. Some authors analysed water and energy savings together. Proença & Ghisi (2013) estimated that potable water savings were 6.1 to 21.2% using RWH. It also analysed the environmental impacts in terms of embodied energy for materials and fabrication of the system. The embodied energy for RWH was found to be higher than other comparable options considered. Nazer et al. (2010) have showed that the percentage reduction of annual environmental impacts were 8% and 38% for using a low-flow shower head and RWH systems, respectively. The environmental impacts were evaluated in terms of pollutant emissions to air, water and soil resulting from the changes in water use, wastewater production and energy consumption. LCA was carried out for the production (i.e. material, fabrication and installation), operation & maintenance phases only, without considering the disposal phase. Pollutant reduction was analysed in terms of water savings from the mains water supply, which was also a partial consideration of the whole scenario. Runoff and pollutant reductions by RWH could have been added to the LCA, to evaluate the net environmental impact, but was not done in this study? Vargas-Parra et al. (2013) used the LCA approach to compare the performance of RWH in terms of ‘exergy’ (quantity of exergy in a material or subsystem is measure of potential work, it is measurable in the same units as energy and work). It was identified that the highest ‘exergy’ required was for transportation of the materials to the construction site. Materials, transportation, construction, operation, maintenance, deconstruction and transportation of deconstructed materials to waste management plant were included in their LCA study. However, processing of deconstructed materials at the end of their life was not included in the study. Morales-Pinzon et al. (2014) used global warming potential and energy use indicators to analyse environmental impacts. Materials, construction and operation phases were included for LCA.

Runoff and pollutant loads from catchments are responsible for degradation of natural water bodies. Therefore, impacts of these two elements should also be considered together in the study of RWH. Studies are being done to quantify runoff and pollutant loads and to mitigate its impact on environment. Walsh et al. (2014) showed the volumetric reduction of runoff and the corresponding cost of runoff reduction by RWH at the watershed-scale. Sample & Liu (2014) estimated runoff capture reliability of RWH through simulation. Khastagir & Jayasuriya (2010) have simulated the reduction in pollutant through use of rainwater tanks in a single household using model for urban stormwater improvement conceptualisation (MUSIC). Rahman et al. (2010) concluded that inclusion of runoff and pollutant reductions would have made the RWH systems sustainable. However this was not included in their study due to unavailability of proper data.

From the above discussion it is clear that RWH, so far, was studied on the basis of one or two aspects, whereas it is essential to consider all the above mentioned aspects to get a comprehensive picture of sustainability. Most of the authors gave emphasis to water and energy savings. Some authors included impacts of RWH on environment through LCA, however, none of them have included all the components of LCA. Morales-Pinzón et al. (2012) have tried to integrate financial and environmental indicators to conclude that systems that are more financially viable are not necessarily the best in terms of environmental impacts. It is necessary to consider all of the above mentioned aspects comprehensively, for assessing the net impacts of RWH. Ironically, runoff and pollutant load reduction have been quantified by different studies, but the environmental impacts due to these reductions have not been studied yet. As an initial attempt, all of the above aspects, except LCC, are being considered for this study. The outcome of the research will add a new feature to the sustainability study of RWH.
2. METHODOLOGY

2.1 Scope and Study Area

A catchment of residential area (204 lots in 15.9 ha) in Wyndham City Council, Melbourne was selected. The catchment represents a complete stormwater drainage network. SWMM was used to simulate catchment drainage network runoff and pollutant load (e.g. total suspended solid (TSS), total phosphorous (TP), total nitrogen (TN), nitrate, phosphate, lead and zinc) responses for variations in RWH installations (including size and percentage of houses with RWH) and storm events. The subsequent environmental impacts due to runoff and pollutant reductions were evaluated through LCA using SimaPro software. Water and energy savings, and runoff and pollutant reductions, as parts of LCA, were used to estimate the net impacts on environment. The LCA on the RWH system indicates the environmental sustainability of the system. The boundary of the system in LCA was defined as the water mains at the user end, different RWH components, runoff and pollutant load. The system boundary represents the scope of LCA in a particular study. Water mains plumbing and stormwater drainage networks were excluded from this study, as it was assumed that these would exist in the system with or without RWH. It was assumed that the residential lots had installations of rainwater tanks of different sizes as mentioned in Table 1.

2.2 Life Cycle Analysis (LCA)

LCA is a tool for quantifying the environmental performances or impacts of products or a system. It takes into account the life cycle such as production of raw materials, construction, operation & maintenance and disposal of the products including material recycling. In this study SimaPro was used as LCA software. SimaPro provides a professional tool to collect, analyse and monitor the sustainability performances of products and services. It is integrated with various databases and impact assessment methods.

This study considered life cycle to include: production of raw materials, construction, operation and disposal of the system components including recycling. The LCA method, ‘Australian indicator set v3 V3.01 / Australian total’ was used in this study. The impact categories considered in this study are global warming, ozone depletion, eutrophication, human toxicity-carcinogenic, eco toxicity-freshwater, eco toxicity-marine and eco toxicity-terrestrial. For comparing the environmental impacts of the systems with and without RWH, the scenarios shown in Table 1 were considered. With the combination of tank sizes as shown in Table 1, the environmental impacts of 48 scenarios were compared with the system without RWH. Tank sizes of 2000 to 9000L were used in combinations of 60, 80 and 100% of demand met, in different rainfall years, for different RWH components, which resulted in a total of 48 scenarios run in SimaPro.

Table 1. Scenarios considered for life cycle analysis (LCA)

<table>
<thead>
<tr>
<th>Tank size (L)</th>
<th>Non potable demand met (%)</th>
<th>Components in RWH system</th>
<th>Annual rainfall (mm)</th>
<th>Tank material type</th>
<th>Catchment covered by RWH system (%)</th>
<th>Water use</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000, 3000, 6500, 9000</td>
<td>60, 80, 100</td>
<td>Pump used, Pump not used, No first flush, No tank base</td>
<td>Driest - 463 Average - 654 Wettest - 914</td>
<td>High density polyethylene (HDPE)</td>
<td>100</td>
<td>Toilet + gardening</td>
</tr>
</tbody>
</table>

2.3 Quantifying Runoff and Pollutant Load Reductions

SWMM was used to quantify runoff and pollutant load reductions. It is a dynamic rainfall-runoff simulation model developed by Environmental Protection Authority (EPA) USA for single event or long-term (continuous) simulation of runoff quantity and quality primarily from urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the
quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth of water in each pipe and channel during a simulation period. A simulation was carried out in SWMM for quantification of runoff and pollutant loads with (for 100% of lots) and without RWH. As validation was not done, simulation parameters were adjusted using the pollutant concentration data from Egodawatta et al. (2013), Valtanen (2014) and Miguntanna et al. (2013). Average runoff generated per lot was quantified by simulation, as shown in Table 2. Annual rainfall data for dry, average and wet years was taken from Imteaz et al. (2011). A typical two hours storm event of 43 mm rain was assumed, to calculate the runoff as shown in Table 2.

Table 2. Average runoff (KL) generated per lot per year from Storm Water Management Model (SWMM)

<table>
<thead>
<tr>
<th>Rainfall, mm</th>
<th>Tank Size (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No tank</td>
</tr>
<tr>
<td>914 – wet yr</td>
<td>296.0</td>
</tr>
<tr>
<td>654 – av yr</td>
<td>211.7</td>
</tr>
<tr>
<td>463 – dry yr</td>
<td>150.4</td>
</tr>
</tbody>
</table>

Average concentration of pollutants generated from the study area quantified by SWMM simulation are shown in Table 3.

Table 3. Average concentration of pollutants generated from the study area

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>TSS</th>
<th>Lead</th>
<th>Zinc</th>
<th>Nitrate</th>
<th>Phosphate</th>
<th>Total Nitrogen</th>
<th>Total Phosphorous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration (mg/L)</td>
<td>223.67</td>
<td>0.06</td>
<td>0.08</td>
<td>0.35</td>
<td>0.12</td>
<td>6.96</td>
<td>1.49</td>
</tr>
</tbody>
</table>

2.4 Raw Data and Data Source for LCA

High density polyethylene (HDPE) was considered as the tank material for this study. Weight of the tank was taken from the web site of the tank industry. Electricity and natural gas consumed to produce a tank was taken from the literature. The weight of the tank, and energy consumption for producing various tank sizes, were determined through interpolation. The tank sizes considered in this study were 2000, 3000, 6500 and 9000 L. Average transportation distance for the tanks was considered as a 30 km radius around Melbourne. A small pump and 20 m of PVC plumbing pipe were included as the other components of the RWH system. Non-potable demand of water usage was taken as 185 L/day/person from Imteaz et al. (2011). The RWH system life cycle was assumed as 20 years in this study.

3. RESULTS AND DISCUSSION

3.1. Comparison of Impacts of the Systems with and without RWH

Comparison of the environmental impacts between the systems with and without RWH is shown in Figure 1(a-g). The system with RWH (pump used) of all considered tank sizes had more negative environmental impacts than the system without RWH in all the impact categories considered. RWH system (no pump used) of all considered tank sizes had less negative environmental impacts (Figure 1a-f) than the system without RWH in all impacts categories considered, except ozone depletion (Figure 1g). The RWH system with larger tank sizes contributed more negative environmental impacts than the system with smaller tank sizes. It was observed that CO2 equivalent emissions by the HDPE tank were about 90% of the whole emissions by the RWH system (no pump used). Electricity was the prime contributor to the negative environmental impact in HDPE tank manufacturing process. LCA result also showed that CO2 equivalent emissions by the pump component were about 75% of the whole emission of the RWH system. Electricity usage was mostly responsible for the emissions due to pump manufacturing and operation together. Therefore, pump and rainwater tank (HDPE) are the prime contributors to the negative environmental impacts. For the non-potable water demand met by RWH,
Figure 1. Environmental impacts for systems with and without rainwater harvesting (RWH) for average annual rainfall condition; a. global warming, b. eutrophication, c. human toxicity-carcinogenic, d. echo toxicity-freshwater, e. echo toxicity-marine, f. echo toxicity-terrestrial and g. ozone depletion.
less egative environmental impact was found if no pump was used in the system. The RWH system (no pump used) meeting 100% of the non potable demand showed lower impacts than the 60% demand. 

Runoff and pollutant load reduction affected eutrophication and ecotoxicity-freshwater only. This was because of less nutrients being carried to the natural water bodies due to less runoff. There was no effect on other impact categories due to runoff and pollutant load reduction.

If a pump was used, the system meeting 100% non potable demand had higher impacts than the system meeting 60% demand (Figure 1a-f). This was because of operation of the pump.

Recycling of RWH components such as pump (steel and aluminium), rainwater tank (HDPE) and plumbing pipe (PVC) contribute positively to the environment.

Table 4 shows the impacts for different tank sizes in dry, average and wet condition for 80% non potable demand (no pump used). There was no effect of annual rainfall amount on impacts categories except eutrophication and ecotoxicity-freshwater. However, these categories exhibit less negative impacts in dry year. This is because of less nutrients are carried with stormwater runoff into natural water bodies.

Table 4. Environmental impacts for different rainwater tank sizes in dry, average and wet conditions for 80% non-potable demand met (RWH without pump)

<table>
<thead>
<tr>
<th>Tank Size (L) /annual rainfall condition</th>
<th>Global warming (Kg CO2 eq)</th>
<th>Ozone depletion (Kg CFC11 eq) x 10^3</th>
<th>Eutrophication (PO4 eq)</th>
<th>Human toxicity-carcinogenic (DALY) x 10^6</th>
<th>Eco toxicity-freshwater (DAY) x 10^6</th>
<th>Eco toxicity-marine (DAY) x 10^6</th>
<th>Eco toxicity-terrestrial (DAY) x 10^12</th>
</tr>
</thead>
<tbody>
<tr>
<td>No RWH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>43.8</td>
<td>0.518</td>
<td>0.040</td>
<td>2.30</td>
<td>0.40</td>
<td>0.78</td>
<td>2.48</td>
</tr>
<tr>
<td>Av.</td>
<td>43.8</td>
<td>0.518</td>
<td>0.050</td>
<td>2.30</td>
<td>0.40</td>
<td>0.78</td>
<td>2.48</td>
</tr>
<tr>
<td>Wet</td>
<td>43.8</td>
<td>0.518</td>
<td>0.060</td>
<td>2.30</td>
<td>0.45</td>
<td>0.78</td>
<td>2.48</td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>16.1</td>
<td>1.33</td>
<td>0.031</td>
<td>0.74</td>
<td>0.20</td>
<td>0.36</td>
<td>0.58</td>
</tr>
<tr>
<td>Av.</td>
<td>16.1</td>
<td>1.33</td>
<td>0.039</td>
<td>0.74</td>
<td>0.24</td>
<td>0.36</td>
<td>0.58</td>
</tr>
<tr>
<td>Wet</td>
<td>16.1</td>
<td>1.33</td>
<td>0.051</td>
<td>0.74</td>
<td>0.29</td>
<td>0.36</td>
<td>0.58</td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>17.3</td>
<td>1.35</td>
<td>0.031</td>
<td>0.81</td>
<td>0.21</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>Av.</td>
<td>17.3</td>
<td>1.35</td>
<td>0.039</td>
<td>0.81</td>
<td>0.24</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>Wet</td>
<td>17.3</td>
<td>1.35</td>
<td>0.050</td>
<td>0.81</td>
<td>0.29</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>6500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>21.7</td>
<td>1.44</td>
<td>0.034</td>
<td>1.03</td>
<td>0.23</td>
<td>0.74</td>
<td>0.56</td>
</tr>
<tr>
<td>Av.</td>
<td>21.7</td>
<td>1.44</td>
<td>0.039</td>
<td>1.03</td>
<td>0.25</td>
<td>0.74</td>
<td>0.56</td>
</tr>
<tr>
<td>Wet</td>
<td>21.7</td>
<td>1.44</td>
<td>0.046</td>
<td>1.03</td>
<td>0.26</td>
<td>0.74</td>
<td>0.56</td>
</tr>
<tr>
<td>9000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>24.5</td>
<td>1.50</td>
<td>0.035</td>
<td>1.17</td>
<td>0.24</td>
<td>0.92</td>
<td>0.55</td>
</tr>
<tr>
<td>Av.</td>
<td>24.5</td>
<td>1.50</td>
<td>0.039</td>
<td>1.17</td>
<td>0.25</td>
<td>0.92</td>
<td>0.55</td>
</tr>
<tr>
<td>Wet</td>
<td>24.5</td>
<td>1.50</td>
<td>0.044</td>
<td>1.17</td>
<td>0.27</td>
<td>0.92</td>
<td>0.55</td>
</tr>
</tbody>
</table>

4. CONCLUSION

Systems with RWH (pump used) had more negative environmental impacts than systems without RWH in all considered impact categories. The RWH systems with a pump are responsible for higher negative environmental impacts because of the electricity consumption by the pump manufacturing and operation. Smaller tank sizes show less negative environmental impacts except ozone depletion. Larger tank sizes contributing more negative impacts because of HDPE. Further study can be done by replacing HDPE with other tank materials such as mild density polyethylene (MDPE), steel and ferro cement. As the pump is one of the major negative impacts contributors, further study could be carried out, including the effects of raising the tank base, so that rainwater can be supplied by gravitational force. Additionally, some scenarios could be created by adding a first flush component, varying water usage, varying transporation distance and varying the percemtage of the lot covered by RWH.

This study had some limitations with regard to some raw data (electricity and natural gas consumed to produce a tank and average transportation distance for the tanks) used for LCA and SWMM simulation.
There was some interpolation involved, due to unavailability of real life data, and the simulation results were not validated in this study. These limitations would be overcome in further study.

Runoff and pollutant load reduction had impacts on eutrophication and ecotoxicity-freshwater only. This is because of the conveyance of nutrients by stormwater to natural water bodies. The comparison of environmental impacts between rainwater tank and other water sensitive urban design (WSUD) elements such as bioretention swales, bioretention basins and aquifer storage and recovery, have not been studied. Further work is required to assess the impacts on the environment with respect to reducing the same quantity of runoff and pollutants by WSUD elements other than rainwater tanks.

It would consolidate the feasibility study of RWH if the above discussed limitations are removed through further study, and scenarios are assessed in future studies. This would help to reduce the uncertainty related to performance of RWH approaches in Australia, and elsewhere, on a catchment-scale.

REFERENCES


