Underground Plastic Recharge Chambers in Stormwater Management

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Land development typically requires stormwater control measures (SCMs) to limit runoff volume, reduce peak flow, delay discharge to streams, and reduce pollutant loads to receiving waters, with the ideal goal of mimicking the natural hydrologic system. Life cycle assessment is used to systematically evaluate the environmental impact of underground plastic recharge chambers (RCs) used for stormwater management. Using cradle-to-gate life cycle assessment and a functional unit of 1 m3 stormwater capacity, different RC structure types, manufacturing processes and materials are considered. The inventory is based on various commercially available RCs, including injection-molded or extruded polypropylene and polyvinylchloride polymers and typical installation materials and methods. A new dataset is developed to estimate the manufacture and use of recycled polypropylene granulate. TRACI 2.1 is used to investigate the midpoint life cycle impact assessment metrics, acidification, eutrophication, global warming, and fossil fuel resources.

Keywords: life cycle assessment ; green infrastructure ; stormwater management

1. Introduction

Land development typically requires stormwater control measures (SCMs) to limit runoff volume, reduce peak flow, delay discharge to streams, and reduce pollutant loads to receiving waters, with the ideal goal of mimicking the natural hydrologic system [1]. Another goal of stormwater management is to minimize the area dedicated to SCMs and maximize the utility of developed land such that the land is most efficiently used to the benefit of the owner. Over the last century, SCMs have transitioned from large, centralized installations focused on conveyance to small and decentralized installations located near the impervious area where the runoff is generated and focused on retention and infiltration [2][3]. SCM designers and practitioners have options to choose from as they consider which green and/or gray SCMs will be selected for each impervious surface area site.

Engineers, designers, landowners, and governing bodies need to consider regulations, technical performance, cost, and environmental impact when planning SCMs. Even with infiltration-focused SCMs being applied to all impervious surface areas, peak flow and discharge time, although mitigated, are altered by land development and urbanization [4]. Examples of SCMs include bioretention cells, swales, detention and retention ponds, infiltration trenches, and underground recharge chambers (RCs).

RCs are part of the market segment known as modular tank systems, which represent a 59% share of the USD 516.1 million worldwide stormwater detention system market as of 2021 [5]. RCs allow for decentralized infiltration, with installations placed nearby each area of impervious surface area. They are popular in urban streetscapes and often placed under parks and recreation areas to achieve green space requirements in suburban developments [6]. Moreover, approaches that limit stormwater runoff from the urban built environment align with green building rating systems and guidelines such as LEED, which place an emphasis on best management practices for stormwater management. The RC SCM features an underground structure that collects water during storm events, allowing the collected storm water to slowly infiltrate into the underlying soil over 24 or 48 h following the rain event. Infiltration capability of the underlying soil is a key consideration for RC design. The underground structures are assembled as building blocks or positioned as individual units to accommodate the geometry of the site. The individual building block structures take the form of a box or an arch with significant void space for water storage. Materials used for these structures include concrete or plastic, among which polypropylene (PP) and polyvinyl chloride (PVC) may be used. Some solutions can be stacked as layers deeper into the ground to reduce the surface area footprint. Examples of single-layer plastic box and arch structures are illustrated in **Figure 1**.

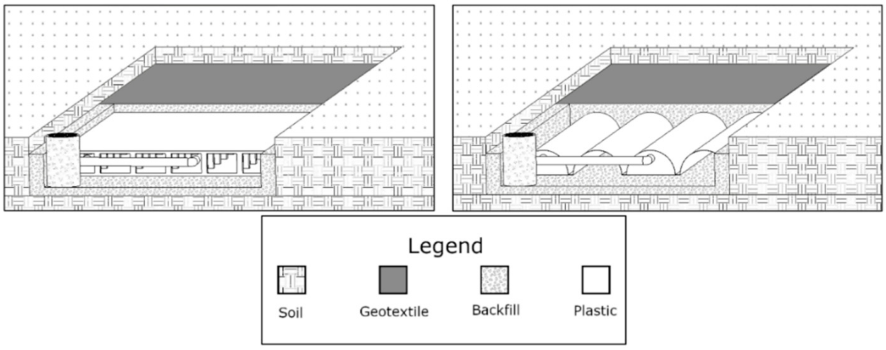

Figure 1. Example of single-layer recharge chamber structure installation with cutaway views, showing undisturbed soil, geotextile fabric, backfill material, and plastic box (**left view**) and arch (**right view**).

2. Infiltration Studies Involving RCs

RCs were included in the list of SCMs employed for understanding infiltration, recharge, and streamflow at a watershed scale [4][7][8][9]. Hopkins et al. [4] showed that decentralized infiltration-focused SCMs mitigated peak flow and runoff volumes better than centralized detention-focused SCMs, although decentralized infiltration-focused SCMs did not perform as well as forested conditions. Bhaskar's work [7] evaluated stream flow changes as agricultural and forested land was developed with low-impact development (LID) SCMs including some RCs. Urbanization was positively correlated with increased baseflow and reduced evapotranspiration, meaning that infiltration-focused SCMs recharged stormwater that previously would have been evaporated or stored in soil moisture for plant take-up. Another body of work by Bhaskar [8] looked at the movement of infiltrated stormwater within an urbanized setting utilizing LID SCMs, some of which were RCs. The recharge-to-precipitation ratio was found to be more negatively correlated with precipitation magnitude and more positively correlated with duration in developed and urbanized areas compared to undeveloped land. A faster rate of the rise and fall of groundwater levels was found to be positively correlated with closer proximity of the recharge facility to monitoring wells and a farther distance from the recharge facility to the stream. Rhea [9] utilized a unit hydrograph model to evaluate precipitation to streamflow at catchments in Maryland where RCs were some of the SCMs utilized, finding that land use and construction grading were predictors of precipitation to streamflow. Burszta-Adamiak [10] studied the deterioration of infiltration rates for surface basins and underground basins over time and presented a mathematical model to estimate module clogging.

3. Water Quality Studies Involving RCs

A study comparing downstream water quality between traditional SCMs and LID SCMs at the watershed scale, where two RCs were part of the LID SCMs employed, found the LID SCMs implemented close to the source of the stormwater runoff offered better pollutant removal efficiency. Notably, the pollutant removal efficiency (PRE) for each SCM was cited from prior literature where available, but the PRE for the RC was assumed to be equivalent to an infiltration trench due to a paucity of available RC literature [11]. Regarding stormwater treatment performance of the underground chamber, Drake [12] compared a stormwater pond and a concrete underground detention basin for water quality and water temperature, finding that both ponds and underground basins reduced pollutant concentrations; however, the underground detention basin provided cooler outlet water temperatures, which better aligned with the thermal regime of the local habitat.

4. Testing of Mechanical Properties of RCs under Loads

Load testing of plastic box and arch RCs was found to be critical to civil and structural design considerations for stormwater systems. The strength and deformation properties of materials for RCs, whether using virgin or recycled polymers, were critical given the loads they were subjected to over their service lives [13][14][15][16][17][18][19]. Since RC structures are frequently utilized under parking lots or driven over in some capacity, a standard load test method was defined by the American Association of State Highway and Transportation Officials (AASHTO) to specify truck axle loads that can safely travel over a structure such as a bridge or an underground structure [20]. McGrath and Mailhot's work [18] focused on arch structures, defining key design elements of loads, profile sections, and associated time-dependent properties. Masada's work focused on the live-load testing of buried plastic arch structures [14], the finite element modeling of the arch structure revealing the critical nature of the foot design [15], and deflection formulas intended for use by practicing engineers [13]. Aung's work [19] investigated the stress on modules under roads. Brachman and Moore's work [16][17] focused on the live-load testing and failure mechanisms of buried plastic box structures resulting from backfill compaction on the sides, different soil types, and thickness of the top layer over the buried structure. The plastic and the backfill materials are critical components for the structural performance of these SCMs.

5. LCA Studies of SCMs Other Than RCs

Increasingly in recent years, LCA has been used to support decision making on alternative SCMs, predominantly in urban settings [21][22][23][24][25][26], although also in rural settings [27]. LCA was also used to understand the environmental impacts and tradeoffs of many SCMs, such as ponds, surface basins, detention tanks, sand filters, trenches, rain gardens, and green roofs [22][23][24][25][26][27][28][29][30][31][32][33][34][35]. Spatari et al. [34] compared the life cycle environmental performance of underground stormwater storage including gravel basin, virgin HDPE pipe in a gravel bed, and recycled HDPE pipe in a gravel bed. Their work found that recycled and virgin HDPE pipe in a gravel bed offered less environmental impact on energy demand (MJ) and global warming potential (kg CO_2 eq.) than traditional gravel basin storage. There is, however, a significant gap in the literature related to LCA of RCs, both box and arch structures, utilizing polypropylene (PP) and polyvinylchloride (PVC) plastic polymers and processed via injection molding and extrusion.

6. RCs as an SCM

As RCs are a commonly applied SCM, understanding their potential life cycle environmental impacts can support engineering design and implementation decisions, since those impacts are influenced by polymer, RC design, and manufacturing methods. Various studies defined different functional units for their assessment, which means that direct comparison of potential midpoint impact from one study to another is complex or not feasible. Sand filter, concrete vortex, rain garden, and filter swale infiltration trench SCMs were studied utilizing a functional unit of one m^3 of stormwater [22][23][28]. Coupled with a study of surface basins, floodplain restoration, permeable paving, and underground stormwater infiltration basins (USIBs, also known as RCs), SCMs were found to range from a global warming midpoint impact of less than 50 kg CO_2 eq per cubic meter of managed stormwater for green solutions, such as filter swale infiltration trenches, surface basins, floodplain restorations, and rain gardens, to more than 300 kg CO_2 eq per cubic meter of managed stormwater for permeable paving and plastic RC solutions [22][23][27][28].

Prior research by Peterson et al. [27] undertook a cradle-to-grave LCA of a plastic box RC product and other SCMs including surface basins, permeable paving, and floodplain restoration. The installation phase of the plastic box RC represented more than half the life cycle potential midpoint impacts for the categories of acidification (kg SO_2 eq), eutrophication (kg N eq), global warming (kg CO_2 eq), and fossil fuel resources (MJ surplus energy. The authors chose those midpoint impact categories for their relevance to construction (global warming, fossil fuel resources, and acidification) and water resources (acidification and eutrophication). One insight derived by the authors was that the plastic box structure in the RC installation represented over 80% of the installation phase potential impact across these four midpoint impact categories. These findings reveal the dominance of the installation phase compared to the maintenance and end-of-life phases in determining the environmental footprint for one type of RC and led to this expanded study of different types of RC products. This new study elucidates the cradle-to-gate installation phase of various commercially available RC products. Once installed, any RC will have similar maintenance and end-of-life phases; however, the different types of polymer materials, different plastic manufacturing processes, and different installation site backfill materials could significantly impact the magnitude of the installation phase potential midpoint impact for that particular RC.

7. Summary of Results

Limited available land can constrain stormwater management options in development projects. Buried solutions such as RCs can overcome those challenges while also promoting streetscapes, parks, and green spaces. The life cycle environmental impact categories evaluated for plastic RCs reveal that the box structures have higher values than the arch structures for managing stormwater, predominantly because of the higher mass of plastic used in box structures compared to arch structures. The arch structures are favored from the perspective of minimizing midpoint impact; however, the option to use the extruded process for the box structure results in lower midpoint impacts. If the design allows the use of sand, the midpoint impacts could be reduced to less than 50% of impacts for gravel assuming equivalent transport distance. However, in the case where sand needs to be transported longer distances than gravel, careful analysis of tradeoffs between backfill material impacts and transport distance impacts must be considered.

Recycling injection molding process scrap, which is common practice among RC fabricators, reduces fossil resource consumption and global warming impact compared with using primary polymeric material alone. The reduced burden comes without collection and sorting processes that are needed when using post-consumer plastic resin.

In summary, the results obtained show the dominance of the plastic and backfill transport distance in relevant potential midpoint impacts for both plastic RC design types of box and arch structures. There is wide variation in these results, which is driven by the choice of plastic and choice of manufacturing process used for the product. In general, sand as backfill material around the box structure RC installation provides a smaller global warming impact compared to gravel, although the impact of large transport distances could favor local sources of gravel over remote sources of sand.

References

1. US EPA. Low Impact Development (LID) Literature Review Document #EPA-841-B-00-005; United States Environmental Protection Agency, Office of Water: Washington, DC, USA, 2000.
2. Hale, R. Spatial and temporal variation in local stormwater infrastructure use and stormwater management paradigms over the 20th century. Water 2016, 8, 310.
3. McPhillips, L.E.; Matsler, A.M. Temporal evolution of green stormwater infrastructure strategies in three US cities. Front. Built Environ. 2018, 4.
4. Hopkins, K.G.; Bhaskar, A.S.; Woznicki, S.A.; Fanelli, R.M. Changes in event-based streamflow magnitude and timing after suburban development with infiltration-based stormwater management. Hydrol. Processes 2019, 34, 387–403.
5. Market Study Report. Global Stormwater Detention System Market Size, Status and Forecast 2021–2027Document #MSR3951641. 2021, p. 117. Available online: https://www.marketstudyreport.com/reports/global-stormwater-detention-system-market-size-status-and-forecast-2021-2027 (accessed on 28 March 2022).
6. Bailey, J. Personal communication on recharge chambers including applications and installations. 2017.
7. Bhaskar, A.S.; Hogan, D.M.; Archfield, S.A. Urban base flow with low impact development. Hydrol. Processes 2016, 30, 3156–3171.
8. Bhaskar, A.S.; Hogan, D.M.; Nimmo, J.R.; Perkins, K.S. Groundwater recharge amidst focused stormwater infiltration. Hydrol. Processes 2018, 32, 2058–2068.
9. Rhea, L.; Jarnagin, T.; Hogan, D.; Loperfido, J.V.; Shuster, W. Effects of urbanization and stormwater control measures on streamflows in the vicinity of Clarksburg, Maryland, USA. Hydrol. Processes 2015, 29, 4413–4426.
10. Burszta-Adamiak, E.; Lomotowski, J. Modelling of percolation rate of stormwater from underground infiltration systems. Water Sci. Technol. 2013, 68, 2144–2150.
11. Sparkman, S.A.; Hogan, D.M.; Hopkins, K.G.; Loperfido, J.V. Modeling watershed-scale impacts of stormwater management with traditional versus low impact development design. J. Am. Water Resour. Assoc. 2017, 53, 1081–1094.
12. Drake, J.; Young, D.; McIntosh, N. Performance of an underground stormwater detention chamber and comparison with stormwater management ponds. Water 2016, 8, 211.
13. Masada, T. Deflection formulas for buried chamber structures. J. Pipel. Syst. Eng. Pract. 2017, 8, 4017005.
14. Masada, T. Full-scale field load testing of storm-water storage chamber structures. J. Perform. Constr. Facil. 2011, 25, 317–325.
15. Masada, T.; Zhu, J.Q. Computer analysis of buried stormwater chamber structures. J. Pipel. Syst. Eng. Pract. 2015, 6, 4014013.
16. Brachman, R.W.I.; LeBlanc, J.M. Short-term lateral response of a buried modular polymer stormwater collection structure to compaction and overburden pressure. J. Geotech. Geoenviron. Eng. 2017, 143, 4017070.
17. Moore, I.D.; Brachman, R.W.I.; Elshimi, T.; Rahman, K. Analysis and testing to characterize the strength of buried infrastructure. In Proceedings of the 13th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Melbourne, Australia, 9–13 May 2011; p. 6.
18. McGrath, T.J.; Mailhot, D. Designing stormwater chambers to meet AASHTO specifications. J. ASTM Int. 2010, 7, 1–8.
19. Aung, T.H.; Khabbaz, H.; Fatahi, B. Parametric study of applied stresses on infiltration modular cells installed under roads. Procedia Eng. 2016, 143, 1325–1332.
20. AASHTO Standard Specifications. Available online: https://www.transportation.org/ (accessed on 11 December 2021).
21. Montalto, F.; Behr, C.; Alfredo, K.; Wolf, M.; Arye, M.; Walsh, M. Rapid assessment of the cost-effectiveness of low impact development for CSO control. Landsc. Urban Plan. 2007, 82, 117–131.
22. Petit-Boix, A.; Sevigne-Itoiz, E.; Rojas-Gutierrez, L.A.; Barbassa, A.P.; Josa, A.; Rieradevall, J.; Gabarrell, X. Environmental and economic assessment of a pilot stormwater infiltration system for flood prevention in Brazil. Ecol. Eng. 2015, 8

4, 194–201.

23. Vineyard, D.; Ingwersen, W.W.; Hawkins, T.R.; Xue, X.B.; Demeke, B.; Shuster, W. Comparing green and grey infrastructure using life cycle cost and environmental impact: A rain garden case study in Cincinnati, OH. J. Am. Water Resour. Assoc. 2015, 51, 1342–1360.
24. Fathollahi, A.; Coupe, S.J. Life cycle assessment (LCA) and life cycle costing (LCC) of road drainage systems for sustainability evaluation: Quantifying the contribution of different life cycle phases. Sci. Total Environ. 2021, 776, 145937.
25. Hengen, T.J.; Sieverding, H.L.; Stone, J.J. Lifecycle assessment analysis of engineered stormwater control methods common to urban watersheds. J. Water Resour. Plan. Manag.-ASCE 2016, 142, 04016016.
26. Andrew, R.M.; Vesely, E.T. Life-cycle energy and CO2 analysis of stormwater treatment devices. Water Sci. Technol. 2008, 58, 985–993.
27. Peterson, L.A.; Awerbuch, P.M.; Spatari, S. Environmental and economic implications of stormwater management alternatives in rural development. J. Ind. Ecol. 2021, 24, 1076–1088.
28. O'Sullivan, A.D.; Wicke, D.; Hengen, T.J.; Sieverding, H.L.; Stone, J.J. Life Cycle Assessment modelling of stormwater treatment systems. J. Environ. Manag. 2015, 149, 236–244.
29. Byrne, D.M.; Grabowski, M.K.; Benitez, A.C.B.; Schmidt, A.R.; Guest, J.S. Evaluation of life cycle assessment (LCA) for roadway drainage systems. Environ. Sci. Technol. 2017, 51, 9261–9270.
30. Flynn, K.M.; Traver, R.G. Green infrastructure life cycle assessment: A bio-infiltration case study. Ecol. Eng. 2013, 55, 9–22.
31. De Sousa, M.R.C.; Montalto, F.A.; Spatari, S. Using life cycle assessment to evaluate green and grey combined sewer overflow control strategies. J. Ind. Ecol. 2012, 16, 901–913.
32. Moore, T.L.C.; Hunt, W.F. Predicting the carbon footprint of urban stormwater infrastructure. Ecol. Eng. 2013, 58, 44–51.
33. Rivela, B.; Cuerda, I.; Olivieri, F.; Bedoya, C.; Neila, J. Life Cycle Assessment for ecodesign of ecological roof made with Intemper TF ecological water-tank system. Mater. Constr. 2013, 63, 131–145.
34. Spatari, S.; Hubler, J.F.; Hsuan, Y.G.; Marcellus, K. Beneficial use of plastic pipe in sustainable stormwater infrastructure. In Proceedings of the 1st International Specialty Conference on Sustaining Public Infrastructure, Edmonton, AB, Canada, 6–9 June 2012.
35. Spatari, S.; Yu, Z.W.; Montalto, F.A. Life cycle implications of urban green infrastructure. Environ. Pollut. 2011, 159, 2174–2179.