PLANT BIOFILTRATION FOR URBAN STORMWATER RUNOFF PURIFICATION IN SOUTH AFRICA

by

Dylan Michael Jacklin

Dissertation presented in fulfilment of the requirements for the degree of Doctor of Philosophy in the Faculty of Engineering at Stellenbosch University

Supervisor: Dr IC Brink
Co-supervisor: Prof SM Jacobs

April 2022

Department of Civil Engineering: Water and Environmental Engineering Group

DECLARATION

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

This dissertation includes six original papers of which four have been published in peer-reviewed journals, one in press, and one submitted for publication, as well as one international conference presentation. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

April 2022

Date

PLAGIAATVERKLARING / *PLAGIARISM DECLARATION*

(updated March 2021)

1 Plagiaat is die oorneem en gebruik van die idees, materiaal en ander intellektuele eiendom van ander persone asof dit jou eie werk is.
Plagiarism is using ideas, material and other intellectual property of another's work and presenting it as my own.

2 Ek erken dat die pleeg van plagiaat 'n strafbare oortreding is aangesien dit 'n vorm van diefstal is.
I agree that plagiarism is a punishable offence because it constitutes theft.

3 Ek verstaan ook dat direkte vertalings plagiaat is.
I also understand that direct translations are plagiarism.

4 Dienooreenkomstig is alle aanhalings en bydraes vanuit enige bron (ingesluit die internet) volledig verwys (erken). Ek erken dat die woordelikse aanhaal van teks sonder aanhalingstekens (selfs al word die bron volledig erken) plagiaat is.
Accordingly, all quotations and contributions from any source whatsoever (including the internet) have been cited fully. I understand that the reproduction of text without quotation marks (even when the source is cited) is plagiarism.

5 Ek verklaar dat die werk in hierdie skryfstuk vervat, behalwe waar anders aangedui, my eie oorspronklike werk is en dat ek dit nie vantevore in die geheel, of gedeeltelik, ingehandig het om enige kwaifikasie te verwerf nie.
I declare that the work contained in this thesis/dissertation, except where otherwise stated, is my original work, and that I have not previously in its entirety, or in part, submitted this thesis/dissertation to obtain any qualification.

DM Jacklin	**18/02/2022**
Voorletters en van / *Initials and surname*	Datum / *Date*

ABSTRACT

A major consequence of urbanisation is the large-scale conversion of pervious to impervious surfaces, which significantly alters the natural hydrological cycle in terms of both hydrology and quality. Together with climate change, urbanisation and the associated stormwater runoff are regarded as major threats to water resource security worldwide, due to the variety of pollutants generated and transported. Conventional urban stormwater management rapidly collects and transports runoff for discharge into the nearest watercourse, triggering a plethora of public and ecological health concerns. In response, the Water Sensitive Urban Design (WSUD) concept, of which plant biofiltration is a component, is increasingly preferred as a sustainable alternative to conventional systems as it considers stormwater as a resource to protect rather than a substance of which to dispose. Plant biofiltration promotes a spatial network of passive, ecologically sound treatment solutions to the diffused nature of urban stormwater pollution, for discharge into existing drainage systems or watercourses.

South Africa, one of the most rapidly urbanising countries in Africa, experiences some of the worst environmental deterioration globally. Stormwater runoff discharge, together with aging and defective conventional treatment systems, threaten the country's already limited freshwater resources. Therefore, the South African Water Research Commission seeks to promote the adoption of WSUD, thus representing a significant shift from the linear drainage strategy currently adopted at local level to a holistic management approach of the urban water cycle and its integration into urban design. Although the value of ecosystem services is increasingly recognised, WSUD and particularly plant biofiltration as one of its components, is under-utilised, as the current framework in South Africa only provides broad philosophical guidance lacking scientific premise for practical design considerations.

Variable performances have been reported in standard and modified plant biofilters, stagnating treatment optimisation knowledge. The difficulty of plant biofilter optimisation stems from the complex pollutant removal processes, which vary between physical designs and operational conditions. Therefore, appropriate design demands that both engineering hydrology and the scientific functioning of natural elements be considered; however, the latter is not currently included in the training of the civil engineer who can be the professional responsible for plant biofilter planning and design. Furthermore, current plant biofilter models insufficiently account for design modification and its associated removal processes. Limited local research and design specifics are currently available, which has resulted in injudicious plant selection and erroneous plant biofilter design, inhibiting treatment performance and threatening the recipient site's natural biodiversity. Thus, the main aim of this research is to advance knowledge in stormwater plant biofiltration for improved urban water management in South Africa.

This research initially presents potential phytoremediators, plants for the *in situ* treatment of pollutants, which are indigenous to the Western Cape, South Africa, as an aid to the practicing engineer for use in local plant biofiltration initiatives. Although chosen plant species were from the local Western Cape area for logistic reasons (the University is situated in the Western Cape), the techniques presented to identify species are transferable to other biogeographic areas. Informed by this undertaking, a phyto-guide is developed for identifying novel phytoremediators, adept at adjusting to the recipient habitat's dynamic conditions and further incentivised by South Africa's extensive biodiversity. The initial approach to plant biofilter optimisation investigated four engineered materials as potential growth media amendments, promoting attapulgite combinations for use in small-scale stormwater biofilters in the spatially constrained urban area. Progressing with plant biofilter optimisation, nine indigenous South African biofilters were investigated as effective yet sustainable alternatives to exotic phytoremediators, and *Prionium serratum,* among others, was found to exhibit enhanced removal capabilities. Physically modifying the plant biofilter as the final component to optimisation, following growth media and plant species, showed that combining standard biofiltration techniques with upflow filtration, plenum aeration and anaerobic zone saturation is the most efficient solution; removing on average 96% of synthetic stormwater loads. The novel sequential modifications between designs highlighted pollutant-specific removal processes and proffered plant biofilter designs for optimised treatment performance.

Empirical findings based on the data captured by the preceding investigations contribute statistical output for future local in-depth modeling endeavours. Additionally, in developing the conceptual deterministic plant biofilter model for stormwater treatment, possible applications of existing models for the various nutrient, and potentially heavy metal, removal processes are summarised. In conclusion, this research contributes physical design specifics and both experimental and mathematical models to urban stormwater treatment researchers and practitioners, constantly improving the understanding of plant biofilter complexity.

OPSOMMING

Groot nagevolge van verstedeliking is die grootskaalse omskakeling van deurlaatbare na ondeurdringbare oppervlaktes, wat die natuurlike hidrologiese siklus aansienlik verander in terme van beide hidrologie en kwaliteit. Tesame met klimaatsverandering word verstedeliking en die gepaardgaande stormwaterafloop beskou as primêre bedreigings vir waterhulpbronsekuriteit wêreldwyd, as gevolg van die verskeidenheid besoedelstowwe wat gegenereer en vervoer word. Konvensionele stedelike stormwaterbestuur versamel en vervoer vinnig afloop vir afvoer in die naaste waterloop, wat 'n oorvloed van openbare en ekologiese gesondheidsprobleme veroorsaak. In reaksie hierop word die “Water Sensitive Urban Design” (WSUD)-konsep, waarvan biofiltrasie 'n komponent is, toenemend verkies as 'n volhoubare alternatief vir konvensionele stelsels, aangesien dit stormwater beskou as 'n hulpbron om te beskerm eerder as 'n stof waarvan ontslae geraak moet word. Plantbiofiltrasie bevorder 'n ruimtelike netwerk van passiewe ekologies gesonde behandelingsoplossings vir die verspreide aard van stedelike stormwaterbesoedeling, vir afvoer in bestaande dreineringstelsels of waterlope.

Suid-Afrika, een van die mees verstedelikte lande in Afrika, is besig om vinnig te verstedelik en ervaar van die ergste omgewingsagteruitgang wêreldwyd. Stormwaterafloopafvoer tesame met veroudering en gebrekkige konvensionele behandelingstelsels bedreig die land se reeds beperkte varswaterbronne. Daarom poog die Suid-Afrikaanse waternavorsingskommissie om WSUD te bevorder, wat dus 'n beduidende verskuiwing verteenwoordig van die huidige lineêre dreineringstrategie na 'n holistiese bestuursbenadering van die stedelike watersiklus en die integrasie daarvan in stedelike ontwerp. Alhoewel die waarde van ekosisteemdienste toenemend erken word, word WSUD onderbenut, aangesien die huidige raamwerk in Suid-Afrika slegs breë filosofiese leiding verskaf sonder wetenskaplike uitgangspunte.

Wisselende optredes is egter in standaard en gemodifiseerde plantbiofilters gerapporteer, wat gevolglik lei tot die stagnering van behandelingsoptimalisering. Die probleem van plantbiofilteroptimalisering spruit uit die komplekse besoedelingsverwyderingsprosesse, wat wissel tussen fisiese ontwerpe en operasionele toestande. Daarom vereis toepaslike ontwerp dat beide ingenieurshidrologie en die wetenskaplike funksionering van natuurlike elemente oorweeg moet word, met laasgenoemde tans nie ingesluit in die opleiding van die siviele ingenieur wat dikwels verantwoordelik is vir plantbiofilterbeplanning en -ontwerp nie. Verder slaag huidige plantbiofiltermodelle nie daarin om ontwerpmodifikasie en die gepaardgaande verwyderingsprosesse tot ‘n voldoende mate in te reken nie. Beperkte plaaslike navorsing en ontwerp spesifikasies is tans beskikbaar, wat gelei het tot onoordeelkundige plantseleksie en foutiewe plantbiofilterontwerp, wat behandelingsprestasie inhibeer en die ontvangerterrein se natuurlike biodiversiteit bedreig. Die hoofdoel van hierdie navorsing is dus om stormwaterplantbiofiltrasie te bevorder vir verbeterde stedelike waterbestuur in Suid-Afrika.

Hierdie navorsing se aanvaklike doel was om potensiële fitoremediators vir oorsprong kontaminant behandeling wat inheems is aan die Wes-Kaap, Suid-Afrika, te versaf as 'n hulpmiddel vir die praktiserende ingenieur vir gebruik in plaaslike plantbiofiltrasie-inisiatiewe. Alhoewel gekose plantspesies om logistieke redes uit die plaaslike Wes-Kaap area kom (weens die Universiteit wat in die Wes-Kaap geleë is), is die voorgestelde plantspesies seleksie tegnieke oordraagbaar na ander biogeografiese gebiede. Op grond van hierdie onderneming word 'n fitogids ontwikkel vir die identifisering van nuwe fitoremediators, wat in staat daarvan is om aan te pas by die ontvangerhabitat se dinamiese toestande en verder aangespoor word deur Suid-Afrika se uitgebreide biodiversiteit. Die aanvanklike benadering tot plantbiofilteroptimering het vier gemanipuleerde materiale as potensiële groeimedia-aanpassings ondersoek, wat attapulgietkombinasies vir gebruik in kleinskaalse stormwaterbiofilters in die ruimtelik beperkte stedelike gebied bevorder het. Met die optimering van biofilterontwerp is nege inheemse Suid-Afrikaanse plantbiofilters ondersoek as effektiewe tog volhoubare alternatiewe vir eksotiese fitoremediators en het *Prionium serratum*, onder andere, geïdentifiseer om verbeterde verwyderingsvermoëns te toon. Die fisiese wysiging van die plantbiofilter as die finale komponent tot optimalisering, opvolgende groeimedia en plantspesies, binne die ontwerpingenieur se beheer, het gekombineerde standaard biofiltrasietegnieke met opvloeifiltrasie, plenumbelugting en anaërobiese soneversadiging as die mees doeltreffende geïdentifiseer; met verwydering van gemiddeld 96% van sintetiese stormwaterladings. Die nuwe opeenvolgende wysigings tussen ontwerpe het besoedeling-spesifieke verwyderingsprosesse uitgelig, sowel as plantbiofilterontwerpe vir geoptimaliseerde behandelingsprestasie.

Laastens, dra empiriese bevindinge gebaseer op die data wat vasgelê is deur die voorafgaande ondersoeke, statistiese uitsette by vir toekomstige plaaslike in-diepte modellering pogings. By die ontwikkeling van die konseptuele deterministiese plantbiofiltermodel vir stormwaterbehandeling, word moontlike toepassings van bestaande modelle vir die verskillende voedingstowwe, en potensieel swaarmetale, verwyderingsprosesse opgesom. In opsomming, dra hierdie navorsing fisiese ontwerp spesifikasies sowel as beide eksperimentele en wiskundige modelle by vir stedelike waterbehandeling navorsers en praktisyns, en so voortdurend die begrip van plant biofilter kompleksiteit verbeter.

ACKNOWLEDGEMENTS

I would like to thank the following people and organisations for their assistance and contribution to the success of this research:

- My supervisor, Dr Isobel C Brink, for her unwavering support, guidance and mentorship during this research journey, as well as providing me the opportunity to make use of her Water Quality Laboratory. Notwithstanding her exceptional leadership and expertise, Dr Brink allows the necessary freedom from which myself and this study benefitted.
- My co-supervisor, Prof Shayne M Jacobs, for his constant guidance and support, continuously emphasizing the scientific premise.
- My co-author, Mr Izak SW van der Merwe, for his remarkable insight, a mensch and a dear friend, Jovially Open to Engage Year after year.
- The National Research Foundation (NRF) Thuthuka Fund, project identity: TTK180418322426, for the financial support.
- The Hydraulic Laboratory staff, particularly Mr Johann Nieuwoudt for his interest, technical assistance and emotional support throughout the study.
- My family, particularly my father Mr Michael B Jacklin, for the love and continuous support during this research, always willing to help and acted as constant submission date reminders.
- My partner, Ms Lari A Opperman, for her unending love, support, understanding and patience, as well as igniting my passion for SuDS.

"*That's what I call, high quality H_2O*" – Bobby Boucher Jr

CONTRIBUTING MATERIAL

Paper i. Jacklin D. M., Brink I. C. & Jacobs S. M. 2021 Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators with a focus on green infrastructure. *Water SA*, **47**(3), 317-325.

Paper ii. Jacklin D. M., Brink I. C. & Jacobs S. M. 2021 A phyto-guide to species selection for optimised South African green infrastructure. *Water SA*, **47**(4), 515-522.

Paper iii. Jacklin D. M., Brink I. C. & Jacobs S. M. 2021 Urban stormwater nutrient and metal removal in small-scale green infrastructure: Exploring engineered plant biofilter media optimisation. *Water Science and Technology,* **84**(7), 1715-1731.

Paper iv. Jacklin D. M., Brink I. C. & Jacobs S. M. 2021 Efficiencies of indigenous South African plant biofilters for urban stormwater runoff water quality improvement with a focus on nutrients and metals. *AQUA – Water Infrastructure, Ecosystems and Society,* **70**(7), 1094-1110.

Paper v. Jacklin D. M., Brink I. C. & Jacobs S. M. (in press) Comparison of urban stormwater plant biofilter designs for nutrient and metal removal in South Africa. *Water Practice and Technology.*

Paper vi. Jacklin D. M., Van der Merwe I.S.W. & Brink I. C. (for submission) Urban stormwater pollutant removal in small scale plant biofilters: A technical note on modeling approaches. *Urban Water Journal.*

Conference presentation. Jacklin D. M., Brink I. C. & Jacobs S. M. 2020 *Selecting indigenous South African plant species for the phytoremediation of polluted urban runoff,* Water Institute of Southern Africa Online Conference: Urban water management – Manage the resource for a capable economy.

Paper i is based on secondary research conducted to establish a decision framework for plant selection in the experiments, where its findings were implemented in obtaining the results for Paper ii. These findings were presented in the proceedings of the Water Institute of Southern Africa Online Conference. Papers iii, iv and v are based on primary research (laboratory experiments) conducted at Stellenbosch University, South Africa, which relied on the findings of Paper ii for their experimental designs. Paper vi further analysed the findings from Papers iv and v, as well as conducted secondary research for deterministic model development. The author's contribution and copyright permissions for each Paper are outlined in Appendix B and C respectively.

TABLE OF CONTENTS

DECLARATION ... i
ABSTRACT ... iii
OPSOMMING ... v
ACKNOWLEDGEMENTS ... vii
CONTRIBUTING MATERIAL ... viii
TABLE OF CONTENTS ... ix
LIST OF FIGURES ... xi
LIST OF TABLES ... xiii
LIST OF ABBREVIATIONS AND ACRONYMS ... xiv
LIST OF CHEMICAL ELEMENTS AND COMPOUNDS ... xvi
LIST OF SYMBOLS ... xviii

CHAPTER 1 ... 1
Introduction ... 1
1.1 Problem statement ... 5
1.2 Thesis statement ... 6
1.3 Research aim and objectives ... 6
1.4 Research significance ... 7
1.5 Limitations and assumptions ... 9
1.6 Methods ... 10
1.7 Dissertation Structure ... 15
1.8 References ... 16
CHAPTER 2 ... 23
Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators - with a focus on Green Infrastructure ... 24
CHAPTER 3 ... 45
A phyto-guide to species selection for optimized South African green infrastructure – Technical note ... 46
CHAPTER 4 ... 65
Urban stormwater nutrient and metal removal in small-scale green infrastructure: Exploring engineered plant biofilter media optimisation ... 66
CHAPTER 5 ... 91
Efficiencies of indigenous South African plant biofilters for urban stormwater runoff water quality improvement – with a focus on nutrients and metals ... 92

CHAPTER 6 116

Comparison of urban stormwater plant biofilter designs for nutrient and metal removal in South Africa 117

CHAPTER 7 144

Urban stormwater pollutant removal in small scale plant biofilters: A technical note on modeling approaches 145

CHAPTER 8 190

Conclusions 190

8.1 Research summary and contributions 190

8.2 Main research findings 194

Chapter 2: Indigenous Western Cape phytoremediators 194

Chapter 3: The phyto-guide 194

Chapter 4: Engineered media 195

Chapter 5: Indigenous South African biofilters 196

Chapter 6: Optimised biofilter design 196

Chapter 7: Modeling approach 197

8.3 Recommended future research 198

ADDENDA 200

Appendix A: International conference proceeding 200

Appendix B: Author declarations 205

Appendix C: Copyright permissions 211

LIST OF FIGURES

CHAPTER 1

Figure 1.1 Constructed laboratory growth chamber for primary research objectives………....11

Figure 1.2a-c Soil excavated for experimental use, the 100 L pan mixer for uniform soil conditions, and perspex columns for infiltration....……………………………………………….11

Figure 1.3a-b PVC biofilter drainage outlets and irrigation dripper in front of a *Prionium serratum* specimen……………………………………………………………………….......12

CHAPTER 3

Figure 1. Phyto-guide to species selection for optimized South African green infrastructure, as an aid during planning and design to the practicing civil engineer……………………........55

CHAPTER 4

Graphical abstract………………..67

Figure 1. Schematic of experimental biofilter, vegetated Juncus effusus and unvegetated columns……………………...69

Figure 2. Mean percentage nutrient load removal between media for the duration of the experiment…………………………………………………………………………………..…77

Figure 3. Mean percentage metal removal between media for the duration of the experiment……………………………………………………………………………………....78

Figure 4. Infiltration rates (IRs) of unvegetated and vegetated media under alternating influent dosages with time………………………………………………………………………..79

Figure 5. Effluent TS and turbidity of unvegetated and vegetated media through time, with change in effluent clarity illustrated by photographic captures……………………………........82

CHAPTER 5

Graphical abstract…………………………………………………………………………….....93

Figure 1. Schematic of experimental column and biofilters at initiation (February 2020) and established (May 2021) state……………………………………………...……………....95

Figure 2. Mean percentage nutrient and metal load removals of the experimental biofilters for the duration of the study…………………………………………………...……………........100

Figure 3. Mean low strength nutrient and metal removal by vegetated and unvegetated biofilters with time………………………………………………………………………………..105

Figure 4. Mean typically observed strength nutrient and metal removal by vegetated and unvegetated biofilters with time…………………………………………………......………..105

Figure 5. Mean high strength nutrient and metal removal by vegetated and unvegetated biofilters with time………………………………………………………………………………..106

Figure 6. Development of above-ground traits, leaf number and mean lengths recorded on 16 occasions during the experimental period………………………………………......….110

CHAPTER 6

Graphical abstract……………………………………………………………………………….119

Figure 1. Schematic of the six plant biofilter designs, with photographic panels illustrating significant aspects of the experiment…………………....…………………………...……....122
Figure 2. Boxplots of nutrient loads removed by the different biofilter designs over the sampling rounds………………………………...……...……………………..…………....132
Figure 3. Boxplots of metal loads removed by the different biofilter designs over the sampling rounds…………………………………………………………………...............133
Figure S1. Mean percentage nutrient and metal load removals of the six engineered plant biofilters over 5 sampling rounds……………………………………………………….....143

CHAPTER 7

Graphical abstract………………………………………………………………………….146
Figure 1. Inorganic N removal processes and pathways in an urban stormwater biofilter…149
Figure 2. Dissolved P and heavy metal removal processes and pathways in an urban stormwater biofilter…………………………………………………………………….....151
Figure 3. Experimental schematic of the indigenous plant and design amended biofilter....156
Figure 4. Schematic presentation of a biofilter, magnification of its growth media, and different components of a biofilm system: substratum, biofilm, mass transfer boundary layer and bulk liquid..163
Figure S1. Linear regression models of percent removal over non log-transformed time as the independent variable for indigenous plant experimental biofilters............................178
Figure S2. Linear regression models of percent removal over non log-transformed time as the independent variable for local experimental design amended biofilters...................179
Figure S3. Linear regression models of percent removal over log-transformed influent load as the independent variable for indigenous plant and design amended experimental biofilters..180

LIST OF TABLES

CHAPTER 1

Table 1.1 Material used in the experimental biofilter columns……......................................13

Table 1.2 Investigated plant species, their South African distribution, as well as above- and below-ground traits………………………………………………………………………..14

CHAPTER 2

Table 1. Potential WC autochthonous phytoremediation plants of least conservation concern and minimal biological invasive threat………………………………………………..31

CHAPTER 4

Table 1. Particle size distribution of the material..70

Table 2. Engineered filter media proportions for initial infiltration within 100 – 300 mm/hr.....71

Table 3. Influent pollutant concentrations...72

Table 4. Ranked media performance by mean percentage stormwater pollutant removal over time for all sampling rounds……………………………………………...………………..78

Table 5. Physiological trait development of *Juncus effusus* in different media.………...….....83

Table 6. Optimised engineered media ranking across all performance factors through time…………………………………………………………………………………….....85

CHAPTER 5

Table 1. Indigenous South African plant species for urban stormwater pollutant removal.....96

Table 2. Influent synthetic stormwater………………………………………………………......97

Table 3. Estimate of pollutant load distribution………………………………………….........107

Table 4. Development of below-ground traits, initial and final root number and length of longest root………………………………………………………………………………….......108

CHAPTER 6

Table 1. Overview of the six biofilter designs under study…………………………………....120

Table 2. Influent synthetic stormwater concentrations and overall performance of the engineered plant biofilters………………………………………………………………………127

CHAPTER 7

Table 1. Statistical output for percent pollutant load removal with time (non log-transformed): R^2, F-test p-value and model coefficient…………………………......158

Table 2. Statistical output of linear regression models for percent pollutant load removal as a function of influent load (log-transformed): R^2, F-test p-value and model coefficient...160

Table 3. Stoichiometry and kinetics expression matrix for biofilm reaction processes……..169

Nomenclature……………………………………………………………………………………..176

Table S1. Overview of the local laboratory experiments from which data was collected, depicting influent synthetic stormwater, biofilter descriptions, media properties incorporated into the layers and literature sources from which motivation for plant and engineered media inclusion originated from…………………………………...……......177

LIST OF ABBREVIATIONS AND ACRONYMS

AIPLSA	Alien Invasive Plant List for South Africa
AT1	Attapulgite 0.5-1.4mm
AT2	Attapulgite 1.4-4.5mm
BISA	Biological Invasions in South Africa
CABI	Centre for Agriculture and Bioscience International
CFR	Cape Floristic Region
CIB	Centre of Excellence for Invasion Biology
CR	Critically Rare
D	Declining
DDD	Data Deficient
DNRA	Dissimilatory Nitrate Reduction to Ammonia
DO	Dissolved oxygen
DWS	Department of Water and Sanitation
EC	Electrical conductivity
EW	Extinct in the Wild
GI	Green Infrastructure
GISD	Global Invasive Species Database
GL	Geotextile lined
IAPs	Invasive alien plants
ISSG	Invasive Species Specialist Group
IR	Infiltration rate
IUCN	International Union for the Conservation of Nature
LED	Light-emitting diode
LID	Low Impact Development
LS	Loamy sand
LSA	Loamy sand + Attapulgite
LSD	Fisher Least Significant Difference
LSP	Loamy sand + Perlite
LSPA	Loamy sand + Perlite + Attapulgite
LSPV	Loamy sand + Perlite + Vermiculite
LSPVA	Loamy sand + Perlite + Vermiculite + Attapulgite
LSPVZ	Loamy sand + Perlite + Vermiculite + Zeolite
LSPZ	Loamy sand + Perlite + Zeolite
LSV	Loamy sand + Vermiculite
LSZ	Loamy sand + Zeolite
MR	Metal removal
NEM:BA	National Environmental Management: Biodiversity Act, 2004
NRF	National Research Foundation
NR	Nutrient removal
NT	Near Threatened

PA	Plenum aeration
PE	Perlite
PGCFR	Plants of the Greater Cape Floristic Region
pH	Potential hydrogen
POSA	Plants of Southern Africa
PVC	Polyvinyl chloride
R	Rare
RE	Regionally Extinct
SA	South Africa
SANBI	South African National Biodiversity Institute
SAIPC	South African Indigenous Plants Catalogue
SAPIA	South African Plant Invaders Atlas
SBIMSA	Status of Biological Invasions and their Management in South Africa
STD	Standard
SuDS	Sustainable urban Drainage Systems
SUNBG	Stellenbosch University Botanical Garden
SZ	Saturated zone
TDS	Total dissolved solids
TS	Total solids
TSS	Total suspended solids
TU	Turbidity
UF	Upflow filtration
VE1	Vermiculite 0.35-0.5mm
VE2	Vermiculite 0.5-1.4mm
VE3	Vermiculite 1.4-4mm
WC	Western Cape
WRC	Water Research Commission
WSUD	Water Sensitive Urban Design
ZAR	South African rand
ZE1	Zeolite 0.8-1.4mm
ZE2	Zeolite 1.4-2mm
ZE3	Zeolite 2-6mm

LIST OF CHEMICAL ELEMENTS AND COMPOUNDS

Ag	Silver
Al	Aluminium
As	Arsenic
Ba	Barium
C	Carbon
Ca	Calcium
Cd	Cadmium
$CdCl_2$	Cadmium chloride
CO	Carbon monoxide
Co	Cobalt
Cr	Chromium
Cu	Copper
$CuSO_4$	Copper(II) sulfate
Fe	Iron
Hg	Mercury
HMX	Octogen
K	Potassium
K_2HPO_4	di-potassium hydrogen phosphate
KNO_3	Potassium nitrate
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NH_3 -N	Ammonia -nitrogen
NH_4^+	Ammonium
NH_3 -N	Ammonium -nitrogen
NH_4Cl	Ammonium chloride
Ni	Nickel
NO	Nitric oxide
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_3^- -N	Nitrate -nitrogen
P	Phosphorous
PAHs	Polycyclic Aromatic Hydrocarbons
Pb	Lead
$PbCl_2$	Lead(II) chloride
PO_4^{3-}	Phosphate

PO_4^{3-} -P	Orthophosphate –phosphorous / Soluble reactive phosphorous
RDX	Research Demolition Explosive
Se	Selenium
Si	Silicon
Sr	Strontium
Th	Thorium
TCE	Trichloroethylene
TNT	Trinitrotoluene
TPHs	Total Petroleum Hydrocarbons
U	Uranium
Zn	Zinc
$ZnCl_2$	Zinc chloride

LIST OF SYMBOLS

A	Cross-sectional area of the growth media
A_F	Surface area of biofilm within a plug compartment
A_b	Area of biofilter
a	Cross-sectional area of biofilter column
$b_{ina,A}$ (T)	Autotrophic organism inactivation rate as a function of temperature
$b_{ina,H}$ (T)	Heterotrophic organism inactivation rate as a function of temperature
$b_{res,A}$ (T)	Autotrophic organism respiration rate as a function of temperature
$b_{res,H}$ (T)	Heterotrophic organism respiration rate as a function of temperature
C	Dissolved pollutant, substrate or nutrient concentration
C_B	Pollutant, substrate or nutrient concentration in the bulk liquid phase
C_F	Pollutant, substrate or nutrient concentration in the biofilm
C_{LF}	Pollutant, substrate or nutrient concentration at the biofilm surface
C_R	Pollutant, substrate or nutrient concentration at the surface of the plant root
C_d	Dissolved biodegradable organics concentration
C_{eff} / C_e	Effluent concentration
C_{inf} / C_i	Influent concentration
C_p	Particulate biodegradable organics concentration
D_F	Diffusion coefficient in the biofilm
D_W	Diffusion coefficient in the water phase
F_{am}	Ammonia Preference Factor for biomass assimilation
F_c	Pollutant, substrate or nutrient preference factor for plant assimilation
F_{ox}	Oxygen Preference Factor for heterotrophic oxidation
f_{CX}	Ratio of COD to VSS in the biofilm biomass
f_H	Unbiodegradable fraction of biofilm biomass
f_{NC}	Ratio of nitrogen to COD in particulate organic matter
f_{NX}	Ratio of nitrogen to VSS in biofilm biomass
f_{PC}	Ratio of phosphorus to COD in particulate organic matter
f_{PX}	Ratio of phosphorus to VSS in biofilm biomass
f_{cp}	Ratio pollutant, substrate of nutrient mass to plant biomass relationship
$h_1 – h_0$	Head readings taken at t_1 and t_0 respectively
J_{BL}	Pollutant, substrate or nutrient flux in the water phase
J_{LF}	Pollutant, substrate or nutrient flux at the biofilm surface
K_L	Langmuir half-saturation concentration
K_N	Half-saturation constant for nitrification
$K_{O,A}$	Half-saturation constant for oxygen utilisation by autotrophic organisms
$K_{O,H}$	Half-saturation constant for oxygen utilisation by heterotrophic organisms
$K_{S,am}$	Half-saturation constant for ammonium preference
K_a	Biofilter percentage of contributing catchment area
K_f	Freundlich coefficient
K_r	Percentage urban runoff

K_s	Half-saturation constant for heterotrophic oxidation of biodegradable dissolved organics
k	Coefficient of permeability
k	Rate of sorption/desorption
k_{ep} (T,I)	Plant photorespiration (or excretion) rate as a function of temperature and sunlight
k_{gp} (C,T,I)	Plant growth rate as a function of the pollutant concentration, temperature and sunlight
k_{mp} (T)	Plant's mortality rate as a function of temperature
k_p	Dissolution rate of particulate biodegradable organics to dissolved biodegradable organics
k_{rp} (T)	Plant dark respiration rate as a function of temperature
L	Growth media depth
L_F	Biofilm thickness
L_L	Thickness of the mass transfer boundary layer at a biofilm
L_{gm}	Length/height of the biofilter growth media
L_{rem} / K_{rem}	Pollutant load removed
N_a	Ammonia concentration
N_i	Nitrate concentration
n_f	Freundlich exponent
P	Precipitation event rainfall
P	Soluble reactive phosphorous (Chapter 7)
P_j	Rate of process *j*
Q_{eff}	Effluent flow rate out of the plug compartment
Q_{et}	Evapotranspiration rate
Q_{inf}	Influent flow rate into the plug compartment
R_L	External mass transfer resistance for biofilm
R_{LP}	Mass transfer resistance factor for plant roots
r_F	Rate of pollutant, substrate or nutrient of substrate conversion per biofilm volume
r_{Fi}	Rate of pollutant, substrate or nutrient conversation for state per biofilm volume parameter *i*
S	Sorped concentration
S_{max}	Langmuir Maximum site density
t	Time
$t_1 - t_0$	Elapsed time between head readings
$u_{d,S}$	Constant biofilm detachment velocity
V_B	Bulk liquid phase volume of a plug compartment
V_{eff} / V_e	Effluent volume
V_{inf} / V_i	Influent volume
$v_{i,j}$	Stoichiometric coefficient of state parameter *i* for proses rate *j*
X_A	Autotrophic organism concentration

X_H	Heterotrophic organism concentration
X_I	Inert Biomass
x	Distance from the biofilm surface
Y_A	Autotrophic organism yield coefficient
Y_H	Heterotrophic organism yield coefficient in terms of COD ($=f_{CX}Y_{Hv}$)
Y_{Hv}	Heterotrophic organism yield coefficient in terms of VSS
Δ_Z	Thickness of a plug compartment
Θ	Porosity of biofilter
μ_A (T)	Heterotrophic organism growth rate as a function of temperature
μ_H (T)	Autotrophic organism growth rate as a function of temperature
ρ_F	Biofilm density
ρ_S	Solid phase density of sorbed pollutant

CHAPTER 1

Introduction

Together with climate change, urban water managers regard urbanisation as a major threat to water resource quantity and quality (Wong *et al.* 2002). Urbanisation significantly alters the hydrological cycle of natural catchments in terms of both hydrology and quality (Gunawardena *et al.* 2018), with urban stormwater runoff often linked to the degradation of environmental quality, including water resource quality (Cullis *et al.* 2019). In order to accommodate the rural to urban migration of individuals, continuous urban spatial expansion and densification is required, impacting watercourses and aquatic ecosystems (Hamel, Daly & Fletcher 2013). Habitat modifications, even at low levels of urbanisation, significantly alter natural processes, environmental quality and resource consumption, disturbing flow regimes and altering water quality (Bratieres *et al.* 2008; Wenger *et al.* 2009). The pervious to impervious surface conversion produces enlarged runoff volumes (Muerdter, Wong & LeFevre 2018), decreased runoff lag time (McGrane 2016), enhanced evaporation (Wadzuk *et al.* 2015), elevated peak discharges and deteriorated water-quality (Fletcher *et al.* 2015).

Urban stormwater and its management are a primary concern to civil and environmental engineers. In the urban water cycle, stormwater connecting urban infrastructure and the urbanised natural environment generate and transport a variety of pollutants, deteriorating receiving watercourses and triggering harmful ecological impacts (Brudler *et al.* 2019). Urban runoff is susceptible to a variety of nonpoint pollution sources emanating from different land uses, making it difficult to characterise and quantify. As a consequence, conventional treatment approaches have in many instances failed (Burns *et al.* 2012). Due to water's absorption capacity being one of the most powerful of all solvents, portions of nearly all solvents are collected (Abbasi & Abbasi 2011). In addition, highly degraded conventional drainage infrastructure in most urbanised cities are overwhelmed, inflicting considerable water resource and ecological system challenges (Geberemariam 2016).

Among the many pollutants commonly detected in urban stormwater runoff, those of particular concern are nutrients (Shrestha, Hurley & Wemple 2018), as the primary contributors to eutrophication (Davis *et al.* 2006), heavy metals (Davis & Birch 2010), which pose a threat to human and environmental health (Reddy, Xie & Dastgheibi 2014) and particulates (Søberg *et al.* 2020), aggravating sedimentation and erosion (Armitage *et al.* 2013). In comparison with other anthropogenic activities, such as consumption and irrigation, these pollutants are the main contributors to ecotoxicity, causing >97% of the total impacts (Risch *et al.* 2018; Brudler *et al.* 2019). In response, the Water Sensitive Urban Design (WSUD) and similarly Green Infrastructure (GI) concepts, which are land planning and engineering design approaches based on sustainability principles within urban water cycle management, are increasingly adopted for their improved stormwater management capacity where conventional methods are inadequate (Fitchett 2017; Al-Ameri *et al.* 2018).

The WSUD approach develops adaptive systems that prioritise water management in cooperation with conventional infrastructure, for urbanisation relief, climate change adaptation, and runoff mitigation within the urban water cycle (Dumitru *et al.* 2021). Holistically considering the environmental, social and economic consequences of water management infrastructure represents a significant shift from the linear drainage management strategy into urban design, through which sustainable development can be achieved (Wong *et al.* 2002; Armitage *et al.* 2014). Biofiltration systems, a WSUD stormwater treatment technology, provides both water quality and quantity benefits by reducing flow rates, runoff volumes and pollutant loads via physical (filtration, evaporation), chemical (sorption, ion exchange, precipitation) and biological (phytoremediation, assimilation, microbial-mediated transformation, transpiration) processes within a soil-plant matrix (Hsieh & Davis 2005; Feng *et al.* 2012). As a cost-effective method for stormwater management, biofiltration promotes the use of ecologically sound solutions for the on-site treatment of pollutants in the urban environment (Yang *et al.* 2015). Typically comprised of intricately selected vegetation supported by underlying growth media, transition and drainage layers, biofilters discharge treated stormwater into existing drainage systems or watercourses (Blecken *et al.* 2010).

Small-scale biofilters can be practically introduced into dense and confined urban areas, while large-scale biofilters are strategically located near distinct stormwater network confluences (Le Coustumer *et al.* 2012). An appropriately designed spatial network of biofilters provide dispersed and passive treatment to the diffused nature of urban stormwater pollution (Brink 2019), ameliorating deficient hydrologic functions. This treatment network creates an integrated water quality improvement sequence, enhancing overall performance and sustainability, by overcoming environmental and operational conditions that commonly restrict the efficacy of conventional management approaches. In contrast to conventional approaches, which regard stormwater as a substance to dispose of rather than a resource to protect, improved management treats pollution and reduces hydrologic disturbance, whilst considering stormwater as a supplementary resource (Barbosa, Fernandes & David 2012; Fletcher *et al.* 2015). In doing so, secondary benefits are offered by means of additional water supply, increased biodiversity, and improved microclimate (Ashley *et al.* 2013). An additive advantage of treatment biofilters is its ability to assist existing conventional storm infrastructure, while the utilised plant species enhance conservation, sustainability and urban aesthetics (Shrestha, Hurley & Wemple 2018).

In biofilters, favourable conditions are provided for plant uptake, sorption and ubiquitous biofilm establishment, promoting vital treatment processes for the remediation of polluted water (Taylor *et al.* 2005; Del Castillo *et al.* 2020). Vegetation further enhances the biofilter's treatment performance and sustainability (Read *et al.* 2008), this occurs either directly through pollutant sorption, transformation and uptake by plants, or indirectly by altering the physio-chemical properties of the soil and associated microbial activities (Bratieres *et al.* 2008). The *in situ* treatment of pollutants, via a process known as phytoremediation, is attractive due to its cost-efficacy, aesthetic advantage, long-term applicability, employment generation capacity, and pollutant scope and removal ability (Abhilash 2015; Marrugo-Negrete *et al.* 2015). The permanent removal pathway known as phytoextraction, particularly in metal-accumulating species, requires regular harvesting and maintenance plans (Kumar, Smita & Flores 2017). Additionally, the cumulative pollutant load extraction capabilities prior to mortality, where extracted toxins are deposited back into the system vary between species (Chowdhury *et al.* 2020). Furthermore, due to physiological, morphological and chemical differences between plants exposed to different pollutants, removal performance varies between species (Read *et al.* 2010). Therefore, plant selection is a critically important contributor to the successful functioning of a plant biofilter. The establishment of biofilms, which are gel-like aggregations of microorganisms and other particles, which grow on the biofilter's soil, compost, detritus litter, engineered media and plant roots, improve water quality by supporting pollutant biodegradation via destruction or immobilisation processes (Wanner *et al.* 2006). The biofilm contact area, regulated by the substratum's surface area, interact with pollutants from the stormwater bulk liquid via solute utilisation by microorganisms (Morgenroth 2008). Therefore, enhancing the surface area for microbial adherence and water retention, supporting biofilm growth and pollutant transformation, improves biofilter performance (Wanner *et al.* 2006). Within vegetated biofilters, sites for biofilm establishment are enhanced by growth media, its amendments and plant roots (Maurya, Singh & Kumar 2020). An additive benefit of biofilms to stormwater biofilters is the potential development of anaerobic conditions within the biofilm, regardless of external aerobic conditions, promoting nitrification-denitrification processes and, thus, removal of problematic nutrients (Morgenroth 2008).

Due to the release of large amounts of pollutants to South Africa's soil and water resources, from urbanisation, agriculture, industry, mining, waste disposal, dysfunctional sewage works and unsewered formal and informal human settlements, the country experiences some of the most severe environmental degradation globally (De Klerk *et al.* 2016). Nationally, the pollutant discharge from aging and defective conventional infrastructure into receiving watercourses have resulted in a 500% increase (1999-2011) of main rivers classified as having poor ecological conditions, posing a threat to the country's potable water resources (Oberholster & Ashton 2008; DWS 2018). A comprehensive investigation by De Villiers & Thiart (2007) assessing the 20 largest river catchments in South Africa, found that all but one exceeded the recommended water quality guidelines for plant life, whilst dissolved phosphorous levels exceeded the recommendations for aquatic animal life in all but 6 catchments. Hedden & Cilliers (2014) investigated the over-exploitation of South Africa's freshwater resources and found that more than 60% of river ecosystems are threatened by pollution, whilst from an ecological perspective one-quarter is critically endangered (Donnenfeld *et al*. 2018).

Urban area stormwater runoff discharge, the focus of this study, contributes a wide range of pollutants to the country's freshwater ecosystems (Milandri *et al.* 2012; Musingafi & Tom 2014), which resulted in the Department of Water and Sanitation (DWS) classifying stormwater pollution as one of the primary threats to water provision and ecosystem health (DWS 2017). Historically, conventional South African urban stormwater management has predominantly focused on the rapid collection and transportation of runoff to the nearest watercourse for removal, resulting in significant environmental degradation due to erosion, sedimentation and pollution (Armitage *et al.* 2013). Therefore, to improve resource quality and restore ecosystem function, local urban water management requires proper resource mitigation strategies. Thus, as an alternative approach, sensitive to the issues of water sustainability and environmental protection, the South African Water Research Commission (WRC) promotes the adoption of WSUD (Armitage *et al.* 2014).

Civil engineers are often tasked with optimising local biofiltration systems, however, design is complex and requires both engineering hydrology knowledge and insight into the functioning of natural elements, not generally included in the training of the practicing engineer (Brink 2019). For instance, proper biofilter planning and design must account for the numerous pollutant removal processes and pathways associated with various pollutant parameters, operational conditions and biofilter designs. In addition, the potential invasion threat to the recipient site's ecosystem biodiversity when introducing plant species, as urban areas are often the initial sites from which invasions spread, must be considered (Zengeya & Wilson 2020). This is particularly important in South Africa, which has long been subjected to plant introduction and invasion, with entire natural ecosystems in some cases having been transformed (Le Maitre *et al.* 2020), impacting negatively on an ecosystem's capacity to deliver goods and services, and in some cases severely threatening human livelihoods (Shackleton, Shackleton & Kull 2019). The use of plant biofilters in stormwater quality improvement therefore requires multi-disciplinary knowledge involving not only typical civil engineering filter design elements, but also natural science knowledge of living systems to incorporate unharmful indigenous vegetation in a correct manner.

It is imperative that stormwater plant biofilters are sustainably optimised for enhanced treatment efficacy across the range of pollutants of concern. In order to do so, research must explore and improve biofilter design and plant selection, as well as pollutant and hydrological treatment prediction, under varying operational conditions (Li *et al.* 2021). Various models have been developed and widely applied in an attempt to provide reliable and accurate predictions of biofilter treatment (Dussaillant, Wu & Potter 2004). These, however, rely on comprehensive knowledge of treatment processes within biofiltration, influenced by pollutants of concern, operational conditions and design. In the past, urban stormwater biofilter modeling has primarily focused on hydrological improvements (Stewart *et al.* 2017) and particulate capture (Li & Davis 2008), whilst others have eluded to accounting for varying designs and operational conditions (Khan *et al.* 2013; Wang, Zhang & Li 2019). Only recently, have data-driven statistical models initiated insight into the influence of varying design and operational conditions on nutrient removal, a step towards improving model performance (Zhang *et al.* 2021).

Plant biofiltration, as an interconnected set of natural and engineered systems offer an effective and sustainable approach to urban stormwater quality management, providing critical maintenance, rehabilitation and purification services. The biggest concerns surrounding plant biofiltration in South Africa are; ineffective design and injudicious plant introduction, absence of indigenous phytoremediators, variable pollutant treatment performances, lack of knowledge regarding pollutant removal processes and pathways, and lack of research into applicable models that account for differences in plant biofilter designs and operational conditions. Despite these challenges, plant biofiltration possesses remarkable potential as fit-for-purpose solutions, based on scientific knowledge and engineered techniques, to meet specific infrastructure and service needs within the local natural habitat, at a fraction of the cost of conventional systems.

1.1 Problem statement

Stormwater runoff as a cause of poor urban water and environmental quality, contributes to enhanced pollution and subsequent deterioration of urban watercourses and ecosystem health. Urban areas generate a variety of pollutants, which are transported via stormwater runoff and discharged into urban watercourses. This results in the rapid deterioration of water quality, raising a plethora of public and environmental health concerns. Due to its diffused nature, stormwater pollution and its treatment towards water quality improvement is considered one of the greatest challenges facing urban water managers, requiring alternatives to current ineffective conventional strategies for stormwater runoff control.

Plant biofiltration is an ecologically acceptable method for urban stormwater management and has shown promising results for the on-site reduction of peak flows, removal of environmental pollutants and protection of urban waters. From a logistic perspective, plant biofilters can be easily introduced into the urban landscape as spatially distributed green networks. Variable biofilter performances have, however, been reported for nutrients and heavy metals, with recent modifications to design for improved treatment showing some unsatisfactory findings. The difficulty in optimising these systems originate from the complexity of the processes and pathways influencing pollutant removal (particularly dissolved nutrients and heavy metals), which vary between biofilter designs and operational conditions, making it difficult to consistently maintain treatment performance. Additionally, pollutant removal varies between plant species.

Phytoremediators exhibiting traits linked to invasiveness, which are mirrored in beneficial traits for effective pollutant removal (e.g. rapid growth and spread, hardiness and disease and pest resistance), highlight the importance of appropriate and meticulous plant selection. Therefore, the consequence of injudicious plant selection may be twofold, with ineffective species inhibiting treatment performance, as well as imprudent species threatening the natural biodiversity of the site in need of remediation. Prior to introducing a phytoremediator, it is vital to assess its pollutant affinity, habitat behaviour and ecosystem dynamics which regulate potential future invasiveness, however, in many cases the acting civil engineer and urban water manager lack the necessary natural science expertise and knowledge background to do so.

While numerous investigations have focused on the treatment performance of stormwater biofilters, research into model predictions of biofilter performance is more limited, particularly in South Africa. In addition, the majority of those that have been undertaken still lack the basic understanding of appropriate design adaptations, and removal processes and pathways influencing the models, with most models insufficiently comprehensive nor accurate in predicting biofilter performance.

Therefore, successful plant biofilter design towards practical civil engineering application in stormwater quality improvement currently lacks necessary foundational knowledge in correct plant selection methods, soil and design optimisation methods as well as applicable modeling approaches.

1.2 Thesis statement

"Indigenous South African plants species, identified with the aid of a phytoremediator selection-tool, for use in intricately designed stormwater plant biofilters effectively reduce nutrient and heavy metal pollution, with performance potentially quantified by a stormwater model based on the functioning of biofilm reactor."

1.3 Research aim and objectives

The aim of this research is to advance practical knowledge to support stormwater plant biofiltration civil engineering design methods for improved urban runoff water quality improvement in South Africa. In order to achieve this aim, six objectives are listed below:

1. To identify indigenous plant species as potential pollutant phytoremediators in the Western Cape, South Africa, informed by global and local bioremediation literature.
2. To develop a decision framework to the practicing civil engineer and water manager in the form of a phyto-guide, from lessons learnt in objective 1 as a basis, to facilitate plant

selection for South African green infrastructure in general and plant biofiltration in particular.

3. To evaluate ten engineered media combinations exposed to typically observed (as reported in literature) urban stormwater pollution loads for biofilter growth media optimisation. Here, removal performance, infiltration capacity and particulate discharge of varying unvegetated sandy loam, perlite, vermiculite, zeolite and attapulgite combinations are assessed, as well as media influence on *Juncus effusus* functional traits.
4. To investigate the performance of nine indigenous South African plant species, selected from the outcome of objective 2, exposed to three urban stormwater pollution loads (obtained from literature, artificial dosing) for use as effective yet sustainable alternatives to exotics in local plant biofiltration initiatives.
5. To investigate the performance of six biofilter designs for urban stormwater quality improvement, with design considerations and utilised plant species based on the outcomes of objectives 3 and 4 respectively.
6. To apply empirical modeling on the outcome of objectives 4 and 5, providing insight into pollutant removal processes and improve understanding for future local modeling endeavours. Additionally, a conceptual deterministic model for pollutant removal in stormwater biofilters is presented, as a theoretical foundation for future modeling research.

1.4 Research significance

South Africa, already one of the most urbanised countries in Africa with more than 67% of its citizens residing in urban areas is rapidly urbanising even more (PMG 2021; statista 2021). By 2035, the proportion of urban dwellers is expected to grow to 80%, which would constrain the already limited freshwater resources (Cilliers 2017). The discharge of pollutants to South Africa's urban watercourses by stormwater runoff, a primary threat to water provision and ecosystem health, and aging and defective conventional systems, poses a significant risk to human and environmental health (Musingafi & Tom 2014; DWS 2018). Conventionally, stormwater runoff flows over hardened non-permeable surfaces designed to carry excess stormwater to catchpits, where the effluent is collected and transported to drainage networks via stormwater pipes and culverts, for urban stream deposition. Due to water's absorption capacity, being one of the strongest of all solvents, pollutants are effectively absorbed, collected and transported, transforming urban stormwater runoff into the main pollutant vector of natural water systems (Abbasi & Abbasi 2011).

The threat of stormwater runoff in the local context is evident in nutrient and heavy metal pollution levels, as well as pathogens and hydrocarbons, exceeding national effluent water quality guidelines (Sibanda, Selvarajan & Tekere 2015; Robertson, Armitage & Zuidgeest

2019). Although the value of ecosystem services and its potential value to the country is increasingly recognised (O'Farrell, Le Maitre & Reyers 2007), WSUD as a national approach is an under-utilised asset (DWS 2018) due to a lack of research on sustainable urban stormwater management and design specifications (Pasquini & Enqvist 2019). This research therefore advanced, in a practical manner, foundational knowledge towards plant biofiltration application as part of the WSUD approach. It is hoped that this will ease the general adoption of the WSUD approach by addressing some of the barriers, specifically lack of scientifically based design premise, to practical implementation of, specifically, plant biofilters in the urban landscape.

The South African WSUD framework primarily provides philosophical guidance and does not yet deliver design specifics, particularly for stormwater biofilters (Armitage *et al.* 2014). Similarly, the sustainable urban drainage system (SuDS) component focuses on stormwater management rather than design specific parameters and has fallen within the field of environmental science (Brink 2019). In order to produce practical design recommendations, an interdisciplinary approach between engineering and science is required, and it is here where research and development is most lacking. Consequently, the civil and environmental engineer, as the urban water management practitioner, becomes exposed to an unknown set of variables during planning and design. This research, therefore focused on the investigation into and development of practical plant selection methods that a professional civil engineer, without necessarily having a natural science background, can follow. Here, the involvement of plant experts in infrastructure design of this type is still emphasised and recommended.

The treatment of nonpoint polluted effluent by spatially distributed plant biofiltration systems throughout the urban landscape, alleviates adverse stormwater discharge into watercourses and assist existing conventional storm infrastructure, thereby tangibly decreasing the harmful effects of urban pollution. The nutrient and heavy metal removal capabilities of urban stormwater plant biofilters, incorporating indigenous plant species, possess remarkable potential as local holistic resource improvement solutions. Importantly, optimising plant biofilters cannot be prioritised over conservation concerns, thus, the utilisation of biodiversity and urban aesthetic towards enhancing indigenous phytoremediators must be preferred. This, in turn, enhances current South African research (Milandri *et al.* 2012; Frenzel 2018), into discovering naturally occurring species as potential phytoremediators, further inspired by the country's rich biodiversity. In this research, local plant species as well as different soil combinations were exposed to varying levels of nutrient and metals pollution to determine their pollutant removal capabilities. The outcomes of this research contributes tangible information that can be used in future plant biofilter design and implementation by civil engineering professionals.

Models which characterise the physical, chemical and biological processes aid in quantifying and evaluating the treatment capacity of stormwater biofilters (Liu, Chen & Peng 2014). However, for biofilter optimisation a comprehensive understanding is required, due to the complexity of the treatment processes and pathways, as well as factors influencing treatment performance. By assessing the processes and operational conditions influencing biofilter performance of local plant species and designs, an improved understanding of biofilter modeling is achieved, with the additive benefit of accumulating statistical output which contributes to future local modeling endeavours. Furthermore, based on modeling equations of a biofilm reactor, which accounts for the primary removal processes and pathways identified in the experimental biofilters, a conceptual stormwater biofilter model for predicting pollutant removal is proffered. This research therefore contributes a foundational modeling summary of empirical modeling results as well as a theoretical deterministic model that can be used as a base for future research into plant biofilter modeling.

For the design engineer to have confidence in a well understood local vegetated stormwater solution for water quality assurance and pollutant removal prediction, requires not only a valid set of data, but also a practical design criterion based on the amalgamation of scientific knowledge and engineered techniques. Therefore, the contribution of this research will ease the future implementation of effective yet sustainable alternatives for stormwater quality improvement in engineered urban design, at a fraction of the cost of conventional systems. This sets the foundation from which the civil engineer, in correspondence with relevant experts, can implement sustainable solutions in the large-scale, as well as manage small-scale projects where it is not viable to commission scientific experts. This represents a significant shift in the urban water cycle and drainage management strategy. From simple flood reduction to the comprehensive recognition of the stochastic nature of interactions between hydrology and the physical and biochemical processes influencing water quality (Wong *et al.* 2002), pertinent in both stormwater treatment facilities and receiving urban waters.

1.5 Limitations and assumptions

General limitations and assumptions are listed below. Specific limitations and assumptions to specific research areas can be found in the relevant chapters and journal articles.

The limitations of this research are as follows:

- For research objectives 3, and 4 and 5, plant species were transplanted into PVC columns which were limited to 110mm and 160mm in diameter respectively, as such prolonged acclimatisation was be required.
- Three influent nutrient and metal stormwater pollutant loads were selected.
- One influent stormwater volume was selected.
- Influent suspended solids pollution was not included in the research scope.

- Sampling and analyses were limited by time and funding constraints.
- Evapotranspiration by individual plant species was not measured.
- Redox potential was not measured.

The assumptions of the experimental setup are as follows:

- Completely mixed conditions exist within the nutrient and metal influent storage containers.
- There were no variations between influent loads.
- Biofilter baseline concentrations were constant throughout the sampling regime.
- Ammonia volatilisation was negligible.
- Difference in flow rates across drippers was negligible.
- Difference in engineered media ratios of the growth media between biofilter columns was negligible.
- All detritus litter was removed prior to transplantation.
- Light distribution was uniform across the laboratory growth chamber.
- Biofilter column leakage was negligible.
- Laboratory conditions did not significantly influence plant growth.
- Acclimatisation period was sufficient.

1.6 Methods

Due to the dissertation layout incorporating a journal article (paper) based format, all details of the laboratory design could not be incorporated in said articles. An initial short explanation of the laboratory setup is therefore provided here as background to help orient the reader and support the reading of this dissertation.

The experimental biofiltration columns, designed and constructed to investigate objectives 3, 4 and 5 were grown in an indoor artificial light producing laboratory growth chamber (Figure 1.1). The chamber, a 5 x 4 x 3m structure, constructed in the Hydraulic Laboratory at the Department of Civil Engineering at Stellenbosch University, made it possible to assess the change in pollutant loads between influent and effluent, compare biofilter performances between indigenous plant species and designs, and effectively control environmental and operational conditions.

Artificial lighting was provided by eight 58W *Osram®* *Biolux*™ and eighteen 18W *T8®* Plant growth SMD LED tubes to produce a uniform distribution throughout the growth chamber. These tubes are ideal for plants that do not receive enough natural light or in agricultural applications, by producing light in blue (450nm) and red (660nm) wavelengths, promoting photo-biological processes in plants (Osram 2018). The tubes were controlled by a programmable timer, scheduled to produce light between 05h30 and 20h00, to simplistically mimic the general local natural ultraviolet cycle.

Figure 1. 1 Constructed laboratory growth chamber for primary research objectives.

The soil used as the traditional growth medium for this research was excavated (Figure 1.2a) from the Swartland region in the Western Cape (GPS co-ordinates: 33°51'94.16"S, 18°80'77.55"E), with all visible detritus litter removed, prior to drying, and weighed in preparation for a wet sieve analysis. Conducted at the Geotechnical and Transport Engineering laboratory at Stellenbosch University, analyses classified the soil type according to the USDA system as loamy sand. Growth media was circulated in a 100 L pan mixer to ensure completely mixed soil conditions (Figure 1.2b). An average infiltration rate of 145±17 mm/hr was established by investigating the media using clear perspex columns allowing visible tracing of the drop in water level (Figure 1.2c). This was deemed sufficient to support plant growth and establishment, as well as to maintain water infiltration through the growth media (Le Coustumer *et al.* 2012; Payne *et al.* 2015).

Figure 1.2a-c Soil excavated for experimental use, the 100 L pan mixer for uniform soil conditions, and perspex columns for infiltration.

Biofilter columns were constructed from polyvinyl chloride (PVC) piping at varying lengths, determined by the relevant research objectives, and sealed at the base by male PVC stop-ends (Figure 1.3a). Each column incorporated a drainage outlet and valve that protruded from the base, for columns adapted with a saturated layer a secondary raised valve was incorporated, enabling effluent collection into sampling containers directly below.

Irrigation was supplied via an automated irrigation system to maintain a consistent dosage regime, with frequency set at twice-weekly intervals. The system was fitted with four submersible pumps, one for each of the three influent strengths within their respective synthetic stormwater storage containers, as well as an unpolluted dosing with municipal tap water for comparing plant functional response. Pump agitators continuously mixed the synthetic solution to ensure uniform dispersion. Each submersible pump transferred the influent by 15mm irrigation pipes attached to 32 constructed biofilter columns via drippers (Figure 1.3b), fitted with *Emjay*® inline filters to extract particulates, which may impede flow.

Figure 1.3a-b PVC biofilter drainage outlets and irrigation dripper in front of a *Prionium serratum* specimen.

Transition layers comprised of coarse sand and aggregate covering the drainage outlet were added below the growth media. This was done to prevent sedimentation and subsequent clogging of the drainage outlet. In addition to loamy sand as growth media, as well the coarse sand and aggregate for effective transition, a number of engineered materials were added to the experimental biofilters (Table 1.1). The additive perlite, vermiculite, zeolite and attapulgite, were introduced at varying quantities and locations as potential contributors to removal performance and longevity.

Loamy sand is traditionally used as it provides support for plant growth, however, has been found to be ineffective for a number of pollutants, particularly heavy metals and nitrate (Hsieh & Davis 2005). Perlite and vermiculite, capable of adsorbing organic and inorganic pollutants, are often used in stormwater improvement projects as infiltration media (Hashem, Amin & El-Gamal 2015). Zeolite, due to its effective ion-exchange and sorption capabilities, is a popular amendment for water quality improvement (Chmielewská 2015). Lastly, inexpensive attapulgite, recognised for its high adsorption capacity, porous structure, high surface area and cation exchange capacity, is increasingly adopted in remediation initiatives (Mamba *et al.*

2009). The biofilter growth media consisted of loamy sand, compost and perlite, for research objectives 4 and 5, whilst specific combinations of media were implemented for objective 3.

Table 1.1 Material used in the experimental biofilter columns.

Material	Particle size distribution (mm) [Density (g/L)]	Illustration	Material	Particle size distribution (mm) [Density (g/L)]	Illustration
Loamy sand	0.05-3.4 [1037]		Vermiculite	1.4-4 [133.9]	
Sand*	0.6-2 [1391.1]		Zeolite	0.8-1.4 [852.2]	
Aggregate*	7-18 [1311.3]		Zeolite	1.4-2 [825.3]	
Perlite	1-3 [104.2]		Zeolite	2-6 [902.1]	
Vermiculite	0.35-0.5 [155.6]		Attapulgite	0.5-1.4 [747.4]	
Vermiculite	0.5-1.4 [193.9]		Attapulgite	1.4-4.5 [719.8]	

*For use in transition layers.

The variation in pollutant removal performance, with some species displaying affinity to only certain pollutants, as well as the threat of invasion leading to ecosystem services loss from injudicious species introduction, necessitates a balance between conservation and phytoremediation efficacy. Therefore, nine indigenous South African plant species were selected to investigate their individual nutrient and heavy metal removal capabilities, based on the outcomes of research objectives 1 and 2. The use of indigenous non-invasive species as phytoremediators of pollutants, rather than their invasive counterparts, benefit local biodiversity conservation initiatives (Leguizamo, Gómez & Sarmiento 2017). Due to its extensive biodiversity, South Africa offers an abundance of potential alternatives with many indigenous and endemic species exhibiting fast growing, high biomass and competitive traits, which are advantageous properties for pollutant removal (Schachtschneider, Muasya & Somerset 2010). These species satisfy the phyto-guide determining factors, which are distribution, invasiveness and vulnerability, physiological characteristics, morphological traits and aesthetics (Table 1.2).

Table 1.2 Investigated plant species, their South African distribution, as well as above- and below-ground traits.

Species [Common name]	Habitat [Local distribution]	Above-ground biomass	Below-ground biomass
Agapanthus africanus [African lily]	Terrestrial [Endemic]		
Carpha glomerata [Vleibiesie]	Aquatic [Endemic]		
Chasmanthe aethiopica [Cobra lily]	Terrestrial [Endemic]		
Cynodon dactylon [Common couch grass]	Terrestrial [Indigenous]		
Cyperus textilis [Umbrella sedge]	Umbrella sedge [Endemic]		
Dietes iridioides [Small wild iris]	Terrestrial [Indigenous]		
Juncus effusus [Soft rush]	Aquatic [Indigenous]		
Prionium serratum [Palmiet]	Wet-terrestrial [Endemic]		
Strelitzia reginae [Bird-of-paradise]	Terrestrial [Indigenous]		

The vegetated experimental biofilter columns received municipal tap water for 10 months to allow plant establishment, after which the columns were exposed to synthetic influent.

The preparation of synthetic stormwater for nutrient and heavy metal urban runoff pollution, was based on loads retrieved from both local and international stormwater studies (Göbel, Dierkes & Coldeway 2007), as well as similar laboratory experiments (Barron *et al.* 2019). Nutrients were provided by three analytical grade compounds; ammonium chloride (NH_4Cl), potassium nitrate (KNO_3) and di-potassium hydrogen phosphate (K_2HPO_4), which represented ammonia (NH_3), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) respectively. For metals, the pollutants were initially provided by four analytical standard solutions for cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn), after which analytical grade cadmium chloride ($CdCl_2$), copper(II) sulfate ($CuSO_4$), lead(II) chloride ($PbCl_2$) and zinc chloride ($ZnCl_2$) were used, for their cost-efficiency. For research objective 4, a single typically observed synthetic stormwater influent load was applied, whilst objectives 5 and 6 exposed biofilter columns to three influent loads, reflecting low, typically observed and high urban stormwater runoff pollution as established from literature.

Informed by the South African requirements for a successful water resource assessment, the parameters selected are an indication of water quality and ecosystem health (Clesceri, Greenberg & Eaton 1998; Coleman 2001; Ginsburg, Crafford & Harris 2010). These parameters are as follows: pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS) and turbidity. In addition to physical water parameters, the local and international threat of nutrient enrichment leading to eutrophication (Davis *et al.* 2006; Shrestha, Hurley & Wemple 2018), and heavy metal-induced toxicity resulting in high morbidity and mortality rates (Reddy, Xie & Dastgheibi 2014; Rehman *et al.* 2018), substantiate their inclusion in this water resource improvement study.

1.7 Dissertation Structure

This dissertation comprises research presented in six scientific papers either published, submitted for publication or to be submitted for publication at a future time as written chapters following the PhD by publication structure of Stellenbosch University.

Chapter 1, *Introduction*, outlines the research conducted by providing background of: urbanisation, stormwater pollution and its challenges, the concepts of water sensitive urban design and biofiltration within a global and South African context, and lastly the current state of stormwater biofilter modeling. The problem and dissertation statements are provided, as well as the research aim and objectives, which motivate the significance and novelty of this study. Furthermore, the limitations and assumptions of the study are given. Relevant background content and associated methodologies pertaining to each paper are provided by each chapter and, therefore, only a brief explanation of the laboratory setup's design and construction is supplied for the reader's benefit.

Chapter 2, *Paper i,* addresses objective 1 by investigating global and local literature to identify indigenous plant species phytogeographically distributed in the Western Cape province, South Africa, for use as pollutant phytoremediators in green infrastructure technologies.

Chapter 3, *Paper ii,* addresses objective 2 by developing a decision framework to facilitate plant selection for South African green infrastructure initiatives. Provided to the practicing civil engineer and water manager in the form of a phyto-guide, relevant indexes and factors affecting species inclusion are discussed and diagrammatically illustrated.

Chapter 4, *Paper iii,* addresses objective 3 by evaluating ten engineered media combinations exposed to typically observed nutrient and heavy metal loads for biofilter growth media optimisation. The varying growth media are assessed according to their pollutant removal performance, infiltration rate, particulate deposition and ability to support plant growth.

Chapter 5, *Paper iv,* addresses objective 4 by investigating nine indigenous South African plant species exposed to low, typically observed and high nutrient and heavy metal loads. Plant species that are effective in removing nutrient and heavy metal pollutants offer potential for use in local sustainable WSUD initiatives, particularly biofilters.

Chapter 6, *Paper v,* addresses objective 5 by investigating six biofilter designs exposed to low, typically observed and high nutrient and heavy metal loads. The various adaptations seek to allow comparison between designs, highlighting the influence of biofilter features on pollutant-specific processes and pathways, accentuated by comparative analyses of pollutant removal.

Chapter 7, *Paper vi,* addresses objective 6 by providing the nutrient and heavy metal removal processes and pathways, as well as a modeling approach of pollutant removal in urban stormwater biofilters. An empirical approach makes use of collective data produced by this research compilation to determine the contribution of specific design adaptations, which assists future local modeling endeavours. Furthermore, a conceptual deterministic model based on fundamental mechanisms of a biofilm reactor is investigated for potential biofilter performance prediction. A shortened version of this chapter to be submitted for publication as a Technical Note.

Chapter 8, *Conclusions,* presents the research summary and contributions, primary findings, as well as recommendations for future local and international urban stormwater biofilter research.

Contribution declarations for each paper/chapter, as well as legal approvals from the publishers for re-use, can be found in the Addenda.

1.8 References

Abbasi T. & Abbasi S. A. 2011 Sources of pollution in rooftop rainwater harvesting systems and their control. *Critical Reviews in Environmental Science & Technology*, **41**(23), 2097–2167.

Abhilash P. C. 2015 Managing soil resources from pollution and degradation: The need of the hour. *Journal of Cleaner Production*, **102**, 550–551.

Al-Ameri M., Hatt B. E., Le Coustumer S., Fletcher T. D., Payne E. G. I. & Deletić A. 2018 Accumulation of heavy metals in stormwater bioretention media: A field study of temporal and spatial variation. *Journal of Hydrology*, **567**, 721–731.

Armitage N. P., Vice M., Fisher-Jeffes L., Winter K., Spiegel A. & Dunstan J. 2013 *Alternative technology for stormwater management.* Report no TT 558/13, WRC, Gezina, South Africa.

Armitage N. P., Fisher-Jeffes L., Carden K., Winter K., Naidoo V., Spiegel A., Mauck B. & Coulson D. 2014 *Water sensitive urban design (WSUD) for South Africa: Framework and guidelines.* Report no TT 588/14, WRC, Gezina, South Africa.

Ashley R., Lundy L., Ward S., Shaffer P., Walker A. L., Morgan C., Saul A., Wong T. H. F., et al. 2013 Water-sensitive urban design: opportunities for the UK. *Proceedings of the Institution of Civil Engineers: Municipal Engineer*, **166**(2), 65-76.

Barbosa A. E., Fernandes J. N., David L. M. 2012 Key issues for sustainable urban stormwater management. *Water Research*, **46**(20), 6787-6798.

Barron N. J., Deletić A., Jung J., Fowdar H., Chen Y. & Hatt B. E. 2019 Dual-mode stormwater-greywater biofilters: The impact of alternating water sources on treatment performance. *Water Research*, **159**, 521–537.

Blecken G. T., Zinger Y., Deletić A., Fletcher T. D., Hedström A. & Viklander M. 2010 Laboratory study on stormwater biofiltration: Nutrient and sediment removal in cold temperatures. *Journal of Hydrology*, **394**(3–4), 507–514.

Bratieres K., Fletcher T. D., Deletić A. & Zinger Y. 2008 Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water Research*, **42**(14), 3930–3940.

Brink I. C. 2019 Small-scale dispersed green infrastructure – a fitting civil engineering solution to stormwater quality improvement? *Journal of the South African Institution of Civil Engineering*, **61**(4), 42–49.

Brudler S., Rygaard M., Arnbjerg-Nielsen K., Hauschild M. Z., Ammitsøe C. & Vezzaro L. 2019 Pollution levels of stormwater discharges and resulting environmental impacts. *Science of the Total Environment*, **663**, 754–763.

Burns M. J., Fletcher T. D., Walsh C. J., Ladson A. R. & Hatt B. E. 2012 Hydrologic shortcomings of conventional urban stormwater management and opportunities to reform. *Landscape and Urban Planning,* **105**(3), 230-240.

Chmielewská E. 2015 Abundantly available natural or bioinspired materials for aqueous pollutants removal. *Current Green Chemistry*, **2**(4), 371–378.

Chowdhury R., Abaya J., Ksiksi T., Mohamed M., Beecham S. & Rahman A. 2020 Distribution of heavy metals in vegetative biofiltration columns. *Water*, **12**(3), 747-759.

Cilliers J. 2017 *Fate of the Nation: 3 Scenarios for South Africa's Future,* Jonathan Ball Publishers, Johannesburg, South Africa.

Clesceri L., Greenberg A. & Eaton A. (eds.) 1998 *Standard methods for the examination of water and wastewater*, 20th edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Coleman T. J. 2001 *Expert system for the design of stormwater management systems for urban runoff quality*. Report no TT 156/01, WRC, Gezina, South Africa.

Cullis J. D. S., Horn A., Rossouw N., Fisher-Jeffes L., Kunneke M. M. & Hoffman W. 2019 Urbanisation, climate change and its impact on water quality and economic risks in a water scarce and rapidly urbanising catchment: case study of the Berg River Catchment. *H_2Open Journal,* **2**(1), 146-167.

Davis A. P., Shokouhian M., Sharma H. & Minami C. 2006 Water quality improvement through bioretention media: Nitrogen and phosphorus removal. *Water Environment Research*, **78**(3), 284–293.

Davis B. & Birch G. 2010 Comparison of heavy metal loads in stormwater runoff from major and minor urban roads using pollutant yield rating curves. *Environmental Pollution*, **158**(8), 2541–2545.

De Klerk A. R., Oberholster P. J., Van Wyk J. H., Truter J. C., Schaefer L. M. & Botha A. M. 2016 The effect of rehabilitation measures on ecological infrastructure in response to acid mine drainage from coal mining. *Ecological Engineering,* **95**, 463–474.

De Villiers S. & Thiart C. 2007 The nutrient status of South African rivers: Concentrations, trends and fluxes from the 1970s to 2005. *South African Journal of Science* **103** (7–8) 343-349.

Del Castillo A., Verduzco Garibay M., Senés-Guerrero C., Yebra-Montes C., De Anda J. & Gradilla-Hernández M. S. 2020 Mathematical modeling of a domestic wastewater treatment system combining a septic tank, an up flow anaerobic filter, and a constructed wetland. *Water*, **12**(11), 3019-3038.

Donnenfeld Z., Crookes C. & Hedden S. 2018 *A delicate balance – Water scarcity in South Africa.* Southern Africa Report 13, Institute for Security Studies Papers (ISS), Pretoria, South Africa. https://journals.co.za/doi/pdf/10.10520/EJC-1486c3180a (accessed 11 October 2021).

Dumitru A., Wendling L., Arnbjerg-Nielsen K., Baldacchini C., Connop S., Dubovik M., Fermoso J., et al. 2021 Indicators of NBS performance and impact. In: *Evaluating the impact of nature-based solutions: A handbook for practitioners,* A. Dumitru & L. Wendling (eds.), 1st edn, European Union, Luxembourg, pp. 114-173.

Dussaillant A. R., Wu C. H. & Potter K. W. 2004 Richards equation model of a rain garden. *Journal of Hydrologic Engineering*, **9**(3), 219–225.

DWS (Department of Water and Sanitation) 2017 Strategic overview of the water sector in South Africa. http://ws.dwa.gov.za/downloads/WS/P_I/Adhoc/AWensley/2017%20SOWS_A6_12%20Oct%202017_print%20crop.pdf (accessed 12 August 2019).

DWS (Department of Water and Sanitation) 2018 National water and sanitation master plan. *https://static.pmg.org.za/200818national-water-and-sanitation-master-plandf.pdf* (accessed 20 August 2020).

Feng W., Hatt B. E., McCarthy D. T., Fletcher T. D. & Deletić A. 2012 Biofilters for stormwater harvesting: Understanding the treatment performance of key metals that pose a risk for water use. *Environmental Science & Technology*, **46**(9), 5100–5108.

Fitchett A. 2017 SuDS for managing surface water in Diepsloot informal settlement, Johannesburg, South Africa. *Water SA,* **43**(2), 310-322.

Fletcher T. D., Shuster W., Hunt W. F., Ashley R., Butler D., Arthur S., Trowsdale S., Barraud S., et al. 2015 SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal,* **12**(7), 525–542.

Frenzel P. 2018 Investigating the potential of floating wetlands in small farm dams in the Western Cape, South Africa. MSc thesis, Stellenbosch University.

Geberemariam T. 2016 Post construction green infrastructure performance monitoring parameters and their functional components. *Environments*, **4**(1), 2-12.

Ginsburg A. E., Crafford J. G., Harris K. R. 2010 *Framework and Manual for the evaluation of aquatic ecosystems services for the Resource Directed Measures.* Report no TT 462/10, WRC, Gezina, South Africa.

Göbel P., Dierkes C. & Coldewey W. G. 2007 Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology*, **91**(1–2), 26–42.

Gunawardena J. M. A., Liu A., Egodawatta P., Ayoko G. A. & Goonetilleke A. 2018 Primary traffic related pollutants and urban stormwater quality. In*: Influence of traffic and land use on urban stormwater quality*, J. M. A. Gunawardena., A. Liu., P. Egodawatta., G. A. Ayoko. & A. Goonetilleke (eds.), 1st edn, Springer, Singapore, pp. 1-16.

Hamel P., Daly E. & Fletcher T. D. 2013 Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. *Journal of Hydrology*, **485**, 201–211.

Hashem F. S., Amin M. S. & El-Gamal S. M. A. 2015 Chemical activation of vermiculite to produce highly efficient material for Pb^{2+} and Cd^{2+} removal. *Applied Clay Science*, **115**, 189–200.

Hedden S. & Cillers J. 2014 *Parched prospects – the emerging water crisis in South Africa.* African Futures Paper 11, Institute for Security Studies Papers (ISS), Pretoria, South Africa. http://www.issafrica.org/research/papers/parched-prospects-the-emerging-water-crisis-in-south-africa (accessed 05 October 2021).

Hsieh C. & Davis A. P. 2005 Evaluation and optimization of bioretention media for treatment of urban storm water runoff. *Journal of Environmental Engineering,* **131**(11), 1521–1531.

Khan U. T., Valeo C., Chu A. & He J. 2013 A data driven approach to bioretention cell performance: Prediction and design. *Water*, **5**(1), 13–28.

Kumar B., Smita K. & Flores L. C. 2017 Plant mediated detoxification of mercury and lead. *Arabian Journal of Chemistry,* **10**, 2335-2342.

Le Coustumer S., Fletcher T. D., Deletić A., Barraud S. & Poelsma P. 2012 The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Research,* **46**(20), 6743–6752.

Le Maitre D. C., Blignaut J. N., Clulow A., Dzikiti S., Everson C. S., Görgens A. H. M. & Gush M. B. 2020 Impacts of plant invasions on terrestrial water flows in South Africa. In: *Biological invasions in South Africa*, D. Simberloff (ed.), Springer, Cham, pp. 431-457.

Leguizamo M. A. O., Gómez W. D. F. & Sarmiento M. C. G. 2017 Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands - A review. *Chemosphere*, **168**, 1230–1247.

Li H. & Davis A. P. 2008 Urban particle capture in bioretention media II: Theory and model development. *Journal of Environmental Engineering*. **134**(6), 419–432.

Li G., Xiong J., Zhu J., Liu Y. & Dzakpasu M. 2021 Design influence and evaluation model of bioretention in rainwater treatment: A review. *Science of The Total Environment*, **787**, 147592.

Liu W., Chen W. & Peng C. 2014 Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. *Ecological Modelling*, **291**, 6–14.

Mamba B. B., Dlamini N. P., Nyembe D. W. & Mulaba-Bafubiandi A. F. 2009 Metal adsorption capabilities of clinoptilolite and selected strains of bacteria from mine water. *Physics & Chemistry of the Earth,* **34**(13–16), 830–840.

Marrugo-Negrete J., Durango-Hernández J., Pinedo-Hernández J., Olivero-Verbel J. & Díez, S. 2015 Phytoremediation of mercury-contaminated soils by Jatropha curcas. *Chemosphere*. **127**, 58–63.

Maurya A., Singh M. K. & Kumar S. 2020 Biofiltration technique for removal of waterborne pathogens. In: *Waterborne Pathogens*, M. N. V. Prasad & A. Grobelak (eds.), Elsevier, Cambridge, pp. 123-141.

McGrane S. J. 2016 Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal*, **61**(13), 2295–2311.

Milandri S. G., Winter K. J., Chimphango S. B. M., Armitage N. P., Mbui D. N., Jackson G. E. & Liebau V. 2012 The performance of plant species in removing nutrients from stormwater in biofiltration systems in Cape Town. *Water SA,* **38**(5), 275–662..

Morgenroth E. 2008. Modelling Biofilms. In *Biological Wastewater Treatment: Principles, Modelling & Design*, M. Henze., M. D. M. Van Loosdrecht., G. A. Ekama, and D. Brdjanovic (eds.), IWA Publishing, London, England, pp. 457-492.

Muerdter C. P., Wong C. K. & LeFevre G. H. 2018 Emerging investigator series: The role of vegetation in bioretention for stormwater treatment in the built environment: Pollutant removal, hydrologic function, and ancillary benefits. *Environmental Science: Water Research & Technology*, **4**(5), 592–612.

Musingafi M. C. C. & Tom T. 2014. Fresh water sources pollution: A human related threat to fresh water security in South Africa. *Journal of Public Policy & Governance,* **1**(2), 72–81.

O'Farrell P. J., Le Maitre D. C. & Reyers B. 2007 Ecosystems services in South Africa: A research theme that can engage environmental, economic and social scientists in the development of sustainability science? *South African Journal of Science*, **103**(9–10), 367–376.

Oberholster P. J. & Ashton P. J. 2008 State of the nation report: An overview of the current status of water quality and eutrophication in South African rivers and reservoirs. https://www.researchgate.net/publication/242668373_An_Overview_of_the_Current_Status_of_Water_Quality_and_Eutrophication_in_South_African_Rivers_and_Reservoirs (accessed 14 June 2020).

Osram. 2018 Biolux T8 Product data sheet. http://www.osram.com/osram_com/products/lamps/fluorescentlamps/%0Afluorescentlamps-t8/fluorescent-lamps-t8-special-versions/biolux-t8/index.jsp (accessed 17 July 2017).

Pasquini L. & Enqvist J. P. 2019 Green infrastructure in South African cities. https://www.africancentreforcities.net/wp-content/uploads/2020/01/CSP_green-infrastructure_paper_LPasquini_JEnqvist_11.pdf (accessed 15 July 2020).

Payne E. G. I., Hatt B. E., Deletić A., Dobbie M. F., McCarthy D. T. & Chandrasena G. I. 2015 *Adoption guidelines for stormwater biofiltration systems - Summary report*. Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

PMG (Parliamentary Monitoring Group) 2021 Urbanisation. https://pmg.org.za/page/Urbanisation (accessed 10 October 2021).

Read J., Wevill T., Fletcher T. D. & Deletić A. 2008 Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research*, **42**(4–5), 893–902.

Read J., Fletcher T. D., Wevill T. & Deletić A. 2010 Plant traits that enhance pollutant removal from stormwater in biofiltration systems. International *Journal of Phytoremediation*, **12**(1), 34–53.

Reddy K. R., Xie T. & Dastgheibi S. 2014 Removal of heavy metals from urban stormwater runoff using different filter materials. *Journal of Environmental Chemical Engineering*, **2**(1), 282–292.

Rehman K., Fatima F., Waheed I. & Akash M. S. H. 2018 Prevalence of exposure of heavy metals and their impact on health consequences. *Journal of Cellular Biochemistry*, **119**(1), 157–184.

Risch E., Gasperi J., Gromaire M. C., Chebbo G., Azimi S., Rocher V., Roux P., Rosenbaum R. K., et al. 2018 Impacts from urban water systems on receiving waters – how to account for severe wet-weather events in LCA? *Water Research,* **128**(1), 412-423.

Robertson A., Armitage N. P. & Zuidgeest M. H. P. 2019 Stormwater runoff quality on an urban highway in South Africa. *Journal of the South African Institution of Civil Engineering,* **61**(2), 51–56.

Schachtschneider K., Muasya M. & Somerset V. 2010 *Are indigenous sedges useful for phytoremediation and wetland rehabilitation?* Report no NE04-PO, CSIR, Pretoria, South Africa.

Shackleton R. T., Shackleton C. M. & Kull C. A. 2019 The role of invasive alien species in shaping local livelihoods and human well-being: a review. *Journal of Environmental Management,* **229**, 145-157.

Shrestha P., Hurley S. E. & Wemple B. C. 2018 Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. *Ecological Engineering*, **112**, 116–131.

Sibanda T., Selvarajan R. & Tekere M. 2015 Urban effluent discharges as causes of public and environmental health concerns in South Africa’s aquatic milieu. *Environmental Science & Pollution Research*, **22**(23), 18301–18317.

Søberg L. C., Al-Rubaei A. M., Viklander M. & Blecken G. 2020 Phosphorus and TSS removal by stormwater bioretention: Effects of temperature, salt, and a submerged zone and their interactions. *Water, Air, & Soil Pollution*, **231**, 1–12.

statista 2021 South Africa: Urbanisation from 2010 to 2020. https://www.statista.com/statistics/455931/urbanization-in-south-africa/ (accessed 07 October 2021).

Stewart R. D., Lee J. G., Shuster W. D. & Darner R. A. 2017 Modelling hydrological response to a fully-monitored urban bioretention cell. *Hydrological Processes*, **31**(26), 4626–4638.

Taylor G. D., Fletcher T. D., Wong T. H. F., Breen P. F. & Duncan H. P. 2005 Nitrogen composition in urban runoff - implications for stormwater management. *Water Research,* **39**(10), 1982–1989.

Wadzuk B. M., Hickman J. M. & Traver R. G. 2015 Understanding the role of evapotranspiration in bioretention: Mesocosm study. *Journal of Sustainable Water in the Built Environment*, **1**(2), 4014002.

Wang R., Zhang X. & Li M. 2019 Predicting bioretention pollutant removal efficiency with design features: A data-driven approach. *Journal of Environmental Management*, **242**, 403–414.

Wanner O., Eberl H. J., Morgenroth E., Noguera D. R., Picioreanu C., Rittman B. E. & Van Loosdrecht M. C. M. 2006 *Mathematical modeling of biofilms.* Scientific and Technical Report Series Report no 18. IWA Publishing, London.

Wenger S. J., Roy A. H., Jackson C. R., Bernhardt E. S., Carter T. L., Filoso S., Gibson C. A., Hession W. C., et al. 2009 Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. *Journal of the North American Benthological Society*, **28**(4), 1080–1098.

Wong T. H. F., Fletcher T. D., Duncan H. P. & Coleman J. R. 2002 *A model for urban stormwater improvement: Conceptualization.* Ninth International Conference on Urban Drainage – In: Global solutions to Urban drainage, Portland, Oregon, pp. 1-14.

Yang B., Li S., Wall H. A., Blackmore P. & Wang Z. 2015 Green infrastructure design for improving stormwater quality: Daybreak community in the United States West. *Landscape Architecture Frontiers*, **3**(4), 12-22.

Zengeya T. A. & Wilson J. R. (eds.) 2020 The status of biological invasions and their management in South Africa in 2019 [Final Version]. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch, South Africa.

Zhang K., Liu Y., Deletić A., McCarthy D. T., Hatt B. E., Payne E. G. I., Chandrasena G., Li Y., et al. 2021 The impact of stormwater biofilter design and operational variables on nutrient removal-a statistical modelling approach. *Water Research*, **188**, 116486.

CHAPTER 2

Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators - with a focus on Green Infrastructure

This chapter addresses research objective 1, which is to investigate both local and global literature to identify indigenous plant species for potential use as phytoremediators in GI technologies in the Western Cape, South Africa.

This chapter was undertaken as the initial step of this research to identify potential indigenous plant species for use in the laboratory experiments conducted for chapters 4, 5 and 6, which address study objectives 3, 4 and 5 respectively. The Western Cape experiences soil, water and sediment pollution and resource overexploitation, posing major human and environmental health challenges. For practical reasons the vegetation used in this research was limited to the Western Cape, as this is where the Research University is situated. However, it is envisaged that the method of enquiry used here can also be applied in other biomes.

As an aid to the practicing engineer, a list of endemic and indigenous proven effective phytoremediators in the Western Cape for potential use in local GI was researched and is presented. This provided a basis from which plant species were selected for further research here and can be used in future design endeavors. This list consists of 56 non-invasive plant species of least conservation concern, likely to aid resource remediation without jeopardising conservation and biodiversity. These species, with some further selected for the experimental biofilter columns in chapter 4, are potentially capable of increasing heterogeneity and adjusting to the dynamic conditions of the recipient habitat, whilst effectively remediating a range of environmental pollutants.

The research outcomes indicated that there is a need for a decision framework for the practicing engineer to assist with selecting potential species. Therefore, such a framework is presented in chapter 3, objective 4, in the form of a phyto-guide. In addition to chapter 3, the findings of this study were presented at the Water Institute of Southern Africa Online Conference: Urban water management - manage the resource for a capable economy (Appendix A).

Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediatiors with a focus on Green Infrastructure

DM Jacklin[1], IC Brink[1], SM Jacobs[2]

[1]Department of Water and Environmental Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

[2]Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

Reproduced and reformatted from an article published in **Water SA, 47(3), 317-325**, with permission from the copyright holder, the South African Water Research Commission.

Abstract

Soil, water and sediment pollution from anthropogenic origin poses a major environmental and human health challenge to urban water managers, engineers and conservation ecologists. The Western Cape (WC) province of South Africa has been subjected to similar deleterious impacts, with urbanisation, industrialisation, population growth and agricultural development placing pressure on the limited water and soil resources. In addressing this resource degradation an effective, affordable and sustainable solution is required. The implementation of Green Infrastructure (GI) initiatives, such as phytoremediation, involves the use of plant species with large root systems, high tolerance and aggressive growth properties to hinder pollutant transport, attenuate runoff flow and remediate resources to a pollution-free state in order to protect the health of the population and the environment. However, care must be taken when selecting plant species due to various species exhibiting invasive behavior, and affecting ecosystem dynamics. As a result of the need for resource remediation in both urban and rural areas, the use of non-invasive indigenous species is vital to an efficient and sustainable technology, as urban areas are often the initial sites for introduction from which invasions spread. This paper proposes indigenous WC species for potential use in GI technologies, identified for remediation efficacy from global literature relating to various bioremediation projects, as an aid to the practicing civil engineer and water manager responsible for the intricate design and management of the phytotechnology. These indigenous species offer potential as phytoremediators in local GI initiatives and recommends the types of plants for further investigation as indigenous alternatives to effective exotics. In selecting vegetation for local GI systems, plant conservation status and invasiveness to the recipient region were also considered. The investigation returned 56 non-invasive WC plant species of least conservation concern, likely to aid resource remediation without jeopardising the conservation and biodiversity of the administered area. The selected vegetation is potentially capable of increasing heterogeneity and adjusting to the dynamic biogeographic conditions of the recipient habitat. Thus promoting the use of distinct species capable of remediating a wide

range of environmental contaminants, into the diverse habitats of the WC, at a fraction of the cost of conventional techniques.

Keywords: green infrastructure, phytoremediation, phytotechnologies, water quality, ecological engineering

INTRODUCTION

Persistent and excessive release of heavy metal, organic and inorganic pollutants from anthropogenic activities is blamed for destroying entire natural ecosystems, posing a major human and environmental health problem (Cunningham et al. 1995; Salt et al. 1995; Dhir et al. 2009; Abhilash et al. 2012, Choudhary et al. 2015; Tripathi et al. 2015). The Western Cape (WC) province of South Africa has been subjected to similar deleterious impacts, with increased urbanisation, high population growth, agricultural development, dysfunctional water and waste water treatment works, and industrialisation placing enormous pressure on the limited soil and water resources (Giliomee, 2006; Nomquphu et al. 2007).

The widespread contamination of soil, a non-renewable natural resource in the short term and very expensive to reclaim once physically or chemically degraded, has for decades been a global remediation and management challenge (Ali et al. 2015; Rada et al. 2019). This rampant degradation is evident with more than 25% of global soil resources highly degraded and roughly 44% moderately degraded, predominantly as a result of pollution (Peuke and Rennenberg, 2005). Alarmingly, South Africa is recognised as one of the regions experiencing the most rapid environmental degeneration (Abhilash, 2015). The WC receives various pollutants of anthropogenic origin to the soils, which include significant amounts of bioavailable heavy metals (Schloemann, 1995), fertilisers, pesticides, herbicides and fungicides (Malan et al. 2015), as well as stormwater, waste water and sewage runoff (Chen et al. 2008; Müller et al. 2014).

Similarly, pollutant deposition deteriorate water-quality in urban and rural watercourses and groundwater aquifers, raising a plethora of public and environmental health concerns (Constantine et al. 2014; Sibanda et al. 2015; Pakdel and Peighambardoust, 2018). In South Africa, main rivers classified as having a poor ecological condition increased by 500% between 1999 and 2011, with some beyond the point of recovery, posing a threat to the country’s potable water resources (Oberholster and Ashton, 2008; DWS, 2018). This is as a result of the nationwide failure to properly treat wastewater, where 56% of the sewage treatment works are failing and 11% are dysfunctional (DWS, 2018). De Villiers and Thiart (2007) found that 6 of the 20 largest river catchments in South Africa that are under eutrophication are located in the WC. In addition, the findings of Musingafi and Tom (2014) and Milandri et al. (2012) point to the fact that urban effluent discharge contribute a wide range of pollutants to freshwater ecosystems.

Green infrastructure (GI) is the interconnected set of natural and engineered ecological systems to provide environmental services (Fletcher et al. 2015). In comparison with traditional grey infrastructure, these systems have been found to reduce financial costs by up to 42% (Vineyard et al. 2015). These systems offer a novel and sustainable approach to polluted water and soil systems, hindering pollutant transport and reducing resource toxicity, by combining resource remediation with sustainable civil engineering methods (Choudhary et al. 2015; Kondo et al. 2015; Malan et al. 2015; Malherbe et al. 2018). The GI engineered approach has the ability to complement or replace existing technological or grey infrastructure designs, presenting a more cost-effective, self-sustaining and versatile long term alternative (Nel et al. 2014). In South Africa, GI is currently an under-realised asset (DWS, 2018).

Critical to GI efficiency, phytoremediation uses appropriately selected plants for the *in situ* treatment of environmental contaminants from soils, sediments and water (Terry and Banuelos, 1999; Dietz and Schnoor, 2001; Visoottiviseth et al. 2002; Peuke and Rennenberg, 2005; Payne et al. 2014). A large number of plants possess potential to detoxify, degrade and/or remove pollutants from the environment, and have gained importance globally, receiving significant scientific and commercial attention (Salt 1998; Gleba et al. 1999; Guerinot and Salt, 2001; Krämer and Chardonnens, 2001; Meagher, 2000; Peuke and Rennenberg, 2006). This green engineering solution is popular due to its cost-effectiveness, aesthetic advantages, long-term applicability, employment generation capacity and scope of pollutant remediation efficacy (Raskin et al 1994; Abhilash, 2015; Marrugo-Negrete et al. 2015). Although effective, plants and their rhizosphere organisms phytoremediate in different ways, with various mechanisms suitable for different pollutants (Read et al. 2010). The use of field and vegetable crops cultivated for commercial use as phytoremediators have proven valuable in bioremediating municipal and industrial discharge from failing sewage treatments works, as well as rehabilitating old and abandoned mining sites (Poonam et al. 2014; Rizwan et al. 2016). In designing a sustainable GI remediation technology, the responsible engineer must assess the potential adverse impacts induced by the introduction of chosen effective pollutant-specific remediators from the findings of previous investigations (Leguizamo et al. 2017). Prior to plant selection for use in remediation projects, the ecosystem-related and ecological functions of the plants need to be established (Budelsky and Galatowitsch, 2004). For instance, failure to consider invasion threat, may lead to creating an artificial or altered environment in which alien species thrive (Castro-Diez et al. 2014). In particular, remediation measures must endeavor to utilise plants that are indigenous to the site, in an attempt to return the resource to a sustainable state (Peer et al. 2005). A practicing civil engineer who lacks expertise in plant behavior or ecosystem dynamics which regulate plant's potential future invasiveness in phytogeographic environments may be ill-equipped to design an effective yet sustainable engineered remediation technology.

It is for this reason that this study focused on indigenous plant species naturally occurring in the WC for potential use in pollutant bioremediation technologies. The plants were selected on the basis of their presence in global phytoremediation literature, phytogeographic distribution, conservation status and invasiveness. This article discusses the phytoremediation process and WC vegetation whilst emphasising the impact their introduction may have on the recipient ecosystem. Finally after investigating plant species from relevant literature, potential indigenous species and cultivated crops effective for GI technologies in the WC are recommended.

Phytoremediation processes within Green Infrastructure engineering

The term phytoremediation is applied to a technology that makes use of both wild and transgenic plant species for the treatment of contaminated soils, sediments, water and air, with the aim to effectively restore, protect or ameliorate environmental degradation by removing pollutants or render them harmless (Salt, 1998; Terry and Banuelos, 1999; Dietz and Schnoor, 2001). These pollutants are predominantly generated by agricultural and industrial products and practices, urban pollution, stormwater runoff and defective wastewater treatment facilities (Khan et al. 2000). All plants have the ability to accumulate heavy metals that are essential for growth and development from soil and water, including Cu, Fe, Mg, Mn, Mo, Ni and Zn, with some plants able to accumulate heavy metals such as Ag, Cd, Co, Cr, Hg, Pb and Se, that offer no biological function (Dhir et al. 2009). Various phytoremediation processes exist making use of different species of plants for each contaminant (Cunningham et al. 1997; Dietz and Schnoor, 2001). There is, however, a limit to the extent which plants can accumulate these metals, beyond which they become toxic, with plants varying in removal efficiency and tolerance (Read et al. 2010). The intricate planning and design of GI technologies must consider both the type pollution and habitat of the specific site, to appropriately identify and select potential species for optimised phytoremediation. Therefore, the use of use of non-invasive species, adept at remediating the pollution at hand whilst limiting the risk of biodiversity loss, should always be promoted (Payne et al. 2015). Numerous laboratory and field assessments have developed a better understanding of heavy metal, petrochemical site, ammunition waste, chlorinated solvent, landfill leachate, nonpoint source agricultural runoff (pesticides and fertilisers) and urban stormwater runoff phytoremediation (Salt et al. 1995; Chaney et al. 1997; Macek et al. 2000; Pilon-Smits, 2005; Abhilash et al. 2012; Milandri et al. 2012). GI capitalises on the innate abilities of photosynthetic plants to eliminate a variety of pollutants, by destruction, inactivation, extraction, volatilisation or immobilisation, with some extracted metals even recycled for value (Raskin et al. 1994; Peuke and Rennenberg, 2006; Leguizamo et al. 2017).

The effect of biological invasion

Biological invasions alter the structure and function of the natural ecosystem, causing a loss of an ecoregion's characteristic species and may result in loss of indigenous biota (Yang et al. 2015). South Africa has a long history of plant introduction and invasion transforming ecosystems, posing a major threat to the country's biodiversity, impacting negatively on the ecosystem's capacity to deliver goods and services, and in some cases severely threatening human livelihoods (Le Maitre et al. 2020). Alien plant invasion, costs the country ZAR 2 billion annually for its control (Van Wilgen et al. 2020; Zengeya, 2020). This widespread degradation is particularly evident in the WC province with the most extensive as well as the greatest number of invasive species, notably reducing the value of fynbos ecosystems by over ZAR 195 billion due to a loss in ecosystem services (Van Wilgen et al. 2001; Pyšek and Richardson, 2010; Van Wilgen et al. 2020).

The WC is home to 70% of the Cape Floristic Region (CFR), recognised as one of the richest habitats in the world, regarding its floristic heterogeneity and endemism (Von Hase et al. 2003). With a prominent diversity of over 9000 species of which 70% are endemic, the CFR is one of only 25 globally accepted biodiversity hotspots (Giliomee, 2006). For its tiny size, the area most likely has the richest flora worldwide (McDowell and Moll, 1992).

METHODOLOGY

This paper investigated 800 literature sources to guide the selection of proven effective phytoremediation species for potential use in GI technologies in the WC. In compiling a list of potential phytoremediators, peer reviewed articles, books, reports, case studies, conference proceedings, theses and dissertations, as well as online databases were investigated. The findings related to various studies of bioremediation initiatives for stormwater quality improvement, sustainable urban drainage systems, water sensitive urban designs, water and soil rehabilitation initiatives and plant affinity for heavy metal accumulation. From these findings, potential endemic and indigenous candidates to the WC were identified by comparing herbarium records from the South African National Biodiversity Institute's Red List of South African Plants (SANBI) and Plants of Southern Africa (POSA), Plants of the Greater Cape Floristic Region (PGCFR), and Stellenbosch University Botanical Garden (SUNBG) with the species from literature. Plants displaying invasive characteristics whose introduction may threaten the sustainability of a phytoremediation project and increase ecosystem vulnerability were excluded, based on local and international standards. Regional and online records from the Centre for Agriculture and Bioscience International Invasive Species Compendium (CABI), the Global Invasive Species Database (GISD), the Alien Invasive Plant List for South Africa (AIPLSA), the National Environmental Management: Biodiversity Act, 2004 – Alien and Invasive Species List (NEM:BA A&IS), the Status of Biological Invasions and their

Management in South Africa (SBIMSA), Biological Invasions in South Africa (BISA), the Information Retrieval and Submission System of the Centre for Invasion Biology (CIB) and the South African Plant Invaders Atlas (SAPIA) also provided basis for exclusion of certain plants. In considering existing recommendations and reported presence in literature, spatial distribution, invasive threat and vulnerability to extinction, erroneous introduction of potential plants into engineered designs and natural ecosystems is minimised.

RESULTS AND DISCUSSION

The investigation delivered 1 410 plant species, from 582 genera with 136 subspecies and variations for potential use in GI phytoremediation initiatives. Analysis returned 257 indigenous and naturalised South African plant species of which 174 were distributed phytogeographically throughout the WC province. Of the species, 80 were found to be registered as either endemic or indigenous to the province, with 56 of these regarded as non-invasive and of least conservation concern (Table 1). These plants are likely to aid remediation without jeopardising the conservation and biodiversity of the recipient ecoregion. In reporting, emphasis is placed on effective phytoremediators, their distribution as endemics or indigenous to the WC, conservation status and invasiveness.

Of the 56 phytoremediators, 3 are endemic, and 53 are indigenous to the WC. None of the species are registered as invasive to the WC. The list includes both aquatic and terrestrial plants with varying seasonal activity, which benefit GI initiatives, by resisting comprehensive dormancy during periods of drought. Although the species listed are registered as non-invasive, caution must be taken when introducing plants, as they may with new evidence threaten the sustainability of the recipient ecosystem. In addition, the behaviour of non-endemic species should be assessed prior to introduction in recipient habitats, whereafter approval from satisfied relevant ecologists must be sought. The practising civil engineer is cautioned to enlist the help of plant experts when choosing a species for application in GI.

Phytoremediation and Western Cape vegetation

The results show that WC plant species are effective over a range of pollutants, which include urban and rural stormwater runoff, agricultural effluent in the form of pesticides, herbicides and fertilisers, heavy metals, explosives and ammunition wastes, radionuclides, organic pollutants, carcinogenic air, water and soil chlorinated aliphatic hydrocarbons, petroleum contaminants, domestic and industrial wastewater effluent, landfill leachate, sewage discharge and tannery waste. The list in Table 1 includes 10 endemic South African species, which are; *Agapanthus africanus, Agapanthus praecox* subsp. *minimus, Arctotis acaulis, Aristea capitata, Berkheya zeyheri* subsp. *rehmannii* var. *rogersiana, Carpobrotus edulis* subsp. *edulis, Carpobrotus edulis* subsp. *parvifolius, Cyperus textilis, Elegia tectorum* and *Prionium serratum.* The number of endemics, in proportion to total indigenous species identified suggests immense potential for South African phytoremediators yet to be investigated, specifically in the WC, which offers unparalleled biodiversity richness.

The risk of invasive plants in Green Infrastructure

Allochthonous plant species are alien to a phytogeographic area, with autochthonous plant species indigenous, and include naturalised plants originally regarded as allochthonous (Leguizamo et al. 2017). The naturalised allochthonous plants establish themselves in the environment, without human assistance, and are not regarded as indigenous members of the plant community (Ojasti, 2001). Therefore, only the use of non-invasive indigenous plants in bioremediation technologies supports plant acclimatisation, alleviates specimen sourcing and contributes to ecosystem conservation initiatives, bolstering the biodiversity and heterogeneity of a habitat by limiting exposure to invasive species. A dynamic resident biota influenced by natural factors, as well as the recipient site's conditions, must be accounted for in order determine potential invasiveness of introduced species. Thus, consultation with a number of disciplines within science and engineering is imperative, to promote an amalgamation of knowledge for the creation of a sustainable design science for GI.

From the findings, some species must be diligently selected, due to their aggressive growth properties and hardiness, common traits shared among efficient remediators. The species demanding caution are *Ceratophyllum demersum, Panicum repens, Phragmites australis* and *Pteris cretica*, which have been identified as prospective menacing species. This, however, does not recuse caution for the remaining plants, which may be classified as invasive with new evidence. The traits linked to invasiveness in ecosystems, mirrored in traits supporting phytoremediation efficiency, e.g. rapid growth and spread, hardiness and disease and pest resistance, as well as interactions with resident biota in prevailing environmental conditions will determine their alien probability, and may contribute to invasiveness (Le Roux et al. 2020).

In investigating WC crops, 8 species were identified for potential phytoremediation from reported literature (not shown). These species are *Beta vulgaris* subsp. *vulgaris, Brassica rapa* subsp*. rapa, Cannabis sativa, Daucus carota* subsp*. sativus, Linum usitatissimum, Nicotiana tabacum, Sorghum bicolor* and *Vigna unguiculata* subsp. *protracta*. Although the WC crops offer prospect for phytoremediation, it is the authors' opinion that they should not be considered for animal feed or human consumption, pending research continuation on environmental toxin accumulation. The removed toxins are stored in different vascular compartments of the plant until mortality (Vamerali et al. 2010). During cultivation, these toxins may still pose a threat to environmental and human health (Khan et al. 2015). For a site exposed to extreme contamination, the use of cultivated crops can, however, mitigate the immediate environmental threat, supporting their inclusion as potential remediators.

Table 1. Potential WC autochthonous phytoremediation plants of least conservation concern and minimal biological invasive threat.

Species	Common name	SA Endemic	WC Distribution		Pollutants	Reference
			Endemic	Indigenous		
Agapanthus africanus	Agapanthus	x	x	x	Petroleum	(Tsao and Tsao, 2003; Famulari, 2011)
Agapanthus praecox subsp. minimus	Na	x		x	NH_3, NO_3^- & PO_4^{3-}	(Milandri et al. 2012)
Alectra sessiliflora	Verfblommetjie			x	Co & Cu	(Brooks et al. 1986; Baker and Brooks, 1989)
Arctotis acaulis	Renoster Marigold	x		x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Jacklin et al. 2020)
Aristea capitata	Blue Sceptre	x	x	x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Jacklin et al. 2020)
Berkheya zeyheri subsp. rehmannii var. rogersiana	Na	x		x	Ni & Se	(Przybylowicz et al. 2001; Groeber et al. 2015; CMLR, 2017)
Blotiella glabra	Na			x	Cu & Zn	(Mkumbo et al. 2012)
Bolboschoenus maritimus	Sea Club-rush			x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Jacklin et al. 2020)
Bulbine frutescens	Snake Flower			x	Petroleum	(Tsao and Tsao, 2003; Famulari, 2011)
Carpobrotus edulis subsp. edulis	Hottentots Fig	x		x	NH_3, NO_3^- & PO_4^{3-}	(Milandri et al. 2012)
Carpobrotus edulis subsp. parvifolius	Na	x	x	x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Jacklin et al. 2020)
**Ceratophyllum demersum*	Na			x	As, Cd, Cr, Cu, Ni & Pb; Explosives; Radionuclides; Organophosphorous, Organochlorine & Chlorobenzenes	(Dietz and Schnoor, 2001; Dhir et al. 2009; El-Khatib et al. 2014)
Chlorophytum comosum	Bracket Plant			x	C; CO; Formaldehyde; Toluene & Xylene	(Wolverton and Wolverton, 1993; Wolverton and Wolverton, 1996)
Cladium mariscus subsp. jamaicense	Saw Grass			x	Al, Fe, Mg & Mn	(Schachtschneider et al. 2010)
Conyza scabrida	Bakbesembossie			x	Cu & Zn	(Mkumbo et al. 2012)

Species	Common name	SA Endemic	WC Distribution Endemic	WC Distribution Indigenous	Pollutants	Reference
Cotula coronopifolia	Brass Buttons			x	Heavy Metals & Sewage Effluent	(Finlayson and Mitchell, 1982; Leguizamo et al. 2017)
Cyperus difformis	Smallflower Umbrella Plant			x	Cd, Ni & Pb	(Ewais, 1997; Leguizamo et al. 2017)
Cyperus dives	Ikhwane			x	NH_3, NO_3^- & PO_4^{3-}	(Wright et al. 2017; Frenzel, 2018)
Cyperus fastigiatus	Mothoto			x	NH_3, NO_3^- & PO_4^{3-}	(Wright et al. 2017)
Cyperus textilis	Umbrella Sedge	x		x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Wright et al. 2017; Jacklin et al. 2020)
Dodonaea viscosa	Sand Olive			x	Al, Cd, Cr, Cu, Mn, N, P, Pb & Zn	(Read et al. 2008; Read et al. 2010)
Elegia tectorum	Dakriet	x		x	NH_3, NO_3^- & PO_4^{3-}	(Milandri et al. 2012)
Eleocharis limosa	Schrad			x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Jacklin et al. 2020)
Ficinia nodosa	Vleibiesie			x	Al, Cd, Cr, Cu, Mn, N, P, Pb, & Zn; NH_3, NO_3^- & PO_4^{3-}	(Read et al. 2010; Milandri et al. 2012)
Gerbera jamesonii	Barberton Daisy			x	Benzene, TCE; Formaldehyde	(Famulari, 2011)
Gunnera perpensa	Rivierpampoen			x	NH_3, NO_3^- & PO_4^{3-}	(Wright et al. 2017)
Juncus effusus	Common Rush			x	Al, As, Cd, Co, Cr, Cu, Fe, K, Mn, Ni, Zn; NH_3, NO_3^- & PO_4^{3-}; Anthracene & Mine Effluent	(Deng et al. 2004; Leguizamo et al. 2017; Schachtschneider et al. 2017)
Juncus kraussii	Dune Slack Rush			x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate; N	(Payne et al. 2014; Jacklin et al. 2020)
Juncus lomatophyllus	Leafy Juncus			x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Frenzel, 2018; Jacklin et al. 2020)
Kyllinga brevifolia	Green Kyllinga			x	Ba, Ni, Pb, Sr, Th & U; PAHs	(Li et al. 2011; Leguizamo et al. 2017)
Leersia hexandra	Rasp Grass			x	Cd, Cr, Cu, Pb & Zn	(Deng et al. 2004; Zhang et al. 2007; CMLR, 2017)
Lemna gibba	Duck's Meat			x	As, Cd, Ni & U; Radionuclides; Phenol & 2,4,5-trichlorophenol	(Mkandawire and Dudel, 2005; Dhir et al. 2009)

Species	Common name	SA Endemic	WC Distribution		Pollutants	Reference
			Endemic	Indigenous		
Lemna minor	Duckweed			x	As, Ba, Cd, Cr, Cu, Fe, Hg, Pb, Ni, Se & Zn; Petroleum; Radionuclides; Wastewater Effluent; 2,4,5-trichlorophenol, halogenated phenols; Isoproturon, Glyphosate; Landfill Leachate	(Bonomo et al. 1997; Vardanyan and Ingole, 2006; Dhir et al. 2009)
Mentha aquatica	Aromatic Thyme			x	Cd, Cu, Fe, Ni, Pb & Zn	(Dhir et al. 2009; Branković et al. 2012)
Mentha longifolia subsp. polyadena	Wild Spearmint			x	Cr	(Dhir et al. 2009)
Mentha longifolia subsp. wissii	Wild Mint			x	Cr	(Zurayk et al. 2001)
Merwilla plumbea	Blue Squill			x	Cd	(Lux et al. 2011)
**Panicum repens*	Couch Panicum			x	Cd & Pb	(Zeng et al. 2015)
**Phragmites australis*	Common Reed			x	Al, Ca, Cd, Cr, Cu, Fe, K, Mn, Ni, Pb, Si & Zn; NH_3, NO_3^- & PO_4^{3-}; Domestic and Wastewater Effluent; Benzene, Phenanthrene; Atrazine & Pentachlorophenol	(Kumari and Tripathi, 2015; Ranieri et al. 2016; Ye et al. 1997)
Potamogeton nodosus	Fonteingras			x	HMX, RDX & TNT	(Bhadra et al. 2001; Dietz and Schnoor, 2001)
Potamogeton pectinatus	Fennel-leaved Pondweed			x	Cd, Cr, Cu, Mn, Ni, Pb & Zn; Radionuclides	(Singh et al. 2005; Dhir et al. 2009)
Prionium serratum	Palmiet	x		x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Frenzel, 2018; Jacklin et al. 2020)
Pteridium aquilinum subsp. aquilinum	Eagle Fern			x	Zn	(Mkumbo et al. 2012)
**Pteris cretica*	Avery Fern			x	As	(Zhao et al. 2002; CMLR, 2017)
Pteris vittata	Ladder Brake			x	As, Cr, Cu, Hg, Ni, Pb & Zn	(Visoottiviseth et al. 2002; Wang et al. 2002)

Species	Common name	SA Endemic	WC Distribution		Pollutants	Reference
			Endemic	Indigenous		
Rumohra adiantiformis	Seven-weeks Fern			x	Petroleum	(Tsao and Tsao, 2003; Famulari, 2011)
Ruppia maritima	Beaked Tasselweed			x	Se	(Gao et al. 2003; Peer et al. 2005)
Schoenoplectus corymbosus	Matjiesgoed			x	Al, Fe, Mg & Mn	(Schachtschneider et al. 2010; Schachtschneider et al. 2017)
Schoenoplectus scirpoides	Steekbiesie			x	NH_3, NO_3^- & PO_4^{3-}	(Wright et al. 2017; Frenzel, 2018)
Senecio coronatus	Sybossie			x	Al, Cu, Mn, Ni & Zn	(Mesjasz-Przybyłowicz et al. 1994; Boyd et al. 2002; Boyd et al. 2008)
Sporobolus virginicus	Brakgras			x	N	(Payne et al. 2014)
Stenotaphrum secundatum	Cape Kweek			x	N & P; PAHs & TPHs	(Flathman and Lanza, 1998; McCutcheon and Schnoor, 2003; Milandri et al. 2012)
Strelitzia nicolai	Natal Mock Banana			x	Domestic Greywater Effluent	(Fowdar et al. 2017; Barron et al. 2019)
Strelitzia reginae	Bird-of-Paradise			x	Domestic Greywater Effluent & Petroleum	(Tsao and Tsao, 2003; Fowdar et al. 2017)
Typha capensis	Bulrush			x	Al, Cd, Cu, Fe, Mn, Ni, Pb, Se & Zn; Fertilizer & Herbicide: NH_3, NO_3^-, PO_4^{3-} & Glyphosate; Radionuclides; Hydrophobic Organics	(Dietz and Schnoor, 2001; Schachtschneider et al. 2017)
Zantedeschia aethiopica	Arum Lily			x	NH_3, NO_3^-, PO_4^{3-} & Glyphosate	(Milandri et al. 2012; Jacklin et al. 2020)

HMX – Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine; PAHs – Polycyclic Aromatic Hydrocarbons; RDX – Research Demolition Explosive (Hexahydro-1,3,5-trinitro-1,3,5-triazine); TCE – Trichloroethylene; TNT – Trinitrotoluene-2-methyl-1,3,5-trinitrobenzene; TPHs – Total Petroleum Hydrocarbons.

*Care when using in sustainable and sensitive systems, as they display aggressive properties.

Various environmental factors to consider that contribute to a dynamic ecosystem include nitrogen pollution, atmospheric carbon dioxide concentration, inter-species interactions, and rhizospheric fluctuations due to pollutant deposition. The climate change scenario assessing future vulnerability in a dynamic environment seeks to mitigate plant characteristic adaptations of introduced species. Reported non-invasive species may exhibit greater aggressiveness and, with new evidence, be designated as invasive, which may warrant their exclusion for use in green infrastructure initiatives. Selection of plants for resource remediation, assisted by the recommended indigenous plant list, must consider ecosystem dynamism in fluctuating biotic conditions and a changing climate. The assessment of ecosystem characteristics and plant specific invasiveness, whilst incorporating precautionary principles of plant introduction, are crucial prerequisites for effective planning, demanding a multidisciplinary approach between engineering and science (Richardson et al. 2020). It is for these reasons that the civil engineer assessing plant inclusion in the proposed species for phytoremediation initiatives must consult relevant specialists in environmental science, field botany, conservation ecology and soil science, prior to introducing plant species into GI. In considering the vast habitats and scope of plant species located in the WC, this interdisciplinarity will equip the practising engineer with the necessary skills and knowledge backed by scientific literature to design an effective but sustainable phytoremediation system for runoff remediation and site rehabilitation initiatives.

CONCLUSIONS

Increased anthropogenic activities have exposed the urban and rural WC to sustained environmental degradation, posing a major environmental and human health problem (Malherbe et al. 2018). In an effort to sustainably remediate deleterious contaminants from soil and water, engineered strategies of an effective and affordable nature are required. GI offers a sustainable and cost-effective solution for various environmental contaminants from soil, sediment and water (Terry and Banuelos, 1999). In combating biodiversity loss, the selection of potential plants for bioremediation initiatives, must consider species that are naturally acclimatised to the recipient ecosystem, and which do not threaten the natural biodiversity. This is particularly important for urban remediation technologies as urban areas are often the initial sites for introduction, and from which invasions spread (Zengeya, 2020). Reduced ecosystem biodiversity poses one of the greatest ecological engineering challenges (Tilman and Lehman, 2001). The need to use effective plant species for remediation cannot overshadow the need to protect and conserve the ecosystem. Thus the use of indigenous plant species that ameliorate the degraded environment and contribute to preservation must be considered. Although a specific species may not be recorded as invasive to the WC phytogeographic area, with introduction to a new habitat, the non-invasive species may threaten habitat sustainability (Richardson et al. 2020). For this reason, species sourced from similar habitual conditions must be preferred.

The listed potential phytoremediators may aid in regulating the natural ecosystem, maintain equilibrium, and increase heterogeneity. They are also capable of adjusting to dynamic biogeographic conditions of various recipient habitats. This heterogeneity between species and phytogeographic distributions creates opportunities for the introduction of distinct vegetation into the diverse habitats of the WC, capable of remediating a wide range of environmental contaminants, at a fraction of the cost of conventional techniques. The non-invasive plants offer an attractive alternative to known invasive alien plants, while supporting natural biodiversity and conservation initiatives (Pyšek and Richardson, 2010).

In selecting potential phytoremediators the dynamic factors that mediate plant species' interactions with resident biota and prevailing conditions, affecting potential invasiveness within a specific ecosystem need to be considered. It is imperative that the practicing engineer receives input from relevant specialists, and that plant introduction is only undertaken with their satisfaction. It would be advantageous for the Water Research Commission (WRC) to work towards establishing a guideline, accounting for different pollution and ecosystem contexts, with input from the following specialists: hydrologists, town and regional planners, disaster management practitioners, ecologists and soil scientists, environmental and municipal managers, and landscape architects, which engineers could use with less oversight.

In decontaminating sites exposed to extreme and continuous pollution, field crops potentially contribute to phytoremediation in toxic conditions due to their short life cycle, large biomass production and adaptability to the changing environment (Ciura et al. 2005), in turn, mitigating severe environmental effects and greatly reducing environmental cost (Santos-Jallath et al. 2012). This can, however, only be done with greater monitoring of pollutant toxicity tolerance and rotation over a number of cropping cycles under strict circumstances.

Acknowledging the WC's global biodiversity richness status (Von Hase et al. 2003), the absence of research relating to the phytoremediation potential of the WC plant species for GI initiatives reinforces the need for further studies. In highlighting the remediation efficacy of endemic species, the vegetation may be granted an additional economic value that could aid the decisions which encourage protection and development (Barbier et al. 1997).

ACKNOWLEDGEMENT

This research was funded by the National Research Foundation (NRF) Thuthuka Fund, with project identity: TTK180418322426.

REFERENCES

ABHILASH PC, POWELL JR, SINGH HB and SINGH BK (2012) Plant–microbe interactions: novel applications for exploitation in multipurpose remediation technologies. *Trends in*

Biotechnology **30** (8) 416–420.

ABHILASH PC (2015) Managing soil resources from pollution and degradation: the need of the hour. *Journal of Cleaner Production* **102** 550–551.

ALI S, CHAUDHARY A, RIZWAN M, ANWAR HT, ADREES M, FARID M, IRSHAD MK, HAYAT T and ANJUM SA (2015). Alleviation of chromium toxicity by glycinebetaine is related to elevated antioxidant enzymes and suppressed chromium uptake and oxidative stress in wheat (*Triticum aestivum L.*). *Environmental Science and Pollution Research*. **22** (14) 10669–10678.

BAKER AJM and BROOKS R (1989) Terrestrial higher plants which hyperaccumulate metallic elements. A review of their distribution, ecology and phytochemistry. *Biorecovery* **1** (2) 81–126.

BARBIER E, ACREMAN M and KNOWLER D (1997) *Economic valuation of wetlands: a guide for decision-makers and planners.* Gland: Ramsar Convention Office. 155 pp.

BARRON NJ, DELETIC A, JUNG J, FOWDAR H, CHEN Y and HATT BE (2019) Dual-mode stormwater-greywater biofilters: The impact of alternating water sources on treatment performance. *Water Research* **159** 521–537.

BHADRA R, WAYMENT DG, WILLIAMS RK, BARMAN SN, STONE MB, HUGHES JB and SHANKS JV (2001) Studies on plant-mediated fate of the explosives RDX and HMX. *Chemosphere* **44** (5) 1259–1264.

BONOMO L, PASTORELLI G & ZAMBON N (1997) Advantages and limitations of duckweed-based wastewater treatment systems. *Water Science and technology* **35** (5) 239.

BOYD RS, DAVIS MA, WALL MA and BALKWILL K (2002) Nickel defends the South African hyperaccumulator Senecio coronatus (Asteraceae) against *Helix aspersa* (Mollusca: Pulmonidae). *Chemoecology* **12** (2) 91–97.

BOYD RS, DAVIS MA and BALKWILL K (2008) Elemental patterns in Ni hyperaccumulating and non-hyperaccumulating ultramafic soil populations of Senecio coronatus. *South African Journal of Botany* **74** (1) 158–162.

BROOKS RR, NAIDU SM, MALAISSE F and LEE J (1986) The elemental content of metallophytes from the copper/cobalt deposits of Central Africa. In: *Bulletin de la Société Royale de Botanique de Belgique/Bulletin van de Koninklijke Belgische Botanische Vereniging* 179–191 pp.

BUDELSKY R and GALATOWITSCH S (2004) Establishment of *Carex stricta* Lam. seedlings in experimental wetlands with implications for restoration. *Plant Ecology* **175** (1) 91–105.

CASTRO-DIEZ P, VALLE G, CONZALEZ-MUNOZ N and ALONSO A (2014) Can the life-history strategy explain the success of the exotic trees *Ailanthus altissima* and *Robinia pseudoacacia* in Iberian floodplain forests? *PloS one* **9** (6).

CHANEY RL, MALIK M, LI YM, BROWN SL, BREWER EP, ANGLE JS and BAKER AJ (1997) Phytoremediation of soil metals. *Current Opinion in Biotechnology* **8** (3) 279–284.

CHEN M, LI XM, YANG Q, ZENG GM, ZHANG Y, LIAO DX, LIU JJ, HU JM and GUO L (2008) Total concentrations and speciation of heavy metals in municipal sludge from Changsha, Zhuzhou and Xiangtan in middle-south region of China. *Journal of Hazardous Materials* **160** (2–3) 324–329.

CHOUDHARY MP, CHAUHAN GS and KUSHWAH YK (2015) Environmental degradation: causes, impacts and mitigation. In: *National Seminar on Recent Advancements in Protection of Environment and Its Management Issues*, February 2015, Rajasthan.

CIURA J, PONIEDZIALEK M, SEKARA A and JEDRSZCZYK E (2004) The possibility of using crops as metal phytoremediants. *Polish Journal of Environmental Studies* **14** (1) 17-22.

CMLR (Centre for Mined Land Rehabilitation) (2017) Global Hyperaccumulator Database. URL: http://hyperaccumulators.smi.uq.edu.au/collection/ (Accessed 15 March 2020).

CONSTANTINE M, MUSINGAFI C and TOM T (2014) Fresh water sources pollution: A human related threat to fresh water security in South Africa. *Res. Acad. Soc. Sci.* **1** (2) 72-81.

CUNNINGHAM SD, BERTI WR and HUANG JW (1995) Phytoremediation of contaminated soils. *Trends in Biotechnology* **13** (9) 393–397.

CUNNINGHAM SD, SHANN JR, CROWLEY DE and ANDERSON TA (1997) Phytoremediation of Contaminated Water and Soil. In: Kruger EL, Anderson TA and Coats JR (eds.) *Phytoremediation of Soil and Water Contaminants.* ACS Symposium Series, Iowa.

DE VILLIERS and THIART C (2007) The nutrient status of South African rivers: Concentrations, trends and fluxes from the 1970s to 2005. *South African Journal of Science* **103** (7–8) 343-349.

DENG H, YE ZH and WONG MH (2004) Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China. *Environmental Pollution* **132** (1) 29–40.

DHIR B, SHARMILA P and SARADHI PP (2009) Potential of Aquatic Macrophytes for Removing Contaminants from the Environment. *Critical Reviews in Environmental Science and Technology* **39** (9) 754–781.

DIETZ AC and SCHNOOR JL (2001) Advances in phytoremediation. *Environmental health perspectives* **109** 163–168.

DWS (DEPARTMENT OF WATER AND SANITATION) (2018) National water and sanitation master plan (V 10.1). Pretoria.

EL-KHATIB AA, HEGAZY AK and ABO-EL-KASSEM AM (2014) Bioaccumulation potential and physiological responses of aquatic macrophytes to Pb pollution. *International Journal of Phytoremediation* **16** (1) 29–45.

EWAIS EA (1997) Effects of cadmium, nickel and lead on growth, chlorophyll content and proteins of weeds. *Biologia Plantarum* **39** (3) 403–410.

FAMULARI S (2011) The Phytoremediation Plant Index. URL: http://www.steviefamulari.net/phytoremediation/index.php (Accessed 17 March 2020).

FINLAYSON CM and MITCHELL DS (1982) Treatment of rural wastewaters in Australia with aquatic plants: a summary. *Der Tropenlandwirt-Journal of Agriculture in the Tropics and Subtropics* **83** (2) 155–165.

FLATHMAN PE and LANZA GR (1998) Phytoremediation: current views on an emerging green technology. *Journal of soil contamination* **7** (4) 415–432.

FLETCHER TD, SHUSTER W, HUNT WF, ASHLEY R, BUTLER D, ARTHUR S,

TROWSDALE S, BARRAUD S, SEMADENI-DAVIES A, BERTRAND-KRAJEWSKI J, MIKKELSEN PS, RIVARD G, UHL M, DAGENAIS D and VIKLANDER M (2015) SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal* **12** (7) 525-542.

FOWDAR HS, HATT BE, BREEN P, COOK PLM and DELETIC A (2017) Designing living walls for greywater treatment. *Water Research* **110** 218–232.

FRENZEL P (2018) Investigating the potential of floating wetlands in small farm dams in the Western Cape, South Africa. MSc thesis, Stellenbosch University.

GAO S, TANJI K, PETERS D, LIN Z and TERRY N (2003) Selenium removal from irrigation drainage water flowing through constructed wetland cells with special attention to accumulation in sediments. *Water, Air, and Soil Pollution* **144** (1) 263–284.

GILIOMEE JH (2006) Conserving and increasing biodiversity in the large-scale, intensive farming systems of the Western Cape, South Africa. *S. Afr. J. Sci.* **102** 9–10.

GLEBA D, BORISJUK NV, BORISJUK LG, KNEER R, POULEV A, SKARZHINSKAYA M, DUSHENKOV S, LOGENDRA S, GLEBA YY and RASKIN I (1999) Use of plant roots for phytoremediation and molecular farming. *Proceedings of the National Academy of Sciences* **96** (11) 5973–5977.

GROEBER S, PRZYBYAOWICZ W, EXHEVARRIA G, MONTARGES-PELLETIER E, BARNABAS A and MESJASZ-PRZYBYAOWICZ (2015) Fate of nickel and calcium in seedlings of the hyperaccumulator *Berkheya coddii* during germination. *Biologia plantarum* **59** (3) 560.

GUERINOT ML and SALT DE (2001) Fortified foods and phytoremediation. Two sides of the same coin. *Plant physiology* **125** (1) 164.

JACKLIN D, BRINK IC and DE WAAL JH (2020) The potential use of plant species within a Renosterveld landscape for the phytoremediation of glyphosate and fertiliser. *Water SA* **46** (1) 94–103.

KHAN AG, KUEK C, CHAUDHRY TM, KHOO CS and HAYES WJ (2000) Role of plants, mycorrhizae and phytochelators in heavy metal contaminated land remediation. *Chemosphere* **41** (1–2) 197–207.

KHAN AG, KHAN S, KHAN MA, QAMAR Z and WAQAS M (2015) The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. *Environmental Science and Pollution research* **22** (18) 13772-13799.

KONDO MC, LOW SC, HENNING J and BRANAS CC (2015) The impact of green stormwater infrastructure installation on surrounding health and safety. *American Journal of Public Health* **105** (3) 114–121.

KRÄMER U and CHARDONNENS A (2001) The use of transgenic plants in the bioremediation of soils contaminated with trace elements. *Applied Microbiology and Biotechnology* **55** (6) 661–672.

KUMARI M and TRIPATHI BD (2015) Efficiency of *Phragmites australis* and *Typha latifolia* for heavy metal removal from wastewater. *Ecotoxicology and Environmental Safety* **112** 80–86.

LE MAITRE DC, BLIGNAUT JN, CLULOW A, DZIKITI S, EVERSON CS, GÖRGENS AHM and GUSH MB (2020) Impacts of plant invasions on terrestrial water flows in South Africa. In: Simberloff D (ed.) *Biological Invasions in South Africa.* Springer, Cham.

LE ROUX JJ, CLUSELLA-TRULLAS S, MOKOTJOMELA TM, MAIRAL M, RICHARDSON DM, SKEIN L, WILSON JR, WEYL OLF and GEERTS S (2020) Biotic interactions as mediators of biological invasions: insights from South Africa. In: Simberloff D (ed.) *Biological Invasions in South Africa.* Springer, Cham.

LEGUIZAMO MAO, GOMEZ WDF and SARMIENTO MCG (2017) Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands — A review. *Chemosphere* **168** 1230–1247.

LI G, HU N, DING D, ZHENG J, LIU Y, WANG Y and NIE X (2011) Screening of plant species for phytoremediation of uranium, thorium, barium, nickel, strontium and lead contaminated soils from a uranium mill tailings repository in south China. *Bulletin of Environmental Contamination and Toxicology* **86** (6) 646–652.

LUX A, VACULÍK M, MARTINKA M, LIŠKOVÁ D, KULKARNI MG, STIRK WA and VAN STADEN J (2011) Cadmium induces hypodermal periderm formation in the roots of the monocotyledonous medicinal plant *Merwilla plumbea*. *Annals of Botany* **107** (2) 285–292.

MACEK T, MACKOVÁ M and KÁŠ J (2000) Exploitation of plants for the removal of organics in environmental remediation. *Biotechnology Advances* **18** (1) 23–34.

MALAN M, MÜLLER F, CYSTER L, RAITT L and AALBERS J (2015) Heavy metals in the irrigation water, soils and vegetables in the Philippi horticultural area in the Western Cape Province of South Africa. *Environmental Monitoring and Assessment* **187** (1) 1–8.

MALHERBE H, GEBEL M, PAULEIT S and LORZ C (2018) Land use pollution potential of water sources along the southern coast of South Africa. *Change and Adaptation in Socio-Ecological Systems* **4** (1) 7–20.

MARRUGO-NEGRETE J, DURANGO-HERNÁNDEZ J, PINEDO-HERNÁNDEZ J, OLIVERA-VERBEL J and DIETZ S (2015) Phytoremediation of mercury-contaminated soils by Jatropha curcas. *Chemosphere* **127** 58–63.

MCCUTCHEON S and SCHNOOR J (2003) Overview of phytotransformation and control of wastes. In: Schnoor J (ed.) *Phytoremediation: Transformation and Control of Contaminants*. John Wiley and Sons, Ltd., New Jersey.

MCDOWELL C and MOLL E (1992) The influence of agriculture on the decline of west coast renosterveld, south-western Cape, South Africa. *Journal of Environmental Management* **35** (3) 173–192.

MEAGHER RB (2000) Phytoremediation of toxic elemental and organic pollutants. *Current opinion in plant biology* **3** (2) 153–162.

MESJASZ-PRZYBYLOWICZ J, BALKWILL K, PRZYBYLOWICZ WJ and ANNEGARN HJ (1994) Proton microprobe and X-ray fluorescence investigations of nickel distribution in serpentine flora from South Africa. *Nuclear Institute and Methods in Physics Research* **89** (1–4) 208–212.

MILANDRI M, WINTER KJ, CHIMPANGO SBM, ARMITAGE NP, MBUI DN, JACKSON GE and LIEBAU V (2012) The performance of plant species in removing nutrients from stormwater in biofiltration systems in Cape Town. *Water SA* **38** (5) 275–662.

MKANDAWIRE M and DUDEL EG (2005) Accumulation of arsenic in *Lemna gibba L.*(duckweed) in tailing waters of two abandoned uranium mining sites in Saxony, Germany. *Science of the Total Environment* **336** (1–3) 81–89.

MKUMBO S, MWEGOHA W and RENMAN G (2012) Assessment of the phytoremediation potential for Pb, Zn and Cu of indigenous plants growing in a gold mining area in Tanzania. *International journal of environmental sciences* **2** (4) 2425–2434.

MÜLLER FL, JOUBERT ME, CYSTER LF and RAITT LM (2014) Heavy metal retention by soils and the subsequent uptake thereof by Cripps Pink/M7 apple trees under organic and chemical fertilizer applications. *Photon: International Journal of Agriculture* **125** 340–346.

MUSINGAFI CM and TOM T (2014) Fresh Water Sources Pollution : A Human Related Threat To Fresh Water Security in South Africa. *Journal of Public Policy & Governance* **1** (2) 72–81.

NEL JL, LE MAITRE DC, NEL DC, REYERS B, ARCHIBALD S, VAN WILGEN BW, FORSYTH GG, THERON AK, O'FARRELL PJ, KAHINDA JMM and co-authors (2014) Natural hazards in a changing world: a case for ecosystem-based management. *PloS one* **9** (5).

NOMQUPHU W, BRAUNE E and MITCHELL S (2007) The changing water resources monitoring environment in South Africa. *South Arican Journal of Science* **103** (7–8) 306–310.

OBERHOLSTER PJ and ASHTON PJ (2008) State of the nation report: An overview of the current status of water quality and eutrophication in South African rivers and reservoirs. Council for Scientific and Industrial Research (CSIR), Pretoria.

OJASTI J (2001) Study on the current state of exotic species. April 2001, Quito.

PAKDEL P and PEIGHAMBARDOUST S (2018) A review on acrylic based hydrogels and their applications in wastewater treatment. *Journal of Environmental Management* **217** 123–143.

PAYNE EGI, HATT BE, DELETIC A, DOBBIE MF, MCCARTHY DT and CHANDRASENA GI (2015) Adoption guidelines for stormwater biofiltration systems - Summary report. Cooperative Research Centre for Water Sensitive Cities, Melbourne.

PAYNE EGI, PHAM T, COOK PLM, FLETCHER TD, HATT BE and DELETIC A (2014) Biofilter design for effective nitrogen removal from stormwater--influence of plant species, inflow hydrology and use of a saturated zone. *Water Science and Technology* **69** (6) 1312–1319.

PEER WA, BAXTER IR, RICHARDS EL, FREEMAN JL and MURPHY AS (2005) Phytoremediation and hyperaccumulator plants. In: *Molecular biology of metal homeostasis and detoxification*. 299-340 pp. Springer, Berlin.

PEUKE AD and RENNENBERG H (2005) Phytoremediation with transgenic trees. *Journal of biosciences* **60** (3–4) 199–207.

PEUKE AD and RENNENBERG H (2006) Heavy metal resistance and phytoremediation with transgenic trees. In: Fladung M and Ewald D (eds.) *Tree Transgenesis* 137–155 pp. Springer, Berlin.

PILON-SMITS E (2005) Phytoremediation. *Annual Review of Plant Bioogy* **56** 15-39.

POONAM, BHARDWAJ R, SHARMA R, HANDA N, KAUR H, KAUR R, SIRHINDI G and THUKRAL AK (2014) Prospects of field crops for phytoremediation of contaminants. In: AHMAD P and RASOOL S (eds.) *Emerging technologies and management of crop stress tolerance*. Elsevier, Amsterdam.

PRZYBYLOWICZ WJ, PINEDA CA, RAMA DBK and MESJASZ-PRZYBYLOWICZ J (2001) Elemental distribution in *Senecio anomalochrous*, a Ni hyperaccumulator from South Africa. *South African Journal of Sciience* **97** (11) 593–595.

PYŠEK P (1995) On the terminology used in plant invasion studies. *Plant invasions: general aspects and special problems* 71–81.

PYŠEK P and RICHARDSON DM (2010) Invasive species, environmental change and management, and health. *Annual review of environment and resources* 35*.*

RADA EC, ANDREOTTOLA G, ISTRATE IA, VIOTTI P, CONTI F and MAGARIL ER (2019) Remediation of soil polluted by organic compounds through chemical oxidation and phytoremediation combined with DCT. *International journal of environmental research and public health* **16** (17) 3179.

RANIERI E, FRATINO U, PETRELLA A, TORRETTA Vand RADA EC (2016) *Ailanthus Altissima* and *Phragmites Australis* for chromium removal from a contaminated soil. *Environmental Science and Pollution Research* **23** (16) 15983–15989.

RASKIN I, KUMAR PN, DUSHENKOV S and SALT DE (1994) Bioconcentration of heavy metals by plants. *Current Opinion in Biotechnology* **5** (3) 285–290.

READ J, WEVILL T, FLETCHER TD and DELETIC A (2008) Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research* **42** (4–5) 893–902.

READ J, FLETCHER TD, WEVILL T and DELETIC A (2010) Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *International Journal of Phytoremediation* **12** (1) 34–53.

RICHARDSON DM, FOXCROFT LC, LATOMBE G, LE MAITRE DC, ROUGET M and WILSON JR (2020) The biogeography of South African terrestrial plant invasions. In: Simberloff D (ed.) *Biological Invasions in South Africa.* Springer, Cham.

RIZWAN M, ALI S, RIZVI H, RINKLEBE J, TSANG DCW, MEERS E, OK YS and ISHAQUE W (2016) Phytomanagement of heavy metals in contaminated soils using sunflower: a review. *Critical reviews in environmental science and technology* **46** (18) 1498-1528.

SALT DE, SMITH RD and RASKIN I (1998) *Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biol*ogy **49** (1) 643–668.

SALT DE, BLAYLOCK M, KUMAR NPBA, DUSHENKOV V, ENSLEY BD, CHET I and RASKIN I (1995) Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. *Biotechnology* **13** (5) 468–474.

SANTOS-JALLATH J, CASTRO-RODRÍGUEZ A, HUEZO-CASILLAS J and TORRES-BUSTILLOS L (2012) Arsenic and heavy metals in native plants at tailings impoundments in Queretaro, Mexico. *Physics and Chemistry of the Earth, Parts A/B/C* **37** 10-17.

SCHACHTSCHNEIDER K, MUASYA M and SOMERSET V (2010) Are indigenous sedges useful for phytoremediation and wetland rehabilitation? Report no CSIR NE04-PO, CSIR, Pretoria.

SCHACHTSCHNEIDER K, CHAMIER J and SOMERSET V (2017) Phytostabilization of metals by indigenous riparian vegetation. *Water SA* **43** (2) 177.

SCHLOEMANN H (1995) The geochemistry of some common Western Cape soils (South Africa) with emphasis on toxic and essential elements. PhD dissertation, University of Cape Town.

SIBANDA T, SELVARAJAN R and TEKERE M (2015) Urban effluent discharges as causes of public and environmental health concerns in South Africa's aquatic milieu. *Environmental Science and Pollution Research* **22** (23) 18301–18317.

SINGH NK, PANDEY GC, RAI UN, TRIPATHI RD, SINGH HB and GUPTA DK (2005) Metal Accumulation and Ecophysiological Effects of Distillery Effluent on Potamogeton pectinatus L. *Bulletin of Environmental Contamination and Toxicology* **74** (5) 857–863.

TERRY N and BAÑUELOS GS (1999) *Phytoremediation of contaminated soil and water*. CRC Press, Boca Raton.

TILMAN D and LEHMAN C (2001) Human-caused environmental change: Impacts on plant diversity and evolution. *Proceedings of the National Academy of Sciences of the United States of America* **98** (10) 5433.

TRIPATHI V, FRACETO LF and ABHILASH PC (2015) Sustainable clean-up technologies for soils contaminated with multiple pollutants: plant-microbe-pollutant and climate nexus. *Ecological Engineering* **82** 330–335.

TSAO K and TSAO D (2003) Analysis of phytoscapes Species for BP Retail Sites, BP Group Environmental Management Company. Report published as Capstone Project paper to Benedictine University, Lile.

VAN WILGEN BW, RICHARDSON DM, LE MAITRE DC MARAIS C and MAGADLELA D (2001) The economic consequences of alien plant invasions: examples of impacts and approaches to sustainable management in South Africa. *Environment, development and sustainability* **3** (2) 145-168.

VAN WILGEN BW, WILSON JR, WANNENBURGH A and FOXCROFT LC (2020) The extent and effectiveness of alien plant control projects in South Africa. In: Simberloff D (ed.) *Biological Invasions in South Africa.* Springer, Cham.

VAMERALI T, BANDIERA M and MOSCA G (2010) Field crops for phytoremediation of metal-contaminated land, A review. *Environmental Chemistry Letters* **8** (1) 1–17.

VARDANYAN LG and INGOLE BS (2006) Studies on heavy metal accumulation in aquatic macrophytes from Sevan (Armenia) and Carambolim (India) lake systems. *Environment International* **32** (2) 208–218.

VINEYARD D, INGWERSEN WW, HAWKINS TR, XUE X, DEMEKE B and SHUSTER W (2015) Comparing green and grey infrastructure using life cycle cost and environmental impact: A rain garden case study in Cincinatti, OH. *Journal of the American Water Resources Association* **52** (5) 1342-1360.

VISOOTTIVISETH P, FRANCESCONI K and SRIDOKCHAN W (2002) The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environmental Pollution* **118** (3) 453–461.

VON HASE A, ROUGET M, MAZE K and HELME N (2003) A finescale conservation plan for Cape lowlands Renosterveld: technical report. Report no CCU 2/03. Cape Conservation Unit, Botanical Society of South Africa, Claremont.

WANG J, ZHAO FJ, MEHARG AA, RAAB A, FELDMANN J and MCGRATH SP (2002) Mechanisms of arsenic hyperaccumulation in Pteris vittata. Uptake kinetics, interactions with phosphate, and arsenic speciation. *Plant physiology* **130** (3) 1552–1561.

WOLVERTON BC and WOLVERTON JD (1993) Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. *Journal of the Mississippi Academy of Sciences* **38** (2) 11–15.

WOLVERTON BC and WOLVERTON JD (1996) Interior plants: their influence on airborne microbes inside energy-efficient buildings. *Journal of the Mississippi Academy of Sciences* **41** (2) 99-105.

WRIGHT D, PURNELL A, ALTERN S and FRENZEL P (2017) Floating wetlands - increasing biodiversity and cleaning water in farm dams. Table Mountain Fund, Cape Town.

YANG F, YANG Y, LI H and CAO M (2015) Removal efficiencies of vegetation-specific filter strips on nonpoint source pollutants. *Ecological Engineering* **82** 145.

YE ZH, BAKER AJM, WONG MH and WILLIS AJ (1997) Zinc, Lead and Cadmium Tolerance, Uptake and Accumulation by the Common Reed, *Phragmites australis* (Cav.) Trin. ex Steudel. *Annals of Botany* **80** (3) 363–370.

ZENG Z, GAO G, YANG J, YUAN J and YANG Z (2015) The integrated response of torpedograss (*Panicum repens*) to Cd–Pb co-exposures. *Ecological Engineering* **82** 428–431.

ZENGEYA TA and WILSON JR (2020) The status of biological invasions and their management in South Africa in 2019 [SECOND ORDER DRAFT]. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.

ZHANG XH, LIU J, HUANG HT, CHEN J, ZHU YN and WANG DQ (2007) Chromium accumulation by the hyperaccumulator plant *Leersia hexandra* Swartz. *Chemosphere* **67** (6) 1138–1143.

ZHAO FJ, DUNHAM SJ and MCGRATH SP (2002) Arsenic hyperaccumulation by different fern species. *New phytologist* **156** (1) 27–31.

ZURAYK R, SUKKARIYAH B and BAALBAKI R (2001) Common hydrophytes as bioindicators of nickel, chromium and cadmium pollution. *Water, Air, and Soil Pollution* **127** (1–4) 373–388.

CHAPTER 3

A phyto-guide to species selection for optimized South African green infrastructure – Technical note

This chapter addresses research objective 2. A decision framework was developed that facilitates plant selection without solely relying on known effective phytoremediators, for South African GI. This tool is provided to the practicing civil or environmental engineer in the form of a phyto-guide and considers relevant indexes, plant physiology and morphology, as factors affecting species inclusion, which are discussed and diagrammatically illustrated.

Environmental deterioration and resource overexploitation is not only limited to the Western Cape, with South Africa adjudged to experience some of the most rapid degradation globally, posing major ecological engineering challenges. As mentioned, although vegetated GI offers a pertinent resource mitigation solution, the pollutant and hydrologic remediation capacities of plants vary substantially. Additionally, the spread of alien plants which negatively impacts an ecosystem's ability to deliver goods and services is a serious risk.

The need for this research is highlighted in the engineer's lack of expertise pertaining to plant behaviour and ecosystem dynamics, as well as the general lack of knowledge pertaining to species specific removal efficiencies. For the user's benefit the phyto-guide seeks to combine existing phytoremediator recommendations, scientifically backed botanical records, knowledge of removal processes, physiological and morphological traits, as well as species heterogeneity and aesthetics. This amalgamation between science and engineering upholds interdisciplinarity at the core of the phyto-guide's modus operandi, whilst pollutant removal efficacy and habitat sustainability are considered equally important contributors to successful GI functioning. An additive benefit of the phyto-guide is its consideration of relevant plant traits, as well as plant distribution, behaviour and diversity during the decision-making process, advancing the limitation of relying solely on previously identified phytoremediators. Consequently, local GI initiatives may benefit from South Africa's rich biodiversity and endemism which have been not yet been verified for use as phytoremediators.

The research significance is this opportunity to engage novel South African plant species as potential phytoremediators, thereby minimising GI's inefficacy and invasive threat. Thus, the phyto-guide was applied to identify indigenous plant species for use in the experimental biofilters, chapter 5, objective 4. In addition, similar to chapter 2, the phyto-guide and some of its findings were presented at the Water Institute of Southern Africa Online Conference (Appendix A).

A phyto-guide to species selection for optimized South African green infrastructure – Technical note

DM Jacklin[1], IC Brink[1] and SM Jacobs[2]

[1]Department of Civil Engineering: Water and Environmental Engineering Group, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

[2]Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

Reproduced and reformatted from an article published in **Water SA, 47(4), 515-522**, with permission from the copyright holder, the South African Water Research Commission.

Abstract

In South Africa, rapid environmental degeneration caused by anthropogenic pollution poses a major ecological engineering problem, demanding proper resource mitigation strategies. For the treatment of polluted water and degraded soil systems, green infrastructure (GI) offers an effective, sustainable and affordable nature-based alternative to grey infrastructure. An additive benefit within GI, plant species provide enormous potential to treatment; however, species vary substantially in their pollutant removal and hydrologic performance. South African civil engineers tasked with designing GI often lack expertise and knowledge of plant behaviour and ecosystem dynamics. Therefore, this paper proposes a decision framework to facilitate selection for designing local GI in the form of a phyto-guide, based on existing recommendations and knowledge of removal processes and plant behaviour. Interdisciplinarity at the core of the phyto-guide relies on continuous specialist collaboration with each selection criteria, whilst efficiency and sustainability are considered equally important contributors to successful GI functioning. The spread of invasive alien plants, whether accidental or deliberate, negatively impacts an ecosystem's capacity to deliver goods and services. Thus, the desire to optimize GI by incorporating effective phytoremediators cannot be prioritised over conservation concerns. In addition, this paper seeks to advance the GI limitation of relying solely on previously identified phytoremediators, by including evaluation criteria of beneficial plant traits as well as plant distribution, behaviour and diversity into the decision-making process for optimized GI. It is recommended that future research engages in discovering less invasive, naturally occurring local species as potential phytoremediators, inspired by South Africa's rich biodiversity and endemism, as well as conveying the importance of consultation with engineers and ecologists for optimized GI.

Keywords: green infrastructure, ecological engineering, phytoremediation, phytotechnologies, practical guide

INTRODUCTION

Pollution of the South African biosphere by anthropogenic organic and inorganic materials, and heavy metals, has resulted in the release of large amounts of contaminants to urban and rural soil and water resources, posing a major human and environmental health problem (Nomquphu et al., 2007; Govender et al., 2011; Constantine et al., 2014; Malan et al., 2015). Due to urbanisation, agriculture, industry, mining, waste disposal, dysfunctional sewage works and unsewered formal and informal human settlements, South Africa is experiencing some of the most rapid environmental degradation globally, requiring proper mitigation strategies to restore ecosystem function and improve resource quality (Oberholster and Ashton, 2008; De Klerk et al., 2016).

Internationally, nature-based solutions have been demonstrated to provide critical maintenance, rehabilitation and purification services to degraded areas in a more cost-effective way than traditional solutions, with research in this domain receiving significant scientific and commercial attention (Postel and Thompson, 2005; Peuke and Rennenberg, 2006). Green infrastructure (GI) offers a sustainable yet effective approach for, inter alia, the on-site treatment of stormwater and amelioration of degraded soil systems, as well as playing an integral role in various rehabilitation efforts, thus conserving dwindling natural resources (Hufnagel and Rottle, 2014; Choudhary et al., 2015; Yang et al., 2015; Wirth et al., 2018). GI is the interconnected set of natural and engineered ecological systems on different spatial levels that cooperatively produce valuable services in areas such as energy, security, climate regulation, aesthetics and resource management, in an efficient and self-sustaining way, promoting a versatile nature-based alternative to grey infrastructure (Cole et al., 2017; Pauleit et al., 2017; Pasquini and Enqvist, 2019). If implemented correctly, GI has the potential of eventually being more sustainable than traditional solutions, as well as providing a range of ecosystem services to society (Kitha and Lyth, 2011; Wertz-Kanounnikoff et al., 2011). These services mitigate the growing risks associated with grey infrastructure, rapid urban development and climate change, aiding general urban sustainability through water filtration, storage and recycling (Culwick et al., 2016; Pasquini and Enqvist, 2019).

Within GI, selected plant species are used for the in-situ treatment of environmental pollutants, a process known as phytoremediation, by improving water quality compared with unvegetated soil media (Dietz and Schnoor, 2001; Denman et al., 2006; Henderson et al., 2007). Phytoremediation is a relatively inexpensive yet effective form of ecological engineering utilising plants to detoxify, degrade and/or remove pollutants from the environment, effectively restoring and ameliorating degraded environments (Terry and Bañuelos, 1999; Meagher, 2000; Visoottiviseth et al., 2002). Plant selection has a substantial influence on GI performance, due to varying pollutant removal efficiencies affected by environmental, physiological and morphological inconsistencies between species (Read et al., 2008; Read et al., 2010). During the planning and design process of GI, the devised set of green networks, distributed throughout the urban area for site-specific pollutant remediation, ecosystem functioning and risk attenuation, are required to meet specific infrastructure and service needs with the local natural habitat in need of remediation considered (Ahern, 2007). The addition of ecosystem value assessment for both rural and urban areas allows for the implementation of fit-for-purpose, sustainable yet effective infrastructure solutions (Culwick et al., 2016). Vital to GI success is the appropriate design and spatial distribution of green networks, due to the diffuse nature of pollutant influent received (Brink, 2019). Optimal GI design is complex and requires both engineering hydrology knowledge and insights into the functioning of natural elements, not generally included in the typical training of the practicing engineer (Brink, 2019). This amalgamation of knowledge for scientifically backed design can only be achieved by embracing collaboration with a range of local specialists integrating disciplines from engineering, planning and science (Wong, 2006; Tanner and Möhr-Swart, 2007; Davis et al., 2009; Armitage et al., 2014).

The recognition of ecosystem services and its value to human health in South Africa (Le Maitre et al., 2007) has initiated a growing movement towards the acceptance of the water-sensitive urban design (WSUD) philosophy, which has the potential to mitigate the negative effects of water scarcity, manage and reverse water pollution, increase sustainability, and develop resilience to natural disasters and climate change within water systems (Armitage et al., 2014). Within WSUD, the augmentation of knowledge and skills by the practicing engineer represents a holistic approach to stormwater engineering, promoting stormwater management through sustainable (urban) drainage systems (SuDS) (Armitage et al., 2014). Although the WSUD framework provides philosophical guidance, it does not yet provide design specifics; similarly, the SuDS component focuses on the management of stormwater rather than design specifics (Brink, 2019). A concerning trend has emerged during planning and application in South Africa as a direct result of a lack in design guidelines complicating implementation, which is that GI is perceived as a new concept that does not yet fit into established municipal guidelines (Pasquini and Enqvist, 2019). Thus, increasing emphasis is placed on expanding knowledge, skills and support to engineers that are frequently tasked with selecting and designing appropriate GI, based on complex engineered solutions within dynamic natural processes for remediation success (Culwick et al., 2016).

Therefore, this paper builds on existing recommendations and knowledge to provide a strategic guide to the South African practicing engineer for the appropriate selection of plant species to optimize GI remediation technologies, at the same time limiting injudicious plant introduction into engineered designs and natural ecosystems. In supporting GI feasibility, the proposed phyto-guide regards remediation efficiency and sustainability as equal contributors to success, thus including plant ecology and conservation together with the other disciplines throughout the design process. In addition to species presence in global bioremediation literature, distribution, invasiveness, conservation status and behaviour, the phyto-guide considers plant physiological characteristics such as growth and vegetative expansion, natural tolerance for extreme environmental and climatic conditions, and hardiness to biotic and abiotic stresses (where such information is available). Furthermore, plant morphological traits are assessed, with biomass and root characteristics contributing to pollutant remediation efficiency (Ghosh and Singh, 2005; Read et al., 2010). Due to the importance of biodiversity and aesthetics, the combination of effective phytoremediators with desirable traits, and non-invasive less effective phytoremediators with some but not all desirable traits, is explored, encouraging diversity of species and species traits in GI projects.

RATIONALE FOR SELECTION OF FACTORS INFLUENCING GI PERFORMANCE

In an effort to optimize GI, factors determining potential plant selection can be grouped into the following broad categories: species presence in global bioremediation literature; distribution, invasiveness and conservation status; physiological characteristics and responses; morphological traits; and heterogeneity and aesthetics.

Species presence in global bioremediation literature

Bioremediation literature provides valuable information on proven effective phytoremediators, along with their associated pollutant affinities, to the GI designer, who can select potential species on the basis of removal efficacy, distribution or invasiveness, for use in site-specific remediation initiatives. In assessing reported literature, though limited to case-specific bioremediation research, the practicing engineer is supplied with information on effective species and their target pollutants. Bioremediation studies of importance include investigations of stormwater quality improvement, sustainable urban drainage systems, water-sensitive urban design, low-impact development systems, water and soil rehabilitation initiatives and reported plant encounters in metal-rich environments.

Plant distribution, invasiveness and conservation status

The introduction of invasive exotic phytoremediators to remediation initiatives alters the natural environment and may increase the threat of biological invasion, thereby impeding GI function (Budelsky and Galatowitsch, 2004) and increasing ecological risk (Leguizamo et al., 2017). Thus, endemic or indigenous species capable of adapting to the recipient habitat, enhancing remediation performance and limiting the risk of biodiversity loss by alien invasion, are considered (Oversby et al., 2014). These species are naturally distributed to a region and have established themselves in the environment without human assistance (Leguizamo et al., 2017). For example, in South Africa *Agapanthus africanus* and *Alectra sessiliflora* are representatives of endemic and indigenous phytoremediator species, respectively (see Jacklin et al., 2021).

The introduction of invasive alien plants (IAPs) often negatively affects the recipient natural ecosystems, generating massive economic losses, and causing a major environmental problem (Van Wilgen et al., 2001). For instance, introduced IAPs may disturb local vegetation, jeopardizing existing mutualistic edaphic networks, thereby limiting an ecosystem's natural capacity for resilience and recovery (Montes et al., 2007; Rodríguez-Echeverría, 2009). The difficulty, however, is that many behavioural properties advantageous for phytoremediation are shared with invasiveness (Leguizamo et al., 2017). Thus, to reduce the threat of invasion, the use of non-invasive species should always be promoted (Payne et al., 2015). The use of species of little or no conservation concern, which are generally more abundant and available than species in short supply or at risk of extinction, enhances practicability of GI initiatives (Visoottiviseth et al., 2002). However, there are instances in complex GI situations where vulnerable species offer potential for use, due to their delicate local inter-species relationship and ease of adaptation to the recipient habitat (Barbier et al., 1997).

The demand for vulnerable species (in low abundance naturally or due to degradation) may strengthen their population numbers and enhance species survival (Prasad, 2004). It is paramount that species experiencing dwindling population numbers, and in danger of extinction, are only considered along with or following sustained conservation initiatives, in consultation with conservation ecologists and botanists, to mitigate their vulnerability and potential invasiveness.

Plant physiological characteristics and responses

The ability of vegetation to acclimate after introduction plays an important role in new GI projects, influencing the system's resilience, recovery and remediation efficiency (Payne et al., 2015). In different ecosystems species are exposed to varying climatic and habitat conditions and species selection must reflect this change to hinder dormancy in species not accustomed to the applicable conditions, as well as increase productivity through species diversity (Leguizamo et al., 2017). Establishment success and long-term GI efficiency is influenced by plant growth rate, their ability to tolerate water stress during periods of drought by regulating opening and closing of the stomata (Arve et al., 2011), maintaining plant maturation rate and supporting effluent runoff infiltration into the growth media (Farrell et al., 2013). In addition, an inherently fast growth rate is a performance trait advantageous in wet conditions, contrasting with species of slower growth which are better performers in dry conditions (Oversby et al., 2014).

Similarly, appropriate plant lifespans vary according to specific site conditions and intended target pollutants (Roca et al., 2017). For instance, plants naturally distributed on metalliferous soils with shorter lifespans are frequently equipped to phytoremediate heavy metal pollution, although not all heavy metals are removed to the same extent, emphasizing the importance of species choice (Visoottiviseth et al., 2002). Traditionally, plants with longer lifespans and high growth rates are preferred for sustainability; however, plants with a shorter lifespan and high growth rate are preferred for heavy metal remediation in metalliferous soils (Visoottiviseth et al., 2002; Leguizamo et al., 2017). A short lifespan assisted by rapid growth encourages metal hyperaccumulation, by exposing the plants to greater toxicity and with time resulting in plant mortality (Salt et al., 1998; Conesa et al., 2009).

The ability of GI to prevail in extreme climatic conditions by tolerating intermittent periods of rainfall, drought and flood events is improved with appropriate plant selection (Oversby et al., 2014). Thus, variation in local rainfall and seasonal patterns require species accustomed to both periods of drought and inundation, which may reduce the system's efficiency if not engineered properly (Robinson et al., 2015).

Plant morphological traits

Morphological traits for water quality improvement have been found to correlate with some highly specialized physiological functions, confirming the importance of intricately selecting species with appropriate traits to GI systems (Payne et al., 2015). Morphological traits known to enhance phytoremediation efficiency and ultimately the performance of GI are above- and below-ground plant biomass, as well as root composition (Visoottiviseth et al., 2002; McGrath and Zhao, 2003; Read et al., 2010). Root systems composed of deep, fibrous and large biomass roots, with a high root:shoot ratio within the biofilter growth media, influence pollutant interaction and support microbial communities (Read et al., 2008; Oversby et al., 2014). Although the removal performance of plants with thick taproots differ from species with abundant fibrous roots, thick roots create macropores throughout the filter media which assist with infiltration (Hatt et al., 2009).

Heterogeneity and aesthetics of green infrastructure

Due to the dynamic processes affecting appropriate species selection, as well as their varying efficiencies over a range of pollutants, vegetative combination contributes to GI water quality and infiltration performance (Read et al., 2010). An approach to enhance vegetative heterogeneity combines known effective phytoremediators with desirable physiological and morphological traits as a majority, with some less effective species exhibiting some but not all desirable traits, to achieve GI optimization throughout fluctuating seasons and environmental conditions (Oversby et al., 2014). Support of the local community, the relevant stakeholders and beneficiaries is more easily obtained by aesthetically pleasing GI systems, contributing to the importance of such heterogeneous species mixes. During design, the engineer must seek to incorporate the local context through the potential use of efficient local species supporting biodiversity, which provide diversity and habitat to enhance microclimate benefits, whilst serving as visually stimulating attractions (Payne et al., 2015).

The effect of natural factors influencing a dynamic resident biota as well as its prevailing site and climatic conditions must be considered in order to account for potential invasiveness within an ecosystem (Richardson et al., 2020). Thus, specialist collaboration from a number of disciplines within science and engineering promotes the amalgamation of knowledge required for the creation of a design science for GI.

UNPACKING THE PHYTO-GUIDE PROCESS FOR SOUTH AFRICA

In South Africa civil engineers frequently tasked with the optimization of sustainable GI technologies, equipped with typical engineering hydrology knowledge, may lack the necessary insights into the functioning of natural ecosystems. Thus, to facilitate species selection during GI planning and design, the phyto-guide provides the user with a decision framework for the appropriate selection of South African plant species. This selection process considers removal efficiency and sustainability as equally important factors for successful GI technologies, facilitating greater accuracy in risk assessments of introduced species. Although the process of considering these factors is vital during planning and design for the optimization of all GI technologies, here we present the systematic plant selection process, together with relevant sources, in the South African context only.

Applying the phyto-guide

The phyto-guide for appropriate species selection during planning and design consists of five main categories influencing selection, with each step requiring input from relevant specialists (Fig. 1). The initial step of the process relies on the user's ability to conduct a literature investigation of published bioremediation research to identify proven effective phytoremediators as potential candidates. This step is, however, not critical to the phyto-guide's success and can be bypassed by commencing with the second selection step – evaluating reported distribution, invasiveness and conservation characteristics of species from various readily available herbarium records and online databases. This step requires specialist input from the fields of botany, ecology and invasion biology. In continuing the selection process, the third step considers the physiological characteristics of species identified thus far, as indicators of potential efficacy in remediation initiatives. Here collaboration with specialists such as ecologists, invasion biologists, soil scientists and environmental scientists is crucial to account for complex interactions with resident biota, ecosystem dynamism as well as potential invasiveness, due to rapid growth and vegetative expansion, hardiness and disease and pest resistance – all desired traits for phytoremediation. The penultimate step, largely aided by the botanist and ecologist, assesses the morphological traits of potential species as indicators for remediation. Similar to plant physiology, the desired morphological traits vary according to ecosystem conditions and the pollutant of concern, with heavy metal accumulators markedly different in biomass as opposed to nutrient phytoextractors. Finally, with species thoroughly assessed, the phyto-guide process seeks to include a combination of effective and less effective species to stimulate an appealing, biodiverse and sustainable system, requiring input from urban planning and landscape architecture to achieve GI heterogeneity and aesthetics. In concluding the process, collaboration with all specialists is sought, achieving planning interdisciplinarity for effective yet sustainable GI solutions.

Identifying South African phytoremediators from literature

In assessing potential phytoremediator species for use in site-specific GI projects, the most valuable source of information at the engineer's disposal is available literature on the topic of bioremediation. The scope of available published global bioremediation literature in the form of peer-reviewed articles, books, reports, case studies, conference proceedings, theses and dissertations, as well as online databases, allows for the identification of proven efficient phytoremediators and their associated pollutants for use in GI. This dataset continuously grows and is refined with the addition of new evidence, allowing more reliable assessment of the capabilities of potential phytoremediators.

For this reason, the initial step of the phyto-guide framework requires the responsible engineer to perform a literature investigation of previously reported findings, accessible from scholarly literature sources across an array of published formats and disciplines, as well as compiled online databases (Famulari, 2011; CMLR, 2017). Species classified as less efficient phytoremediators, although undesirable based on remediation efficiency, are not rejected for use as they may contribute to the system's heterogeneity and aesthetics, promoting GI diversity. In a concurrent study exploring potential Western Cape (South Africa) plant species for polluted water and soil phytoremediation, the authors applied the phyto-guide and successfully processed data from 800 literature sources and 2 online databases. At the time of writing, the database had recorded 4 171 data entries, encompassing 1 410 species from 582 genera with 136 subspecies and variants, with 257 indigenous or naturalised South African species, of which 56 endemic or indigenous species were phytogeographically distributed in the Western Cape; the smaller subset are all non-invasive and of least conservation concern (Jacklin et al., 2021).

Although findings from the literature investigation will potentially supply the phyto-guide user with knowledge of proven phytoremediator species for distribution-, invasiveness- and vulnerability-assessments with regard to the individual recipient site, the phyto-guide's success does not solely rely on this step. For instance, if the user is ill-equipped to initiate a literature investigation, information on efficient phytoremediators is lacking, or if the habitat, environmental or climatic conditions within the recipient site in need of remediation do not support the proposed species, the user may bypass the initial literature investigation and commence with the plant distribution assessment as illustrated (Fig. 1).

Assessing distribution, invasive status and vulnerability to extinction

Due to the risk of native biodiversity loss, species within the recipient habitat can be identified by assessing their phytogeographic distribution and herbarium records from the South African Indigenous Plants Catalogue (SAIPC: Random Harvest, 2020), the International Union for the Conservation of Nature Red List of Threatened Species (IUCN, 2020), the South African National Biodiversity Institute's Red List of South African Plants (SANBI, 2020b) and Plants of Southern Africa (SANBI, 2020a). In addition to evaluating the herbarium records, the aid of conservation specialists who may have a greater understanding of the ecosystem processes within the habitat in need of remediation must be sought.

In the interest of sustainability, species displaying invasiveness, whose introduction may threaten GI longevity, are disregarded by the phyto-guide based on local and international standards, as well as being reported in regional and online databases from the International Invasive Species Compendium (CABI, 2020), the Invasive Species Specialist Group Global Invasive Species Database (ISSG, 2020), the Alien Invasive Plant List for South Africa (AIPLSA, 2019), the National Environmental Management: Biodiversity Act, 2004 – Alien and Invasive Species List (NEM:BA, 2004), the Status of Biological Invasions and their Management in South Africa (Zengeya and Wilson, 2020), Biological Invasions in South Africa (Van Wilgen et al., 2020), the Information Retrieval and Submission System of the Centre of Excellence for Invasion Biology (CIB, 2020) and the South African Plant Invaders Atlas (SAPIA: ARC, 2020). All species listed by NEM:BA under invasive categories 1a, 1b, 2 or 3, as described below, are excluded for use in South African GI technologies. Category 1a stipulates all species for which the person in control must take immediate steps to combat or eradicate the invasive species, with Category 1b enforcing the person in control to contain the invasive species. Category 2 species requires that the individual that carries out the effective control of the invasive within a specified area be in possession of the appropriate permit. Species listed as Category 3 are subject to exemptions and prohibitions as specified by NEM:BA, Act No. 10 of 2004 (RSA, 2004), and may consider registered species occurring in riparian areas for Category 1b management as above. In terms of conservation status, the phyto-guide considers abundant and available species of least conservation concern only, as listed in the South African National Biodiversity Institute's Threatened Species Programme (SANBI, 2020c), and International Union for the Conservation of Nature's Red List of Threatened Species (IUCN, 2020) records.

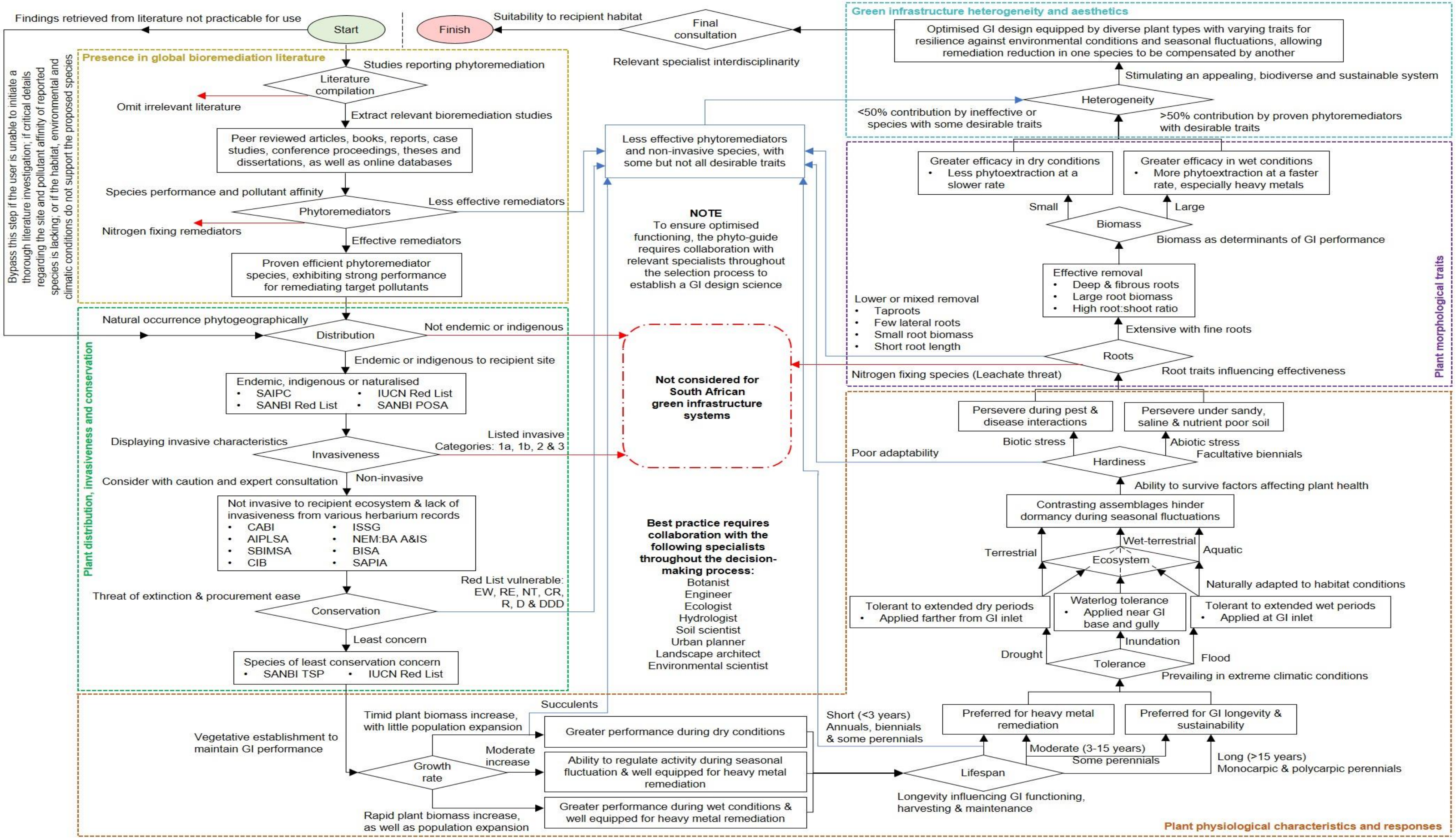


Figure 1. Phyto-guide to species selection for optimized South African green infrastructure, as an aid during planning and design to the practicing civil engineer.

AIPLSA – Alien Invasive Plant List for South Africa; BISA – Biological Invasions in South Africa; CABI – Centre for Agriculture and Bioscience International, International Invasive Species Compendium; CIB – Centre of Excellence for Invasion Biology, Information Retrieval and Submission System; ISSG – Invasive Species Specialist Group, Global Invasive Species Database; IUCN Red List – International Union for Conservation of Nature, Red List; NEM:BA A&IS – National Environmental Management Biodiversity Act, 2004, Alien and Invasive Species List; SAIPC – South African Indigenous Plants Catalogue; SANBI POSA – South African National Biodiversity Institute, Plants of South Africa; SANBI Red List – South African National Biodiversity Institute, Plants of Southern Africa; SANBI TSP – South African National Biodiversity Institute, Threatened Species Programme; SAPIA – South African Plant Invaders Atlas; SBIMSA – Status of Biological Invasions and their Management in South Africa. Species of conservation concern: EW – Extinct in the Wild; RE – Regionally Extinct; NT – Near Threatened; CR – Critically Rare; R – Rare; D – Declining; DDD – Data Deficient.

Evaluating appropriate physiological characteristics

The appropriate growth rate, ability to proliferate and lifespan exhibited by potential species varies with habitat conditions and target pollutants. Species exhibiting rapid growth and population expansion have been found to exhibit greater performance during wet conditions, with species exhibiting low growth and expansion better equipped during dry conditions. For habitats experiencing seasonal climatic fluctuation, species with more moderate growth and expansion are preferred. In addition, species with rapid and moderate growth rate, with longer lifespans such as some monocarpic and polycarpic plants, support GI sustainability and longevity, whereas plants with a rapid growth rate and shorter lifespan, such as annuals, biennials and some perennials, reach maturity faster and are preferred for toxic heavy metal accumulation. Exposing hyperaccumulating plants to toxic pollutants will result in plant mortality. If the objective of the GI project is to establish a community, the phyto-guide attempts to include a combination of growth rates and lifespans for strengthening diversity, with rapidly maturing, longer-lived species an attractive option for promoting vegetative establishment of new GI systems, whilst the shorter-lived metal-accumulating species require a harvesting and removal maintenance plan, before the extracted toxins are deposited back into the system after plant mortality. In the absence of heavy metal pollution, annuals are not considered effective phytoremediators, with slow-growing succulents only contributing to GI in diversity and heterogeneity.

Performance in extreme climatic and habitat conditions, as well as prevalence under biotic and abiotic stress, is evaluated by assessing species' tolerance to sustained periods of drought and inundation, rhizospheric change with increased salinity, poor nutrient and sandy media, and resistance to pests and diseases. Species accustomed to waterlogged roots are expected to proliferate at or near the GI inlet or base, as these areas are prone to saturation, with areas further away or upslope from the saturated zone drier, and plant selection as well as planting location must reflect this distinction between terrestrial, wet-terrestrial and aquatic species affinity. The phyto-guide includes species' natural growth environments, where their ability to thrive in specific habitat conditions provides a rationale for assuming adaptability to various climatically and nutritionally challenging sites, supporting candidates less susceptible to stress. For instance, certain metal hyperaccumulators thrive in heavily contaminated environments which others would find too harsh, inferring their use as resilient species in harsh conditions.

Morphological traits as performance indicators

In assessing morphological traits for potentially novel phytoremediators, species displaying extensive root systems with deep and fibrous roots, a large root biomass and a high root:shoot ratio provide contact with the pollutants in the rhizosphere, improving remediation efficiency, and are favoured for use. Highly fibrous roots within the rhizosphere growth media, where pollutant interaction occurs, support large microbial communities which promote pollutant degradation, uptake and ultimate extraction by the root system. Species with inefficient root systems, i.e., taproots and few lateral roots, small root biomass and short root length, do not notably aid in establishing new GI systems but will contribute to remediation efficiency with time, as differences in root biomass among species are diminished as plants mature and GI longevity is improved by taproots hindering clogging. The phyto-guide avoids nitrogen-fixing species due to a potential nitrogen saturation threat (Payne et al., 2015). In addition to plant roots, the phyto-guide assesses plant biomass as another morphological indicator of phytoremediation capacity. Species with a large total biomass, recognized for their intense phytoextraction capabilities and rapid growth with large root masses, possess greater efficacy in wet conditions, especially for the remediation of heavy metals. Species with slower growth, low above-ground plant biomass and reduced leaf mass exhibit a lower phytoextraction rate and are better performers during dry conditions. This relationship between morphology and habitat further enhances the need for heterogeneity, with diverse root structures, including grasses, sedges, rushes, shrubs and, to a lesser extent, trees, increasing GI diversity.

Optimizing GI through heterogeneity

In concluding the phyto-guide selection process, species identified as proven phytoremediators, with relevant distribution and behaviour, and appropriate physiological characteristics and morphological traits, are recommended to comprise at least 50% of GI projects, with the less effective remediator species with some desirable traits comprising less than 50% (Oversby et al., 2014). This strategy maintains treatment efficiency whilst diversifying plant types with varying traits for resilience against environmental conditions and seasonal fluctuations, allowing low ability for remediation in one species, as well as periodic dormancy during seasonal change to be compensated by another. The addition of species temporarily omitted due to absence of evidence as effective phytoremediators from literature, threat of extinction, poor adaptability to stress, short lifespan and timid root traits, will contribute to GI's runoff infiltration capacity, sustainability and success by supporting local biodiversity and aesthetics. The use of both effective phytoremediators with desirable traits and ineffective phytoremediators with less desirable traits stimulates a diverse, efficient and visually appealing system, for individual site-specific conditions.

During the phyto-guide decision-making process, the practicing engineer assessing plants for potential introduction in GI is required to consult and collaborate with relevant specialists in environmental science, field botany, conservation ecology, soil science, and landscape architecture, if aesthetic enhancement and phytoremediation is to be achieved. Although potential species are identified by investigating their phytogeographic distribution, invasiveness and vulnerability from herbarium records, input from specialists is crucial for the creation of GI design science for the phyto-guide's success, as indigenous non-invasive species may become invasive with introduction, or as conditions change. For instance, proposed species may still be of conservation concern to the specific habitat requiring remediation, as their introduction may disrupt natural complex and dynamic interactions.

CONCLUSIONS

Anthropogenic pollution of South Africa's resources has the ability to alter entire natural ecosystems, leading to degradation, and posing a major ecological engineering problem. GI offers a sustainable yet cost-effective treatment technology with plant choice having a substantial influence on treatment capacity and hydrological conditions. In South Africa, civil engineers are frequently tasked with selecting and designing appropriate GI, while often lacking expertise in plant behaviour and ecosystem dynamics.

The phyto-guide proposed here provides a decision framework for the practicing engineer to facilitate and enhance species selection during planning and design, for the consistent optimization and functioning of sustainable GI technologies. In considering factors associated with vegetative efficacy and consultation with a range of relevant specialists to avoid erroneous species selection, the phyto-guide adopts interdisciplinarity as a fundamental principle, in order to establish an overarching planning approach for GI design science. Factors determining appropriate selection for optimized GI were species presence in global phytoremediation literature, their distribution, invasiveness and vulnerability, physiological characteristics, morphological traits, and heterogeneity and aesthetics, coupled with specialist collaborative input to develop a strategy reflecting recipient habitat conditions. The phyto-guide considers factors influencing remediation efficiency and sustainability as equally important contributors to successful optimization and, although relevant to all GI, demonstrated the selection process within the South African context.

The phyto-guide promotes proven non-invasive indigenous South African phytoremediators of least conservation concern, inhabiting terrestrial or aquatic ecosystems, exhibiting appropriate plant growth, population expansion and tolerance to climatic and environmental conditions, with biomass and root characteristics as contributors to GI success. Selected proven effective phytoremediation species with desirable traits are recommended to occupy greater than 50% of the GI, with less effective phytoremediators and species containing some but not all desirable traits contributing less than 50%. The combination of proven effective and ineffective species improves heterogeneity, diversifying plant types, behaviour and characteristics, equipping GI with resilience against a range of climatic conditions, allowing dormancy in one species to be compensated by another. The less desirable species with regard to phytoremediation efficiency contribute to GI sustainability and success by supporting local biodiversity and aesthetics, and stimulating a diverse and visually appealing system. In concluding the phyto-guide decision-making process, final consultation should include the following experts: wastewater and stormwater engineers, hydrologists, town and regional planners, disaster management practitioners, ecologists and soil scientists, environmental and municipal managers, and landscape architects.

Furthermore, the spread of IAPs causes a major environmental problem, jeopardising the recipient ecosystem and impairing the functioning of intricately designed GI. South Africa has a long history of alien invasion, with some species having transformed entire natural ecosystems, threatening the country's biodiversity and negatively impacting the ecosystem's capacity to deliver goods and services. Species promoted for use in GI may still be of conservation concern to the ecosystem requiring remediation, due to ecosystem dynamism, habitat processes, climate change, and prevailing environmental conditions. With the physiological characteristics contributing to efficient phytoremediation shared with potential invasiveness in ecosystems, e.g., rapid growth and vegetative expansion, hardiness and disease and pest resistance, as well as their complex interactions with resident biota, selected species may contribute to invasiveness. Thus, the desire to optimize GI technologies by introducing plant species for remediation cannot overshadow conservation. Failing to consider invasion threat during the planning and design process of both urban and rural GI remediation initiatives may lead to creating an artificial or altered environment in which alien species thrive, as urban areas are often the initial sites for introduction from which invasions spread. Due to the country's rich biodiversity, future projects must engage in studies of endemic South African plants as potential phytoremediators to minimize the potential invasive threat.

ACKNOWLEDGEMENTS

This research was funded by the National Research Foundation (NRF) Thuthuka Fund, with project identity: TTK180418322426.

REFERENCES

AHERN J (2007) Green infrastructure for cities: the spatial dimension. In: Novotny V and Brown P (eds) *Cities of the Future: Towards Integrated Sustainable Water and Landscape Management.* IWA Publishing, London.

AIPLSA (2019) Alien Invasive Plants List for South Africa, South Africa's national listed invasive species. URL: https://www.environment.co.za/weeds-invaders-alien-vegetation/alien-invasive-plants-list-for-south-africa.html (Accessed 15 July 2020).

ARC (Agricultural Research Council, South Africa (2020) South African Plant Invaders Atlas (SAPIA), Agricultural Research Council: Weeds and Invasive Plants. URL: http://www.arc.agric.za/arc-ppri/weeds/ (Accessed 15 July 2020).

ARMITAGE N, FISHER-JEFFES L, CARDEN K, WINTER K, NAIDOO V, SPIEGEL A, MAUCK B and COULSON D (2014) Water sensitive urban design (WSUD) for South Africa:

Framework and guidelines. WRC Report No. TT 588/14. Water Research Commission, Pretoria.

ARVE LE, TORRE S, OLSEN JE and TANINO KK (2011) Stomatal responses to drought stress and air humidity. In: Shanker A and Venkateswarlu B (eds) *Abiotic Stress In Plants – Mechanisms and Adaptations*. InTech Publishers, Rijeka.

BARBIER E, ACREMAN M and KNOWLER D (1997) *Economic Valuation of Wetlands: A Guide for Decision-Makers and Planners.* Ramsar Convention, Gland.

BRINK IC (2019) Small-scale dispersed green infrastructure – a fitting civil engineering solution to stormwater quality improvement? *J. S. Afr. Inst. Civ. Eng.* **61** (4) 42–49. https://doi.org/10.17159/2309-8775/2019/v61n4a4

BUDELSKY R and GALATOWITSCH S (2004) Establishment of *Carex stricta* Lam. seedlings in experimental wetlands with implications for restoration. *Plant Ecol.* **175** (1) 91–105. https://doi.org/10.1023/B:VEGE.0000048102.72101.50

CABI (2020) Centre for Agriculture and Bioscience, International Invasive Species Compendium. URL: https://www.cabi.org/ISC (Accessed 20 July 2020).

CHOUDHARY MP, CHAUHAN GS and KUSHWAH YK (2015) Environmental degradation: causes, impacts and mitigation. In: *National Seminar on Recent Advancements in Protection of Environment and Its Management Issues*, February 2015, Rajasthan.

CIB (2020) Centre of Excellence for Invasion Biology, DSI-NRF Information Retrieval and Submission System. URL: https://ir.sun.ac.za/cib/community-list (Accessed 16 July 2020).

CMLR (2017) Centre for Mined Land Rehabilitation, Global Hyperaccumulator Database. URL: http://hyperaccumulators.smi.uq.edu.au/collection/ (Accessed 15 March 2020).

COLE LB, MCPHEARSON T, HERZOG CP and RUSS A (2017) Green infrastructure. In: Russ A and Krasny ME (eds) *Urban Environmental Education Review.* Cornell University Press, New York. https://doi.org/10.7591/cornell/9781501705823.003.0028

CONESA HM, MORADI AB, ROBINSON BH, KÜHNE G, LEHMANN E and SCHULIN R (2009) Response of native grasses and *Cicer arietinum* to soil polluted with mining wastes: implications for the management of land adjacent to mine sites. *Environ. Exp. Bot.* **65** (2–3) 198–204. https://doi.org/10.1016/j.envexpbot.2008.09.004

CONSTANTINE M, MUSINGAFI C and TOM T (2014) Fresh water sources pollution: A human related threat to fresh water security in South Africa. *J. Public Polic. Gov.* **1** (2) 72–81.

CULWICK C, BOBBINS K, CARTWRIGHT A, OELOFSE G, MANDER M and DUNSMORE S (2016) A framework for a green infrastructure planning approach in the Gauteng City-Region. Volume No. 04. Gauteng City-Region Observatory, Johannesburg.

DAVIS AP, HUNT WF, TRAVER RG and CLAR M (2009) Bioretention technology: overview of current practice and future needs. *J. Environ. Eng.* **135** (3) 109–117. https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(109)

DE KLERK AR, OBERHOLSTER PJ, VAN WYK JH, TRUTER JC, SCHAEFER LM and BOTHA AM (2016) The effect of rehabilitation measures on ecological infrastructure in response to acid mine drainage from coal mining. *Ecol. Eng.* **95** 463–474. https://doi.org/10.1016/j.ecoleng.2016.06.070

DENMAN L, MAY PB and BREEN PF (2006) An investigation of the potential to use street trees and their root zone soils to remove nitrogen from urban stormwater. *Australas. J. Water Resour.* **10** (3) 303–311. https://doi.org/10.1080/13241583.2006.11465306

DIETZ AC and SCHNOOR JL (2001) Advances in phytoremediation. *Environ. Health Perspect.* **109** 163–168. https://doi.org/10.1289/ehp.01109s1163

FAMULARI S (2011) The Phytoremediation Plant Index. URL: http://www.steviefamulari.net/phytoremediation/index.php (Accessed 17 March 2020).

FARRELL C, SZOTA C, WILLIAMS NSG and ARNDT SK (2013) High water users can be drought tolerant: using physiological traits for green roof plant selection. *Plant Soil* **372** (1–2) 177–193. https://doi.org/10.1007/s11104-013-1725-x

GHOSH M and SINGH SP (2005) A comparative study of cadmium phytoextraction by accumulator and weed species. *Environ. Pollut.* **133** (2) 365–371. https://doi.org/10.1016/j.envpol.2004.05.015

GOVENDER T, BARNES JM and PIEPER CH (2011) Contribution of water pollution from inadequate sanitation and housing quality to diarrheal disease in low-cost housing settlements of Cape Town, South Africa. *Am. J. Public Health* **101** (7) 4–9. https://doi.org/10.2105/AJPH.2010.300107

HATT BE, FLETCHER TD and DELETIC A (2009) Hydrologic and pollutant removal performance of stromwater bofiltration systems at the field scale. *J. Hydrol.* **365** 310–321. https://doi.org/10.1016/j.jhydrol.2008.12.001

HENDERSON C, GREENWAY M and PHILLIPS I (2007) Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms. *Water Sci. Technol.* **55** (4) 183–191. https://doi.org/10.2166/wst.2007.108

HUFNAGEL C and ROTTLE N (2014) Introduction and overview. In: *Selecting Green Infrastructure Stormwater Controls.* Water Environment Federation, Alexandria.

ISSG (Invasive Species Specialist Group) (2020) Global Invasive Species Database. URL: http://www.issg.org/ (Accessed 20 July 2020).

IUCN (International Union for Conservation of Nature) (2020) Red List of Threatened Species. URL: https://www.iucnredlist.org/ (Accessed 17 July 2020).

JACKLIN DM, BRINK IC and JACOBS SM (2021) Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators with a focus on green infrastructure. *Water SA* **47** (3) 317–325.

KITHA J and LYTH A (2011) Urban wildscapes and green spaces in Mombasa and their potential contribution to climate change adaptation and mitigation. *Enviro. Urbanization* **23** (1) 251–265. https://doi.org/10.1177/0956247810396054

LE MAITRE DC, O'FARRELL PJ and REYERS B (2007) Ecosystems services in South Africa: A research theme that can engage environmental, economic and social scientists in the development of sustainability science? *S. Afr. J. Sci.* **103** (9–10) 367–376.

LEGUIZAMO MAO, GOMEZ WDF and SARMIENTO MCG (2017) Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands — A review. *Chemosphere* **168** 1230–1247. https://doi.org/10.1016/j.chemosphere.2016.10.075

MALAN M, MÜLLER F, CYSTER L, RAITT L and AALBERS J (2015) Heavy metals in the irrigation water, soils and vegetables in the Philippi horticultural area in the Western Cape Province of South Africa. *Environ. Monit. Assess.* **187** (1) 1–8. https://doi.org/10.1007/s10661-014-4085-y

MCGRATH SP and ZHAO FJ (2003) Phytoextraction of metals and metalloids from contaminated soils. *Curr. Opin. Biotechnol.* **14** (3) 277–282. https://doi.org/10.1016/S0958-1669(03)00060-0

MEAGHER RB (2000) Phytoremediation of toxic elemental and organic pollutants. *Curr. Opin. Plant Biol.* **3** (2) 153–162. https://doi.org/10.1016/S1369-5266(99)00054-0

MONTES C, RENDÓN-MARTOS M, VARELA L and CAPPA M (2007) Mediterranean wetland restoration manual. Ministry of Environment, Seville.

NOMQUPHU W, BRAUNE E and MITCHELL S (2007) The changing water resources monitoring environment in South Africa. *S. Afr. J. Sci.* **103** (7–8) 306–310.

OBERHOLSTER PJ and ASHTON PJ (2008) State of the nation report: An overview of the current status of water quality and eutrophication in South African rivers and reservoirs. Council for Scientific and Industrial Research (CSIR), Pretoria.

OVERSBY B, PAYNE EGI, FLETCHER TD, BYLEVELD G and HATT BE (2014) Vegetation guidelines for stormwater biofilters in the south-west of Western Australia. Water for Liveability Centre, Melbourne.

PASQUINI L and ENQVIST JP (2019) Green infrastructure in South African cities. Report for CSP, African Centre for Cities, National Treasury, South Africa.

PAULEIT S, HANSEN R, RALL EL, ZÖLCH T, ANDERSSON E, LUZ AC, SZARAZ L, TOSICS I and VIERIKKO K (2017) Urban landscapes and green infrastructure. In: Shugart (ed.) *Oxford Research Encyclopedia of Environmental Science*. Oxford University Press, New York. https://doi.org/10.1093/acrefore/9780199389414.013.23

PAYNE EGI, HATT BE, DELETIC A, DOBBIE MF, MCCARTHY DT and CHANDRASENA GI (2015) Adoption guidelines for stormwater biofiltration systems – summary report. Cooperative Research Centre for Water Sensitive Cities, Melbourne.

PEUKE AD and RENNENBERG H (2006) Heavy metal resistance and phytoremediation with transgenic trees. In: Fladung M and Ewald D (eds) *Tree Transgenesis.* 137–155. Springer, Berlin. https://doi.org/10.1007/3-540-32199-3_7

POSTEL SL and THOMPSON BH (2005) Watershed protection: Capturing the benefits of nature's water supply services. *Nat. Resour. For.* **29** (2) 98–108. https://doi.org/10.1111/j.1477-8947.2005.00119.x

PRASAD MNV (2004) Phytoremediation of metals in the environment for sustainable development. *Proc. Indian Natl Sci. Acad.* **71** (1) 71–98.

RANDOM HARVEST (2020) South African Indigenous Plant Catalogue (SAIPC). URL: https://www.randomharvest.co.za/South-African-Indigenous-Plants (Accessed 20 July 2020).

READ J, WEVILL T, FLETCHER TD and DELETIC A (2008) Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Res.* **42** (4–5) 893–902. https://doi.org/10.1016/j.watres.2007.08.036

READ J, FLETCHER TD, WEVILL T and DELETIC A (2010) Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *Int. J. Phytoremed.* **12** (1) 34–53. https://doi.org/10.1080/15226510902767114

RICHARDSON DM, FOXCROFT LC, LATOMBE G, LE MAITRE DC, ROUGET M and WILSON JR (2020) The biogeography of South African terrestrial plant invasions. In: Van Wilgen BW, Measey J, Richardson DM, Wilson JR and Zengeya TA (eds.) *Biological Invasions in South Africa.* Springer, Cham. https://doi.org/10.1007/978-3-030-32394-3_3

ROBINSON BH, ANDERSON CWN and DICKINSON NM (2015) Phytoextraction: Where's the action? *J. Geochem. Explor.* **151** 34–40. https://doi.org/10.1016/j.gexplo.2015.01.001

ROCA M, ESCARAMEIA M, GIMENO O, DE VILDER L, SIMM JD, HORTON B and THORNE C (2017) *Green Approaches In River Engineering – Supporting Implementation of Green Infrastructure*. HR Wallingford, Oxfordshire.

RODRÍGUEZ-ECHEVERRÍA S (2009) Soil organisms: the invisible dimension in the invasion by exotic plant species. *Ecosistemas* **18** (2) 32–43.

RSA (Republic of South Africa) (2004) National Environmental Management: Biodiversity Act (No. 10 of 2004). Department of Environmental Affairs (DEA), Pretoria.

SALT DE, SMITH RD and RASKIN I (1998) Phytoremediation*. Annu. Rev. Plant Physiol. Plant Molec. Biol.* **49** (1) 643–668. https://doi.org/10.1146/annurev.arplant.49.1.643

SANBI (South African National Biodiversity Institute) (2020a) Plants of Southern Africa. URL: http://posa.sanbi.org/sanbi/Explore (Accessed 15 July 2020).

SANBI (South African National Biodiversity Institute) (2020b) Red List of South African Plants. URL: http://redlist.sanbi.org/ (Accessed 15 July 2020).

SANBI (South African National Biodiversity Institute) (2020c) South African National Biodiversity Institute, Threatened Species Programme. URL: https://www.inaturalist.org/projects/redlist-s-afr (Accessed 15 July 2020).

TANNER P and MÖHR-SWART M (2007) Guidelines for the rehabilitation of mined land. *Chamber of Mines of South Africa/Coal Tech*, Johannesburg.

TERRY N and BAÑUELOS GS (1999) *Phytoremediation of Contaminated Soil and Water*. CRC Press, Boca Raton.

VISOOTTIVISETH P, FRANCESCONI K and SRIDOKCHAN W (2002) The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environ. Pollut.* **118** (3) 453–461. https://doi.org/10.1016/S0269-7491(01)00293-7

VAN WILGEN BW, RICHARDSON DM, LE MAITRE DC, MARAIS C and MAGADLELA D (2001) The economic consequences of alien plant invasions: examples of impacts and approaches to sustainable management in South Africa. *Environ. Dev. Sustainability* **3** (2) 145–168. https://doi.org/10.1023/A:1011668417953

VAN WILGEN BW, MEASEY J, RICHARDSON DM, WILSON JR and ZENGEYA TA (2020) Biological invasions in South Africa: an overview. In: Van Wilgen BW, Measey J, Richardson DM, Wilson JR and Zengeya TA (eds.) *Biological Invasions in South Africa*. Springer, Cham. https://doi.org/10.1007/978-3-030-32394-3

WERTZ-KANOUNNIKOFF S, LOCATELLI B, WUNDER S and BROCKHAUS M (2011) Ecosystem-based adaptation to climate change: What scope for payments for environmental services? *Clim. Dev.* **3** (2) 143–158. https://doi.org/10.1080/17565529.2011.582277

WIRTH P, CHANG J, SYRBE RU, WENDE W and HU T (2018) Green infrastructure: a planning concept for the urban transformation of former coal-mining cities. *Int. J. Coal Sci. Technol.* **5** (1) 78–91. https://doi.org/10.1007/s40789-018-0200-y

WONG THF (2006) Australian runoff quality: a guide to water sensitive urban design. National Committee on Water Engineering, New South Wales.

YANG B, LI S, WALL HA, BLACKMORE P and WANG Z (2015) Green infrastructure design for improving stormwater quality: Daybreak community in the United States West. *Landscape Architect. Front.* **3** (4) 12-22.

ZENGEYA TA and WILSON JR (2020) The status of biological invasions and their management in South Africa in 2019. (Second order draft). South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.

CHAPTER 4

Urban stormwater nutrient and metal removal in small-scale green infrastructure: Exploring engineered plant biofilter media optimisation

This chapter addresses research objective 3 by experimentally assessing ten engineered media combinations exposed to typically observed nutrient and heavy metal pollution, for use as biofilter growth media. Different growth media combinations are evaluated according to their pollutant removal, infiltration, and particulate deposition capabilities, as well as supporting plant growth.

This chapter seeks to contribute to improved growth media performance in urban stormwater biofilters by understanding the influence of relative media proportions on factors affecting biofilter efficacy, sustainability and longevity. Although biofilters have shown promising results for the on-site reduction of peak flows and removal of pollutants, a distinct disadvantage is that it naturally deteriorates and clogs with time. Inadequately functioning growth media, a common cause of ineffective or failed systems, results in overflows, extended ponding time, increased particulate discharge, plant mortality and reduced pollutant removal performance, particularly for heavy metals and nitrate. In addition, to enhance the feasibility and cost-efficiency of biofilter initiatives, it is imperative that the use of locally sourced media be preferred. It is for these reasons that growth media is considered an essential contributor to performance and sustainability, thus, a crucial factor when designing intricate urban stormwater biofilter technologies. To achieve optimisation in stormwater biofilters through the improvement of various underperforming and unsatisfactory facets of a biofilter, adequately functioning growth media is required.

Therefore, the introduction of engineered media such as perlite, vermiculite, zeolite and attapulgite, in combination with loamy sand as a carbon source, was evaluated in an unvegetated column experiment exposed to synthetic stormwater for improved performance. In addition, it is important to not only optimise treatment but also consider media's effect on plant health and vitality, due to the significant role of plants influencing biofilter performance.

All engineered media outperformed traditional loamy sand across criteria, with engineered attapulgite consistently among the best performers. No reportable difference existed in vegetation exposed to different material combinations, although all vegetated biofilters showed increased pollutant removal, emphasizing its importance in biofilters, further investigated in chapter 5. The findings of this investigation provided the basis from which to improve urban stormwater biofilter design and is incorporated in various quantities and locations, chapter 6, objective 5, for sequential pollutant-specific targeted removal, in an effort to optimise design. Appropriate growth media encourages small-scale GI in the spatially limited urban area.

Urban stormwater nutrient and metal removal in small-scale green infrastructure: Exploring engineered plant biofilter media optimisation

DM Jacklin[a], IC Brink[a], SM Jacobs[b]

[a]*Department of Water and Environmental Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

[b]*Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

Reproduced and reformatted from an article published in **Water Science and Technology, 84(7), 1715-1731**, with permission from the copyright holder, IWA Publishing.

Abstract

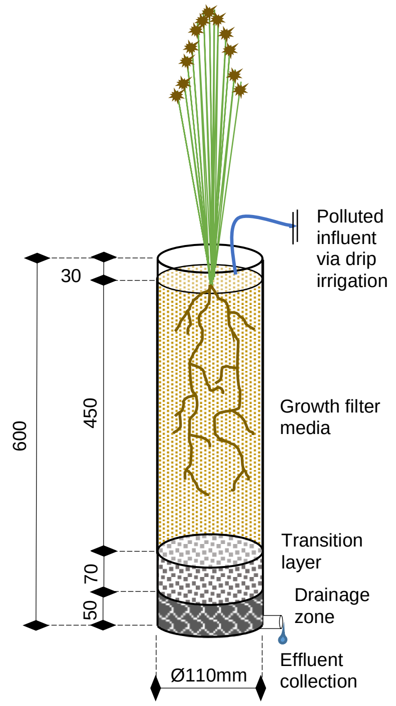
The present study evaluated engineered media for plant biofilter optimisation in an unvegetated column experiment to assess the performance of loamy sand, perlite, vermiculite, zeolite and attapulgite media under stormwater conditions enriched with varying nutrients and metals reflecting urban pollutant loads. Sixty columns, 30 unvegetated and 30 *Juncus effusus* vegetated, were used to test: pollutant removal, infiltration rate, particulate discharge, effluent clarity and plant functional response, over six sampling rounds. All engineered media outperformed conventional loamy sand across criteria, with engineered attapulgite consistently among the best performers. No reportable difference existed in vegetation exposed to different material combinations. For all media, the results show a net removal of NH_3 -N, PO_4^{3-} -P, Cd, Cu, Pb and Zn and an increase of NO_3^- -N, emphasizing the importance of vegetation in biofilters. Growth media supporting increased rate of infiltration whilst maintaining effective remediation performance offers potential for reducing the area required by biofilters, currently recommended at 2% of its catchment area, encouraging the use of small-scale green infrastructure in the urban area. Further research is required to assess the carrying capacity of engineered media in laboratory and field settings, particularly during seasonal change, gauging the substrate's potential moisture availability for root uptake.

Key words: biofiltration, ecological engineering, engineered media, green infrastructure, stormwater

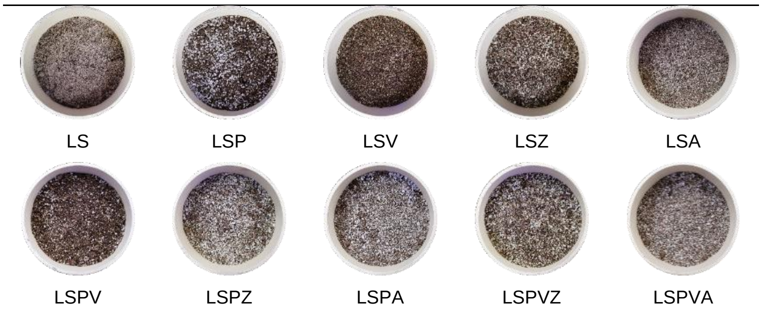
Highlights

- The first study to investigate urban pollutant removal by attapulgite in urban stormwater biofilters.
- Consistent ammonia, orthophosphate and metal removal.
- Time-lapse photographic captures of sediment discharge in new biofilters.
- Infiltration rate enhanced while pollutant removal performance was maintained.

GRAPHICAL ABSTRACT



Identifier	Representative media	Infiltration
LS	Loamy sand	112 mm/hr
LSP	Loamy sand + Perlite	125 mm/hr
LSV	Loamy sand + Vermiculite	121 mm/hr
LSZ	Loamy sand + Zeolite	147 mm/hr
LSA	Loamy sand + Attapulgite	162 mm/hr
LSPV	Loamy sand + Perlite + Vermiculite	170 mm/hr
LSPZ	Loamy sand + Perlite + Zeolite	179 mm/hr
LSPA	Loamy sand + Perlite + Attapulgite	202 mm/hr
LSPVZ	Loamy sand + Perlite + Vermiculite + Zeolite	212 mm/hr
LSPVA	Loamy sand + Perlite + Vermiculite + Attapulgite	218 mm/hr



INTRODUCTION

Pollution associated with increasing urbanisation impacts both human and environmental health (McGrane 2016). Stormwater runoff from impermeable and semi-permeable areas in urban centres such as parking lots, sidewalks and rooftops have resulted in larger peak flows, flow volumes and pollutant loads that are typically discharged into urban surface waters (Fletcher *et al.* 2015). This increases the ecotoxicity risk on surface- and groundwater (Gosset *et al.* 2017), thereby threatening entire aquatic ecosystems, posing a drainage challenge to urban water engineers (Brudler *et al.* 2019).

Plant biofiltration, a Green Infrastructure (GI) technology, is an ecologically acceptable method for urban stormwater management and have shown promising results for the on-site reduction of peak flows, removal of environmental contaminants and protection of urban waters (Armitage *et al.* 2014). From a technical perspective, plant biofilters can be easily introduced into the urban landscape, with small-scale biofilters best applied in dense built-up areas and large-scale biofilters most effective at distinct stormwater network confluences (Le Coustumer *et al.* 2012).

It has, however, been found that a distinct disadvantage of plant biofilter performance is that it can deteriorate over time, leading to more frequent overflows, extended ponding time, increased particulate discharge and reduced pollutant treatment particularly for heavy metals and nitrate (Al-Ameri *et al.* 2018; Le Coustumer *et al.* 2009). Incorrect media selection is a common cause of poorly functioning or failed systems, resulting in leaching, channel clogging and plant mortality (Payne *et al.* 2015). Furthermore, inadequately functioning growth media negates intricate planning and design, which considers plant and media selection as essential contributors to performance and sustainability (Le Coustumer *et al.* 2012). Media selection has therefore been indicated to be a very important design element in plant biofiltration technologies.

In an effort to optimise plant biofilters, the introduction of engineered growth media such as zeolite (see Li *et al.* 2014), perlite (see Le Coustumer *et al.* 2012) and vermiculite (see Li *et al.* 2018) in combination with traditional loamy sand as a carbon source (see Bratieres *et al.* 2008) may potentially increase stormwater remediation efficacy and biofilter longevity (Chandrasena *et al.* 2017). It is therefore important to not only optimise growth media, but also to consider the effects of the media on plant health and vitality (Malézieux *et al.* 2007).

Loamy sand, typically used as growth media, with a low nutrient content, is effective for the remediation of certain stormwater pollutants (Milandri *et al.* 2012). Although it provides adequate support for plant growth, it frequently is lacking in preventing pathogen, heavy metal and nutrient (particularly nitrate) leachate (Hsieh & Davis 2003). Perlite and vermiculite are capable of adsorbing both organic and inorganic substances and are often used in stormwater management systems as filtration and anti-clogging media (Hashem *et al.* 2015). For the removal of heavy metals vermiculite is better equipped due to its cation exchange capacity (Hatt *et al.* 2007). In removing nutrients, the use of perlite or vermiculite in isolation is inadequate due to the prevalence of nutrient leachate (Prodanovic *et al.* 2018). Zeolites are environmentally and economically acceptable hydrated materials with effective ion-exchange, sorption and acid catalysis properties and are well known to remove organic and inorganic pollutants (Chmielewská 2015). For some pollutants however it has been inconsistent, with pathogen and heavy metal removal inefficiencies reported (Mamba *et al.* 2009). Attapulgite, with its high adsorption capacity, porous structure, high surface area and cation exchange capacity offers potential as growth media to biofilters (Zhang *et al.* 2015). It is inexpensive and has been reported to show great potential in practical environmental remediation (Tichapondwa & Van Biljon 2019). Although overlooked for implementation in biofilters, this material offers a possible alternative to conventional ineffective media, specifically for the remediation of nutrient and heavy metal pollutants.

A need for research relating to a clear delineation of relative media proportions to use, as well as how different combinations would affect remediation performance, plant stress, infiltration capacity, particulate transport and longevity has been suggested in literature (see Prodanovic *et al.* 2018). Additionally, research on the evaluation of nanocomposite attapulgite for use in biofilters is warranted (Wang *et al.* 2018). Although considerable efforts have been made to assess the role of vegetation in maintaining long term biofilter performance, research into growth media has generally been limited, with typical investigations focusing predominantly on single use media (Chandrasena *et al.* 2017). Further research into media combinations towards plant biofilter media improvement is therefore required.

This paper presents the results of an exploratory laboratory study on the optimisation of plant biofilter growth media for urban stormwater biofiltration. An experimental approach was used to establish the performance of unvegetated loamy sand, perlite, vermiculite, zeolite and attapulgite media combinations. In an effort to assess plant biofilter success, a secondary investigation evaluated media infiltration and solids discharge in the presence and absence of vegetation. Additionally, plant functional response to media and typically observed urban pollutants were evaluated by assessing the above- and below-ground traits of *Juncus effusus*, irrigated with synthetic stormwater and potable municipal water.

METHODOLOGY

Biofilter design

In order to explore media optimisation, sixty biofilter columns were constructed from Ø110 mm x 600 mm PVC piping, complying with stormwater design guidelines as recommended by Payne *et al. (*2015). Each column included a drainage zone covering the drainage outlet below the transition layer, topped with 450 mm growth filter media of varying combinations to support plant establishment (see Figure 1).

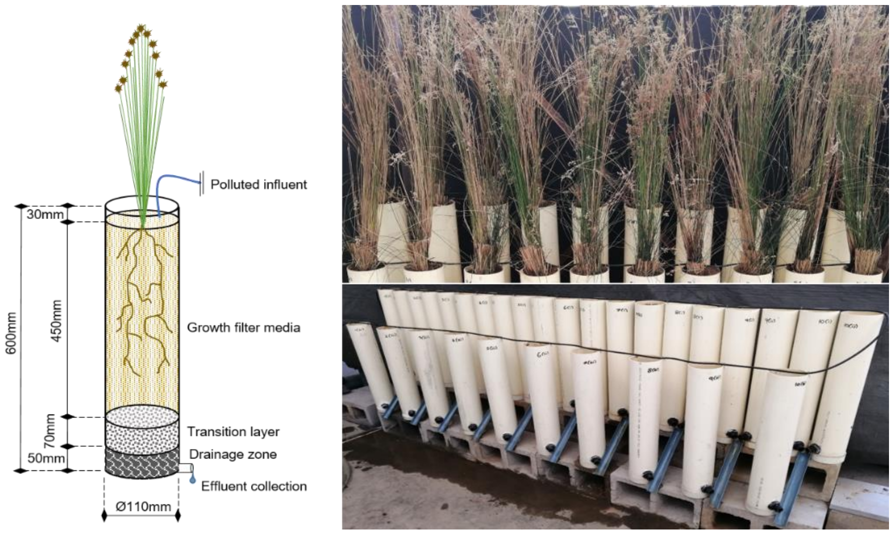


Figure 1. Schematic of experimental biofilter, vegetated *Juncus effusus* and unvegetated columns.

The inner walls of the columns were abraded to minimise preferential flow and sealed at the base, allowing effluent extraction for analyses. Growth media included material at varying ratios, maintaining infiltration rates of 100 - 300 mm/hr at the start of the study, with thirty unvegetated columns assessing the filtration performance of growth media only. Additionally, thirty vegetated columns containing *Juncus effusus* were used to assess plant response to urban pollution, plant stress in varying media, and effect on infiltration and sedimentation. The growth media consisted of varying combinations of loamy sand, perlite, vermiculite, zeolite and attapulgite with particle size distributions with ranges as shown in Table 1 below:

Table 1. Particle size distribution of the material.

Material	Size (mm)	Identifier	Material	Size (mm)	Identifier
Loamy sand	0.05-3.4	LS	Vermiculite	0.5-1.4	VE2
Perlite	1-3	PE	Vermiculite	1.4-4	VE3
Attapulgite	0.5-1.4	AT1	Zeolite	0.8-1.4	ZE1
Attapulgite	1.4-4.5	AT2	Zeolite	1.4-2	ZE2
Vermiculite	0.35-0.5	VE1	Zeolite	2-6	ZE3

The *Juncus effusus* plants were approximately 24 months old and sourced from a local nursery prior to transplantation into the experimental columns. Special care was taken to remove all foreign organic matter and soil from the roots. During transplantation a half strength Hoagland solution was added to all vegetated columns to provide essential nutrients to support growth (see Li & Cheng 2015). Both the vegetated and unvegetated biofilter columns were subjected to twice-weekly watering using municipal tap water for 18 weeks to provide time for plant establishment and natural hydraulic compaction (Read *et al.* 2008). This period was followed by 10 weeks of synthetic dosing to reflect local urban stormwater pollution and runoff events for all the unvegetated columns and half of the vegetated columns. The remaining vegetated columns received municipal tap water, to assess plant functional response to engineered media in the absence of nutrient and metal pollutants.

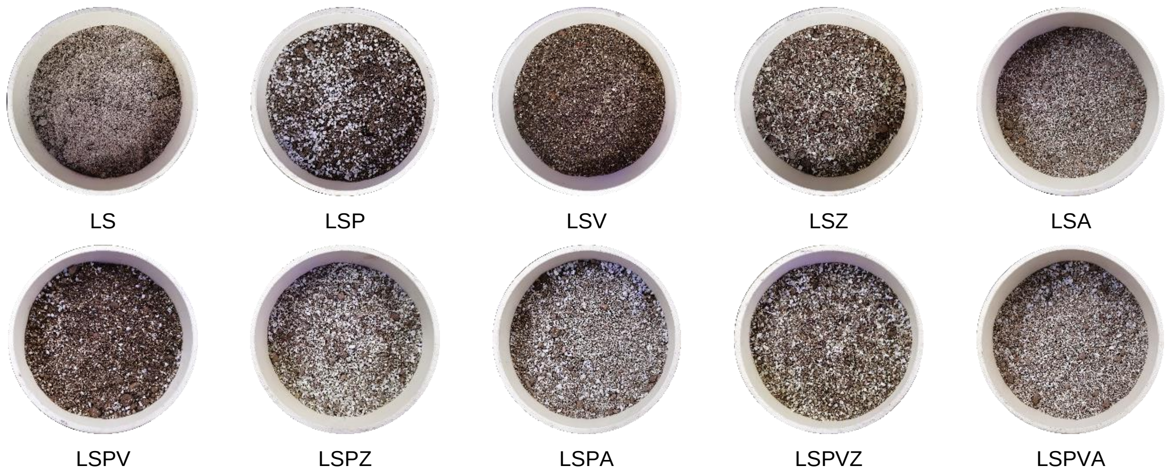
Experimental design

A preliminary investigation of the saturation rate of the media at varying influent volumes was done using clear perspex columns, which allowed visible tracing of the drop in water level. This was used to establish media ratios that were practically capable of maintaining the recommended 100 – 300 mm/hr rate (Payne *et al.* 2015). Previous biofilter studies investigating pollutant removal of engineered media (excluding loamy sand), showed performance to be in the order zeolite>vermiculite>perlite, with attapulgite, effective in pollutant removal from aqueous solutions, overlooked for use in biofilters (Al-Sharify & Athab 2012; Zinger *et al.* 2013; Chandrasena *et al.* 2017; Prodanovic *et al.* 2018; Tichapondwa & Van Biljon 2019).

Therefore, effort was made to implement greater proportions of the most effective material, see Table 2 below. A low initial unvegetated infiltration rate was selected due to vegetation's ability to increase infiltration and decrease clogging (Le Coustumer *et al.* 2012). Ten different media of varying material contributions, supporting rhizospheric conditions and pollutant interaction, whilst encouraging plant growth were evaluated. Three replicates of each growth media was used.

Table 2. Engineered filter media proportions for initial infiltration within 100 – 300 mm/hr range.

Identifier	Representative Media	Contribution (Volume)	Infiltration rate (mm/hr)
LS	LS	1	112
LSP	LS:PE	3:2	125
LSV	LS:VE1:VE2	3:1:1	121
LSZ	LS:ZE1:ZE2	3:1:1	147
LSA	LS:AT1	3:2	162
LSPV	LS:PE:VE1:VE2	6:0.5:1.75:1.75	170
LSPZ	LS:PE:ZE1:ZE2	6:0.5:1.75:1.75	179
LSPA	LS:PE:AT1	6:0.5:3.5	202
*LSPVZ[a]	LS:PE:VE1:VE2:ZE1:ZE2	5:0.5:0.25:0.25:1.75:1.75	212
*LSPVA[b]	LS:PE:VE1:VE2:AT1	5:0.5:0.25:0.25:3.5	218



* Transition layer's coarse sand media exchanged for [a]ZE3 (2-6 mm zeolite) and [b]AT2 (1.4-4.5 mm attapulgite).

For practicality during biofilter construction, the filter material was added as a mixture above the transition layer, as opposed to a layered design. Columns LSPVZ and LSPVA exchanged the normal coarse sand transition layer for coarse zeolite (ZE3) and attapulgite (AT2) respectively, with both offering additional remediation as opposed to filtering fine particles only.

Stormwater dosing and monitoring

Synthetic stormwater was prepared from analytical grade compounds to correspond with local Stellenbosch (South Africa) urban pollutant levels (Rauch & Brink in preparation), as well as global urban water pollutant concentrations as depicted in Table 3 (Göbel *et al.* 2007; Bratieres *et al.* 2008; Barron *et al.* 2019). Synthetic stormwater was continuously mixed in a storage tank to ensure uniform dispersion and irrigated with an automated drip irrigation system, with influent concentrations monitored throughout.

Table 3. Influent pollutant concentrations.

Pollutant	Parameter	Concentration C_i (mg/L)	Source
Nutrients	Ammonia-N	0.40	NH_4Cl
	Nitrate-N	0.95	KNO_3
	Orthophosphate-P	0.35	K_2HPO_4
Metals	Cd	0.0045	$CdCl_2$
	Cu	0.045	$CuSO_4$
	Pb	0.15	$PbCl_2$
	Zn	0.30	$ZnCl_2$

Equation 1 calculated dosage volumes (V_i) to simulate appropriate biofilter influent volumes under impermeable area surface dynamics based on the characteristics of the Stellenbosch urban area (South Africa). The effect of specific watershed conditions on influent concentrations was omitted, thus we considered the rate at which stormwater accumulate pollutants to be uniform across influent. It was attempted to include contributing runoff factors despite the fact that the outcome of this equation may not have been an entirely accurate depiction of runoff. This study was, however, designed to be performed under laboratory conditions in which influent variability was limited rather than, necessarily, to precisely model and scale runoff volumes. Further explanation of reasoning behind included factors is discussed below. This produced a twice-weekly drip dosing per filter setup of 0.63 L, as well as an increased dosing of 9.41 L at 60-day intervals which lasted several hours to simulate average annual rainfall- and intense uninterrupted storm- event volumes respectively, for Ø110 mm biofilter columns in the local urban catchment.

$$V_i = \left(\frac{A_b}{K_a} \text{ x } P\right) \text{ x } K_r \qquad \text{Equation 1}$$

where

V_i = influent dosage volume (L)

A_b = area of biofilter (m^2)

K_a = biofilter percentage of contributing catchment area (%)

P = precipitation event rainfall (mm)

K_r = percentage urban runoff (%)

In urban areas impermeable surfaces increase runoff volume and elevate peak discharge into stormwater biofilters, however, not all rainfall is translated to runoff, with permeable and impermeable infiltration and evapotranspiration reducing runoff flow (Ragab *et al.* 2003 McGrane 2016; Rammal & Berthier 2020). Hence dosage volumes, influenced by the contributing catchment area's extent and type of imperviousness must account for potential runoff losses over site-specific urban surfaces. Fortunately, the integrative nature of imperviousness allows for predicting cumulative water resource impacts, which include the contribution of hydrological changes to runoff volume and nonpoint source pollution, but only if the extent of the contributing catchment area is defined (Schueler 1992).

For Stellenbosch, Musakwa and Van Niekerk (2015) reported a 19% increase in impermeable surface area from 777.6 ha to 925.2 ha in the decade from 2000-2010. Following this trend, we interpolated imperviousness for 2020 to be 1072.9 ha of the total 2475 ha area, amounting to 43.4% of Stellenbosch's area. This level of imperviousness, between 35 and 50%, corresponds with a 30% conversion of precipitation to urban runoff, with the remaining 35, 20 and 15% lost to evapotranspiration, shallow infiltration and deep infiltration respectively (Arnold & Gibbons 1996). In estimating the volume required to reflect typical biofilter inflow, an assessment of typical- and uninterrupted intense Stellenbosch storm events produced an average annual rainfall of 619 mm of which three 66 mm intense rainfall events occur, based on the local climatic pattern from 2010-2020 (SAWS 2020). To avoid overwhelming the biofilter, shortening its lifespan and hindering remediation efficacy, an appropriate minimum biofilter size of at least 2% of the catchment area contributing runoff to the biofilter's inflow volume is required (Payne *et al.* 2015). Due to the laboratory design of the experiment using Ø110 mm biofilter columns, the corresponding contributing runoff area was adjusted, altering the runoff volume available for discharge into the system. Therefore, in summary, the dosage volumes were calculated based on 30% urban runoff conversion at 43.4% imperviousness for Stellenbosch, sized at 2% of its potential contributing catchment area, receiving twice-weekly dosages of 2.08 mm and 66 mm every 60 days to reflect typical- and maximum intense-precipitation events respectively.

Pollutant removal

The pollutant removal efficiencies of the media combinations were evaluated with effluent sampling initiated 30 days after the first day of synthetic stormwater dosing at 10-day intervals, collected in 500 mL containers directly below the drainage pipes of each unvegetated biofilter column. This 30-day period allowed for the transport of excess non-polluted tap water that may have lingered within the growth media, thus, negating pollutant dilution. Thirty days were proven sufficient by evaluating the transport time required for a water soluble dye to be discharged from the experimental biofilter columns. Vegetated *Juncus effusus* columns were excluded for pollutant removal analysis. Samples were collected on 6 occasions, with the first sample round evaluating the existing concentration prior to dosing.

Pollutant load removal efficiencies cannot be quantified by analysing concentration alone, as biofilters are not closed systems, with volume loss occurring due to plant-water uptake and evapotranspiration. Thus, pollutant load removal must account for the difference in concentration, as well as the alternating influent volumes and measured effluent volumes.

Overall pollutant removal percentage efficiencies for each biofilter was calculated as the mean across all sampling rounds ($\bar{x}K_{rem}$), Equation 2.

$$K_{rem} = \frac{C_i V_i - C_e V_e}{C_i V_i} \text{ x } \frac{100}{1} \qquad \text{Equation 2}$$

where

K_{rem} = pollutant load removal (%)

C_i = influent concentration (mg/L)

V_i = influent dosage volume (L)

C_e = effluent concentration (mg/L)

V_e = effluent volume (L)

Various water quality parameters were analysed in the Stellenbosch University Water Quality Laboratory to determine the performance of each of the ten media combinations. These included pH, dissolved oxygen (DO), electrical conductivity (EC), ammonia N (NH_3-N), nitrate N (NO_3^--N) and orthophosphate P (PO_4^{3-}-P). Cadmium (Cd), Copper (Cu), Lead (Pb) and Zinc (Zn) were analysed at the Stellenbosch University Central Analytical Facility: ICP-MS division.

The pH, DO and EC were measured using a HACH HQ440d Benchtop Multi-Parameter. Measurement of nutrient and metal concentrations required effluent filtration with a 0.45 µm syringe filter prior to analyses. The NH_3 -N, NO_3^- -N and PO_4^{3-} -P concentrations were measured colorimetrically using a Hach DR3900 Benchtop Spectrophotometer. The Cd, Cu, Pb and Zn concentrations were analysed on an Agilent 8800 QQQ ICP-MS instrument, with polyatomic interferences removed by a 4th generation Octopole Reaction System.

Infiltration capacity

In order to assess media infiltration capacity under typical- and intense- storm events, the twice-weekly and 60-day interval dosages were administered. This was done by comparing the infiltration rate (IR) between the various unvegetated columns, as well as with their vegetated counterparts over time. The surface infiltration rate measurements were taken at 20-day intervals, with the first round of sampling initiated on the day the growth media was added and the vegetation planted, after which the columns received dosing. This sampling regime produced 11 measurements over a 28-week period throughout the experiment, adequate time to achieve hydraulic compaction (Le Coustumer *et al.* 2012). The Falling Head test applied immediately following dosing of the columns on the day of sampling, measured the drop in depth of the ponded influent relative to the media surface at 1 minute intervals, Equation 3. The average hydraulic performance for each column was calculated as the slope of the drop in water level across the measurement time (mm/hr) (Knappett & Craig 2012).

$$k = 2.3\ \frac{aL}{A\,(t_1 - t_0)} \log \frac{h_0}{h_1}$$ Equation 3

where

k = coefficient of permeability (m/s)

a = cross-sectional area of the column (m^2)

L = growth media depth (m)

A = cross-sectional area of growth media (m^2)

$t_1 - t_0$ = elapsed time between head readings (s)

$h_1 - h_0$ = head readings taken at t_1 and t_0 respectively (m)

As mentioned, a preliminary clear perspex column investigation of media infiltration satisfied suppressed rapidity of the head drop, substantiating the use of the above equation.

Particulate discharge

The role of vegetation in mitigating soil erosion and sediment discharge in urban areas during GI construction and establishment was assessed by analysing effluent deposition of the unvegetated and vegetated biofiltration columns throughout the 28-week irrigation regime. Similar to analysing infiltration capacity above, effluent sampling was initiated on the day of column establishment, taken at 20-day intervals producing 11 measurements. Comparisons were conducted between unvegetated and vegetated columns, and among media combinations. Effluent samples were analysed in triplicate for turbidity, total suspended solids (TSS) and total dissolved solids (TDS) presented as total solids (TS = TSS + TDS), in both the presence and absence of vegetation. Turbidity readings were measured using a 2100Q Portable Turbidimeter, with TSS and TDS analysed by means of the HACH DR3900 Benchtop Spectrophotometer Photometric method and the IntelliCAL CDC401 probe of the HACH HQ440d Benchtop Multi-Parameter meter respectively.

Plant functional response

The effect of the engineered media on plant growth was evaluated by assessing above- and below-ground plant functional traits within the vegetated columns. With the conclusion of the 28-week experimental period, two whole *Juncus effusus* specimens (one receiving synthetic- and the other municipal dosing) were excavated from their biofilter columns for each of the ten media combinations and above-ground and below-ground traits measured after extraneous soil particulate and organic matter was removed. Below-ground traits were divided into number of roots and length of the longest root, which was taken to indicate the specimen's response to media exposure. In determining plant response, root:shoot ratios were assessed. Investigating the influence of polluted urban runoff on plant growth over the extent of the experimental period, initial roots and shoots and final roots and shoots were compared between plants receiving synthetic stormwater and municipal supply.

Data analysis

To test for normality and homoscedasticity the *Lilliefors test* and the *Bartlett's test* were used respectively. The *One-Factor ANOVA* was used to ascertain the significance of difference in normally distributed results of growth media. With statistically significant difference in results found from the one-factor ANOVA, an unadjusted α *Pairwise t-Test* was performed with a pooled standard deviation to compare unvegetated and vegetated columns. Where data was not found to be normally distributed, the nonparametric ANOVA *Kruskal-Wallis H-test* was used to analyse differences in the growth media results, whilst the *Wilcoxon Rank-Sum test* was used to compare the unvegetated and vegetated columns. The *Fisher Least Significant Difference (LSD) test* was used to display media that are not significantly different. In this experiment statistical analyses were conducted using R Statistical Software with an unadjusted α = p-value, to maintain the power of the test (Feise 2002). Significance was accepted at p-value $\leq .05 = \alpha$, for all analyses.

RESULTS AND DISCUSSION

Urban pollutant remediation

In evaluating nutrient removal, all media successfully removed ammonia -N and orthophosphate -P at varying efficiencies (Table 4). For nitrate, however, a net effluent increase rather than a net decrease was found across the unvegetated media, similar to previous findings reporting nitrate -N leachate in biofilters (Bratieres *et al.* 2008). From Figure 2, all engineered media combinations outperformed traditional LS, reporting decrease and increase differences of 27.3%, 20.8% and 113.8% for NH_3 -N, PO_4^{3-} -P and NO_3^- -N, respectively. As the worst nutrient remediating media, traditional LS averaged percentage load removals of 49.2% and 34.9% for NH_3 -N and PO_4^{3-} -P respectively, as well as producing 277.3% of NO_3^- -N. In contrast, the best performing media was engineered LSPVA, with removal averaging 89.7% and 66.3% for NH_3 -N and PO_4^{3-} -P. In addition, LSPVA most effectively restricted nitrate release into the effluent, reporting a net increase of 90.3% for NO_3^- -N, the least by any media.

Analysis of nutrient removal by unvegetated media for NH_3 -N, NO_3^- -N and PO_4^{3-} -P did not satisfy normality, thus the nonparametric ANOVA Kruskal-Wallis H-test evaluated statistically significant differences for pollutant load removals for each nutrient. Between media, significant differences were found for NH_3 -N only ($p = .0023$) with no significant differences reported for NO_3^- -N ($p = .075$) and PO_4^{3-} -P ($p = .23$). Although differences between unvegetated media for NO_3^- -N and PO_4^{3-} -P removal was not significantly different, the Wilcoxon Rank-Sum test implemented a pairwise comparison, with differences represented by Fisher's LSD test, illustrated in Figure 2.

From the results, effective ammonia reduction and nitrate increase in all media combinations suggest volatilisation at the surface area or an enhancement of the nitrification process in biofilters, converting ammonium to nitrate even in the absence of vegetation (also see Barth *et al.* 2020). This may be due to a weak dependence by microbial activity responsible for nitrification on plant presence (Gerardi 2003). Experiencing similar nitrate increase, Davis *et al.* (2001) suggested that nitrate leachate could be the biological transformation of captured ammonia and organic nitrogen to oxidised nitrogen (nitrate and nitrite) between outflow events. In the unvegetated biofilters, due to oxidized nitrogen's anionic form there is little adsorption onto soil, resulting in negligible removal and only minimal denitrification (Henderson *et al.* 2007). Under intense dosing, limiting adsorption opportunities, and inadequate denitrification to complete the nitrogen removal process, nitrate leaching increased. This observation was similar for orthophosphate -P, where minimal removal directly after an increase in dosage volume was observed. Dissolved phosphorous after these events may over time decrease, as phosphorous adsorbs to soil (Asomaning 2020).

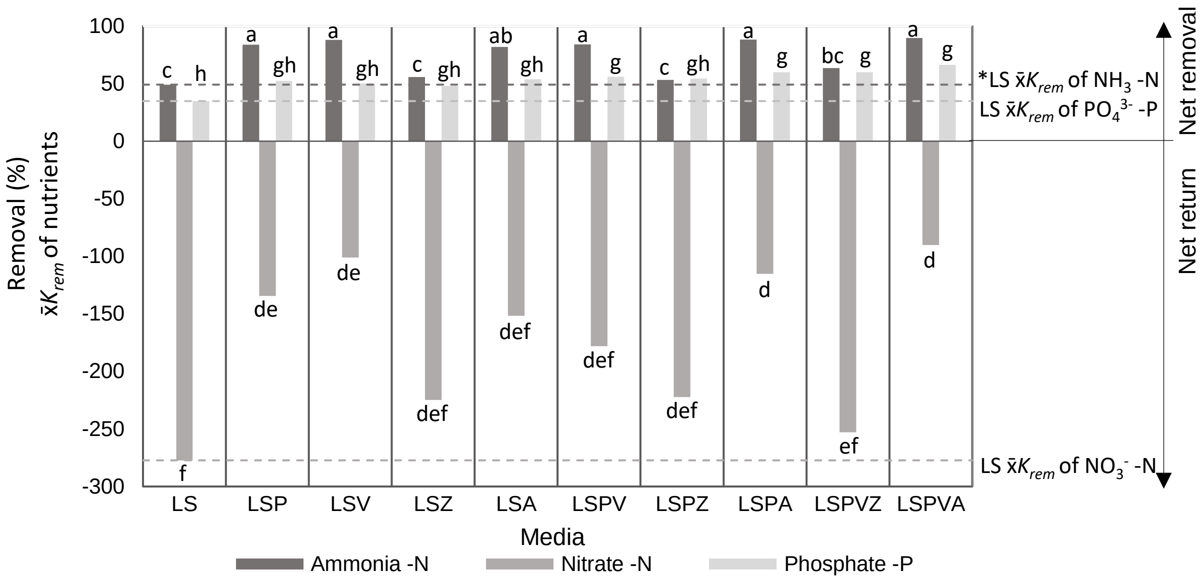


Figure 2. Mean percentage nutrient load removal between media for the duration of the experiment. Means with the same letter are not significantly different (Fisher's LSD test).
*LS$\bar{x}K_{rem}$: Mean percentage removal by LS.

Metal removal was effective in all media combinations with traditional LS again maintaining the lowest percentage reduction. Cd outflow concentrations were below the 0.000045 mg/L laboratory detection limit in 96% of the samples, registering only one measurable data point in two separate sampling rounds, 97.8% and 98.1% pollutant removal by LSA and LSPV respectively, inferring effective Cd removal.

From Figure 3, high average removal percentages were observed for Pb (> 94.7%) and Zn (> 98.1%). Cu removal was more moderate, ranging from 59.3% in traditional LS to 81.8% in LSPVZ media. Similarly to nutrient removal, traditional LS was the worst performer, reporting mean differences of 13.2% for Cu, 3.9% for Pb and 0.8% for Zn when compared with the average removal by engineered media, Table 3.

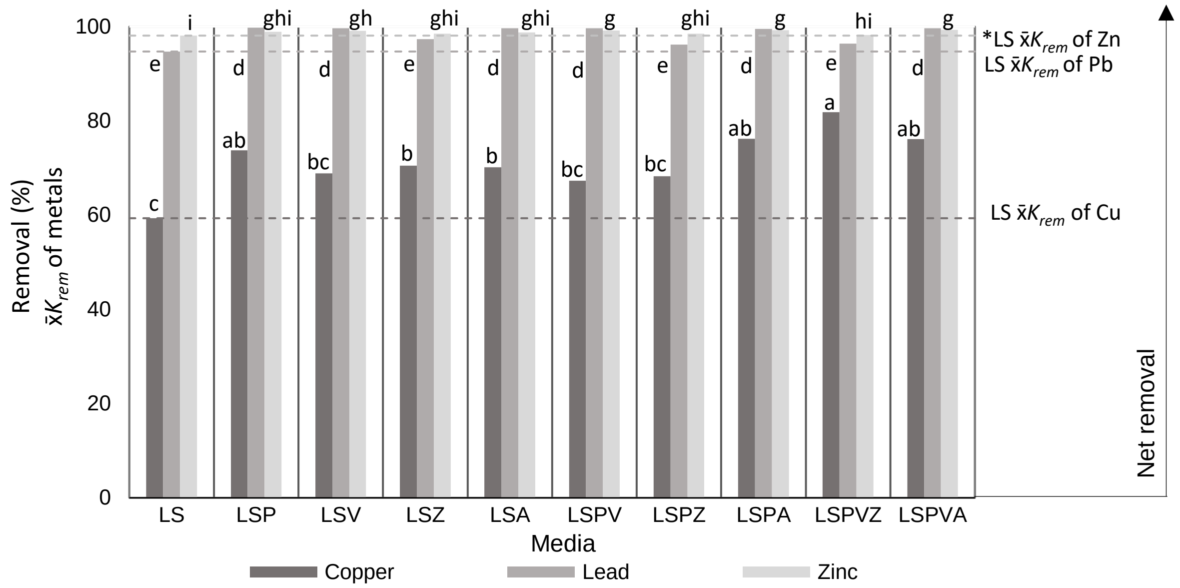


Figure 3. Mean percentage metal removal between media for the duration of the experiment. From Fisher's LSD test, bars with the same letter are not significantly different.
*LS$\bar{x}K_{rem}$: Mean percentage removal by LS.

Table 4. Ranked media performance by mean percentage stormwater pollutant removal over time for all sampling rounds. *BDL: Below detection limit.

Rank	Media	Pollutants removed ($\bar{x}$%)	Nutrient removal			Metal removal			
			NH_3 -N	NO_3^- -N	PO_4^{3-} -P	Cd	Cu	Pb	Zn
			Mean percentage pollutant load removal $\bar{x}K_{rem}$ (%)						
1	LSPVA	56.80	89.70	-90.32	66.29	BDL*	76.15	99.65	99.32
2	LSPA	51.29	88.20	-115.37	60.00	BDL	76.19	99.49	99.21
3	LSV	50.81	87.95	-101.05	50.29	BDL	68.88	99.67	99.12
4	LSA	50.05	81.90	-151.58	53.71	97.74	70.17	99.65	98.77
5	LSPV	46.61	84.15	-178.11	56.00	98.10	67.28	99.64	99.18
6	LSP	45.72	83.85	-134.53	52.57	BDL	73.76	99.76	98.90
7	LSPVZ	27.98	63.45	-232.00	60.00	BDL	81.81	96.36	98.24
8	LSPZ	24.67	53.20	-222.32	54.29	BDL	68.22	96.17	98.47
9	LSZ	24.19	55.70	-224.84	48.00	BDL	70.46	97.36	98.46
10	LS	8.82	46.05	-277.26	32.00	BDL	59.33	94.71	98.08

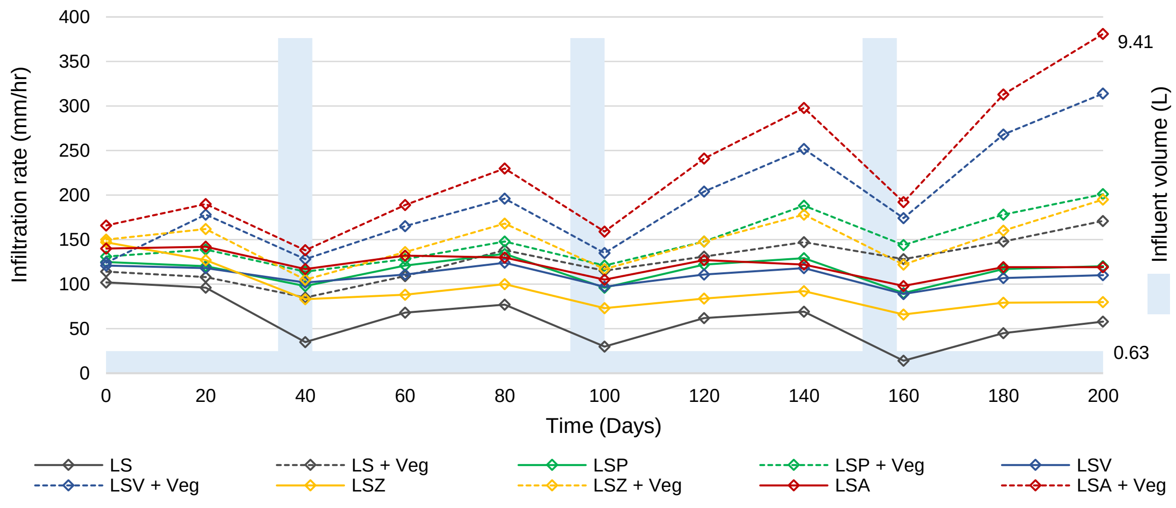
Statistical analysis of metal removal by unvegetated media was undertaken for Cu, Pb and Zn (Cd was excluded due to lack of measurable values). Similar to nutrients, normality was not satisfied, therefore the nonparametric ANOVA Kruskal-Wallis H-test was used. Statistically significant differences in percentage removals was found for all metals between unvegetated media, Cu (p = .0070), Pb (p = .00036) and Zn (p = .033). This necessitated the Wilcoxon Rank-Sum pairwise comparison test between the media, with Fisher's LSD test results depicted in Figure 3.

High removal percentages were observed due to filtration and adsorption being the major removal pathways for metals in stormwater biofilters (also see Barron *et al.* 2019). Although the majority of Cu was successfully removed, removals were constantly lower in comparison with Pb and Zn, similar to other findings (see Blecken *et al.* 2010). For improved Cu uptake, in addition to soil remediation, the introduction of plants create a direct uptake pathway (Muerdter *et al.* 2018). Phytoremediators have the ability to accumulate metals that are essential for growth and development, indicating the importance vegetation for optimised plant biofiltration (Dhir *et al.* 2009).

In the event of an intense precipitation event the average nutrient removal efficacy across all media decreased by 18.9% for NH_3 -N and 32.9% for PO_4^{3-} -P, with a net increase of 182.9% observed for NO_3 -N after 3 days of increased dosing. Metal removal was unaffected with no change in removal efficacy after the increased dosing period. Ten days post increased dosing, under typical volume irrigation, pollutant removal increased. This shows that pollutant remediation recovered post dosing stress. Statistical analysis showed no significant difference in removal efficiencies between media for each stormwater pollutant.

Hydraulic performance

Figure 4 depicts the varying surface IRs of the ten different media over time. The best performing unvegetated media for the duration of the experiment was LSPVZ, averaging an IR of 161.1 mm/hr. In contrast, the worst performer was traditional LS, averaging 59.6 mm/hr, along with LSZ (92.64 mm/hr) and LSPV (99.55 mm/hr) below the recommended 100 mm/hr minimum biofilter requirement. The one-factor ANOVA analysing the surface IRs of the unvegetated media showed significant differences, indicating that at least one comparison between media to be significant, necessitating pairwise t-tests. In analysing the differences between the unvegetated media, traditional LS showed significant differences ($p \leq .05$) with all other media. Of interest, the effective infiltrating LSPVA and LSPVZ media also showed significant differences compared to each of the other media, except with each other.



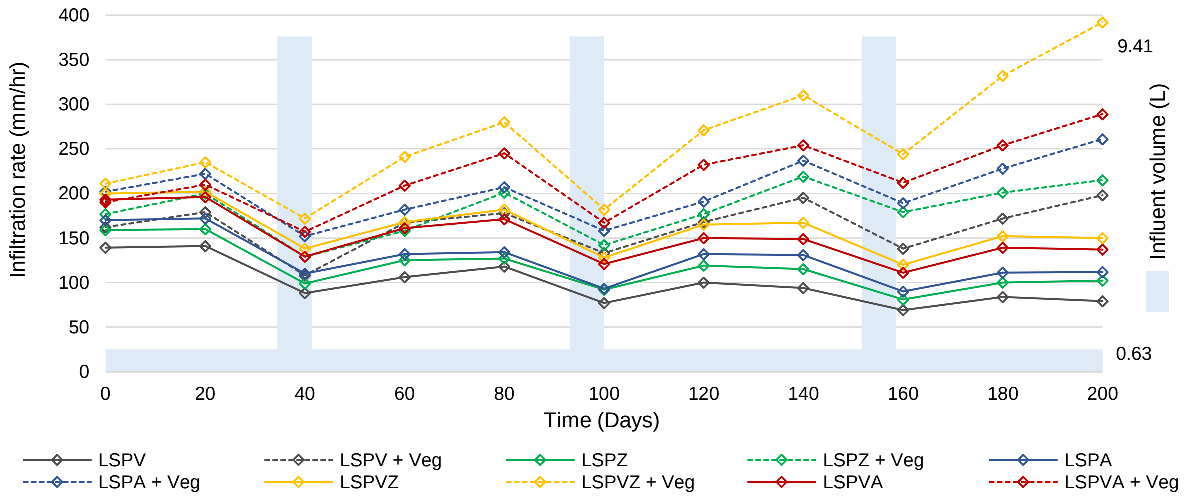


Figure 4. Infiltration rates (IRs) of unvegetated and vegetated media under alternating influent dosages with time.

In the presence of vegetation all media showed greater average surface IRs than the required 100 mm/hr. Similar to the best unvegetated performer, the best performing media in the presence of vegetation was LSPVZ, with an IR of 260.9 mm/hr. From Figure 4, it is clear that vegetated media consistently outperformed unvegetated media across all combinations, infiltrating on average 71.9 mm/hr faster than the unvegetated media for the duration of the experiment. The pairwise comparison of surface IRs between unvegetated and vegetated media with time showed significant differences across all media combinations, manifesting significantly greater surface infiltration in biofilters equipped with plants.

In addition, the influence of vegetation is further illustrated by a surface IR increase with time for all vegetated media, producing on average 99.6 mm/hr or 60.9% infiltration increase over the 28 weeks. In contrast, after the same period infiltration decreased on average by 42.9 mm/hr or 26.7% in unvegetated media.

In the event of increased precipitation, simulated by increasing dosage from 0.63 L to 9.41 L, the average surface IR of the media combinations decreased by 40.6 mm/hr and 55.1 mm/hr for unvegetated and vegetated biofilters respectively. Although the vegetated columns exhibited a larger loss in IR during these events, the columns still maintained a faster surface IR in comparison with the unvegetated columns. Statistically comparing the response by unvegetated with vegetated media under increased dosing, using the nonparametric *Kruskal-Wallis H-test,* showed significant differences. This finding supports the notion that biofilters equipped with vegetation are significantly more capable of sustaining infiltration during precipitation changes, as opposed to unvegetated biofilters. In addition to the contribution of non-traditional engineered media supporting infiltration, the specific root system of *Juncus effusus*, which is capable of extending downward or laterally, maintained adequate infiltration throughout fluctuating influent volumes. All of the engineered media exhibited greater capacity to endure runoff volumes from typical as well as intense precipitation events than traditional

LS. Influent stormwater build-up was observed above the growth media in unvegetated LS, LSZ, LSPV, LSV, LSP and LSPZ columns exposed to intense drip dosing over several hours, reporting IRs ranging from 59.6 mm/hr to 116.1 mm/hr. For the unvegetated LSPA column, reporting the slowest surface IR in the absence of build-up (126.1 mm/hr), surface saturation was observed, an indication of waterlogged soil. Thus, from the reported values in Figure 4, an IR above 126.1 mm/hr under the experimental dosing regime, prevented stormwater build-up, which may lead to overflow. The use of prolonged drip irrigation, the method adopted for experimental dosing, reduced the influent flow rate, hndering surface build-up whilst encouraging effluent discharge.

Solids discharge

Figure 5 illustrates the solids measured as turbidity and TS in the effluent of the ten media in the absence and presence of vegetation, at 20-day intervals for the duration of the 28-week experimental period. Analyses showed that the best and worst unvegetated media corresponded for both TS and turbidity. The best performer was LSPVA, producing final turbidity and TS values of 35 FTU and 78 mg/L respectively. In contrast, the worst unvegetated performer was LS, producing final values of 524 FTU and 422 mg/L for turbidity and TS respectively.

Analysing turbidity and TS with time (one-factor ANOVA), showed statistically significant differences for turbidity ($p = .0017$) and TS ($p = .0016$) between unvegetated media. With further comparison (pairwise t-test), showing only LSPVZ to be significantly different to all other media for both turbidity and TS. Although not significantly different to all other media, traditional LS differed significantly with the greatest number of media, as can be seen in the Fisher's LSD test, Figure 5.

For vegetated media, the nonparametric Kruskal-Wallis H-test indicated statistically significant differences for turbidity ($p = .0037$) and no statistically significant differences for TS ($p = .42$). Therefore, the influence of vegetation on TS was not further assessed. For turbidity, the Wilcoxon Rank-Sum test indicated no statistically significant turbidity difference between individual unvegetated and vegetated media, implying a greater statistical influence by specific media on turbidity than vegetation. In other words, it seems that, although solids removal improved in the presence of vegetation, the media type was the primary influence on decreased turbidity and TS. Results were further analysed using the Fisher's LSD test (Figure 5).

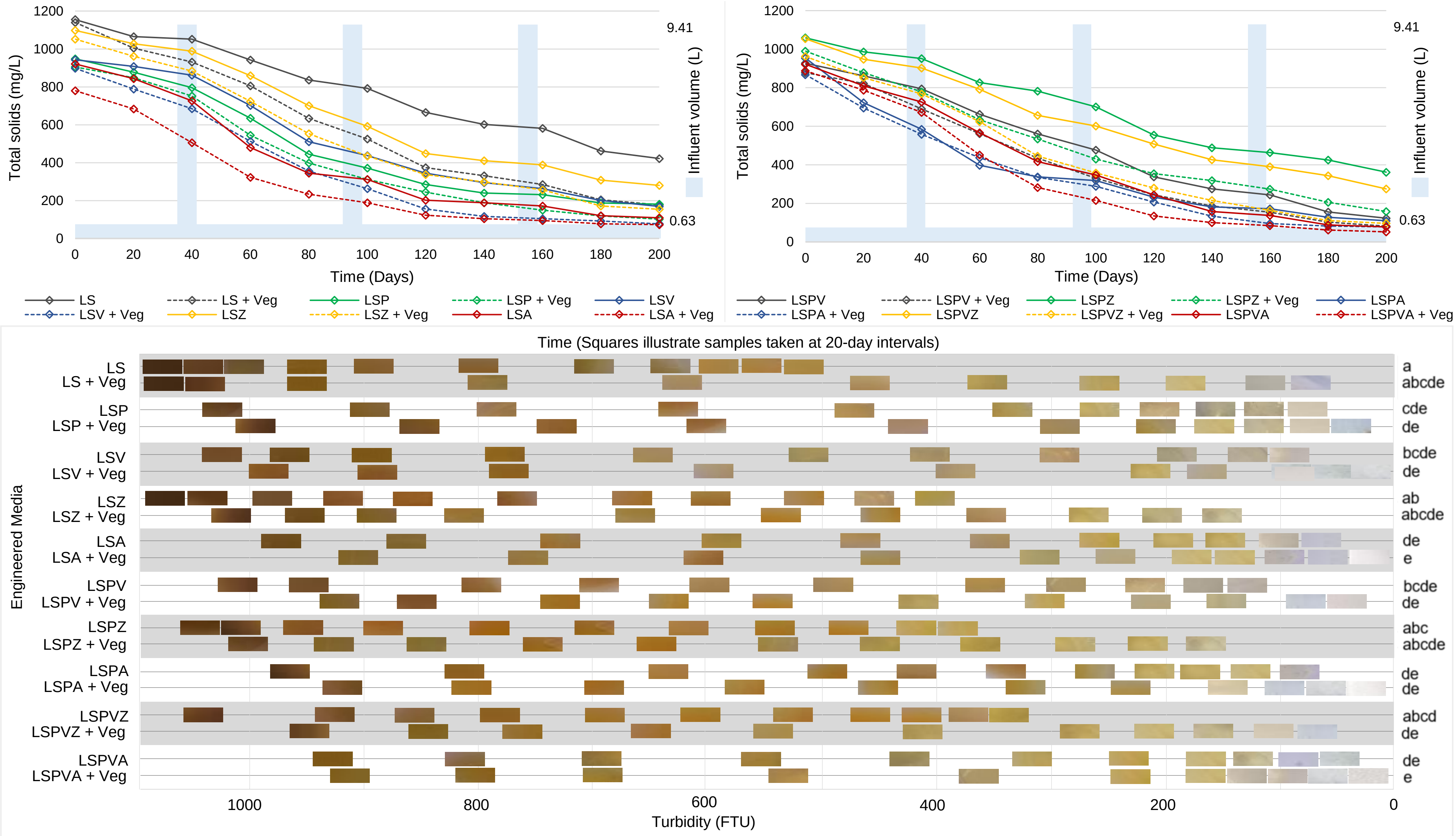


Figure 5. Effluent TS and turbidity of unvegetated and vegetated media through time, with change in effluent clarity illustrated by photographic captures. From Fisher's LSD test on turbidity, media with the same letter are not significantly different. LS: Loamy sand; LSP: Loamy sand + Perlite; LSV: Loamy sand + Vermiculite; LSZ: Loamy sand + Zeolite; LSA: Loamy sand + Attapulgite; LSPV: Loamy sand + Perlite + Vermiculite; LSPZ: Loamy sand + Perlite + Zeolite; LSPA: Loamy sand + Perlite + Attapulgite; LSPVZ: Loamy sand + Perlite + Vermiculite + Zeolite; LSPVA: Loamy sand + Perlite + Vermiculite + Attapulgite.

From Figure 5, it is evident that effluent turbidity and TS of both unvegetated and vegetated media decreased with time, improving water clarity and reducing solids in stormwater runoff. The turbidity decrease across the media mixtures over the 28-week study period ranged from 564 FTU – 943 FTU ($\bar{x}$ = 808.7 FTU) for unvegetated biofilters and 834 FTU – 991 FTU ($\bar{x}$ = 904.8 FTU) for vegetated biofilters, denoting average percentage decreases of 79.7% and 93.8% respectively. Similarly, the decrease in TS ranged from 697 mg/L – 844 mg/L ($\bar{x}$ = 787.2 mg/L) and 707 mg/L – 963 mg/L ($\bar{x}$ = 831.2 mg/L) in unvegetated and vegetated biofilters respectively, denoting percentage decreases of 79.6% and 89.1% respectively. Effluent solids removal was generally lower in the presence of vegetation, encouraging the removal of particulate organic nitrogen and phosphorous.

Plant response

Similar tussock growth (above-ground area and number of shoots) of *Juncus effusus* exposed to different media under non-polluted influent was observed, with no significant difference between media. Over the 28-week experimental period, tussock growth was most vigorous when exposed to LSZ and most reduced when exposed to traditional LS (Table 5), recording percentage growth of 300% and 82.8% respectively. Similarly root growth, as an established indicator of pollutant removal (Read *et al.* 2010), was assessed at harvest, reporting the greatest increase in length of the longest root when exposed to LSZ. Unsurprisingly, the length of the longest root showed a close relationship with infiltration (r^2 = .69).

Table 5. Physiological trait development of *Juncus effusus* in different media.

Media	**Tussock surface area (mm^2)**		**Longest root (mm)**		**Number of roots**		**Number of shoots**		**Root:shoot**	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
LS	1590.43	4901.67	150	248	23	60	46	54	0.50	1.11
LSP	2290.22	4185.39	149	229	20	54	36	48	0.56	1.13
LSV	1661.90	4071.50	159	224	22	54	40	52	0.55	1.04
LSZ	1256.64	5026.55	161	265	23	75	50	65	0.46	1.15
LSA	1520.53	4417.86	159	253	22	72	48	66	0.46	1.09
LSPV	1809.56	4185.39	167	238	22	70	49	64	0.45	1.09
LSPZ	1963.50	6082.12	149	241	21	62	38	52	0.55	1.19
LSPA	1809.56	5674.50	162	257	22	64	41	60	0.54	1.07
LSPVZ	1734.94	6221.14	160	270	20	69	39	61	0.51	1.13
LSPVA	1590.43	5281.02	149	260	19	68	36	59	0.53	1.15

From Table 5, initially the number of shoots outnumbered roots as opposed to roots outnumbering shoots at study completion, indicating a change in plant trait development. This trait development, consistent across media, is expressed by a change in the mean root:shoot ratio of 0.50 to 1.12, at initiation and study completion respectively. A root:shoot ratio increase indicates that although the aboveground portions (tussock area and shoots) of the plants were still experiencing an increase, the root systems were increasing at an even greater rate. Between the media combinations none were found to significantly influence above-ground or below-ground plant growth, thus no specific growth response in relation to media was observed.

In assessing the effect of polluted stormwater on plant development, the number of initial roots and shoots were compared with the number of final roots and shoots of *Juncus effusus* for both municipal and polluted stormwater treatments. The growth of new roots and shoots in plants receiving synthetic stormwater was constantly greater than plants under municipal dosing, with the stormwater acting as fertiliser to the vegetated biofilters. For roots, this increase can be seen in the initial mean synthetic stormwater (initial root) : municipal supply (initial root) ratio of 1.02 being smaller than the final mean synthetic stormwater (final root) : municipal supply (final root) ratio of 1.13 across all engineered media combinations. Similarly for shoots, the initial mean synthetic stormwater (initial shoot) : municipal supply (initial shoot) ratio of 1.09 was less than the final mean synthetic stormwater (final shoot) : municipal supply (final shoot) ratio of 1.14 across all media. The lack of noticeable nutrient and metal toxicity on the species' plant growth rate (with species in reality thriving in synthetic stormwater) and historical pollutant removal performance, *Juncus effusus* and potential similar species are well equipped for urban load reduction (Ullah *et al.* 2015).

Ranked engineered media for plant biofilter optimisation

Rating potential media for biofilter optimisation was based on performance across all relevant factors influencing GI efficacy and sustainability. The pollutant load removal, infiltration capacity and particulate discharge of each media was taken into account. Plant response was omitted due to similarity between engineered media. Individual performances were used to identify potential optimised biofiltration media capable of removing urban pollutants efficiently whilst sustaining local habitat and climate stress.

Generally, all included media combinations depicted desirable operational traits for effective urban stormwater remediation, making them suitable for use as plant biofilter growth media. For nutrients, although a nitrate increase was observed, effective ammonia-N and orthophosphate-P reduction was achieved. All media leached low levels of metal ions and produced very high removal efficiencies (>85%), with the exception of LS. Therefore, the three best media for general performance were LSPVA, LSA and LSPA. These media achieved high stormwater pollutant load removals, hindered possible sediment transport and maintained adequate infiltration rates under regular and intense dosing. Table 6 below can be used to determine media for targeted application, for example LSPVZ, which did not perform best across all factors, performed especially well with metal removal and infiltration and can contribute in scenarios requiring specific biofiltration.

Table 6. Optimised engineered media ranking across all performance factors through time.

Engineered media	Ranked Performance across GI factors NR:MR:IR:TS:TU
Loamy sand + Perlite + Vermiculite + Attapulgite	1:2:2:1:1
Loamy sand + Attapulgite	5:5:4:2:2
Loamy sand + Perlite + Attapulgite	5:3:5:3:3
Loamy sand + Perlite	4:4:3:6:4
Loamy sand + Perlite + Vermiculite + Zeolite	7:1:1:7:7
Loamy sand + Vermiculite	2:6:6:5:5
Loamy sand + Perlite + Vermiculite	6:8:9:4:6
Loamy sand + Zeolite	9:7:8:7:9
Loamy sand + Perlite + Zeolite	8:9:7:9:8
Loamy sand	10:10:10:10:10

NR: Nutrient removal; MR: Metal removal; IR: Infiltration rate; TS: Total solids; TU: Turbidity

The results highlight the variability of media performance, where media better equipped at improving a certain GI condition may perform worse in others. This variability highlights the importance of intricate biofilter planning and design, accounting for the target pollutant and the conditions of the recipient habitat in need of remediation.

CONCLUSIONS

The study investigated the nutrient and metal removal, infiltration rate, solids removal and plant response of nine engineered growth media combinations and one traditional loamy sand medium, towards the potential optimisation of urban plant biofiltration systems. Unvegetated column experiments were used to evaluate the pollutant removal efficiencies of the media, whereas vegetated *Juncus effusus* columns were used to assess the influence of vegetation on biofilter infiltration and solids removals.

All unvegetated engineered media effectively removed NH_3 -N, PO_4^{3-} -P, Cd, Cu, Pb and Zn from synthetic urban stormwater runoff. For NO_3^- -N, leachate was observed across all media. During typical and intense precipitation events nutrient and metal removal efficiencies varied. A decrease in some nutrient removals were observed during increased dosing, whereas no differences were shown for metal removals.

The engineered media combinations maintained greater surface infiltration under varying influent dosages than traditional LS for the duration of the experiment, supporting their selection in clogging mitigation and overflow reduction. The implementation of infiltration enhancing media in small-scale GI offers opportunity to decrease the required minimum size of biofilters, currently recommended at 2% of its catchment area, an attractive alternative for space-limited urban scenarios. In the presence of vegetation under varying influent dosages, the infiltration capacities of all biofilters significantly increased, supporting GI sustainability.

All media combinations effectively mitigated particulate deposition, improving effluent sedimentation and clarity. In the presence of vegetation, although insignificant, greater effluent clarity and sediment load reduction attributed to media stabilization and minimising media movement was observed. This is particularly important during GI construction and establishment where phytostabilisation is threatened, leading to particulate discharge, erosion and clogging of urban drainage networks (Fletcher *et al.* 2013). Sediment accumulation leads to more frequent overflows and extended ponding time, reducing GI's pollutant treatment capacity, resulting in watercourse and in-stream habitat degradation (Hatt *et al.* 2009; Le Coustumer *et al.* 2012).

The presence of above- and below-ground plant growth in all media indicated acceptable substrate in the experimental biofilter columns, encouraging vegetative establishment (Read *et al.* 2008). Between media there was no significant difference in plant functional response, supporting the inclusion of all combinations for use in biofilters. The root:shoot change showed a greater growth rate in the root system, ideal for phytoremediation favouring high root:shoot ratios due to enhanced contact with the pollutants in the rhizosphere (Payne *et al.* 2015). Although not significant, overall growth in plants receiving synthetic stormwater outperformed plants receiving municipal supply, with no signs of growth inhibition. This may be due to this experiment's relatively low stormwater nutrient and metal toxicity and exclusion of other potential toxicants, which may be different in other conditions.

From the findings, the best performing media with regard to pollutant removal, infiltration, and solids discharge, were LSPVA, LSA and LSPA. Although ranking identified the best performing experimental media, selecting media for use in optimised GI projects must consider the recipient site's target pollutant, conditions of the contributing catchment area affecting the minimum biofilter size, available and appropriate phytoremediator species, habitat and climate. Thus, in considering the conditions of the site in need of remediation, additional features may be required to optimise biofiltration, like the use of a saturated zone for enhanced nitrate removal (Barron *et al.* 2019).

In concluding, the findings of this study provide important proof-of-concept for the application of engineered media in new and existing biofiltration systems for the removal of nutrient and metal pollutants from urban stormwater. The identified media aid in establishing, replenishing and maintaining treatment performance whilst resisting habitat and climatic stresses. Similar to previous studies, the results highlight the importance of vegetation in pollutant removal, infiltration and phytostabilisation (Henderson *et al.* 2007), in addition to contributing to microbial communities and socio-economic value (Hsu & Chao 2020). The use of engineered media improved pollutant removal, infiltration and particulate discharge, whilst supporting vegetative growth in a laboratory setting. Here engineered media as substrate tolerated increased dosing compared with traditional media mitigating overflow and pollutant runoff. Overflow allows runoff to evade treatment, picking up chemicals and pollutants along the way prior to discharge into urban waterways, deteriorating urban water quality, diminishing the efforts of the urban water engineer.

Further research is required to assess the carrying capacity of engineered media in laboratory and field settings, particularly during periods of drought, to gauge the substrate's potential moisture availability for root uptake and redox potential. Thus, determining at which infiltration rate specific engineered media impedes remediation and microbial activity. The size requirement of small-scale GI systems constructed with infiltration enhancing media, whilst maintaining treatment performance in the urban area must be determined, with a cost analysis included. Although the current study assessed general urban nutrient and metal remediation, additional contaminants of varying toxicity should be tested. In addition, evaluating biofilter response to a wider range of stresses and a greater variety of plant species would better equip the GI designer with knowledge regarding species' ability to tolerate inundation, drought and biofilter media substrate. Finally, in order to assess the validity of biofilter performance, we propose budget calculations over pollutant removal, along the effluent probability method, with additional data captured from similar laboratory and field studies.

ACKNOWLEDGEMENT

This research was funded by the National Research Foundation (NRF) Thuthuka Fund, with project identity: TTK180418322426.

REFERENCES

Al-Ameri M., Hatt B. E., Le Coustumer S., Fletcher T. D., Payne E. G. I. & Deletić A. 2018 Accumulation of heavy metals in stormwater bioretention media: A field study of temporal and spatial variation. *Journal of Hydrology*, **567**, 721–731.

Al-Sharify A. N. & Athab Z. H. 2012 Evaluation of the potential of using Attapulgite clay as adsorbent for removal of P-chloroaniline (PCA) from aqueous solutions. *Journal of University of Babylon*, **22**(1), 454–463.

Armitage N. P., Fisher-Jeffes L., Carden K., Winter K., Naidoo V., Spiegel A., Mauck B. & Coulson D. 2014 *Water sensitive urban design (WSUD) for South Africa: Framework and guidelines.* Report no TT 588/14, WRC, Gezina.

Arnold C. L. & Gibbons C. J. 1996 Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American planning Association*, **62**(2), 243–258.

Asomaning S. K. 2020 Processes and factors affecting phosphorus sorption in soils. In: *Sorption in 2020s*, Kyzas G. & Lazaridis N (eds.), IntechOpen, London, pp. 45-59.

Barron N. J., Deletić A., Jung J., Fowdar H., Chen Y. & Hatt B. E. 2019 Dual-mode stormwater-greywater biofilters: The impact of alternating water sources on treatment performance. *Water Research*, **159**, 521–537.

Barth G., Otto R., Almeida R. F., Cardoso E. J. B. N., Cantarella H. & Vitti G. C. 2020 Conversion of ammonium to nitrate and abundance of ammonium-oxidizing-microorganism in tropical soils with nitrification inhibitor. *Scientia Agricola*, **77**(4), 1-5.

Blecken G. T., Zinger Y., Deletić A., Fletcher T. D., Hedström A. & Viklander M. 2010 Laboratory study on stormwater biofiltration: Nutrient and sediment removal in cold temperatures. *Journal of Hydrology*, **394**(3–4), 507–514.

Bratieres K., Fletcher T. D., Deletić A. & Zinger Y. 2008 Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water Research*, **42**(14), 3930–3940.

Brudler S., Rygaard M., Arnbjerg-Nielse, K., Hauschild M. Z., Ammitsøe C. & Vezzaro L. 2019 Pollution levels of stormwater discharges and resulting environmental impacts. *Science of the Total Environment,* **663**, 754–763.

Chandrasena G. I., Shirdashtzadeh M., Li Y. L., Deletić A., Hathaway J. M. & McCarthy D. T. 2017 Retention and survival of E. coli in stormwater biofilters: Role of vegetation, rhizosphere microorganisms and antimicrobial filter media. *Ecological Engineering*, **102**, 166–177.

Chmielewská E. 2015 Abundantly available natural or bioinspired materials for aqueous pollutants removal. *Current Green Chemistry*, **2**(4), 371–378.

Davis A. P., Shokouhian M., Sharma H. & Minami C. 2001 Laboratory study of biological retention for urban stormwater management. *Water Environment Research*, **73**(1), 5–14.

Dhir B., Sharmila P. & Saradhi P. P. 2009 Potential of aquatic macrophytes for removing contaminants from the environment. *Critical Reviews in Environmental Science and Technology*, **39**(9), 754–781.

Feise R. J. 2002 Do multiple outcome measures require p-value adjustment? *BMC medical Research Methodology*, **2**(1), 1–4.

Fletcher T. D., Andrieu H. & Hamel P. 2013 Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources* **51**, 261–279.

Fletcher T. D., Shuster W., Hunt W. F., Ashley R., Butler D., Arthur S., Trowsdale S., Barraud S., Semadeni-Davies A., Bertrand-Krajewski J. L. & Mikkelsen P. S. 2015 SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, **12**(7), 525–542.

Gerardi M. H. 2003 *Nitrification and denitrification in the activated sludge process*. John Wiley & Sons Inc., New York.

Göbel P., Dierkes C. & Coldewey W. G. 2007 Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology*, **91**(1–2), 26–42.

Gosset A., Durrieu C., Orias F., Bayard R. & Perrodin Y. 2017 Identification and assessment of ecotoxicological hazards attributable to pollutants in urban wet weather discharges. *Environmental Science: Processes & Impacts*, **19**(9), 1150–1168.

Hashem F.S., Amin M. S. & El-Gamal S. M. A. 2015 Chemical activation of vermiculite to produce highly efficient material for $Pb2^+$ and $Cd2^+$ removal. *Applied Clay Science*, **115**, 189–200.

Hatt B. E., Deletić A. & Fletcher T. D. 2007 Stormwater reuse: designing biofiltration systems for reliable treatment. *Water Science and Technology,* **55**(4), 201–209.

Hatt B. E., Fletcher T. D. & Deletić A. 2009 Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology,* **365**(3-4), 310–321.

Henderson C., Greenway M. & Phillips I. 2007 Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms. *Water Science and Technology*, **55**(4), 183–191.

Hsieh C. & Davis A. P. 2003 Evaluation of bioretention for treatment of urban storm water runoff. World Water & Environmental Resources Congress, Pennsylvania, United States, pp. 1–8.

Hsu K. W. & Chao J. C. 2020 Economic valuation of green infrastructure investments in urban renewal: The case of the station district in Taichung, Taiwan. *Environments*, **7**(8), 56.

Knappett J. A. & Craig R. F. 2012 *Craig's soil mechanics.* Spon Press, New York.

Le Coustumer S., Fletcher T. D., Deletić A., Barraud S. & Lewis J. F. 2009 Hydraulic performance of biofilter systems for stormwater management: Influences of design and operation. *Journal of hydrology,* **376**(1–2), 16–23.

Le Coustumer S., Fletcher T. D., Deletić A., Barraud S. & Poelsma P. 2012 The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Research,* **46**(20), 6743–6752.

Li H. & Cheng Z. 2015 Hoagland nutrient solution promotes the growth of cucumber seedlings under light-emitting diode light. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* **65**(1), 74–82.

Li Y., McCarthy D. T. & Deletić A. 2014 Stable copper-zeolite filter media for bacteria removal in stormwater. *Journal of hazardous materials*, **273**, 222–230.

Li Y., Wen M., Li J., Chai B. & Jiang C. 2018 Reduction and accumulative characteristics of dissolved heavy metals in modified bioretention media. *Water*, **10**(10), 1488.

Malézieux E., Lamanda N., Laurans M., Tassin J. & Gourlet-Fleury S. 2007 Plant functional traits and types: Their relevance for a better understanding of the functioning and properties of agroforestry systems. Second international symposium on multi-strata agroforestry systems with perennial crops, Turrialba, Costa Rica.

Mamba B. B., Dlamini N. P., Nyembe D. W. & Mulaba-Bafubiandi A. F. 2009 Metal adsorption capabilities of clinoptilolite and selected strains of bacteria from mine water. *Physics and Chemistry of the Earth, Parts A/B/C*, **34**(13–16), 830–840.

McGrane S. J. 2016 Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal*, **61**(13), 2295–2311.

Milandri S. G., Winter K. J., Chimphango S. B. M., Armitage N. P., Mbui D. N., Jackson G. E. & Liebau V. 2012 The performance of plant species in removing nutrients from stormwater in biofiltration systems in Cape Town. *Water SA*, **38**(5), 275–662.

Muerdter C. P., Wong C. K. & LeFevre G. H. 2018 Emerging investigator series: the role of vegetation in bioretention for stormwater treatment in the built environment: pollutant removal, hydrologic function, and ancillary benefits. *Environmental Science: Water Research & Technology*, **4**(5), 592–612.

Musakwa W. & Van Niekerk A. 2015 Monitoring sustainable urban development using built-up area indicators: a case study of Stellenbosch, South Africa. *Environment, Development and Sustainability*, **17**(3), 547–566.

Payne E. G. I., Hatt B. E., Deletić A., Dobbie M. F., McCarthy D. T. & Chandrasena G. I. 2015 Adoption guidelines for stormwater biofiltration systems - Summary report. Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

Prodanovic V., Zhang K., Hatt B. E., McCarthy D. & Deletić A. 2018 Optimisation of lightweight green wall media for greywater treatment and reuse. *Building and Environment*, **131**, 99–107.

Ragab R., Rosier P., Dixon A., Bromley J. & Cooper J. D. 2003 Experimental study of water fluxes in a residential area: 2. Road infiltration, runoff and evaporation. *Hydrological processes,* **17**(12), 2423–2437.

Rammal M. & Berthier E. 2020 Runoff losses on urban surfaces during frequent rainfall events: A review of observations and modeling attempts. *Water*, **12**(10), 2777.

Rauch I. & Brink I. C. (in preparation) Consideration of stormwater runoff from a parking lot for domestic use with a focus on metal pollutants: a case study.

Read J., Wevill T., Fletcher T. D. & Deletić A. 2008 Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research*, **42**(4–5), 893–902.

Read J., Fletcher T. D., Wevill T. & Deletić A. 2010 Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *International Journal of Phytoremediation*, **12**(1), 34–53.

SAWS. 2020 South African Weather Service. https://www.weathersa.co.za/ (accessed 13 August 2020).

Schueler T. R. 1992 Mitigating the adverse impacts of urbanization on streams: a comprehensive strategy for local government. In: *Watershed Restoration Sourcebook,* Kimble P. & Schueler T. (eds.), Metropolitan Council of Governments, Washington, United States, pp. 21–31.

Tichapondwa S. & Van Biljon J. 2019 Adsorption of Cr (VI) pollutants in water using natural and modified attapulgite clay. *Chemical Engineering Transactions*, **74**, 355–360.

Ullah N., Ling X., Shafaqat A., Naeem I. & Weijun Z. 2015 Mat rush (*Juncus effusus*) trounces manganese toxicity through ultra-morphological modifications and manganese restriction in roots. *Pakistan Journala of Botany,* **47**(1), 241–246.

Wang Y., Feng Y., Jiang J. & Yao J. 2018 Designing of recyclable attapulgite for wastewater treatments: a review. *ACS Sustainable Chemistry & Engineering*, **7**(2), 1855-1869.

Zhang Y., Wang W., Zhang J., Liu P. & Wang A. 2015 A comparative study about adsorption of natural palygorskite for methylene blue. *Chemical Engineering Journal*, **262**, 390–398.

Zinger Y., Blecken G. T., Fletcher T. D., Viklander M. & Deletić A. 2013 Optimising nitrogen removal in existing stormwater biofilters: Benefits and tradeoffs of a retrofitted saturated zone. *Ecological Engineering,* **51**, 75–82.

CHAPTER 5

Efficiencies of indigenous South African plant biofilters for urban stormwater runoff water quality improvement – with a focus on nutrients and metals

This chapter addresses research objective 4 by investigating nine indigenous South African plant species exposed to low, typically observed and high stormwater pollution loads in an experimental column study. Local plant species effective at removing nutrient and heavy metal pollutants from urban runoff offer potential for use in local sustainable WSUD initiatives, particularly spatially dispersed small scale plant biofilters.

This chapter seeks to assess the performance of indigenous plant species either identified in chapter 2 on account of their previously reported nutrient and heavy metal removal capabilities, or based on their physiological and morphological traits, aided by the phyto-guide in chapter 3. As mentioned in chapter 4, appropriate growth media contributes to the effective functioning of biofilters and is required for improved biofilter performance. However, appropriate growth media is but one contributor toward biofilter optimisation, with plant species and physical design additive components. As mentioned, although the presence of vegetation enhances biofilter performance via phytoremediation processes, pollutant immobilisation and extraction varies between plant species. Additionally, due to the competitive nature required of plants for biofilter success, injudicious species introduction potentially threatens invasion.

Therefore, in equipping stormwater biofilters with effective yet sustainable alternatives to exotic phytoremediators, the utilisation of South Africa's extensive biodiversity is initiated. From the findings, indigenous plant species removed significant loads of dissolved heavy metals and ammonia; whereas removal of nitrate and orthophosphate was more variable. Compared with unvegetated media, the plant biofilters were 11% more efficient in removing synthetic stormwater pollution, improving performance as the study developed. Furthermore, comparing indigenous biofilters with alien phytoremediators from similar stormwater biofilter studies, as well as with *Cynodon dactylon* (registered indigenous but may undergo reclassification due to its invasive characteristics), the indigenous plants either outperformed or performed similarly to these. This supports their application in biofilters within local urban stormwater GI initiatives, as well as expands the record of indigenous species proven to be effective phytoremediators.

The best performing plant species (*Prionium serratum*) is promoted for use in biofilter design optimisation, chapter 6, objective 5. In addition, the nutrient and metal removal pathways identified, and the data retrieved from each species' removal performances exposed to the influent range, contributes statistical output for advancing future local modeling endeavours, chapter 7, objective 6.

Efficiencies of indigenous South African plant biofilters for urban stormwater runoff water quality improvement with a focus on nutrients and metals

DM Jacklin[a], IC Brink[a], SM Jacobs[b]

[a]*Department of Water and Environmental Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

[b]*Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

Reproduced and reformatted from an article published in **AQUA – Water Infrastructure, Ecosystems and Society, 70(7), 1094-1110**, with permission from the copyright holder, IWA Publishing.

Abstract

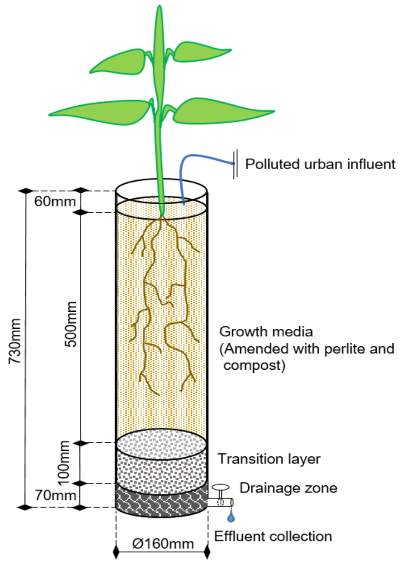
In South Africa, urban activities contribute high levels of pollution to rivers and groundwater via stormwater runoff. In reducing urban stormwater loads engineered plant biofiltration, an effective and self-sustaining component of Green Infrastructure, is a treatment option. The country's extensive natural biodiversity offers untapped potential of indigenous species' use in plant biofilters. This paper presents the findings of a plant biofilter column experiment, which investigated the performance of nine indigenous plant species under varied urban stormwater pollutant load strengths. On average significant loads of dissolved Cd (> 98%), Cu (> 84%), Pb (> 99%) and Zn (> 95%), as well as NH_3 -N (> 93%), were removed by the plant biofilters; whereas removal of NO_3^- -N (-37 to 79%) and PO_4^{3-} -P (-81 to 63%) was more variable. Biofilters equipped with indigenous plant species were on average at least 11% more efficient than unvegetated soil in the removal of urban nutrient and metal pollutants. Over time, planted biofilters improved nutrient and metal removal efficiencies. The results support the inclusion of indigenous plants in biofilters within urban stormwater Green Infrastructure initiatives. Further research to inform plant biofilter design practicalities and assess plant biofilter performance in the field is warranted.

Key words: urban stormwater runoff, metals pollution, nutrients pollution, plant biofilter, Green Infrastructure

Highlights

- This is the first study investigating nutrient and metal removal by indigenous South African plant species.
- Assessment of low, typically observed and high strength pollutant load removal.
- Consistently greater removal by vegetation as opposed to unvegetated soil.
- PO_4^{3-} -P and dissolved Cu removal influenced by compost.

GRAPHICAL ABSTRACT



INTRODUCTION

Increased urban surface imperviousness caused by the rapid growth and densification of cities during urbanisation alters stormwater runoff volume, frequency and quality (Bratieres *et al.* 2008). Urban stormwater consists of a broad range of pollutants that can have a detrimental impact on aquatic systems, posing a major human and environmental health problem (Lim *et al.* 2015). In South Africa, aging, poor quality and poorly maintained conventional grey infrastructure in some cases contribute high levels of pollution to receiving waters, leading to a 500% classification increase (1999 - 2011) of main rivers having poor ecological conditions (DWS 2018). As a result, the country experiences some of the most severe environmental degradation globally, requiring proper urban mitigation strategies to restore ecosystem function and improve resource quality (De Klerk *et al.* 2016).

In contrast to conventional infrastructure approaches that typically consider stormwater as a substance to dispose of rather than a resource to protect, improved urban stormwater management seeks to treat nonpoint pollution, reduce hydrologic disturbance and utilise stormwater as a supplementary resource (Barbosa *et al.* 2012; Fletcher *et al*. 2015). The water sensitive urban design (WSUD) approach promotes the integration of Green Infrastructure (GI) and nature-based solutions to ensure holistic water quality and provision in the urban water cycle (Armitage *et al.* 2014; Dumitru & Wendling 2021). As an efficient and self-sustaining interconnected set of natural and engineered ecological systems, GI has been proven to be capable in successfully treating urban runoff (Prodanovic *et al.* 2018). Internationally, GI has been demonstrated to provide critical maintenance, rehabilitation and purification services in a more cost-effective way than conventional infrastructure (Postel & Thompson 2005).

The use of plant biofiltration has become increasingly popular within GI due to its ability to slow stormwater runoff rates, reduce runoff volumes, decrease particulate transport and retain pollutants prior to discharge into watercourses (Lim *et al.* 2015). As a form of ecological engineering, biofiltration technologies utilise plants to detoxify, degrade and/or remove pollutants from the environment (Visoottiviseth *et al.* 2002). In South Africa, GI is currently an under-realised approach (DWS 2018). The addition of vegetation for the treatment of pollutants enhances removal and sustainability, a process known as phytoremediation, improving biofilter performance (Dietz & Schnoor 2001). The extraction and immobilisation of pollutants by plants does, however, vary between plant species, making the process of plant selection critical to biofilter performance (Read *et al.* 2008). In addition, due to the competitive nature of plants within biofilters, plant selection must consider invasion threat to the recipient ecosystem's biodiversity (Leguizamo *et al.* 2017).

In South Africa, the introduction and invasion of some plants have transformed entire ecosystems, posing a major threat to the country's biodiversity and impacting negatively on ecosystem health (Le Maitre *et al.* 2020). For sustainable GI, conservation cannot be overshadowed by the need for treatment efficiency. Therefore, the use of non-invasive indigenous species which can enhance biofilter performance and are capable of adapting to the recipient habitat, whilst limiting the risk of biodiversity loss should always be promoted (Payne *et al.* 2015). South Africa, recognised as having the world's richest temperate flora comprising of approximately 20 500 plant species (of which 13 265 are endemic) is considered to be both a biodiversity hotspot and a megadiverse country (Hoveka *et al.* 2020). This extensive biodiversity offers relatively untapped potential of indigenous plant species for use in GI that are naturally acclimatised to recipient ecosystems and which do not threaten biodiversity. In urban areas this is particularly important, as urban areas are often the initial sites from which invasions spread (Zengeya & Wilson 2020).

As a result of a lack in local research and design guidelines, South Africa faces a number of GI application challenges. The technology is still perceived as a new concept, which does not yet fit into established municipal guidelines (Pasquini & Enqvist 2019). In response to this need for local research, this paper presents the findings of a large-scale laboratory plant biofilter column study of indigenous South African species for application to urban stormwater quality improvement. In the study we investigated the individual efficiencies of nine indigenous plant species and unvegetated soil exposed to varying concentrations (loads) of nutrients and metals based on published figures of stormwater runoff pollution concentrations and loads. In assessing the indigenous species for potential South African phytoremediation, efficiencies were compared between species across all pollutant loads and with unvegetated soil. Furthermore, plant response to the pollutants and biofilter columns were assessed by comparing leaf and root development. Based on these findings, the potential for indigenous plant species inclusion in local urban stormwater GI initiatives is discussed. This experiment forms part of a larger study on urban stormwater plant biofilter optimisation (Jacklin *et al.* 2021a; Jacklin *et al.* 2021b).

METHODOLOGY

Experiment design

Ninety biofilter columns were constructed from Ø160mm x 730mm PVC piping based on typical urban design guidelines as recommended by Payne *et al.* (2015). Within the columns a drainage outlet was covered by a 70mm drainage zone below a 100mm media transition layer, topped with 500mm growth media amended with compost to support plant establishment (Figure 1). The inner wall of each column was abraded to minimise preferential flow and sealed at the base, allowing effluent extraction for analyses. All the treatments were done in duplicate, with two columns per treatment. A local sandy loam soil type (Stellenbosch, South Africa) with an infiltration rate of 145±17 mm/hr was used, allowing the diffusion of water through the growth media, establishing opportunity for pollutant interaction (Le Coustumer *et al.* 2012).

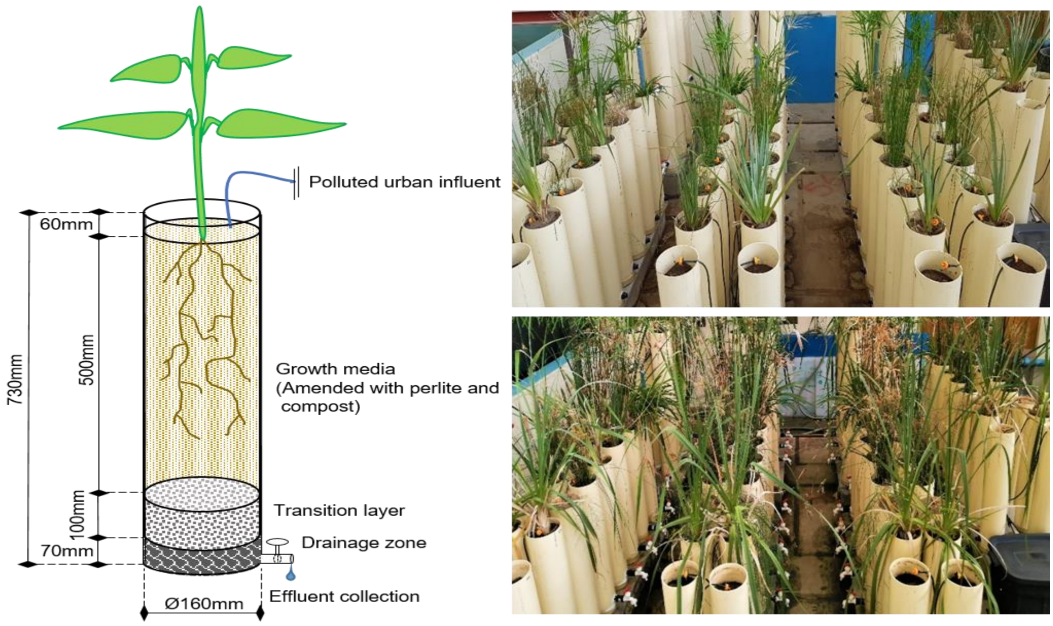


Figure 1. Schematic of experimental column and biofilters at initiation (February 2020) and established (May 2021) state.

The selection of indigenous plant species for South African GI considered knowledge of removal pathways, species distribution, physiological characteristics and morphological traits. The selection process attempted to include plants from varying climatic and environmental conditions, increasing productivity through plant diversity (Leguizamo *et al.* 2017). For optimised phytoremediation, plant growth rate, lifespan, tolerance and hardiness, as well as biomass and roots were considered (Pilon-Smits 2005). The selected plants (Table 1) consist of species adept at varying moisture content, enabling potential use in GI during seasonal fluctuations and at different distances from the stormwater influent source. The plants are capable of rapidly maturing during the experimental period, as well as tolerating inundation and periods of drought, providing distinct assessment of urban pollutant removal performances.

Table 1. Indigenous South African plant species for urban stormwater pollutant removal.

Species	Common name	Habitat	Distribution to South Africa
Prionium serratum	Palmiet	Wet-terrestrial	Endemic
Chasmanthe aethiopica	Cobra lily	Terrestrial	Endemic
Agapanthus africanus	African lily	Terrestrial	Endemic
Cyperus textilis	Umbrella sedge	Aquatic	Endemic
Carpha glomerata	Vleibiesie	Aquatic	Endemic
Strelitzia reginae	Bird-of-paradise	Terrestrial	Indigenous
Dietes iridioides	Small wild iris	Terrestrial	Indigenous
Cynodon dactylon	Common couch grass	Terrestrial	Indigenous
Juncus effusus	Soft rush	Aquatic	Indigenous

The growth media of all biofilter columns were amended with a solid phase commercial compost mixture during transplantation in February 2020 and received municipal tap water for 10 months to allow plant establishment prior to dosing and testing. During the last 2 months of the establishment period the columns were subjected to a flushing regime with each column receiving 5 L tap water per day. This was done to stimulate the discharge of excess nutrients and metals which may have lingered within the columns. During flushing, four preliminary samples were collected at 15 day intervals to confirm the time at which effluent concentration constancy was achieved. After 30 days similar concentrations were measured over 3 sampling rounds. In addition, throughout the study effluent discharge concentrations from the non-polluted biofilter columns recorded were constant, supporting the assumption that existing column concentrations remained constant during synthetic dosing. Following this period, the biofilter columns received four months of synthetic stormwater dosing.

Experimental procedure

Synthetic stormwater (Table 2) was prepared from analytical grade compounds to reflect published low, typically observed and high urban nutrient and metal stormwater pollutant concentrations (obtained from Göbel *et al.* 2007; Barron *et al.* 2019), as well as replaced every 10 days and continuously mixed with pump agitators to ensure uniform dispersion. Irrigation was done by means of submersible pumps via an automated drip irrigation system, with influent concentrations monitored throughout.

Although impermeable urban surfaces increase runoff volume and peak discharge into stormwater biofilters not all rainfall is translated to runoff since flow is reduced by infiltration, ponding and evaporation (Rammal & Berthier 2020). Due to the consolidating nature of urban area imperviousness, the collective impact on water resources can be predicted (Schueler 1992). The experimental dosing regime simulated potential influent volumes over urban area for biofilters sized at 2% of catchment area under typical rainfall events. This produced a twice-weekly dosing of 1.32L for Ø160mm biofilter columns based on typical climatic patterns (i.e. temperate climate with an average annual rainfall of 619 mm) and urban area characteristics (i.e. 37.4% impervious surface area) of Stellenbosch, South Africa (Musakwa & Van Niekerk 2015; SAWS 2020).

Table 2. Influent synthetic stormwater.

Pollutant	Parameter	Influent concentration (mg/L)			Source Chemical
		Low	Typically observed	High	
Nutrients	Ammonia -N	0.20	0.40	2.5	NH_4Cl
	Nitrate -N	0.50	0.95	13.5	KNO_3
	Orthophosphate -P	0.22	0.35	1.5	K_2HPO_4
Metals	Cadmium	0.002	0.0045	0.032	$CdCl_2$
	Copper	0.02	0.045	6.8	$CuSO_4$
	Lead	0.08	0.15	2.8	$PbCl_2$
	Zinc	0.15	0.30	35	$ZnCl_2$

Effluent sampling was undertaken 30 days after initiating the synthetic stormwater dosing and was done at 15 day intervals. The 30 day period ensured removal of non-polluted tap water (used during the establishment phase) from the saturated growth media to limit dilution of the dosing mixtures.

Six sampling rounds were undertaken from December 2020 - March 2021 during which the majority of the species are most active (excluding *C. aethiopica*), with the first round establishing the existing biofilter conditions, prior to synthetic stormwater dosing. A separate assessment period from July - September 2020 was selected for *C. aethiopica* due to the plant's seasonal growth pattern, made possible by its rapid development rate. Water loss to evapotranspiration regulated by individual plant uptake, as well as drying of the media between dosage events, prevents the quantification of pollutant removal by assessing concentration alone. Therefore, the percentage pollutant removal (L_{rem}), considered the influent ($C_{inf}V_{inf}$) and effluent ($C_{eff}V_{eff}$) pollutant loads of each biofilter, rather than concentrations.

$$L_{rem} = \frac{C_{inf}\,V_{inf} - C_{eff}\,V_{eff}}{C_{inf}\,V_{inf}} \text{ x } \frac{100}{1} \qquad \text{Equation 1}$$

where

L_{rem} = pollutant load removal (%)

C_{inf} = influent concentration (mg/L)

V_{inf} = total influent volume for sampling round (L)

C_{eff} = effluent concentration (mg/L)

V_{eff} = effluent volume of sampling round (L)

The effluent samples were tested for dissolved ammonia (NH_3 -N), nitrate (NO_3^- -N) and orthophosphate (PO_4^{3-} -P) in the Stellenbosch University Water Quality Laboratory using a HACH DR3900 spectrophotometer. Metals tests were performed on an Agilent 8800 QQQ ICP-MS instrument for dissolved cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) at the Stellenbosch University Central Analytical Facility: ICP-MS division. Prior to analysis, 0.45 µm syringe filters were used to filter the effluent samples into two 30mL Falcon® tubes for nutrient and metal analyses.

Determination of plant growth response to medium term exposure (6 months) as well as different urban stormwater nutrient and metal strengths, involved an inspection of above- and below-ground physical plant traits. Above-ground traits (leaves or stems) were recorded from February 2020 on a monthly basis, producing 16 measurements, whereas below-ground measurement (roots) were taken only at experiment initiation and conclusion. The number and average lengths of the leaves/stems of each species were compared between pollution strengths, as well as with plants receiving only non-polluted irrigation and plants unamended with compost under typically observed pollutant dosing for the duration of the experiment. For root response to pollution strength and growth media, number of roots and length of the longest root at transplantation were compared with measurements taken for each species at conclusion of the experiment. Due to species' variation in physiological development some measurement differences were noted, e.g. *C. dactylon's* lateral development made recording impractical. In addition, the natural dying back and regrowing cycle of *C. aethiopica* limited physical measurements for the entire study and were excluded.

Data analysis

Statistical analyses were conducted with R Statistical Software. A nonparametric approach was adopted since data were non-normally distributed, as shown by the *Lilliefors test*. Thus, the *Kruskal-Wallis H-test* nonparametric *ANOVA* ascertained the significance of difference in removal percentages. With significance, the *Wilcoxon Rank Sum paired test* compared the percent removal of each pollutant parameter between the plant biofilters for all three influent pollution strengths. Similarly, in assessing the difference in removal performance between vegetated and unvegetated soil over time, the *Wilcoxon Rank Sum paired test* was used. All analyses accepted significance at an unadjusted $p \leq 0.05$.

RESULTS AND DISCUSSION

Effect of influent pollutant strengths on removal efficiencies

The mean nutrient and dissolved metal pollutant load removal percentages over the sampling rounds are depicted in Figure 2. From the figure, it can be seen that percentage removal was influenced by influent values, with higher influent loads generally resulting in higher percentage removals. Different plant species, however, displayed variable results indicating differences in possible treatment pathways. Additionally, percentage load removals varied across pollutant type (nutrient vs metal). Dissolved metal removals were consistently greater than nutrient removals across the dosing strengths, with the exception of Cu, which was less efficiently reduced than nutrient NH_3 -N.

High influent dosing values resulted in efficient dissolved metal removal outcomes (> 99.6%) with no discernible large differences between biofilter columns and plant species. Similarly, nutrients NH_3 -N (> 99.4%) and NO_3^- -N (> 88.2%) loads were efficiently reduced with high dosing values. In contrast, PO_4^{3-} -P was less efficiently removed, with *C. dactylon* (-6.8%) and unvegetated soil (-22.2%) biofilters, returning PO_4^{3-} -P back into the water column, resulting in a net pollutant increase.

When exposed to the more moderate typically observed urban stormwater pollution levels, more variation in percent removal was observed for different plant species, in particular for nutrients and Cu. Contrary to this, all biofilters maintained high Pb removal percentages (> 99.6%). Similar to the high dosing outcomes, P increases were recorded in some biofilters (with associated negative load removal percentages): these were *D. iridioides* (-16.6%), *S. reginae* (-51.1%), *C. aethiopica* (-60.2%) and unvegetated soil (-83.5%). In addition, unvegetated soil was found to leach NO_3^- -N, resulting in a mean pollutant load increase, instead of decrease, of 70.1% over the study period.

Under low strength dosing levels a clearer differentiation of individual biofilter removal performances was found. For dissolved metals, similar to typically observed and high urban dosing strengths, all metals were removed at varying degrees by the different biofilter columns. Consistent with the findings of mean percent pollutant load removal in moderate and high pollution, Cu was more variable than the other metals (ranging between 41.9 and 81.3%), with Pb consistently most successfully removed (> 99.1%). Nutrients removal, however, was found to be more variable with NO_3^- -N and PO_4^{3-} -P showing negative removals (i.e. substances in the effluent were higher than in the dosed influent) in the majority of the biofilter columns. Only the *P. serratum* (61.9%), *J. effusus* (35.6%) and *C. textilis* (40.1%) biofilters removed NO_3^- -N, whilst PO_4^{3-} -P was removed by the *P. serratum* (51.4%) and *J. effusus* (15.9%) columns only. From Figure 2, it can be seen that unvegetated soil biofilters consistently removed the lowest amounts of nutrient and dissolved metal loads across the three pollution strengths for the duration of the study, with a mean pollutant removal percentage of 45.7%.

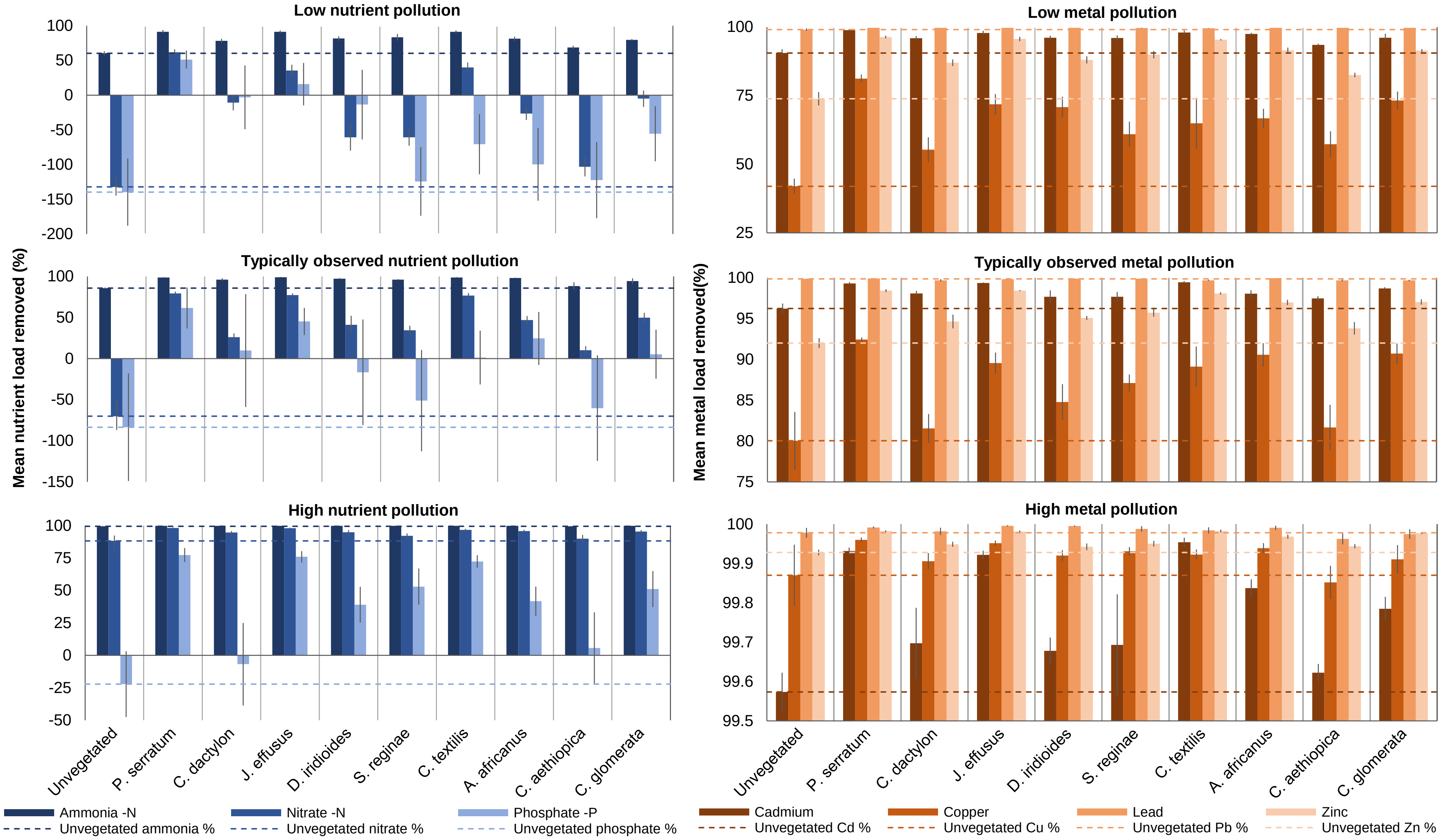


Figure 2. Mean percentage nutrient and metal load removals of the experimental biofilters for the duration of the study. *Note horizontal lines indicating unvegetated soil removal and the variation in vertical axes, error bars indicate ± standard error of each mean.*

All the vegetated biofilters outperformed unvegetated soil for mean removals, with the worst performer being *C. aethiopica,* which had a mean removal of 56.3%, only 10.6% greater than unvegetated soil. In addition, applying the Wilcoxon Rank Sum test to compare removal efficiencies between individual plant species and the unvegetated soil with time, found only *C. aethiopica* not to be significantly different to soil ($p = 0.22$). All other plant species showed significant differences ($p \leq 0.05$) in pollutant load reduction when compared with unvegetated soil. The most efficient biofilters (based on average percentage load removals), with their corresponding significance values, were *P. serratum* ($p = 0.00014$), *J. effusus* ($p = 0.00032$) and *C. textilis* ($p = 0.0018$), removing on average 89.8, 85.3 and 78.6% of urban stormwater pollutant loads respectively.

Plant species performance and possible pollutant removal pathways

Nutrients removal

For the removal of NH_3-N, all vegetated biofilters outperformed unvegetated soil across the low, typically observed and high dosing strengths. Overall, the best performing biofilters were *J. effusus*, *P. serratum* and *C. textilis*, reporting NH_3-N mean percentage removals > 96.7% for all three, whilst unvegetated soil achieved 81.8% mean removal. The worst performing plant biofilter, as well as being the only plant biofilter not significantly different ($p = 0.081$) compared with unvegetated soil was *C. aethiopica*, removing 85.6% of pollutants, which was only 3.8% greater than unvegetated soil. Biological processes for nitrogen removal are known to occur across both aerobic and anaerobic conditions within the different areas of the biofilter column (Payne *et al.* 2014). Efficient NH_3-N removals found in all plant biofilters and unvegetated soil, suggest an enhancement of the NH_4^+ to NO_3^- nitrification process in the upper oxygenated layers of the columns, as well as possibly some volatilisation at the surface area (Blecken *et al.* 2009; Turner *et al.* 2010), even in the absence of vegetation (Barth *et al.* 2020). In the presence of organic matter, of relevance to this study due to the compost amendment during biofilter construction, NH_3-N sorbed to soil through electrostatic and ion exchange interactions can be rapidly nitrified (McNevin *et al.* 1999). The removal of NH_3-N in unvegetated soil, although less efficient than in the presence of plants, suggests a lack of full dependence by the microbial activity, which is responsible for nitrification, on symbioses with plants (Bratieres *et al.* 2008). Within the rhizosphere of the biofilter columns, microbial communities controlling the aerobic conversion of NH_3 to NO_2^- are *Nitrosomonas* bacteria, after which *Nitrobacter* bacteria convert NO_2^- to NO_3^-, which is easily leached, as can be seen when assessing NO_3^--N removal (Hunt *et al.* 2015). The results suggest the occurrence of these processes in the biofilter columns.

For the removal of NO_3^--N, all vegetated biofilters were significantly ($p \leq 0.05$) more efficient than unvegetated soil. Between them, the best performing biofilters were *P. serratum, C.*

textilis and J. effusus, reporting mean removal percentages of 79.8, 71.1 and 70.3%, whilst unvegetated soil leached 37.9% (negative removal). Similar to NH_3 -N, the worst performing plant biofilter for NO_3^- -N removal was *C. aethiopica*, leaching 0.9% (producing rather than removing) of pollutants, which was only 37% more efficient than unvegetated soil. NO_3^- -N increases and low inefficient removal performances by the biofilter columns for the duration of the experiment is an indication of successful biological transformation of captured NH_4^+, NO_2^- and NO_3^-. Resulting in minimal sorption to biofilter media due to oxidized nitrogen's anionic form, releasing NO_3^- -N to the water column (Henderson *et al.* 2007). Experiencing similar NO_3^- increase, Davis *et al.* (2001) suggested incomplete N removal processes due to a combination of inadequate denitrification and natural NO_3^- formation from additional sources within the biofilters between effluent events were responsible for increased NO_3^- -N leaching. From the results, enhanced NO_3^- -N removal in the presence of plants via direct uptake and the rhizosphere's influence on microbial nitrification and denitrification, highlights the importance of vegetation (Muerdter *et al.* 2018).

For the removal of PO_4^{3-} -P, all vegetated biofilters outperformed unvegetated soil across dosing strengths, with the best performing biofilters being *P. serratum, J. effusus* and *D. iridioides,* removing 63.5, 45.7 and 2.9% respectively, with 81.7% leached on average (negative removal) by unvegetated soil. Similar to other nutrients, in releasing 58.9% of the influent PO_4^{3-} -P load *C. aethiopica* was the worst performing plant biofilter, which was only 22.8% more efficient than unvegetated soil. Comparing the plant biofilters with unvegetated soil, the Wilcoxon Rank Sum test reported only two significantly better performers: *P. serratum* ($p = 0.016$) and *J. effusus* ($p = 0.029$). Compared with the other nutrients, removal of PO_4^{3-} -P was more variable, reporting a net increase in pollutant load in some biofilters instead of a decrease under each of the influent strengths. Phosphorous in soil is sorbed to soil particles or incorporated into organic matter and released by sorption and desorption (Holtan *et al.* 1988). Biofilters equipped with plants extract PO_4^{3-}, which is then concentrated 100 – 1000 times in the xylem sap and stored for future plant use in the plant tissue, typically 0.5% phosphorous by dry weight (Muerdter *et al.* 2018). Of note in this study, the best performing plant biofilters were equipped with *P. serratum* and *J. effusus*, recognised for their high biomass content. Removal, however, varies between plant species and is influenced by direct and mycorrhizal (symbiotic association between a plant and a fungus) uptake (Fowdar *et al.* 2017). In addition, amending biofilter columns with compost have been found to increase PO_4^{3-} -P in effluent runoff, severely hindering pollutant load removal compared to unamended biofilters (Lenth & Dugapolski 2011). In this study PO_4^{3-} -P removal increased with time. This was reported in all three pollution treatments, with performance in unvegetated and vegetated columns improving from 125.7% production in sampling round 1 to 64.1% removal in sampling round 5.

Metals removal

The mean dissolved metal load removal percentages (Figure 2) were relatively high across dosing strengths. Similar to nutrient removal, all vegetated biofilters outperformed unvegetated soil for metal removals as illustrated by the horizontal lines on the graphs. The ecological consequences of heavy metals in biofilters are mainly related to heavy metal solubility and mobility, which influences leaching and removal via microbial activity and, ultimately, plant uptake via adsorption and desorption (Krishnamurti *et al.* 2005). In urban biofilters, heavy metal movement through the soil profile occurs mainly in solution phase for effluent deposition and has been found to be of limited extent, even in highly polluted conditions (Emmerich *et al.* 1982). For stormwater quality improvement purposes, the amounts available to plants for uptake influences plant growth and water quality, with potential removal varying with regard to plant species, pH, ionic strength, redox potential, composition of solution and valence (Da Silva & Williams 1976). A benefit of plant biofilters is the acidification of the rhizosphere during effective NH_3 -N uptake and subsequent proton release, which can influence metal speciation due to altered soil particle surface charge, thereby facilitating redox reactions (Laurenson *et al.* 2013). Therefore, given the complex processes affecting metals removal in plant biofilters, the differences in removal efficiencies and potential effects based on measured data were reported with reference to possible removal mechanisms provided as supposition only. However, further research into this area is warranted.

The influent concentrations of highly toxic Cd was lower when compared with Cu, Pb and Zn, due to the metal being generally present at low concentrations in terrestrial environments (originating from mainly anthropogenic activities) (Alloway & Steinnes 1999). The mean Cd, Zn and Pb removal percentages by the biofilters were high across the different pollution dosing strengths, ranging from 90.5 to 99.9%, 73.9 to 99.9% and 99.1 to 99.9% respectively. The practical effects of these differences were considered to be minimal and it was accepted that all plant biofilters removed these metals adequately. The most efficient plant biofilters for the removal of Cd contained the species *P. serratum*, *C. textilis* and *J. effusus*, with mean removal percentages > 99.1% for all three. As reported by the Wilcoxon Rank Sum test, removal of Cd by all plant biofilters were significantly different ($p \leq 0.05$) compared with unvegetated soil, which removed 95.4% of the influent load.

For Pb, the most effective biofilters contained the species *A. africanus, P. serratum and D. iridioides,* each with > 99.8% mean percentage removals. In contrast to Cd, for the removal of Pb, all plant biofilter did not have significant percentage removal differences ($p > 0.05$) compared with unvegetated soil, which removed 99.6% of pollutants.

Similar to Cd, *P. serratum, J. effusus* and *C. textilis* biofilters most effectively removed Zn, with mean percentage removals of 98.3, 98.1 and 97.8% respectively. For the removal of Zn, all plant biofilters showed statistically significant percentage removals ($p \leq 0.05$) when compared with unvegetated soil, which removed 88.6% of the pollutant loads.

These high removal percentages found are similar to published findings reporting on alternating influent sources (see Barron *et al.* 2019), biological retention (see Davis *et al.* 2001) and the impact of a carbon source on heavy metal removal (see Blecken *et al.* 2009). Although minimal, in the presence of vegetation removal is enhanced, with non-essential Cd and Pb taken up without offering any known direct biological benefit to plants (see Ali *et al.* 2013).

Cu removal was found to be more variable with mean removal across the different dosing strengths ranging from 41.9 to 99.9%. This is consistent with similar published investigations (see Davis *et al.* 2001; Lenth & Dugapolski 2011). The *P. serratum, C. glomerata* and *J. effusus* biofilters were most efficient for the removal of Cu, with 91.2, 87.9 and 87.1% mean removals respectively. For the removal of Cu, all plant biofilters were significantly more efficient than unvegetated soil ($p \leq 0.05$), which achieved 73.9% removal, except for two biofilters containing the species *C. dactylon* ($p = 0.073$) and *C. aethiopica* ($p = 0.088$). This variation may be due to the formation of Cu-organic matter complexes in the presence of compost, since Cu has the strongest affinity to organic matter out of all tested metals (Ponizovsky *et al.* 2006). Organic matter in solid or dissolved form significantly influences treatment in stormwater biofilters, while solid organic matter adsorption with Cu through immobilisation is a main pathway for Cu filtration in soil (Temminghoff *et al.* 1997). Dissolved organic matter has been reported to mobilise Cu (Amery *et al.* 2007) and in some cases have resulted in Cu leaching lasting several years (Mullane *et al.* 2015). The organic matter added to the biofilter columns was in the form of a high solid content compost, thus it is accepted that Cu immobilising likely occurred.

In summary, the removal of dissolved metals were high overall in both unvegetated and vegetated plant biofilters. This is in line with published literature as the majority of metals are expected to have been removed by unvegetated mechanisms such as filtration and adsorption (Hatt *et al.* 2007). Rapid metal removal has been reported to occur in the top layers of biofilters, with > 82% removal in the first 150 mm found by Blecken *et al.* (2009) varying slightly with the findings of Davis *et al.* (2001) reporting > 92% removal in the upper 270 mm of the growth media. The removal of micronutrients Cu and Zn via direct uptake pathways is enhanced in the presence of plants (Muerdter *et al.* 2018), whilst non-essential toxic Cd and Pb is extracted and distributed to all plant organs (Hocaoglu-Ozyigit & Genc 2020). The additive, though relatively small, metal uptake by plants can provide a permanent pollutant removal pathway via harvesting as metal accumulation in plant tissue occurs over time (Kumar *et al.* 2017). However, long term (years or decades) metal accumulations warrant further investigation.

Effect of vegetation and time on removal efficiencies

In assessing the influence of vegetation on urban stormwater pollutant removal over time, the combined average load removals efficiencies were compared with that of unvegetated soil for nutrient and metals removals. For low dosing (Figure 3), Wilcoxon Rank Sum statistical analysis showed that the presence of vegetation had a significant effect on overall nutrient ($p = 0.0046$) and metal ($p = 0.0000051$) removal efficiencies over time. Vegetation consistently removed greater pollutant loads than unvegetated soil for the duration of the experiment.

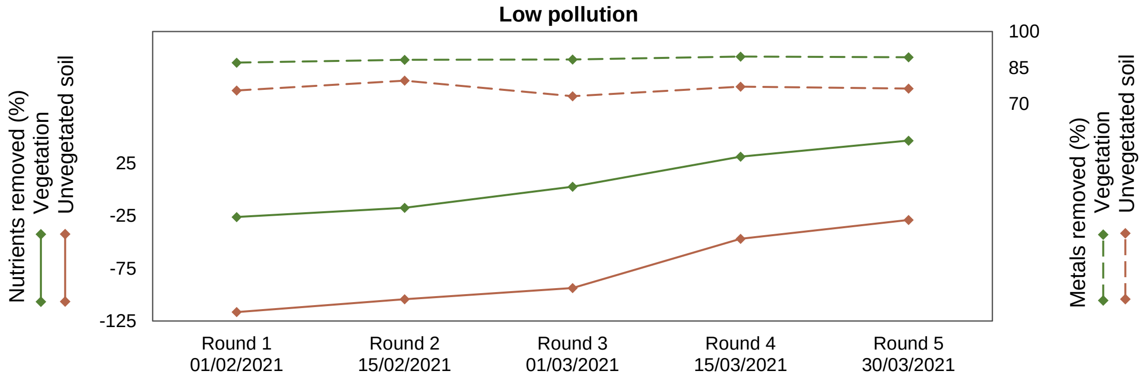


Figure 3. Mean low strength nutrient and metal removal by vegetated and unvegetated biofilters with time.

Exposed to typically observed pollution levels (Figure 4), similar results to low pollution for nutrient and metal removal were found. In comparing removal efficiencies, vegetation was found to be significantly more efficient than unvegetated soil for the removal of both nutrients $p = 0.0093$) and metals ($p = 0.0060$). In addition, metal removal efficiencies in unvegetated soil declined over the last round of sampling, whilst vegetation maintained removal efficiency.

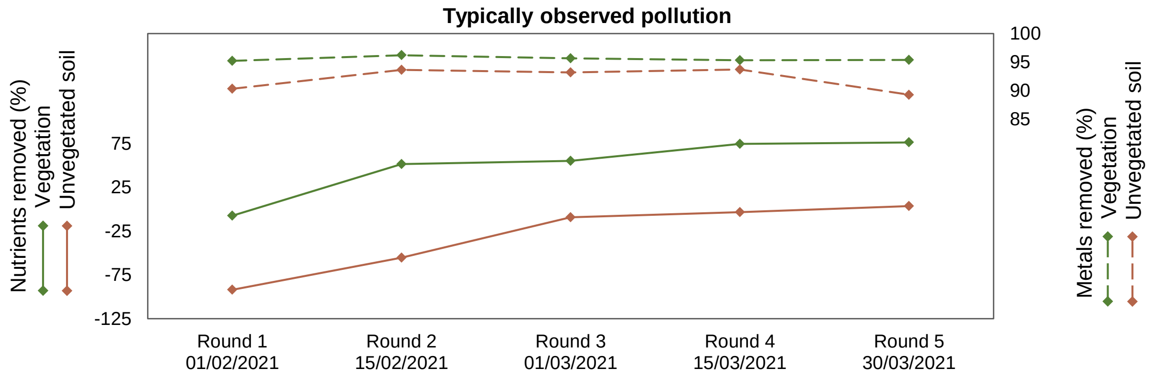


Figure 4. Mean typically observed strength nutrient and metal removal by vegetated and unvegetated biofilters with time

In comparing removal performances between vegetated and unvegetated soil for high strength urban pollution (Figure 5), no significant differences were found for both nutrient ($p = 0.096$) and metal ($p = 0.076$) removals. Similar to typically observed pollution levels, metal removal efficiencies in unvegetated soil declined in the final sampling round, whilst vegetation maintained treatment efficiency. Although removal was consistently greater in the presence of vegetation, due to percent concentration reduction being strongly dependent on influent concentration, the high influent concentration may have been the reason for the high removal percentages, particularly for metals (see Lampe *et al.* 2015), as this function also applies to pollutant loads.

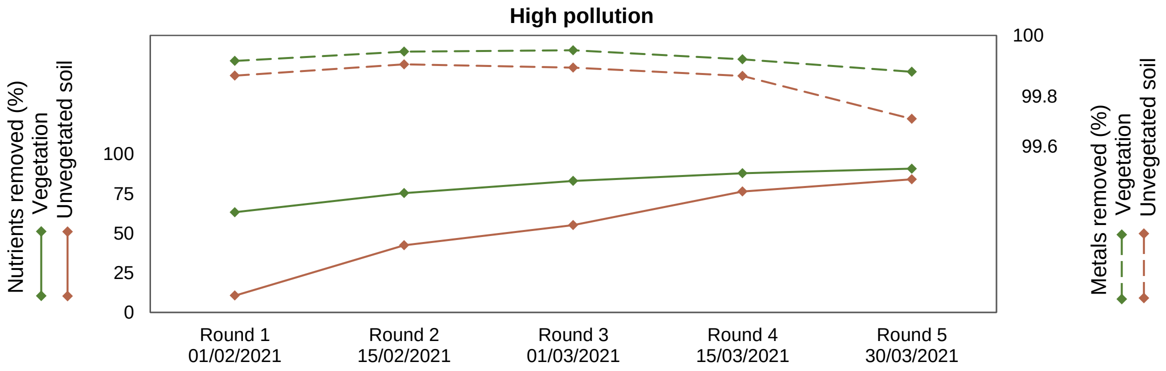


Figure 5. Mean high strength nutrient and metal removal by vegetated and unvegetated biofilters with time.

Efficient urban pollutant removal by unvegetated soil in this study, particularly of metals, emphasizes the growth media's role in plant biofiltration systems. Notwithstanding the importance of this filtration medium, removal efficiencies for unvegetated biofilters were found to decline or reach a possible upper limit over time. This may have been due to the reaching of maximum soil adsorption capacities and / or biofilms formation in and over the growth media (see Singh *et al.* 2018), clogging the biofilters. As stated previously, further longer term studies are required to ascertain the practical efficient lifespans of these types of plant biofilters. For nutrients, with similar studies using soil unamended with compost, large portions of nutrients were removed by unvegetated soil via filtration processes (see Hatt *et al.* 2007; Henderson *et al.* 2007). Over time, enhanced nutrient removal in both the vegetated and unvegetated biofilters was observed, particularly during PO_4^{3-} -P flushing due to possible media desorption and ultimate leaching from the biofilters. This nutrient removal enhancement is suspected to have been predominantly as a result of the appreciable PO_4^{3-} -P release from the amended compost growth media at experimental initiation, which stabilises with time. Metals removal, although generally efficient, varied between vegetated and unvegetated biofilters with time, with a slight decline in performance observed in unvegetated soil over the last round of sampling, whilst vegetation maintained treatment efficacy.

Plant species appear to have a significant effect on maintaining infiltration (see Le Coustumer *et al.* 2012), enhancing removal performance, highlighting the importance of vegetation for nutrient and metal removal by biofilters. As mentioned, plants present additional removal pathways for pollutants in biofilters, for example direct uptake and indirectly by optimising soil microbial conditions (Read *et al.* 2008).

Pollutant load as an insight into plant biofilter performance

The distribution of pollutant loads (Table 3) was calculated as a rough estimate to provide better insight into biofilter efficiencies, as the use of concentration as a compound parameter alone, accounting for mass and volume, does not consider variation in through flow volumes, nor is it a reflection of the extent of pollutants entering and leaving a system. For each water quality sampling round, the effluent discharged by each biofilter column during the 15 day period was collected to assess hydrologic improvements. A significant amount of water was retained by the biofilters and did not drain from the system. This water was eventually lost through evapotranspiration, with pollutants either retained by the soil or removed by the plants. Each plant's water retention capacity was established, by deducting the retention contribution of the growth media only (unvegetated soil) from the recorded plant biofilter columns, allowing for estimating pollutant load distribution as the influent and effluent concentrations and volumes were controlled and recorded respectively. Vegetative pollutant load retention considered the mean retention across the plant biofilter columns. For precise assessment of water quality improvement, GI initiatives needs to consider the extent of water evapotranspiration, influencing mass load reductions.

Table 3. Estimate of pollutant load distribution.

Pollution type	Pollutant path	Total pollutant mass after 5 sampling rounds (mg)						
		NH_3 -N	NO_3^- -N	PO_4^{3-} -P	Cd	Cu	Pb	Zn
Low	Influent mass	6.60	16.50	7.26	0.066	0.66	2.64	4.95
	Retained by soil only	3.99	-21.79	-10.14	0.048	0.28	2.62	3.66
	Retained by vegetation	5.48	-2.39	-3.40	0.051	0.44	2.63	4.50
Typically observed	Influent mass	13.20	31.35	11.55	0.148	1.49	4.95	9.90
	Retained by soil only	11.32	-23.57	-9.65	0.143	1.02	4.86	9.11
	Retained by vegetation	12.71	15.88	0.25	0.146	1.13	4.90	9.55
High	Influent mass	82.50	445.50	49.50	1.056	225.06	91.08	1155.00
	Retained by soil only	82.04	392.79	-10.98	1.051	224.77	91.06	1154.17
	Retained by vegetation	82.32	423.50	22.50	1.054	224.88	91.07	1154.58

Pollutant distribution of the biofilters for low, typically observed and high strength pollution depict biofiltration as an effective treatment method. There is however some variation, with vegetation consistently outperforming unvegetated soil, but only significantly for the removal of low and typically observed urban stormwater pollution. Poorly retained nutrients NO_3^- -N and PO_4^{3-} -P, which were found to leach out of the system, may deteriorate the water-quality of receiving watercourses and degrade natural ecosystems. To combat this threat, the responsible engineer is required to optimise the biofiltration system and make the necessary changes to design. For instance, the results highlight the importance of selecting appropriate plant species for NO_3^- -N removal, with plants differing in removal efficacy. In addition, by adding solid phase compost during biofilter construction, PO_4^{3-} -P leachate may be mitigated. As some plants rely on compost for establishment, the use of solid material must be promoted, supplying carbon for NO_3^- -N denitrification and limiting the dissolution and deposition of dissolved Cu.

Plant functional response

The root number and length of the longest root for each plant was taken on two occasions (Table 4), during transplantation and experiment conclusion, whilst the length and number of above-ground traits (Figure 6) for each plant were recorded on a monthly basis. Plant species exposed to each of the urban stormwater pollution dosing strengths were compared with each other, as well as with similar specimens receiving non-polluted tap water under similar volumetric dosing regimes. In addition, to assess the need for compost during biofilter construction, the plants' traits were compared between amended and unamended biofilters.

Table 4. Development of below-ground traits, initial and final root number and length of longest root.

Species	Low pollution		Typically observed pollution		High pollution		Polluted* unamended with compost		Non-polluted amended with compost	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	Number of roots									
P. serratum	38	106	45	121	41	101	49	83	43	68
J. effusus	91	366	114	398	122	341	104	337	120	260
D. iridioides	61	157	79	176	88	183	74	169	58	134
S. reginae	5	10	4	12	5	10	5	11	4	7
C. textilis	156	523	127	588	134	545	174	513	149	461
A. africanus	32	64	24	75	28	69	29	75	31	51
C. glomerata	64	134	66	144	58	125	61	139	65	117
	Length of the longest root (cm)									
P. serratum	34.1	66.7	29	72.8	38.9	63.4	27.1	66.8	28.9	51.9
J. effusus	21.2	77.7	24.5	69.4	23.3	66.1	26.8	64.8	27.5	47.3
D. iridioides	17.8	58.8	14.8	59.4	20.1	60.9	16.8	61.1	19.6	51.3
S. reginae	9.5	15.4	10.3	18.8	8.9	16.9	11.3	17.6	10.1	13.6
C. textilis	30.3	69.7	27.9	74.6	34.8	68.8	31.3	64.6	31.5	48.5
A. africanus	23.4	35.5	25.8	37.6	24.9	38	20	36	21.1	31.4
C. glomerata	18.1	38.9	17.8	42.5	18.9	44.3	17.7	37.7	19	29.6

*Exposed to typically observed pollution strength.

As a result of the natural dying back and regrowing cycle of *C. aethiopica* limiting physical measurements, it was excluded from analyses. Furthermore, the common phytoremediator *C. dactylon* specimens were not assessed, as those exposed to typically observed and high urban pollution strengths had wilted and died in April 2021, indicating a negative functional response. Mortality in only *C. dactylon* may be due to the plant's morphological development which extends laterally, increasing above ground contact with pollutants during dosage events, particularly high concentration metals.

Statistical analyses used to compare the above- and below-ground traits between the same species across the three pollution dosing strengths indicated no significant differences ($p > 0.05$) in plant growth for each species. Similarly, although greater variation in above- and below-ground traits were reported when comparing plants exposed to typically observed synthetic stormwater pollution and plants receiving non-polluted water, both amended with compost, no significant differences were reported for all species. Here, the number and length of leaves (stems for *J. effusus, C. textilis* and *C. glomerata*) of compost amended plants irrigated with synthetic stormwater was greater than non-polluted plants, presenting a positive functional response to synthetic stormwater. Improved trait development in polluted species may be due to the availability of nutrients for uptake, with metals not adversely affecting growth due to possibly majority sorption and ultimate stagnation in the top parts of the growth columns.

In comparing plant trait development between biofilters amended with compost and biofilters in unamended soil, both under synthetic stormwater irrigation, no statistically significant differences were found. Although the plants amended with compost showed greater root and leaf/stem numbers and lengths, the differences were not of any practical importance since all the plants maintained strong development. This may have been due to the dosed influents supplying plants with adequate nutrients to support plant growth and establishment, even in the absence of composted soils. The practical significance of this result is the possibility of using compost to establish plants initially in outdoor (less sheltered) environments, thereafter allowing polluted stormwater to provide plant nourishment without the need to add compost as an ongoing maintenance measure. This may also put a time limit on the initial nutrient leaching (as was found in this study) from the compost, allowing for more stable nutrient removals once the plants are established and the initial compost leaching has stabilised.

CONCLUSIONS

For the removal of low, typically observed and high urban stormwater pollution, biofilters equipped with indigenous South African plant species were more efficient than unvegetated soils. Significant loads of dissolved Cd, Cu, Pb and Zn, as well as NH_3 -N were removed from the synthetic stormwater, whereas removal of NO_3^- -N and PO_4^{3-} -P was more variable. The addition of organic matter to the biofilter growth media, in the form of amended compost during construction, resulted in leached PO_4^{3-} -P and possibly hindered dissolved Cu sorption to the soil. The general removal capacity of indigenous South African plant species, support their inclusion as phytoremediators in efficient as well as sustainable GI initiatives to reduce nutrient and metal loads in urban stormwater runoff, supplementing the findings of Milandri *et al.* (2012) whom investigated the nutrient removal performance of locally-occurring plant species.

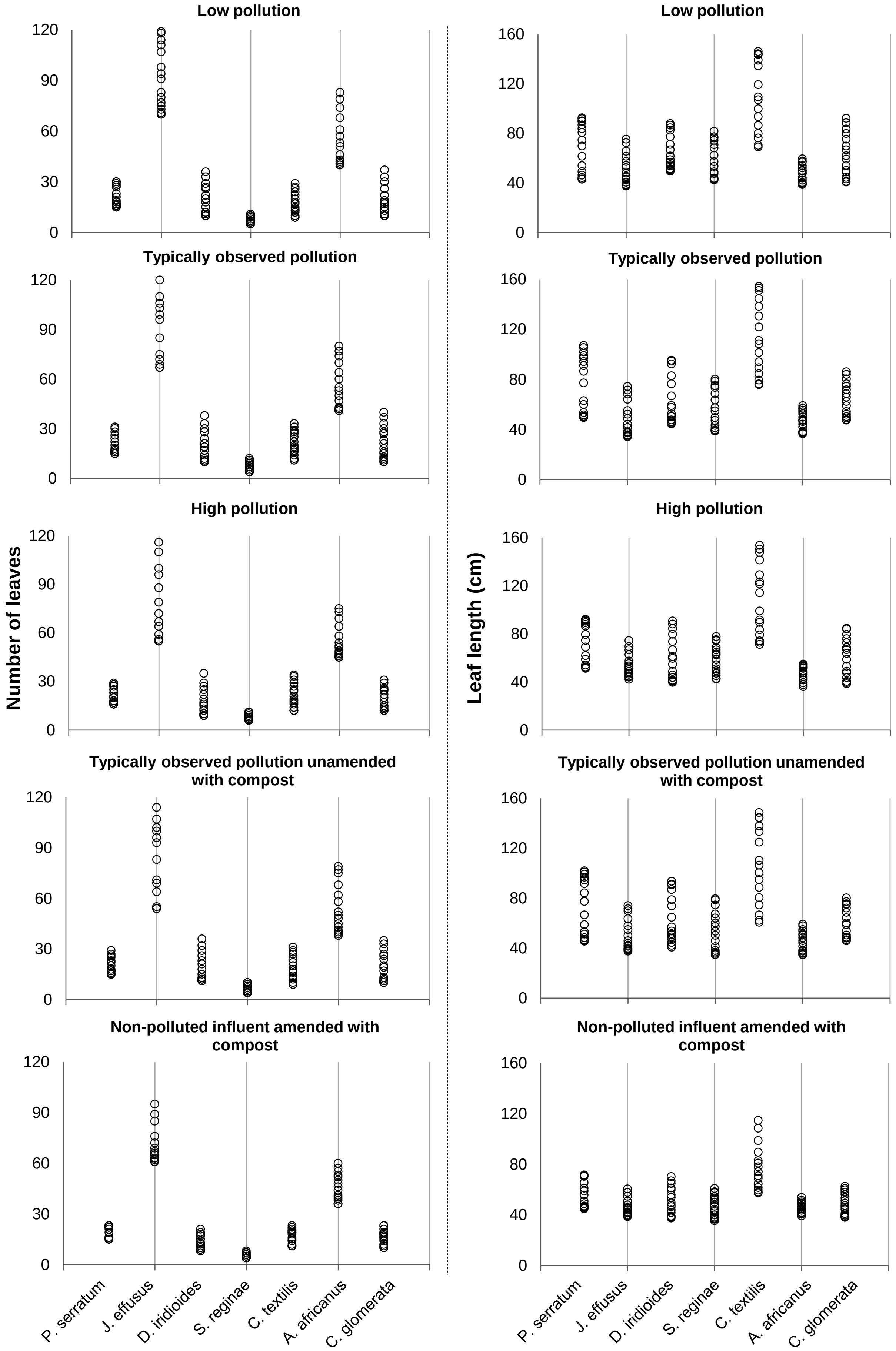


Figure 6. Development of above-ground traits, leaf number and mean lengths recorded on 16 occasions during the experimental period.

In South Africa, due to variable seasonal conditions, species selection must promote a variation of indigenous plants accustomed to different local environmental and climatic conditions. This local heterogeneity will allow dormancy in one species to be compensated for by another, optimising GI pollutant treatment whilst maintaining conservation.

Effective metal sorption, particularly to soil in the top layer of the biofilter column (see Blecken *et al.* 2010), creates potential for shallow biofiltration systems. These systems are more easily constructed and potentially homogenous with existing drainage infrastructure, promoting the integration of small-scale biofilters in local GI systems throughout a spatially limited urban area. This adaptation in urban planning and design is effective yet sensitive to issues of water protection and environmental conservation (Wong 2006). Due to the potential threat of invasion by introducing potentially invasive, rapid growing, hardy and tolerant species to local urban areas, we recommend longer laboratory studies and field investigations to verify the results.

ACKNOWLEDGEMENT

This research was funded by the National Research Foundation (NRF) Thuthuka Fund, with project identity: TTK180418322426.

REFERENCES

Ali H., Khan E. & Sajad M. A. 2013 Phytoremediation of heavy metals- concepts and applications. *Chemosphere*, **91**(7), 869-881.

Alloway B. J. & Steinnes E. 1999 Anthropogenic additions of cadmium to soils. In: *Cadmium in soils and plants*, M. J. McLaughlin & B. R. Singh (eds.), Springer, Heidelberg.

Amery F., Degryse F., Degeling W., Smolders E. & Merckx R. 2007 The copper-mobilizing-potential of dissolved organic matter in soils varies 10-fold depending on soil incubation and extraction procedures. *Environmental Science and Technology*, **41**(7), 2277–2281.

Armitage N., Fisher-Jeffes L., Carden K., Winter K., Naidoo V., Spiegel A., Mauck B. & Coulson D. 2014 *Water sensitive urban design (WSUD) for South Africa: Framework and guidelines.* Report no TT 588/14, WRC, Gezina.

Barbosa A. E., Fernandes J. N. & David L. M. 2012 Key issues for sustainable urban stormwater management. *Water Research*, **46**(20), 6787–6798.

Barron N. J., Deletić A., Jung J., Fowdar H., Chen Y. & Hatt B. E. 2019 Dual-mode stormwater-greywater biofilters: The impact of alternating water sources on treatment performance. *Water Research*, **159**, 521–537.

Barth G., Otto R., Almeida R. F., Cardoso E. J. B. N., Cantarella H. & Vitti G. C. 2020 Conversion of ammonium to nitrate and abundance of ammonium-oxidizing-microorganism in tropical soils with nitrification inhibitor. *Scientia Agricola*, **77**(4).

Blecken G. T., Zinger Y., Deletić A., Fletcher T. D. & Viklander M. 2009 Impact of a submerged zone and a carbon source on heavy metal removal in stormwater biofilters. *Ecological*

Engineering, **35**(5), 769–778.

Blecken G. T., Zinger Y., Deletić A., Fletcher T. D., Hedström A. & Viklander M. 2010 Laboratory study on stormwater biofiltration: Nutrient and sediment removal in cold temperatures. *Journal of Hydrology*, **394**(3–4), 507–514.

Bratieres K., Fletcher T. D., Deletić A. & Zinger Y. 2008 Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water Research*, **42**(14), 3930–3940.

Bunt A. C. 2012 *Media and mixes for container-grown plants: A manual on the preparation and use of growing media for pot plants*. Unwin Hyman Ltd, London.

Da Silva J. J. R. F. & Williams R. J. P. 1976 The uptake of elements by biological systems. In: *Biochemistry*, Springer, Heidelberg, pp. 67–121.

Davis A. P., Shokouhian M., Sharma H. & Minami C. 2001 Laboratory study of biological retention for urban stormwater management. *Water Environment Research*, **73**(1), 5–14.

De Klerk A. R., Oberholster P. J., Van Wyk J. H., Truter J. C., Schaefer L. M. & Botha A. M. 2016 The effect of rehabilitation measures on ecological infrastructure in response to acid mine drainage from coal mining. *Ecological Engineering*, **95**, 463–474.

Dietz A. C. & Schnoor J. L. 2001 Advances in phytoremediation. *Environmental Health Perspectives*, **109**, 163–168.

DWS 2018 Department of Water and Sanitation: National water and sanitation master plan. https://www.gov.za/sites/default/files/gcis_document/201911/national-water-and-sanitation-master-plandf.pdf (accessed 07 June 2021).

Emmerich W. E., Lund L. J., Page A. L. & Chang A. C. 1982 Movement of heavy metals in sewage sludge-treated soils. *Journal of Environmental Quality*, **11**(2), 174-178.

Fletcher T. D., Shuster W., Hunt W. F., Ashley R., Butler D., Arthur S., Trowsdale S., Barraud S., Semadeni-Davies A., Bertrand-Krajewski J. L. & Mikkelsen P. S. 2015 SUDS, LID, BMPs, WSUD and more: The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, **12**(7), 525–542.

Fowdar H. S., Hatt B. E., Cresswell T., Harrison J. J., Cook P. L. M. & Deletić A. 2017 Phosphorus fate and dynamics in greywater biofiltration systems. *Environmental Science and Technology*, **51**(4), 2280–2287.

Göbel P., Dierkes C. & Coldewey W. G. 2007 Storm water runoff concentration matrix for urban areas. *Journal of contaminant hydrology*, **91**(1–2), 26–42.

Hatt B. E., Fletcher T. D. & Deletić A. 2007 Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes. *Water Science and Technology*, **56**(12), 11–19.

Henderson C., Greenway M. & Phillips I. 2007 Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms. *Water Science and Technology*, **55**(4), 183–191.

Hocaoglu-Ozyigit A. & Genc B. N. 2020 Cadmium in plants, humans and the environment. *Frontiers in Life Sciences and Related Technologies*, **1**(1), 12–21.

Holtan H., Kamp-Nielsen L. & Stuanes A. O. 1988 Phosphorus in soil, water and sediment: An overview. *Phosphorus in freshwater ecosystems*, 19–34.

Hoveka L. N., Van der Bank M. & Davies T. J. 2020 Evaluating the performance of a protected area network in South Africa and its implications for megadiverse countries. *Biological Conservation*, **248**, 108577.

Hunt W. F., Lord B., Loh B. & Sia A. 2015 Selection of plants that demonstrated nitrate removal characteristics. In: *Plant selection for bioretention systems and stormwater treatment practices*, Springer, Singapore, pp. 7-20.

Jacklin D. M., Brink I. C. & Jacobs S. M. 2021a Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators with a focus on green infrastructure. *Water SA,* **47**(3), 317-325.

Jacklin D. M., Brink I. C. & Jacobs S. M. 2021b Urban stormwater nutrient and metal removal in small-scale green infrastructure: Exploring engineered plant biofilter media optimisation. *Water Science and Technology,* **84**(7), 1715-1731.

Krishnamurti G. S. R., McArthur D. F. E., Wang M. K., Kozak L. M. & Huang P. M. 2005 Biogeochemistry of soil cadmium and the impact on terrestrial food chain contamination. In: *Biogeochemistry of trace elements in the rhizosphere*, P. M. Huang & G. Gobran (eds.), Elsevier, Amsterdam, Netherlands, pp. 197–257.

Kumar B., Smita K. & Flores L. C. 2017 Plant mediated detoxification of mercury and lead. *Arabian Journal of Chemistry*, **10**, 2335-2342.

Lampe L., Barrett M., Woods-Ballard B., Martin P., Jefferies C. & Hollon M. 2005 *Performance and whole life costs of Best Management Practices (BMPs) and Sustainable Urban Drainage Systems (SUDS)*, Water Environment Research Foundation (WERF), Abertay University, London.

Laurenson G., Laurenson S., Bolan N., Beecham S. & Clark I. 2013 The role of bioretention systems in the treatment of stormwater. *Advances in Agronomy*, **120**, 223–274.

Le Coustumer S., Fletcher T. D., Deletić A., Barraud S. & Poelsma P. 2012 The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Research,* **46**(20), 6743–6752.

Le Maitre D. C., Blignaut J. N., Clulow A., Dzikiti S., Everson C. S., Görgens A. H. M. & Gush M. B. 2020 Impacts of plant invasions on terrestrial water flows in South Africa. In: *Biological Invasions in South Africa*, D. Simberloff (ed.), Springer, Cham, pp. 431–457.

Leguizamo M. A. O., Gómez W. D. F. & Sarmiento M. C. G. 2017 Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands: A review. *Chemosphere*, **168**, 1230–1247.

Lenth J. & Dugapolski R. 2011 *Compost-amended biofiltration swale evaluation,* Report WA-RD793.1, Washington State Department of Transportation, Washinton, United States of America.

Lim H. S., Lim W., Hu J. Y., Ziegler A. & Ong S. L. 2015 Comparison of filter media materials for heavy metal removal from urban stormwater runoff using biofiltration systems. *Journal of Environmental Management*, **147**, 24–33.

McNevin D., Barford J. & Hage J. 1999 Adsorption and biological degradation of ammonium and sulfide on peat. *Water Research,* **33**(6), 1449–1459.

Muerdter C. P., Wong C. K. & LeFevre G. H. 2018 Emerging investigator series: The role of vegetation in bioretention for stormwater treatment in the built environment: Pollutant removal, hydrologic function, and ancillary benefits. *Water Research and Technology*, **4**(5), 592–612.

Mullane J. M., Flury M., Iqbal H., Freeze P. M., Hinman C., Cogger C. G. & Shi Z. 2015 Intermittent rainstorms cause pulses of nitrogen, phosphorus, and copper in leachate from compost in bioretention systems. *Science of the Total Environment*, **537**, 294–303.

Musakwa W. & Van Niekerk A. 2015 Monitoring sustainable urban development using built-up area indicators: a case study of Stellenbosch, South Africa. *Environment, Development and Sustainability*, **17**(3), 547–566.

Pasquini L. & Enqvist J. P. 2019 *Green infrastructure in South African cities,* Report CSP, African Centre for Cities, National Treasury, South Africa.

Payne E. G. I., Fletcher T. D., Cook P. L. M., Deletić A. & Hatt B. E. 2014 Processes and drivers of nitrogen removal in stormwater biofiltration. *Critical Reviews in Environmental Science and Technology*, **44**(7), 796–846.

Payne E. G. I., Hatt B. E., Deletić A., Dobbie M. F., McCarthy D. T. & Chandrasena G. I. 2015 *Adoption guidelines for stormwater biofiltration systems - Summary report*. Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

Pilon-Smits E. 2005 Phytoremediation. *Annual Review of Plant Biology,* **56**, 15–39.

Ponizovsky A. A., Thakali S., Allen H. E., Di Toro D. M. & Ackerman A. J. 2006 Effect of soil properties on copper release in soil solutions at low moisture content. *Environmental Toxicology and Chemistry: An International Journal*, **25**(3), 671–682.

Postel S. L. & Thompson B. H. 2005 Watershed protection: Capturing the benefits of nature's water supply services. *Natural Resources Forum*, **29**(2), 98-108.

Prodanovic V., Zhang K., Hatt B. E., McCarthy D. & Deletić A. 2018 Optimisation of lightweight green wall media for greywater treatment and reuse. *Building and Environment*, **131**, 99–107.

Rammal M. & Berthier E. 2020 Runoff losses on urban surfaces during frequent rainfall events: A review of observations and modeling attempts. *Water*, **12**(10), 2777.

Read J., Wevill T., Fletcher T. D. & Deletić A. 2008 Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research*, **42**(4–5), 893–902.

SAWS. 2020 South African Weather Service. https://www.weathersa.co.za/ (accessed 13 August 2020).

Schueler T. R. 1992 Mitigating the adverse impacts of urbanization on streams: a comprehensive strategy for local government. In: *Watershed Restoration Sourcebook,* P. Kimble & T. Schueler (eds.), Washington, United States, pp. 21–31.

Singh R., Bhunia P. & Dash R. R. 2018 Understanding intricacies of clogging and its alleviation by introducing earthworms in soil biofilters. *Science of The Total Environment*, **633**, 145–156.

Temminghoff E. J. M., Der Zee S. E. & De Haan F. A. M. 1997 Copper mobility in a copper-contaminated sandy soil as affected by pH and solid and dissolved organic matter. *Environmental Science and Technology*, **31**(4), 1109–1115.

Turner D. A., Edis R. B., Chen D., Freney J. R., Denmead O. T. & Christie R. 2010 Determination and mitigation of ammonia loss from urea applied to winter wheat with N-(n-butyl) thiophosphorictriamide. *Agriculture, Ecosystems and Environment*, **137**(3), 261–266.

Visoottiviseth P., Francesconi K. & Sridokchan W. 2002 The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environmental Pollution*, **118**(3), 453-461.

Dumitru A. & Wendling L. 2021 Indicators of NBS performance and impact. In: *Evaluating the impact of nature-based solutions: A handbook for practitioners,* A. Dumitru & L. Wendling (eds.), 1st edn, European Union, Luxembourg, pp. 114-173.

Wong T. H. F. 2006 Water sensitive urban design - the journey thus far. *Australasian Journal of Water Resources*, **10**(3), 213–222.

Zengeya T. A. & Wilson J. R. (eds.) 2020 The status of biological invasions and their management in South Africa in 2019 [Final Version]. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch, South Africa. https://zenodo.org/record/3947613#.YL-AYfkzZPY (accessed 02 May 2021).

CHAPTER 6

Comparison of urban stormwater plant biofilter designs for nutrient and metal removal in South Africa

This chapter addresses research objective 5 by investigating six biofilter designs exposed to low, typically observed and high stormwater pollution loads in an experimental biofilter column study. The technical differences between designs highlight the influence of biofilter features on pollutant-specific processes and pathways, which is accentuated by means of a comparative analyses of pollutant removal.

This chapter seeks to assess the performance of urban stormwater biofilters that benefit from incorporating the engineered media and indigenous plant species findings of chapters 4 and 5 respectively. From the engineered media experiment it was evident that certain media show affinity for certain pollutants, as well as maintaining hydrologic conditions at varying efficiencies. In addition, although treatment efficacy varied between plants, the indigenous plant species improved biofilter performance compared with unvegetated soil, with some species outperforming others. These findings potentially contribute to an optimised system by combining appropriate and effective engineered media, plant species and physical design features influencing treatment performance as technical adjustable factors within the practicing engineer’s control. In recent years, adaptations to filter depth, filter media, carbon source, plant species and design via anaerobic saturation, have been made to optimise biofiltration. Although demonstrating improved performance in some hydrologic or pollutant instances, no obvious differences and some unsatisfactory findings have also been observed. Despite increased popularity, designing biofiltration systems for overall pollutant removal has stagnated since integrating a saturated zone; with current adaptations reliant on broad philosophic guidance and lacking scientific premise.

Therefore, to advance the practice of plant biofilter design for stormwater runoff quality improvement in South Africa, the performance of novel plenum aeration and upflow filtration in combination with zone saturation whilst vegetated by *Prionium serratum* was investigated. From the findings, the most efficient design was found to include standard plant biofiltration techniques in combination with more advanced removal mechanisms.

Comparing the treatment performance of each nutrient and heavy metal pollutant between designs allowed for identifying specific pollutant removal processes and pathways relevant to each biofilter. Allowing the design of a system for site and pollutant specific water treatment which addresses appropriate hydrologic and water-quality targets. Understanding removal processes, together with data retrieved from each design, is further applied in developing a conceptual model based on similar biofilm reactor processes, chapter 7, objective 6.

Comparison of urban stormwater plant biofilter designs for nutrient and metal removal in South Africa

DM Jacklin[a], IC Brink[a], SM Jacobs[b]

[a]*Department of Civil Engineering: Water and Environmental Engineering Group, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

[b]*Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

Reproduced and reformatted from an article published in **Water Practice and Technology, (in press)**, with permission from the copyright holder, IWA Publishing.

Abstract

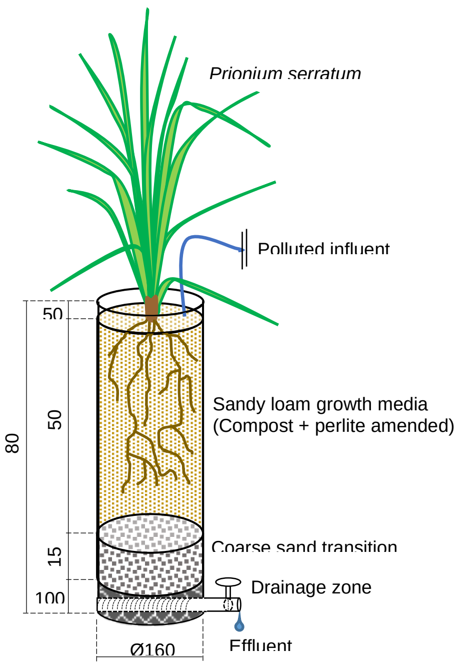
This paper presents a comparison of six plant biofilter designs for urban stormwater quality improvement and reports on their performances. Thirty-six columns were populated with the endemic South African plant *Prionium serratum*, representing plant biofilter designs which incorporate different pollutant removal mechanisms in the biofiltration process. The experimental biofilter columns were subjected to low, typically observed and high urban nutrient and metal synthetic stormwater pollution for five months. Significant loads of NH_3 -N and dissolved Cd, Pb and Zn were removed, whereas removal of NO_3^- -N, PO_4^{3-} -P and dissolved Cu was more variable. The most efficient design was found to include standard plant biofiltration techniques with upflow filtration, plenum aeration and a saturated zone supporting anaerobic microbial activity. It was found that the most efficient design removed on average 96% of urban stormwater nutrient and metal loads.

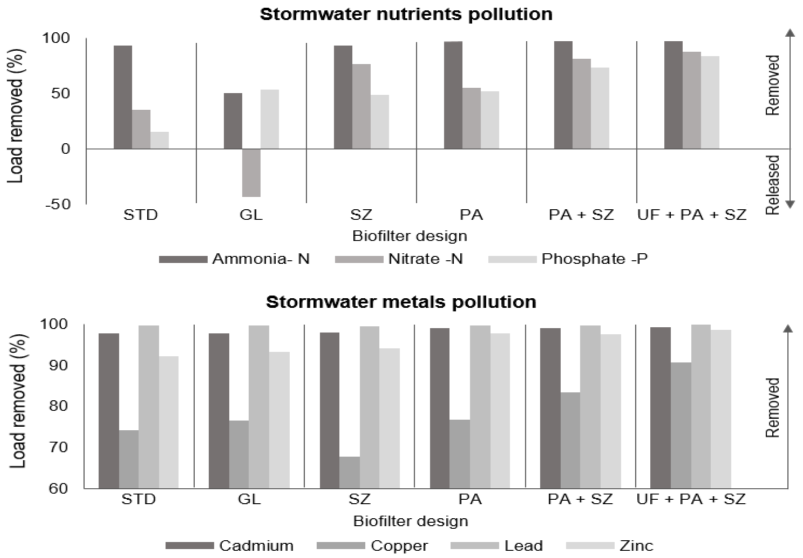
Key words: plant biofilter design, metals removal, nutrients removal, urban stormwater runoff pollution

Highlights

- Assessment of various plant biofilter designs (air plenum, different media, geotextile inclusion, saturated zone inclusion).
- Inclusion of endemic South African plant *Prionium serratum* and nationally available materials.
- Significant NH_3 -N and dissolved Cd, Pb and Zn removal.
- Varied NO_3^- -N, PO_4^{3-} -P and dissolved Cu removal.

GRAPHICAL ABSTRACT





STD = Standard; GL = Geotextile lined; SZ = Saturated zone; PA = Plenum aeration; PA+SZ = Plenum aeration + saturated zone; UF+PA+SZ = Upflow filtration + plenum aeration + saturated zone.

INTRODUCTION

Rapid urbanisation has led to a significant increase in runoff volumes, peak flows, sedimentation and nutrient and metal pollution to urban stormwater, resulting in urban watercourse degradation (Line & White 2007; Al-Ameri *et al.* 2018). Due to the absorption capacity of water, many substances are collected by stormwater runoff; making urban stormwater one of the primary pollution vectors to natural water systems (Abbasi & Abbasi 2011). To mitigate these impacts, improved urban stormwater management strategies such as Water Sensitive Urban Design (WSUD) and Low Impact Development (LID), are increasingly preferred in South Africa (Armitage *et al.* 2014). The WSUD approach promotes the systematic integration of Green Infrastructure (GI) and nature-based solutions into urban spaces as key components of climate change adaptation and runoff mitigation strategies (Dumitru & Wendling 2021). Within GI, sustainable yet effective plant biofiltration systems provide both water quality and quantity benefits to the dense and confined urban area (Payne *et al.* 2015). Plant biofiltration makes use of vegetation and soil infiltration to attenuate runoff flows (Hatt *et al.* 2009); and improve water quality (Shrestha *et al.* 2018) through particulate discharge, filtration, sorption, plant and microbial uptake and evapotranspiration (Wadzuk *et al.* 2015; Wang *et al.* 2018a).

Both laboratory and field plant biofiltration studies investigating nutrients have demonstrated effective ammonia (NH_3) removal (Davis *et al.* 2001). However, more variable removal efficiencies have been reported for nitrate (NO_3^-) (Hatt *et al.* 2009) and orthophosphate (PO_4^{3-}

) (Hsieh *et al.* 2007). In some studies high NO_3^- (Bratieres *et al.* 2008) and PO_4^{3-} (Dietz & Clausen 2006) leaching was reported, resulting in poor overall nutrient removal. Leaching of NO_3^--N, the primary obstacle for effective nutrient removal in GI initiatives, is due to inadequate anaerobic denitrification (Zinger *et al.* 2013). For PO_4^{3-} -P, leaching into discharged stormwater due to weathering and mineralisation processes have been found to increase in the presence of organic matter (Henderson *et al.* 2007), further exacerbated with compost amendments (Mullane *et al.* 2015). Enhanced nutrient removal by vegetation occurs either directly through plant uptake, root retention and soil maintenance or indirectly through enhanced microbial activity in the root zone (Bratieres *et al.* 2008).

In stormwater runoff, dissolved metals contribute a large proportion of pollutants with those of most interest, viz. cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) present naturally or caused by anthropogenic activities (Hocaoglu-Ozyigit & Genc 2020). In biofilters, the primary metal removal pathway is sorption to the upper layer of the growth media until breakthrough or infiltration failure occurs as a result of clogging (Le Coustumer *et al.* 2012). Varying metal removal has been demonstrated, particularly in anaerobic conditions which has been found to decrease redox potential (Dietz & Clausen 2006), whilst Cu, Pb and Zn are further influenced by organic matter (Al-Ameri *et al.* 2018; Warren & Haack 2001) and may leach (Blecken *et al.* 2010; Lenth & Dugapolski 2011). The contribution by vegetation, though to a lesser extent when compared with unvegetated mechanisms (Blecken *et al.* 2009), is the extraction of micronutrients Cu and Zn as well as non-essential, potentially toxic Cd and Pb (Tangahu *et al.* 2011).

In biofilters stocked with vegetation, pollutants are removed through physical, chemical or biological processes, enhancing water quality (Wang *et al.* 2018b) and providing a permanent removal mechanism via harvesting (Kumar *et al.* 2017); this highlights the importance of vegetation for urban stormwater quality improvement (Bratieres *et al.* 2008). The processes and pathways affecting nutrient and metal removal are complex and vary between biofilter designs and operational conditions, making it difficult to consistently maintain overall treatment performance, particularly for dissolved pollutants (Hunt *et al.* 2008).

Inadequate dissolved nutrient and metal treatment negates biofiltration initiatives as pollutants are most bioavailable in these forms (Maniquiz-Redillas & Kim 2016). Therefore, removing particulate pollutants only will not adequately reduce the negative impacts on water systems (Winston *et al.* 2017). In recent years adaptations in filter depth (Bratieres *et al.* 2008), filter media (Reddy *et al.* 2014), carbon sources (Blecken *et al.* 2009), plant species (Payne *et al.* 2018), stepped retention (Wang *et al.* 2017), intermittent dry-wet cycles (Hatt *et al.* 2007) and anaerobic saturation (Zinger *et al.* 2013) have been made to optimise biofiltration. Such adaptations demonstrated improved performance of certain biofilter elements, however, no obvious differences and some unsatisfactory findings were also observed (Wang *et al.* 2018b). For example, biofilters integrating a saturated zone for enhanced denitrification (the preferred method for optimisation) have in some cases shown no improvement (Dietz & Clausen 2006) and in others leached pollutants (Zinger *et al.* 2013).

Despite increased popularity for GI application (Kim & Song 2019), design of scientifically based plant biofiltration systems for overall pollutant removal has not evolved greatly since integrating a saturated zone as the primary removal mechanism of NO_3^-. Therefore, to advance the knowledge on plant biofilter design for stormwater runoff quality improvement in South Africa, the performance of novel plenum aeration and upflow filtration in combination with zone saturation was investigated in this study additional to more common biofilter designs. Here a proven efficient South African endemic phytoremediator, viz. *Prionium serratum* (See Jacklin *et al.* 2021) was included in the designs.

This experiment forms part of a larger study on South African urban stormwater management, the country's underutilization of WSUD, potential advancements, and development of a conceptual urban stormwater biofilter model.

METHODS

Engineered plant biofilter design

Thirty-six columns populated with *Prionium serratum* were constructed from Ø160mm PVC piping, for the introduction of various engineered media and removal pathways to each of the six plant biofilter designs (see Table 1 below), in duplicate and for three different pollutant dosing strengths (Low, Typically Observed and High). All columns received municipal tap water for nine months to allow the establishment of *Prionium serratum* prior to synthetic stormwater dosing and testing.

Table 1. Overview of the six biofilter designs under study.

Design identifier	Biofilter description (All designs integrated a standard growth media layer with Prionium serratum)	Additional to soil media (All growth media integrated sandy loam amended with compost + perlite)
STD	Standard stormwater plant biofilter	None
GL	Geotextile lined	None
PA	Plenum aeration	Zeolite
SZ	Saturated zone	Vermiculite + attapulgite
PA+SZ	Plenum aeration + saturated zone	Zeolite + vermiculite + attapulgite
UF+PA+SZ	Upflow filtration + plenum aeration + saturated zone	Zeolite + vermiculite + attapulgite

This period allowed for excess nutrient and metal discharge out of the columns to achieve consistency in effluent concentration, confirmed by recordings over the last month of tap water dosing. Following this period, a twice-weekly 1.94L synthetic stormwater dosing, as well as effluent sampling continued for 4 months.

Standard design features

The following design features were standard within all the biofilters:

A drainage outlet for each biofilter was covered by a 100 mm depth gravel drainage zone and a 150mm coarse sand transition layer. This was topped with 500 mm depth growth media (with varying designs in between these layers – see section below) to support root development and plant growth as recommended by Payne *et al.* (2015). The inner column walls of the Ø160mm PVC piping were abraded to prevent preferential surface flow (excluding the Geotextile Layer (GL) biofilter) and sealed at the base.

The growth media consisted of Sandy Loam with a tested typical infiltration rate of 145±17 mm/hr. This was amended with 5% compost (solid phase organic matter) as a carbon source and 5% perlite for its natural drainage and water absorption capabilities (Payne *et al.* 2015; Prodanovic *et al.* 2018). This combination of materials was chosen to maintain influent water diffusion through the growth media and alleviate transplantation stress (Le Coustumer *et al.* 2012).

The selection of *Prionium serratum* as the plant species used in this research was derived by a desktop study, which resulted in a phyto-guide (Jacklin *et al.* in press,b), which relies on existing recommendations and knowledge of removal processes of South African phytoremediators, and previous research into South African plant species for application to stormwater runoff treatment biofilters (Jacklin *et al.* in press,a). Additionally, plant physiological properties such as growth rate, lifespan, tolerance and hardiness as well as morphological traits such as above- and below-ground biomass were considered. This species was deemed appropriate due to the plant's rapid growth rate and biomass production, as well as its vegetative contribution to water quality improvement, which was deemed sufficient over the planned experimental period. For South African GI initiatives where the use of *P. serratum* would be unsuitable, due to climatic or habitat conditions, the use of potential alternatives should be promoted (see Jacklin *et al.* 2021).

Growth and filter media design variations

The six different plant biofilter designs are illustrated in Figure 1. Design variations were informed by research reported in published literature as indicated. The Standard (STD) biofilter represents a typical design for plant biofiltration systems, which rely primarily on plant uptake and media sorption processes for pollutant removal (Bratieres *et al.* 2008). The Geotextile Layer (GL) biofilter replaces inner column wall abrasion with nonwoven geotextile fabric for possible additive microbial establishment (see Valentis & Lesavre 1990).

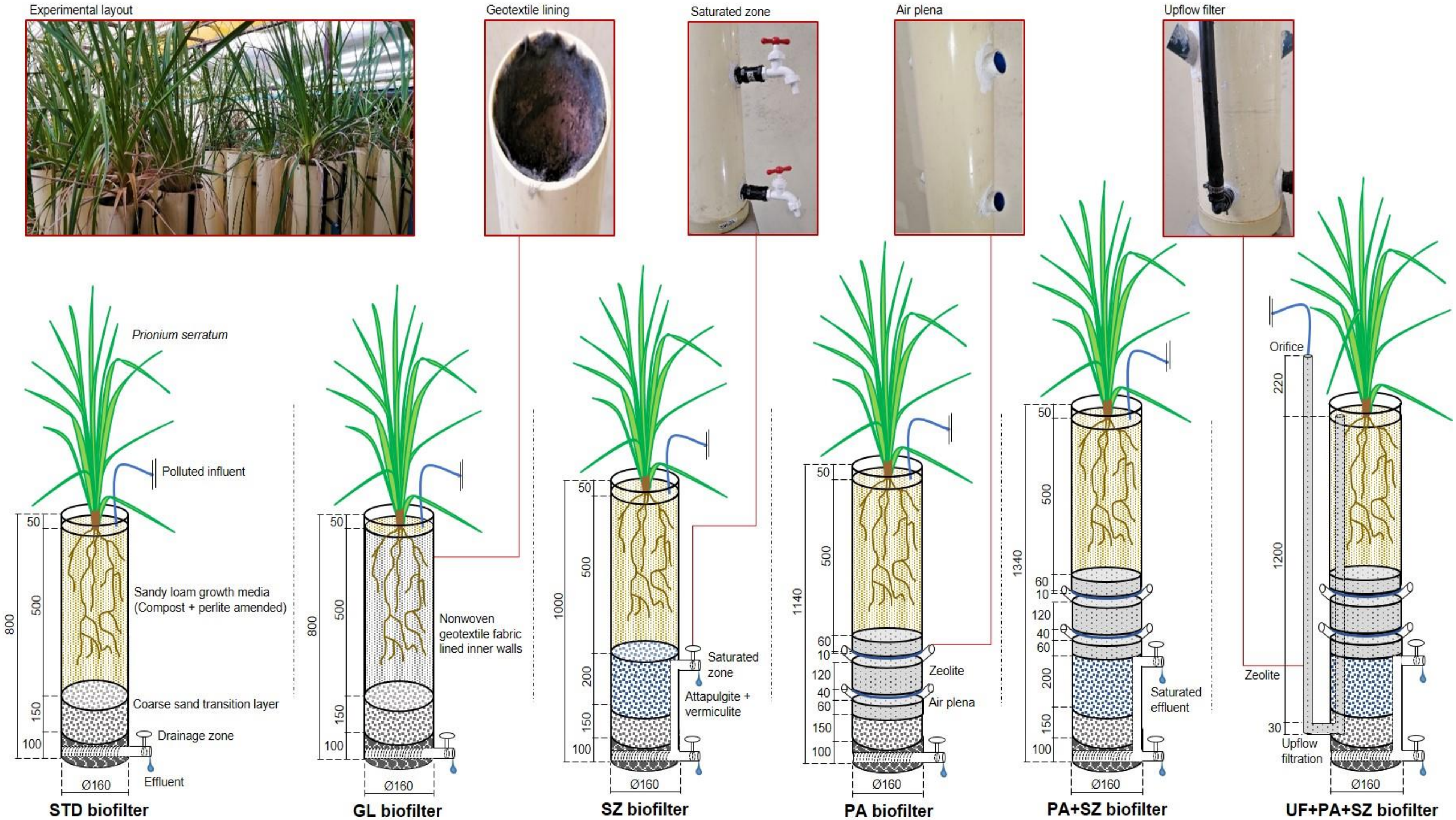


Figure 1. Schematic of the six plant biofilter designs, with photographic panels illustrating significant aspects of the experiment. *Note: STD = Standard; GL = Geotextile lined; SZ = Saturated zone; PA = Plenum aeration; PA+SZ = Plenum aeration + saturated zone; UF+PA+SZ = Upflow filtration + plenum aeration + saturated zone.*

In this GL biofilter design, geotextile was inserted along the length of the PVC pipe inner walls, instead of laterally across the biofilter to avoid clogging (see Palmeira *et al.* 2008); it therefore increase the potential load treated. Restricting clogging minimises influent loss to surface runoff (Le Coustumer *et al.* 2012). For the Saturated Zone (SZ) plant biofilter, an anaerobic saturated zone was included which consisted of a 1:1 mixture of vermiculite (0.5-1.4 mm) and attapulgite (0.5-1.4 mm) media at a depth of 200 mm within the experimental column for enhanced nutrient and metal removal (see Wang *et al.* 2018b), whilst the growth media and vegetation above supplied carbon for denitrification (see Payne *et al.* 2015). Similar to the GL plant biofilter, the Plenum Aeration (PA) biofilter integrated zeolite (0.8-1.4 mm) based on an experimental concept devised by Smith (2015) for the removal of pollutants from household wastewater. Two Ø40 mm horizontal air plena were constructed between three zeolite media layers below the growth media for enhanced passive aeration, increasing oxygen ingress to support nitrification. The Plenum Aeration + Saturated Zone (PA+SZ) plant biofilter design combined nitrification and denitrification process within a single plant biofilter column by supplying atmospheric -oxygen for nitrification and -carbon dioxide (carbon source) for denitrification. Finally, the Up Flow + Plenum Aeration + Saturated Zone (UF+PA+SZ) plant biofilter design was included for investigation. The influent drained into a Ø30 mm orifice and was driven vertically through the upflow filter by the difference in water head at the rate of experimental influent between the influent orifice and the surface of the growth media (Cucarella & Renman 2009). Integrating upflow filtration as a pretreatment may reduce the maintenance frequency required to combat top layer clogging and media breakthrough (the point where sorption sites on the media are exhausted and pollutants leach), decreasing the cost of rehabilitation and ensuring long term functionality (Blecken *et al.* 2017).

Synthetic stormwater dosing and effluent testing

Synthetic stormwater (Table 2) was prepared to reflect published low, typically observed and high urban stormwater nutrient and metal concentrations, as well as similar stormwater biofilter investigations (see Taylor *et al.* 2005; Göbel *et al.* 2007). Dissolved metals were selected as the majority of Cd, Cu, Pb and Zn species are typically found in this form and are most mobile within biofilters (Sun & Davis 2007). Irrigation was done by submersible pumps in separate dosing tanks for each pollution treatment via an automated system equipped with pump agitators to ensure uniform dispersion. Influent concentrations were monitored throughout and synthetic stormwater was replaced with a freshly mixed batch at 10 day intervals.

Five effluent sampling rounds were initiated after a month of synthetic stormwater dosing at 20-day intervals. This 30-day dosing period prior to effluent collection ensured discharge of non-polluted tap water (used for establishing *Prionium serratum*) from the columns. This period further provided time for the polluted influent to saturate the anaerobic zones in the SZ, PA+SZ and UF+PA+SZ biofilter columns, as well as filling the upflow filtration chamber. Due to potential water loss to evapotranspiration as well as drying of the media between irrigation events, percentage pollutant load removal (L_{rem}) was used and considered the influent ($C_{inf}V_{inf}$) and effluent ($C_{eff}V_{eff}$) loads of each design for every sampling round (see Equation 1). The overall percentage pollutant load removed for each design was then estimated as the mean of the 5 sampling rounds.

$$L_{rem} = \frac{C_{inf}\,V_{inf} - C_{eff}\,V_{eff}}{C_{inf}\,V_{inf}} \text{ x } \frac{100}{1} \qquad \text{Equation 1}$$

Where
L_{rem} = pollutant load removed (%),
C_{inf} = influent concentration (mg/L),
V_{inf} = total influent volume for sampling round (L),
C_{eff} = effluent concentration (mg/L),
V_{eff} = effluent volume of sampling round (L).

Various water quality parameters were analysed in the Stellenbosch University Water Quality Laboratory for each plant biofilter design and influent pollution strength. These included NH_3 -N, NO_3^- -N, PO_4^{3-} -P and total suspended solids (TSS), all measured with the HACH DR3900 spectrophotometer, by implementing TNTplus™ methods 10205, 10206, 10209 and photometric method 8006 respectively. Temperature, pH, electrical conductivity (EC), dissolved oxygen (DO) and total dissolved solids (TDS) were measured with the HACH HQ440d benchtop multi-parameter meter. Dissolved Cd, Cu, Pb and Zn were analysed at the Stellenbosch University Central Analytical Facility: ICP-MS division on an Agilent 8800 QQQ ICP-MS instrument, with polyatomic interferences removed by a 4th generation Octopole Reaction System (Agilent 2015). Prior to nutrient and metal analyses, samples were filtered with 0.45 µm syringe filters.

Data analysis

Statistical analyses were conducted using R Statistical Software and statistically significant differences was accepted at an unadjusted p-value ≤ 0.05 to maintain the power of the test (Feise 2002). Since data was typically non-normally distributed, as established by the *Lilliefors test*, the *Kruskal-Wallis H-test* was used to ascertain the significance of difference in influent concentrations, as well as between the effluent concentrations and percent removals of the six engineered designs for each pollution strength and parameter. With significance, *the Wilcoxon Rank Sum paired test* was used to compare pollutant influent and effluent concentrations, in addition to comparing effluent concentrations and percent removal between designs to assess plant biofilter treatment performance. With this information, the *Fisher Least Significant Difference (LSD) test* was used to detect the differences in percent removal between designs for each pollutant parameter.

RESULTS AND DISCUSSION

Engineered plant biofilter water quality results, as well as the low, typically observed and high influent stormwater concentrations are listed in Table 2. Prior to determining percent removals, results of the Kruskal-Wallis H-test confirmed that influent concentrations, monitored throughout the study, were not statistically significantly different ($p > 0.05$) for each pollution strength between sampling rounds, allowing comparisons of effluent quality among the biofilter designs (Winston *et al.* 2017).

Effluent concentration quality

As shown in Table 2 the mean effluent concentrations and percentage load removals by the biofilter designs varied across pollutant type and were influenced by influent strengths. The plant biofilters had lower mean effluent concentrations compared to those of the influent in 92 (73%) of the 126 treatments, with substantially decreased NH_3 -N and dissolved Cd, Pb and Zn, which were consistently lower in all engineered designs for all pollution strengths. Furthermore, on four and six occasions for Cd and Pb respectively, the effluent concentrations were below laboratory detection limits (i.e. Cd < 0.0000045 mg/L and Pb < 0.000047 mg/L).

In contrast, removal performance was more variable for PO_4^{3-} -P and NO_3^- -N, as well as for dissolved Cu. Here, mean effluent PO_4^{3-} -P concentrations were higher in all designs exposed to low and typically observed pollution dosage, as well as from the STD, PA and PA+SZ biofilters exposed to high pollution dosage. For NO_3^- -N, mean effluent concentrations were higher than the influent in all designs exposed to low and typically observed pollution, except for the UF+PA+SZ biofilter, which was lower than the corresponding typically observed influent concentration. In addition, when exposed to high NO_3^- -N pollution, only the GL biofilter was observed to generate leachate. For dissolved Cu under low strength pollution only, the GL biofilter had a reduced mean effluent concentration, whilst under typically observed pollution higher mean effluent concentrations were produced by the SZ and PA columns with the remaining designs showing effluent concentrations that were lower than the influent concentrations.

Statistical analysis using the Wilcoxon Rank Sum test for comparing influent and effluent concentrations for each pollutant parameter over the three pollution strengths showed significant differences ($p \leq 0.05$) in almost all the treatments. The plant biofilters where statistically significant differences were not found between influent and effluent concentrations were: GL in low PO_4^{3-} -P ($p = 0.63$) and high NO_3^- -N ($p = 0.45$) pollution; SZ and PA in typically observed Cu ($p = 0.17$ and $p = 0.44$) and high PO_4^{3-} -P ($p = 0.74$ and $p = 0.26$) pollution; PA in high NO_3^- -N ($p = 0.82$) pollution; PA+SZ in high PO_4^{3-} -P ($p = 0.85$) pollution; and UF+PA+SZ in low dissolved Cu ($p = 0.54$) and typically observed PO_4^{3-} -P ($p = 0.17$) pollution. In evaluating effluent quality, the results showed reduced pollutant concentrations in the majority of the treatments, suggesting biofilter efficiency, with the exception of NO_3^- -N, PO_4^{3-} -P and dissolved Cu. This notion which considers concentration only, however, is inadequate in assessing water-quality treatment, as it does not account for the change in volume (Li & Davis 2009).

Pollutant load removal performance

The mean nutrient and metal load removal percentages over all sampling rounds are reported in Table 2 with further illustrations on the performances between designs provided in the supplementary material (Figure S1). As mentioned above, determining plant biofilter performance by solely evaluating effluent concentrations can be misleading, since a biofilter treating high influent concentrations will always appear more efficient than one treating low influents, even if both are achieving the same effluent quality (Strecker 2002). This dependence is of importance in this study, as the function also applies to pollutant loads (Lampe *et al.* 2005). From the reported values, percent load removals were found to be influenced by influent strength, as opposed to effluent concentrations, further demonstrated by the Wilcoxon Rank Sum test comparing percent removal between the low, typically observed and high influent strengths for each pollutant. For all dissolved metals, removal between the three influent strengths were significantly different ($p \leq 0.05$). Similarly, percent removal of high influent nutrients was significantly different to the other pollution strengths. Between low and typically observed nutrient pollution, however, this was not the case, recording no significant differences ($p > 0.05$) in percent removal.

Substantial percent removal in dissolved metals were recorded for Cd (>96%), Pb (>99%) and Zn (>89%) across the dosing strengths, whilst the generally more variable removal of nutrients NO_3^- -N and PO_4^{3-} -P, as well as dissolved Cu ranged from -44 to 99%, 15 to 94% and 59 to 99% respectively. Notably, the mean percent removal of NH_3 -N was high (>89%) across all biofilter designs, except GL, which ranged from 49 to 75%. Furthermore, the common issue of NO_3^- -N leaching, the main obstacle to effective nutrient removal in biofilters (Zinger *et al.* 2013), was found in only the GL biofilter. Overall the most efficient engineered designs (based on mean percentage loads removed across the pollution strengths) were the UF+PA+SZ, PA+SZ and SZ biofilters, removing on average 96, 93 and 88% of urban pollutants respectively.

Nutrients

Effective NH_3 -N load removal was found in almost all engineered designs, across the pollution strengths, suggesting an enhancement of the nitrification process. The best performing design was the UF+PA+SZ biofilter, reporting efficient (>98%) mean NH_3 -N removal. In contrast, the GL biofilter was least efficient, ranging from 49 to 75%, which may have been due to its inability to retain water, decreasing the hydraulic retention time thereby decreasing water-quality improvement (Hunt *et al.* 2012).

Table 2. Influent synthetic stormwater concentrations and overall performance of the engineered plant biofilters. *Note effluent concentration > influent concentration assigned a +. C_{inf} = influent concentration; $\bar{x}C_{eff}$ = mean effluent concentration; $\bar{x}L_{rem}$ = mean percent load removed.*

Pollution strength	**Prepared influent synthetic stormwater concentrations – C_{inf} (mg/L)**						
	NH_3 -N	**NO_3^- -N**	**PO_4^{3-} -P**	**Cd**	**Cu**	**Pb**	**Zn**
Low	0.20	0.50	0.22	0.002	0.02	0.08	0.15
Typically observed	0.40	0.95	0.35	0.0045	0.045	0.15	0.30
High	2.5	13.5	1.5	0.032	6.8	2.8	35
Source chemical	NH_4Cl	KNO_3	K_2HPO_4	$CdCl_2$	$CuSO_4$	$PbCl_2$	$ZnCl_2$

Biofilter design type	**Measured mean effluent concentrations and mean loads removed**													
	NH_3 -N		**NO_3^- -N**		**PO_4^{3-} -P**		**Cd**		**Cu**		**Pb**		**Zn**	
	$\bar{x}C_{eff}$ (mg/L)	**$\bar{x}L_{rem}$ (%)**	**$\bar{x}C_{eff}$ (mg/L)**	**$\bar{x}L_{rem}$ (%)**	**$\bar{x}C_{eff}$ (mg/L)**	**$\bar{x}L_{rem}$ (%)**	**$\bar{x}C_{eff}$ (mg/L)**	**$\bar{x}L_{rem}$ (%)**	**$\bar{x}C_{eff}$ (mg/L)**	**$\bar{x}L_{rem}$ (%)**	**$\bar{x}C_{eff}$ (mg/L)**	**$\bar{x}L_{rem}$ (%)**	**$\bar{x}C_{eff}$ (mg/L)**	**$\bar{x}L_{rem}$ (%)**
Low pollution strength														
STD	0.065	89	1.24 +	23	0.60 +	15	0.00019	96	0.026 +	59	0.0016	99	0.05	89
GL	0.18	50	1.33 +	-44	0.23 +	43	0.00014	96	0.015	59	0.00058	99	0.027	90
SZ	0.18	89	1.11 +	74	1.10 +	42	0.00051	97	0.07 +	59	0.0052	99	0.11	91
PA	0.065	96	2.26 +	47	1.10 +	41	0.00023	98	0.05 +	70	0.0026	99	0.04	96
PA+SZ	0.069	96	1.03 +	76	0.64 +	66	0.00021	98	0.04 +	76	0.0028	99	0.04	96
UF+PA+SZ	0.032	98	0.63 +	85	0.35 +	81	0.00013	99	0.023 +	86	0.00055	99	0.02	98
Typically observed pollution strength														
STD	0.037	97	1.60 +	47	0.96 +	15	0.00023	98	0.016	88	0.00094	99	0.052	94
GL	0.30	59	2.49 +	-42	0.23 +	63	0.00005	99	0.0052	93	0.00052	99	0.019	96
SZ	0.11	96	1.74 +	78	1.33 +	56	0.00045	98	0.092 +	76	0.0054	99	0.098	96
PA	0.062	98	3.02 +	63	1.14 +	62	0.00024	99	0.067 +	82	0.0035	99	0.032	98
PA+SZ	0.055	98	1.15 +	85	0.58 +	80	0.00032	99	0.037	90	0.0014	99	0.05	98
UF+PA+SZ	0.034	99	0.79	90	0.42 +	86	0.00024	99	0.022	94	0.00099	99	0.038	98
High pollution strength														
STD	0.12	98	9.94	77	2.46 +	49	0.00022	99	0.023	99	0.0025	99	0.033	99
GL	1.11	75	14.36 +	42	1.02	63	0.0001	99	0.0098	99	0.0013	99	0.018	99
SZ	0.30	98	7.85	93	1.44	88	0.0005	99	0.12	99	0.009	99	0.077	99
PA	0.096	99	12.39	89	1.79 +	86	0.00026	99	0.097	99	0.005	99	0.039	99
PA+SZ	0.06	99	7.52	93	1.54 +	88	0.00024	99	0.045	99	0.002	99	0.059	99
UF+PA+SZ	0.04	99	5.50	95	0.74	94	0.00025	99	0.041	99	0.002	99	0.036	99

In addition to some surface volatilisation, removal primarily occurs in the biofilter rhizosphere under aerobic conditions via biological processes which convert NH_3 -N to NO_3^- -N for plant uptake (Payne *et al.* 2014). In the presence of organic matter, applicable to this study due to growth media amendment with compost, NH_3 -N can be rapidly nitrified (Hunt *et al.* 2015). From the results, although efficiency was recorded in all biofilter columns, NH_3 -N removal was consistently enhanced in designs incorporating air-plena, suggesting successful microbial nitrification in aerobic conditions.

Percent NO_3^- -N removal varied notably between designs and pollution strengths, however, in almost all designs the influent load was reduced, with the exception of the worst performing GL biofilter, which was observed to leach NO_3^- -N for low (-44%) and typically observed (-42%) pollution dosages. Similar to the case of NH_3 -N, the best performing design was the UF+PA+SZ biofilter, reporting efficient (>85%) mean NO_3^- -N removal. Removal processes for NO_3^- -N rely on denitrification and biotic assimilation within the biofilter, without which NO_3^- -N is released to the water column and leaching is observed (Henderson *et al.* 2007).

In the presence of plants and a carbon source NO_3^- -N removal is enhanced via the promotion of microbial nitrification and denitrification, as well as direct uptake, emphasizing the importance of vegetation and compost (in the appropriate solid phase) in plant biofilters (Muerdter *et al.* 2018). It is believed that biotic assimilation, which include NO_3^- -N uptake by plants, bacteria, fungi and other microbes, is the major removal pathway in plant biofilters (Payne *et al.* 2014), with denitrification accounting for <15% of treatment (Fowdar *et al.* 2018). This assumption is however not applicable to all biofilters, when influent NO_3^- -N nears 10 mg/L as revealed by Barron *et al.* (2019), the influence of denitrification has shown to increase in proportion to a decrease in plant assimilation. In the current study, with all columns similarly incorporating *Prionium serratum,* variations in NO_3^- -N load removal between biofilter designs suggest a shift in reliance from plant assimilation to denitrification. In addition, the notion that this shift from plant assimilation to denitrification is wholly reliant on high influent concentration is uncertain from the findings of our study, as varying percent NO_3^- -N removal between designs under low, typically observed and high concentrations were reported. Therefore, engineering biofilter design (SZ, PA, UF or a combination of these features), other than plant species selection, may significantly influence treatment performance in varying NO_3^- -N environments. From the results in this study, designs incorporating a saturated zone increased NO_3^- -N removal, inferring enhanced denitrification and plant uptake in anaerobic conditions.

For mean percent PO_4^{3-} -P removal, the influent load was reduced by all biofilter designs. Similar to the other nutrient pollutants, the best performing design was the UF+PA+SZ biofilter, efficiently (>81%) removing the greatest pollutant loads. The worst performing biofilter design was STD, recording mean PO_4^{3-} -P removal ranging from 15 to 49%. The main removal pathway for PO_4^{3-} -P within plant biofilters is unvegetated media filtration and sorption (Fowdar *et al.* 2017), with plants contributing through direct uptake and storage between roots, as well as the provision of oxygen for additive media to root sorption (Barron *et al.* 2019). Due to the presence of the high above- and below-ground biomass *Prionium serratum* species in the plant biofilters, enhanced PO_4^{3-} -P removal can be explained by its extensive root system and presence of root hairs (Bratieres *et al.* 2008). In addition, amending biofilter growth media with compost has been found to increase PO_4^{3-} -P in effluent runoff, decreasing percent removal (Lenth & Dugapolski 2011). Somewhat surprisingly, in this study the rapidly infiltrating GL biofilter outperformed SZ, PA and PA+SZ, suggesting possible filtration and sorption to the geotextile fabric.

Metals

As shown in Table 2 and further illustrated in Figure S1, dissolved metals were efficiently removed. The addition of carbon (from compost) and perlite to the biofilter growth media, with a higher capacity of removal than soil only, absorb heavy metals like Cd, Cu, Pb and Zn (Bratieres *et al.* 2008). Similar to what was found in the case of nutrient load removal, the best performing biofilter design for dissolved metal removal was the UF+PA+SZ filter. The mean load removal percentages achieved by the various engineered designs were high across the different influent pollution strengths for Cd (>96%), Pb (>99%) and Zn (>89%). In addition, for high influent dissolved Cu, percent removal was also high (>99%). These negligible removal variations between the biofilter designs for dissolved Cd, Pb and Zn were of little practical importance given the consistently high removal, which supports previous findings (Barron *et al.* 2019). For Cu, however, removal was less efficient and more variable between designs, with the SZ biofilter recording the lowest percent removal, ranging from 59 to 99%. As the influent strength decreased, variation in percent Cu removal increased, ranging from 59 to 86% and 76 to 94% for low and typically observed pollution dosing levels respectively, which is consistent with similar published investigations (see Davis *et al.* 2001; Lenth & Dugapolski 2011). Variation may be due to the formation of Cu-organic matter complexes within the biofilter growth media as Cu has a strong affinity to organic matter (Ponizovsky *et al.* 2006). This process is significantly influenced by the form of organic matter, while solid organic matter adsorbtion of Cu is a main removal pathway in biofilters (Temminghoff *et al.* 1997). Dissolved organic matter tends to mobilise Cu and in some instances can result in leaching lasting several years (Mullane *et al.* 2015). In this study, the growth media amended with compost consisted of solid phase organic matter. Therefore, it is believed that Cu immobilisation likely occurred. The SZ biofilter consistently had the least efficient removal values for Cu and Pb, and in some instances Cd and Zn. These findings suggest a reduction in redox potential, an important mechanism for dissolved metal removal in stormwater biofiltration, within the anaerobic saturated zone, which corresponds with previous studies (see Dietz & Clausen 2006).

High metal extraction may be provided by metal hyperaccumulating plants, however, their use in biofiltration is relatively untested (Kratky *et al.* 2017). While *Prionium serratum* is not identified as a hyperaccumulator species, it has been found to offer water purification services (Rebelo 2018) and enhance treatment efficiency in laboratory investigations (Jacklin *et al.* 2020). The plant benefits from a large above-ground biomass and extensive root system, appropriate traits for metal removal in biofilters (Sun & Davis 2007). Micronutrients Cu and Zn, as well as non-essential toxic Cd and Pb uptake by plants, though relatively small compared with unvegetated mechanisms such as filtration and adsorption in the upper layer of the growth media (Blecken *et al.* 2009), provides a permanent pollutant removal pathway via harvesting as metal accumulation occurs over time (Kumar *et al.* 2017).

Comparison of the 6 different designs

As mentioned previously, water-quality treatment cannot be examined without considering hydrologic improvements, as reducing effluent volume from biofilters is an important mechanism in reducing total pollutant loads. In many successful GI initiatives, the primary reason effluent load is reduced from the influent load is as a result of modifying hydrology and water balance (Hunt *et al.* 2012) and through decreasing immediate discharge by increasing evapotranspiration (Davis *et al.* 2009). Although the use of percentage load removal (which considers variation in through flow volumes) is a better reflection than effluent concentration of biofilter efficiency, it is not a representation of the extent of pollutants entering and leaving a system.

A significant amount of influent volume was retained by the engineered biofilters and did not drain from the system, comparable with a study by Hunt *et al.* (2006), reporting more than 50% reduction in effluent volumes. In our study the influent and effluent volume ratios over the sampling periods (20 days), ranged from 0.54 to 0.12 for the six engineered designs, almost identical to the findings of Li & Davis (2008), reporting ratios ranging from 0.60 to less than 0.10 in field biofiltration systems. We postulate that a combination of the plenum-aerated zones, the dry periods between dosing events, as well as the water uptake potential of *Prionium serratum* (transpiration and water within plant tissue) and its extensive moisture retaining root system reduced discharge.

The variability in effluent concentrations and percent removals between experimental biofilters alludes to differences in removal pathways within the designs. For the optimisation of plant biofiltration, design must seek to combine appropriate removal mechanisms for overall urban stormwater pollutant treatment. Therefore, we assessed the performance of each biofilter design with the aim of ascertaining possible pollutant removal pathways. Differences in influent loads and ranges of removed nutrients and metals loads between designs are shown in Figure 2 and Figure 3 respectively. The differences in removal efficiency between the biofilter designs for each pollutant parameter was analysed by use of the Wilcoxon Rank-Sum test, with statistically significant differences represented by the outcomes of the Fisher's LSD test.

The Standard design

The Standard biofilter design (STD) mean influent to effluent volume ratio of 0.31, relied primarily on plant uptake and media sorption for pollutant removal. The growth media, amended with perlite and compost (solid phase organic matter) as a carbon source for denitrification was replicated for all designs. The STD biofilter, supporting aerobic nitrification, performed well for NH_3 -N load removal compared with the other designs (Fig. 2). For NO_3^- -N, the STD biofilter was not as efficient, resulting in significantly lower loads removed compared with all other designs, except for the GL biofilter as a result of the lack in anaerobic sites required for successful denitrification. For the removal of PO_4^{3-} -P, STD was significantly less efficient than all other designs, a common finding in new and establishing standard design biofilters (see Blecken *et al.* 2009). Removal of PO_4^{3-} -P by the STD biofilter, which recorded leaching in lower strength pollution (low and typically observed pollution), improved with time. This finding may be as a result of the influence of plant growth and solid state organic matter (see Lenth & Dugapolski 2011; Fowdar *et al.* 2017). Whilst biofilters can benefit from solid state organic matter for removing certain pollutants, like dissolved metals (Bratieres *et al.* 2008), the breakdown reaction of organic matter can result in the release of PO_4^{3-} -P (Hsieh *et al.* 2007). As expected, all dissolved metals were efficiently removed, as rapid metal removal occurs via sorption and / or filtration in the upper layer of the growth media. This was similarly found in other published literature (see Davis *et al.* 2001). The removal of dissolved metal loads were comparable with other designs, as a result of the similar vegetated growth media layer between designs.

The Geotextile Lined design

The Geotextile lined biofilter design (GL) had a mean influent to effluent volume ratio of 0.54 and introduced nonwoven geotextile fabric to support increased microbial activity and infiltration (Valentis & Lesavre 1990). During dosing events, some effluent discharge was detected within 5 minutes of initiating irrigation under saturated media conditions, which decreased to mere seconds in high volume irrigation under dry media conditions. This suggests rapid preferential flow through the geotextile fabric instead of the growth media, decreasing hydraulic retention time. Therefore, it is recommended that this design not be employed.

Separation of pollutants from the influent flow requires time for various removal mechanisms to be effective and any design that decreases hydraulic retention time is expected to decrease water-quality treatment (Hunt *et al.* 2012). This may explain the significantly less NH_3 -N and NO_3^- -N loads removed compared with the other designs, as insufficient retention time hampered the nitrification and denitrification processes. In contrast, flow down the inner walls of the columns through the fabric minimised interactions within the growth media, thereby preventing the breakdown reaction of compost and restricting PO_4^{3-} -P mobilisation and ultimate deposition. Efficient dissolved metal load reduction was observed, with the GL biofilter the only design recording below laboratory detectable limits in some cases (two measurements for Cd and four for Pb in typically observed and high pollution dosage levels). This may have been due to microbial community establishment on the fabric or direct sorption enhancing metals removal, which warrants further investigation in future research.

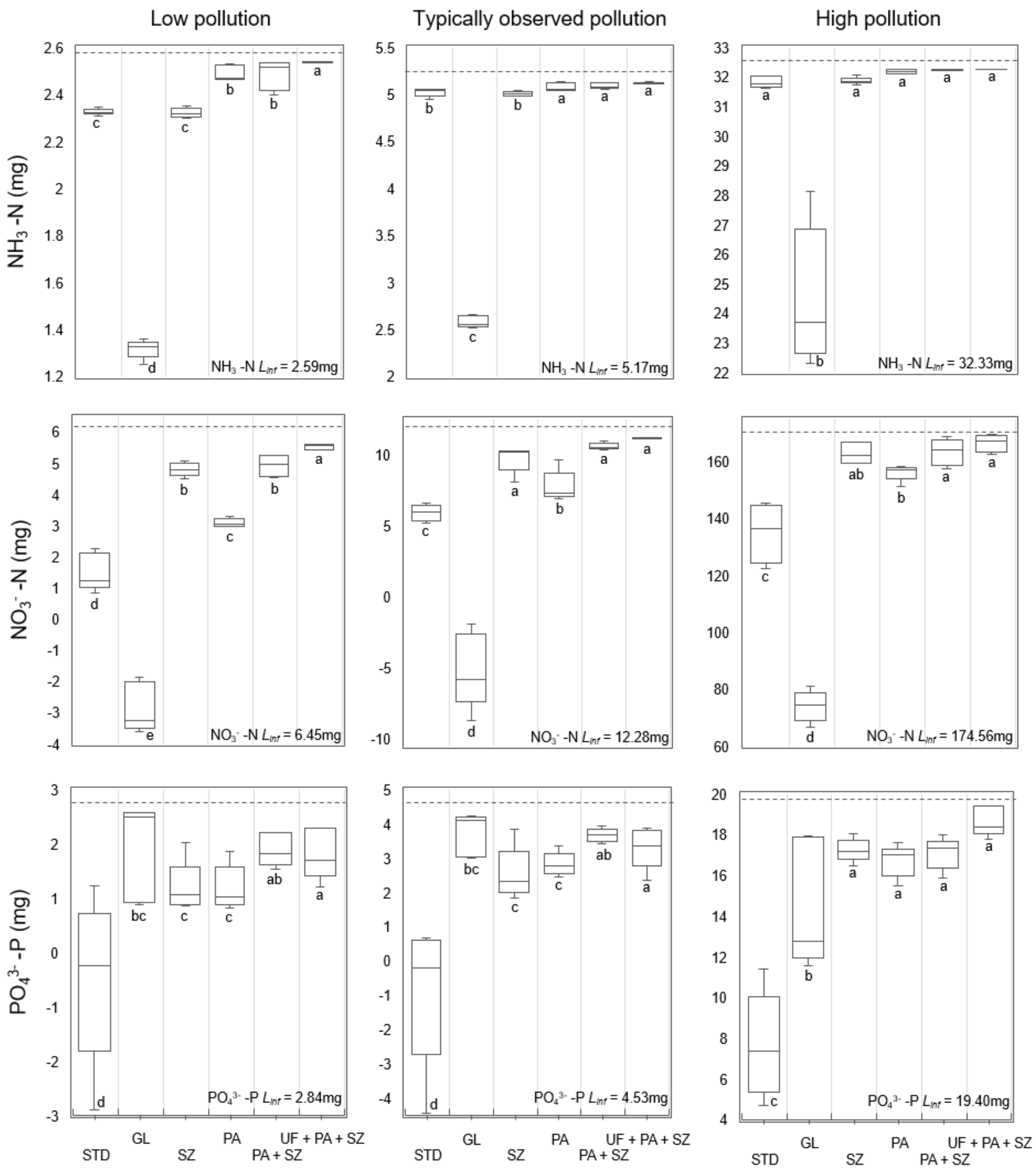


Figure 2. Boxplots of nutrient loads removed by the different biofilter designs over the sampling rounds. Note the different scales of vertical axes; L_{inf} = influent pollutant load, illustrated by the dotted lines. Designs with the same letter did not show statistically significant differences (Fisher's LSD test).

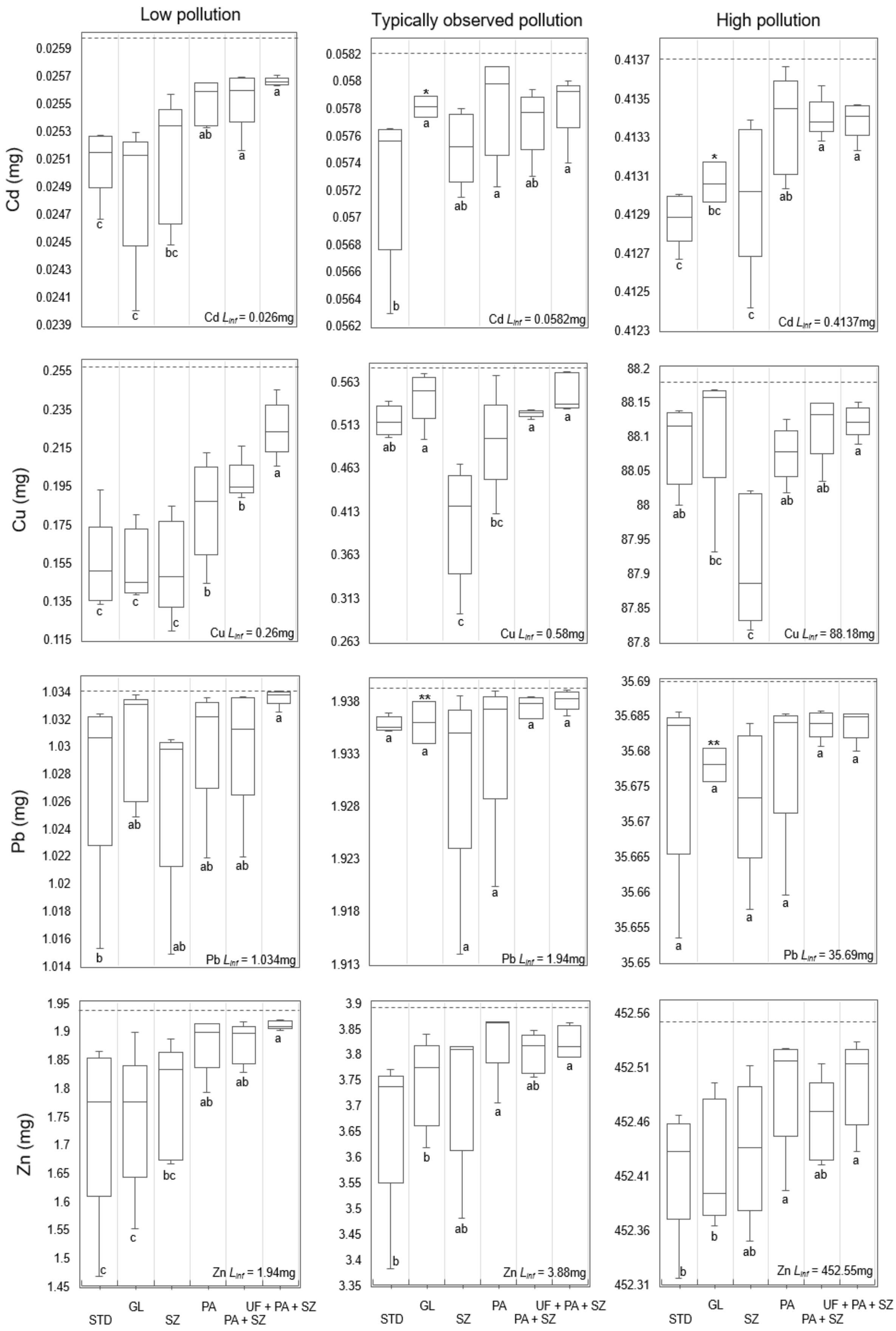


Figure 3. Boxplots of metal loads removed by the different biofilter designs over the sampling rounds. Note the different scales of vertical axes; L_{inf} = influent pollutant load, illustrated by the dotted lines; * = below detectable limit. Designs with the same letter did not show statistically significant differences (Fisher's LSD test).

The Saturated Zone design

The Saturated zone biofilter design (SZ) had a mean influent to effluent volume ratio of 0.21 with an anaerobic saturated zone consisting of inexpensive vermiculite and attapulgite media with increased surface area, adsorption and cation exchange capacities. These media have been found to offer great potential as alternatives to conventional sand for the removal of stormwater pollutants in the saturated zone (Tichapondwa & Van Biljon 2019). Carbon came from the growth media and root exudates, which likely supported denitrification (Payne *et al.* 2015).

In the presence of a saturated zone the removal efficiency of NO_3^- -N increased significantly compared with other designs, whilst the differences in removal of NH_3 -N and PO_4^{3-} -P were not significant (except for the GL and STD biofilters respectively as discussed earlier). The slightly lower (but not statistically significantly different) PO_4^{3-} -P removal recorded by the SZ biofilter when compared with designs aimed at increasing aerobic conditions is in contrast with the findings by Palmer *et al.* (2013), who reported significant effluent PO_4^{3-} -P increase under anaerobic conditions. For the removal of dissolved metals, although the differences for Cd, Pb and Zn between biofilter designs were not statistically significant and of no practical importance, significantly lower Cu loads were removed compared with the other designs. This is similar to previous findings reporting a reduction in redox potential under anaerobic conditions, with the filter acting as a source of pollutants rather than a sink (Dietz & Clausen 2006). A reduction in redox potential hinders metal speciation which decreases metal adsorption to media, which is the primary metal removal pathway in biofilters (Muerdter *et al.* 2018).

The Plenum Aerated design

The Plenum aerated biofilter design (PA) had a mean influent to effluent volume ratio of 0.12 and contained two horizontal air plena between zeolite media layers to enhance passive aeration for the nitrification process by increasing the surface area available for oxygen ingress (Smith 2015). In the case of high influent pollution dosing levels the standard biofilter growth media becomes saturated and may clog, requiring a correspondingly high oxygen demand by the media for successful nitrification (Blecken *et al.* 2009). Offering higher cation exchange capacities, sorption and acid catalysis properties than soil (Mondal *et al.* 2021), zeolite media decreases clogging and increases nutrient and metal removal from polluted water whilst supporting microbial growth and oxygenating biological regeneration (Markou *et al.* 2014).

In assessing load removal between designs, enhanced NH_3 -N removal by the PA biofilter suggests successful growth media oxygenation. A lack in anaerobic conditions for denitrification may be the cause of significantly lower loads of NO_3^- -N removed when compared with designs containing a saturated zone. In contrast, no statistically significant differences were recorded in assessing PO_4^{3-} -P load removal between this and other designs, possibly as a result of filtering and sorption to the zeolite media. For the removal of dissolved metals loads, though not significantly different, removal efficiency may have benefitted from zeolite's high cation exchange capacity, favouring adsorption.

The Plenum Aerated + Saturated Zone design

The Plenum aerated + saturated zone biofilter design (PA+SZ) had a mean influent to effluent volume ratio of 0.12 and combined pollutant removal pathways for support of enhanced nitrification and denitrification.

In comparing the performance of the PA+SZ biofilter with the other designs (excluding UF+PA+SZ) for nitrogen removal, statistically significantly reduced loads of both NH_3 -N and NO_3^- -N inferred successful microbial nitrification (in the growth media) and denitrification (in the saturated zone) as well as direct plant uptake. Similar to the other nutrients, reduced yet not statistically significantly different PO_4^{3-} -P loads were recorded between this and other designs not benefitting from a combination of removal pathways. This type of efficiency is predominantly attributed with extending biofilter depth (Davis *et al.* 2006), and / or the addition of engineered filter media increasing the possibility of sorption. Similar to other biofilter designs, the majority of dissolved metals were removed and was presumed to occur in the upper layer of the growth media.

The Upflow Filtration + Plenum Aerated + Saturated Zone design

The Upflow filtration + plenum aerated + saturated zone biofilter design (UF+PA+SZ) had a mean influent to effluent volume ratio of 0.12 and combined efficient removal pathways for improved urban stormwater pollutant removal. The zeolite upflow filter propelled polluted influent against gravity through engineered filter media (Sanz *et al.* 1996), providing additional removal mechanisms for particles, nutrients and dissolved metals (Winston *et al.* 2017).

In comparing loads removed between designs the UF+PA+SZ biofilter consistently outperformed all other designs across each pollutant parameter, though not always statistically significantly different. The upflow filter relies primarily on filtration and adsorption to the zeolite media, which may be prone to clogging and exhaustion as a mechanism for removal, possibly resulting in treatment failure long term. In this event refinements to design for optimised urban stormwater treatment may be meaningless and will require periodic maintenance to ensure long-term functionality (Blecken *et al.* 2017). Therefore, positioning the upflow filter as a separate entity on the outside rather than inside of the biofilter will facilitate media replacement and/or regeneration, a possible improvement to design. This also promotes the possible use of interchangeable cartridges in the event of clogging or exhaustion, simplifying the media maintenance process and increasing design feasibility (Winston *et al.* 2017).

CONCLUSIONS

This study demonstrated the pollutant removal performances of six different plant biofilter designs exposed to low, typically observed and high influent nutrients and metals dosing levels for urban stormwater runoff quality improvement. In addition to the endemic South African species *Prionium serratum*, the designs incorporated various engineered media using nationally available materials (perlite, vermiculite, zeolite and attapulgite) as well as biofilter column modifications (geotextile lining, saturated zone, plenum aeration and upflow filtration) for performance testing. The most efficient design combined standard plant biofiltration techniques with upflow filtration, plenum aeration and a saturated zone for anaerobic microbial activity support; removing on average 96% of urban stormwater nutrients and metals loads. In all plant biofilter designs significant differences in loads of NH_3 -N and dissolved Cd, Pb and Zn were removed from the synthetic stormwater, whereas removal of NO_3^- -N, PO_4^{3-} -P and dissolved Cu was more variable.

Although appropriate removal pathways were suggested for their affinity to specific urban stormwater pollutants, some unsatisfactory findings were observed which may jeopardize the performance of intricately designed biofilters. For example, the rapid preferential flow of the geotextile lined biofilter resulting in poor hydraulic retention time, decreasing water-quality treatment, thus we recommend that this design not be considered. In addition, retrofitting of a saturated layer into plant biofilters for enhanced denitrification have resulted in unsatisfactory metal treatment. Coupled with conflicting reports regarding the effect of redox potential on metal solubility (Rieuwerts *et al.* 1998), retrofitting a saturated layer must consider the target contaminant of concern since no clear benefit was observed for the treatment of all pollutants.

The findings of this study confirm the notion that plant biofilters as applied to treatment of stormwater to improve quality treatment must include consideration of hydrologic improvements, as modifications in the water balance may be a contributing factor for a reduced pollutant load. Recognising the benefits of the various removal pathways to plant biofilters, it is possible to design a system for site and pollutant specific water treatment by addressing appropriate hydrologic and water-quality targets respectively. In urban stormwater biofilters the plant uptake, media sorption, microbial activity and infiltration benefits offered to water-quality treatment by these types of systems are valid and practically applicable.

This study focused on nutrient and metal pollutants under consistent dosages and future work should investigate other pollutants under variable and intermittent dosages. In addition, the influence of conversion from tap water to synthetic stormwater on plant and associated microbial activity must be assessed, with future work advised to measure the physiological state (redox potential) within the biofilters at short intervals (i.e. twice-weekly) following conversion. Due to the degradatory influence of total suspended solids, as a result of conventional stormwater management techniques, it is imperative that the biofilters are subjected to influent suspended solids over an extended period of time to determine the conditions under which failure occurs, warranting future research. Furthermore, future work could investigate the feasibility of interchangeable upflow filtration cartridges in the event of media clogging or exhaustion, simplifying the maintenance process. Finally, risks associated with polluted-laden media disposal during replacing or replenishing, must be assessed due to the disposed media's potential to act as a pollution source.

ACKNOWLEDGEMENT

This research was funded by the National Research Foundation (NRF) Thuthuka Fund, with project identity: TTK180418322426.

REFERENCES

Abbasi T. & Abbasi S. A. 2011 Sources of pollution in rooftop rainwater harvesting systems and their control. *Critical Reviews in Environmental Science and Technology*, **41**(23), 2097–2167.

Agilent 2015 Agilent 8800 Triple Quadrupole ICP-MS. https://www.agilent.com/cs/library/brochures/5991-0079EN_8800_ICPQQQ_Brochure.pdf (accessed 01 August 2021).

Al-Ameri M., Hatt B. E., Le Coustumer S., Fletcher T., Payne E. G. I. & Deletić A. 2018 Accumulation of heavy metals in stormwater bioretention media: A field study of temporal and spatial variation. *Journal of Hydrology*, **567**, 721–731.

Armitage N. P., Fisher-Jeffes L., Carden K., Winter K., Naidoo V., Spiegel A., Mauck B. & Coulson D. 2014 *Water sensitive urban design (WSUD) for South Africa: Framework and guidelines.* Report no TT 588/14, WRC, Gezina.

Barron N. J., Deletić A., Jung J., Fowdar H., Chen Y. & Hatt B. E. 2019 Dual-mode stormwater-greywater biofilters: The impact of alternating water sources on treatment performance. *Water Research*, **159**, 521–537.

Blecken G. T., Zinger Y., Deletić A., Fletcher T. D. & Viklander M. 2009 Impact of a submerged zone and a carbon source on heavy metal removal in stormwater biofilters. *Ecological Engineering*, **35**(5), 769–778.

Blecken G. T., Zinger Y., Deletić A., Fletcher T. D., Hedström A. & Viklander M. 2010 Laboratory study on stormwater biofiltration: Nutrient and sediment removal in cold temperatures. *Journal of Hydrology*, **394**(3–4), 507–514.

Blecken G. T., Hunt W. F., Al-Rubaei A. M., Viklander M. & Lord W. G. 2017 Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. *Urban Water Journal*, **14**(3), 278–290.

Bratieres K., Fletcher T. D., Deletić A. & Zinger Y. 2008 Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water Research*, **42**(14), 3930–3940.

Le Coustumer S., Fletcher T. D., Deletić A., Barraud S. & Poelsma P. 2012 The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Research,* **46**(20), 6743–6752.

Cucarella V. & Renman G. 2009 Phosphorus sorption capacity of filter materials used for on-site wastewater treatment determined in batch experiments: A comparative study. *Journal of Environmental Quality*, **38**(2), 381–392.

Davis A. P., Shokouhian M., Sharma H. & Minami C. 2001 Laboratory study of biological retention for urban stormwater management. *Water Environment Research*, **73**(1), 5–14.

Davis A. P., Shokouhian M., Sharma H. & Minami C. 2006 Water quality improvement through bioretention media: Nitrogen and phosphorus removal. *Water Environment Research*, **78**(3), 284–293.

Davis A. P., Hunt W. F., Traver R. G. & Clar M. 2009 Bioretention Technology: Overview of Current Practice and Future Needs. *Journal of Environmental Engineering*, **135**(3), 109–117.

Dietz M. E. & Clausen J. C. 2006 Saturation to improve pollutant retention in a rain garden. *Environmental Science & Technology*, **40**(4), 1335–1340.

Dumitru A. & Wendling L. 2021 Indicators of NBS performance and impact. In: *Evaluating the impact of nature-based solutions: A handbook for practitioners,* A. Dumitru & L. Wendling (eds.), 1st edn, European Union, Luxembourg, pp. 114-173.

Feise R. J. 2002 Do multiple outcome measures require p-value adjustment? *BMC medical Research Methodology*, **2**(1), 1–4.

Fowdar H. S., Hatt B. E., Cresswell T., Harrison J. J., Cook P. L. M. & Deletić A. 2017 Phosphorus fate and dynamics in greywater biofiltration systems. *Environmental Science and Technology*, **51**(4), 2280–2287.

Fowdar H. S., Deletić A., Hatt B. E. & Cook P. L. M. 2018 Nitrogen removal in greywater living walls: insights into the governing mechanisms. *Water*, **10**(4), 527-540.

Göbel P., Dierkes C. & Coldewey W. G. 2007 Storm water runoff concentration matrix for urban areas. *Journal of contaminant hydrology*, **91**(1–2), 26–42.

Hatt B. E., Deletić A. & Fletcher T. D. 2007 Stormwater reuse: Designing biofiltration systems for reliable treatment. *Water Science and Technology*, **55**(4), 201–209.

Hatt B. E., Fletcher T. D. & Deletić A. 2009 Hydrologic and pollutant removal performance of stromwater bofiltration systems at the field scale. *Journal of Hydrology*, **365**(3-4), 310–321.

Henderson C., Greenway M. & Phillips I. 2007 Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms. *Water Science and Technology*, **55**(4), 183–191.

Hocaoglu-Ozyigit A. & Genc B. N. 2020 Cadmium in plants, humans and the environment. *Frontiers in Life Sciences and Related Technologies*, **1**(1), 12–21.

Hsieh C., Davis A. P. & Needelman B. A. 2007 Bioretention column studies of phosphorus removal from urban stormwater runoff. *Water Environment Research,* **79**(2), 177–184.

Hunt W. F., Jarrett A. R., Smith J. T. & Sharkey L. J. 2006 Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. *Journal of Irrigation and Drainage Engineering*, **132**(6), 600–608.

Hunt W. F., Smith J. T., Jadlocki S. J., Hathaway J. M. & Eubanks P. R. 2008 Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, North Carolina. *Journal of Environmental Engineering*m, **134**(5), 403–408.

Hunt W. F., Davis A. P. & Traver R. G. 2012 Meeting hydrologic and water quality goals through targeted bioretention design. *Journal of Environmental Engineering*, **138**(6), 698–707.

Hunt W. F., Lord B., Loh B. & Sia A. 2015 Selection of plants that demonstrated nitrate removal characteristics. In: *Plant selection for bioretention systems and stormwater treatment practices*, Springer, Singapore, pp. 7-20.

Jacklin D. M., Brink, I. C. & De Waal, J. 2020 The potential use of plant species within a Renosterveld landscape for the phytoremediation of glyphosate and fertiliser. *Water SA,* **46**(1), 94–103.

Jacklin D. M., Brink I. C. & Jacobs S. M. 2021 Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators with a focus on green infrastructure. *Water SA,* **47**(3), 317-325.

Jacklin D. M., Brink I. C. & Jacobs S. M. (in press,a) Efficiencies of indigenous South African plant biofilters for urban stormwater runoff water quality improvement with a focus on nutrients and metals.

Jacklin D. M., Brink I. C. & Jacobs S. M. (in press,b) A phyto-guide to species selection for optimised South African green infrastructure - technical note.

Kim D. & Song S. K. 2019 The multifunctional benefits of green infrastructure in community development: An analytical review based on 447 cases. *Sustainability*, **11**(14), 3917-3933.

Kratky H., Li Z., Chen Y., Wang C., Li X. & Yu T. 2017 A critical literature review of bioretention research for stormwater management in cold climate and future research recommendations. *Frontiers of Environmental Science and Engineering*, **11**(4), 1–15.

Kumar B., Smita K. & Flores L. C. 2017 Plant mediated detoxification of mercury and lead. *Arabian Journal of Chemistry*, **10**, 2335-2342.

Lampe L., Barrett M., Woods-Ballard B., Martin P., Jefferies C. & Hollon M. 2005 *Performance and whole life costs of Best Management Practices (BMPs) and Sustainable Urban Drainage Systems (SUDS)*, Water Environment Research Foundation (WERF), Abertay University, London.

Lenth J. & Dugapolski R. 2011 *Compost-amended biofiltration swale evaluation,* Report WA-RD793.1, Washington State Department of Transportation, Washington, United States of America.

Li H. & Davis A. P. 2008 Heavy metal capture and accumulation in bioretention media. *Environmental Science and Technology*, **42**(14), 5247–5253.

Li H. & Davis A. P. 2009 Water quality improvement through reductions of pollutant loads using bioretention. *Journal of Environmental Engineering*, **135**(8), 567–576.

Line D. E. & White N. M. 2007 Effects of development on runoff and pollutant export. *Water Environment Research*, **79**(2), 185–190.

Maniquiz-Redillas M. C. & Kim L. H. 2016 Evaluation of the capability of low-impact development practices for the removal of heavy metal from urban stormwater runoff. *Environmental Technology*, **37**(18), 2265–2272.

Markou G., Vandamme D. & Muylaert K. 2014 Using natural zeolite for ammonia sorption from wastewater and as nitrogen releaser for the cultivation of *Arthrospira platensis*. *Bioresource Technology*, **155**, 373–378.

Mondal M., Biswas B., Garai S., Sarkar S., Banerjee H., Brahmachari K., Bandyopadhyay P. K., Maitra S., Brestic M., Skalicky M., Ondrisik P. & Hossain A. 2021 Zeolites enhance soil health, crop productivity and environmental safety. *Agronomy*, **11**(3), 448-477.

Muerdter C. P., Wong C. K. & LeFevre G. H. 2018 Emerging investigator series: The role of vegetation in bioretention for stormwater treatment in the built environment: Pollutant removal, hydrologic function, and ancillary benefits. *Water Research and Technology*, **4**(5), 592–612.

Mullane J. M., Flury M., Iqbal H., Freeze P. M., Hinman C., Cogger C. G. & Shi Z. 2015 Intermittent rainstorms cause pulses of nitrogen, phosphorus, and copper in leachate from compost in bioretention systems. *Science of the Total Environment*, **537**, 294–303.

Musakwa W. & Van Niekerk A. 2015 Monitoring sustainable urban development using built-up area indicators: A case study of Stellenbosch, South Africa. *Environment, Development and Sustainability*, **17**(3), 547–566.

Palmeira E. M., Remigio A. F. N., Ramos M. L. G. & Bernardes R. S. 2008 A study on biological clogging of nonwoven geotextiles under leachate flow. *Geotextiles and Geomembranes*, **26**(3), 205–219.

Palmer E. T., Poor C. J., Hinman C. & Stark J. D. 2013 Nitrate and phosphate removal through enhanced bioretention media: mesocosm study. *Water Environment Research,* **85**(9), 823–832.

Payne E. G. I., Pham T., Cook P. L. M., Fletcher T. D., Hatt B. E. & Deletic A. 2014 Biofilter design for effective nitrogen removal from stormwater, influence of plant species, inflow hydrology and use of a saturated zone. *Water Science and Technology*, **69**(6), 1312–1319.

Payne E. G. I., Hatt B. E., Deletic A., Dobbie M. F., McCarthy D. T. & Chandrasena G. I. 2015 *Adoption guidelines for stormwater biofiltration systems - Summary report*. Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

Payne E. G. I., Pham T., Deletic A., Hatt B. E., Cook P. L. M. & Fletcher T. D. 2018 Which species? A decision-support tool to guide plant selection in stormwater biofilters. *Advances in Water Resources*, **113**, 86–99.

Ponizovsky A. A., Thakali S., Allen H. E., Di Toro D. M. & Ackerman A. J. 2006 Effect of soil properties on copper release in soil solutions at low moisture content. *Environmental Toxicology and Chemistry: An International Journal*, **25**(3), 671–682.

Prodanovic V., Zhang K., Hatt B., McCarthy D. T. & Deletic A. 2018 Optimisation of lightweight green wall media for greywater treatment and reuse. *Building and Environment*, **131**, 99–107.

Rammal M. & Berthier E. 2020 Runoff losses on urban surfaces during frequent rainfall events: A review of observations and modeling attempts. *Water*, **12**(10), 2777.

Rebelo A. J. 2018 *Ecosystem services of Palmiet wetlands: The role of Ecosystem composition and function*. PhD thesis, Stellenbosch University, Stellenbosch, South Africa.

Reddy K. R., Xie T. & Dastgheibi S. 2014 Removal of heavy metals from urban stormwater runoff using different filter materials. *Journal of Environmental Chemical Engineering*, **2**(1), 282–292.

Rieuwerts J. S., Thornton I., Farago M. E. & Ashmore M. R. 1998 Factors influencing metal bioavailability in soils: Preliminary investigations for the development of a critical loads approach for metals. *Chemical Speciation and Bioavailability*, **10**(2), 61–75.

Sanz J. P., Freund M. & Hother S. 1996 Nitrification and denitrification in continuous upflow filters-process modelling and optimization. *Water Science and Technology*, **34**(1–2), 441–448.

SAWS. 2020 South African Weather Service. https://www.weathersa.co.za/ (accessed 13 August 2020).

Schueler T. R. 1992 Mitigating the adverse impacts of urbanization on streams: a comprehensive strategy for local government. In: *Watershed Restoration Sourcebook,* Kimble P. & Schueler T. (eds.), Washington, United States, pp. 21–31.

Shrestha P., Hurley S. E. & Wemple B. C. 2018 Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. *Ecological Engineering*, **112**, 116–131.

Smith D. P. 2015 Plenum-aerated biofilter for local-scale nitrogen removal. *Journal of Environmental Engineering*, **141**(11), 4015031.

Strecker E., Urbonas B., Quigley M., Howell J., & Hesse T. 2002 *Urban stormwater BMP performance monitoring: A guidance manual for meeting the national stormwater bmp database requirements*, Report EPA/821/B/02/001, United States Environmental Protection Agency, Washington, United States of America.

Sun X. & Davis A. P. 2007 Heavy metal fates in laboratory bioretention systems. *Chemosphere,* **66**(9),1601–1609.

Tangahu B. V., Sheikh Abdullah S. R., Basri H., Idris M., Anuar N. & Mukhlisin M. 2011 A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering*, **2011**, 1-31.

Taylor G. D., Fletcher T. D., Wong T. H. F., Breen P. F. & Duncan H. P. 2005. Nitrogen composition in urban runoff - Implications for stormwater management. *Water Research*, **39**(10), 1982-1989.

Temminghoff E. J. M., Der Zee S. E. & De Haan F. A. M. 1997 Copper mobility in a copper-contaminated sandy soil as affected by pH and solid and dissolved organic matter. *Environmental Science and Technology*, **31**(4), 1109–1115.

Tichapondwa S. & Van Biljon J. 2019 Adsorption of Cr (VI) pollutants in water using natural and modified attapulgite clay. *Chemical Engineering Transactions*, **74**, 355–360.

Valentis G. & Lesavre J. 1990 Wastewater treatment by attached-growth microorganisms on a geotextile support. *Water Science and Technology*, **22**(1–2), 43–51.

Wadzuk B. M., Hickman J. M. & Traver R. G. 2015 Understanding the role of evapotranspiration in bioretention: Mesocosm study. *Journal of Sustainable Water in the Built Environment*, **1**(2), 4014002.

Wang M., Zhang D. Q., Su J., Dong J. W. & Tan S. K. 2018a Assessing hydrological effects and performance of low impact development practices based on future scenarios modeling. *Journal of Cleaner Production*, **179**, 12–23.

Wang M., Zhang D., Li Y., Hou Q., Yu Y., Qi J., Fu W., Dong J. & Cheng Y. 2018b Effect of a submerged zone and carbon source on nutrient and metal removal for stormwater by bioretention cells. *Water*, **10**(11), 1629-1642.

Wang S., Lin X., Yu H., Wang Z., Xia H., An J. & Fan G. 2017 Nitrogen removal from urban stormwater runoff by stepped bioretention systems. *Ecological Engineering*, **106**, 340–348.

Warren L. A. & Haack E. A. 2001 Biogeochemical controls on metal behaviour in freshwater environments. *Earth-Science Reviews*, **54**(4), 261-320.

Winston R. J., Hunt W. F. & Pluer W. T. 2017 Nutrient and sediment reduction through upflow filtration of stormwater retention pond effluent. *Journal of Environmental Engineering*, **143**(5), 6017002.

Zinger Y., Blecken G. T., Fletcher T. D., Viklander M. & Deletić A. 2013 Optimising nitrogen removal in existing stormwater biofilters: Benefits and tradeoffs of a retrofitted saturated zone. *Ecological Engineering*, **51**, 75–82.

CHAPTER 6. SUPPLEMENTARY MATERIAL

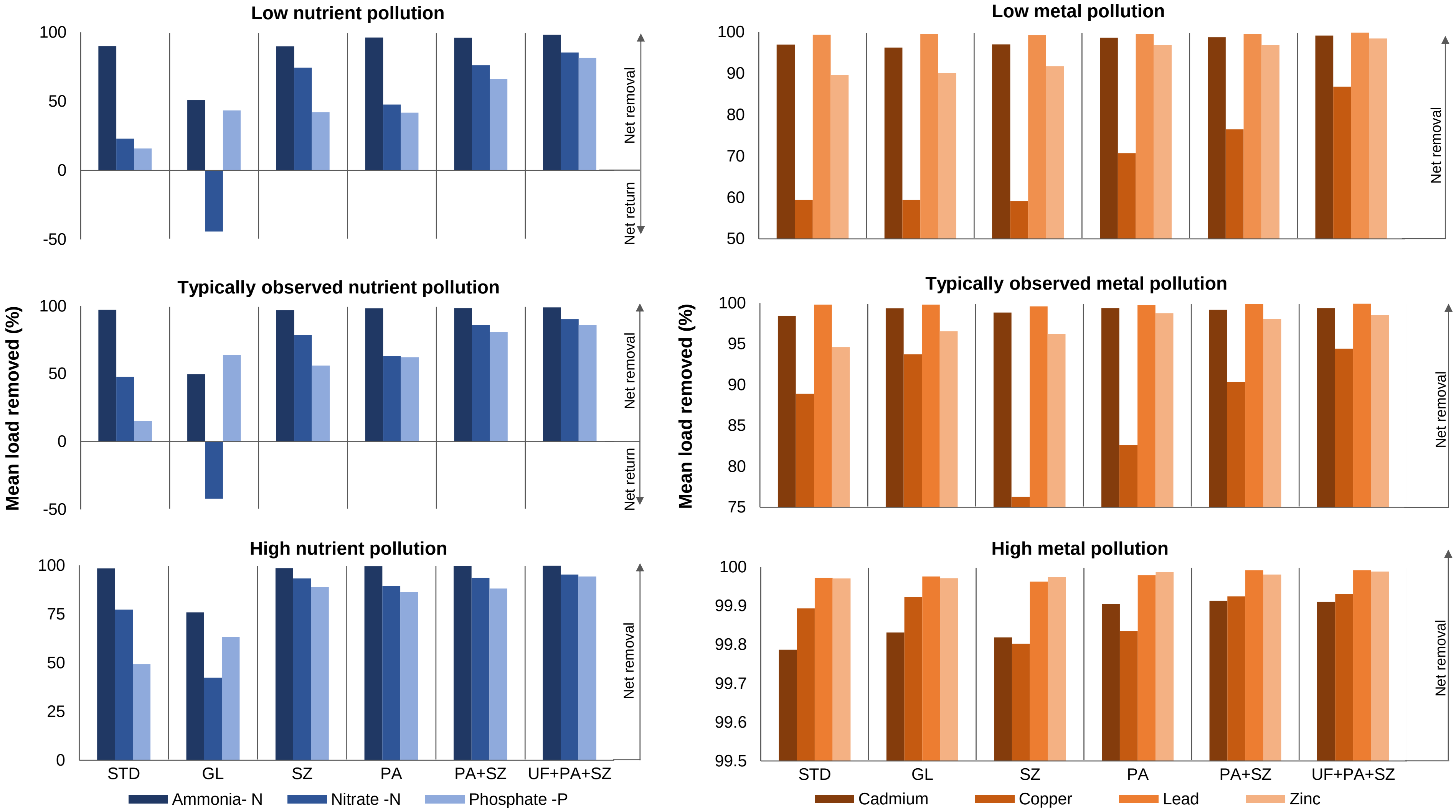


Figure S1. Mean percentage nutrient and metal load removals of the six engineered plant biofilters over 5 sampling rounds. *Note: STD = Standard; GL = Geotextile lined; SZ = Saturated zone; PA = Plenum aeration; PA+SZ = Plenum aeration + saturated zone; UF+PA+SZ = Upflow filtration + plenum aeration + saturated zone.*

CHAPTER 7

Urban stormwater pollutant removal in small scale plant biofilters: A technical note on modeling approaches

This chapter addresses research objective 6 by providing a comprehensive theoretical breakdown of the nutrient and heavy metal removal processes and pathways within an urban stormwater plant biofilter. In addition, an empirical modeling approach is undertaken to advance future local biofilter modeling endeavours. Lastly, the theoretical development of a conceptual plant biofilter model for pollutant removal, based on mathematical equations of a biofilm reactor, is proffered.

This chapter seeks to contribute to the knowledge of pollutant removal in urban stormwater biofilters by recognising the different pollutant specific removal processes and pathways, which were experimentally established from the findings of chapters 5 and 6, and collated with theory. To advance the WSUD concept in South Africa, by encouraging the adoption of stormwater biofilters, statistical output of local laboratory biofilters is retrieved from chapters 5 and 6. This empirical evidence of removal performance encompassing locally sourced engineered media and indigenous plant species accounts for the influence of operational conditions (varying influent strengths, different technical considerations and time-series), in the form of statistical regressions. Thus, initiating the currently lacking field of South African plant biofilter modeling. Furthermore, comparative analyses of the various biofilter designs' removal performances together with previously published findings of pollutant removal, enabled the identification of specific nutrient and metal pollutant removal processes and pathways. This makes it possible to develop a conceptual model, based on the mathematical equations of similar functioning removal processes and pathways in a biofilm reactor.

Therefore, in advancing the perceived novel and under-utilised WSUD concept in South Africa, via improved understanding of urban stormwater biofilters and the processes affecting their performance, this chapter employed a modeling approach. From the findings, regression modeling found influent strength to statistically significantly influence removal performance, corroborating the notion that biofilters treating high influent appear more efficient than those treating low influents. In addition, the fundamental mechanisms presented can be applied in the development of a conceptual biofilter model which, with further refinements, can be solved numerically.

The significance of this chapter is the identification of pollutant-specific removal processes and pathways in stormwater biofilters, as well as the provision of relevant equations for future modeling research.

Urban stormwater pollutant removal in small scale plant biofilters: A technical note on modeling approaches

DM Jacklin[a], ISW van der Merwe[b], IC Brink[a,*]

[a]*Department of Civil Engineering: Water and Environmental Engineering Group, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*

[b]*Zutari, P.O. Box 494, Cape Town 8000, South Africa*

Shortened version to be reproduced and reformatted for publication as a technical note with the **Urban Water Journal**

Abstract

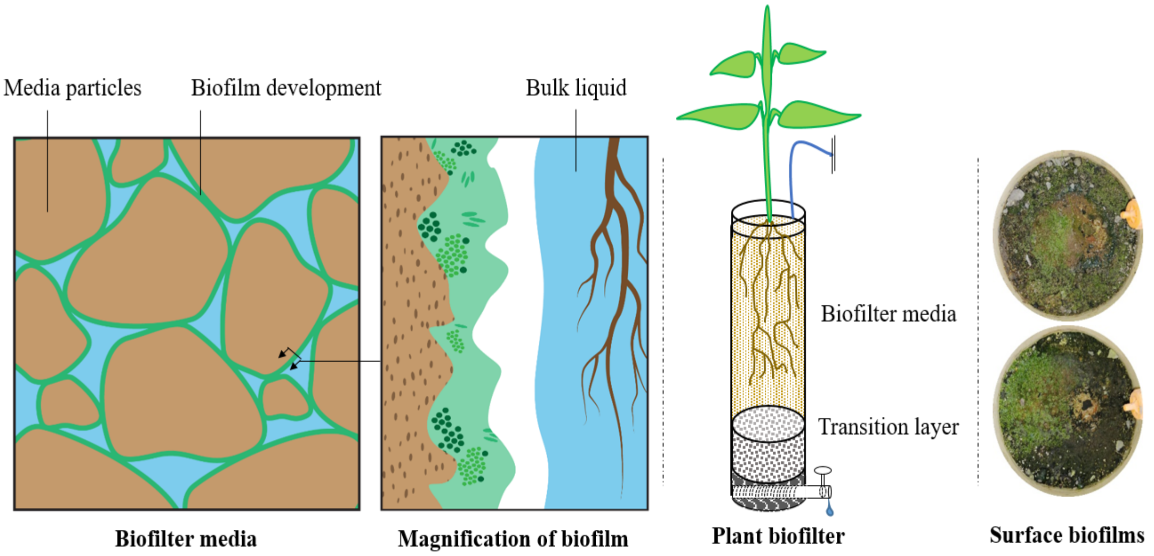
Stormwater runoff is a primary cause of urban water quality impairment. Due to the diffused nature and pollutant range of this type of water network, its treatment is considered one of the greatest challenges facing urban water managers. In response, the water sensitive urban design concept, along with plant biofiltration, is increasingly adopted. In South Africa, due to pollutant removal process complexity, coupled with the view that stormwater plant biofiltration application is still only an emerging concept lacking operational data and guidance, this sustainable alternative to conventional stormwater treatment approaches is an under-utilised asset. Therefore, this note includes a review of relevant nutrient and metal removal processes, empirical modeling output for data capture and a conceptual plant biofilter model for pollutant removal. The empirical findings contribute statistical output for future local in-depth modeling endeavours, whilst the conceptual model summarises possible applications of existing models for different removal pathways in plant biofilters towards modeling NH_3, NO_3^-, PO_4^{3-} and metal pollutant change.

Key words: stormwater quality modeling, water sensitive urban design, biofilters, biofilms, pollutant removal

Highlights

- A summary of complex nutrient and metal removal processes and pathways in a biofilter is given.
- Empirical analyses returned 420 local South African linear regressions, as a foundation to future modeling endeavours (see Supplementary Material).
- A conceptual model of a standard plant biofilter is presented as developed based on a biofilm reactor.
- Model refinements for numerical solving provided.

GRAPHICAL ABSTRACT



INTRODUCTION

The discharge of stormwater runoff consisting of elevated volumes and intensities, and increased loads of nonpoint source pollutants, is a primary cause of urban water quality impairment (Hatt, Fletcher, and Deletić 2008). Among the wide range of pollutants commonly transported by urban runoff those of particular concern are: nutrients (Shrestha, Hurley, and Wemple 2018), as the primary contributors to eutrophication (Davis et al. 2006), and heavy metals (Davis and Birch 2010), which pose a threat to public and environmental health (Reddy, Xie, and Dastgheibi 2014). Due to its diffused nature and contaminant variety, stormwater pollution and its treatment is considered one of the greatest challenges facing urban water managers (Fowdar et al. 2017). In response, Water Sensitive Urban Design (WSUD) a land planning and engineering approach integrating urban water cycle management, planning and design, based on sustainability principles is increasingly adopted (Al-Ameri et al. 2018).

Plant biofiltration systems, a holistic stormwater treatment technology within WSUD, reduces flow rates, runoff volumes (Davis et al. 2009) and pollutant loads through physical (filtration, evaporation), chemical (sorption, ion exchange, precipitation) and biological (phytoremediation, microbial-mediated transformation, transpiration) treatment processes within the soil-plant matrix (Hsieh and Davis 2005; Feng et al. 2012). Plant biofilters typically consist of vegetated growth media underlain with transition and drainage layers for the discharge of treated water into conventional stormwater drainage networks or watercourses (Blecken et al. 2010). Integrating small-scale biofilters throughout the urban area provides dispersed and passive treatment to the spatially diffused nature of urban stormwater pollution (Brink 2019), restoring natural hydrologic functions to pre-development conditions. In addition, plant biofilters alleviate pressure on existing conventional storm infrastructure, whilst enhancing urban biodiversity and aesthetics (Shrestha, Hurley, and Wemple 2018). There is growing evidence that plant biofiltration systems are effective water quality treatment technologies for heavy metals (Sun and Davis 2007), however, nutrient removal performance is more variable (Bratieres et al. 2008; Dietz and Clausen 2006).

Vegetation enhances biofilter performance directly through pollutant adsorption, transformation and uptake by plants, as well as maintaining soil porosity, or indirectly by modifying the physio-chemical properties of soil and soil microbial activities (Bratieres et al. 2008), highlighting the importance of equipping biofiltration systems with plants (Read et al. 2008). However, due to physiological, morphological and chemical variations between species, plants perform significantly different to others when exposed to different pollutants (Read et al. 2010), making plant selection a critically important step toward improved biofiltration, particularly for dissolved nitrogen (Payne et al. 2018). For dissolved phosphorous and dissolved heavy metals, although plant uptake and microbial immobilisation play a role, removal is less sensitive to plant selection and more dependent on the filtration, sorption and ion exchange physio-chemical properties of the growth media (Sun and Davis 2007; Li and Davis 2016).

In addition, within the biofilter growth media beneficial conditions for ubiquitous biofilm establishment is provided, facilitating treatment processes for the removal of pollutants from water (Del Castillo et al. 2020; Taylor et al. 2005). Here, gel-like aggregations of microorganisms and other particles are embedded in extracellular polymeric substances and grow on the substratum (soil, compost, detritus litter, engineered media and plant roots) of the biofilter, enhancing the *in situ* biodegradation of pollutants via destruction or immobilisation (Wanner et al. 2006). Intricately designed vegetated stormwater biofilters provide enhanced surface area for microbial adherence and water retention (Maurya, Singh, and Kumar 2020), whilst inert plant roots excrete substrates that support biofilm growth and pollutant transformations (Wanner et al. 2006).

South African urban stormwater management has historically predominantly sought to rapidly collect and channel runoff to the nearest watercourse, resulting in significant environmental degradation through erosion, sedimentation and pollution (Armitage et al. 2013). As an alternative approach sensitive to the issues of water sustainability and environmental protection, the Water Research Commission seeks to adopt the WSUD concept (Armitage et al. 2014). However, due to a deficiency in local research and design guidelines, the application of WSUD faces a number of challenges, with the concept still perceived as novel (Pasquini and Enqvist 2019). In response to this need for South African research, novel laboratory research investigating local engineered media and indigenous South African plant species for nutrient and heavy metal removal (Jacklin, Brink, and Jacobs 2021a, 2021b), as well as biofilter designs promoting pollutant removal pathways for optimised urban stormwater quality improvement in local WSUD initiatives, have recently been concluded (Jacklin, Brink, and

Jacobs 2021c). Comparisons of pollutant removal performances from these investigations have already been reported on, therefore, the produced data is utilised in this paper as a first step towards plant removal pathway modeling through exploratory linear regression model with time and varying pollutant loads. Furthermore, to provide a theoretical foundation to future modeling research, a theoretical review of pollutant removal pathways for plant biofilters is provided together with a subsequently informed summary of suitable theoretical deterministic models to be included in future numerical research.

Urban stormwater biofiltration models have in the past focused predominantly on hydrological improvements (Stewart et al. 2017) and particulate capture (Li and Davis 2008), whilst others have eluded varying designs and in some instances did not consider important operational conditions (Khan et al. 2013; Wang, Zhang, and Li 2019). More recently, Zhang et al. (2021) applied statistical models, which accounted for both biofilter design components and operational conditions to predict nutrient removal performance (total nitrogen and total phosphorous). Therefore, linear regression models specific to design modifications (coupled with engineered media) and plant species, exposed to varying nutrient and heavy metal loads, provide insight for improved understanding of operational condition influence on plant biofilter performance. Thus, laying the foundation for future, currently lacking, local modeling endeavours. Additionally, the novelty of this study is promoted by the development of a conceptual and theoretical combination of suitable equations in the form of a deterministic model for the removal of pollutants in a stormwater plant biofilter.

The processes affecting nutrient and metal removals, particularly for dissolved pollutants, are complex and vary between biofilter designs, growth media and organic matter amendments, rhizosphere conditions and plant choice (Hunt et al. 2008). Prior to model development an explicit understanding of dissolved nutrient and heavy metal treatment processes in biofiltration is required. Therefore, focusing on inorganic and dissolved nutrients and metals, this study consists of four main objectives: (i) Examine the primary pollutant removal processes and pathways of ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn), in plant biofiltration systems; (ii) apply empirical modeling on the removal performance of South African plant species and biofilter designs, along time-series and operational conditions as a first step investigation; (iii) present the fundamental mechanisms for deterministic pollutant removal modeling in stormwater biofilters; (iv) offer recommendations and refinements, prior to being solved numerically in future biofilter modeling research endeavours.

POLLUTANT REMOVAL PROCESSES AND PATHWAYS

Inorganic nitrogen

Inorganic nitrogen (N) in urban biofilters is primarily comprised of NH_4^+ and NO_3^- (Hsieh, Davis, and Needelman 2007b), and its treatment in both laboratory and field studies has been highly variable, with removal (Barron et al. 2019) and production (leaching) reported (Shrestha, Hurley, and Wemple 2018). Within a biofilter exposed to stormwater runoff, inorganic N's primary removal processes (Figure 1) vary based on design features and / or environmental conditions. Although NO_3^- is predominantly responsible for leaching, leaching of NH_4^+ in biofilters has been reported (Hatt, Fletcher, and Deletić 2009). Leaching is attributed to a lack of vegetation (Read et al. 2010), incorrect plant species selection (Payne et al. 2018), desorption within the growth media (Hatt, Fletcher, and Deletić 2008), decomposition from stored organic matter (Henderson, Greenway, and Phillips 2007), or erroneous biofilter design (Zinger et al. 2013).

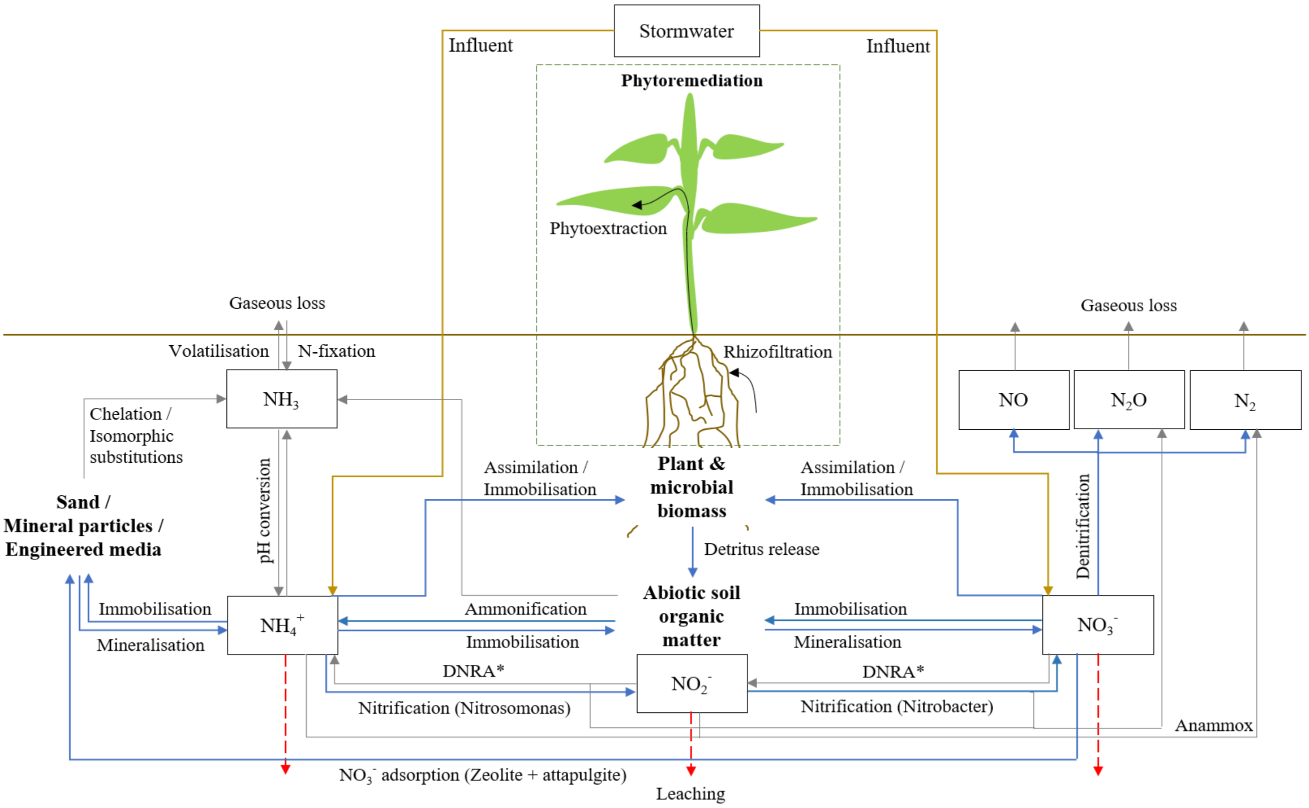


Figure 1. Inorganic N removal processes and pathways in an urban stormwater biofilter. *Note, blue and grey lines indicate primary and less-common removal processes respectively, while gold lines indicate influent pollution and red lines leaching.*
*DNRA = Dissimilatory Nitrate Reduction to Ammonia

As influent NH_4^+ and NO_3^- infiltrate through the biofilter, physical processes and some rapid chemical reactions occur, whilst slower biogeochemical transformations are more limited due to a lack of contact time within the soil-plant matrix (Hsieh, Davis, and Needelman 2007b). In addition, inorganic N may be immobilised or assimilated by the biotic biomass and taken up by the plants (Payne, Fletcher, Cook, et al. 2014). Cationic NH_4^+ is typically temporarily immobilised by negatively charged soil, mineral particles, engineered media or organic matter (compost + detritus) through sorption and ion exchange processes, and released when microorganisms die (Wang et al. 2021). In contrast, anionic NO_3^- is highly mobile in soils, resulting in significantly lower immobilisation to growth media via sorption (Hsieh and Davis 2005).

With greater retention between influent dosing events, increasing both contact surfaces and time, inorganic N may undergo a range of more complex chemical and biological transformation processes and pathways (Gobler et al. 2021). Here removal is primarily dependent on two major pathways, biotic assimilation which includes uptake by plants, bacteria, fungi and other microbes, and the nitrification-denitrification process (Osman et al. 2019). Within a biofilter these processes occur somewhat simultaneously, with nitrification contributing NO_3^- (as the most available form of N to plants for biotic uptake) prior to the denitrification process (Fowdar et al. 2018). Assimilation is the primary fate of NO_3^- in biofilters, though in biofilters populated with inefficient plant uptake species, denitrification will play a greater role (Payne, Fletcher, Russel, et al. 2014).

Phytoextraction, a phytoremediation process, offers a permanent inorganic N removal pathway through plant harvest (Pilon-Smits 2005). Within the biotic biomass, N may be returned to organic matter via detritus release (exudation, senescence or organism death), after which the ammonification process, mediated by microbes, release decomposed NH_4^+ via mineralisation (Fowdar et al. 2018). The released NH_4^+ may then undergo rapid reassimilation by the biotic biomass or infiltrate through the biofilter resulting in leaching. Additionally, biofilters amended organic matter as compost, as a source of carbon (C), may leach NO_3^- into the receiving watercourses (Mullane et al. 2015).

The aerobic nitrification process oxidizes NH_4^+ to NO_3^- across two reaction steps, mediated by the microbial *Nitrosomonas* and *Nitrobacter* species, after which transformed NO_3^- may be assimilated into the biotic biomass by plants or microbes (Payne, Fletcher, Cook, et al. 2014). In addition, NO_3^- may be immobilised by soil organic matter and either leached from the biofilter with the next dosing event, or denitrified into gaseous N forms (NO, N_2O and N_2) by heterotrophic bacteria in anaerobic C rich conditions (Zinger et al. 2013). The reliance of denitrification on NO_3^- produced by nitrification, as well as C from the biofilter growth media's organic matter, promotes opportunity for optimised N processing by equipping biofilters with successive aerobic to anaerobic layers (Muerdter, Wong, and LeFevre 2018).

The less common non-primary N removal pathways include the anaerobic microbial conversion of NO_3^- to ammonia (NH_3) in the Dissimilatory Nitrate Reduction to Ammonia (DNRA) process, which the biofilter retains N in the form of NH_4^+ (Van Den Berg et al. 2016). Similarly, in anaerobic conditions NH_4^+ and nitrite (NO_2^-) may be transformed into gaseous N_2

through the anammox process. Furthermore, NH_3 volatilisation in biofilters refers to the interaction of NH_4^+ with mineral and organic particles through adsorption, chelation and isomorphic substitution reactions (Reddy and DeLaune 2008). For the purpose of this study the N removal by these less common processes are considered negligible and not discussed, though, their collective environmental impacts need to be accounted for in real world biofilter initiatives.

Dissolved phosphorous

Similar to N, the removal of dissolved phosphorous (P) in the form of soluble reactive phosphorous, here referred to simply as PO_4^{3-}, by biofilters is highly variable and pollutant load reduction is commonly only owed to the reduction in runoff volume (Liu and Davis 2014). Biofilter growth media, consisting of sand, organic matter and engineered media, is inherently composed of some P, which may be held via adsorption or, particularly in the case of organic matter, released with time due to weathering and mineralisation (Marvin, Passeport, and Drake 2020). Organic matter mineralisation occurs as labile P release, followed by mobilisation for uptake by biotic plant and microbial biomass (Li and Davis 2016). In addition, new and establishing biofilters may leach P into discharged stormwater which is exacerbated with compost amendments (Mullane et al. 2015), however, this may decrease with time as the media ages (Jay et al. 2017).

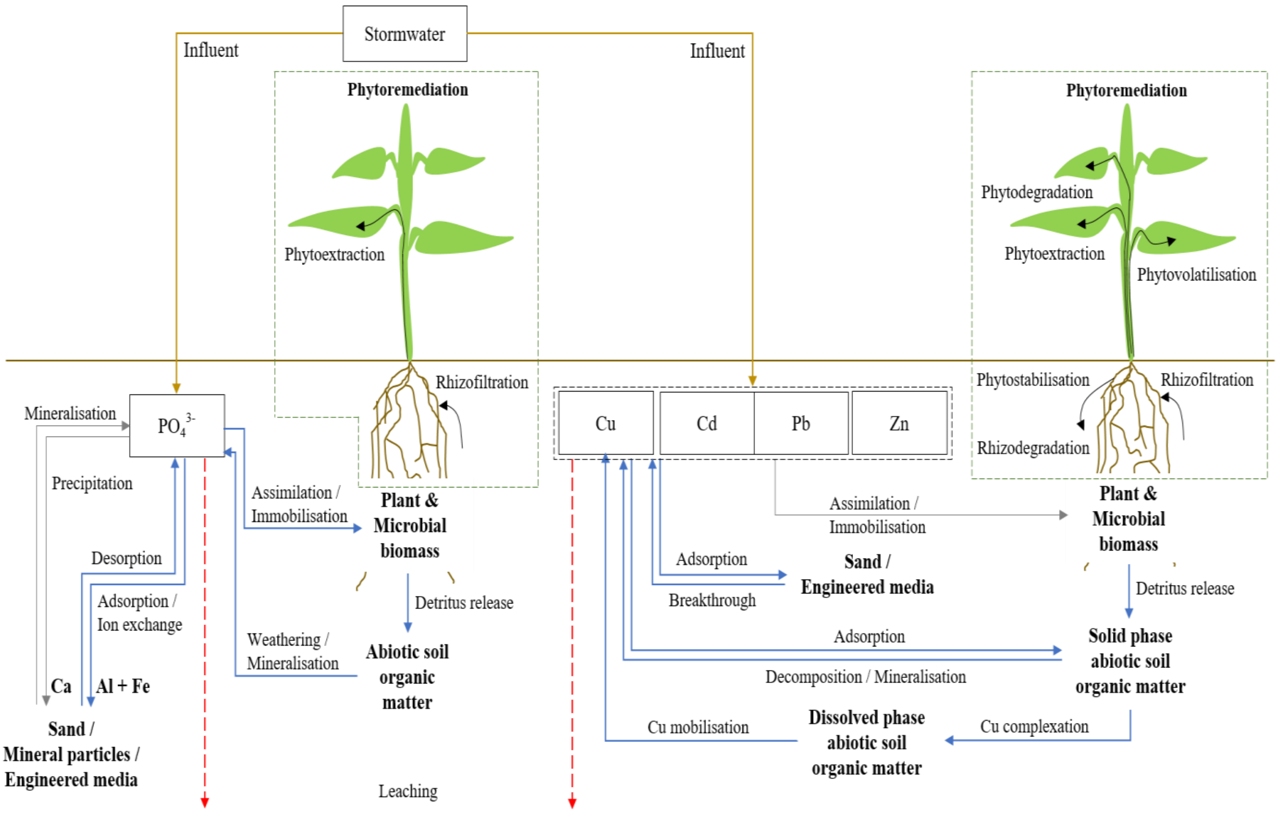


Figure 2. Dissolved P and heavy metal removal processes and pathways in an urban stormwater biofilter. *Note, blue and grey lines indicate primary and less-common removal processes respectively, while gold lines indicate influent pollution and red lines leaching.*

The primary removal pathways for PO_4^{3-} in plant biofilters (Figure 2), is adsorption and ion exchange in the upper layer of the growth media during infiltration (Fowdar et al. 2017), as well as precipitation, however, biotic assimilation and immobilisation are important, as PO_4^{3-} is the only bioavailable form of P to plants (Li and Davis 2016). Sorption is dependent on interactions with minerals calcium (Ca), aluminium (Al) and iron (Fe) in the growth media and highly influenced by pH (Li and Davis 2016). In alkaline conditions, PO_4^{3-} removal processes occur primarily via precipitation with Ca, whilst PO_4^{3-} is primarily removed via Al and Fe adsorption and ion-exchange processes (Marvin, Passeport, and Drake 2020). During influent dosing, rapid ion exchange reactions with Al and Fe on particle surfaces enable the movement of PO_4^{3-} from stormwater to growth media (Hsieh, Davis, and Needelman 2007a). Similar to the N transformation processes, between dosing events slower adsorption reactions allow for the dispersion of sorped PO_4^{3-} into particle interiors, freeing available adsorption surfaces for the next dosing event (Marvin, Passeport, and Drake 2020). Extended exposure of the growth media to polluted stormwater will reduce its removal capacity due to PO_4^{3-} accumulation and saturation, which leads to breakthrough and exhaustion, resulting in leaching (O'Neill and Davis 2012). For this reason, various engineered media amendments with high surface area, exchange and adsorption capacities, have been introduced to increase the contribution of biofilter growth media for the removal of PO_4^{3-} (Søberg et al. 2020).

In the presence of vegetation, PO_4^{3-} removal is enhanced via plant and microbial assimilation and immobilisation, whilst plant decay through detritus release returns PO_4^{3-} back into the system (Glaister et al. 2014). Plant and microbial biomass require nutrients for growth, thus, bioavailable PO_4^{3-} is taken up from the biofilter media as well as from the mycorrhiza by plants. During plant harvesting (phytoextraction), a permanent removal pathway in biofilters is created (Davis et al. 2006). Another contribution by plants is the provision of oxygen to the growth media through its roots, aiding the oxidation of Fe, increasing adsorption capacity (Marvin, Passeport, and Drake 2020). In addition, plants ameliorate the soil structure, hindering preferential flow through cracks between extended dry periods, therefore, reducing the contact time required for successful adsorption (Ding et al. 2019).

Dissolved heavy metals

In contrast to variable inorganic N and PO_4^{3-} removal, dissolved heavy metals has been shown to be effectively treated in plant biofiltration systems, with > 95% of metals Cd, Cu, Pb and Zn found to accumulate in the top 5-20cm of the growth media (Blecken et al. 2009). This accumulation in the top layer of the growth media is to be expected, as a result of immobilisation via adsorption being the primary dissolved metal removal pathway in biofilters (Figure 2) (Al-Ameri et al. 2018). Adsorption interactions are complex and encompass cation exchange, precipitation and complexation processes (Blecken, Marsalek, and Viklander 2011). Some of the less common metal removal processes are sedimentation and filtration, with plant assimilation only playing a supporting role (Hatt, Fletcher, and Deletić 2008). The efficacy of adsorption in metal removal can be seen from an investigation by Trenouth and Gharabaghi (2015), who reported up to 72% heavy metal removal within the first 7 cm of the growth media. Similarly, Sun and Davis (2007) observed 88-97% adsorption of Cd, Cu, Pb and Zn to the growth media, whilst 0.5-3.3% was assimilated by plants, and further suggested that a greater plant biomass would improve metal uptake. Metal availability for plant uptake is influenced by plant species, pH, ionic strength, redox potential, solution composition and valence (Da Silva and Williams 1976).

Heavy metal adsorption efficacy is highly correlated to the particle size of the media, with a greater proportion of fines increasing retention time, resulting in effective adsorption in the top layer of the growth media (Hermawan et al. 2021). Due to the metals being predominantly in dissolved form in urban stormwater, the use of growth media with a high adsorption capacity significantly increases heavy metal removal (Al-Ameri et al. 2018). In addition, introducing engineered media with high adsorption and ion exchange capacities further enhances removal in stormwater biofilters (Wang et al. 2018).

Within biofilters heavy metal removal may be facilitated by additional removal processes and / or media properties. For instance, with the acidification of the rhizosphere during NH_4^+ removal and subsequent proton release, influencing metal speciation due to altered media particle surface charge, redox reactions are promoted (Laurenson et al. 2013). Additionally, organic matter has been found to both increase (Jang, Seo, and Bishop 2005), as well as decrease Cu, Pb and Zn removal (Schmitt et al. 2002). Furthermore, in the presence of organic matter metal removal is influenced by its specific phase, as can be seen from Al-Ameri (2018), reporting Pb and more specifically Cu mobility correlated with dissolved phase organic matter.

The most important removal pathway for easily mobilised dissolved Cu is the formation of Cu-organic matter complexes, since the metal has the strongest affinity to organic matter out of all metals (Ponizovsky et al. 2006). Though organic matter in solid or dissolved form significantly affects Cu mobility in biofilters, it does not affect the Cu complexation affinity (Blecken et al. 2009). Whilst Cu adsorbs to solid phase organic matter, thereby immobilising the metal (Amery et al. 2007), dissolved phase organic matter mobilises Cu and in some cases have resulted in Cu leaching lasting several years (Mullane et al. 2015). However, since Cu-organic matter complexes are less toxic than free Cu ions, compost amendments may still reduce the risk of watercourse degradation (Chahal, Shi, and Flury 2016).

Similar to PO_4^{3-}, prolonged heavy metal exposure to the growth and engineered media will result in saturation and exhaustion of adsorption sites, which may lead to leaching via metal breakthrough, affecting biofilter performance, and subsequently risk ecosystem health (Hatt et al. 2011). Thus, effectively managing heavy metals in plant biofilters requires sustainable permanent removal pathways, like periodic scraping of the exhausted top surface layer as metals accumulate in the plant tissue with time. Furthermore, regular harvesting of plant species (Kumar, Smita, and Flores 2017), initiates a permanent phytoremediation-metal removal pathway (Chowdhury et al. 2020). Micronutrients Cu and Zn are removed via direct assimilation pathways in the presence of plants (Muerdter, Wong, and LeFevre 2018), whilst non-essential toxic Cd and Pb are extracted and distributed to the plant organs without offering any benefit (Hocaoglu-Ozyigit and Genc 2020). The additive, though small compared with media adsorption, metal uptake by plants through phytoremediation is greater in both complexity and number of processes compared with nutrients (Figure 2). Unpacking the different phytoremediation processes falls outside the scope of this study, however, the reader is invited to explore the concepts and applications of heavy metal phytoremediation by Ali, Khan, and Sajad (2013).

Modifying standard biofilters

Modifications to standard stormwater biofilters have been made to enhance pollutant removal efficiency and improve treatment consistency, particularly for nutrients NO_3^- and PO_4^{3-}. For the removal of inorganic N, modifications are primarily introduced through design components, with plenum aerobic (Smith 2015) and upflow filtration (Zhou and Xu 2019) found to enhance NH_4^+ removal. Additionally, saturated anaerobic layers have been found to increase the removal of NO_3^- (Zinger et al. 2013). Within the plenum layer, atmospheric oxygen and carbon is supplied to the nitrification process prior to denitrification in the saturated layer, advancing NH_4^+ removal. In addition, engineered media may increase N removal through immobilisation, with vermiculite found to effectively adsorb NH_4^+ (Mazloomi and Jalali 2017), and zeolite and attapulgite deemed effective at adsorbing both NH_4^+ and NO_3^- (Dong et al. 2018; Liu et al. 2012).

For PO_4^{3-}, biofilter performances have been enhanced with the inclusion of upflow filtration (Winston, Hunt, and Pluer 2017) and saturated anaerobic layers (Glaister et al. 2017). In addition, the use of engineered vermiculite (Lee 2020), zeolite (Gizaw et al. 2021) and attapulgite (Li et al. 2016) media have shown potential to enhance PO_4^{3-} removal through adsorption in stormwater technologies.

Design modifications for enhanced heavy metal removal have previously entailed the use of upflow filtration (Zouboulis, Lazaridis, and Grohmann 2002) and saturated anaerobic layers (Chu et al. 2021). In addition, engineered media amendments have also been reported to increase the heavy metal adsorption capabilities, with vermiculite (Hashem, Amin, and El-Gamal 2015), zeolite (Reddy, Xie, and Dastgheibi 2014) and attapulgite (Wang et al. 2017) improving biofilter performance.

This study, which forms part of a larger project seeking to advance South African research into biofiltration, similarly explored the performance of varying local engineered media (Jacklin, Brink, and Jacobs 2021b), indigenous plant species (Jacklin, Brink, and Jacobs 2021a), and physical design modifications (Jacklin, Brink, and Jacobs 2021c). These investigations were conducted in a laboratory environment for the collection of data utilised in empirical modeling.

DATA COLLECTION

The details of the laboratory investigations on indigenous South African plant species and designs for urban stormwater pollutant removal which the linear regression models in this study rely for data, is discussed in previously submitted and published papers (Jacklin, Brink, and Jacobs 2021a, 2021c). The methodologies are briefly discussed here (Figure 3), and the reader is furthermore referred to supplementary material, Table S1.

A twice-weekly dosing regime reflected published low, typically observed and high urban stormwater nutrient and metal pollutant concentrations (Jacklin, Brink, and Jacobs 2021a). Biofilter construction was based on typical urban design guidelines as recommended by Payne et al. (2015) (see Jacklin, Brink, and Jacobs 2021c). Standard biofilters, with compost and perlite amended growth media, were either populated with nine indigenous plants (14 month establishment period), or modified by five distinct designs and populated with *Prionium serratum* (15 month establishment period). Design modifications sought to make use of varying engineered media whilst introducing and finally combining saturated anaerobic, plenum aerobic and upflow filtration removal pathways for optimal performance (See Figure 3).

Nutrient samples were collected on five occasions and assessed for NH_3 -N, NO_3^- -N and PO_4^{3-} -P in the Stellenbosch University Water Quality Laboratory. Similarly, separate samples were collected and analysed for dissolved Cd, Cu, Pb and Zn by the Stellenbosch University Central Analytical Facility: ICP-MS division.

Effluent load data (concentration x volume) collected for each of the seven pollutants (as stated above) across the nine indigenous plant species, one growth media (unvegetated soil) and five biofilter designs, exposed to three varying influent pollution strengths (low, typically observed and high) over five sampling rounds produced 225 samples. Therefore, analyses produced 1575 nutrient and heavy metal observations, 1050 and 525 for the plant species and biofilter designs respectively.

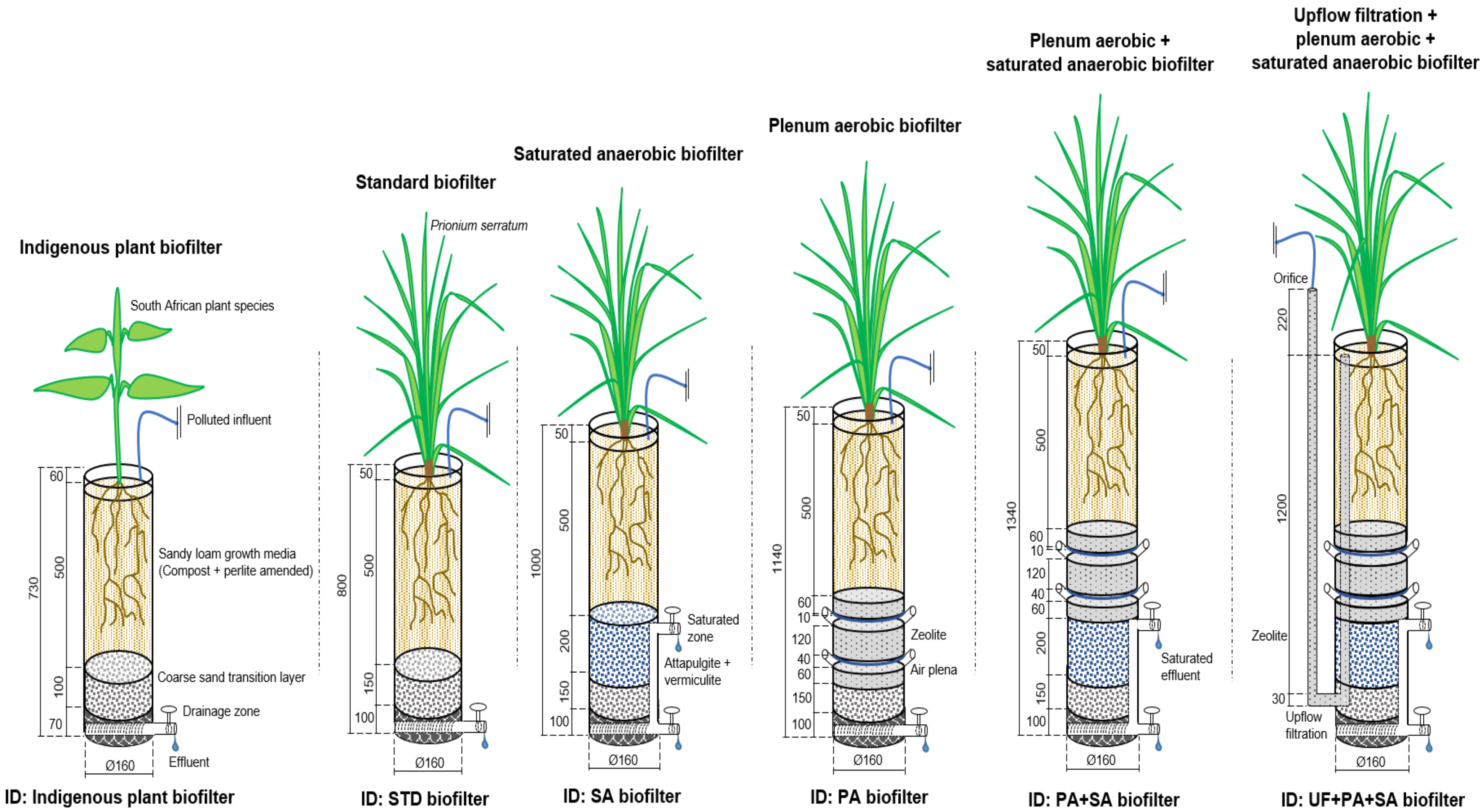


Figure 3. Experimental schematic of the indigenous plant and design amended biofilters. *Note: STD = Standard; SA = Saturated anaerobic; PA = Plenum aerobic; PA+SA = Plenum aerobic + saturated anaerobic; UF+PA+SA = Upflow filtration + plenum aerobic + saturated anaerobic* (Jacklin, Brink, and Jacobs 2021c).

EMPIRICAL MODELING

As a first step investigation into data, simple linear regression analyses was used to examine correlations between pollutant load removed with time and influent load strength for both the indigenous plant species and biofilter designs. Due to the large range and unequal distribution of influent strengths, a logarithmic transformation was applied to the independent influent strength variables, producing a semi-log model. Statistical analyses were conducted in R Statistical Software, which applied ANOVA F-tests to the results, the reader is referred to Tables 1-2 below for a discussion of the results. Significance was accepted at $p \leq 0.05$ and a model with relatively accurate goodness-of-fit at $R^2 \geq 0.70$.

Percent pollutant load reduction was included as the dependent variable in the analysis. The calculation of load (a function of measured concentrations x measured volumes) was used in lieu of concentrations (only) due to volume loss in plant biofilters. A Kruskal-Wallis H-test assessed the variation in influent concentrations between sampling rounds which, due to statistically insignificant differences ($p > 0.05$) between influent loads over the sampling period, permitted the use of linear regression analyses of biofilters' percent pollutant load removals.

Empirical analyses provided plant and design specific correlations between the independent (influent load) and dependent (percent removal) variables, highlighting the influence of different operational conditions on biofilter performance.

Effect of time on biofilter performance

Analysing pollutant removal by indigenous species and biofilter designs exposed to varying influent strengths for each pollutant parameter returned 315 linear regressions, with statistical output provided by Table 1, as well as plotted trends depicted in supplementary material, Figures S1-S2. Non log-transformed independent variables were used due to the small range and uniform distribution (Selbig and Fienen 2012), as well as the expectation that percent removal follows a linear trend over time for nutrients (see Bratieres et al. 2008) and heavy metals (see Blecken et al. 2009). In addition, log-transforming the independent variables were not found to improve the outcomes of the linear regression model.

Focusing on pollutants, variations in percent removal with time were better explained by the linear regression models for nutrients than for heavy metals exposed to all three influent pollutant strengths. Nutrients NH_3-N and PO_4^{3-}-P with time were explained relatively well ($R^2 \geq 0.70$) by the linear regression models in 46.67% and 86.67% of the experimental biofilters respectively. In contrast, the best performing linear models for heavy metals only explained 13.3% of the percent Cu and Pb removal percentages relatively accurately. This outcome indicates a very complicated functioning using multiple removal pathways. Variation in outcome was also observed not only in different pollutant type, but also in plant biofilter design.

Table 1. Statistical output for percent pollutant load removal with time (non log-transformed): R^2, F-test p-value and model coefficient. *Note: Shaded cells = significant relationships.*

Biofilter	NH_3 -N			NO_3^- -N			PO_4^{3-} -P			Cd			Cu			Pb			Zn		
	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef
Low pollution																					
A. africanus	0.93	0.0072	0.27	0.14	0.53	0.34	0.98	0.0011	4.49	0.67	0.091	-0.02	0.59	0.12	0.02	0.13	0.54	0.05	0.24	0.40	-0.00
C. glomerata	0.99	0.0004	0.11	0.01	0.88	0.10	0.96	0.0039	3.66	0.28	0.36	-0.02	0.79	0.040	0.29	0.65	0.098	-0.00	0.04	0.74	-0.01
C. aethiopica	0.90	0.013	0.04	0.10	0.60	0.42	0.98	0.001	5.12	0.43	0.23	0.01	0.31	0.33	0.17	0.00	0.92	-0.00	0.61	0.12	-0.04
C. dactylon	0.73	0.063	-0.23	0.20	0.45	-0.47	0.86	0.023	4.01	0.37	0.27	0.03	0.48	0.19	0.19	0.02	0.80	-0.00	0.01	0.88	-0.01
C. textilis	0.82	0.034	0.16	0.20	0.45	-0.30	0.92	0.011	3.90	0.64	0.10	-0.05	0.65	0.098	0.34	0.04	0.74	0.00	0.00	0.96	-0.00
D. iridioides	0.20	0.44	-0.13	0.39	0.26	1.14	0.79	0.044	4.20	0.37	0.27	-0.01	0.92	0.0098	0.72	0.02	0.84	0.00	0.06	0.67	-0.01
J. effusus	0.75	0.057	0.14	0.10	0.60	0.25	0.88	0.017	2.71	0.85	0.025	-0.03	0.70	0.079	0.29	0.01	0.86	-0.00	0.19	0.46	-0.05
P. serratum	0.95	0.0055	0.23	0.44	0.22	-0.27	0.87	0.019	1.14	0.88	0.017	-0.02	0.27	0.36	0.18	0.13	0.56	0.00	0.32	0.31	-0.04
S. reginae	0.45	0.21	-0.31	0.42	0.24	0.76	0.99	0.00068	4.63	0.04	0.73	0.004	0.26	0.38	-0.07	0.06	0.69	0.00	0.67	0.089	-0.03
Growth media	0.81	0.036	-0.26	0.07	0.66	0.19	0.97	0.002	3.26	0.59	0.12	0.02	0.76	0.055	0.37	0.76	0.054	-0.00	0.49	0.18	-0.08
STD	0.40	0.25	0.01	0.14	0.54	0.04	0.91	0.010	1.01	0.28	0.35	-0.00	0.53	0.16	-0.09	0.07	0.66	0.00	0.77	0.12	-0.20
SA	0.59	0.12	-0.01	0.14	0.54	-0.04	0.83	0.033	0.42	0.79	0.043	-0.00	0.54	0.16	-0.12	0.22	0.43	0.00	0.49	0.18	-0.12
PA	0.65	0.091	-0.00	0.04	0.75	-0.01	0.87	0.021	0.43	0.06	0.67	-0.00	0.13	0.55	0.05	0.64	0.10	-0.00	0.44	0.22	-0.05
PA+SA	0.88	0.017	0.001	0.18	0.48	-0.07	0.93	0.0086	0.32	0.06	0.68	-0.00	0.09	0.63	-0.02	0.25	0.39	-0.00	0.29	0.35	-0.03
UF+PA+SA	0.04	0.76	-0.00	0.07	0.67	-0.01	0.94	0.0068	0.08	0.43	0.23	-0.00	0.02	0.83	-0.01	0.11	0.57	-0.00	0.05	0.73	-0.00
Typically observed pollution																					
A. africanus	0.04	0.74	0.02	0.47	0.20	0.32	0.65	0.10	2.46	0.68	0.087	-0.02	0.01	0.87	0.02	0.17	0.49	-0.00	0.00	0.92	0.00
C. glomerata	0.60	0.12	0.25	0.41	0.24	0.13	0.75	0.058	2.45	0.24	0.40	-0.01	0.05	0.73	0.04	0.65	0.099	-0.00	0.34	0.30	-0.02
C. aethiopica	0.70	0.078	0.15	0.54	0.15	0.35	0.90	0.013	2.53	0.40	0.25	-0.01	0.94	0.0067	0.08	0.36	0.28	0.00	0.78	0.046	-0.01
C. dactylon	0.20	0.45	-0.04	0.01	0.95	0.02	0.88	0.019	2.56	0.47	0.20	-0.01	0.50	0.18	0.06	0.60	0.13	-0.00	0.78	0.048	-0.03
C. textilis	0.03	0.79	0.03	0.12	0.57	0.15	0.93	0.0077	2.69	0.67	0.090	-0.01	0.00	0.96	0.01	0.10	0.60	-0.00	0.07	0.67	0.01
D. iridioides	0.01	0.89	0.03	0.17	0.48	0.20	0.88	0.017	2.78	0.65	0.10	-0.01	0.61	0.12	0.19	0.68	0.088	-0.00	0.67	0.092	0.02
J. effusus	0.01	0.88	0.01	0.01	0.96	0.02	0.83	0.032	1.41	0.12	0.57	-0.00	0.05	0.71	-0.02	0.78	0.046	-0.00	0.01	0.85	0.00
P. serratum	0.01	0.91	0.01	0.00	0.99	-0.00	0.78	0.047	1.56	0.99	0.00074	-0.01	0.02	0.81	-0.00	0.78	0.047	-0.00	0.10	0.60	0.01
S. reginae	0.58	0.14	-0.06	0.48	0.19	0.36	0.91	0.011	2.53	0.10	0.59	-0.00	0.01	0.89	0.01	0.07	0.67	-0.00	0.70	0.076	-0.03
Growth media	0.80	0.039	-0.14	0.98	0.00	-1.21	0.94	0.0069	3.21	0.02	0.84	-0.00	0.28	0.36	0.03	0.06	0.70	0.00	0.01	0.85	-0.00
STD	0.25	0.38	0.00	0.75	0.057	-0.13	0.98	0.0010	0.82	0.02	0.83	0.00	0.02	0.83	0.01	0.03	0.80	-0.00	0.07	0.67	-0.01
SA	0.72	0.061	-0.01	0.01	0.85	-0.02	0.81	0.037	0.49	0.89	0.017	-0.01	0.62	0.12	-0.17	0.37	0.27	-0.00	0.00	0.92	0.00
PA	0.28	0.35	-0.01	0.16	0.49	0.05	0.91	0.011	0.22	0.00	0.92	0.00	0.70	0.075	-0.17	0.57	0.14	-0.00	0.49	0.19	-0.04
PA+SA	0.54	0.15	-0.00	0.06	0.69	0.01	0.57	0.14	0.11	0.78	0.045	-0.01	0.02	0.81	-0.00	0.90	0.013	-0.00	0.01	0.88	0.00
UF+PA+SA	0.30	0.34	-0.00	0.12	0.57	-0.00	0.84	0.029	0.10	0.47	0.19	-0.01	0.66	0.093	-0.09	0.80	0.039	-0.00	0.38	0.27	0.01
High pollution																					
A. africanus	0.89	0.017	0.01	0.59	0.13	0.07	0.93	0.0073	1.03	0.27	0.37	0.00	0.01	0.91	0.00	0.68	0.084	-0.00	0.48	0.20	-0.00
C. glomerata	0.87	0.057	0.00	0.60	0.12	0.08	0.86	0.024	1.21	0.12	0.56	0.00	0.88	0.019	-0.00	0.87	0.022	-0.00	0.76	0.052	-0.00
C. aethiopica	0.83	0.084	0.00	0.79	0.043	0.25	0.86	0.023	2.40	0.62	0.11	-0.00	0.03	0.80	0.00	0.69	0.083	-0.00	0.87	0.021	-0.00
C. dactylon	0.87	0.021	0.00	0.39	0.26	0.06	0.93	0.0085	2.89	0.23	0.42	-0.00	0.10	0.60	-0.00	0.45	0.22	-0.00	0.87	0.021	-0.00
C. textilis	0.83	0.032	0.00	0.56	0.14	0.06	0.88	0.019	0.43	0.04	0.74	-0.00	0.34	0.30	-0.00	0.41	0.25	-0.00	0.29	0.35	0.00
D. iridioides	0.92	0.010	0.00	0.61	0.12	0.12	0.91	0.011	1.24	0.12	0.56	-0.00	0.03	0.78	0.00	0.07	0.66	-0.00	0.58	0.14	-0.00
J. effusus	0.82	0.033	0.00	0.97	0.0019	0.05	0.91	0.011	0.40	0.47	0.20	-0.00	0.49	0.19	-0.00	0.00	0.93	-0.00	0.00	0.97	-0.00
P. serratum	0.63	0.11	0.00	0.50	0.18	0.03	0.76	0.055	0.44	0.00	0.94	0.00	0.69	0.083	-0.00	0.47	0.20	-0.00	0.10	0.60	-0.00
S. reginae	0.77	0.051	0.00	0.52	0.17	0.13	0.90	0.013	1.25	0.07	0.67	-0.00	0.05	0.72	-0.00	0.67	0.088	-0.00	0.71	0.071	-0.00
Growth media	0.46	0.21	0.00	0.77	0.051	-0.15	0.98	0.0014	3.07	0.66	0.096	-0.00	0.72	0.069	-0.00	0.86	0.024	-0.00	0.80	0.039	-0.00
STD	0.05	0.71	0.00	0.90	0.013	-0.18	0.94	0.0060	0.55	0.42	0.24	-0.00	0.06	0.69	-0.00	0.13	0.55	-0.00	0.48	0.19	-0.00
SA	0.08	0.64	-0.00	0.88	0.018	-0.06	0.11	0.58	0.03	0.62	0.12	0.00	0.09	0.62	0.00	0.02	0.82	0.00	0.12	0.56	-0.00
PA	0.00	0.92	-0.00	0.04	0.74	-0.01	0.53	0.16	0.09	0.01	0.88	-0.00	0.11	0.58	-0.00	0.53	0.16	-0.00	0.30	0.34	-0.00
PA+SA	0.05	0.72	-0.00	0.86	0.024	-0.07	0.00	0.92	-0.01	0.00	0.94	0.00	0.22	0.43	0.00	0.33	0.31	-0.00	0.01	0.87	0.00
UF+PA+SA	0.72	0.047	-0.00	0.86	0.023	-0.05	0.15	0.52	0.03	0.12	0.57	0.00	0.31	0.33	0.00	0.45	0.21	-0.00	0.04	0.75	-0.00

No clear pattern was observed indicating that future modeling approaches would require case specific approaches linked to a specific design in order to determine modeling parameters for deterministic models. In other words, a specific plant biofilter design will need to undergo laboratory testing for determination of specific correct model parameters for the design. In addition to high R^2-values reported by the linear regression models for the removal of PO_4^{3-} -P, it was also the only pollutant that was consistently significantly ($p \leq 0.05$) influenced by time and maintained greater coefficients over the influent strengths. Therefore, among the pollutant parameters only the increase in percent PO_4^{3-} -P removal was shown to be significantly influenced by time and relatively well explained by linear regression model, for the duration of this study.

Comparing indigenous plant biofilters across influent strengths, the biofilter with the most number of linear regression models that relatively accurately explained the changes in percent removal of low strength influent pollution was *J. effusus,* with R^2-values ≥ 0.70 for NH_3 -N, PO_4^{3-} -P, Cd and Cu. For typically observed pollution, the models fitted to *C. aethiopica* explained the data the best, reporting R^2-values of NH_3 -N, PO_4^{3-} -P, Cu and Zn greater than 0.70. Exposed to high pollution, the linear regression models fitted to the *C. glomerata* biofilter explained the percent removal changes the best, with NH_3 -N, PO_4^{3-} -P, Cu, Pb and Zn all reporting R^2-values greater than 0.70. Therefore, although it was found that the linear regression models were able to explain percent removal variation in some pollutants (specifically PO_4^{3-} -P) in a number of the experimental biofilters, time was observed not to significantly influence nutrient and heavy metal removal, over the study period.

The linear regression models inadequately explained percent removal as a function of time, with the exception of PO_4^{3-} -P. This is a very interesting result, indicating that empirical modeling approaches may very well be useable in the biofilter designs investigated here. If supported by future research, a simple linear regression approach to PO_4^{3-} -P load changes could provide welcome simplification to otherwise highly complex deterministic modeling.

The reader must take cognisance of the somewhat limited study period. It was observed that variation in percent nutrient removal with time was better explained by the linear regression models than for heavy metals, across all three influent pollutant strengths, indicating greater fluctuation in metal removal. Due to the constrained period study period, a longer assessment is required to validate this finding and its potential cause.

Effect of influent load on biofilter performance

Analysing pollutant removal by indigenous species and biofilter designs for all pollutant parameters across the three influent strengths returned 105 linear regressions, with their corresponding statistical output provided by Table 2, as well as plotted trends depicted in supplementary material, Figure S3.

Table 2. Statistical output of linear regression models for percent pollutant load removal as a function of influent load (log-transformed): R^2, F-test p-value and model coefficient. *Note: Shaded cells = significant relationships.*

Pollutant		*A. africanus*			*C. glomerata*			*C. aethiopica*	
	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef
NH_3	0.81	0.0000043	7.59	0.65	0.00027	7.09	0.93	0.0000000093	12.44
NO_3^-	0.79	0.0000086	32.13	0.70	0.000091	25.73	0.78	0.000014	50.13
PO_4^{3-}	0.32	0.029	67.77	0.33	0.025	52.06	0.22	0.078	55.33
Cd	0.79	0.0000084	0.84	0.77	0.000015	0.85	0.97	0.000000000015	2.11
Cu	0.61	0.00056	4.43	0.66	0.00024	3.69	0.88	0.000000022	7.11
Pb	0.33	0.025	0.032	0.37	0.015	0.049	0.54	0.0019	0.072
Zn	0.63	0.00043	1.20	0.68	0.00016	1.23	0.87	0.00000062	2.78
Pollutant		*C. dactylon*			*C. textilis*			*D. iridioides*	
	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef
NH_3	0.86	0.00000059	8.27	0.45	0.0058	3.00	0.49	0.0039	6.58
NO_3^-	0.87	0.00000033	29.99	0.68	0.00017	14.60	0.70	0.000092	39.99
PO_4^{3-}	0.033	0.52	15.74	0.43	0.0079	67.62	0.097	0.26	28.66
Cd	0.70	0.00011	1.33	0.41	0.0097	0.61	0.90	0.000000075	1.06
Cu	0.84	0.0000018	6.74	0.48	0.0042	4.27	0.74	0.000037	4.35
Pb	0.96	0.00000000017	0.059	0.95	0.00000000053	0.082	0.74	0.000036	0.048
Zn	0.79	0.0000092	2.012	0.78	0.000012	0.70	0.78	0.000013	1.86
Pollutant		*J. effusus*			*P. serratum*			*S. reginae*	
	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef
NH_3	0.45	0.0059	2.96	0.39	0.013	2.96	0.47	0.0048	8.33
NO_3^-	0.66	0.00022	16.35	0.69	0.00010	10.21	0.73	0.000048	38.97
PO_4^{3-}	0.25	0.059	28.79	0.15	0.16	13.83	0.43	0.0077	80.31
Cd	0.62	0.00054	0.51	0.54	0.0019	0.37	0.80	0.0000068	0.97
Cu	0.63	0.00038	3.83	0.75	0.000033	2.63	0.63	0.00038	5.26
Pb	0.61	0.00056	0.048	0.39	0.013	0.034	0.55	0.0016	0.033
Zn	0.59	0.00085	0.64	0.71	0.000087	0.56	0.77	0.000016	1.60
Pollutant		**Growth media**			**STD biofilter**			**SA biofilter**	
	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef
NH_3	0.94	0.0000000018	15.65	0.61	0.00058	2.87	0.69	0.00012	3.13
NO_3^-	0.93	0.0000000070	59.62	0.88	0.00000022	14.95	0.84	0.0000014	5.54
PO_4^{3-}	0.36	0.018	68.92	0.30	0.033	17.57	0.73	0.000049	23.93
Cd	0.97	0.000000000030	2.98	0.83	0.0000019	0.87	0.79	0.000011	0.83
Cu	0.99	0.000000000000010	10.41	0.60	0.00070	5.59	0.73	0.000045	6.02
Pb	0.85	0.0000011	0.24	0.80	0.0000059	0.071	0.75	0.000029	0.096
Zn	0.65	0.00037	3.72	0.36	0.019	1.48	0.39	0.013	1.13
Pollutant		**PA biofilter**			**PA+SA biofilter**			**UF+PA+SA biofilter**	
	R^2	p-value	Coef	R^2	p-value	Coef	R^2	p-value	Coef
NH_3	0.87	0.00000031	1.41	0.88	0.00000019	1.43	0.93	0.0000000049	0.63
NO_3^-	0.97	0.000000000060	12.13	0.70	0.000099	4.58	0.82	0.0000037	2.66
PO_4^{3-}	0.76	0.000020	21.51	0.53	0.0021	9.84	0.78	0.000013	6.41
Cd	0.68	0.00015	0.44	0.81	0.0000044	0.43	0.63	0.00042	0.25
Cu	0.73	0.000056	3.67	0.75	0.000034	3.39	0.70	0.00019	1.86
Pb	0.60	0.00066	0.047	0.46	0.0053	0.058	0.40	0.011	0.021
Zn	0.28	0.041	0.46	0.53	0.0020	0.50	0.73	0.000051	0.27

Plotting the data a clear curvilinear relationship between percent removal and influent strength was observed, to be expected as percent removals are highly dependent on influent concentrations (Strecker et al. 2002). This observation is important in this study, as the function also applies to pollutant loads (Lampe et al. 2005). Thus, log-transforming the independent variable was applied due to the large range and unequal distribution of influent strengths, producing a semi-log model.

From the results, in contrast to percent removal with time (discussed above), variation in percent removal of PO_4^{3-} -P was relatively well explained by the linear regression models fitted to the log-transformed independent variables the least effectively, with only three experimental biofilters, the SA biofilter, PA biofilter and UF+PA+SA biofilter producing R^2-values greater than 0.70. In addition, PO_4^{3-} -P was the only pollutant that was in some cases insignificantly ($p > 0.05$) influenced by influent strength, as observed in five biofilters. However, this result is not accepted to be of great meaning since good correlations were found in most cases. The nutrient and heavy metal percent removal that were explained best by the linear regression models were for NO_3^- -N and Cd, reporting R^2-values greater than 0.70 in 80% and 73.33% of the experimental biofilters respectively. In contrast, as mentioned, the percent removal of nutrient PO_4^{3-} -P was explained the worst ($R^2 \geq 0.70$ in 20% of the biofilters) by the regression models, whilst heavy metal Pb was relatively well explained in only 40% of the biofilters.

Comparing indigenous plant biofilter, the biofilter comprised of the most number of linear regression models fitted to the log-transformed independent influent pollution strengths that relatively accurately explain the changes in percent removal was *C. dactylon,* reporting R^2-values greater than 0.70 for NH_3 -N, NO_3^- -N, Cd, Cu, Pb and Zn. In contrast, the indigenous plant biofilter with the least amount of relatively accurate fitted linear models was *J. effusus*, reporting no R^2-values greater than 0.70. In addition, removal for all pollutants (with the exception of PO_4^{3-} -P in some cases) were significantly influenced ($p \leq 0.05$) by influent load strength. This suggests that the linear regression models fitted to the log transformed independent variables are statistically significant, corroborating the notion by Strecker et al. (2002) that biofilters treating high influent concentration appear to be more efficient than those treating low influents. The reader is, however, once again reminded of the constrained study period. It is possible that longer study times will result in filter clogging, reducing the correlations between influent load strength and percent removals. This possibility warrants future research.

Variability in the linear regression model coefficients support the previous conclusion that the biofilter systems investigated here were unique, indicating once again that specific designs will require case specific testing of parameters to inform any modeling applications to said design. In other words, from these results it seems as if a “one size fits all” design approach to plant biofilter systems is unlikely to be feasible, unless removal pathways as discussed above can be very well defined with in depth understanding of and data for parameter change and interactions between different biofilter functionalities (i.e. microbial action – plant root interface, adsorption and desorption etc.).

The next section discusses possible deterministic modeling approaches to inform future modeling endeavours. As indicated by the results of the linear regression modeling, future plant biofilter modeling of specific designs should incorporate laboratory testing to determine the correct applicable model parameters.

DETERMINISTIC MODELING

The explicit understanding of the pollutant-specific removal processes and pathways in a stormwater plant biofilter, as identified by the laboratory investigations or retrieved from literature, informed the identification of theoretically suitable modeling approaches. Here, suitable applications to the different removal pathways for a standard vegetated biofilter are summarised, explained and motivated. This to act as a foundational base, supported by theoretical background, for determination of numerical parameter values in future research.

Biofilm reactors are widely used for the treatment of wastewater and although there are various types, all biofilm reactors share the following characteristics (Morgenroth 2008):

- Microorganisms grow on a substratum which is retained in the biofilm reactor;
- The microorganisms form a biofilm, which remains attached to the substratum;
- As wastewater moves through the reactor, pollutants are adsorbed from the wastewater into the biofilm;
- The flux of pollutant from the wastewater to the biofilm is used by the microorganisms for growth and cell maintenance;
- Detachment controls biofilm growth and plays an important role in preventing the biofilm from blocking the flow of liquid through the reactor.

Based on the characteristics given above it is believed that biofilm modeling equations can be adopted to model the removal of pollutants in a stormwater biofilter, as follows:

- Polluted stormwater enters the biofilter in the bulk liquid phase;
- A biofilm develops onto the particles of the growth and / or engineered media (substratum);
- Pollutants are removed from the bulk liquid to the biofilm through diffusion;
- In addition to pollutant diffusion to the biofilm, the biofilter provides additional removal processes and pathways such as plant assimilation and adsorption to the growth and engineered media.

Figure 4 illustrates the proposed structure through which a biofilter can be modeled deterministically. This involves the use of a plug flow reactor to model the changes in a pollutant's concentration as it moves from the top to the bottom of the biofilter. For each "plug compartment" in the biofilter, the biofilm, plant assimilation and adsorption kinetics, responsible for this change in the pollutant's concentration are modeled according to the simplification of the biofilm compartments, also shown in Figure 4 (Morgenroth 2008).

The structure of the proposed biofilter model is similar to the pseudo two-dimensional model described in the mathematical biofilm modeling report by Wanner et al. (2006). This study, comparable with the International Water Association task team's report, defines dimensions / units according to the SI base quantities, length (L), mass (M) and time (T).

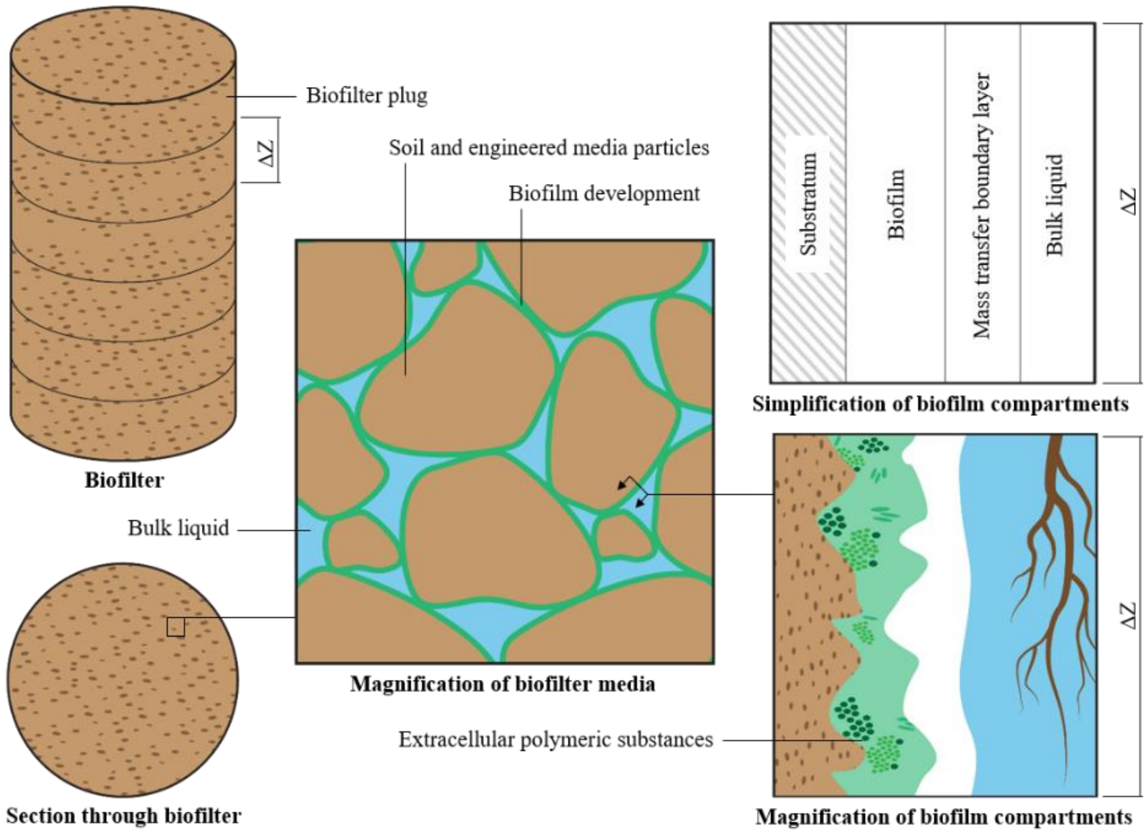


Figure 4. Schematic presentation of a biofilter, magnification of its growth media, and different components of a biofilm system: substratum, biofilm, mass transfer boundary layer and bulk liquid. *Note: The simplification of the biofilm compartments has been adapted from Wanner et al. (2006).*

Bulk liquid layer

The model structure proposed is a one-dimensional plug flow approximation of the bulk liquid phase kinetics in a biofilter, therefore, the assumption is made that completely mixed conditions exist in the other two dimensions. In addition, due to the presence of plants and the outdoor nature of plant biofilters, the volume of water removed from the system due to evapotranspiration can be a signification proportion of the total influent. It is therefore also important to incorporate the loss of water due to transpiration (and to a lesser extent, due to evaporation) over each plug compartment. Therefore, the water flow balance over a plug compartment in a saturated biofilm is as follows:

$$Q_{inf} = Q_{eff} + Q_{et} \quad (1)$$

where Q_{inf} = influent flow into the plug compartment (L^3/T), Q_{eff} = effluent flow out of the plug compartment (L^3/T), Q_{et} = evapotranspiration rate (L^3/T)

In a low influent flow biofilter equipped with a submerged zone at its base, coupled with a high evapotranspiration rate, water moves upward from the submerged zone due to capillary rise (Randelovic et al. 2016). If such conditions exist, the water flow balance over the biofilter will have to be carefully considered. Equation 1 will therefore only apply to a biofilter without a permanently submerged zone, i.e. with a bottom drainage outlet, where capillary rise is deemed to be negligible. Model approximations for the rate of evapotranspiration can be found in Randelovic et al. (2016).

The pollutant mass balance over a single plug component in a biofilter is as follows:

$$\begin{Bmatrix} Change \\ of\ mass \\ in\ a \\ plug \end{Bmatrix} = \underbrace{\begin{Bmatrix} Mass \\ increase \\ via\ flow \\ into\ the \\ plug \end{Bmatrix} - \begin{Bmatrix} Mass \\ decrease \\ via\ flow \\ out\ of \\ the\ plug \end{Bmatrix} \pm \begin{Bmatrix} Mass \\ change \\ via \\ adsorption \\ and\ desorption \end{Bmatrix}}_{Physical\ Processes} \pm \underbrace{\begin{Bmatrix} Mass \\ change \\ via \\ diffusion \\ into/from \\ the\ biofilm \end{Bmatrix} - \begin{Bmatrix} Mass \\ change\ due \\ plant\ uptake \\ or\ release \end{Bmatrix}}_{Biological\ Processes}$$

In addition to the mass balance process above, suspended microbial activity may occur in the bulk liquid phase. In a biofilter, however, the bulk liquid is assumed to be relatively small, hindering microbial development in this phase. Furthermore, due to the relatively low porosity of a standard biofilter, most suspended microbes can be assumed to be removed via filtration, essentially becoming part of the biofilm (Wanner et al. 2006). Thus, the assumption is made that the activity by suspended microbes in the bulk liquid phase is negligible.

As shown in the mass balance equation for the bulk liquid phase, in addition to the pollutant mass flow into and out of a plug compartment, the adsorption, biofilm diffusion and plant assimilation / respiration processes, must also be accounted for in the model.

Diffusion

The transport of a pollutant into a biofilm, due to the development of concentration gradients, known as diffusion can be expressed as shown in Equation 2 (Morgenroth 2008):

$$V_B \frac{dC}{dt} = -J_{LF} A_F \tag{2}$$

where J_{LF} = flux at the biofilm surface from the bulk liquid layer into the biofilm (M/L^2/T), A_F = surface area of the biofilm within a plug compartment (L^2), V_B = bulk liquid phase volume of a plug compartment (L^3).

Equation 2 is simply the flux at the biofilm surface multiplied with the biofilm area, where the flux can be calculated from the biofilm kinetics that are discussed in the subsequent biofilm phase section. It should be noted that, although diffusion generally represents pollutants moving into the biofilm, dissolved pollutants can also move from the biofilm to the bulk liquid phase. For example, in the case of a biofilter where the influent has a high NH_3 concentration and a low NO_3^- concentration. In the presence of oxygen, NH_3 is transformed to NO_3^- / NO_2^- by autotrophic organisms in the biofilm. In the absence of denitrification, the NO_3^- / NO_2^- is released from the biofilm into the bulk liquid phase.

Sorption

Pollutant sorption in a biofilter will occur until an equilibrium is reached between the influent and sorped concentrations. Once this equilibrium is reached, the rate of sorption and desorption is the same and pollutants will not be removed from the biofilter. In the event that the influent concentration decreases, the equilibrium concentration will reduce, which will result in net desorption taking place i.e., the pollutants leach from the biofilter. Sorption isotherms are the mathematical approximation of the sorption equilibrium between a pollutant's dissolved (*C* in M/L^3) and solid (*S* in M/M) phase concentrations. The Langmuir and Freundlich isotherms are most commonly used to calculate the equilibrium concentrations (Reichert 1998; Chapra 2008):

Langmuir: $S = \frac{S_{max}C}{K_L + C}$ (3)

Freundlich: $S = K_f C^{\frac{1}{n_f}}$ (4)

where S = sorped concentration (M/M), C = dissolved concentration (M/L^3), S_{max} = Langmuir maximum site density (M/M), K_L = Langmuir half-saturation concentration (M/L^3), K_f = Freundlich coefficient, n_f = Freundlich exponent.

The rate of sorption at time *t* can be modeled with a first order rate constant (*k*) multiplied with the difference in the actual solid phase concentration at time *t* (*S*) and the equilibrium solid phase concentration at time *t* (S_{eq}), as shown in Equation 5 and Equation 6. The equilibrium solid phase concentration (S_{eq}) at time *t* can be calculated with either the Langmuir or Freundlich isotherms for a dissolved phase concentration at time *t* (Reichert 1998).

$$\frac{dS}{dt} = k(S_{eq}(t) - S(t)) \quad (5)$$

$$\frac{dC}{dt} = -\rho_s \frac{1-\theta}{\theta} k(S_{eq}(t) - S(t)) \quad (6)$$

where k = rate of sorption / desorption (T^{-1}), ρ_s = solid phase density of pollutant (M/L^3), θ = porosity of biofilter.

Plant assimilation and respiration

The modeling of nutrient assimilation and release from plants is not a new concept in the water quality modeling discipline. That said, the existing deterministic models mostly only account for nutrient uptake and release from non-vascular plants such as phytoplankton (Chapra 2008; Cole and Wells 2013). Therefore, modeling of nutrient kinetics for vascular plants is lacking in existing water quality models. Recently, Mayo and Hanoi (2017) modeled N uptake in water hyacinth by employing a zero-order uptake rate. In addition, Kirk and Kronzucker (2005) approximated the flux of NH_3 and NO_2^- into the roots of wetland plants by using zero-order Michaelis-Menten kinetics, based on the concentration of NH_3 / NO_3^- at the plant's root surface. Similarly, Chapra (2008) modeled nutrient uptake and release by making use of first-order Michaelis-Menten kinetics, in addition to incorporating temperature and sunlight availability. Consequently, it is proposed to model nutrient uptake in vascular plants in a biofilter by using zero-order Michaelis-Menten kinetics as per Kirk and Kronzucker's model, as well as include the temperature and sunlight growth limitations as per Chapra's model. The proposed equation structure to model nutrient uptake in vascular plants is given in Equation 7:

$$\frac{dC}{dt} = -f_{cp}\frac{\Delta z}{L_{gm}}[F_c k_{gp}(C,T,I) + k_{rp}(T) + k_{ep}(T,I) + k_{mp}(T)] \tag{7}$$

where f_{cp} = pollutant to plant biomass relationship (M/M), F_c = nutrient preference factor, Δz = thickness of a plug compartment (L), L_{gm} = entire length of the growth media (L), $k_{gp}\ (C,T,I)$ = plant growth rate as a function of the pollutant concentration, temperature and sunlight (M/T), $k_{rp}\ (T)$ = plant dark respiration rate as a function of temperature (M/T), $k_{ep}\ (T,I)$= plant photorespiration (or excretion) rate as a function of temperature and sunlight (M/T), $k_{mp}\ (T)$ = plant mortality rate as a function of temperature (M/T).

In applying zero-order rate constants in the vascular plant growth model, the assumption is that the growth, respiration, excretion and mortality rates; and consequently the rate of nutrient uptake and release, are not dependent on the size or mass of the plant. This might not always be accurate, especially for younger plants, however, when the vascular plant is mature and its roots have filled populated the entire growth area of the biofilter, this assumption should hold. The plant growth, respiration, excretion and mortality rates given in Equation 7 are functions of the nutrient concentrations, temperature and solar radiation. The general form of this equation will require that the maximum growth rate at a certain temperature be multiplied by the temperature, nutrient and temperature limiting factors. The temperature limiting factor takes the form of the commonly applied Arrhenius relationship for temperate dependency in water quality models (Chapra 2008; Van der Merwe and Brink 2018). The nutrient limiting factor takes the form of the Michaelis-Menten equation. The Michaelis-Menten equation has been successfully applied for nutrient limitation in various water quality models (Chapra 2008; Cole and Wells 2013, Ekama and Wentzel 2008). The Michaelis-Menten formulation can also be applied for sunlight, however, this only allows for growth limitation at low light intensities whereas plant growth can also be limited at high intensities of sunlight (Chapra 2008). This low-high light intensity limitation supported the development of a model by Steele (1966), to calculate light limitation for plant growth, by accounting for growth limitation at both high and low levels of sunlight.

Furthermore, since the growth, respiration, excretion, and mortality rates are zero-order, to obtain nutrient uptake and release for a single plug compartment, the $\frac{\Delta z}{L_{gm}}$ factor was introduced. In applying this factor it is assumed that the plant maintains a uniform root structure throughout the length of the biofilter i.e., the root surface area per unit biofilter length remains constant.

The nutrient preference factor, Equation 7, accounts ability to retrieve a specific nutrient from two sources e.g., N from NH_3 and NO_3^-. Here, Cole and Wells (2013) presented a method for calculating the NH_3 preference factor (F_{am}) by calculating the plant's preference for NH_3 over NO_3^-, Equation 8. Therefore, in calculating NH_3 uptake, F_c in Equation 7 will be equal to F_{am} and in calculating NO_3^- uptake, F_c will be equal to (1-F_{am}).

$$F_{am} = N_a \frac{N_i}{(K_{S,am} + N_a)(K_{sam} + N_i)} + N_a \frac{K_{sam}}{(N_a + N_i)(K_{S,am} + N_i)} \tag{8}$$

where N_a = NH_3 concentration (M/L^3), N_i = NO_3^- concentration (M/L^3), $K_{S,am}$ = half-saturation constant for NH_4^+ preference (M/L^3).

In the case of a biofilm, discussed below, pollutant diffusion into the vascular plant roots develops a localized concentration gradient, or mass transfer boundary layer, around the roots. The impact of this mass transfer boundary layer will depend on the mixing conditions within the bulk liquid phase. It is proposed that the mass transfer boundary layer surrounding plant roots be modeled according to the mass transfer resistance equations presented by Morgenroth (2008). Further explored by Equation 11 and Equation 12, and discussed in the biofilm section below.

Biofilm phase

Anchored to the solid substratum on one side, which typically undergoes no transformations due to being inert and impermeable, the biofilm is in contact with the polluted influent on the other side where dissolved and particulate components are exchanged between the biofilm and the bulk liquid (Morgenroth 2008).

In order to model the flux into the biofilm, as required by the bulk liquid mass balance, the biofilm itself will need to be modeled. Biofilms are highly complex and heterogeneous aggregates, and although complex multidimensional spatial biofilm models have been developed, biofilm models can be simplified to one dimensional structures, as shown in Figure 3 (Morgenroth 2008). This requires the assumption that process rates, biomass density and composition, and substrate concentrations can be averaged in plains parallel to the substratum. This results in reactions and molecular diffusion within the biofilm, and an external hypothetical mass transfer boundary layer. By adopting the plug flow reactor, inaccuracies introduced are theoretically reduced as assumptions will only apply over the thickness of the plug and not across the entire biofilter (or reactor). However, cumulative error due to addition of error per plug can still occur due to inherent error in calculation (due to simplification).

The mathematical representation of the change in a pollutant's concentration over time in a biofilm is based on Fick's second law of diffusion, Equation 9 (Morgenroth 2008):

$$\underbrace{\frac{\partial C_F}{\partial t}}_{Accumulation} = \underbrace{D_F \frac{\partial^2 C_F}{\partial x^2}}_{Diffusion} - \underbrace{r_F}_{Reaction} \tag{9}$$

where C_F = substrate concentration in the biofilm (M/L^3), x = distance from the biofilm surface (L), t = time (T), D_F = diffusion coefficient in the biofilm (L^2/T), r_F = rate of substrate conversion per biofilm volume (M/L^3/T).

The reaction term in Equation 9 represents the biological processes influencing a pollutant's concentration in a biofilm, and will need to be expanded to account for the biofilm processes and pathways applicable to each pollutant of concern. Analytical solutions for the reaction term are only available for first and zero-order expressions assuming steady state. Therefore, expanding the term to include complex equations using Michaelis-Menten Kinetics, numerical solutions are required (Wanner et al. 2006). In approaching the biofilter model as a plug flow reactor from the top to the bottom, with each plug consisting of a pollutant flux into the biofilm, Equation 9 has to be solved over the thickness of the biofilm.

Table 3 provides the stoichiometry and kinetics expression matrix required for modeling the various biofilm reaction processes (r_{F_i}):

$$r_{F_i} = \sum_j v_{i,j} P_j \tag{10}$$

where r_{F_i} = rate of substrate conversation for state parameter *i* (M/L^3/T), $v_{i,j}$ = stoichiometric coefficient of state parameter *i* for proses rate *j* (M/M or -), P_j = rate of process *j* (M/L^3/T).

Table 3. Stoichiometry and kinetics expression matrix for biofilm reaction processes.
Modifications primarily from Morgenroth (2008), with additions from Kirk and Kronzucker (2005), Ekama and Wentzel (2008), and Van der Merwe and Brink (2018).

↓*j*	→*i*	1	2	3	4	5	6	7	8	9	
		State Variables									
Process Name		**Heterotrophic organisms (X_H)**	**Autotrophic organisms (X_A)**	**Inert biomass (X_I)**	**Dissolved biodegradable organic matter (C_d)**	**Particulate biodegradable organic matter (C_p)**	**NH_3 (N_a)**	**NO_3^- / NO_2^- (N_i)**	**PO_4^{3-} (P)**	**Dissolved oxygen (DO)**	**Process Rate**
		$\mathrm{M_{VSS}/L^3}$	$\mathrm{M_{VSS}/L^3}$	$\mathrm{M_{VSS}/L^3}$	$\mathrm{M_{COD}/L^3}$	$\mathrm{M_{COD}/L^3}$	$\mathrm{M_{NH_3-N}/L^3}$	$\mathrm{M_{NO_3{}^--N}/L^3}$	$\mathrm{M_{PO_4{}^{3-}-P}/L^3}$	$\mathrm{M_{O_2}/L^3}$	
1	**Heterotrophic Growth**	1			$-\frac{1}{Y_{Hv}}$		$f_{NC}\frac{1}{Y_{Hv}} - f_{NX}F_{am}$	$-f_{NX}(1-F_{am}) - (1-F_{ox})\frac{1-Y_H}{2.86Y_{Hv}}$	$f_{PC}\frac{1}{Y_{Hv}} - f_{PX}$	$-F_{ox}\frac{(1-Y_H)}{Y_{Hv}}$	$\mu_H(T)\frac{C_d}{K_s+C_d}\frac{(DO+2.86N_i)}{K_{O,H}+(DO+2.86N_i)}X_H$
2	**Heterotrophic Inactivation**	-1		f_H		$f_{CX}(1-f_H)$					$b_{ina,H}(T)\,X_H$
3	**Heterotrophic Respiration**	-1		f_H			$f_{NX}(1-f_H)$		$f_{PX}(1-f_H)$	$-f_{CX}(1-f_H)$	$b_{res,H}(T)\frac{DO}{K_{O,H}+DO}X_H$
4	**Autotrophic Growth**		1				$-\frac{1}{Y_A} - f_{NX}F_{am}$	$\frac{1}{Y_A} - f_{NX}(1-F_{am})$	$-f_{PX}$	$-\frac{(4.57-Y_Af_{CX})}{Y_A}$	$\mu_A(T)\frac{N_a}{K_N+N_a}\frac{DO}{K_{O,A}+DO}X_A$
5	**Autotrophic Inactivation**		-1	f_H		$f_{CX}(1-f_H)$					$b_{ina,A}(T)\,X_A$
6	**Autotrophic Respiration**		-1	f_H			f_{NX}		f_{PX}	$-f_{CX}(1-f_H)$	$b_{res,A}(T)\frac{DO}{K_{O,A}+DO}X_A$
7	**Organic Dissolution**				1	-1					k_pC_p

From Table 3, a method for modeling the biological interactions between the following state variables: heterotrophic organisms (X_H), autotrophic organisms (X_A), inert biomass (X_I), dissolved biodegradable organic matter (C_d), particulate biodegradable organic matter (C_p), NH_3 (N_a), NO_3^- / NO_2^- (N_i), soluble reactive phosphorous as PO_4^{3-} (P) and dissolved oxygen (DO), is proffered.

The initial process provided by Table 3 is Heterotrophic Growth. Heterotrophic organisms consume the soluble organics, which result in an increase in heterotrophic organism concentration and subsequent decrease in the soluble organic concentration. As the heterotrophic organisms consume dissolved organics, the captured N and P in the soluble organics are released back into the solution as NH_3 and PO_4^{3-}. In addition, the heterotrophic organisms assimilate NH_3, NO_3^- and PO_4^{3-} for cell formulation. The consumption of NH_3 and NO_3^- is regulated by the organism's NH_3 preference, modeled with the use of Equation 8. Furthermore, for the conversion of soluble organics, heterotrophic organisms utilise oxygen in aerobic conditions and NO_3^- in anoxic conditions (denitrification). Here, an oxygen preference factor (F_{ox}) is proposed, assuming a similar form to Equation 8, to model the denitrification of NO_3^- (or utilisation of NO_3^- for oxidation of dissolved biodegradable organics) as dissolved oxygen nears depletion.

Heterotrophic Inactivation represents the mortality of heterotrophic organisms within the biofilm, modeled by a temperature dependent first-order rate constant. Heterotrophic organism mortality results in a decrease in the heterotrophic organism concentration, and a subsequent increase in inert biomass and particulate biodegradable organic concentration. Since the biomass of heterotrophic organisms is not completely biodegradable (Ekama and Wentzel 2008), the unbiodegradable mass fraction (f_H) will contribute to the inert biomass.

Heterotrophic Respiration represents the process where the heterotrophic organisms mineralise their own biomass to obtain the energy required for cell maintenance (Ekama and Wentzel 2008). During the respiration process which utilises oxygen, the heterotrophic organism concentration decreases, while the inert biomass, NH_3, and PO_4^{3-} concentrations increase.

In the presence of oxygen, Autotrophic Growth through the conversion of NH_3 to NO_2^-, followed by NO_2^- to NO_3^- occurs (Ekama and Wentzel 2008). This results in increased autotrophic organism and NO_3^- concentrations and decreased NH_3 and oxygen concentrations. Furthermore, autotrophic organisms assimilate NH_3, NO_3^- and PO_4^{3-} for cell formation.

Similar to Heterotrophic Inactivation, Autotrophic Inactivation represents autotrophic organism mortality within the biofilm. This results in a decreased autotrophic organism concentration, and an increase in the inert biomass and particulate biodegradable organic concentrations.

Autotrophic Respiration is a similar process to Heterotrophic Respiration, in which the concentration of the autotrophic organisms decrease with a subsequent increase in the inert biomass, NH_3, and PO_4^{3-} concentrations. Oxygen is also utilised during the respiration process.

The concluding process provided in Table 3, Organic Dissolution, represents the dissolution of the particulate biodegradable organic matter to form dissolved biodegradable organics. It is proposed that this be modeled by using a first-order rate constant. This process importantly, allows for the delay between the formation of particulate biodegradable organic matter (derived from active organism mortality) and the point at which it is readily consumed and converted by heterotrophic organisms.

From Table 3, the kinetic rates are temperature dependent and parameter dependency was accounted for by making use of the Arrhenius relationship (Chapra 2008; Ekama and Wentzel 2008; Van der Merwe and Brink 2018).

Mass transfer boundary layer

Similar to surrounding plant roots, a mass transfer boundary layer between the bulk liquid and biofilm surface develops along a concentration gradient, due to the difference between the flux into the biofilm and diffusion of the pollutant into the bulk liquid phase. This concentration gradient can be modeled as mass transfer resistance instead of modeling it explicitly, as shown in Equation 11 (Morgenroth 2008):

$$J_{BL} = \frac{1}{R_L}\left(C_B - C_{LF}\right) \tag{11}$$

where J_{BL} = substrate flux in the water phase (M/L^2/T), R_L = external mass transfer resistance (T/L), C_B = substrate concentration in the bulk phase (M/L^3), C_{LF} = substrate concentration at the biofilm surface (M/L^3).

By visualising the external mass transfer resistance as a concentration boundary layer provides an instinctive understanding compared to resistance (Morgenroth 2008), where the resistance and thickness of the concentration boundary layer are related as:

$$R_L = \frac{L_L}{D_W} \tag{12}$$

where L_L = thickness of the mass transfer boundary layer (L), D_W = diffusion coefficient in the water phase (L^2/T).

In simplifying biofilm modeling, a constant biofilm thickness is often assumed. This approach delivers accurate results even when the system being modeled is expected to contain deep biofilms, this is because an incorrect assumption will predominantly only influence the thickness of the inert biomass layer at the back of the biofilm. With the assumption that biofilm density and surface area remain constant, it is proposed to calculate the change in biofilm thickness, as shown in Equation 13 which accounts for biofilm detachment processes through a constant detachment velocity ($u_{d,S}$) (Wanner et al. 2006; Morgenroth 2008):

$$\frac{dL_F}{dt} = \frac{\left(\frac{dX_H}{dt} + \frac{dX_A}{dt} + \frac{dX_I}{dt} + \frac{1}{f_{CX}}\frac{dC_P}{dt}\right) - \rho_F}{A_F} - u_{d,S} \qquad (13)$$

where L_F = biofilm thickness (L), ρ_F = biofilm density (M/L^3), $u_{d,S}$ = constant detachment velocity (L/T).

The conceptual deterministic modeling approach discussed in this study, provided a comprehensive strategy for the development of a stormwater biofilter deterministic model. The primary research, experimentally conducted or retrieved from theory, into the kinetic and stoichiometric parameters of the biofilter model assist in advancing model development. With time, and aided by accumulated data, the calibrated deterministic model must continuously be validated against the findings of empirical model outputs from both laboratory and field investigations. As model development progresses, enabling pollutant removal estimation with a high level of confidence, the biofilter model may potentially serve as an invaluable biofilter design and optimisation instrument. Thus, benefitting both small-scale diffused and large-scale drainage network centred holistic treatment solutions to polluted stormwater runoff.

MODEL RECOMMENDATIONS AND REFINEMENTS

Various mathematical equations which are fundamental to the development of a deterministic water quality model for biofilters have been presented in this paper. The equations can be applied to model the transformation processes for pollutants such as organic matter, NH_3, NO_3^- and PO_4^{3-}. The contributing transformation processes included in the model are: plant assimilation and release, sorption, biological transformation through biological organisms such as oxidation, nitrification, denitrification, and microbial assimilation. Furthermore, the model has the capability for application to the sorption of pollutants, such as heavy metals, onto the growth media within the biofilter.

The purpose of this study was not to present a fully developed deterministic model of a biofilter, but rather proffer fundamental mechanisms of the processes and pathways by which a standard design vegetated biofilter removes pollutants from stormwater runoff. Prior to being solved numerically for a biofilter technology, the model requires further refinements, these are as follows:

1. To understand the interface between biofilm development and pollutant sorption on / to the surface of the growth media. In the case where a biofilm has developed on the surface area of the growth media, limiting available sites for pollutant sorption, adsorption and absorption processes are hindered. Therefore, a clear understanding of biofilm development in biofilters is required to estimate which sites act as substratum for biofilm growth and which sites are available for sorption.
2. To have confidence in the kinetic and stoichiometric parameters used in the model development. Although the kinetic and stoichiometric parameters used in this study have been thoroughly researched (Chapra 2008; Ekama and Wentzel 2008; Morgenroth 2008; Cole and Wells 2013; Van der Merwe and Brink 2018), the suitability of the use of these parameter values, as determined in the existing literature, for the proposed plant biofilter model, must be assessed.
3. To have confidence in the kinetic and stoichiometric parameters. The kinetic and stoichiometric parameters used by the model must be calibrated to the specific biofilter application, prior to modeling. These parameters are for plants which are dependent on the specific plants introduced in the biofilter, as well as the sorption isotherms dependent on the media characteristics.
4. To have confidence in the model. Due to the complexity of the model proffered, intensive numerical methods are required to solve the modeling equations. In addition, the applicability of the different numerical models to these equations must be investigated, which includes the assumptions required to implement these numerical approximations.
5. To account for oxygen fluctuation. An appropriate method for modeling the uptake and release of oxygen by the roots of the vascular plants is required, as it fell outside this research scope.
6. To understand the physical processes affecting particulate biodegradable organics in the bulk liquid phase. Although the biofilter model accounted for particulate biodegradable organics, the model does not adequately address it in the bulk liquid phase. In this phase, particulate biodegradable organics will form as a result of plant mortality and biofilm surface detachment processes. Therefore, physical processes such as filtration can potentially prevent particulate organic discharge from occurring.
7. To validate the proposed method which accounts for the heterotrophic organisms' NO_3^- utilisation via denitrification. In calculating the heterotrophic organisms' growth limiting factor for oxygen, the model proposes that the DO together with NO_3^- equivalent oxygen concentration be added together. An oxygen preference factor is then applied to model the utilisation of oxygen vs NO_3^-.

CONCLUSIONS

In South Africa, due to a lack of local research and design guidelines plant biofiltration, a component of WSUD, is perceived as an emerging concept to urban stormwater management and as a consequence faces a number of application challenges. Additionally, the collection of different functioning removal processes within plant biofilters are highly complex, which in many instances hinders biofilter design and implementation undertakings. It is for these reasons that this study investigated and summarised first step research into data exploration and theoretically informed fundamental modeling approaches suitable to plant biofilter application.

Assessing the complex processes and operational conditions influencing plant biofilter performance, based on local plant species and designs, an improved understanding of biofilter modeling was achieved. In addition, the accumulation of statistical output from laboratory investigations contributed to future South African plant biofilter modeling endeavours. Therefore, the empirical modeling approach discerned pollutant removal in local South African experimental plant biofilters, whilst accounting for various design variations (plant species, growth media, standard, plenum aerobic, saturated anaerobic and upflow filtration) along time-series and operational conditions (low, typically observed and high influent pollution).

From the empirical approach, the linear regression models assessing nutrient and metal removal in laboratory biofilters found time to insignificantly influence removal for the duration of the study, while influent strength was found to significantly influence pollutant removal in general. This finding corroborated the notion that other operational conditions have a significant influence on biofilter performance. The data accumulated in these laboratory investigations contribute to future local biofilter modeling endeavours, due to their ability to distinguish causal effects of biofilter performance (valid as a result of varying plant species in identical biofilters and the sequential design modification method). Additionally, if encouraged by future research, a simple linear regression approach to PO_4^{3-} -P load removal may provide desirable simplification to otherwise complex deterministic modeling, however, this proposition only holds with time. The varying removal patterns, across both plant species, designs and pollutants, reveals the need for laboratory testing to determine valid model parameters specific to individual plant biofilter designs. In addition, linear regression model variability, evident from the variable coefficients, corroborates the notion that each investigated biofilter is unique, reaffirming the necessity to undertake case specific testing of the valid parameters in order to adequately inform modeling applications to proposed design.

From the deterministic approach, the fundamental mathematical equations presented can be applied in the development of a conceptual biofilter model with relevant refinements and assumptions. In addition, the proffered equations can be applied to model transformation processes for organic matter, NH_3, NO_3^-, PO_4^{3-} and heavy metal pollutants. The model's significance lies in its ability to account for complex pollutant removal processes and pathways: plant assimilation and release, sorption, transformation via biological organisms such as oxidation, nitrification, denitrification, and microbial assimilation. The evolution of both experimental and mathematical models provide water treatment researchers and practitioners with constantly improving understanding of biofilter complexity.

Future local biofilter modeling endeavours are advised to compare the findings of the linear regression models with statistical output produced by longer laboratory and field investigations, incorporating similar plant species and design modifications. These findings aid in calibrating and subsequently validating the proposed deterministic model. In addition, although the influent loads were pooled to obtain a more precise estimate of the influence of operational conditions on biofilter performance, future investigations must seek to introduce a more comprehensive distribution of influent loads to assess the validity of the linear regression models.

In conclusion, standard stormwater biofilters provide numerous substrata for biofilm growth which interact with pollutants from the influent stormwater. The use of engineered media, with highly irregular surfaces, increase the surface area of the biofilm, thereby increasing the mass transfer interaction area (Wanner et al. 2006). Thus, opportunity arises for South African plant biofilters to enhance pollutant removal by introducing different processes and pathways by combining appropriate design modifications, engineered media and plant species. This optimisation, coupled with biofilter model refinement, would not only improve local biofiltration, but provide sustainable solutions to the urban drainage problem.

FUNDING ACKNOWLEDGEMENT

This work was supported by the National Research Foundation (NRF) Thuthuka Fund under Grant: TTK180418322426.

NOMENCLATURE

Symbol	Description	Unit	Symbol	Description	Unit
A_F	Surface area of the biofilm within a plug compartment	L^2	$k_{rp}\ (T)$	Plant dark respiration rate as a function of temperature	M/T
$b_{ina,A}(T)$	Autotrophic organism inactivation rate as a function of temperature	T^{-1}	k_p	Dissolution rate of particulate biodegradable organics to dissolved biodegradable organics	T^{-1}
$b_{ina,H}(T)$	Heterotrophic organism inactivation rate as a function of temperature	T^{-1}	L_F	Biofilm thickness	L
$b_{res,A}(T)$	Autotrophic organism respiration rate as a function of temperature	T^{-1}	L_L	Thickness of the mass transfer boundary layer at a biofilm	L
$b_{res,H}(T)$	Heterotrophic organism respiration rate as a function of temperature	T^{-1}	L_{gm}	Length/height of the biofilter's growth media	L
C	Dissolved pollutant, substrate or nutrient concentration	M/L^3	N_a	Ammonia concentration	M_{NH_3-N}/L^3
C_B	Pollutant, substrate or nutrient concentration in the bulk liquid phase	M/L^3	N_i	Nitrate concentration	$M_{NO_3^--N}/L^3$
C_F	Pollutant, substrate or nutrient concentration in the biofilm	M/L^3	n_f	Freundlich exponent	-
C_{LF}	Pollutant, substrate or nutrient concentration at the biofilm surface	M/L^3	DO	Dissolved Oxygen concentration	M_{O_2}/L^3
C_R	Pollutant, substrate or nutrient concentration at the surface of the plant root	M/L^3	P	Soluble reactive phosphorus (orthophosphate) concentration	$M_{PO_4^{3-}-P}/L^3$
C_d	Dissolved biodegradable organics concentration	M_{COD}/L^3	P_j	Rate of process *j*	$M/L^3/T$
C_p	Particulate biodegradable organics concentration	M_{COD}/L^3	Q_{eff}	Effluent flow rate out of the plug compartment	L^3/T
D_F	Diffusion coefficient in the biofilm	L^2/T	Q_{et}	Evapotranspiration rate	L^3/T
D_W	Diffusion coefficient in the water phase	L^2/T	Q_{inf}	Influent flow rate into the plug compartment	L^3/T
F_{am}	Ammonia Preference Factor for biomass assimilation	-	R_L	External mass transfer resistance for biofilm	T/L
F_c	Pollutant, substrate or nutrient preference factor for plant assimilation	-	R_{LP}	Mass transfer resistance factor for plant roots	-
F_{ox}	Oxygen Preference Factor for heterotrophic oxidation	-	r_{F_i}	Rate of pollutant, substrate or nutrient conversation for state per biofilm volume parameter *i*	$M/L^3/T$
f_{CX}	Ratio of COD to VSS in the biofilm biomass	M_{COD}/M_{VSS}	r_F	Rate of pollutant, substrate or nutrient of substrate conversion per biofilm volume	$M/L^3/T$
f_{cp}	Ratio pollutant, substrate of nutrient mass to plant biomass relationship	M_C/M_P	S	Sorped concentration	$M_{sorbate}/M_{sorbent}$
f_H	Unbiodegradable fraction of biofilm biomass	M_{VSS}/M_{VSS}	S_{max}	Langmuir Maximum site density	$M_{sorbate}/M_{sorbent}$
f_{NC}	Ratio of nitrogen to COD in particulate organic matter	M_N/M_{COD}	t	Time	T
f_{NX}	Ratio of nitrogen to VSS in biofilm biomass	M_N/M_{VSS}	$u_{d,S}$	Constant biofilm detachment velocity	L/T
f_{PC}	Ratio of phosphorus to COD in particulate organic matter	M_P/M_{COD}	$v_{i,j}$	Stoichiometric coefficient of state parameter *i* for proses rate *j*	M/M or -
f_{PX}	Ratio of phosphorus to VSS in biofilm biomass	M_P/M_{VSS}	V_B	Bulk liquid phase volume of a plug compartment	L^3
J_{BL}	Pollutant, substrate or nutrient flux in the water phase	$M/L^2/T$	X_A	Autotrophic organism concentration	M_{VSS}/L^3
J_{LF}	Pollutant, substrate or nutrient flux at the biofilm surface	$M/L^2/T$	X_H	Heterotrophic organism concentration	M_{VSS}/L^3
K_f	Freundlich coefficient	-	X_I	Inert Biomass	M_{VSS}/L^3
K_L	Langmuir half-saturation concentration	M/L^3	x	Distance from the biofilm surface	L
K_N	Half-saturation constant for nitrification	M_{NH_3-N}/L^3	Y_A	Autotrophic organism yield coefficient	M_{VSS}/M_{NH3-N}
$K_{O,A}$	Half-saturation constant for oxygen utilisation by autotrophic organisms	M_{O_2}/L^3	Y_H	Heterotrophic organism yield coefficient in terms of COD (=$f_{CX}Y_{Hv}$)	M_{COD}/M_{COD}
$K_{O,H}$	Half-saturation constant for oxygen utilisation by heterotrophic organisms	M_{O_2}/L^3	Y_{Hv}	Heterotrophic organism yield coefficient in terms of VSS	M_{VSS}/M_{COD}
$K_{S,am}$	Half-saturation constant for ammonium preference	M_N/L^3	Δz	Thickness of a plug compartment	L
K_s	Half-saturation constant for heterotrophic oxidation of biodegradable dissolved organics	M_{COD}/L^3	θ	Porosity of biofilter	-
k	Rate of sorption/desorption	T^{-1}	$\mu_A(T)$	Heterotrophic organism growth rate as a function of temperature	T^{-1}
$k_{ep}\ (T,I)$	Plant photorespiration (or excretion) rate as a function of temperature and sunlight	M/T	$\mu_H(T)$	Autotrophic organism growth rate as a function of temperature	T^{-1}
$k_{gp}\ (C,T,I)$	Plant growth rate as a function of the pollutant concentration, temperature and sunlight	M/T	ρ_F	Biofilm density	M/L^3
$k_{mp}\ (T)$	Plant's mortality rate as a function of temperature	M/T	ρ_s	Solid phase density of sorbed pollutant	M/L^3

CHAPTER 7. SUPPLEMENTARY MATERIAL

Table S1. Overview of the local laboratory experiments from which data was collected, depicting influent synthetic stormwater, biofilter descriptions, media properties incorporated into the layers and literature sources from which motivation for plant and engineered media inclusion originated from.

Pollutant	Parameter	Influent concentration (mg/L)			Source Chemical
		Low	Typically observed	High	
Nutrients	Ammonium -N	0.20	0.40	2.5	NH_4Cl
	Nitrate -N	0.50	0.95	13.5	KNO_3
	Orthophosphate -P	0.22	0.35	1.5	K_2HPO_4
Metals	Cadmium	0.002	0.0045	0.032	$CdCl_2$
	Copper	0.02	0.045	6.8	$CuSO_4$
	Lead	0.08	0.15	2.8	$PbCl_2$
	Zinc	0.15	0.30	35	$ZnCl_2$

Indigenous plant biofilters – Influent volume: 1.32 L/3.5 days

(Growth media amended with perlite and compost)

Biofilter description	Common name	Length (mm)	*Water quality treatment study
Agapanthus africanus	African lily	730	Zhang et al. 2021
Carpha glomerata	Vleibiesie	730	Na
Chasmanthe aethiopica	Cobra lily	730	Na
Cynodon dactylon	Couch grass	730	Thompson et al. 2021
Cyperus textilis	Umbrella sedge	730	Wright et al. 2017
Dietes iridioides	Small wild iris	730	Na
Juncus effusus	Soft rush	730	Muerdter et al. 2019
Prionium serratum	Palmiet	730	Rebelo et al. 2018
Strelitzia reginae	Bird-of-paradise	730	Fowdar et al. 2017
Growth media (unvegetated)	Na	730	Wang et al. 2017

Design amended plant biofilters – Influent volume: 1.94 L/3.5 days

(Populated with *Prionium serratum* + growth media amended with perlite and compost)

Biofilter description	Length (mm)	*Water quality treatment study
Standard	800	Bratieres et al. 2008
Saturated anaerobic	1000	Barron et al. 2019
Plenum aerobic	1140	Smith 2015
Plenum aerobic + saturated anaerobic	1340	As above
Upflow filtration + plenum aerobic + saturated anaerobic	1340	Winston et al. 2017 + as above

Media properties in various engineered layers

Biofilter layer	Media type	Particle size distribution (mm)	Density (g/L)	Porosity (%)	Volume (cm^3)
Growth media	Sandy loam + perlite + compost	0.05-3.4	990.4	33.3	10053.1
Saturated anaerobic	Vermiculite + attapulgite	0.5-1.4	470.7	27.1	4021.2
Plenum aerobic	Zeolite	0.8-1.4	852.2	35.9	4825.5
Upflow filtration	Zeolite	1.4-2	825.3	29.6	1915.6

*****Existing investigations from which knowledge of different species and designs were derived for local experiments, providing motive for potential amendments in optimised biofilters.
Na = Not applicable.

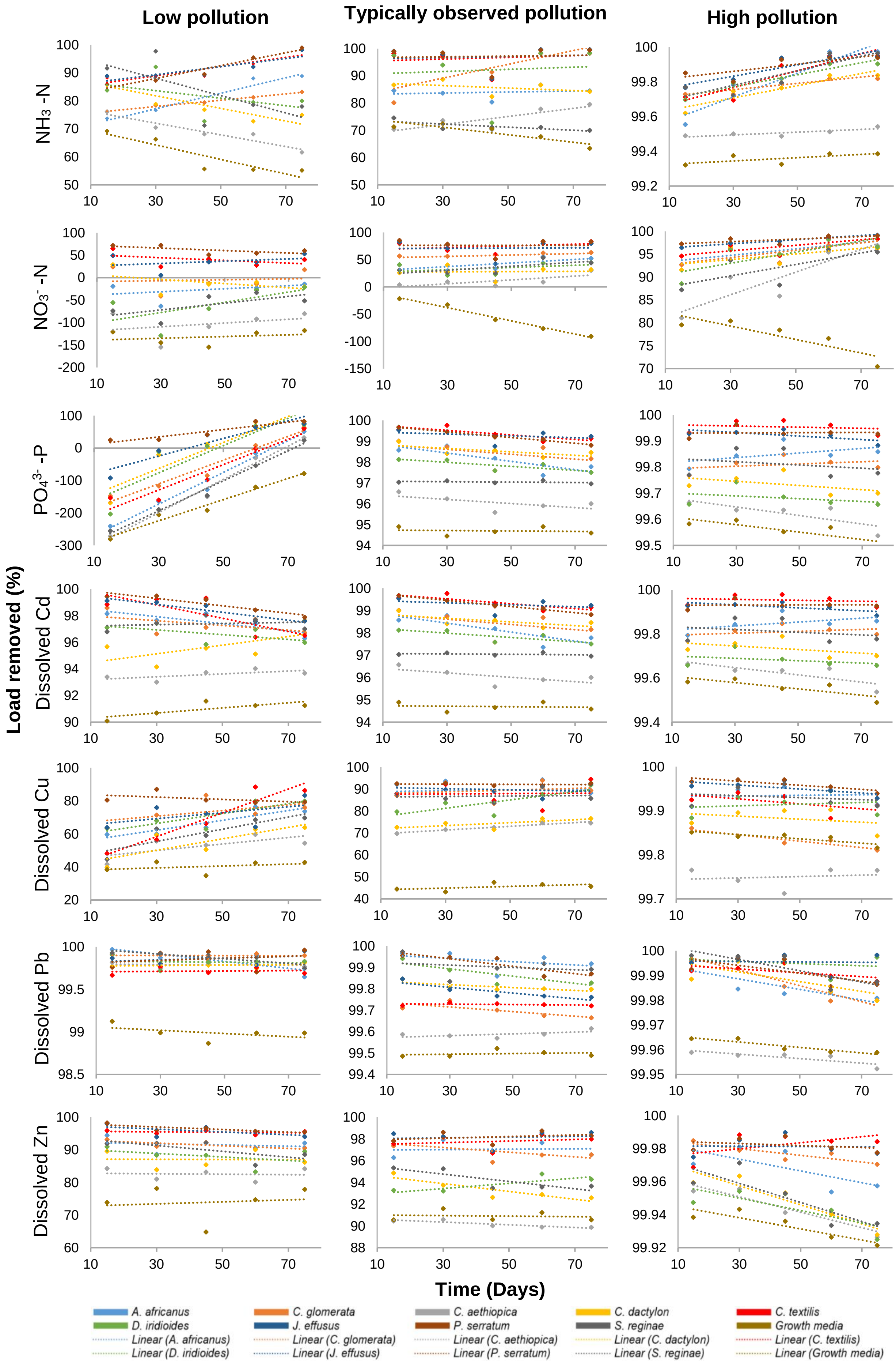


Figure S1. Linear regression models of percent removal over non log-transformed time as the independent variable for indigenous plant experimental biofilters. *Note variation in vertical axes.*

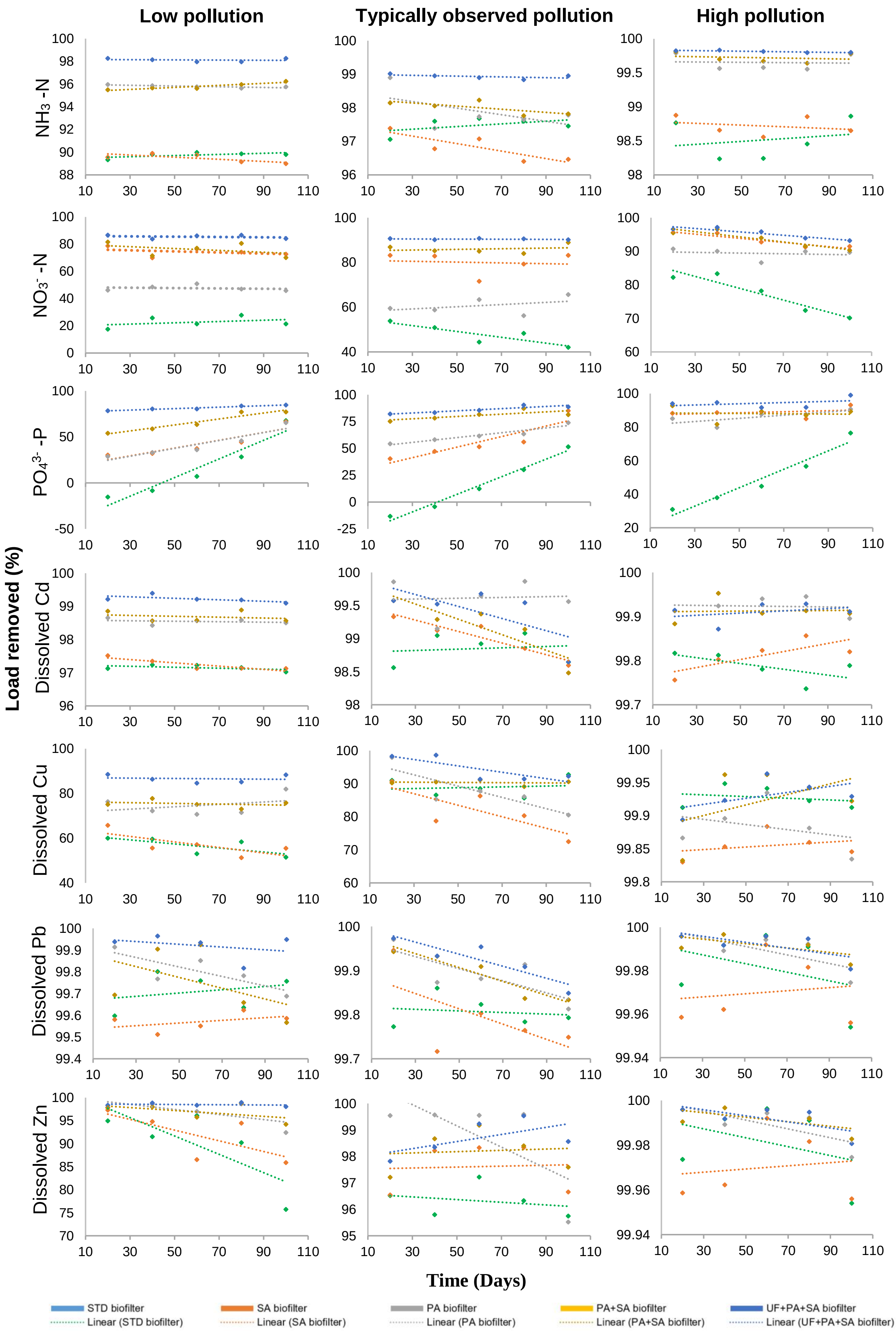


Figure S2. Linear regression models of percent removal over non log-transformed time as the independent variable for local experimental design amended biofilters. *Note variation in vertical axes.*

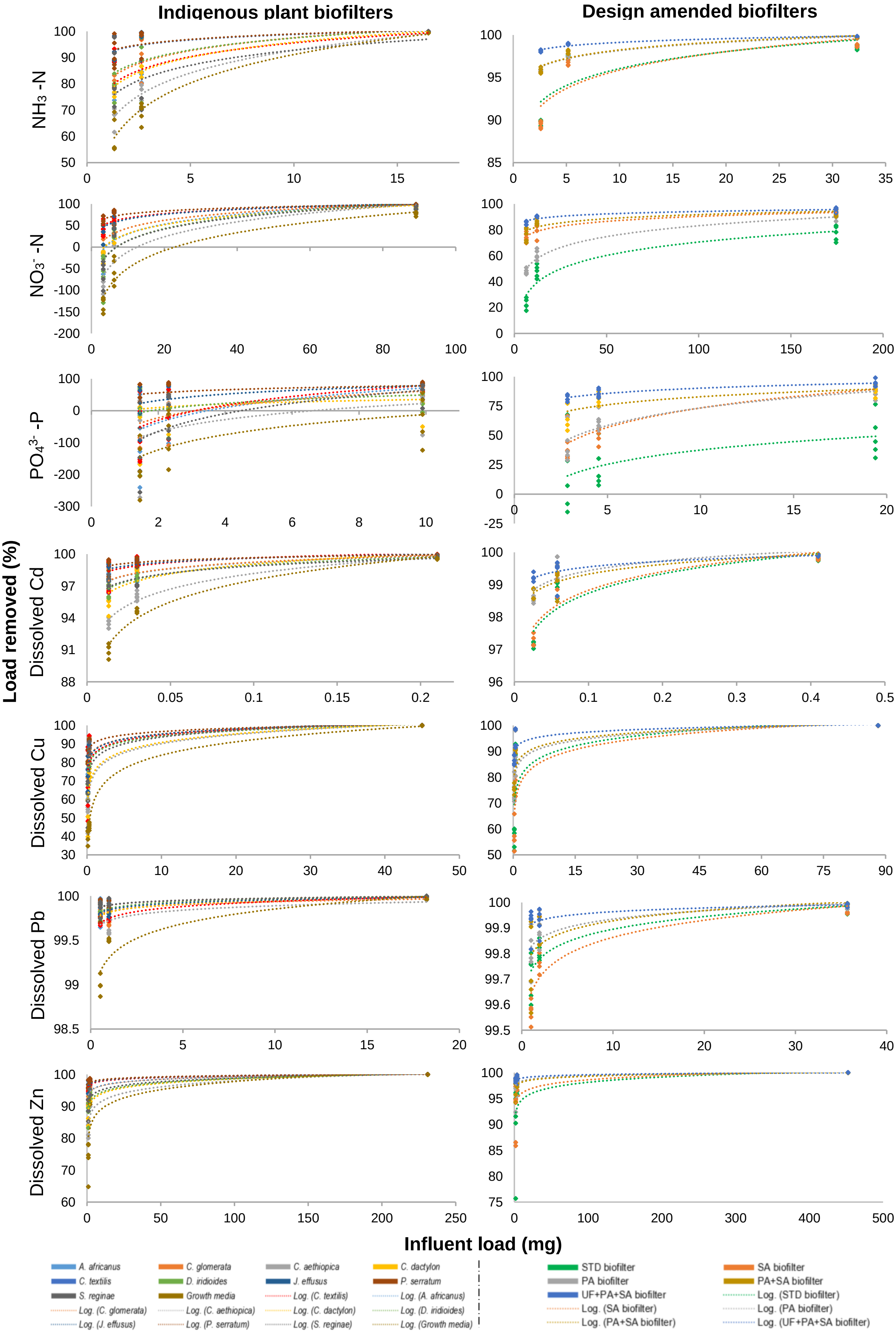


Figure S3. Linear regression models of percent removal over log-transformed influent load as the independent variable for indigenous plant and design amended experimental biofilters. *Note variation in vertical axes.*

REFERENCES

Al-Ameri, M., B. E. Hatt, S. Le Coustumer, T. D. Fletcher, E. G. I. Payne, and A. Deletić. 2018. "Accumulation of Heavy Metals in Stormwater Bioretention Media: A Field Study of Temporal and Spatial Variation." *Journal of Hydrology* 567: 721–731. https://doi.org/10.1016/j.jhydrol.2018.03.027.

Ali, H., E. Khan, and M. A. Sajad. 2013. "Phytoremediation of Heavy Metals: Concepts and Applications." *Chemosphere* 91 (7): 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075.

Amery, F., F. Degryse, W. Degeling, E. Smolders, and R. Merckx. 2007. "The Copper-Mobilizing-Potential of Dissolved Organic Matter in Soils Varies 10-Fold Depending on Soil Incubation and Extraction Procedures." *Environmental Science & Technology* 41 (7): 2277–2281. https://doi.org/10.1021/es062166r.

Armitage, N., M. Vice, L. Fisher-Jeffes, K. Winter, A. Spiegel, and J. Dunstan. 2013. *Alternative Technology for Stormwater Management: The South African Guidelines for Sustainable Drainage Systems.* Report no TT 558/13. Gezina: Water Research Commission.

Armitage, N., L. Fisher-Jeffes, K. Carden, K. Winter, V. Naidoo, A. Spiegel, B. Mauck, and D. Coulson. 2014. *Water Sensitive Urban Design (WSUD) for South Africa: Framework and Guidelines.* Report no TT 588/14. Gezina: Water Research Commission.

Barron, N. J., A. Deletić, J. Jung, H. Fowdar, Y. Chen, and B. E. Hatt. 2019. "Dual-Mode Stormwater-Greywater Biofilters: The Impact of Alternating Water Sources on Treatment Performance." *Water Research* 159: 521–537. https://doi.org/10.1016/j.watres.2019.04.020.

Blecken, G., J. Marsalek, and M. Viklander. 2011. "Laboratory Study of Stormwater Biofiltration in Low Temperatures: Total and Dissolved Metal Removals and Fates." *Water, Air, & Soil Pollution* 219 (1): 303–317. https://doi.org/10.1007/s11270-010-0708-2.

Blecken, G., Y. Zinger, A. Deletić, T. D. Fletcher, A. Hedström, and M. Viklander. 2010. "Laboratory Study on Stormwater Biofiltration: Nutrient and Sediment Removal in Cold Temperatures." *Journal of Hydrology* 394 (3–4): 507–514. https://doi.org/10.1016/j.jhydrol.2010.10.010.

Blecken, G., Y. Zinger, A. Deletić, T. D. Fletcher, and M. Viklander. 2009. "Impact of a Submerged Zone and a Carbon Source on Heavy Metal Removal in Stormwater Biofilters." *Ecological Engineering* 35 (5): 769–778. https://doi.org/10.1016/j.ecoleng.2008.12.009.

Bratieres, K,. T. D. Fletcher, A. Deletić, and Y. Zinger. 2008. "Nutrient and Sediment Removal by Stormwater Biofilters: A Large-Scale Design Optimisation Study." *Water Research* 42 (14): 3930–3940. https://doi.org/10.1016/j.watres.2008.06.009.

Brink, I. C. 2019. "Small-Scale Dispersed Green Infrastructure: A Fitting Civil Engineering Solution to Stormwater Quality Improvement?" *Journal of the South African Institution of Civil Engineering* 61 (4): 42–49. http://dx.doi.org/10.17159/2309-8775/2019/v61n4a4.

Chahal, M. K., Z. Shi, and M. Flury. 2016. "Nutrient Leaching and Copper Speciation in Compost-Amended Bioretention Systems." *Science of the Total Environment* 556: 302–309. https://doi.org/10.1016/j.scitotenv.2016.02.125.

Chapra, S. C. 2008. "Surface Water-Quality Modeling". Long Grove: Waveland Press.

Chowdhury, R., J. Abaya, T. Ksiksi, M. Mohamed, S. Beecham, and A. Rahman. 2020. “Distribution of Heavy Metals in Vegetative Biofiltration Columns.” *Water* 12 (3): 747-759. https://doi.org/10.3390/w12030747.

Chu, Y., L. Yang, X. Wang, X. Wang, and Y. Zhou. 2021. “Research on Distribution Characteristics, Influencing Factors, and Maintenance Effects of Heavy Metal Accumulation in Bioretention Systems: Critical Review.” *Journal of Sustainable Water in the Built Environment* 7 (2): 3120001. https://doi.org/10.1061/JSWBAY.0000930.

Cole, T. M., and S. A. Wells. 2013. "CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.71. Portland: Portland State University.

Da Silva, J. J. R F., and R. J. P. Williams. 1976. “The Uptake of Elements by Biological Systems.” In *Biochemistry*, edited by Dunitz, J. D., Hemmerich, P., Ibers, J. A., Jørgensen, C. K., Neilands, J. B., D. Reinen, and R. J. P. Williams. Heidelberg: Springer. https://doi.org/10.1007/BFb0116519.

Davis, A. P., W. F. Hunt, R. G. Traver, and M. Clar. 2009. “Bioretention Technology: Overview of Current Practice and Future Needs.” *Journal of Environmental Engineering* 135 (3): 109–117. https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(109).

Davis, A. P., M. Shokouhian, H. Sharma, and C. Minami. 2006. “Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal.” *Water Environment Research* 78 (3): 284–293. https://doi.org/10.2175/106143005X94376.

Davis, B., and G. Birch. 2010. “Comparison of Heavy Metal Loads in Stormwater Runoff from Major and Minor Urban Roads Using Pollutant Yield Rating Curves.” *Environmental Pollution* 158 (8): 2541–2545. https://doi.org/10.1016/j.envpol.2010.05.021.

Del Castillo, A. F., M. V. Garibay, C. Senés-Guerrero, C. Yebra-Montes, J. De Anda, and M. S. Gradilla-Hernández. 2020. “Mathematical Modeling of a Domestic Wastewater Treatment System Combining a Septic Tank, an Up Flow Anaerobic Filter, and a Constructed Wetland.” *Water* 12 (11): 3019-3038. https://doi.org/10.3390/w12113019.

Dietz, M. E., and J. C. Clausen. 2006. “Saturation to Improve Pollutant Retention in a Rain Garden.” *Environmental Science & Technology* 40 (4): 1335–1340. https://doi.org/10.1021/es051644f.

Ding, B., F. Rezanezhad, B. Gharedaghloo, P. Van Cappellen, and E. Passeport. 2019. “Bioretention Cells under Cold Climate Conditions: Effects of Freezing and Thawing on Water Infiltration, Soil Structure, and Nutrient Removal.” *Science of the Total Environment* 649: 749–759. https://doi.org/10.1016/j.scitotenv.2018.08.366.

Dong, L., L. Lin, Q. Li, Z. Huang, X. Tang, M. Wu, C. Li, X. Cao, and M. Scholz. 2018. “Enhanced Nitrate-Nitrogen Removal by Modified Attapulgite-Supported Nanoscale Zero-Valent Iron Treating Simulated Groundwater.” *Journal of Environmental Management* 213: 151–158. https://doi.org/10.1016/j.jenvman.2018.02.073.

Ekama, G. A., and M. C. Wentzel. 2008. "Nitrogen Removal." In *Biological Wastewater Treatment : Principles, Modelling and Design,* edited by Henze, M., Van Loosdrecht, M. C. M., G. A. Ekama, and D. Brdjanovic. London: IWA Publishing.

Feng, W., B. E. Hatt, D. T. McCarthy, T. D. Fletcher, and A. Deletić. 2012. “Biofilters for

Stormwater Harvesting: Understanding the Treatment Performance of Key Metals That Pose a Risk for Water Use." *Environmental Science & Technology* 46 (9): 5100–5108. https://doi.org/10.1021/es203396f.

Fowdar, H. S., B. E. Hatt, T. Cresswell, J. H. Harrison, P. L. M. Cook, and A. Deletić. 2017. "Phosphorus Fate and Dynamics in Greywater Biofiltration Systems." *Environmental Science & Technology* 51 (4): 2280–2287. https://doi.org/10.1021/acs.est.6b04181.

Fowdar, H. S., A. Deletić, B. E. Hatt, and P. L. M. Cook. 2018. "Nitrogen Removal in Greywater Living Walls: Insights into the Governing Mechanisms." *Water* 10 (4): 527. https://doi.org/10.3390/w10040527.

Gizaw, A., F. Zewge, A. Kumar, A. Mekonnen, and M. Tesfaye. 2021. "A Comprehensive Review on Nitrate and Phosphate Removal and Recovery from Aqueous Solutions by Adsorption." *Journal of Water Supply: Research & Technology-Aqua*. https://doi.org/10.2166/aqua.2021.146.

Glaister, B. J., T. D. Fletcher, P. L. M. Cook, and B. E. Hatt. 2014. "Co-Optimisation of Phosphorus and Nitrogen Removal in Stormwater Biofilters: The Role of Filter Media, Vegetation and Saturated Zone." *Water Science & Technology* 69 (9): 1961–1969. https://doi.org/10.2166/wst.2014.117.

Glaister, B. J., T. D. Fletcher, P. L. M. Cook, and B. E. Hatt. 2017. "Interactions between Design, Plant Growth and the Treatment Performance of Stormwater Biofilters." *Ecological Engineering* 105: 21–31. https://doi.org/10.1016/j.ecoleng.2017.04.030.

Göbel, P., C. Dierkes, and W. G. Coldewey. 2007. "Storm Water Runoff Concentration Matrix for Urban Areas." *Journal of Contaminant Hydrology* 91 (1–2): 26–42. https://doi.org/10.1016/j.jconhyd.2006.08.008.

Gobler, C. J., S. Waugh, C. Asato, P. M. Clyde, S. C. Nyer, M. Graffam, B. Brownawell, et al. 2021. "Removing 80%-90% of Nitrogen and Organic Contaminants with Three Distinct Passive, Lignocellulose-Based on-Site Septic Systems Receiving Municipal and Residential Wastewater." *Ecological Engineering* 161: 106157. https://doi.org/10.1016/j.ecoleng.2021.106157.

Hashem, F. S., M. S. Amin, and S. M. A. El-Gamal. 2015. "Chemical Activation of Vermiculite to Produce Highly Efficient Material for Pb^{2+} and Cd^{2+} Removal." *Applied Clay Science* 115: 189–200. https://doi.org/10.1016/j.clay.2015.07.042.

Hatt, B. E., T. D. Fletcher, and A. Deletić. 2008. "Hydraulic and Pollutant Removal Performance of Fine Media Stormwater Filtration Systems." *Environmental Science & Technology* 42 (7): 2535–2541. https://doi.org/10.1021/es071264p.

Hatt, B. E., T. D. Fletcher, and A. Deletić. 2009. "Hydrologic and Pollutant Removal Performance of Stormwater Biofiltration Systems at the Field Scale." *Journal of Hydrology* 365 (3-4): 310–321. https://doi.org/10.1016/j.jhydrol.2008.12.001.

Hatt, B. E., A. Steinel, A. Deletić, and T. D. Fletcher. 2011. "Retention of Heavy Metals by Stormwater Filtration Systems: Breakthrough Analysis." *Water Science & Technology* 64 (9): 1913–1919. https://doi.org/10.2166/wst.2011.188.

Henderson, C., M. Greenway, and I. Phillips. 2007. "Removal of Dissolved Nitrogen, Phosphorus and Carbon from Stormwater by Biofiltration Mesocosms." *Water Science &*

Technology 55 (4): 183–191. https://doi.org/10.2166/wst.2007.108.

Hermawan, A. A., K. L. Teh, A. Talei, and L. H. C. Chua. 2021. "Accumulation of Heavy Metals in Stormwater Biofiltration Systems Augmented with Zeolite and Fly Ash." *Journal of Environmental Management* 297: 113298. https://doi.org/10.1016/j.jenvman.2021.113298.

Hocaoglu-Ozyigit, A., and B. N. Genc. 2020. "Cadmium in Plants, Humans and the Environment." *Frontiers in Life Sciences & Related Technologies* 1 (1): 12–21.

Hsieh, C., and A. P. Davis. 2005. "Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff." *Journal of Environmental Engineering* 131 (11): 1521–1531. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:11(1521).

Hsieh, C., A. P. Davis, and B. A. Needelman. 2007a. "Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff." *Water Environment Research* 79 (2): 177–184. https://doi.org/10.2175/106143006X111745.

Hsieh, C., A. P. Davis, and B. A. Needelman. 2007b. "Nitrogen Removal from Urban Stormwater Runoff through Layered Bioretention Columns." *Water Environment Research* 79 (12): 2404–2411. https://doi.org/10.2175/106143007X183844.

Hunt, W. F., J. T. Smith, S. J. Jadlocki, J. M. Hathaway, and P. R. Eubanks. 2008. "Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, NC." *Journal of Environmental Engineering* 134 (5): 403–408. https://doi.org/10.1061/(ASCE)0733-9372(2008)134:5(403).

Jacklin, D. M., I. C. Brink, and S. M. Jacobs. 2021a. "Efficiencies of Indigenous South African Plant Biofilters for Urban Stormwater Runoff Water Quality Improvement with a Focus on Nutrients and Metals." *AQUA - Water Infrastructure, Ecosystems and Society* 70 (7): 1094-1110*. https://doi.org/10.2166/aqua.2021.187*.

Jacklin, D. M., I. C. Brink, and S. M. Jacobs. 2021b. "Urban Stormwater Nutrient and Metal Removal in Small-Scale Green Infrastructure: Exploring Engineered Plant Biofilter Media Optimisation." *Water Science & Technology* 84 (7): 1715-1731*. https://doi.org/10.2166/wst.2021.353.*

Jacklin, D. M., I. C. Brink, and S. M. Jacobs. *Forthcoming.* "Comparison of Urban Stormwater Plant Biofilter Designs for Nutrient and Metal Removal in South Africa." *Water Practice & Technology.*

Jang, A., Y. Seo, and P. L. Bishop. 2005. "The Removal of Heavy Metals in Urban Runoff by Sorption on Mulch." *Environmental Pollution* 133 (1): 117–127. https://doi.org/10.1016/j.envpol.2004.05.020.

Jay, J. G., S. L. Brown, K. Kurtz, and F. Grothkopp. 2017. "Predictors of Phosphorus Leaching from Bioretention Soil Media." *Journal of Environmental Quality* 46 (5): 1098–1105. https://doi.org/10.2134/jeq2017.06.0232.

Khan, U. T., C. Valeo, A. Chu, and J. He. 2013. "A Data Driven Approach to Bioretention Cell Performance: Prediction and Design." *Water* 5 (1): 13–28. https://doi.org/10.3390/w5010013.

Kirk, G. J. D., and H. Kronzucker. 2005. "The Potential for Nitrification and Nitrate Uptake in the Rhizosphere of Wetland plants: A Modelling Study." *Annals of Botany* 96 (4): 639-646.

https://dx.doi.org/10.1093%2Faob%2Fmci216.

Kumar, B., K. Smita, and L. C. Flores. 2017. "Plant Mediated Detoxification of Mercury and Lead." *Arabian Journal of Chemistry* 10: S2335-S2342. https://doi.org/10.1016/j.arabjc.2013.08.010.

Lampe, L., M. Barrett, B. Woods-Ballard, P. Martin, C. Jefferies, and M. Hollon. 2005. *Performance and Whole Life Costs of Best Management Practices (BMPs) and Sustainable Urban Drainage Systems (SUDS)*. Abertay: Water Environment Research Foundation (WERF).

Laurenson, G., S. Laurenson, N. Bolan, S. Beecham, and I. Clark. 2013. "The Role of Bioretention Systems in the Treatment of Stormwater." *Advances in Agronomy* 120: 223–274. https://doi.org/10.1016/B978-0-12-407686-0.00004-X.

Lee, T. 2020. "Accelerated Phosphorus Removal Using Sulfate-Coated Expanded Vermiculite." *Water SA* 46 (4): 615–626. https://doi.org/10.17159/wsa/2020.v46.i4.9075.

Li, J., and A. P. Davis. 2016. "A Unified Look at Phosphorus Treatment Using Bioretention." *Water Research* 90: 141–155. https://doi.org/10.1016/j.watres.2015.12.015.

Li, H., and A. P. Davis. 2008. "Urban Particle Capture in Bioretention Media. II: Theory and Model Development." *Journal of Environmental Engineering* 134 (6): 419–432. https://doi.org/10.1061/(ASCE)0733-9372(2008)134:6(419).

Li, F., W. Wu, R. Li, and X. Fu. 2016. "Adsorption of Phosphate by Acid-Modified Fly Ash and Palygorskite in Aqueous Solution: Experimental and Modeling." *Applied Clay Science* 132: 343–352. https://doi.org/10.1016/j.clay.2016.06.028.

Liu, J., and A. P. Davis. 2014. "Phosphorus Speciation and Treatment Using Enhanced Phosphorus Removal Bioretention." *Environmental Science & Technology* 48 (1): 607–614. https://doi.org/10.1021/es404022b.

Liu, F., Y. Hu, S. H. Ren, and Y. Y. Shi. 2012. "Effect of Activated Attapulgite on Ammonia-Nitrogen Removal." *Advanced Materials Research* 549: 92-95. https://doi.org/10.4028/www.scientific.net/AMR.549.92.

Marvin, J. T., E. Passeport, and J. Drake. 2020. "State-of-the-Art Review of Phosphorus Sorption Amendments in Bioretention Media: A Systematic Literature Review." *Journal of Sustainable Water in the Built Environment* 6 (1): 3119001. https://orcid.org/0000-0001-6235-3918.

Maurya, A., M. K. Singh, and S. Kumar. 2020. "Biofiltration Technique for Removal of Waterborne Pathogens." In *Waterborne Pathogens*, edited by Prasad, M. N. V., and Grobelak, A, 123–141. Oxford: Elsevier.

Mayo, A. W., and E. E. Hanai. 2017. "Modeling Phytoremediation of Nitrogen-polluted water using Water Hyacinth (*Eichhornia crassipes*)." *Physics and Chemistry of the Earth* 100: 170-180. https://doi.org/10.1016/j.pce.2016.10.016.

Mazloomi, F., and M. Jalali. 2017. "Adsorption of Ammonium from Simulated Wastewater by Montmorillonite Nanoclay and Natural Vermiculite: Experimental Study and Simulation." *Environmental Monitoring & Assessment* 189 (8): 1–19. https://doi.org/10.1007/s10661-017-6080-6.

Milandri, S. G., K. J. Winter, S. B. M. Chimphango, N. P. Armitage, D. N. Mbui, G. E. Jackson, and V. Liebau. 2012. “The Performance of Plant Species in Removing Nutrients from Stormwater in Biofiltration Systems in Cape Town” *Water SA* 38 (5): 275–662. https://doi.org/10.4314/wsa.v38i5.2.

Morgenroth, E. 2008. "Modelling Biofilms." In *Biological Wastewater Treatment : Principles, Modelling and Design,* edited by Henze, M., Van Loosdrecht, M. C. M., G. A. Ekama, and D. Brdjanovic. London: IWA Publishing.

Muerdter, C. P., C. K. Wong, and G. H. LeFevre. 2018. “Emerging Investigator Series: The Role of Vegetation in Bioretention for Stormwater Treatment in the Built Environment: Pollutant Removal, Hydrologic Function, and Ancillary Benefits.” *Environmental Science: Water Research & Technology* 4 (5): 592–612. https://doi.org/10.1039/C7EW00511C.

Muerdter, C. P., D. J. Smith, and A. P. Davis. 2020. “Impact of vegetation selection on nitrogen and phosphorus processing in bioretention containers.” *Water Environment Research* 92 (2): 236-224. https://doi.org/10.1002/wer.1195.

Mullane, J. M., M. Flury, H. Iqbal, P. M. Freeze, C. Hinman, C. G. Cogger, and Z. Shi. 2015. “Intermittent Rainstorms Cause Pulses of Nitrogen, Phosphorus, and Copper in Leachate from Compost in Bioretention Systems.” *Science of the Total Environment* 537: 294–303. https://doi.org/10.1016/j.scitotenv.2015.07.157.

O’Neill, S. W., and A. P. Davis. 2012. “Water Treatment Residual as a Bioretention Amendment for Phosphorus. I: Evaluation Studies.” *Journal of Environmental Engineering* 138 (3): 318–327. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000409.

Osman, M., K. W. Yusof, H. Takaijudin, H. W. Goh, M. A. Malek, N. A. Azizan, A. A. Ghani, and A. S. Abdurrasheed. 2019. “A Review of Nitrogen Removal for Urban Stormwater Runoff in Bioretention System.” *Sustainability* 11 (19): 5415. https://doi.org/10.3390/su11195415.

Pasquini, L., and J. P. Enqvist. 2019. *Green Infrastructure in South African Cities*. African Centre for Cities: South Africa.

Payne, E. G. I., T. D. Fletcher, P. L. M. Cook, A. Deletić, and B. E. Hatt. 2014. “Processes and Drivers of Nitrogen Removal in Stormwater Biofiltration.” *Critical Reviews in Environmental Science & Technology* 44 (7): 796–846. https://doi.org/10.1080/10643389.2012.741310.

Payne, E. G. I., T. D. Fletcher, D. G. Russell, M. R. Grace, T. R. Cavagnaro, V. Evrard, A. Deletić, B. E. Hatt, and P. L. M. Cook. 2014. “Temporary Storage or Permanent Removal? The Division of Nitrogen between Biotic Assimilation and Denitrification in Stormwater Biofiltration Systems.” *PloS One* 9 (3): e90890. https://doi.org/10.1371/journal.pone.0090890.

Payne, E. G. I., B. E. Hatt, A. Deletić, M. F. Dobbie, D. T. McCarthy, and G. I. Chandrasena. 2015. *Adoption Guidelines for Stormwater Biofiltration Systems - Summary Report*. Melbourne: Cooperative Research Centre for Water Sensitive Cities.

Payne, E. G. I., T. Pham, A. Deletić, B. E. Hatt, P. L. M. Cook, and T. D. Fletcher. 2018. “Which Species? A Decision-Support Tool to Guide Plant Selection in Stormwater Biofilters.” *Advances in Water Resources* 113: 86–99. https://doi.org/10.1016/j.advwatres.2017.12.022.

Pilon-Smits, E. 2005. “Phytoremediation.” *Annual Review of Plant Biology* 56: 15-39. https://doi.org/10.1146/annurev.arplant.56.032604.144214.

Ponizovsky, A. A., S. Thakali, H. E. Allen, D. M. Di Toro, and A. J. Ackerman. 2006. “Effect of Soil Properties on Copper Release in Soil Solutions at Low Moisture Content.” *Environmental Toxicology and Chemistry: An International Journal* 25 (3): 671–682. https://doi.org/10.1897/04-621R.1.

Randelovic, A., K. Zhang, N. Jacimovic, D. McCarthy, and A. Deletić. 2016. "Stormwater biofilter treatment model (MPiRe) for selected micro-pollutants." *Water Research* 89: 180-191. https://dx.doi.org/10.1016/j.watres.2015.11.046.

Read, J., T. D. Fletcher, T. Wevill, and A. Deletić. 2010. “Plant Traits That Enhance Pollutant Removal from Stormwater in Biofiltration Systems.” *International Journal of Phytoremediation* 12 (1): 34–53. doi:10.1080/15226510902767114.

Read, J., T. Wevill, T. D. Fletcher, and A. Deletić. 2008. “Variation among Plant Species in Pollutant Removal from Stormwater in Biofiltration Systems.” *Water Research* 42 (4–5): 893–902. doi:10.1016/j.watres.2007.08.036.

Rebelo, A. J., Emsens W., K. J. Esler, and P. Meire. 2018. “Quantification of water purification in South African palmiet wetlands.” *Water Science and Technology* 78 (5): 1199-1207. https://doi.org/10.2166/wst.2018.389.

Reddy, K. R., and R. D. DeLaune. 2008. *Biogeochemistry of Wetlands: Science & Applications*. Boca Raton: CRC Press.

Reddy, K. R., T. Xie, and S. Dastgheibi. 2014. “Removal of Heavy Metals from Urban Stormwater Runoff Using Different Filter Materials.” *Journal of Environmental Chemical Engineering* 2 (1): 282–292. https://doi.org/10.1016/j.jece.2013.12.020.

Reichert, P. 1998. "AQUASIM 2.0 - Tutorial." Swiss Federal Institute for Environmental Science and Technology. https://www.eawag.ch/fileadmin/Domain1/Abteilungen/siam/software/aquasim/reichert_1998_aquasim_manual.pdf.

SAWS 2020 (South African Weather Service; accessed August 13, 2020). https://www.weathersa.co.za/.

Schmitt, D., H. E. Taylor, G. R. Aiken, D. A. Roth, and F. H. Frimmel. 2002. “Influence of Natural Organic Matter on the Adsorption of Metal Ions onto Clay Minerals.” *Environmental Science & Technology* 36 (13): 2932–2938. https://doi.org/10.1021/es010271p.

Selbig, W. R., and M. N. Fienen. 2012. “Regression Modeling of Particle Size Distributions in Urban Storm Water: Advancements through Improved Sample Collection Methods.” *Journal of Environmental Engineering* 138 (12): 1186–1193. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000612.

Shrestha, P., S. E. Hurley, and B. C. Wemple. 2018. “Effects of Different Soil Media, Vegetation, and Hydrologic Treatments on Nutrient and Sediment Removal in Roadside Bioretention Systems.” *Ecological Engineering* 112: 116–131. https://doi.org/10.1016/j.ecoleng.2017.12.004.

Smith, D. P. 2015. “Plenum-Aerated Biofilter for Local-Scale Nitrogen Removal.” *Journal of Environmental Engineering* 141 (11): 4015031. https://doi.org/10.1061/(ASCE)EE.1943-

7870.0000960.

Søberg, L. C., A. M. Al-Rubaei, M. Viklander, and G. Blecken. 2020. "Phosphorus and TSS Removal by Stormwater Bioretention: Effects of Temperature, Salt, and a Submerged Zone and Their Interactions." *Water, Air, & Soil Pollution* 231: 1–12. https://doi.org/10.1007/s11270-020-04646-3.

Steele, J. H. 1966. "Notes on Some Theoretical Problems in Production Ecology" In *Primary Production in Aquatic Environments*, edited by C. R. Goldman, 383-398. Berkeley: University of California Press. https://doi.org/10.1525/9780520318182-028.

Stewart, R. D., J. G. Lee, W. D. Shuster, and R. A. Darner. 2017. "Modelling Hydrological Response to a Fully-Monitored Urban Bioretention Cell." *Hydrological Processes* 31 (26): 4626–4638. https://doi.org/10.1002/hyp.11386.

Strecker, E., B. Urbonas, M. Quigley, J. Howell, and T. Hesse. 2002. *Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements.* Report no EPA-821-B-02-001. Washington: United States Environmental Protection Agency.

Sun, X., and A. P. Davis. 2007. "Heavy Metal Fates in Laboratory Bioretention Systems." *Chemosphere* 66 (9): 1601–1609. https://doi.org/10.1016/j.chemosphere.2006.08.013.

Taylor, G. D., T. D. Fletcher, T. H. F. Wong, P. F. Breen, and H. P. Duncan. 2005. "Nitrogen Composition in Urban Runoff - Implications for Stormwater Management." *Water Research* 39 (10): 1982–1989. https://doi.org/10.1016/j.watres.2005.03.022.

Thompson, D., E. Bush, and H. Kirk-Ballard. 2021. "Lead phytoremediation in contaminated soils using ornamental landscape plants." *Journal of Geoscience and Environment Protection* 9 (5): 152-164. https://doi.org/10.4236/gep.2021.95011.

Trenouth, W. R., and B. Gharabaghi. 2015. "Soil Amendments for Heavy Metals Removal from Stormwater Runoff Discharging to Environmentally Sensitive Areas." *Journal of Hydrology* 529: 1478–1487. https://doi.org/10.1016/j.jhydrol.2015.08.034.

Van Den Berg, E. M., M. Boleij, J. G. Kuenen, R. Kleerebezem, and M. Van Loosdrecht. 2016. "DNRA and Denitrification Coexist over a Broad Range of Acetate/N-NO_3^- Ratios, in a Chemostat Enrichment Culture." *Frontiers in Microbiology* 7: 1-12. https://doi.org/10.3389/fmicb.2016.01842.

Van Der Merwe, I. S. W., and Brink, I. C. 2018. "Development of a Deterministic Design Model for a High-Rate Algal Pond." *Water SA* 44 (4): 612-623. http://dx.doi.org/10.4314/wsa.v44i4.10.

Wang, H., X. Wang, J. Ma, P. Xia, and J. Zhao. 2017. "Removal of Cadmium (II) from Aqueous Solution: A Comparative Study of Raw Attapulgite Clay and a Reusable Waste - Struvite/Attapulgite Obtained from Nutrient-Rich Wastewater." *Journal of Hazardous Materials* 329: 66–76. https://doi.org/10.1016/j.jhazmat.2017.01.025.

Wang, J., Y. Zhao, L. Yang, N. Tu, G. Xi, and X. Fang. 2017. "Removal of heavy metals from urban stormwater runoff using bioretention media mix." Water 9 (11): 854-876. https://doi.org/10.3390/w9110854.

Wang, M., D. Zhang, Y. Li, Q. Hou, Y. Yu, J. Qi, W. Fu, J. Dong, and Y. Cheng. 2018. "Effect of a Submerged Zone and Carbon Source on Nutrient and Metal Removal for Stormwater by Bioretention Cells." *Water* 10 (11): 1629. https://doi.org/10.3390/w10111629.

Wang, R., X. Zhang, and M. Li. 2019. "Predicting Bioretention Pollutant Removal Efficiency with Design Features: A Data-Driven Approach." *Journal of Environmental Management* 242: 403–414. https://doi.org/10.1016/j.jenvman.2019.04.064.

Wang, Y., Y. Meng, C. Wang, and B. Wang. 2021. "Ammonium Release and Adsorption Characters of Polyurethane - Biochar Crosslinked Material as an Additive Filler in Stormwater Treatment." *Polymers* 13 (10): 1557. https://doi.org/10.3390/polym13101557.

Wanner, O., H. J. Eberl, E. Morgenroth, D. R. Noguera, C. Picioreanu, B. E. Rittman, and M. C. M. Van Loosdrecht. 2006. *Mathematical Modeling of Biofilms*. Scientific and Technical Report Series Report No 18. London: IWA Publishing.

Winston, R. J., W. F. Hunt, and W. T. Pluer. 2017. "Nutrient and Sediment Reduction through Upflow Filtration of Stormwater Retention Pond Effluent." *Journal of Environmental Engineering* 143 (5): 6017002. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001195.

Wright, D., A. Purnell, S. Altern, and P. Frenzel. 2017. Floating wetlands: Increasing biodiversity and cleaning water in farm dams. Cape Town: Table Mountain Fund.

Zhang, K., N. J. Barron, Y. Zinger, B. E. Hatt, V. Prodanovic, and A. Deletić. 2021b. "Pollutant removal performance of field scale dual-mode biofilters for stormwater, greywater, and groundwater treatment." *Ecological Engineering* 163: 106192. https://doi.org/10.1016/j.ecoleng.2021.106192.

Zhang, K., Y. Liu, A. Deletić, D. T. McCarthy, B. E. Hatt, E. G. I. Payne, G. Chandrasena, et al. 2021a. "The Impact of Stormwater Biofilter Design and Operational Variables on Nutrient Removal - a Statistical Modelling Approach." *Water Research* 188: 116486. https://doi.org/10.1016/j.watres.2020.116486.

Zhou, H., and G. Xu. 2019. "Integrated Effects of Temperature and COD/N on an up-Flow Anaerobic Filter-Biological Aerated Filter: Performance, Biofilm Characteristics and Microbial Community." *Bioresource Technology* 293: 122004. https://doi.org/10.1016/j.biortech.2019.122004.

Zinger, Y., G. Blecken, T. D. Fletcher, M. Viklander, and A. Deletić. 2013. "Optimising Nitrogen Removal in Existing Stormwater Biofilters: Benefits and Tradeoffs of a Retrofitted Saturated Zone." *Ecological Engineering* 51: 75–82. https://doi.org/10.1016/j.ecoleng.2012.12.007.

Zouboulis, A. I., N. K. Lazaridis, and A. Grohmann. 2002. "Toxic Metals Removal from Waste Waters by Upflow Filtration with Floating Filter Medium. I. The Case of Zinc." *Separation Science & Technology* 37 (2): 403–416. https://doi.org/10.1081/SS-120000795.

CHAPTER 8

Conclusions

8.1 Research summary and contributions

This research aims to advance plant biofiltration as fit-for-purpose sustainable yet effective solution to urban stormwater pollution, for improved runoff water quality management in South Africa. In order to achieve this aim several distinct objectives were identified for investigation, consisting of both primary and secondary research, each contributing towards its successful completion. These objectives are sequentially addressed in chapters 2 to 7. The laboratory research, chapters 4, 5 and 6, was conducted in the experimental growth chamber discussed in the methodology section of the dissertation's introduction.

Chapter 2, objective 1, investigated both local and global literature to identify plant species of varying habitat suitability for potential use as indigenous phytoremediators throughout the different phytogeographically distributed ecosystems of the Western Cape. Research application was limited to this area for practical reasons (the Research University is located within the Western Cape), but it is envisaged that these research methods could also be applied to other biogeographic areas. This is due to national scope of the applied indexes. Although plant biofiltration has shown promising results as reported in literature, due to the varying pollutant removal performances between species, plant selection is a critically important yet precarious process during planning and design. Thus, this investigation was undertaken as the initial research step to identify indigenous plant species for use in the laboratory experiments conducted in chapters 4, 5 and 6. However, in exploring an array of bioremediation records it became apparent that a major deficiency in literature pertaining to local GI application and potential phytoremediators exists. The lack of local research and design specifics have resulted in the under-utilisation of the nature based solution with current WSUD frameworks providing philosophical guidance but omitting scientific design premise. An added complication is that the civil engineer who is often tasked with planning and design of plant biofilters, may be unable to adequately assess plant behaviour and ecosystem dynamics as a result of a lack of background in the field of the natural sciences. Therefore, due to biotic functioning not commonly included in the civil engineer's training, the regular urban water manager may be unequipped to exercise the required prudence when designing remediation technologies. This chapter, as an aid to the responsible urban GI designer, provides 56 indigenous non-invasive plant species (focussed within the Western Cape) likely to facilitate resource remediation without jeopardising local conservation and biodiversity. This index is particularly relevant in urban small-scale stormwater plant biofilters, as urban areas are often the initial sites from which invasion spreads.

Chapter 3, objective 2, developed a tool to facilitate plant selection for South African GI plant biofiltration technologies, presented in the form of a phyto-guide. The relevant plant focused selection factors and applicable local and international indexes affecting species inclusion are discussed and diagrammatically illustrated. In response to the country's rapid environmental deterioration by anthropogenic pollution, the WRC seeks to adopt WSUD, with a component of plant biofiltration. However, due to species variation in pollutant removal and hydrologic performance, as well as the threat of alien invasion negatively impacting an ecosystem's ability to deliver goods and services, injudicious plant selection can impair plant biofilter correctness. In addition, due to South Africa's rich biodiversity and endemism, plant species which have not yet been identified for their phytoremediation efficacy, may benefit local plant biofilters. Therefore, the significance and need for the phyto-guide lies in identifying novel phytoremediators by evaluating plant traits, as well as plant distribution, behaviour and diversity, without relying solely on known effective phytoremediators, for solutions sensitive to the threat of invasion. The need for diverse species capable of adjusting to the dynamic environmental and climatic conditions of the recipient habitats in need of remediation, prompted the exploration of South Africa's extensive biodiversity for application as phytoremediators. Due to the scientifically-engineered nature of plant biofilters, the phyto-guide maintains interdisciplinarity through expert consultation as a recommendation at its core. This chapter also made it possible to identify novel indigenous South African plants for use in the subsequent experiments.

Chapter 4, objective 3, evaluated ten engineered media mixes for biofilter growth media optimisation, conducted in the experimental plant growth chamber in the Hydraulic Laboratory at Stellenbosch University. The performances of the various growth media mixes were evaluated according to their stormwater pollutant removal, infiltration, particulate discharge, and plant growth supporting capabilities. The study was undertaken to improve poorly functioning biofilter growth media, a common cause of overflows, extended ponding time, increased particulate discharge, plant mortality and reduced pollutant removal, which have resulted in failed and dysfunctional treatment systems. Furthermore, adding to biofilter feasibility and cost-efficiency locally available engineered material is used, emphasizing potential technical considerations to stormwater management planning and design. Due to the considerable treatment contribution by plants, it is imperative to not only assess the material's treatment performance but also establish its potential as plant-root supporting substrate. Therefore, perlite, vermiculite, zeolite and attapulgite, mixed with local loamy sand, were assessed in vegetated (*Juncus effusus*) and unvegetated columns, exposed to nutrient and metal polluted synthetic stormwater. This chapter proffered local engineered media for improved water treatment and phytoremediator establishment. The infiltration enhancing media offers opportunity to further decrease the area required by plant biofilters, currently recommended at 2% of its catchment area, a significant advantage in space limited urban sites.

Chapter 5, objective 4, investigated nine indigenous South African plant biofilters exposed to low, typically observed and high synthetic stormwater pollution. Similar to engineered media, the performance of the indigenous biofilters were assessed in the laboratory controlled plant growth chamber. This investigation utilised South African species either identified in chapter 2 or promoted for use based on their physiological and morphological traits by the phyto-guide in chapter 3. The need for this research is further emphasized by the diverse and complex pollutant immobilisation and extraction processes affecting remediation performance, which varies between plants and different pollutants. Although the range of plant species used in this experiment only represented a diminutive portion of South Africa's megadiverse plant biodiversity, it presents an initial local phytoremediator favouring endeavour for use in local stormwater plant biofilters. In other words, it provides current information on a selection of plants that can be directly used by the practising civil engineer. Furthermore, the pursuit for urban stormwater plant biofilter optimisation progresses, as this chapter builds on the preceding growth media investigation through the identification of plant species exhibiting enhanced pollutant removal capabilities. These species represent effective yet sustainable alternatives to exotic phytoremediators. With the completion of this chapter, two of the three physical design components for plant biofilter optimisation within the responsible designer's control is concluded.

Chapter 6, objective 5, evaluated six plant biofilter designs exposed to low, typically observed and high synthetic stormwater pollution, and presents the final experiment conducted in the laboratory plant growth chamber. In addition to growth media and plant species, chapters 4 and 5 respectively, modifying physical biofilter design is the final design component towards plant biofilter optimisation within the civil or environmental design engineer's control. From the preceding growth media experiment is apparent that the performance of specific engineered materials vary with regard to pollutants, as well as hydrologic conditions. In addition, treatment efficacy varies between indigenous plant species, albeit consistently greater than unvegetated soil biofilters. Recent modifications to treatment biofilters have delivered no tangible improvement and in some cases reported some unsatisfactory outcomes, somewhat stagnating the design pursuit for plant biofilter optimisation. Consequently, efforts to advance local plant biofiltration is hampered (as this predominantly relies on international innovation), weakening the prospect of the treatment technology's future adoption in South Africa. It is here where the need for this research is emphasized. Therefore, with the intention of optimising sustainable South African stormwater management, novel plant biofilter designs incorporating endemic *Prionium serratum* and various engineered materials (perlite, vermiculite, zeolite and attapulgite) at varying locations and quantities as well as physical modifications (geotextile lining, saturated zone, plenum aeration and upflow filtration) are investigated. These distinct sequential modifications allow for pollutant removal comparisons between designs, thereby highlighting each design component's influence on treatment performance. These comparative analyses identified pollutant-specific removal processes and pathways relevant to each plant biofilter design. Thus, this chapter proffers experimental plant biofilter design modifications for improved nutrient and heavy metal treatment.

Chapter 7, objective 6, provided a comprehensive breakdown of the different primary and secondary nutrient and heavy metal removal processes of a plant biofilter. In addition to undertaking an empirical modeling approach to assist local modeling knowledge and biofilter initiatives, a conceptual deterministic model for estimating stormwater pollutant removal in a biofilter is proposed. This deterministic model is based on the mathematical equations of similar functioning pollutant-specific removal processes in a biofilm reactor. In recognising these removal processes, either theoretically established or experimentally reported in chapters 5 and 6, further understanding of nutrient and metal pollutant removal complexity in urban stormwater plant biofilters is achieved. Empirical modeling, in the form of linear regression analyses, of pollutant removal by indigenous plant species and varying designs exposed to different operational conditions, contribute data to the currently lacking field of plant biofilter modeling in South Africa. Furthermore, the development of the conceptual model for estimating pollutant removal summarised a series of model applications for the different removal processes. The linear regression models found time to be an insignificant influence and influent strength a significant influence of nutrient and metal removal performance of the experimental plant biofilters. This experimental plant biofilter data, emphasizing unique removal patterns between both species and designs, contribute experimental modeling data to future plant biofilter endeavours. Additionally, the conglomeration of statistical output provided by the laboratory experiments distinguish causal effects of biofilter performance, therefore, improving understanding and encouraging adoption.

In essence, this research presents a compilation of investigations that promote plant biofiltration as an effective yet sustainable alternative to conventional infrastructure for stormwater quality improvement at a fraction of the cost. Fundamentally, this improved urban runoff management strategy is based on the interrelation between natural science and engineering knowledge. However, due to the lack in local research and design specifics, WSUD in South Africa is still perceived as an emerging concept in urban stormwater management and as a consequence faces a number of application challenges. To benefit and ultimately advance the local WSUD sector, scientifically based planning and design guidelines are required. These need to be substantiated by data capture of locally available media and indigenous phytoremediators, as well as an explicit understanding of the available design components and consequences to treatment performance from modification. This research has contributed greatly to these requirements.

8.2 Main research findings

Extensive conclusions for each paper are provided in chapters 2 to 7, hence, only the main research findings pertinent to the dissertation are presented here.

Chapter 2: Indigenous Western Cape phytoremediators

- The bioremediation literature investigation delivered 1 410 plant species from 582 genera, with 257 plants autochthonous to South Africa, of which 174 are phytogeographically distributed throughout the Western Cape. Here, 80 are registered as either endemic or indigenous, with 56 (3 endemic and 53 indigenous) regarded as non-invasive and of least conservation concern.
- These species potentially ameliorate a range of environmental contaminants without jeopardising the recipient habitat's biodiversity. The plants regulate the natural ecosystem, maintain equilibrium and enhance heterogeneity, therefore, the use of indigenous alternatives to invasive exotics into the diverse habitats of the province are promoted.
- Although registered as non-invasive, introduction of these plant species must be done in a prudent manner as they may still be of conservation concern. This is due to ecosystem dynamism, habitat processes, climate change, and prevailing environmental conditions, all potentially threatening the recipient habitat's sustainability. This threat supports the significant need for a decision framework which among other factors, consider plant physiological behaviour and potential invasiveness during plant selection for use in plant biofilters.

Chapter 3: The phyto-guide

- The phyto-guide considered pollutant treatment and habitat sustainability as equally important contributors to successful plant biofilter functioning, thus, to the practicing engineer's benefit, selection was based on the amalgamation of natural science and engineering knowledge. This modus operandi, unsurprisingly, encourages interdisciplinarity via recommended specialist consultation throughout the selection process. Central to the decision framework's significance, this input ranges from town planners to botanists, establishing an overarching planning approach to plant biofilter design science.
- The phyto-guide ultimately promoted the following plant characteristics: Non-invasive indigenous South African species of least conservation concern, inhabiting terrestrial and aquatic ecosystems, which exhibit appropriate physiological and morphological

traits. In addition, the phyto-guide stipulates that promoted plant species (by the initial phyto-guide processes) occupy greater than 50% of the plant biofilter, with less appealing species less than 50%. This improved heterogeneity diversifies plant type and behaviour, leading to greater biofilter resilience to a range of dynamic climatic and environmental conditions, where dormancy in one plant is compensated by another.

- An additive advantage of the phyto-guide is that it does not solely rely on previously identified phytoremediator species for potential consideration, thus, opportunity arises to engage with novel South African plant species from the country's extensive biodiversity and endemism. In doing so, plant biofilters are more sensitively aligned to the danger of ecosystem services loss and hopes to mitigate the threat of alien invasion.

Chapter 4: Engineered media

- All tested unvegetated engineered media combinations effectively removed NH_3 -N, PO_4^{3-} -P, Cd, Cu, Pb and Zn from the synthetic influent, whilst NO_3^- -N leaching was observed. Additionally, the unvegetated engineered media outperformed traditional loamy sand with regard to both infiltration and particulate discharge, thereby maintaining treatment performance and potentially resisting habitat and climatic stresses (vegetative disturbance, flooding, drought, sedimentation and contamination).
- Media capable of enhancing infiltration, without compromising pollutant removal, is an important find and offers opportunity to decrease the required size of small-scale biofilters, a significant attribute in space-limited urban areas.
- In the presence of vegetation; pollutant removal, infiltration and particulate discharge improved, further emphasizing the important phytostabilising role of plants for increased biofilter performance. In addition to benefiting pollutant treatment, effective phytostabilisation hinders sediment accumulation, erosion and clogging of the urban drainage networks, which in turn mitigate watercourse and in-stream habitat degradation. Furthermore, assessing the individual plant functional responses exposed to the engineered materials reported no discernable differences, denoting indistinguishable media influence on plant growth. Thus, all media offered similar support as substrate for vegetative establishment, for the stressors and duration of this study.
- In comparing engineered materials, attapulgite consistently performed the best with regard to pollutant removal, infiltration and particulate discharge. It is however important to take cognisance of the variation in media performance when exposed to different pollutants, as growth media effective in ameliorating one pollutant (i.e. Cu) may not be as effective with another (i.e. particulate discharge). This finding is similar to the varying performances between plant species, highlighting the importance of

accounting for the recipient site's target pollutant, habitat and climate, prior to implementation. Furthermore, although engineered media outperformed traditional loamy sand, thereby enhancing treatment, scope for further improvement through appropriate plant inclusion and physical design modifications exist.

Chapter 5: Indigenous South African biofilters

- The presence of vegetation increased biofilter performance, evident by nutrient and heavy metal removal being on average 11% greater in indigenous plant biofilters than unvegetated soil biofilters. Here significant loads of Cd, Cu, Pb, Zn and NH_3 -N were removed, whereas NO_3^- -N and PO_4^{3-} -P removal was more variable. In addition, comparing the performance of indigenous plant biofilters with alien species from similar stormwater biofilter studies, the South African biofilters either outperformed or performed similarly to their equivalent exotics. This finding was corroborated by comparing the indigenous plant biofilters with the currently registered indigenous *Cynodon dactylon* which is deemed to potentially undergo reclassification, due to its aggressive growth, to an invasive. This finding supports the use of indigenous species in local urban stormwater plant biofilters sensitive to the threat of ecosystem loss, thereby further expanding the indigenous South African phytoremediator index.
- The best performing plant biofilters were *Prionium serratum, Juncus effusus* and *Cyperus textilis*, which removed on average 89.9, 85.3 and 78.6% of the synthetic stormwater pollutant loads respectively. In contrast, the worst performing plant biofilter was *Chasmanthe aethiopica*, which removed on average 56.3%, thus, only 10.6% greater than the unvegetated biofilter.
- Amending the plant biofilters with compost during construction increased PO_4^{3-} -P leaching, which may in turn have impeded Cu sorption to the biofilter growth media. This is an important consideration as the formation of Cu-organic matter complexes is the primary removal pathway of dissolved Cu in polluted stormwater. The removal / mobilisation of Cu is significantly influenced by the organic matter phase (liquid vs solid), therefore, compost amendments may still theoretically benefit plant biofilters due to the lower toxicity of Cu-organic matter complexes compared to free Cu-ions, reducing the risk of water degradation. This, however, requires further research.

Chapter 6: Optimised biofilter design

- In addition to a saturated anaerobic zone for anoxic microbial support, the best performing biofilter design combined standard plant biofiltration techniques with novel upflow filtration and plenum aeration; removing on average 96% of nutrient and heavy metal pollutant loads. Engineered materials were present in strategic quantities and locations in the biofilter. Here, zeolite in both the upflow filtration and plenum aeration zones, and a mix of attapulgite and vermiculite in the anaerobic saturation zone, targeted specific pollutants at various stages of biofiltration.

- Prominent metal removal by the biofliters, perceived to be as a result of effective sorption to soil in the upper layer of the growth media, allows for more practicable shallow biofiltration systems. These systems are easily constructed and presents the added advantage of potentially being proportional to existing drainage infrastructure and its associated conventional inlets, thus, easing engineering application.
- The various complex pollutant-specific removal processes and pathways were identified by assessing the nutrient and heavy metal treatment performances of the different biofilter designs. Due to the sequential order of modifications between biofilters, with each design incorporating an additional component, comparative analysis is possible and further utilised in model development.

Chapter 7: Modeling approach

- The accumulation of statistical output from the controlled experiments under various local operational conditions (influent loads, plant species and biofilter designs), contribute to the currently lacking discipline of South African biofilter modeling. From the empirical approach, linear regression model variability (evident from variable coefficients) corroborates the notion that the experimental plant biofilters and their processes were unique, reaffirming the necessity to undertake case specific parameter testing to confidently inform modeling applications of potential design feasibility.
- Empirical analyses found time to be an insignificant influence on removal, however, influent strength was found to statistically significantly influence removal for the duration of the study. This findings corroborates the notion that operational conditions significantly affect biofilter performance, which can be seen in biofilters receiving high influent loads performing significantly better than those receiving low influent loads, or pollutants near their irreducible concentrations.
- The comprehensive analyses of dissolved nutrient and heavy metal removal processes in stormwater plant biofilters enabled the development of a conceptual deterministic model for pollutant removal, based on similar functioning in a biofilm reactor. The mathematical equations presented can be applied, with appropriate refinements and assumptions, to numerically model the transformation process of organic matter, NH_3, NO_3^-, PO_4^{3-} and heavy metal pollutants. The model's significance lies in its ability to account for the complex pollutant removal processes in plant biofilters, which include: plant assimilation and release, sorption transformation via biotic organisms such as oxidation, nitrification, denitrification, and microbial assimilation. This provides the practicing engineer with potential pollutant-specific removal estimations of local urban stormwater plant biofilters, based on scientific premise and engineered techniques.

8.3 Recommended future research

The role and responsibility of the practicing civil engineer, often the project lead in local South African water sensitive urban developments for water resource protection, management and distribution, is determined by the scale of the WSUD project. In small-scale projects, the user experience is improved by the phyto-guide in that the practicing engineer need not continuously consult a range of specialists during the selection process. This is due to the phyto-guide's presentation of the natural dynamic processes applicable in complex engineering solutions for remediation success. In larger scale projects consultation is recommended, particularly where the commissioning of relevant scientific experts is viable, as to mitigate potential erroneous decision-making from the unequipped civil engineer. This application with less oversight, however, requires an inclusive framework which accounts for different pollution and ecosystem contexts. In order to achieve this it is recommended that the South African WRC, capable of collating the necessary specialists to satisfy interdisciplinarity, establish such a framework. This process-optimisation for the urban water management sector would contribute to WSUD understanding and subsequent adoption into municipal guidelines, as well as reiterate its potential as a best management practice. Another benefit of the phyto-guide, as mentioned, is the promotion of novel species as potential phytoremediators naturally adept to the recipient habitat, thereby mitigating the invasive threat and bestowing economic value to the species, which may further encourage species protection and development. Due to the country's rich biodiversity and extensive range of plant types, the user must pursue this relatively untapped resource. It is, however, vital to engage longer laboratory studies and field investigations to verify plant behaviour in treatment initiatives, particularly in urban areas.

The practical applicability of the engineered materials, indigenous plant species and biofilter designs which had performed well in the laboratory experiments, requires further assessment in field or pilot studies, particularly during periods of drought, prolonged inundation and intermittent supply. Due to water's strong absorption capacity resulting in urban stormwater's extensive pollutant range making it difficult to characterise and quantify, biofilter performance exposed to a greater variety of influent pollutants need to be assessed. For South Africa these include: microbial contaminants (particularly relevant due to the aging and poorly maintained sewerage treatment facilities), synthetic chemicals, pesticides, herbicides and fungicides, and pharmaceuticals, commonly transported by stormwater runoff at varying toxicities. Additionally, subjecting the biofilters to suspended solids over an extended period of time is imperative, due to the degradatory influence of clogging, commonly as a consequence of conventional stormwater management techniques. Furthermore, in optimising plant biofilters via modifications to design, the feasibility of an external interchangeable upflow zeolite filtration cartridge which would simplify the maintenance procedure must be investigated. This is particularly important with the inclusion of suspended solids into polluted influent. Disposal of this pollutant-laden media may, however, act as a potential pollutant source. Thus, appropriate replenishing methods are required. For zeolite, this author notes that regeneration has been achieved with sodium chloride, offering a potential remedy to the risks associated with exhausted media, however, requires further investigation.

The empirical evidence of this research, based on local materials and indigenous plant species, functions as an initial contribution to urban stormwater plant biofilter modeling in South Africa, contributing to more in-depth future modeling endeavours. From the findings, varying removal patterns across plant species, designs and pollutants, however, reveals the necessity for continuing laboratory testing to determine relevant and valid model parameters associated to specific plant biofilter designs. Thus, reaffirming the need to undertake longer laboratory and field investigations in order to adequately calibrate and further validate deterministic model applications.

For the responsible engineer to have confidence in designing a competent local vegetated stormwater solution sensitive to the issues of water sustainability and environmental protection, requires not only a valid set of data, but also a technical design strategy to restore ecosystem function and improve resource quality. The evolution of both experimental and mathematical models provide water treatment researchers and practitioners with a constantly improving understanding of plant biofilter complexity, pertinent to stormwater treatment facilities and receiving urban waters. Therefore, the contribution of this research will ease the future implementation of effective yet sustainable alternatives for stormwater quality improvement in civil engineered urban design based on scientific premise, at a fraction of the cost of conventional systems. This represents a significant shift in the urban water cycle and drainage management strategy, from simple flood reduction to the recognition of the stochastic nature of interactions between hydrology and the physical and biochemical processes influencing water quality.

ADDENDA

Appendix A: International conference proceeding

The rationality and findings of Paper i and Paper ii were presented at the Water Institute of Southern Africa online conference – Manage the resource for a capable ecology: Urban water management, 7-11 December 2020, titled "Selecting indigenous South African plant species for the phytoremediation of polluted urban runoff".

Background

7 - 11 December 2020 | South Africa

Stormwater runoff is the leading cause of poor water quality in natural and semi-natural systems, resulting in the release of large amounts of contaminants, posing a major human and environmental health problem.

In South Africa, anthropogenic pollution causes rapid environmental degeneration, posing major ecological engineering problems.

Combating this environmental degeneration within an urban setting requires proper mitigation strategies to restore ecosystem function and improve resource quality.

2.

3.

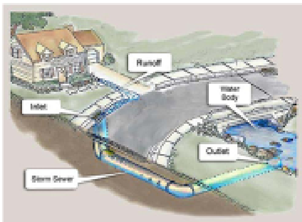
4.

Background

7 - 11 December 2020 | South Africa

Urban landscape, non-permeable surfaces contribute to increased runoff and pollution
- Rooftops
- Roads
- Sidewalks/pavements
- Surfaces compacted by urban development

Drainage networks for urban stream deposition
- Storm drains
- Culverts
- Stormwater pipes and canals



5.

Consequences
- Loss of groundwater recharge
- Reduced stream base flows
- Increased flooding
- Lower water quality

WSUD – Provides philosophical guidance
SuDS – Focuses on stormwater management
Practical implementation is constrained by lack of design specifics

Urban green infrastructure

7 - 11 December 2020 | South Africa

Potential solution: Green infrastructure (GI) utilising phytoremediation technologies
- Frequently designed by civil engineers, potentially lacking the necessary knowledge and expertise

Living natural systems to provide environmental services, such as capturing, cleaning and infiltrating stormwater; creating wildlife habitat; shading and cooling streets and buildings; and calming traffic
Benefits of GI: Physical/Natural, Social, Economic

In SA, GI execution is frequently the responsibility of the civil engineer and urban water manager

Swales

7.

Filters strips

8.

Retention ponds

9.

Constructed wetlands

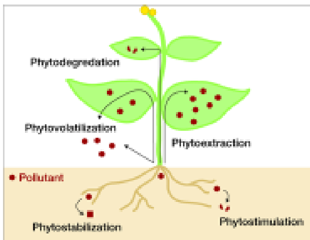
10.

Phytoremediation

7 - 11 December 2020 | South Africa

In situ use of plants for the remediation of contaminated soils, sediments and water containing organic and inorganic pollutants

Effective for the removal of:
- Heavy metals
- Explosives
- Radionuclides
- Polycyclic Aromatic Hydrocarbons
- Ammunition wastes
- Landfill leachate
- Fertilisers, herbicides and pesticides
- Nutrients
- Sediment



6.

Sustainable effective implementation

7 - 11 December 2020 | South Africa

In designing an effective yet sustainable GI remediation system, the following needs to be taken into account when vegetation is introduced:

GI Performance:
Vegetated areas > Unvegetated areas
- Pollutant removal efficiency varies between species, with species displaying affinity to specific pollutants

Influencing the pollutant removal efficiency of GI

Plant physiological and morphological traits:
Known traits contributing towards phytoremediation efficiency are shared with invasiveness
- Physiological (Hardiness and Proliferation)
- Morphological (Above and Below-ground biomass)

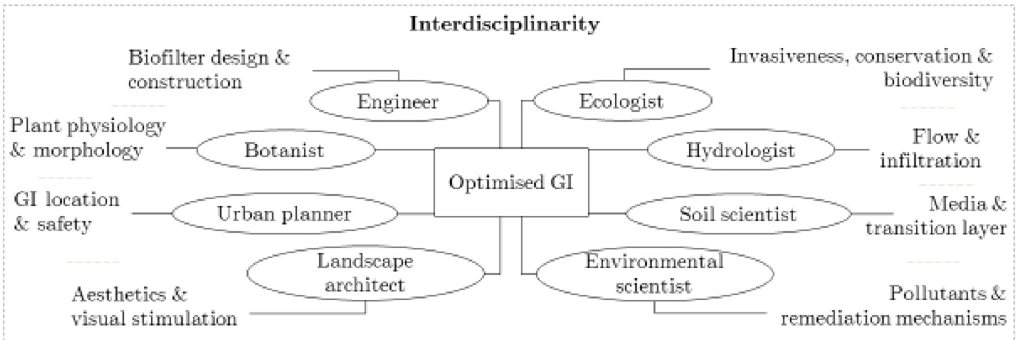
Influencing the sustainability and longevity of GI

The desire to optimise GI by introducing efficient phytoremediators cannot be prioritised over conservation concerns, thus remediation efficiency and sustainability equally contribute to successful GI functioning

The design and planning process

7 - 11 December 2020 | South Africa

Designing a successfully functioning GI system is complex and requires knowledge and input from both engineering and science, satisfying interdisciplinarity, the best practice collaboration approach



Selection criteria: Phyto-guide

GI Optimisation - Species selection influenced by:

1. Species presence in global phytoremediation literature
   - Reported as proven effective species
2. Distribution, invasiveness and conservation status
   - Phytogeographic distribution indicating autochthonous
   - Invasive status as a potential sustainability threat
   - Vulnerability to extinction affecting availability and abundance
3. Physiological characteristics and responses
   - Growth rate and vegetative expansion capabilities
   - Lifespan as an indicator for pollutant affinity and sustainability
   - Tolerance in extreme climatic and habitat conditions
4. Morphological traits
   - Roots and above-ground biomass
5. Heterogeneity and aesthetics
   - Combining proven remediators with less effective species

Diverse species for optimised GI
=
$>$50% Effective performers with desirable traits
+
$<$50% Less effective performers with some desirable traits

SA phytoremediators

Case study:
Exploring autochthonous Western Cape plants as potential water and soil pollutant phytoremediators

Methodology:
Phyto-guide for systemic plant selection in the Western Cape relying on relevant sources, excluding physiological and morphological assessments (Collaboration with specialists required, Steps 3 -5)

Proven effective phytoremediators:
- Investigate 800 literature sources and 2 databases

Potential endemic, indigenous and naturalised species to the WC of least conservation concern:
- SANBI Red List and POSA...

Excluding species displaying invasive characteristics:
- AIPLSA, NEM:BA A&IS and SAPIA...

Results:
1408 global phytoremediators
257 indigenous and naturalised SA species, 174 are WC phytogeographic species, 99 are autochthonous, with 78 regarded as non-invasive of least conservation concern (3 endemic, 56 indigenous, and 22 naturalised)

Conclusions

GI is efficient and cost-effective for soil-water remediation

Pursuit for efficiency cannot overshadow the need for conservation, with species naturally acclimatized to the recipient ecosystem and which do not threaten the natural biodiversity considered

11.

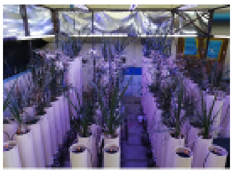
NB in urban remediation technologies, may act as the source of invasion

Ecosystem dynamism in an ever changing climate and fluctuating biotic conditions, demands interdisciplinary consultation with a range of specialists

Conclusions continued

Interdisciplinarity equips the practicing engineer often lacking knowledge and expertise of plant behaviour and ecosystem dynamics, with scientific literature during planning and design for consistent optimisation of sustainable GI technologies

Phyto-guide decision framework aids the practicing engineer in the field



12.

To broaden potential local species, capable of withstanding the conditions that define SA cities, we continuously assess their remediation performances experimentally

Appropriate Green Infrastructure has the potential to generate environmental benefits, liveable cities, reduced water management costs and A large number of jobs

Excerpt of phyto-guide findings

WISA 2020 ONLINE CONFERENCE
7 - 11 December 2020 | South Africa
#allhandsondeck

An example of potential WC phytoremediation plants identified by the phyto-guide

Species	SA Endemic	WC Distribution			Pollutants
		Endemic	Indigenous	Naturalized	
Agapanthus africanus	x	x	x		Petroleum
Agapanthus praecox subsp. *minimus*	x		x		NH_4, NO_3 & PO_4^{3-}
Agrostis gigantean				x	Co & Cu
Alectra sessiliflora			x		Co & Cu
Arabidopsis thaliana				x	Cd, Co, Cr, Cu & Hg
Arctotis acaulis	x		x		NH_4, NO_3, PO_4^{3-} & Glyphosate
Aristea capitata	x	x	x		NH_4, NO_3, PO_4^{3-} & Glyphosate
Arrhenatherum elatius				x	Pb
Berkheya zeyheri subsp. *rehmannii* var. *rogersiana*	x		x		Ni & Se
Bidens pilosa				x	Fertilizer & Herbicide; As, Cd, Cr, Ni & Pb; TPHs
Blotiella glabra			x		Cu & Zn
Bolboschoenus maritimus			x		NH_4, NO_3, PO_4^{3-} & Glyphosate
Bulbine frutescens			x		Petroleum
Carpobrotus edulis subsp. *edulis*	x		x		NH_4, NO_3 & PO_4^{3-}
Carpobrotus edulis subsp. *parviflorus*	x	x	x		NH_4, NO_3, PO_4^{3-} & Glyphosate
Ceratophyllum demersum			x		As, Cd, Cr, Cu, Ni & Pb; Explosives; Radionuclides; Organophosphorous, Organochlorine & Chlorobenzenes
Chlorophytum comosum			x		C; CO; Formaldehyde; Toluene & Xylene
Cladium mariscus subsp. *jamaicense*			x		Al, Fe, Mg & Mn
Conyza scabrida			x		Cu & Zn
Cotula coronopifolia			x		Heavy Metals & Sewage Effluent
Cynodon dactylon				x	Al, As, Cd, Cr, Cu, Ni, Pb, Se, U & Zn; Fertilizers, Pesticides & Herbicides; NH_4, NO_3, PO_4^{3-} & Glyphosate; Ammunition Wastes, Explosives; TPHs, PAHs, PCBs, Petroleum, PHCs, Phenanthrene & Dibenzofuran

References

WISA 2020 ONLINE CONFERENCE
7 - 11 December 2020 | South Africa
#allhandsondeck

1. GHBA (Greater Houston Builders Association) (2019) City of Houston Announces Green Infrastructure Incentives. URL: https://www.ghba.org/city-of-houston-announces-green-infrastructure-incentives/ (Accessed 10 November 2020).
2. USGS (United States Geological Survey) (2019) Manage stormwater runoff. Delaware estuary. URL: www.delawareestuary.org (Accessed 7 November 2020).
3. BMP (Stormwater BMP) (2019) Stormwater management. URL: www.newpig.com/stormwater (Accessed 7 November 2020).
4. Howard County Stormwater Solutions (2019) Stormwater runoff – The good, the bad, the ugly. Clean Howard. URL: www.cleanwaterhoward.com (Accessed 5 October 2020).
5. IQP (2013) Phase II MS4 Permit: Improving Central Massachusetts Stormwater Management. URL: www.wpi.edu (Accessed 5 October 2020).
6. PILON-SMITS E (2005) Phytoremediation. *Annual Review of Plant Biology* **56** 15-39.
7. Land Perspectives (2013) River East Center: A Sustainable Site. URL: https://landperspectives.com/tag/green-sites/ (Accessed 7 September 2020).
8. SuDS Wales (2020) SuDS Techniques – Permeable Conveyance Systems. URL: https://www.sudswales.com/types/permeable-conveyance-systems/swales/ (Accessed 9 September 2020).
9. USEPA (United States Environmental Protection Agency) (2020) Green Infrastructure, Low-Impact Development and Green Infrastructure. URL: https://www.epa.gov/region8/green-infrastructure (Accessed 8 September 2020).
10. Next City (2017) How Cities can Harness the Flood-Fighting Powers of Urban Parks. URL: https://nextcity.org/daily/entry/cities-harness-flood-fighting-powers-urban-parks (Accessed 6 September 2020).
11. JACKLIN DM, BRINK IC and DE WAAL JH (2020) The potential use of plant species within a Renosterveld landscape for the phytoremediation of glyphosate and fertiliser. Water S.A **46** (1) 94-103.
12. JACKLIN DM (2020) Personally captured by author on 19 November 2020 at Stellenbosch University.

Appendix B: Author declarations

Declaration by the candidate for Chapter 2:

With regard to ***Chapter 2***, the nature and scope of my contribution is as follows:

Nature of contribution	Extent of contribution (%)
Development of theory, conducting experimental work, data collection and processing, statistical analyses, writing of manuscript	80

The following co-authors contributed to this ***Chapter 2*** as follows:

Name	Contact	Nature of contribution	Extent of contribution (%)
Dr Isobel Brink	icbrink@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10
Prof Shayne Jacobs	sjacobs@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10

Signature of candidate: Date: 08/11/2021

Declaration by co-authors:

The undersigned hereby confirm that;

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 2,
2. no other authors contributed to Chapter 2 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	09 /11/2021

Declaration by the candidate for Chapter 3:

With regard to ***Chapter 3***, the nature and scope of my contribution is as follows:

Nature of contribution	Extent of contribution (%)
Development of theory, conducting experimental work, data collection and processing, statistical analyses, writing of manuscript	80

The following co-authors contributed to this ***Chapter 3*** as follows:

Name	Contact	Nature of contribution	Extent of contribution (%)
Dr Isobel Brink	icbrink@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10
Prof Shayne Jacobs	sjacobs@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10

Signature of candidate: Date: 08/11/2021

Declaration by co-authors:

The undersigned hereby confirm that;

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 3,
2. no other authors contributed to Chapter 3 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	09 /11/2021

Declaration by the candidate for Chapter 4:

With regard to ***Chapter 4***, the nature and scope of my contribution is as follows:

Nature of contribution	**Extent of contribution (%)**
Development of theory, conducting experimental work, data collection and processing, statistical analyses, writing of manuscript	80

The following co-authors contributed to this ***Chapter 4*** as follows:

Name	**Contact**	**Nature of contribution**	**Extent of contribution (%)**
Dr Isobel Brink	icbrink@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10
Prof Shayne Jacobs	sjacobs@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10

Signature of candidate: Date: 08/11/2021

Declaration by co-authors:

The undersigned hereby confirm that;

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4,
2. no other authors contributed to Chapter 4 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this dissertation.

Signature	**Institutional affiliation**	**Date**
	Stellenbosch University	09 /11/2021

Declaration by the candidate for Chapter 5:

With regard to ***Chapter 5***, the nature and scope of my contribution is as follows:

Nature of contribution	Extent of contribution (%)
Development of theory, conducting experimental work, data collection and processing, statistical analyses, writing of manuscript	80

The following co-authors contributed to this ***Chapter 5*** as follows:

Name	Contact	Nature of contribution	Extent of contribution (%)
Dr Isobel Brink	icbrink@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10
Prof Shayne Jacobs	sjacobs@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10

Signature of candidate: Date: 08/11/2021

Declaration by co-authors:

The undersigned hereby confirm that;

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5,
2. no other authors contributed to Chapter 5 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	09 /11/2021

Declaration by the candidate for Chapter 6:

With regard to ***Chapter 6***, the nature and scope of my contribution is as follows:

Nature of contribution	**Extent of contribution (%)**
Development of theory, conducting experimental work, data collection and processing, statistical analyses, writing of manuscript	80

The following co-authors contributed to this ***Chapter 6*** as follows:

Name	**Contact**	**Nature of contribution**	**Extent of contribution (%)**
Dr Isobel Brink	icbrink@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10
Prof Shayne Jacobs	sjacobs@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10

Signature of candidate: Date: 08/11/2021

Declaration by co-authors:

The undersigned hereby confirm that;

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 6,
2. no other authors contributed to Chapter 6 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this dissertation.

Signature	**Institutional affiliation**	**Date**
	Stellenbosch University	09 /11/2021

Declaration by the candidate for Chapter 7:

With regard to ***Chapter 7***, the nature and scope of my contribution is as follows:

Nature of contribution	Extent of contribution (%)
Development of theory, conducting experimental work, data collection and processing, statistical analyses, model development, writing of manuscript	70

The following co-authors contributed to this ***Chapter 7*** as follows:

Name	Contact	Nature of contribution	Extent of contribution (%)
Mr Izak van der Merwe	izak.vandermerwe@zutari.com	Development of theory, model development, writing of manuscript	20
Dr Isobel Brink	icbrink@sun.ac.za	Reviewing of manuscript, proposed insightful amendments	10

Signature of candidate: Date: 08/11/2021

Declaration by co-authors:

The undersigned hereby confirm that;

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 6,
2. no other authors contributed to Chapter 6 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this dissertation.

Signature	Institutional affiliation	Date
	Zutari	09/11/2021
	Stellenbosch University	09 /11/2021

Appendix C: Copyright permissions

Chapter 2, Paper i

Lynnwood Bridge Office Park, 2nd Floor, Bloukrans Building,4
Daventry Street, Lynnwood Manor, Pretoria

Private Bag X03, Gezina, 0031, South Africa

Tel: +27 (0)12 761 9300
Email: info@wrc.org.za
Web: www.wrc.org.za

30 October 2021

Dylan Michael Jacklin
Stellenbosch University
Department of Civil Engineering
Water and Environmental Engineering Group
Private Bag X1
Matieland 7602
South Africa

Dear Mr Jacklin

Permission to reuse material published in *Water SA*

Thank you for your request to reproduce and reformat the following material published in *Water SA*:

> Jacklin DM, Brink IC and Jacobs SM (2021) Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators with a focus on green infrastructure. *Water SA* **47**(3) 317–325.

As this material was published under a Creative Commons Attribution 4.0 (CC BY 4.0) licence, you have the non-exclusive right to share (copy and redistribute in any medium or format) and adapt (remix, transform and build upon) this publication, on condition of full attribution of the original source (*Water SA* **47**(3) 317–325).

Yours sincerely

____
Tamsyn Sherwill
Editor: *Water SA*

Supporting sustainable development through research funding, knowledge creation and dissemination

Chapter 3, Paper ii

Lynnwood Bridge Office Park, 2nd Floor, Bloukrans Building,4
Daventry Street, Lynnwood Manor, Pretoria

Private Bag X03, Gezina, 0031, South Africa

Tel: +27 (0)12 761 9300
Email: info@wrc.org.za
Web: www.wrc.org.za

30 October 2021

Dylan Michael Jacklin
Stellenbosch University
Department of Civil Engineering
Water and Environmental Engineering Group
Private Bag X1
Matieland 7602
South Africa

Dear Mr Jacklin

Permission to reuse material published in *Water SA*

Thank you for your request to reproduce and reformat the following material published in *Water SA*:

> Jacklin DM, Brink IC and Jacobs SM (2021) A phyto-guide to species selection for optimised South African green infrastructure. *Water SA* **47**(4) 515–522.

As this material was published under a Creative Commons Attribution 4.0 (CC BY 4.0) licence, you have the non-exclusive right to share (copy and redistribute in any medium or format) and adapt (remix, transform and build upon) this publication, on condition of full attribution of the original source (*Water SA* **47**(4) 515–522).

Yours sincerely

____

Tamsyn Sherwill
Editor: *Water SA*

Supporting sustainable development through research funding, knowledge creation and dissemination

Chapter 4, Paper iii

Republic Export Building
1 Clove Crescent
London
Tel: +44(0) 207 654 5500
Web: www.iwa-network.org

Dylan Michael Jacklin
Stellenbosch University
Department of Civil Engineering
Water and Environmental Engineering Group
Private Bag X1
Matieland 7602
South Africa

02 November 2021

Dear Dylan,

In response to the copyright permission for material published in *Water Science and Technology*

> Jacklin, D. M., Brink I. C. & Jacobs, S. M. 2021 Efficiencies of indigenous South African plant biofilters for urban stormwater runoff water quality improvement with a focus on nutrients and metals. *Water Science and Technology* **70** (7), 1094-1110.

Permission is hereby granted to reproduce and reformat the material.

The article above is published Open Access, therefore, you are still the owner of the works. We only require you follow the guidance on the OA licence terms.

Do let me know if you have any further questions.

Yours sincerely,
Emma
Editorial Operations Manager
IWA Publishing
ebuckingham@iwap.co.uk

Chapter 5, Paper iv

Republic Export Building
1 Clove Crescent
London
Tel: +44(0) 207 654 5500
Web: www.iwa-network.org

Dylan Michael Jacklin
Stellenbosch University
Department of Civil Engineering
Water and Environmental Engineering Group
Private Bag X1
Matieland 7602
South Africa

02 November 2021

Dear Dylan,

In response to the copyright permission for material published in *AQUA – Water Science and Technology*

> Jacklin, D. M., Brink I. C. & Jacobs, S. M. 2021 Urban stormwater nutrient and metal removal in small-scale green infrastructure: Exploring engineered plant biofilter media optimisation. *AQUA – Water Science and Technology* **84** (7), 1715-1731.

Permission is hereby granted to reproduce and reformat the material.

The article above is published Open Access, therefore, you are still the owner of the works. We only require you follow the guidance on the OA licence terms.

Do let me know if you have any further questions.

Yours sincerely,
Emma
Editorial Operations Manager
IWA Publishing
ebuckingham@iwap.co.uk

Chapter 6, Paper v

Republic Export Building
1 Clove Crescent
London
Tel: +44(0) 207 654 5500
Web: www.iwa-network.org

Dylan Michael Jacklin
Stellenbosch University
Department of Civil Engineering
Water and Environmental Engineering Group
Private Bag X1
Matieland 7602
South Africa

02 November 2021

Dear Dylan,

In response to the copyright permission for material submitted for publication in *Water Practice and Technology*

> Jacklin, D. M., Brink I. C. & Jacobs, S. M. (in press) Comparison of urban stormwater plant biofilter designs for nutrient and metal removal in South Africa. *Water Practice and Technology.*

Permission is hereby granted to reproduce and reformat the material.

The article above has been selected for Open Access publication, therefore, you will still be the owner of the works. We only require you follow the guidance on the OA licence terms.

Do let me know if you have any further questions.

Yours sincerely,
Emma
Editorial Operations Manager
IWA Publishing
ebuckingham@iwap.co.uk