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Integrating natural and engineered remediation strategies for water quality management within a low-impact development (LID) approach

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Abstract

The objective of this paper is to demonstrate an interdisciplinary strategy combining both engineering- and biology-based approaches for stormwater and wastewater treatment. The work involves a novel and environmentally friendly surface material that can withstand urban load over its design service life, allows preliminary treatment through filtration, and diverts water to the subsurface to conduct secondary treatment below the surface through phytoremediation via the extensive rooting systems of trees. The present study highlights an interdisciplinary low-impact development (LID) approach developed for a polluted industrial wastewater site, for a cleaner and greener environment. The LID system involves (i) rhizofiltration and phytoremediation methods for removing heavy metals and organic pollutants using a hybrid poplar and aspen species; (ii) porous infrastructure produced using industrial waste, referred to as geopolymer pavers; and (iii) use of Silva cells as a tree-friendly and load support system. The design of the pavers over the Silva cells is innovative as it can deal with rainwater runoff and urban transportation loads simultaneously. The proposed system has the ability to extract heavy metals that are common in urban runoff or domestic and industrial effluents thus preserving the ecosystem naturally. The test site is only 15 m², but designed for a water-retention capacity of 2 m³ (roughly 1:100 year design volume draining a 10 × 10 m parking lot), and remediation levels for Cu and Zn are expected to reach 180 mg/kg dry weight and 1200 mg/kg dry weight, respectively.

Keywords

Stormwater
Wastewater treatment
Phytoremediation
Geopolymer
Eco-friendly

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Introduction

The modern world demonstrates a strong need for environmental protection, especially at the peak of industrial and urban development (Ali et al. 2018, 2012a, 2009; Ali 2006, Ali and Jain 2004, Dehghani et al. 2016; Gupta and Ali 2012).

Natural mechanisms are essential for removing contaminants that threaten air and water resources in both developed countries like Canada and developing countries like India. Stormwater and wastewater treatment are both currently undergoing a paradigm shift from a purely engineering approach to an approach that also considers ecology in order to create more sustainable, low-impact solutions. Existing and past stormwater treatments involve underground pipe systems that often directed the polluted water straight to a receiving body. Traditional wastewater and industrial water treatment plants are expensive facilities fed by networks of buried pipes and service large areas in one central facility (Ali et al. 2017a, b; Ali et al. 2016a, b, c; Khan et al. 2011).

However, with the aim of creating more sustainable solutions that treat the waste at the source, sustainable stormwater treatment has led to the development of low-impact development (LID) technologies that treat polluted urban waters by mimicking the pre-developed landscape (Ali et al. 2016d,e,f; Ali et al. 2015, 2014, 2012b; Burns et al. 2012). Phytoremediation, i.e., improving water quality through living plants can play a key part in making LID technologies even more effective. The principle of phytoremediation has been tested and reviewed extensively (Doty 2008, Pilon-Smits 2005, Arthur et al. 2005), but widespread application has been slow.

Municipal wastewater treatment systems (whether large or small) generally involve at least two stages: primary treatment (solids removal) and secondary treatment (chemical and biological removal). More sustainable examples of municipal wastewater treatment include the new wastewater facility in Sechelt (Canada) that uses phytoremediation through the use of plant roots (Ruffen 2017). This facility is primarily indoors and the issue remains that this facility collects wastewater at the “end-of-pipe” instead of as close to the sources as possible. The LID technologies using phytoremediation for removing metals and other pollutants (total suspended solids, phosphorus, and nitrogen, for example) are generally applied in an ad hoc manner with little guidance on vegetation selection (Khan et al. 2013). This is caused by a lack of interdisciplinary input, which is critical in developing solutions that are truly sustainable. However, an attempt has been made by researchers working in multidisciplinary areas to address this concern and provide improved engineering designs that work better are more economical and more sociologically appealing.

One major bottleneck for phytoremediation is a lack of adaptive genotypes of relevant species (Pilon-Smits 2005). While many plants can remove contaminants

from soil or water in a controlled setting, to be useful, they also must persist under natural and potentially stressful environmental conditions. The use of trees, which are well adapted to local conditions, long-lived, and often drought tolerant, is therefore an excellent strategy. Furthermore, trees are superior for phytoremediation due to their large biomass and extensive root systems (Doty 2008, Swamy et al. 2005). In urban centers, phytoremediation is shifting to the use of trees, which provide greater remediation than shrubs and grasses (Khan et al. 2012). A potential problem for the implementation of phytoremediation is that it is expensive and can take up a lot of space then making the land generally not available for other uses.

To be a truly sustainable solution, the treatment infrastructure should have more than one function. In an urban environment, all sustainable solutions must have a secondary purpose within the existing infrastructure and often this means carrying load; that is, it must either carry the weight of a car, a bike or pedestrian, or hold up a roof, a wall, or a building. Since current construction materials are not generally sustainable, the surface must be made of environmentally friendly materials that have known material properties and strength in construction. Recently, alternatives for Portland cement have been developed, one of them being geopolymers concrete. Interestingly, geopolymers concrete is an eco-friendly solution that is prepared by mixing binding materials made using alkali silicate solution and industrial wastes such as fly ash and bottom ash with aggregates as its fundamental ingredients, while still demonstrating similar strength and durability characteristics as normal concrete (Yang and Gupta 2018, Belforti et al. 2017, Gupta and Rathod 2015).

The objectives of this research study were to develop, design, and investigate the effectiveness of a compact, load bearing, new form of urban infrastructure that treats water at the source. The novel methodology described in this paper (case study) reports an interdisciplinary strategy combining both engineering- and biology-based approaches for stormwater treatment. A concept called hybrid absorbable landscapes (HAL) that involves the use of permeable landscapes in combination with systems such as bio-retention cells was first introduced by Valeo and Gupta (2017). Trees such as poplar and Alder are the engineering solutions for decontaminating water through the phytoremediation process occurring below an innovative surface material that not only conducts preliminary water treatment, but at the same time sustains an urban load over its design life. As a result, the LID technique reported in this paper, if implemented appropriately, could result in a significant benefit to stormwater issues faced in countries like India and Canada. The LID system described in this paper can be implemented in many parts of the

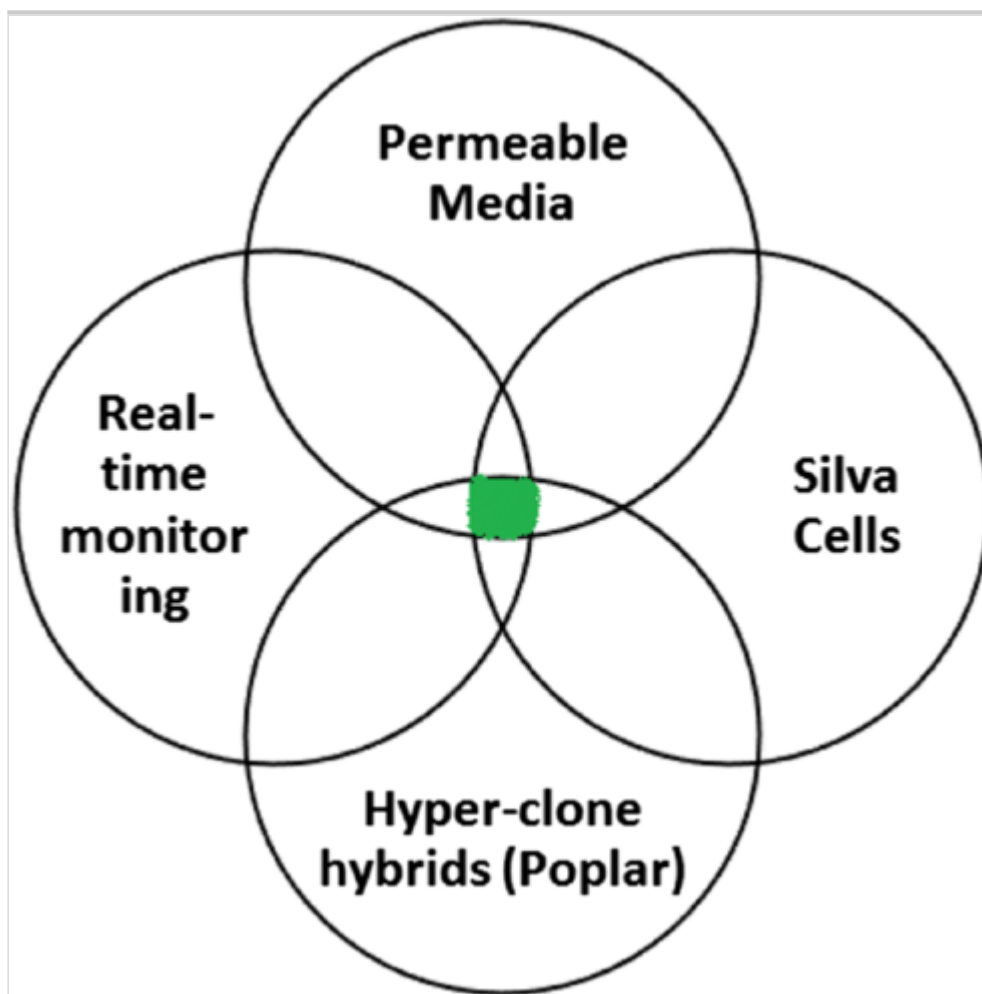
world, but was specifically designed keeping India and Canada in mind, as this was a part of a bigger on-going project.

Materials and methods

This is the first known study where phytoremediation of water sources using poplar trees and real-time wireless monitoring is being carried out in a harsh environmental region. The scope of this project is depicted by the shaded region in Fig. 1. It emphasizes the integration of “green” civil engineering, wastewater treatment, and biological and real-time monitoring as a complete system for a sustainable system.

Fig. 1

Scope of the present research



As mentioned, permeable pavements and bio-retention cells are the two LID options implemented in combination to create a test site that determines the efficacy

of stormwater treatment trains testable at the field scale. Currently, in the HAL site at the University of Victoria in Victoria, Canada, permeable asphalt and Porous Pave® are the current permeable surfaces installed. Each of these can be tested alone or as a part of the inflow to bio-retention cells. The field site is designed to allow determination of where, when, and how stormwater pollutants are removed, maintenance requirements, temporal and spatial changes in hydraulic conductivity, and optimization of these hybrid systems to achieve the most cost-effective and practical low-impact development design.

This study will provide results on monitoring methods relevant for a variety of small and large scale parameters related to performance (including surface infiltration rate, bio-retention hydraulic conductivity, and biological treatment), and the modeling of water flow and pollutants through the treatment train using physically based and statistical methods of this specially designed treatment train. Further, Silva Cells® will be incorporated in this study as a load-bearing urban structural support system that will support tree growth as well.

Pilot study: construction details

The primary treatment is conducted through a novel and environmentally friendly surface material that can withstand vehicular forces and weight, while the subsurface conducts secondary treatment below the surface that includes phytoremediation via a root system of trees. The vegetation growth tests both poplars and alders—ideal species for phytoremediation and water protection (Constabel and Lindroth 2010 2009, Constabel et al. 2014).

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The details to develop this methodology at the University of Victoria are described below in detail.

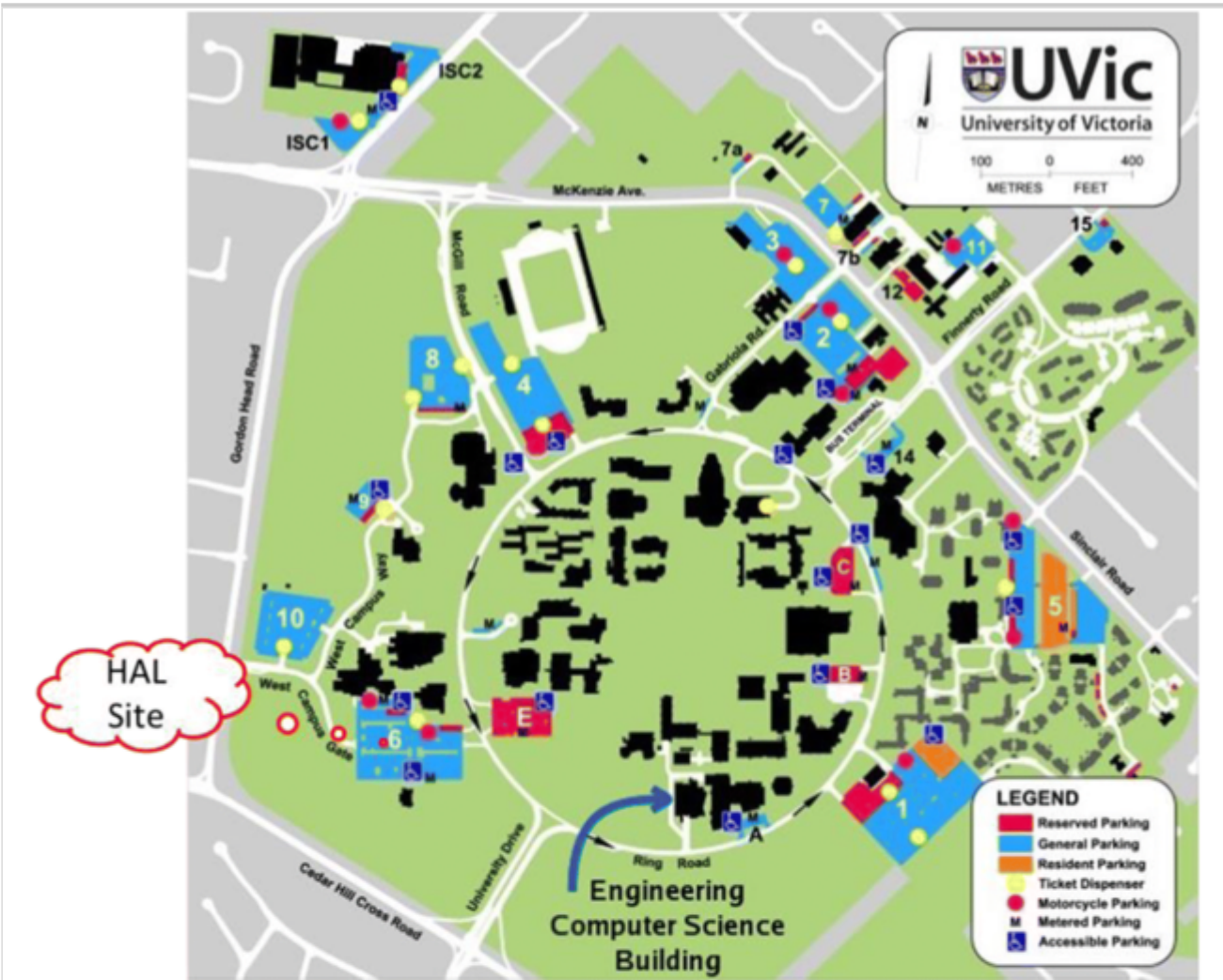
Study site

The new infrastructure was developed on the HAL site (Valeo and Gupta, 2018) at the University of Victoria and is situated in parking Lot 6 (refer to Fig. 2a). One of HAL's testing cells was selected (referred to as the "TestArea" in Fig. 2b). Figure 2b also shows some of the other permeable surfaces such as porous asphalt and a proprietary material, called Porous Pave® (made using recycled rubber and gravel held together by a resin) that are being studied by the group at the University of Victoria. The test area has dimensions of 6.28 m × 2.18 m × 0.5 m depth, and is designed as a treatment train that differs from the other two treatment trains

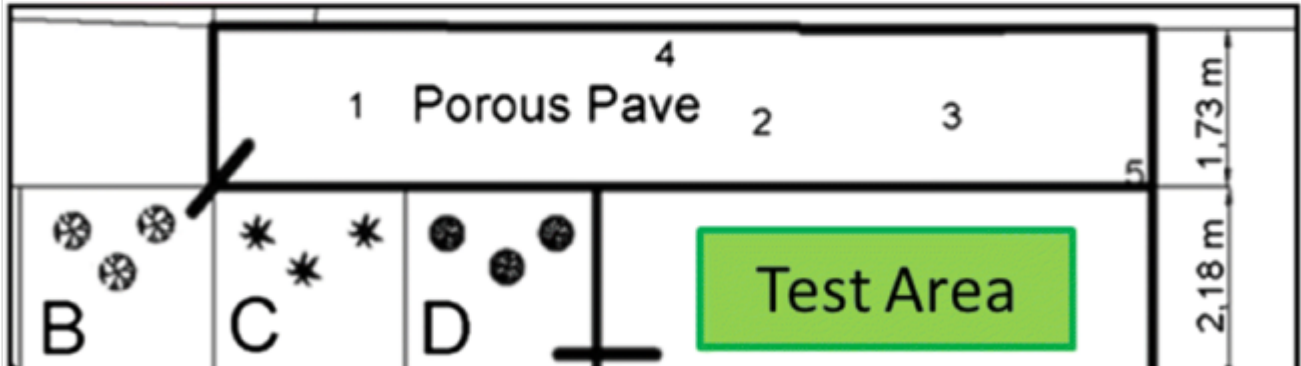
currently on-site. In this design, the test area is itself a hybrid landscape that conducts two treatments in series within one site before being treated further downstream by another process (Cell D in Fig. 2b) in the treatment train.

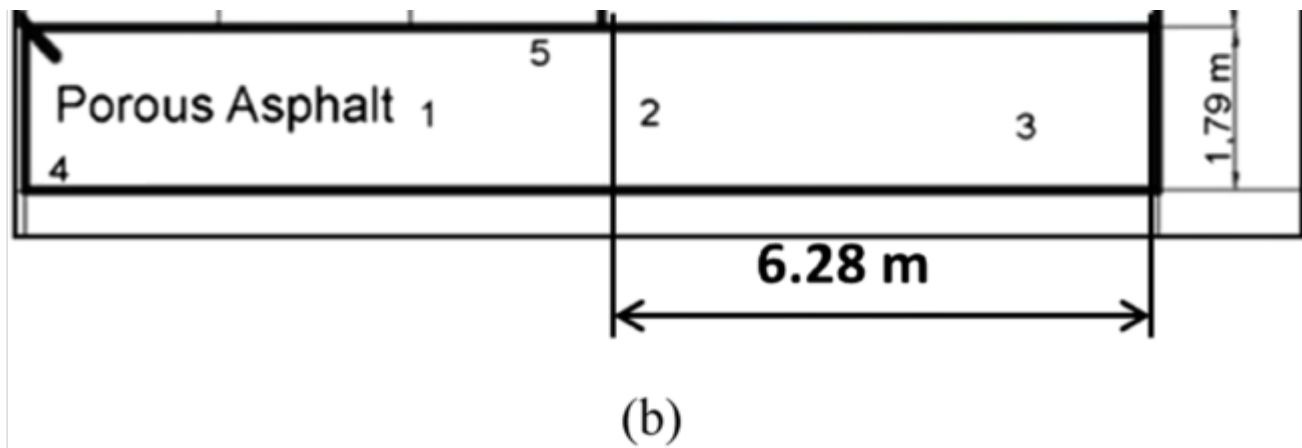
Fig. 2

a Map showing the location of the test site at UVic, **b** Schematic of the technology implementation at the HAL test site, UVic



(a)



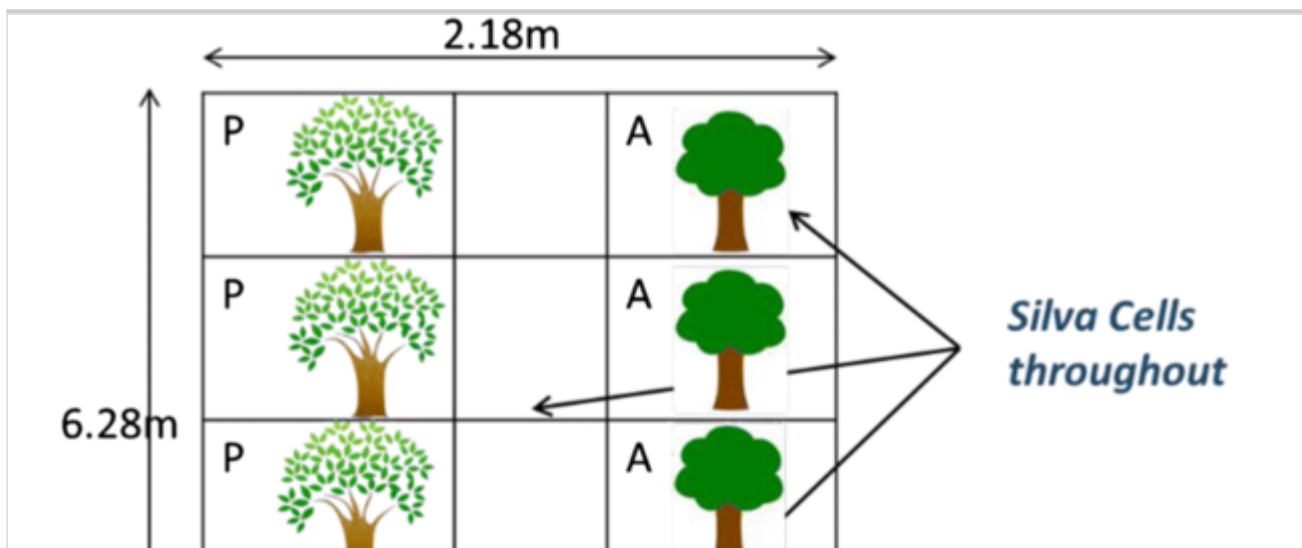


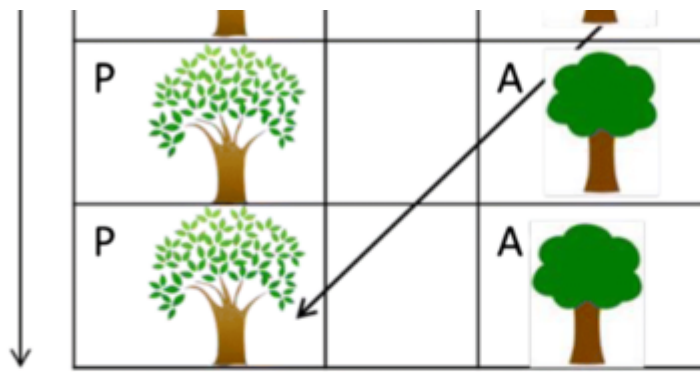
Site planning and tree-installation design

Figure 3a shows a detailed layout of the HAL site, while a birds-eye-view is represented in Fig. 3b of a small subsection. The authors planted two different species of trees as demonstrated clearly in Fig. 3a. The two types of special trees identified for this study are poplar and Alder. Five poplar trees are installed adjacent to five Alder trees as shown in Fig. 3a, and marked as “hatched trapezoids” in Fig. 3b within a special media blend. The Silva Cells® have a 5 cm wide notch for easier sliding of trees into the slot as illustrated in Fig. 3b–c. Three control cells at the top of Fig. 3a are cells with individual liners that are not allowed to drain into the rest of the test area. This is to help determine the relationship between sites with trees and pavers with that of sites with just pavers and sites without pavers. Additionally, sampling pipes have been installed at regular intervals with two depths through each Silva Cell® for monitoring water quality.

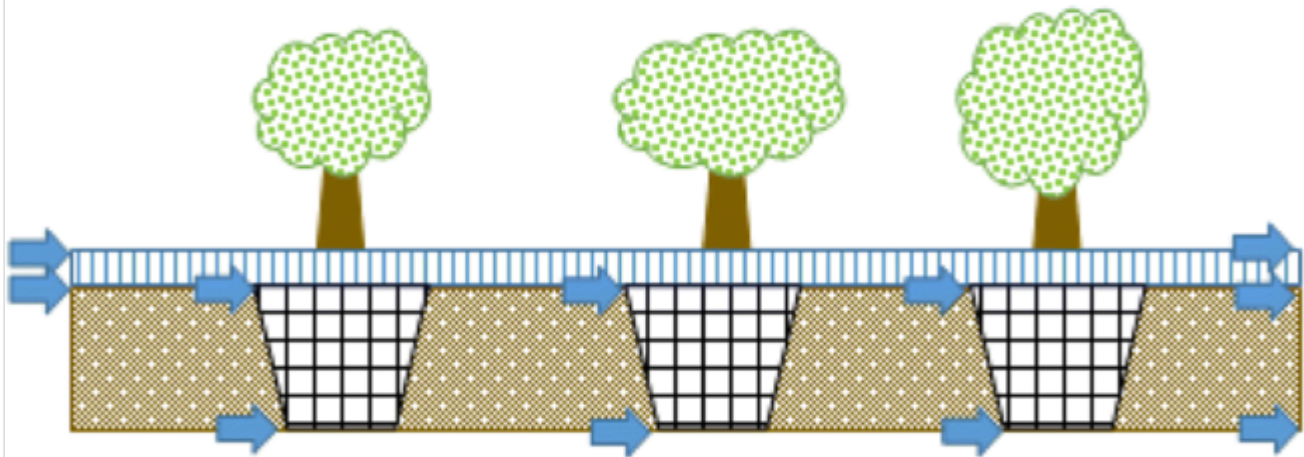
Fig. 3

HAL site: **a** detailed outline, **b** birds-eye-view, **c** Silva cell cage





(a)



(b)



(c)

Excavation

This stage involved the removal of old material from the site and excavation of the site up to 500 mm in depth. After the site was completely excavated, the following steps were taken for site preparation, as discussed below and shown in Fig. 4.

- a) a membrane (impermeable) was placed throughout the base;
- b) fine sand was placed onto the liner to about 2 cm depth level to the bottom;
- c) Silva Cells® were placed at appropriate locations (identified earlier in text);
- d) trees were planted with a locally available proprietary blend of soil sold to the University of Victoria for maximum health and growth;
- e) an extra impervious liner was also placed around the control trees;
- f) 2 cm diameter gravel was spread evenly across the base to fill up all the Silva cells, and the site was fenced to prevent deer from eating the vegetation. The tree root balls are protected from the gravel with a cylindrical, hard plastic sheath of 12 cm in diameter to protect the roots during installation. The roots are free to grow and expand above and below the sheath which is open.

Fig. 4

Site preparation



Membrane

(a) Placement of membrane



Sand level layer

Pipe outlet

(b) 2" level of the bottom, fine sand was placed



(c) Placement of Silva Cells®



Poplar trees

Alder trees



(d) Poplar and Alder trees planted in 'Sunshine Mix' soil within a 1 ft diameter, 1 ft height cylinder and inside 2" Silva Cell® notch



Sampling pipes

(e) Extra impervious layer placed around control trees and installation of sampling pipes throughout the test site



(f) Completed site, fenced and ready for Geopolymer paver surface.

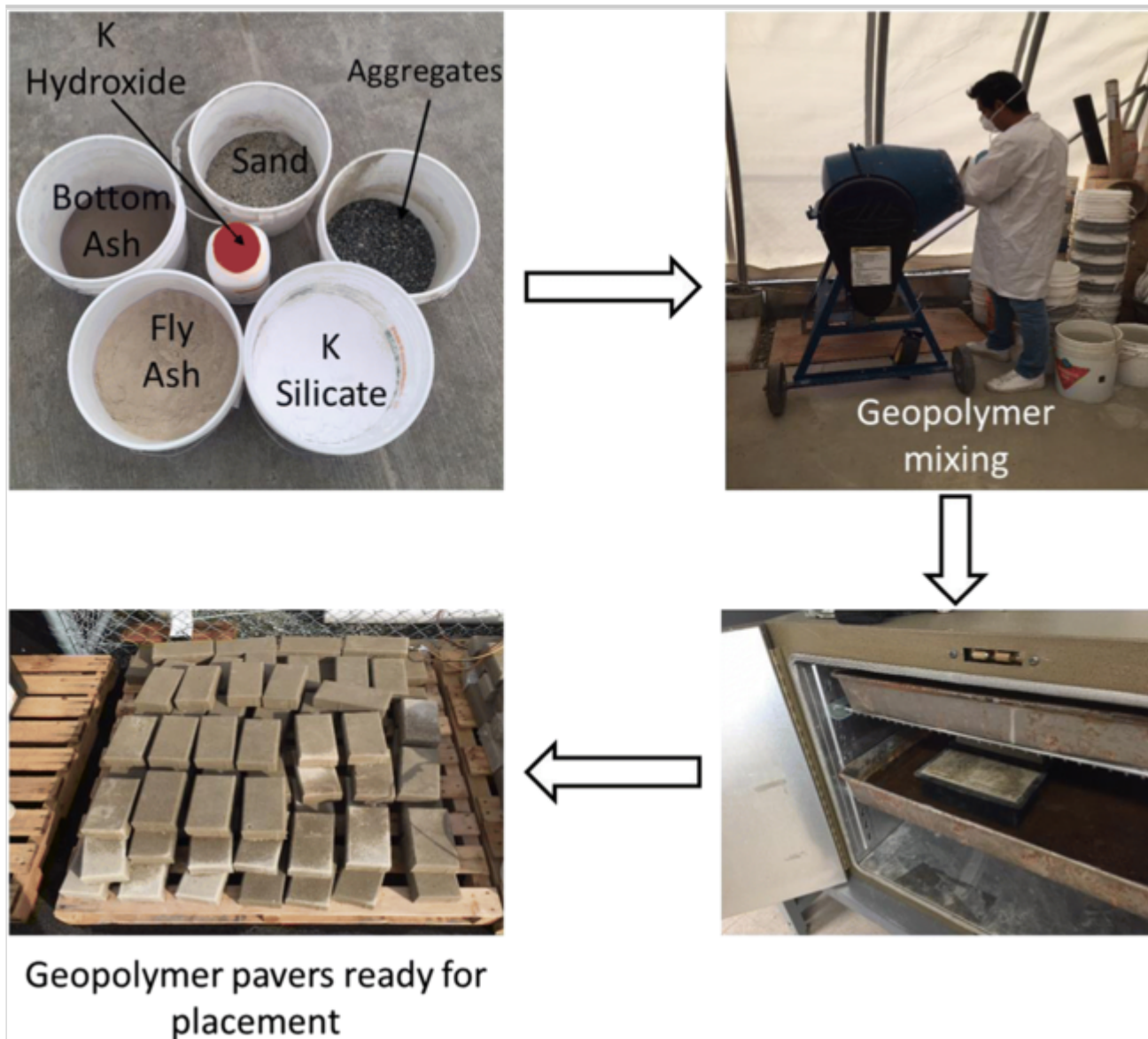
The next stage involved the manufacturing of geopolymer pavers at the Facility for Innovative Materials and Infrastructure Monitoring (FIMIM) at the University of Victoria, and the installation of equipment to measure the water quality, quantity, and surface integrity. Within the test area, the site is designed to have a water-retention capacity of over 2 m³ and a phytoremediation capacity of 0.056 m³ (in terms of volume). Shukla et al. (2011) note that a similar species of poplar in India were able to remove 120 mg of zinc per kg dry weight (DW) of vegetation within the first 12 months and 18 mg/kg DW removal of copper. This test site begins with slightly less mature trees than the Shukla et al. study, but we expect to achieve 10 times these levels of removal (1200 mg/kg DW for Zn and 180 mg/kg DW for Cu) within the first 5 years.

Future scope: eco-friendly pavers—manufacturing and installation

Portland cement concrete is the world's most used construction materials that utilizes cement that is associated with production of a ton of CO₂ for every ton produced. Geopolymer concrete is considered to be the next-generation eco-friendly material as it has the potential to replace Portland cement usage globally and can play a major role in reducing the GHG emissions globally. In the present study, the team has been successful in manufacturing potassium (K)-based geopolymer concrete pavers for the HAL site as shown in Fig. 5. The geopolymer pavers were prepared by thoroughly mixing fly ash, bottom ash, slag, aggregates, and K-based alkali solution in a concrete mixer. Once the concrete was ready, it was placed into the special paver size molds and then steam cured at 80 °C for 24 h and an additional 24 h at ambient temperature. In order to obtain around 30–35 MPa compressive strength of concrete, the pavers were later cured in water for a total of 28 days. Full details of the manufacturing of the pavers is reported by Chen and Gupta [Yang and Gupta 2018]. For comparison purposes, pavers with normal concrete material will be manufactured at FIMIM in the near future.

Fig. 5

Preparation of geopolymer pavers



Once fully completed, the site will be tested by allowing stormwater to permeate first through the pavers and then the permeated run off will be diverted to the Silva Cells® and eventually to the trees planted in the Silva Cells®. The quality of the permeated water will be checked at the various steps including after it has permeated through the pavers, and then through the gravel in Silva Cells® and finally the uptake of contaminants by the trees will be measured.

Monitoring

The function of different equipment installations are essentially to estimate the level of metal uptake by poplar and Alder species by monitoring the water quality at various stages of the treatment. This equipment involves:

- (a) Chemistry kits—knowledge mobilization and learning opportunity;

- (b) Electrical-conductivity sensors, temperature sensors, and pH meters that provide data used as a surrogate for concentrations of metals in the water;
- (c) Display equipment to provide the data in real time to the public visiting the site.

As the objective of this study is to have access to real-time data from anywhere, the solar-operated equipment in (c) above will provide for monitoring and transferring of data wirelessly such that anyone can access the data from around the globe in a fraction of time.

System performance testing

The system is intended to treat various wastewater parameters while at the same time, present an urban, load bearing form of infrastructure. Thus, the system will be studied for two parameters: (i) theoretical load capacity and (ii) water treatment efficacy.

The former will be conducted theoretically given the current design. A numerical model representing a single cell with a tree within a Silva Cell® with aggregate and geopolymer pavers on top will be tested in computer simulations for maximum load.

The latter will be conducted for testing of treatment by flooding the systems with dilutions of water and each contaminant of interest. For example, of direct interest for alders and poplars are copper and zinc as these plant species should have a good uptake for these metals which are of major interest in industrial wastewater. These two contaminants will be placed on the system and monitoring throughout the physical system and in real time for uptake in the trees and removal from the water will be monitored to determine how well the system performs. Surrogates with electrical conductivity, pH, and temperature will be developed to determine the relationship between metal levels and these surrogates which are the parameters monitored in real time and conveyed to the public. This knowledge will then be disseminated by way of a website providing information in real time.

Conclusions

There are several innovative concepts reported in this paper.

1. Phytoremediation technology tends to improve water quality through living plants, which is a key part of this sustainable hybrid technology. The LID

technology using phytoremediation for removing metals and other pollutants (total suspended solids, phosphorus, and nitrogen) has been implemented to develop solutions that are truly sustainable. The poplar and Alder trees are long-lived and durable and therefore, offer themselves as an excellent strategy for stormwater management. Furthermore, these trees are superior for phytoremediation due to their large biomass and extensive root systems.

2. Since many conventional construction materials are not generally sustainable and produce significant environmental contamination, geopolymer pavers as a permeable landscape were manufactured to ameliorate this issue.
3. Further, the poplars and alders were planted in Silva Cells® and covered with geopolymer pavers to withstand vehicular loads such as cars.
4. Lastly, the hybrid bio-engineered system consists of a real-time data collection, wireless access enabled monitoring data system for analyzing the uptake of contaminants in the leaves and woody material of poplars and alders. This system provides access to up-to-date information about the site, growth of trees, and uptake content of contaminants in the leaves of the trees.

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