Life-cycle energy and CO₂ analysis of stormwater treatment devices
R. M. Andrew and É.-T. Vesely

ABSTRACT

Environmental impacts associated with the construction, maintenance, and disposal of low-impact stormwater management devices are one aspect that should be considered during decision-making and life-cycle assessment (LCA) is a suitable method for quantifying such impacts. This paper reports a pilot study that employs LCA to compare life-cycle energy requirements and CO₂ emissions of two stormwater devices in New Zealand. The two devices are a raingarden servicing an urban feeder road, and a sand filter that could have been installed in its stead. With an assumed life-time of 50 years, the life-cycle energy requirements of the built raingarden were almost 20% less than for the sand filter, while the CO₂ emissions were 30% less. Our analysis shows that given the difference between the infiltration rates used in the raingarden design (0.3 m/day) and measured during monitoring (3 m/day) there was potential to make significantly greater life-time savings using a smaller design for the raingarden that would have also met the treatment efficiency expectations. The analysis highlights the significant contribution of transportation—of both materials and staff—and ongoing maintenance to a treatment device’s life-cycle energy and CO₂ profiles.

Key words | life-cycle assessment, raingarden, sand filter, stormwater treatment

INTRODUCTION

The detrimental impacts of urbanisation on the water environment indicate the necessity for changes in urban design and infrastructure. A range of treatment devices has been proposed for implementation of low-impact stormwater management (e.g., Auckland Regional Council 2003). One relevant aspect when considering the implementation of low-impact stormwater treatment devices is their life-cycle cost (NZWERF 2004; Vesely et al. 2005). Life-cycle cost is the sum of the acquisition and ownership costs of an asset over its lifetime from design stage, manufacturing, usage, and maintenance through to disposal. A ‘whole-of-life’ time frame is warranted because future costs associated with the use and ownership of an asset are often greater than the initial acquisition cost and may vary significantly between alternative solutions to a given operational need (Australian National Audit Office 2001).

Alongside the monetary costs of low-impact devices, the environmental impacts associated with their construction, maintenance, and disposal are another aspect to consider during decision-making. Life-cycle assessment (LCA) is a method for analysing the environmental impacts of a product ‘from cradle to grave’. The international standards for this method have been documented in the International Organization for Standardization’s environmental standards ISO 14040:2006 and ISO 14044:2006.

This article documents a pilot study that employs LCA methodology for environmental performance evaluation of stormwater devices in New Zealand. The study compares the relative life-cycle environmental impact—energy and CO₂ emissions—of two stormwater treatment devices: a raingarden built in North Shore City, and a sand filter (Hynds Environmental model) that could have been installed in its stead.

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The device to be compared with the raingarden was selected based on information from Technical Publication (TP) 10 (Auckland Regional Council 2003, especially chapter 4, Tables 1, 2, 8, 9 and 10), to be appropriate for the size of the catchment (0.5 ha) and to provide similar quality treatment levels to the raingarden.

**Functional unit**

Both the raingarden and sand filter are especially suitable for small catchments and are primarily water quality practices with water quantity control benefits limited to relatively small and short, high-intensity events where the devices act to reduce peak discharge flow rates. Therefore we are mainly interested in the water quality treatment provided by the stormwater devices, the functional unit being the treatment of 75 m³ of water quality volume using TP10 designs. TP10 specifies design procedures for both raingardens and sand filters to achieve a 75% removal of Total Suspended Solids on a long-term-average basis. It is expected that levels of many contaminants such as particulate copper, zinc, cadmium, and lead, particulate nutrients, oil, grease, and bacteria would also be reduced because these contaminants attach to sediments.

**Site description**

The raingarden constructed on Paul Matthews Road, North Shore City, has a hydrological catchment of approximately 5,000 m² with 95% imperviousness and an estimated 2-year return period, 24-hour duration storm of 80 mm. Before construction of the raingarden, untreated stormwater from the catchment was directed to an open watercourse, Alexandra Stream. The catchment registers high traffic volumes; during a 7-day survey 95,900 vehicles passed the raingarden site, of which about two-thirds were light and one-third heavy vehicles. Assuming this was a representative sample, nearly 5 million vehicles pass through the catchment every year. Much of the sediment in road runoff, particularly the ecotoxic elements (zinc, copper, lead), comes from vehicular traffic (Simcock et al. 2007).

**System boundary**

Because this is a comparative study, the system boundary has been defined to include operations that were required specifically for each device, while common operations were excluded. Consequently, the works required to divert stormwater from the existing reticulation system (under-road pipes) and from the road surface (single-splay catchpit), the pipe required to direct the output of the device to the watercourse, and the vehicle pad were excluded from the system. However, information on these works is still reported in the inventory for completeness. The system boundary of the raingarden is indicated in Figure 1.

Two additional assumptions define the system boundary: (1) the life-time of both devices is 50 years and (2) the end-of-life (disposal) energy requirements and CO₂ emissions are calculated for one hypothetical scenario consisting of removing the devices to the same landfill and refilling the holes with soil sourced from the same distance (10 km); due to difficulties in foreseeing future regulations, technology, etc., the results are reported with and without the inclusion of the disposal phase. A number of other disposal scenarios could also be envisioned. For example, the concrete components might end up crushed and used as aggregate in a future construction project. The polyethylene pipes are recyclable, and recycling would reduce the use of a limited resource (fossil fuel). While recycling does require energy input, the energy required for recycling is less than is required for production of virgin polyethylene, so recycling could actually be viewed as a negative energy requirement (energy-use offset). The media used in the raingarden might be left in the ground (depending on level of contamination).

The sequestration of carbon dioxide by plants and soil in the raingarden has not been included in the analysis due to lack of data. To estimate the amount of carbon dioxide sequestered during the assumed 50-year life span of the raingarden it would be necessary to measure the growth rate of the raingarden plants at the site, the amount of foliage being lost and decomposed annually, the decomposition rate of the below-ground root carbon, soil respiration rates, and many other factors. Without data on these factors it is impossible to estimate the magnitude of the effect of sequestration over the raingarden’s lifetime (Surinder Saggar, pers. comm.).
METHODS

Following system boundary and functional unit definition the next step of a life-cycle assessment is to perform a life-cycle inventory, i.e., an inventory of all processes involved in the life-time of the system. Inventories for the built raingarden, a hypothetical reduced-size raingarden, and a sand filter are described in this section.

Raingarden inventory

Design

The raingarden was initially designed by Water Engineering Consultants and Landcare Research to handle one-third of the runoff from the 2-year return period, 24-hour duration event calculated to be 121 m$^3$. The required 320-m$^2$ surface area was provided in the original design by a raingarden with two terraces fitted to the contours of the sloping site. However, in order to test a more cost-effective option, the design was modified such that it would only treat 75 m$^3$ of runoff (Smythe et al. 2007). The required surface area, based on an assumed coefficient of permeability of the raingarden medium of 0.5 m/day, was 200 m$^2$. The total area of the raingarden site, including aesthetic and riparian planting and access footpath, is about 1,000 m$^2$.

Monitoring indicates that the raingarden has a mean subsoil permeability of 3.0 m/day – ten times higher than the design level. As a result, the raingarden as constructed could

![Plan view of the raingarden (as built) with the system boundary indicated by the dashed line.](https://iwaponline.com/wst/article-pdf/58/5/985/436327/985.pdf)
treat considerably higher runoff levels or could have been made smaller and still treat the 75 m³ of water quality volume (Robyn Simcock, pers. comm.).

Construction

Construction of the raingarden required the excavation and removal of 675 m³ of soil, installation of five manholes, a single-splay catchpit, and 4.8 tonnes of polyethylene (PE) and concrete pipes, back-filling with 372 m³ of media and planting. The entire operation took about two months to complete. Of the five manholes, one was required only for monitoring purposes because the raingarden forms part of a research project (see Simcock et al. 2007), and three other manholes and a single-splay catchpit were required to divert stormwater to the site, which would be common to whatever treatment option was chosen for the same site. In addition, approximately 1.8 tonnes of the pipes were required for the diversion of stormwater from the existing reticulation system to the site, and are therefore not specific to the raingarden.

Excavation was undertaken with a 66-kW digger whose fuel efficiency was assumed to be 40% (diesel engine) and was estimated to be operating for about 28 hours. Excavated soil was removed to cleanfill, 10 km away, in a 7-m³ truck, requiring 97 return trips.

Pipes were a combination of high-density polyethylene (HDPE; 700 kg in system boundary, 1,200 kg total) and concrete (2,200 kg in system boundary, 3,600 kg total). In addition, 9,500 kg of concrete was required as bedding for the pipe between the raingarden and the waterway. HDPE pipes were sourced 34 km from the site, with concrete pipes only 2.1 km away; two trips were required to transport the pipes to site.

A 380-m², 0.3-mm impermeable liner (104 kg of polypropylene) was laid before the raingarden media were spread.

The media used in the raingarden consisted of (from bottom up) 69 m³ of sand (transported 80 km), 97 m³ of limestone quarry overburden (19 km), and 206 m³ of topsoil (a mix of 30% pumice sand (80 km) and 70% Mangere topsoil (34 km)). A 40-m³ layer of partly composted, chipped greenwaste mulch (29 km) was spread on top of the raingarden media.

A total of 2,635 plants were planted, of which about 700 (a single species known variously as oioi, jointed wire rush, or Apodasmia similis) were planted in the raingarden. The other plants were for landscaping purposes and therefore not functionally required for the raingarden. All plants had been grown for about one year near Tauranga (240 km from site) before delivery in two trips, and had required the use of about 3.5 m³ of potting mix and about 10 kg of LDPE plant bags. LDPE is fully recyclable, but it is not known whether the plant bags were recycled or sent to landfill.

An aggregate path was constructed at the foot of the raingarden to allow access for maintenance crews and other visitors to the site. The area of this path was approximately 35 m², with a depth of 0.1 m. A concrete vehicle pad (4.5 m³ of concrete) was constructed in the footpath to allow perpendicular access to the site while minimally impeding traffic flow.

Maintenance

The maintenance schedule for the raingarden includes both routine (3-monthly) and corrective (7-yearly) actions. Routine maintenance consists primarily of removal of rubbish (estimated to be 60 kg/yr) and green waste, i.e. weeds from the gravel aprons around each of the inlet structures and dead plant material (estimated to be less than 100 kg/yr), both to landfill, and will also include spraying of weeds with glyphosate. During the routine maintenance visits it might be necessary to scarify the surface of the soil manually if compaction has taken place. The mulch applied during the construction phase need not be replaced during routine maintenance because it is expected that the plants, once mature, will form a closed canopy over the soil and therefore suppress weeds and protect the soil from water erosion. This quarterly maintenance is assumed to require a two-tonne truck, and the contractor’s visits will form part of a more extensive maintenance schedule covering other devices as well. The contractor estimated that the total travel distances apportionable to the raingarden would be 10 km each quarter.

The likely frequency of corrective maintenance is estimated from the amount of accumulated sediment. Based on initial monitoring it is expected that the upper 350 mm of the medium (about 70 m³) will need to be
replaced and all surface-deposited sediment (estimated to be 7 tonnes/yr) removed every 7 years. Results of ongoing monitoring might result in this frequency being re-evaluated. With the removal of the upper layer of soil, the plants are also removed and new plants and mulch installed.

Disposal

The disposal scenario assumes that the raingarden would be excavated, transported to a landfill, and the hole backfilled. The calculations are based on the digger usage for original excavation and backfilling and transportation data from the construction phase.

Hypothetical reduced-size raingarden inventory

Given the significant difference between the infiltration rate used in the design (0.3 m/day) and measured during monitoring (3 m/day), it could be argued that the raingarden could have been constructed with only 40 m² of permeable area instead of the actual 200 m². We therefore also present an inventory for the raingarden as if it had been designed and constructed at this smaller area. In particular, we have estimated reductions in the size of the pathway (to 20 m²), the quantity of PE pipes (to 234 kg LDPE), the impermeable liner (to 76 m²), the excavation (to 135 m³) and media, and the number of functional plants (to 140).

The maintenance regime and disposal scenario are assumed to be identical to the constructed raingarden but there are proportionate reductions in impacts associated with quantities of material.

Hypothetical sand filter inventory

This section describes the hypothetical inventory for the construction and operation of a sand filter designed based on TP10 to treat the same water quality volume (75 m³) as the raingarden. Sand filters work by sedimentation and filtration, generally with an inflow point to a sedimentation chamber and an underdrain to a subsequent filtration chamber that discharges filtered stormwater (TP10, p.71). The system boundary excludes the same features as that of the raingarden inventory. It has been assumed that the sand filter would be located on the same site as the raingarden, requiring the same diversion works. However, it might be possible to site the sand filter in such a way that it still serves a similar catchment area but with reduced diversion works.

Design

In-line sand filters from Hynds Environmental are prefabricated in a range of sizes. Hynds Environmental staff determined that the minimum size of sand filter required to treat the 75 m³ of water quality volume would have a single box filter of dimensions $4 \times 3 \times 3$ m ($w \times l \times d$), and a cylindrical sedimentation chamber with the same depth and a diameter of 2 m.

Construction

Excavation of 191 m³ of soil from the site would be achieved with a 20-tonne digger (66 kW) and is estimated to take about 9 hours. Of this excavated soil, 52 m³ would be removed to cleanfill (10 km), and the remainder used as backfill after installation of the sand filter.

The ground underneath the sand filter is stabilised with a 100-mm layer of gravel (6 m³, 9,200 kg, sourced 39 km away from depot). A 150-mm layer of scoria (1.8 m³, 3,200 kg, 33 km) lines the inside base of the sand filter, upon which is placed a 0.3-mm impermeable liner (15 m², 4 kg of polypropylene). A 400-mm layer of sand (4.8 m³, 6,200 kg, 39 km) is spread over the liner. These three aggregates would be transported from the source in 44-tonne trucks to the depot, then transported in a 10-tonne truck the further 49 km to the site.

The sand filter comprises a sedimentation chamber and the filter box culvert, both being made of reinforced concrete. The combined mass is 39,000 kg, and they would be transported from 34 km away with a 44-tonne truck in one trip.

About 25 m of PVC pipes (120 kg) and 2 m of concrete pipes (140 kg) are required to connect the components of the sand filter.

Maintenance

A potential maintenance contractor is based 4 km from the site. It is expected that routine maintenance of the sand filter would be required 6 monthly, and that this would
entail removal of accumulated sediment (estimated at 3,420 kg) and the top 25 mm of sand (400 kg). The quantity of sediment was estimated based on raingarden monitoring data. We have assumed the moisture content of the sand and sediment would be an additional 25% of this total mass. These would be removed to landfill, 15 km away. We have also assumed that any ponding water in the device will be discharged to a nearby sewer with council consent. Based on discussion with sand filter maintenance contractors, we have assumed a 10-tonne truck (or equivalent) would be used to perform this maintenance. Pumping is likely to take between 1.5 and 3 hours per visit, with an average diesel consumption of 45 litres.

Corrective maintenance would be required every 25 years, entailing replacement of the impermeable liner, all sand, and all PVC pipes. Because we have assumed a 50-year lifetime for the device in this study, we assumed the sand filter will only undergo corrective maintenance once during this period.

**RESULTS AND DISCUSSION**

The total energy required for diversion of stormwater to the site and site preparation that was common to both devices was 59 GJ (5 tonnes CO₂). This diversion consisted of the materials and transportation required for four manholes, a single-splay catchpit, footprint repairs, and pipes under road.

Energy use and CO₂ emissions not covered by this analysis include contractors’ offices and the supply chain for those offices, and vehicle maintenance and construction. We have assumed that these are insignificant compared to the other items in the life-cycle inventory.

The results for the raingarden, smaller raingarden and sand filter are summarised in Tables 1 and 2 and described in the following three subsections.

**Raingarden**

The estimated total energy for the construction and maintenance of the raingarden over a 50-year period was 237 GJ¹, with total CO₂ emissions of 16.5 tonnes. Of the energy use, 73% was from transportation² and 27% from materials. The construction phase required about twice as much energy as the use phase (153 GJ vs 84 GJ). Corrective maintenance accounted for 31% of total energy use, with routine maintenance only an additional 4%. During the construction phase 42% of energy use was from materials and 58% from transport, whereas there was no energy from materials in the use phase. Transportation of plants from Tauranga for the initial planting required about 8 GJ (0.5 tonnes CO₂), and for corrective maintenance an additional 21 GJ (1.5 tonnes CO₂). Total energy required to transport the media from source and depots was estimated to be 26 GJ (1.8 tonnes CO₂) during construction and an extra 30 GJ (2.1 tonnes CO₂) because of maintenance during use. With the inclusion of the disposal scenario the energy requirements and CO₂ emissions both increased by 21%.

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¹ GJ is the useable energy content of 28 litres of petrol, or the electricity consumed by an average New Zealand household in 2 weeks. The result of 280 GJ is equivalent to the petrol consumed driving a standard sedan about 87,000 km.

² Note that in this discussion ‘transportation’ denotes all vehicle use, including diggers.
Hypothetical reduced-size raingarden

The total energy for the hypothetical, smaller raingarden was estimated to be 112 GJ (8 tonnes CO₂) over the 50-year period without the disposal phase. With the inclusion of this phase the total energy requirement is estimated at 123 GJ (8.7 tonnes CO₂). The reduced size results in a lower proportion of total embodied energy during the construction phase coming from materials (32%) and a higher proportion from transportation (68%) than for the constructed raingarden (42% and 58%, respectively). The increase due to the inclusion of the disposal phase is less than for the constructed raingarden, 10% for total energy and 9% for CO₂.

Table 1 | Comparison of life-cycle energy requirements (GJ) for each device by phase and major category

<table>
<thead>
<tr>
<th></th>
<th>Raingarden (as constructed)</th>
<th>Raingarden (smaller design)</th>
<th>Sand filter (hypothetical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (without disposal)</td>
<td>237</td>
<td>112</td>
<td>290</td>
</tr>
<tr>
<td>Total (with disposal)</td>
<td>286</td>
<td>123</td>
<td>299</td>
</tr>
<tr>
<td>Construction</td>
<td>153</td>
<td>76</td>
<td>94</td>
</tr>
<tr>
<td>Materials</td>
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<td>24</td>
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<tr>
<td>Transportation</td>
<td>89</td>
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<td>Use</td>
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<td>37</td>
<td>196</td>
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<tr>
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<td>0</td>
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</tr>
<tr>
<td>Transportation</td>
<td>84</td>
<td>37</td>
<td>188</td>
</tr>
<tr>
<td>Disposal scenario</td>
<td>49</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>

Note: Totals may not add due to rounding. The figures for disposal are based on one possible scenario.

Hypothetical sand filter

For the sand filter, the total energy estimated for construction and maintenance over a 50-year period was 290 GJ (23.4 tonnes CO₂). These increase to 299 GJ (24.0 tonnes CO₂) with the inclusion of the disposal scenario. Of the total energy requirements for construction and maintenance, 31% was required for materials and 69% for transportation and pumping. The energy embodied in the concrete of the sand filter’s sedimentation chamber and box culvert amounted to 74 GJ (8.3 tonnes CO₂). Routine maintenance was expected to require 26 GJ in travelling to and from the site and removing material to landfill, and 161 GJ for pumping. The total energy requirement for routine maintenance of the sand filter was therefore expected to amount to 187 GJ (13 tonnes CO₂). In contrast, corrective maintenance every 25 years, and therefore carried out once during the 50-year assumed lifetime, was expected to require only about 9 GJ (0.7 tonnes CO₂). The increase due to the disposal phase is only 3% for both the energy requirement and CO₂ emissions.

The raingarden as constructed has much higher energy requirements during the construction phase (153 GJ) than the sand filter (94 GJ), primarily because of the greater pipe requirement for the raingarden (36 GJ vs 7 GJ) and the large quantity of media required (37 GJ vs 4 GJ). The situation is similar for the disposal phase as well (49 GJ vs 9 GJ). In contrast, the maintenance programme for the constructed raingarden is expected to be less energy-intensive than the sand filter’s (84 GJ vs 196 GJ), primarily because of the pumping requirements (161 GJ) of the sand filter.
The sand filter construction has higher CO₂ emissions in proportion to the energy requirements because it requires significantly more concrete than the raingarden, and the embodied CO₂ of concrete is relatively high in relation to its embodied energy content³.

When compared with the smaller, hypothetical raingarden, the sand filter requires significantly more life-cycle energy independent of whether the disposal phase is included in the analysis (299 GJ vs 123 GJ or 290 GJ vs 112 GJ) and results in almost four times as much CO₂ emission (24.0 tonnes vs 8.7 tonnes CO₂ or 23.4 tonnes vs 8.0 tonnes CO₂). The energy requirements for the removal of the top layer of medium for the raingarden reduce approximately in proportion to the surface area, as do the requirements for provision of new media. However, we have assumed that the transportation of plants from Tauranga still requires one dedicated trip per rotation, which requires 21 GJ (1.5 tonnes CO₂). In addition, the requirements of the regular maintenance regime do not reduce with a smaller garden, being primarily composed of transport of staff to the site and removal of a small amount of surface detritus to landfill.

CONCLUSIONS

When considering stormwater management options councils and land-owners must consider a range of factors including effectiveness in removing contaminants, mimicking the pre-development hydrologic regime, life-cycle cost, available space, public safety, and aesthetics. However, it is also necessary to consider environmental effects beyond those directly associated with stormwater treatment devices. This study has compared two devices for a particular site that are both effective in removing runoff contaminants to the required standard. The comparison is based on life-cycle energy consumption and CO₂ emissions.

When comparing the devices designed to treat 75 m³ of water quality volume within the specified system boundary, the hypothetical reduced-size raingarden is expected to have significantly lower life-cycle energy requirements and CO₂ emissions compared with the sand filter. Even when considering the larger-than-necessary, as-built raingarden, the life-cycle energy requirements associated with the construction and maintenance are about 20% less than for the sand filter, while the CO₂ emissions are 30% less. With one possible disposal scenario included, these differences are reduced to 5% and 20% respectively.

The results presented are highly specific to the site because of the transportation distances involved. Other sites would very probably require quite different transportation distances. Clearly the distance that materials are sourced from is important in the energy balance, but when considering closer sources other factors must be weighed, including any other environmental effects.

Both devices provide benefits beyond the functional unit used for comparative purposes, and these should be factored into any decision as to which device is chosen for a site. For example, a raingarden can be an attractive and educational way to occupy sites otherwise unsuitable for development and is expected to provide carbon sequestration services, whereas a sand filter—which can be installed under an existing paved area—is a good option when space is limited. However, this study highlights the significant contribution of transportation—of both materials and staff—and ongoing maintenance to a treatment device's life-cycle energy and CO₂ profiles.

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³ The chemical reaction involved in cement production releases carbon dioxide.
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