Provisional Green Infrastructure in Indian Megacities: Assessing the Upscaling Potential of In-stream Interventions for Sustainable Urban Water Management

by

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Dedication

For Lee

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Abstract

The management of stormwater and wastewater is a critical challenge for urban sustainability, and one that is increasingly attended to by researchers and designers across a range of disciplines. Traditionally, water quality has been managed through large-scale, centrally managed infrastructure such as pipes, drains, and wastewater treatment facilities. Green infrastructure (GI) is an alternate approach that supplements these systems through decentralized nature-based solutions. This dissertation introduces a new type of GI, Provisional Green Infrastructure (PGI). PGI is posited as a *speculative innovation typology* for sustainable urban water management emerging from the Indian megacity, with important implications for other contexts. PGI is defined as "Informal nature-based retrofits to existing grey infrastructure networks for the purpose of improving water quality within highly unpredictable, space-constrained, and contaminated urban environments."

Throughout the research, PGI serves as a "boundary object" for grounding multiple lines of inquiry. Chapter 2 defines the PGI concept, and suggests its relevance for megacities characterized by a broad range of spatial, infrastructural and governance constraints. I situate PGI in the context of urban informality and introduce two distinct types of upscaling (*spatial* and *organizational)* as pathways for future diffusion. Chapter 3 draws on interviews and surveys to explore barriers to broader PGI adoption, identifying specific misalignments between innovators and Potential Future Adopters (PFA's) using the Diffusion of Innovations (DOI) framework. It is

suggested that additional efforts by innovators should be made to emphasize the *simplicity* and *relative advantage* of PGI to decision-makers. Chapter 4 establishes the efficacy of PGI designs for a range of important water quality parameters, and discusses the limitations on PGI performance in an in-stream context. PGI using both gravel and terracotta substrates both perform reasonably well for detaining or removing physical and biological contaminants, but show limited reductions of pathogens and Ammonia-N (for which there was an increase). K_{BOD5} removal rate was statistically significant for gravel substrate. TP removal was higher in terracotta substrate. Chapter 5 explores the potential for citywide impact using the Stormwater Management Model (SWMM 5) and discusses how various upscaling scenarios and variations in the spatial location and configuration of PGI's may impact cumulative catchment-wide performance (including cost, water quality improvement, and issues of public access). The study is intended to be used as a model for future Decision Support Systems (DSS) for decision-makers by combining Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) along with a post-hoc sensitivity analysis to interpret the results given various weighting of input variables. The results suggest that upgradient dispersed configurations of PGI may be most advantageous in cases where the importance of public access and TSS capture is given more weight. Dispersed configurations of PGI performed better than centralized for reducing TP loading at downstream receiving waters and are higher ranked as advantageous when the importance of TP is given more weight.

Citing the above as evidence-based design, the research concludes that PGI should not be viewed as a functional replacement for conventional wastewater treatment infrastructures, but rather as a supplementary stop-gap function in contexts where functional separation of wastewater and stormwater are unlikely to occur, or where existing large scale WWTP's operate below their designed capacity.

Chapter 1: Introduction

1.1 Research Questions and Methodology

The overarching question that animates this dissertation is: What is the context, impact, and potential of Provisional Green Infrastructure on water quality in megacity watersheds? This larger question informs several *sub-questions* that drive a series of discrete—but interdependent—lines of inquiry:

1. What is PGI and how is it conceptualized as an emergent innovation typology in Indian megacities?
2. How does the form, function and context of PGI differ from the modes of GI pursued in the Global North?
3. How might local building materials, demolition rubble and construction waste be deployed as low-tech, low cost biofilters within PGI interventions?
4. How do variations of substrate type and instream water quality (influent) quality impact the contaminant removal efficiency (effluent) of PGI interventions at a local scale?
5. How are critical performance criteria (removal efficiency, cost, and public access) influenced by both the location and configuration of PGI at the scale of a watershed?

Drawing upon the Design in Science framework, Diffusion of Innovations theory and a range of case studies and grey literature sources, the research that follows addresses whether the emergent, bottom-up tactics evidenced by PGI can be translated into viable transitional strategies for sustainable urban water management in the context of megacity watersheds. Results of the research will contribute new knowledge to the field by focusing rigorous attention onto complex urban contexts and marginalized transdisciplinary design precedents that, due to their small scales and experimental orientation, are rarely examined within refereed literature. By focusing on the development of novel innovations, we believe that the broader impact of this research is the adaptive translation of GI practices across various spatial and cultural boundaries.

1.2 Theoretical frameworks

1.2.1 Provisional Green Infrastructure

What is Green Infrastructure (GI) and how is it distinguished from Provisional Green Infrastructure (PGI)? As it applies to issues of urban hydrology, GI is defined by the US Environmental Protection Agency as "a cost-effective, resilient approach to managing wet weather impacts... [reducing and treating] stormwater at its source while delivering environmental, social, and economic benefits" (*What Is Green Infrastructure*, 2016). GI is also referred to as water sensitive urban design (WSUD) in Australia, and sustainable urban drainage systems (SUDS) in the United Kingdom (Fletcher et al., 2015). These umbrella terms can describe a range of local practices such as retention and detention basins, bioswales, rain barrels, green space, constructed or natural wetlands, green roofs, deep infiltration wells, and permeable pavements. These interventions often focus on ecological benefits such as the reduction of flooding, the augmenting of surface water supplies, groundwater recharge, and the improvement of surface water quality (Prudencio & Null, 2018). GI is often evoked as a palliative for the so-called "urban stream syndrome" an ongoing wicked problem impacting both water quantity and water quality within highly urbanized, impervious environments (Walsh et al., 2005). It is important to recognize that the urban stream syndrome is elevated to new heights of "wickedness" when compounded with the many additional biophysical, governance and cultural realities that mark the rapidly expanding urban agglomerations in the global south. These include:

- Extreme land development pressure and informal patterns of settlement which often preclude land-based, vegetative modes of wastewater retention and management (Wehrmann, 2014).
- Lack of funding or adequate implementation and maintenance of public water infrastructures (Tortajada, 2016).
- Open drainage networks which often follow the natural topographical gradients of the landscape and receive regular inflows of solid waste, and untreated domestic wastewater (Jamwal et al., 2015; Parkinson et al., 2007).

PGI is therefore proposed for the first time here as a speculative innovation typology emerging from Indian megacities, and defined as *"Informal nature-based retrofits to existing grey infrastructure networks by non-state actors for the purpose of improving water quality within highly unpredictable, space-constrained, and contaminated urban environments."*

"Provisional" is commonly defined as that which is "Arranged or existing for the present, possibly to be changed later" (*Provisional, Oxford*, n.d.). The use of this modifier is intended to highlight a range of experimental GI practices which are conceived and initially implemented by a range of non-state actors. As a subsequent review of the grey literature will further suggest, many modes of PGI arise in ways that are quasi-sanctioned through local alliances. As such, their status is uncertain, tenuous, existing in a perpetual state of "beta." They adapt in response to their localized constraints and opportunities, exploiting viable "windows of opportunity" within a complex and ever-changing urban ecosystem. The addition of the 'provisional' serves to highlight the informal processes that influence the particular form, function, and development of these interventions as well as their relative novelty within the megacity context.

PGI draws upon notions of "*Jugaad*"— a colloquial term describing the flexible, frugal and inclusive processes of "improvised innovation" that are observed within the resource-scarce socio-technical contexts of South Asia (Radjou et al., 2012). Although this mode of innovation typically refers to product and service design and has yet to be employed as a lens for GI, it invites an explicit emphasis on the importance of "deliberately and materially fusing the design and execution of a novel production" (Prabhu & Jain, 2015). *Jugaad* offers a relevant theory of action for resource-scarce environments often entailing a process of "cobbling together" or "jerry-rigging" involving rapid makeshift repairs consisting of only the tools and materials at hand (Fig 1).

Figure 1. Examples of "provisional" design and innovation, as observed in online memes

Whereas perspectives from the Global North may exhibit a tendency to view these developments through a dismissive or pejorative lens, *Jugaad* is increasingly celebrated as a legitimate mode of socio-technological innovation throughout the developing world and indicative of resilience that arises from myriad constraints. Therefore PGI extends these theories of action into the unlikely domain of GI, whereby in-stream interventions are understood as informal "stop-gap" measures that are offered as interim solutions until such a time that more formal responses can be implemented. As a subsequent review of the grey literature and case studies will further suggest, many modes of PGI arise in ways that are quasi-sanctioned through local alliances. As such, their status is uncertain, tenuous, existing in a perpetual state of "beta." They adapt in response to their localized constraints and opportunities, exploiting small scale opportunities within a complex and ever-changing urban ecosystem.

In addition to further elucidating how and why PGI is a useful concept for application in megacity contexts, the research that follows identifies explicit upscaling opportunities for individual PGI tactics. Two distinct, yet complementary modes of upscaling are employed here as *organizational* upscaling, and *spatial* upscaling. *Organizational* upscaling will apply to the processes of broader adoption and *diffusion* of novel PGI innovations between and across various types of actors and organizations (e.g. individuals and non-profits, civil society organizations, municipalities). *Spatial* upscaling concerns how PGI interventions might be strategically deployed within a distinct geographic and hydrological context (sub-catchment, and catchment level) to achieve cumulative water quality benefits.

1.2.2 Diffusion of Innovations

Research will examine organizational upscaling by drawing upon the Diffusion of Innovations (DOI) theory, originally proposed by Rogers (1962, 1995), which has been employed as a framework for research in many domains including agriculture, education, management, health care and public health, information technology, and sociology—amassing a significant body of research (Baptista, 1999; Karakaya et al., 2014; Oldenburg & Glanz, 2008;

Wejnert, 2002). Traditionally DOI has been employed as a relevant framework for understanding how new ideas, processes, and products diffuse and spread amongst individuals. More recently, the theory has been adapted for application of diffusion processes within and across organizations (Lundblad, 2003). Rogers defines diffusion as "the process by which an *innovation* is *communicated* through certain channels over *time* among members of a *social system" (Rogers, 1995, p. 10)* and identifies the four key elements of DOI as 1) the innovation, 2) communication, 3) time, and 4) social system.

An *innovation* is defined as "an idea, thing, procedure, or system that is perceived to be new by whomever is adopting it" (Rogers, 2003, p. 10). The innovation does not need to be new in terms of being recently developed, it only needs to be new to the person or organization that is adopting and implementing it. *Communication* refers to the processes by which people and organizations develop and share information with each other to achieve a shared understanding. *Time* refers to various stages of decision making required, and the categories of those involved in the adoption process: Innovators, early adopters, early majority, late majority, and laggards. Time also refers to the rate of adoption whereby the process of diffusion is often generalized and diagrammed as an adoption curve (Fig. 2). *Social System* refers to the context in which diffusion occurs, the members of which may be individuals, groups, organizations or subsystems. The role of opinion leaders, change agents, and champions are also nested under this element and are said to exert influence on decision making processes from within or without the system.

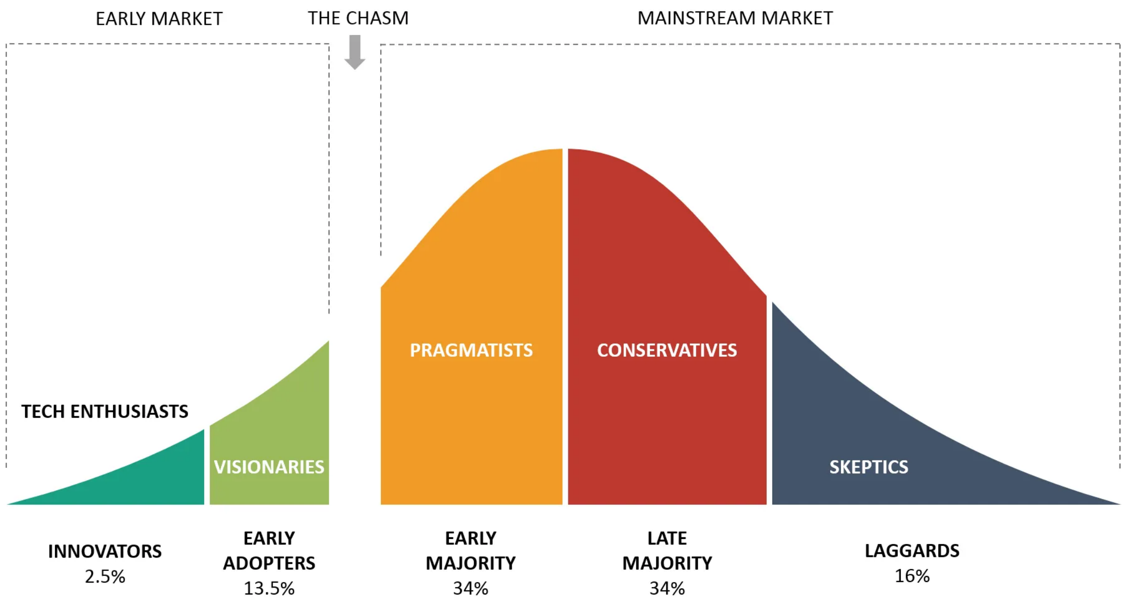

Figure 2. Rogers' diffusion of innovations adoption curve (Rogers, 2003, p. 281).

DOI theory initially identified five characteristics of the innovation itself which influence its success and rate of adoption over time. These characteristics include *relative advantage, compatibility, simplicity, trialability and observability*. Later, *reinvention* was proposed by other scholars as a sixth characteristic, defined as "the degree to which an innovation is changed or modified by a user in the process of its adoption and implementation" (Rogers, 1995, p. 17). This simple framework of innovation characteristics can be applied to the innovation to assess the speed with which it might be diffused (e.g. 'upscaled'). DOI theory states that as each of these characteristics increase, so too does the rate of adoption (with the exception of complexity, for which a decrease in complexity results in an increase in adoption). Several reviews of DOI theory and its application from across many disciplines have confirmed these characteristics show a strong correlation with the adoption rates of innovations, and predict (but do not necessarily guarantee) successful adoption (Greenhalgh et al., 2004). Yet the way in which these characteristics interact appears to be largely a domain-specific phenomena (Baptista, 1999).

1.2.3 Design in Science Framework

Design in Science (DIS), originally elucidated by Nassauer and Opdam (2008) offers a framework for bridging the agency of design with the authority of science and as such has been useful to employ as a broad lens for the transdisciplinary nature of this work. The DIS framework offers a definition of "Design" as *"any intentional change of landscape pattern for the purpose of sustainably providing ecosystem services while recognizably meeting societal needs and respecting societal values"* (Nassauer & Opdam, 2008). It places design (employed as both a noun and a verb) at the critical intersection of an iterative and mutually reinforcing cycle of theory building and theory testing (Fig. 3). DIS posits a more integrated relationship between practice and science in which discrete research efforts are pursued through modelling and field testing, which informs generalizable theory, which in turn drives larger processes of landscape change (via policy adoption, "societal goal setting" and widespread implementation at larger spatial and organizational scales). This is reflected in the general sequence of the academic papers to follow, whereby case studies of existing designs (Chapters 2 and 3) inform small scale field tests (Chapter 4), that in turn inform modelling processes aimed at generalizable insights (Chapter 5) with the ultimate aim of better informing future PGI upscaling and implementation efforts by designers and adopters.

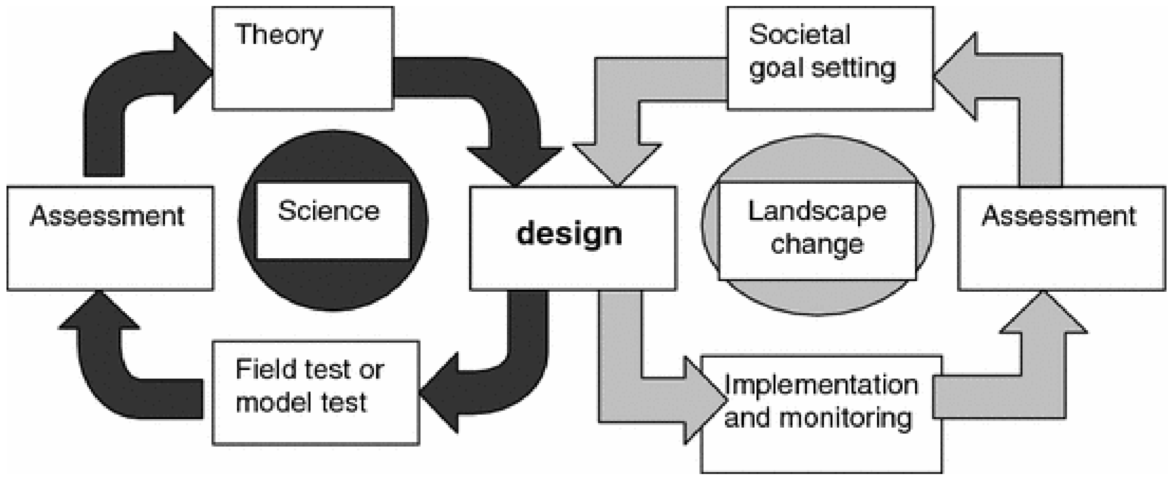

Figure 3. Design as a link between science and landscape change (Nassauer and Opdam 2008).

Also implied in DIS is the strategic alignment of various disciplinary lenses throughout this process, which in this dissertation required engagement with colleagues from civil engineering, planning, and urban hydrology disciplines. A deeper reflection on DIS and its role in the process of transdisciplinary research can be found in Chapter 7.

1.3 Key Terms

Megacity - Defined by the United Nations as urban agglomerations of 10 million or more inhabitants
Nallah - An open-air urban drainage channel, typical of many south Asian megacities.
DWF - Dry Weather Flow, also known as 'baseflow' comprised mainly of untreated or partially treated domestic wastewater
WWF - Wet Weather Flow, consisting of both wastewater and stormwater runoff from precipitation events
STP- Sewage treatment plant
Catchment - A distinct spatial territory (defined by both topography and conveyance networks) which drains to a single point, often flowing into a larger downstream receiving water such as a lake or river.
TP - Total Phosphorus, a key indicator of nutrient contamination, the overabundance of which leads to the eutrophication of waterbodies
Eutrophication - A process in which an excess of nutrients results in the rapid growth of plants and algae, causing oxygen depletion and other negative impacts to aquatic ecosystems
PGI- Provisional Green Infrastructure*. Proposed as a speculative innovation typology arising within the megacity context. Defined as "Informal nature-based retrofits to existing grey infrastructure networks by non-state actors for the purpose of improving water quality within highly unpredictable, space-constrained, and contaminated urban environments."

1.4 Dissertation Outline

This dissertation is divided into seven chapters. Chapters 2-5 are structured as independent academic papers, two of which have already been published or accepted for publication, with two undergoing the peer-review process as of the time of this submission (October 2021). The chapters build on one another in terms of complexity and depth, and are described briefly below.

Following this introductory chapter, in *Chapter 2: Provisional Green Infrastructure: Trans-disciplinary approaches to address contamination in urban streams* I along with my indian colleagues (addressing sub-questions 1 and 2) introduce the notion of PGI as a speculative innovation typology emerging from the Indian megacity context, and suggested ways in which this term might be useful in setting research agendas in this nascent domain of practice. We briefly outline five PGI case-studies from across the Indian subcontinent. For the first time in the discourse of SUWM, we propose the "in-stream" context as an incubator for GI innovation in the Global South. Importantly, we suggest how this context (defined by unpredictability, space-constraints, and acute levels of contamination) require different approaches to the conception and implementation of GI as compared to other contexts in the Global North. Finally we define two primary modes of upscaling as "organizational" upscaling (the broader diffusion and adoption of PGI approaches by various state and non-state actors) and "spatial" upscaling (the spatially explicit manner in which PGI interventions are deployed throughout an urban watershed catchment to maximize cumulative water quality benefits). This is largely a framework that sets a foundation for PGI research, and the cases are further explored in Chapter 3.

In *Chapter 3: Informal diffusion of Green Infrastructure innovations in Indian Megacities: Perspectives from innovators and potential future adopters,* we continue to interrogate sub-questions 1 and 2, and the topic of "organizational" upscaling by digging deeper into the networked communities of practice driving PGI innovation. We employ semi-structured interviews with individual practitioners and broader surveys of potential future adopters (PFA's) using the DOI framework to assess the alignments and misalignments of perceived innovation characteristics amongst these two levels of actors. Sub-questions 3 and 4 are addressed in *Chapter 4 Assessing performance of local substrates for treatment of dry weather flows in open drains: Results of a pilot study in Bangalore, India.* Herein we deploy a field-scale pilot study of a PGI intervention using live wastewater to assess various contaminant removal efficiencies over the course of 15 months. This study demonstrated the applicability of inexpensive, locally available aggregate substrates (gravel and terracotta rubble) in treating the highly variable DWF in open stormwater drains without the use of specialized or mechanical technology. This chapter is important to contextualize the potential and limitations of PGI as a provisional strategy.

In *Chapter 5: Assessing catchment-scale performance of in-stream Green Infrastructure interventions using SWMM-based TOPSIS* we build on Chapter 4 to address sub-question 5. The site-scale insights and data generated by our pilot study inform the development of a series of catchment-wide upscaling simulations in a rapidly urbanizing peri-urban region of Bangalore, India. Five alternative scenarios for upscaling of PGI throughout an urban catchment to address DWF conditions are assessed based on quantitative data reflecting cost, pollutant removal, and public access criteria. This study is intended to demonstrate how the integration of GIS, SWMM modelling and TOPSIS analysis can address various tradeoffs of design implementation, and therefore provide actionable insights for future diffusion and upscaling efforts in the context of Indian megacities.

In *Chapter 6: Final Conclusions and future research trajectories* a summary of key insights is provided. Further it is suggested how these methods and results contribute new knowledge to a) my own continued research and engagement in this domain b) the context of

PGI diffusion in Indian megacities, and c) the broader context of the Landscape Architecture discipline.

Finally, *Chapter 7: Coda: We're not "solving" wicked problems through design and science-is that ok?* presents a broader critical perspective, written in a more publicly accessible style, that interrogates the nature of transdisciplinary design and research itself, positing its epistemological (rather than solutionist) role in addressing "wicked challenges" in urban water management and beyond.

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Chapter 2: Provisional Green Infrastructure: Trans-disciplinary Approaches to Address Contamination in Urban Streams[1]

Abstract: Surface water contamination has emerged as an area of major concern in rapidly growing cities in the Global South, including and especially in the Indian megacity context. We argue here that nallahs (open drainage channels in Indian megacities) should be recognized as potential locus of intervention. These combined stormwater and wastewater networks offer opportunities for flexible, frugal and inclusive retrofits to improve surface and groundwater quality. We propose and define the concept of Provisional Green Infrastructure (PGI) as a *speculative innovation typology* describing in-stream interventions. We argue that PGI should be employed as a shared boundary concept guiding transdisciplinary action and research within the highly unpredictable, space-constrained, and contaminated watersheds. Citing case studies throughout the region and ongoing research in the city of Bangalore, we demonstrate in-stream modifications may be capable of achieving significant improvement in the quality of urban wastewater and may play a complementary role in closing persistent capacity gaps in the operation of both centralized and decentralized treatment practices within megacities. Anticipating the larger diffusion of PGI practices across the region by various early adopters and non-state actors, we suggest a cogent research agenda focused on identifying various

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generalizable “upscaling” opportunities for deploying in-stream interventions across various organizational and spatial domains.

2.1 Introduction

As the broader understanding of the impacts of urbanization on water regimes has increased, the focus of water management in cities has been shifting from water supply and flood protection, to pollution management, environmental protection, and climate change regulation (Brown, Keath, & Wong 2009). This shift has driven innovation in sustainable urban water management (SUWM) practices, and the emergence of various decentralized, nature-based, cost-effective practices commonly referred to (in the Global North) as low-impact development (LID), best management practices (BMP), and sustainable urban drainage systems (SuDS) (Benedict & MacMahon 2001; Mell 2010; Marlow et al. 2013). These practices are comprised of many individual tactics including bioretention cells, porous pavements, constructed wetlands, etc., and are associated with the wider definition of Green Infrastructure (GI) (EPA 2016, Wang & Banzhaf 2018;). To date, surprisingly little attention has been placed on how these principles and practices are being interpreted and advanced within the unique and challenging urban contexts of the Global South. We are therefore interested in understanding what it means to use the megacity as a location for alternative theory building, and theory testing, recognizing that these contexts may produce an entirely different set of approaches, agendas and outcomes for GI than those which have been advanced and pursued elsewhere.

The goal of this review is to establish a shared conceptual framework for ongoing transdisciplinary action and research within a particular domain: the open surface channels (often referred to as “nallahs”) through which both wastewater and stormwater commonly flow in megacities. PGI is defined here as: *"Informal nature-based retrofits to existing grey infrastructure networks by non-state actors for the purpose of improving water quality within highly unpredictable, space-constrained, and contaminated urban environments."* This typology is intended to be employed as a broad "boundary concept" for a range of in-stream interventions undertaken by non-state actors, primarily in the context of Indian megacities (although the concept may ultimately have broader application).

2.1.1 Contextualizing Urban Water Informality in Indian Megacities

With the recognition that the majority of future population growth is expected to be concentrated in the cities of the Global South, there is an increasing need to develop a coherent research agenda that recognizes megacities as a distinctive urban ecosystem, and considers the range of challenges and opportunities they contain (Bronger 1996; Bunnell & Harris 2012; Zhao et al. 2017). Megacities are a relatively recent global phenomena, and have been defined as urban agglomerations of over 10 Million inhabitants (UN 2015). As illustrated in Table 1, Indian megacities are driven by many overlapping informal processes, as well as localized regional and global phenomena which render them highly *unpredictable*, *space-constrained*, and acutely *contaminated*.

Table 1. Characterization of urban informality in Indian megacities

Characteristic	Description	Source
Unpredictable	Piecemeal patterns of unplanned land-settlement and land tenure leading to extreme disparity, fragmented land-use mosaic, and challenges to governability and steering capacity	(Kraas, 2007; Roy, 2005)

	Illegal, legal modes of urban and economic development arising mutually, becoming increasingly inextricable	(AlSayyad & Roy, 2003; Ranganathan, 2018)
	Tension between the state and local governance and planning	(Tortajada, 2016)
	Inefficient, poorly connected supply/conveyance networks, resulting in *Infrastructural disarray*	(Alley et al., 2018)
Space-constrained	High population growth from rural population and international migration	(Kraas, 2007)
	Open public spaces subject to informal occupation and settlement	(Kötter, 2004)
	Extreme land-development pressure, especially in peri-urban areas	(Ranganathan, 2018)
Acutely-contaminated	Rapid increases in impervious surfaces within the catchment due to development	(Ramachandra, Vinay, et al., 2016)
	Inefficient treatment from existing wastewater treatment facilities due to frequent power failures, poor maintenance and training	(Jamwal et al., 2015)
	Inadequate regulatory framework limiting the discharge of many contaminants into urban waterways	(Jamwal et al., 2016)
	Lack of enforcement of existing standards and laws (often exacerbated by corruption, bribery, cronyism, nepotism)	(Jamwal et al., 2016; Kraas, 2007; Tortajada, 2016)
	Lack of separation between stormwater and wastewater conveyance networks.	(Parkinson et al., 2007; Wescoat, 2019)

Growing demand on water resources, top-down capital investment often prioritizing water *supply* over *treatment*	(Tortajada, 2016)
Regular occurrence of dangerous anomalies within the network (eutrophication, fish kills, toxic foam, fire events)	(Benjamin et al., 1996; Jamwal, 2017; Jumbe et al., 2008; Ramachandra, Asulabha, et al., 2016)

The spatial, institutional, infrastructural and ecological conditions presented in Table 1 pose significant challenges to the development and implementation of conventional modes of GI. It is therefore important to recognize a range of novel forms, functions, and mechanisms of adoption for GI that emerge from (or are purpose built for) the unique conditions of the megacity context.

2.1.2 Nallahs as a site of investigation and intervention in PGI

In many cities in the Global South, the separation of sewers from surface drainage systems is relatively rare, even when they have been designed for functional separation (Parkinson, Tayler, & Mark 2007). Hydrologically, Indian megacities are widely characterized by a piecemeal water conveyance network comprised of remnant traces of ancient watercourses, legacies of colonial investment in development, and more contemporary drainage infrastructures comprised of informal connections and surface channels. These infrastructures are widely known throughout the subtropical monsoon environments of south Asia as “nallahs”--surface channels that often follow natural topographic gradients to convey both wastewater and stormwater through the city and outward toward its hinterlands (Parkinson, Tayler, and Mark 2007). Reflecting the distinctive spatial and hydrological regimes of monsoonal environments, this term was once used to designate a small stream, river, rivulet or ravine that is “sometimes dry, and sometimes wet” (Wescoat 2019). Yet since the mid-19th century (and arising in tandem with extensive and rapid urbanization) the term Nallah has carried a primarily negative connotation as a drain or sewer—synonymous with filth and widely regarded as a liability (Fig 4).

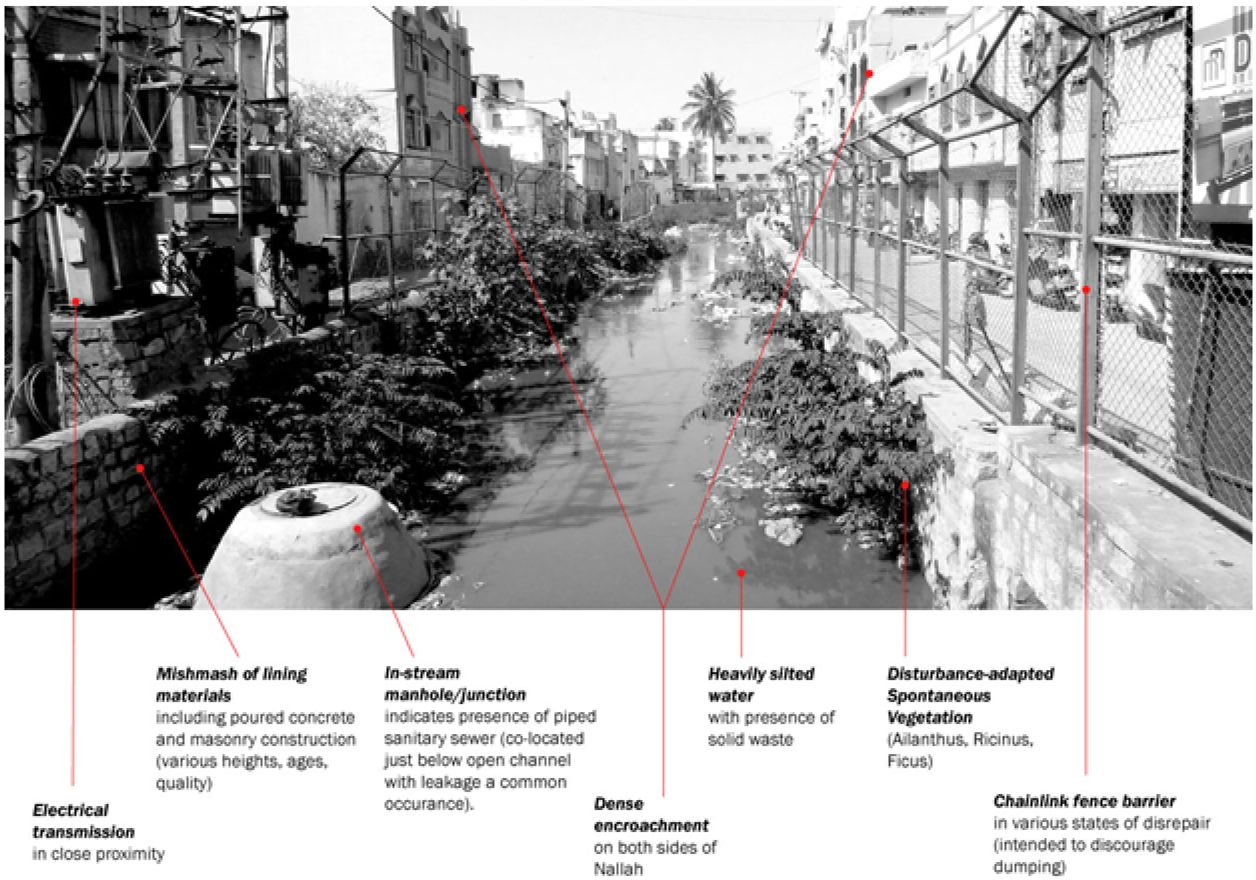
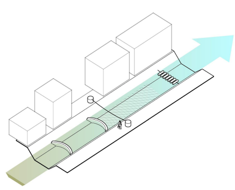
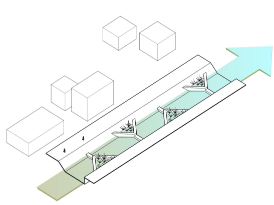
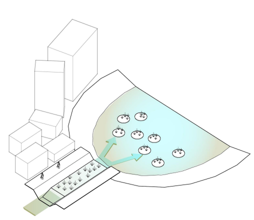
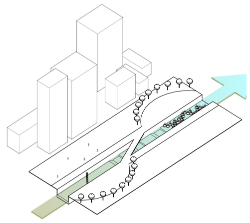
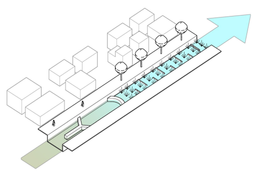


Figure 4. Identifying typical characteristics of a megacity Nallah (Shivaji Nagar Neighborhood, Bangalore) Photo/diagram: Daniel Phillips

Nallahs are arguably among the most highly complex, contested, and contaminated socio-ecological contexts on the planet, yet to date have not been extensively or explicitly explored as a territory for ecological design research (Wescoat 2019). Not only do these infrastructural networks offer a locus to observe the complex spatial relationships, hydrological flows and material metabolisms of the megacity, they represent a unique opportunity to imagine and propose alternative futures that challenge long standing norms of use, maintenance, and value. We argue the in-stream context should therefore be understood as an incubator for tactical experimentation and innovation in SUWM among a range of non-state actors, contributing to a typology of *Provisional Green Infrastructure (PGI)*. PGI describes innovations focused on adaptively retrofitting nallahs with flexible, purpose-built interventions that can be quickly and easily installed, modified, maintained or removed with minimal disturbance to the form and function of the underlying infrastructure into which they are placed. Table 2 identifies five case studies currently under development by various non-state actors across many regions in India.

Table 2. Selected PGI case studies from across urban India

Project		City	Initiator	Status
	**Assi Nadi Experiments**	Varanasi	Indian National Trust for Art and Cultural Heritage (INTACH)	Temporary pilot built
	**Green Bridges**	Udaipur	Shrishti Eco-Research Institute (SERI)	Multiple sites built
	**Hauz Khas Urban Wetland**	Delhi	Evolve Engineering	Local pilot built

	**Irla Nallah Re-invigoration**	Mumbai	PK Das & Associates	Stage 1 built
	**Strategic In-stream Systems**	Bangalore	Commonstudio, ATREE, Biome Trust	Field testing, design development

Ranging from simple in-stream modifications such as silt traps and constructed wetlands, to proposals for broader spatial transformation and greening such as tree planting, pedestrian considerations, and riparian interface design, these tactics are often informally initiated, developed, funded and demonstrated by non-state actors at small local scales(Bhatnagar, 2017; Das & Akhtar, 2018; Jamwal et al., 2019; Joshi, 2015). Although these tactical interventions are crucial in demonstrating initial proof-of-concept at an early stage in their development, the ultimate promise of these nascent practices arguably lies in their ability to be effectively upscaled and widely adopted. The next section will examine one of these cases in more depth, with a particular focus on the megacity of Bangalore.

2.1.3 Current trans-disciplinary research in Bangalore, India

Bangalore, India's fourth largest megacity by population (12.34 million), offers an ideal context to study the implications of PGI for promoting sustainable urban water management (SUWM). Bangalore currently generates approximately 1400 MLD (million liters per day (MLD) of wastewater and has a built capacity to treat 721 MLD (Ramachandra, Vinay, et al. 2016). However, the Bangalore Water Supply and Sewerage Board (BWSSB) estimates that only

520 MLD is actually treated (to a secondary treatment stage) before being released into surface waters as it moves downstream and outwards towards agricultural hinterlands. This lack of efficiency in existing sewage treatment plants (STP's) is due to poor construction and maintenance practices, frequent power failures, and the presence of raw industrial effluents in wastewater entering STP's (Jamwal et al. 2015). This leaves an average of 880 MLD of untreated wastewater flowing through the city daily ("Wastewater Treatment and Reuse | Urban Waters, Bengaluru" n.d.).

In Bangalore, as with many other South Asian megacities, conventional centralized approaches to wastewater management are proving inadequate to meet the demands of a highly modified, rapidly growing urban ecosystem (Jamwal et al. 2015; Ramachandra, Vinay, et al. 2016). The Bangalore Development Authority's (BDA) master plan for 2031 shows that even with planned STP upscaling in the future, nearly 378 (Million Liters Per Day (MLD) of untreated wastewater will continue to be released into surface waters throughout the city (BDA 2018). This suggests that despite these efforts by the state, the surface and groundwater quality in the region are likely to continue to decline if additional supplementary approaches are not implemented (Ramachandra, Vinay, et al. 2016).

Recent research conducted by our trans-national and transdisciplinary team in the megacity of Bangalore serves to demonstrate one of many possible approaches to PGI. Drawing upon ecological design, socio-economic, and urban hydrology perspectives, we are currently developing a PGI tactic referred to Strategic In-stream Systems (STRAINS). STRAINS is targeted at first and second order nallahs which contain primarily mixed effluents or grey water. (Figure 2). It is conceived as a modification to the existing channelized condition of nallahs and is comprised of three basic stages aimed at 1) diverting and collecting solid waste 2) slowing and settling sediment and suspended solids, and 3) lowering Biochemical Oxygen Demand (BOD5), and trace metals levels through biofiltration using locally available aggregate materials (Fig 5).

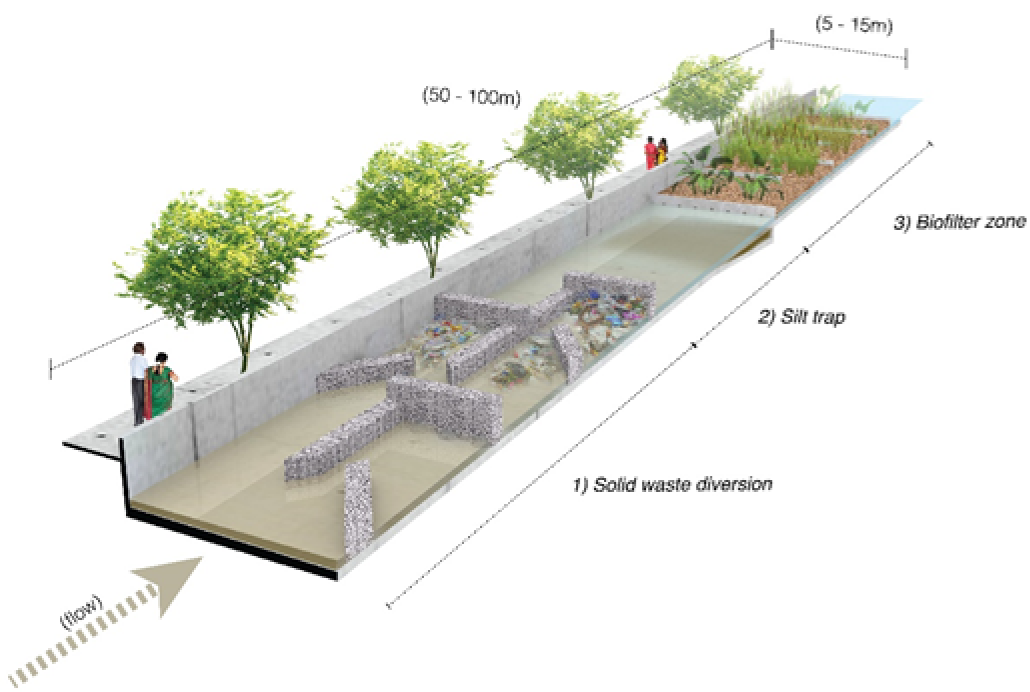


Figure 5. Schematic of Strategic In-stream Systems (STRAINS) intervention showing three stages of operation.

The development of this strategy to date has included iterative design, lab-based material performance testing using various aggregates and synthetic wastewater, physical hydrological modelling, city-wide suitability analysis, and relationship building with local partners. Our initial findings indicate that these systems may be capable of being deployed and scaled at a low cost with an immediate positive impact on localized water quality (Jamwal, Phillips, and Karlsrud 2019).

To further examine the performance characteristics of STRAINS, our team recently conceived and constructed a model nallah, measuring 2 x 2 x 8 Meters. The site of this semi-controlled experiment was chosen to represent a typical megacity context surrounded by dense residential and commercial land uses. The upstream catchment characteristics (Land use/Land cover, population density, imperviousness, etc) of this site will be analyzed to establish a predictable relationship between these factors and measured inflows of various contaminants for DWF conditions. Additionally this study will quantify the anticipated water quality performance and treatment efficiency of a typical PGI intervention under these real world conditions. Dividing this experimental setup into two independent treatment cells (side “A” and side “B”) allows a semi-controlled environment in which to assess the pair-wise performance of various materials and treatments (Figure 6).

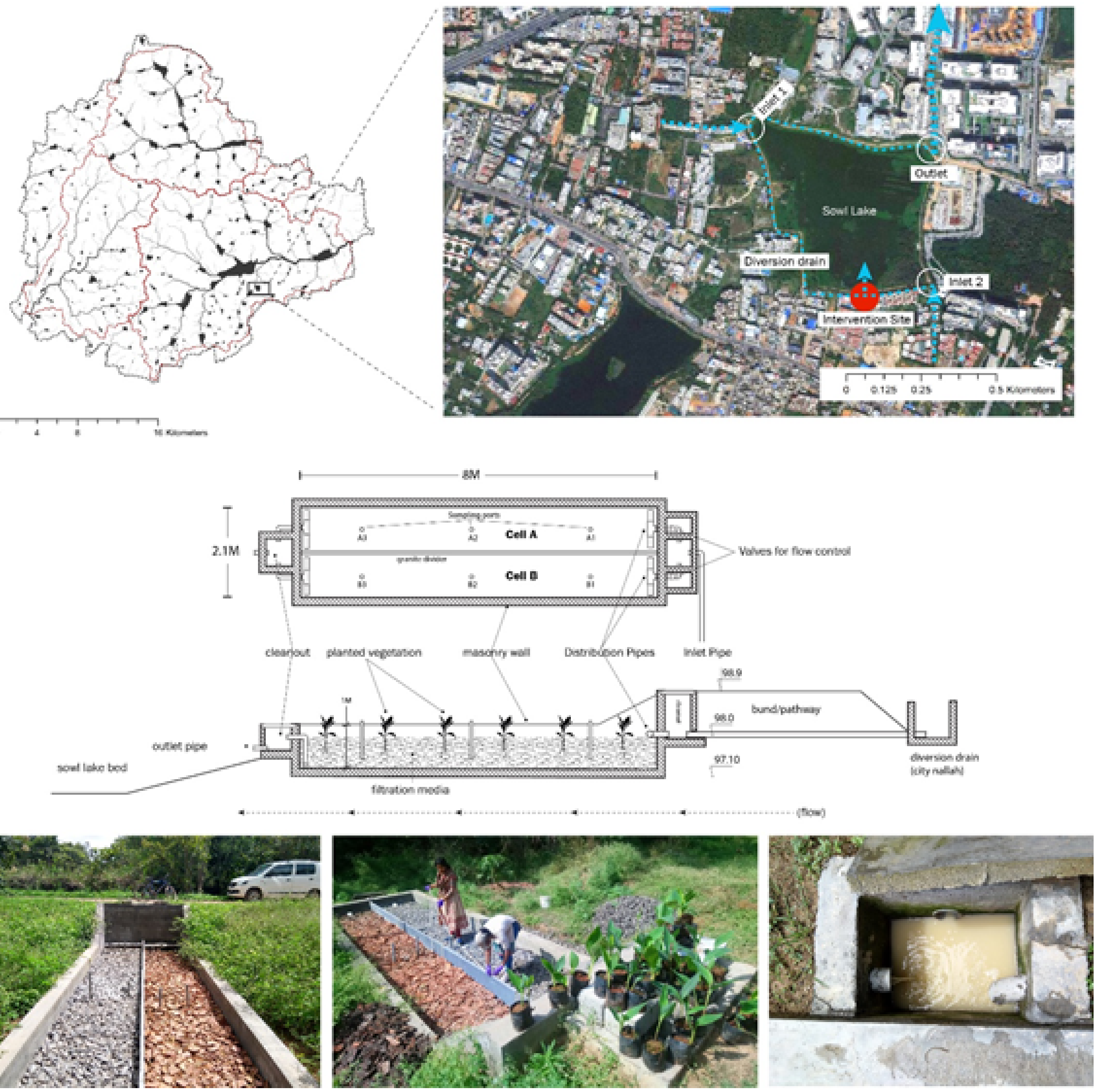


Figure 6. Field-based study at Sowl Lake
to evaluate and compare the performance of local materials in the decontamination of urban surface water in both planted and unplanted conditions. Diagrams: Daniel Phillips, Photos Ramya B.

The current configuration of the model nallah at Sowl lake compares the performance of terracotta rubble to granite gravel aggregate at a depth of 1 m, and vegetation was recently introduced into the system to assess planted vs. non-planted performance characteristics. A bi-monthly field campaign is currently being conducted to collect water samples from the inlet, mid point, and outlets of both sides of this system to assess contaminant removal kinetics of multiple water quality parameters, including reactive phosphorus (Ortho phosphorus), a contaminant of particular concern in Bangalore.

2.2 Identifying future challenges and research trajectories for PGI

Is PGI a viable strategy for improving watershed health and resilience in highly contaminated, rapidly growing South Asian megacities? If so, how, where, what types, and at what scales can PGI be most effective? As the performance of many PGI interventions are typically only evaluated at immediate temporal and spatial scales, it is argued that their local success does not necessarily suggest how or where PGI tactics should be replicated and upscaled over time throughout a larger spatial extent (throughout a catchment, watershed, or region) to maximize their multifunctional benefits. In the context of PGI we define "upscaling" as intentional efforts to increase the impact of interventions that have been successfully tested in local pilot projects, so as to maximize their benefits on a wider and lasting basis (WHO, 2009).

To address these vital questions, we propose two distinct, yet complementary modes of upscaling as 1) *organizational* upscaling, and 2) *spatial* upscaling. *Organizational* upscaling will apply to the processes of broader adoption and "*diffusion*" of novel PGI innovations between and across various types of actors and organizations (e.g. individuals and non-profits, civil society organizations, municipalities). *Spatial* upscaling, concerns how PGI interventions might be strategically deployed within a distinct geographic and hydrological context (sub-catchment, and catchment level) to achieve cumulative water quality benefits.

2.2.1 Organizational Upscaling

It is expected that many forms of PGI will be perceived as novel within the spatial, infrastructural and governance contexts in which they are being proposed, and may take years or decades to gain traction and achieve wider adoption (if at all). The fate, success and upscaling potential of PGI within the megacity context will be driven by many of the same factors which constrain other fields of social and technical innovation (Cels, de Jong, & Nauta 2012). What are the particular innovation characteristics that lead to successful adoption of PGI across various domains? Who is involved in the funding, installation, and maintenance of PGI interventions? It is therefore suggested that a coherent research agenda be developed to answer questions related to the broader diffusion and adoption of PGI approaches by various state and non-state actors. It should also focus on the challenges of long term funding mechanisms for routine maintenance and operation of PGI interventions over time.

This trajectory will likely draw upon the social sciences and employ qualitative research methods such as surveys, interviews, and in-depth case studies. The Diffusion of Innovations Theory (DOI) (Rogers 1962, 1995) is proposed as a possible empirical framework for this mode of research. Cross-case comparison should be exploratory rather than confirmatory, considering various interventions from a range of Indian megacity contexts to "build a typology or working classification of situations that can generate further, more precise research questions" (Deming & Swaffield 2010, page 81). Directly surveying and interviewing PGI innovators will allow insights into a range of unique processes, challenges, perceptions and aspirations that may not be commonly documented in publicly available materials and technical reports. This approach may also create a foundation for long-term longitudinal research, enabling the periodic assessment of successful (or unsuccessful) diffusion efforts over longer spans of time.

2.2.2 Spatial Upscaling

Spatial upscaling refers to the manner in which PGI interventions are deployed throughout a catchment to achieve cumulative water quality benefits while minimizing local risks such as flooding and associated health impacts. Emerging research in GI is beginning to address how variations in the spatial distribution and configuration of interventions influences various quantitative performance metrics (nutrient processing, reduction of peak flow behaviour, flood risk etc) (Jayasooriya 2014). This will require a multi-scale approach to spatial implementation, drawing on fields ranging from field hydrology, ecological design and urban planning, to computational modelling and remote sensing. The goal of this research trajectory should be focused on extrapolating the insights of small-scale localized studies across broader spatial domains. It should also focus on the challenge of flood risk during wet seasonal flow (WSF) conditions. To date there has been a conspicuous lack of inquiry and understanding of how various GI practices might achieve cumulative impacts at larger, or nested scales of an urban watershed catchment. (see Fig 7). Catchment-scale analysis in GI has been recently characterized by Golden and Hoghooghi (2018) an *emerging science*, and is poised to answer complex questions related to the upscaling of established and emerging approaches (including PGI).

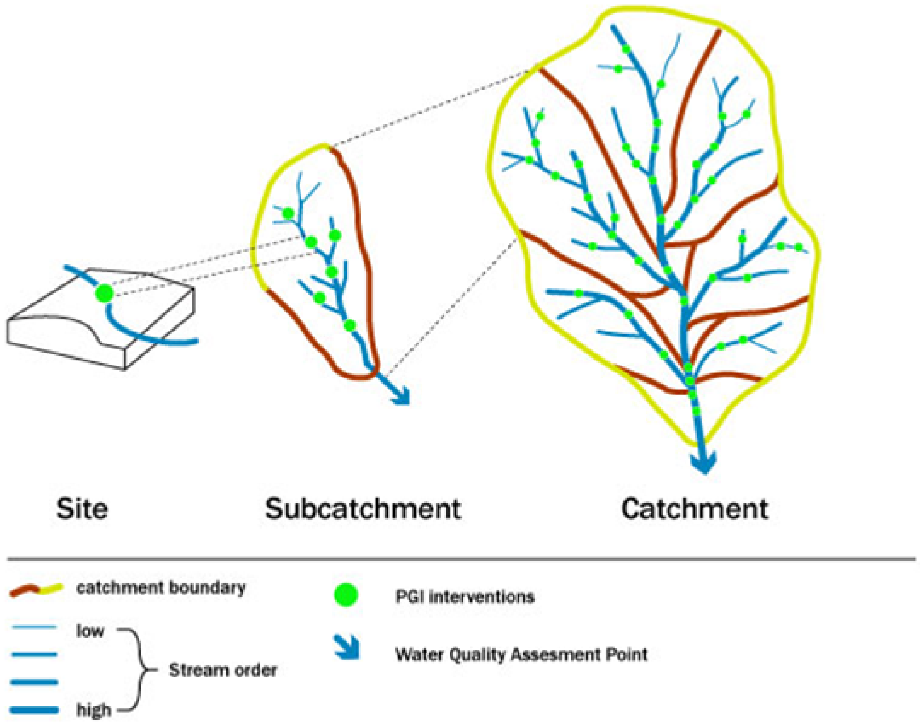


Figure 7. Conceptualizing the scaling effects of PGI interventions on downstream receiving waters from individual sites (left) to nested catchment scales (not to scale). Diagram by Daniel Phillips, adapted in part from Golden & Hoghooghi (2018).

Because the physical implementation of GI interventions throughout an entire catchment area is both time and cost-prohibitive, addressing critical questions related to upscaling necessitates the use of geospatial analysis, speculative design, and dynamic water quality modeling tools simultaneously and iteratively. Modeling software such as the U.S. EPA Stormwater Management Model (SWMM) can be used to rapidly simulate the probable effects of PGI interventions at multiple spatial scales (Rosa, Clausen, & Dietz 2015). Research efforts should focus on specific organic contaminants which contribute to the eutrophication of downstream receiving waters (such as total nitrogen and total phosphorus). Using locally calibrated data as inputs, hydrological modeling processes allow the rapid assessment of concentration and loading of these nutrients throughout a larger sub-catchment or catchment area under various upscaling scenarios. Upscaling scenarios should be informed by both biophysical and socio-cultural criteria as well as underlying policy assumptions within a targeted study area.

2.3 Conclusion

Focusing specifically on the in-stream context is an important but underexplored facet to the larger urban wastewater challenge in megacities and their peri-urban emerging towns and cities. PGI is suggested as a speculative innovation typology which can be employed to better understand various early-stage innovations which are emerging across South Asia, and opportunities for broader organizational and spatial upscaling efforts over time. We anticipate that the adoption of this typology by non-state practitioners and the research community will play an important role in achieving SUWM outcomes in megacities, while providing a shared framework for generating various modes of transdisciplinary insight. By focusing on the development of viable new typologies suitable for adoption in South Asian megacities, we believe that future research will contribute to the adaptive translation of GI practices to new spatial and cultural domains.

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Chapter 3: Informal diffusion of Green Infrastructure Innovations in Indian Megacities: Perspectives From Innovators and Potential Future Adopters[2]

Abstract: Five early-stage sustainable urban water management innovations in India are examined utilizing Diffusion of Innovations theory. Cases are described using grey literature, surveys, and qualitative insights derived from interviews with innovators (N=5). Potential future adopters (PFA's) were also surveyed (N=31), and their attitudes toward adoption is discussed. We identify alignments and misalignments between the goals, perceptions, adoption attitudes, and modes of communication between innovators and PFA's. Innovators and PFA's were largely aligned in their assessment of two innovation characteristics considered "most important" (namely *relative advantage* and *compatibility*), but not aligned regarding *simplicity* (rated "most important") or other "moderately important" to "less important" innovation characteristics (*trialability, observability,* and *reinvention*). We identify the role of communication channels between innovators and PFA's, and suggest that innovators might work to better emphasize the *simplicity* of their approaches to maximize the likelihood of adoption. Finally, we identify opportunities for future research in this under-studied domain.

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3.1 Introduction

The management of stormwater and wastewater is a critical challenge in urban sustainability. The increasing adoption of Green Stormwater Infrastructure (GSI) practices in cities emphasize decentralized nature-based approaches to supplement the inefficient operation of large-scale, centrally managed infrastructure such as pipes, drains, and wastewater treatment facilities (Benedict & MacMahon, 2001; Mell, 2010). Although a growing body of research has advanced the understanding and application of GSI in the context of the Global North, to date surprisingly little attention has been placed on how the principles and practices are developing within the unique and challenging urban contexts of the Global South.

Provisional Green Infrastructure (PGI) broadly defines an innovation typology emerging from Indian megacities, as "Informal nature-based retrofits to existing grey infrastructure networks by non-state actors for the purpose of improving water quality within highly unpredictable, space-constrained, and contaminated urban environments" (Phillips et al., 2020). The use of the term 'provisional' highlights the largely informal processes that influence the design and implementation of these interventions, as well as their relative novelty within the megacity context. Given the nascent status of these innovations, it is anticipated that many forms of PGI may take years or decades to gain traction and achieve wider adoption (if at all). The diffusion potential of PGI within the spatial, social, and organizational context of the megacity is likely driven by many of the same factors that constrain other fields of social and technical innovation, including developing a cogent public value proposition, and achieving legitimacy within a particular authorizing environment (Cels et al., 2012).

Diffusion processes of PGI can be understood as starting from localized scales (i.e.. demonstrations on individual sites) and growing to larger scales through adoption and replication by other actors (nonprofit and non-governmental organizations, municipal, state or national agencies). This places innovators in a dual position as innovators *and* early adopters. Yet with finite resources to sustain their efforts at the local level, innovators also promote their approaches for wider adoption by other actors who may be more well-resourced to bring these approaches to a larger or more lasting scale of implementation.

In an attempt to decouple the innovator as early adopter this study draws on direct insights from both PGI *innovators,* (i.e. those who conceive and implement novel approaches to sustainable urban water management (SUWM) at small or temporary scales), and *potential future adopters* (PFA's) (i.e. those who may be in a position to promote, fund, or implement these innovations at larger scales or on a lasting basis). This mixed-methods case-study of 5 PGI projects uses various case materials, a web-based survey, and semi-structured interviews with innovators. The research has three primary aims: 1) to identify relevant PGI case studies and the innovation characteristics that drive their development in Indian megacities; 2) to identify how innovators characterize and communicate with the targeted adopters for these innovations; and 3) to understand how perceptions of innovation characteristics impact attitudes of adoption amongst PFA's and the likely diffusion pathways that will guide the development of PGI in the future.

3.1.1 Diffusion of Innovations Framework

The Diffusion of Innovations (DOI) theory, originally proposed by Rogers (1962, 1995) is used as a framework for this study due to its well-established value in examining innovations at an early stage of development. DOI has four key elements: 1) the innovation, 2) communication, 3) time, and 4) social system (Rogers, 1962). In this context, *diffusion* is defined as "the process by which an *innovation* is *communicated* through certain channels over *time* among members of a *social system"(Rogers, 1995, p. 10)*. Traditionally DOI theory is employed to understand how new ideas, processes, and products diffuse and spread amongst individuals.

An *innovation* is defined as "an idea, thing, procedure, or system that is perceived to be new by whomever is adopting it" (Rogers, 2003, p. 10). Rogers defines five key characteristics of the innovation itself which influence its success and rate of adoption over time. These characteristics include *relative advantage, compatibility, simplicity, trialability and observability* (Table 3). Later, *reinvention* was proposed by other scholars as a sixth characteristic, defined as "the degree to which an innovation is changed or modified by a user in the process of its adoption and implementation" (Rogers, 1995, p. 17). This simple framework of innovation characteristics (Table 3) can be applied to a given innovation to assess the speed with which it might be diffused or upscaled. DOI theory states that as each of these characteristics increase, so too does the rate of adoption (with the exception of complexity, for which a decrease in complexity results in an increase in adoption). Several reviews of DOI theory and its application from across many disciplines have confirmed these characteristics show a strong correlation with the adoption rates of innovations, and predict (but do not necessarily guarantee) successful adoption (Greenhalgh et al., 2004). Yet the relative importance and interactions between these characteristics appears to be largely a domain-specific phenomena (Baptista, 1999).

More recently, the theory has been adapted for application of diffusion processes within and across organizations (Lundblad, 2003), and has been employed as a framework for research in numerous domains including agriculture, education, management, health care and public health, information technology, and sociology—amassing a significant body of research

(Baptista, 1999; Karakaya et al., 2014; Oldenburg & Glanz, 2008; Wejnert, 2002). It also has been applied to understanding the adoption of green infrastructure (GI) practices in the context of the global north. Carlet (2015) found evidence of strong direct and indirect influences of several innovation characteristics on adoption attitudes amongst local jurisdiction officials. Hamlin & Nielsen-Pincus (2020) used a modified framework for DOI to suggest the ways in which adoption of green infrastructure for flood risk management may be influenced by localized internal factors (ie. innovation by "lone-wolves") and regional factors (ie. adoption via "copy-cats").

Table 3. Innovation Characteristics according to (DOI) Theory (Rogers, 1962, 1995)

Theory Elements	Characteristics	Definitional questions
Innovation	Relative advantage	Will the project actually provide an advantage over the status quo for an identified group of adopters?
	Compatibility	Is the project compatible with its social and physical context, in both scale and scope?
	Simplicity	Can the project be easily understood by a wide segment of the population?
	Trialability	Can the project be tested easily? Can it be easily replicated elsewhere? Is the path to adoption clear and relatively hurdle free?
	Observability	Is the project going to be visible to many others? Will it attract use and attention?
	Reinvention	Can the project be easily modified and adapted by adopters to suit their needs?
Communication	Social Processes	Word of mouth
	Communication channels	Mass media, social media, journals, etc.
Time	Adopter Categories	Innovators, early adopters, early majority, late majority, laggards
	Rate of Adoption	S-shaped curve
	Organization Innovation-Decision Stages	Initiation, Implementation, Routinizing

Social System	Social Structure	Social relationships, networks of communication, norms
	People as influencers	Opinion leaders and Champions (internal to system), change agents (external to the system)
	Consequences	Desirable vs. undesirable, Direct vs. Indirect, Anticipated vs. unanticipated
	Decision making	Optional, Collective, Authority, Contingent
	Organizational structure	Centralization, Organizational complexity, Formality, Interconnectivity, Organizational slack, Size, Leadership, System Openness

While all elements of the abovementioned DOI framework are expected to influence the adoption of PGI, this study focuses primarily on the perception of the six innovation characteristics and secondarily on trans-organizational communication as critical considerations in the early stages of the innovation pipeline. DOI theory states that within any organization, continuous and successful adoption of a new innovation requires both *awareness* and *acceptance* by individual actors with positions of decision-making authority (Rogers, 2003). These individuals discover and evaluate a new idea, and based upon their evaluation, develop a negative or positive *attitude* toward it. DOI offers a viable tool to evaluate how perceptions, values and goals among various actors may be better aligned in the service of actively informing the trajectory of future PGI adoption efforts in the megacity context. It was expected that innovators and PFA's would differ significantly in their perceptions of the relative importance of innovation characteristics and that these differences would likely influence divergent adoption attitudes.

3.2 Materials & Methods

We examine five case-study projects from across the Indian subcontinent, all of which are currently being actively pursued by a range of non-state actors. Although the case-studies are geographically distributed, they share a common infrastructural intention—to transform the performance and perception of highly contaminated open drainage channels (known colloquially as “Nallahs”), through which both wastewater and stormwater commonly flow (Figure 8). These actions by innovators typically consist of simple in-situ interventions that intentionally introduce temporary physical structures, material substrates, bacterial cultures and vegetation into the context of an existing channel or stream to achieve measurable downstream water quality benefits. Using a mixed methods approach combining case studies, surveys and semi-structured interviews we examine how PGI innovators conceptualize and promote their innovations, as compared to the perceptions and attitudes of PFA’s.

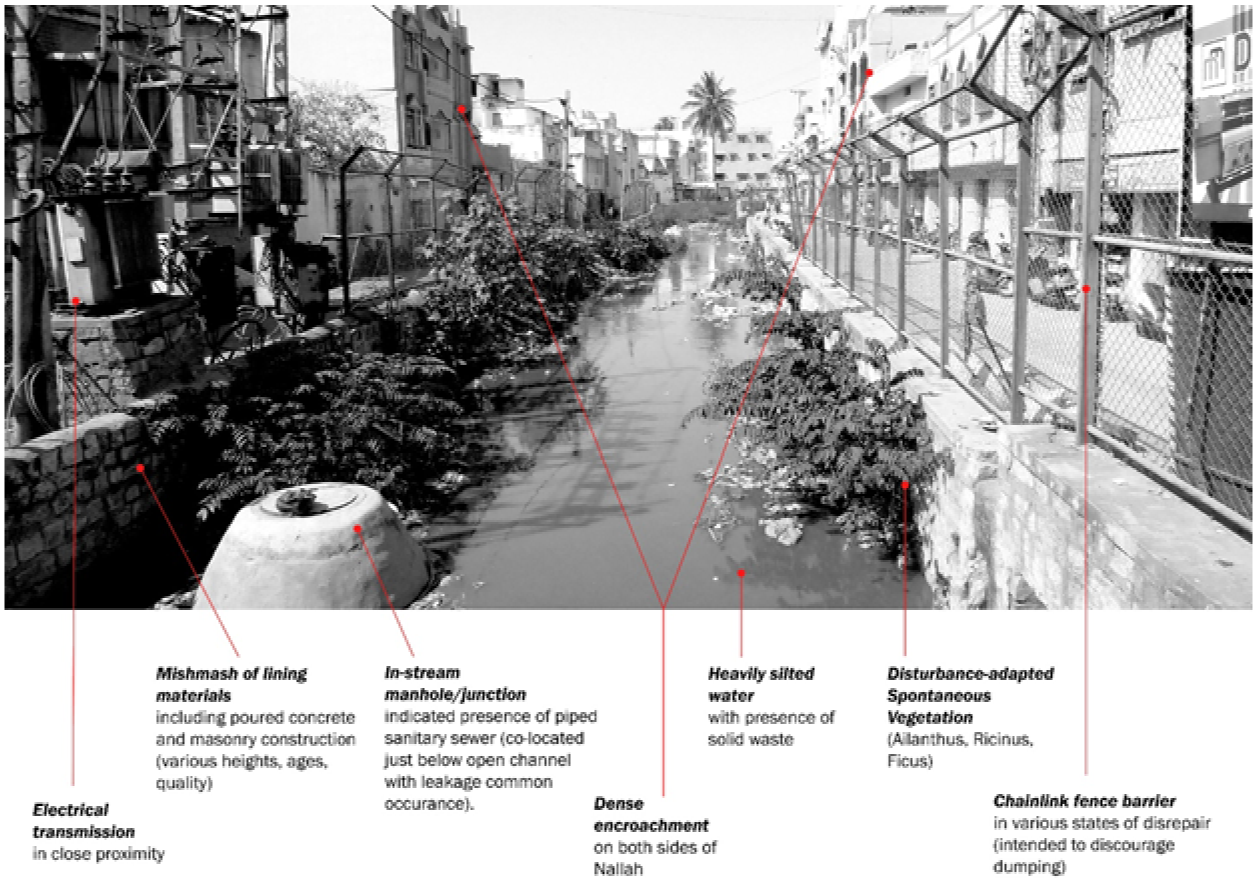

Figure 8. A typical nallah flowing through the densely populated neighborhood of Shivaji Nagar in Bangalore, India.
(Photo by the author)

3.2.1 Case Studies

Case-studies were identified using the authors' professional networks and an extensive review of grey literature and online sources. A brief summary of each is described below. A more extensive account of the context, form and function of the individual cases has also been detailed at length elsewhere by Phillips et al (2020). In summary, the five cases include the 1) Green Bridges Initiative (GBI), initiated by the Shrishti Eco-research Institute (SERI) in the city of Udaipur; 2) Strategic In-stream Systems (STRAINS), developed jointly by the Ashoka Trust for research in Ecology and Environment (ATREE) and Commonstudio in the city of Bangalore; 3) The Irla Nallah Reinvigoration Project (INRP) spearheaded by P.K. Das & Associates in the city of Mumbai; 4) the Hauz Khas Urban Wetland (HKUW), implemented by Evolve Engineering in the city of New Delhi; and 5) the Assi Nadi Experiments (ANE), undertaken by the Indian National Trust for Art and Cultural Heritage (INTACH) in the city of Varanasi. Figure 1 provides an illustration and schematic of each case-study project, with details for each provided below (see Appendix B, Figures 14-17, for more in-depth illustrations of cases):

- ***GBI*** typically consists of an alternating series of wedge-shaped in-stream treatment modules (composed of natural materials) arrayed along the length of an open channel or urban stream. The system is designed to increase retention time and bring contaminated water in contact with various filtration materials (including sand, coconut coir, soil and plants) and beneficial bacteria (Badal okays Buddha Nallah, 2010; D. Das, 2010; Green Bridge draws, 2011).

- ***STRAINS*** proposes a modular system comprising three basic stages for (1) diverting and collecting solid waste, (2) slowing and settling sediment and suspended solids, and (3) biofiltration using locally available aggregate materials and stress-tolerant aquatic plants (Jamwal et al., 2019). Proposed tree planting along the nallah provides social and ecological benefits.

- The goal of ***INRP*** is the creation of a 10 KM tree-lined, flood-free walkway along Irla Nallah in Mumbai (Amrita Nayak Dutta, 2014; P. K. Das & Akhtar, 2018). To date, a 1.5 km “phase one” section of the plan has been completed, which includes desilting, in-stream structures and near-stream improvements for pedestrian and bike access, which has led to an increase in local awareness about the health of the Irla, and a 20% increase in local property values (Lewis, 2013).

- ***HKUW*** consists of (1) a horizontal flow wetland condition within a 50 meter section of an upstream channel flowing into the lake (composed of sand, gravel, and plants), as well as (2) numerous 'floating island' remediation units (comprised of aquatic plants set within buoyant plastic frames) on the surface of the lake near the inlet (*Delhi, Let's Save Our Lakes | The Stories Of Change*, 2018; Three city lakes, 2011). The project allowed private individuals to sponsor a floating island for the project at a cost of 5,000 INR (66 USD).

- ***ANE*** undertook an 'acupunctural' approach along a 3.5 km section of the Assi nadi channel in Varanasi without investment in any permanently built structures (Bhatnagar, 2017). Instead, a series of informal structures were introduced into the waterways to intentionally disrupt the flow of water, debris and contaminants. This included the manual installation of temporary soil bag weirs for increasing retention time and settling out suspended solids, and the introduction of biofilter media and coconut coir logs coupled with beneficial bacterial dousing to accelerate the processes of organic decomposition (Figure 9).

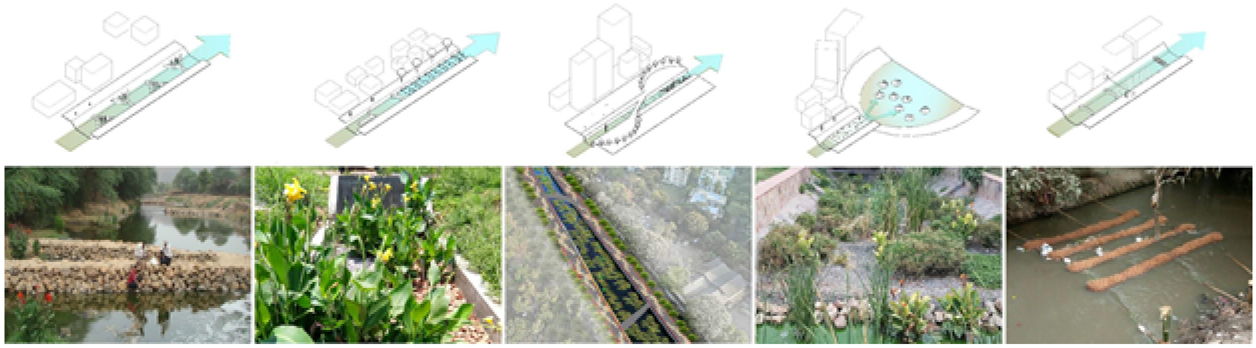

Figure 9. Five PGI case studies from across the Indian subcontinent
(from left to right) 1) Green Bridges Initiative (GBI) 2) Strategic In-stream Systems (STRAINS) 3) Irla Nallah Re-invigoration project (INRP), 4) Hauz Khas Urban Wetland (HKUW), and 5) Assi Nadi Experiments (ANE). See also Phillips et al (2020).

3.2.2 Web survey of PGI innovators

A preliminary 16 question innovators survey was administered online via web browser using Qualtrics (Qualtrics, Provo, Utah). The survey consisted of 1) basic introductory questions related to innovator demographics and organization type, 2) a series of single answer matrix tables and sorting exercises related to innovation characteristics and adopter characterization, and 3) multiple choice questions related to how innovators implement, monitor and disseminate their ideas. Out of a sampling frame of 5 organizations (representing each of the 5 case studies), 5 innovators from 5 organizations completed the survey, each from a primary leadership role. Two respondents were between the age of 35-44, and the remaining 3 respondents were divided among the 25-35, 45-54, and 55-64 age ranges respectively. Mean time to complete the survey was 21.6 minutes with a range of 6.6 to 65 minutes. Wherever applicable, multiple choice questions were designed with five-point likert type scales employing categories for evenly spaced linguistic separation (Munshi, 2014). A complete representation of the questionnaire design is available in Appendix A, Table 9. The study design for human subjects was approved by the institutional review board as exempt before being administered.

3.2.2 Semi-structured interviews with innovators

Following a preliminary web-based survey, PGI innovators were invited to participate in individual semi-structured interviews. The purpose of these interviews were to discuss their innovations and diffusion efforts informally in more depth, and reflect on the challenges they faced in the process of localized implementation efforts. One representative from each of the five case studies (the same individuals who completed the survey) agreed to be interviewed via Zoom, an online platform for virtual meetings that allows live video and audio to be recorded. These interviews, lasting between 43 and 92 minutes, were recorded after receiving verbal consent. Notes were also taken during the interviews. Audio recordings were transcribed for content analysis and organized according to the DOI framework. In addition to interview transcripts and memos, relevant insights on the nature of the projects were derived from various materials provided by the respondents or accessed via organizational websites, news publications, or social media presence. Interview subjects are anonymized in this study and referred to without identifying information (R1-R5). A complete representation of the web survey and semi-structured interview design is available in Appendix A, Table 10.

3.2.3 Web Survey of potential future adopters (PFA's)

In this study PFA's are defined as individuals currently working in India to promote or implement urban watershed interventions at any scale, including municipal decision makers, water experts, private sector actors, and representatives from non-governmental or civil society organizations. PFA's were identified via institutional or municipal websites and recruited using blogs and social media platforms. This survey consisted of 22 questions and was also administered online via web browser using Qualtrics (Qualtrics, Provo, Utah). A total of 68 respondents participated in the survey, with a total of 31 fully completing it. Ages of respondents were 25-34 (29%), 35-44 (25%), 45-54 (21%), 55-64 (21%), with 2% over the age of 65. 37% were from engineering disciplines, 12% from architecture and planning, 27% from water policy or research, governance (10%), local advocacy (4%), maintenance (2%), and "other" (10%). "Other" responses included combinations of the above-mentioned categories (IE "Engineering and governance"), or respondents identifying with public health and wildlife conservation fields. Mean time to complete the survey was 19 minutes with a range of 4.6 to 89.2 minutes. The survey was divided into four parts consisting of 1) questions related to PFA's demographic, organization, and expertise, 2) an introduction to PGI, including a brief overview of PGI case studies (see Appendix B), coupled with simple binary (yes/no) questions related to their existing familiarity with them, 3) a series of single answer matrix tables and sorting exercises related to innovation characteristics, perceived adoption readiness and communication. Wherever applicable, multiple choice questions were designed with five point Likert type scales employing categories for evenly spaced linguistic separation (Munshi, 2014). A complete representation of the questionnaire design is available in Appendix A, Table 11.

3.3 Results & Discussion

3.3.1 Perceptions of Innovation Characteristics

Survey and interview results are discussed below according to the DOI framework. Regarding the relationship between various innovation characteristics, innovators rated their current innovations highest in terms of *observability* and *reinvention* (Table 4). In their assessment of the same PGI case studies, PFA's rated *relative advantage*, *compatibility*, and *reinvention* highest. Innovators and PFA's perception appeared to be most aligned for the characteristics *relative advantage* and *compatibility*, whereas PFA's rated characteristics *simplicity, trialability*, *observability* and *reinvention* (Figure 10, Table 4).

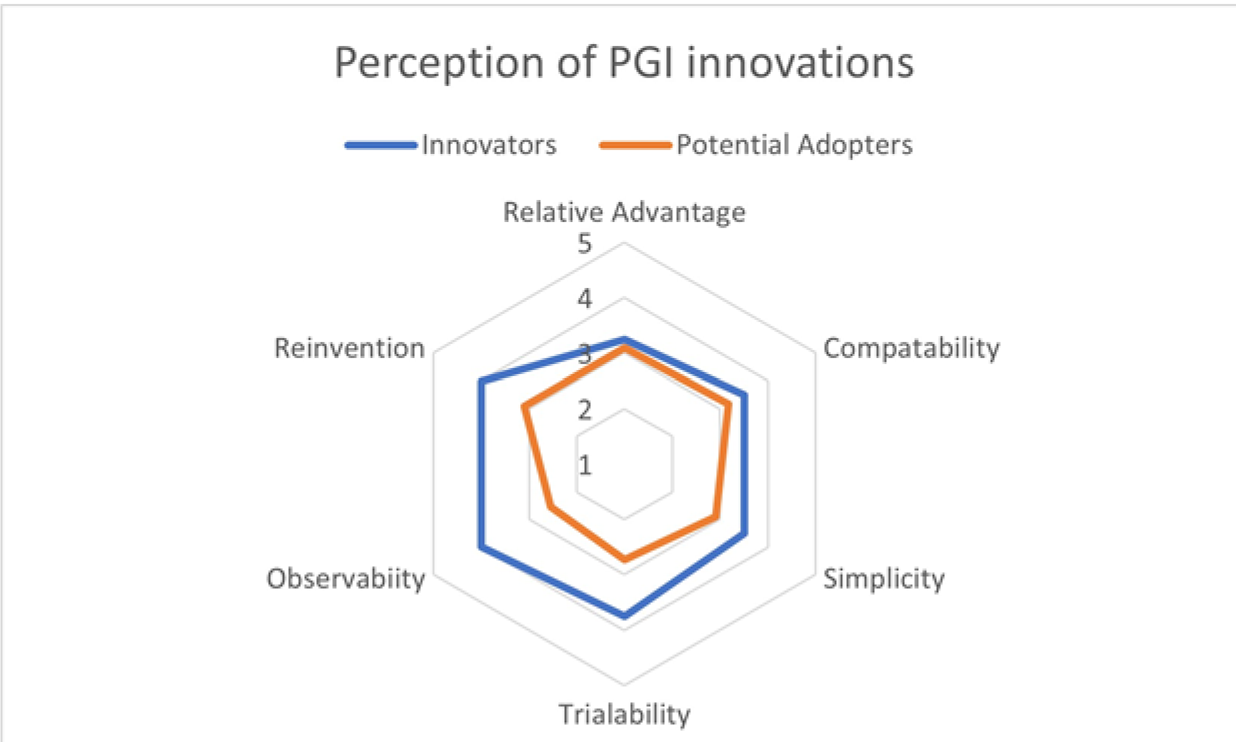

Figure 10. Comparative perceptions of DOI characteristics for existing PGI innovations according to innovators (N=5) and PFA's (N=31). Higher mean likert scores (larger radius) indicate higher degree of agreement that a given characteristic is present in the case studies presented in the survey.

Table 4. Comparative perceptions of DOI characteristics for existing PGI innovations according to innovators (N=5) and PFA's (N=31).

	Innovators		**Potential Future Adopters**		
	Mean*	SD	Mean*	SD	Coef. of Var.
Relative Advantage[1]	3.25	0.83	3.09	0.81	-0.16

Compatibility[2]	3.5	0.50	3.18	0.73	-0.32
Simplicity[3]	3.5	0.87	2.91	0.86	-0.59
Trialability[4]	3.75	0.43	2.73	0.88	-1.02
Observability[5]	4	0.00	2.55	1.01	-1.45
Reinvention[6]	4	0.00	3.09	0.81	0.91

*Likert scale (5=”strongly agree >1=”strongly disagree”)
“To what extent do you agree or disagree with the following statements as they relate to this/these PGI innovation?”
[1]*Relative Advantage: “It provides more/different benefits than other available approaches”*
[2]*Compatibility: “It fits/seem to fit well with the existing context”*
[3]*Simplicity: “It is/seems simple to install, and maintain”*
[4]*Trialability: “It seems it/can be quickly tested and evaluated”*
[5]*Observability: “It is/seems highly visible to many people”*
[6]*Reinvention: “It seems it/can be easily modified and replicated elsewhere”*

These results suggest that innovators and PFA’s may disagree about several key innovation characteristics as they relate to currently available PGI strategies, with innovators tending to consider their own projects to be more simple, triable, observable, and re-inventable than PFA’s. Survey results suggest broad alignment with previous studies in other global contexts suggesting that GI’s functional benefits and perceived ease of use are primary drivers of positive attitudes toward adoption (Carlet, 2015; Venkataramanan et al., 2020). When framed in more general terms (not explicitly related to existing PGI cases), PFA’s rated *simplicity* as the “most important” and *observability* as the “least important” characteristics impacting their future willingness to adopt. Among innovators, *compatibility* was rated “most important” in the future success of their initiatives and *observability* as the “least important”. Figure 11 compares the results of characteristics considered “most important” by innovators and PFA’s, Despite the apparent alignment in perceptions of *observability as* least important, the above results suggest that the relative importance and perception of many innovation characteristics differ between innovators and PFA’s. However, as many of these innovation characteristics are only broadly defined under DOI theory, it is important to understand how practitioners conceptualize them in the context of their current projects. These results are discussed further below in relation to qualitative insights from semi-structured interviews with innovators and a broader discussion on the future diffusion and adoption of PGI interventions in the context of Indian megacities (Fig. 11, Table 5).

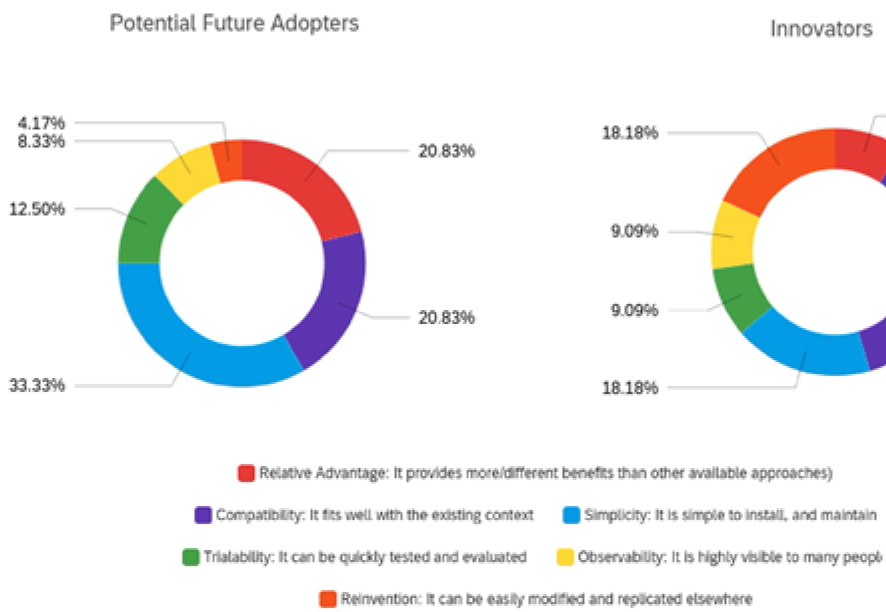

Figure 11. Innovation characteristics considered "most important" to the future adoption or diffusion of PGI in Indian megacities amongst innovators (N=5) and Potential Future Adopters (N=31).

Table 5. Selected excerpts of semi-structured interviews of PGI innovators (N=5) arranged by thematic category

Innovation Characteristics	Theme with selected quotes
Relative Advantage	"Some officials take offense that we're doing a better job than they are...Sometimes we point out mistakes that are being made by the authorities, which they don't like" (R1)
	"Even with a team of just two engineers, we're still doing better than these huge institutions that have huge teams and huge budgets" (R1)

	"We have a very low cost factor… and much quicker time…if I'm given all the wherewithal I can start work on a drain in two weeks whereas [building an STP can take years]." (R2) "Our process is like first aid...a stop-gap solution until [the local authorities] can get their house in order...we are not competing with you" (R2) "We can clean this incredibly polluted waterbody and bring it back to some form of its former glory, and also enable public spaces around it." (R4) "It is flexible and can be scaled up… it does not consume any area in the lakes... we are breaking up [treatment capacity] into smaller parts throughout the catchment." (R5)
Compatibility	"Every site, every drain is different, we need to think of it ecologically... so we need to collaborate with these ecosystems" (R3) "Local material is easily acceptable to local ecosystems, if you import materials from outside the ecosystem, it won't be easily accepted." (R3) "One of the reasons we looked at the nallah as an incredibly high-impact project was because of its scalability… There are 300 KM of nallahs in the city...here is the model we've followed, now take it up!" (R4)
Simplicity	"People see it and they think it's simple, but actually a lot of engineering goes into this kind of work, and many things have to be correct for it to work properly." "We do this all without the need for permanent structures or added concrete!" (R3) "Our system bridges traditional knowledge with modern day knowledge" (R3) "Local material is easily acceptable to local ecosystems, if you import materials from outside the ecosystem, it won't be easily accepted." (R3)
Trialability	"If we can show [impact] at a nallah that is feeding the Ganga [Ganges] then it can be replicated on so many drains and in so many cities, and in a short span of time, we can rid the Ganga of its pollution problems" (R2) "We are an NGO, we have very limited funds, this was only a demonstration" (R2) "If you want something to get done, you do it with your own funding. If you wait for the government to provide funding, your enthusiasm will be lost." (R3)
Observability	"If you have cleaner water you have fewer pathogens, fewer disease vectors, eliminated foul smells." (R2) "Birds are coming back, less fish are dying, there's no smell" (R1) "Property values [in adjacent areas] are increasing" (R2) "At first they're against it...But gradually as they get results, they gain confidence" (R3)
Reinvention	"This is an open system. There is nothing to hide" (R3) "Lots of people copy us...and do a bad job… if we're involved, the budget will be reasonable, the time will be short." (R1)

Relative Advantage (RA)

Relative advantage (RA) refers to whether a new innovation possesses a clear, unambiguous advantage in terms of effectiveness (or cost-effectiveness) as compared to other available options (Rogers, 1995). Within DOI studies, RA is widely considered a foundational innovation characteristic, described as a *sine qua non* for adoption (Greenhalgh et al., 2004). While this characteristic was rated lower in innovators self-assessment, PGI innovators clearly recognize the value of RA, with many respondents contrasting their approaches to existing technologies such as conventional wastewater treatment plants. A common theme echoed by many PGI innovators is the claim that their interventions achieve significant in-situ improvement in various water quality parameters while requiring a fraction of the capital investment that would be spent towards conventional alternatives. However, it is important to note that PGI is not promoted as a *replacement* to conventional SUWM approaches, but rather as a *supplementary* or stop-gap measure. One respondent noted that "Our process is like first aid...a stop-gap solution until [the local authorities] can get their house in order...we are not competing with them" (R2).

However, the ability for PGI innovations to work in tandem with conventional approaches does not appear to be mutually understood between the various actors involved in PGI implementation. "Some officials take offense that we're doing a better job than they are...Sometimes we point out mistakes that are being made by the authorities, which they don't like" (R1). This underscores the oftentimes adversarial relationship that exists between non-state actors (who occupy the dual role as innovators and early-adopters of PGI) and the official agencies that are often identified as targeted adopters. These tensions may indicate barriers for wider diffusion of PGI in the future, and opportunities for reframing the role of these innovations more clearly to potential adopters at the municipal level.

Compatibility

A majority of innovators rated *compatibility* as among the "most important" characteristics in the future success of their PGI innovation, and survey results from PFA's suggest agreement with innovators regarding the high level of compatibility with existing infrastructure when assessing the cases included in this study. This characteristic was often discussed by interview respondents in terms of functional flexibility, or the capability for interventions to accommodate a range of unpredictable site conditions in the field through re-sizing. In contrast to conventional end of pipe infrastructures such as WWTP's that have a fixed operational capacity, PGI interventions can be resized as needed at the site scale, or altered over time as conditions or funding availability changes. Sites of intervention for PGI ranged from highly modified and concretized drainage channels flowing through densely encroached urban centers (in the case of ANE INRP, STRAINS, HKUW), to naturally occurring watercourses with un-modified embankments in a peri-urban context (in the case of GBI). Respondents reported nallah width dimensions ranging from 2M (6') to 20M (65.6'). "Every site, every drain is different, we need to think of it ecologically... so we need to collaborate with these ecosystems" (R3).

Simplicity

PFA's rated *simplicity* as the most important factor impacting their willingness to adopt PGI in the future. Innovators discussed *simplicity* in terms of their ease of installation, maintenance and operation as compared to conventional grey infrastructure approaches such as large-scale wastewater treatment plants or other decentralized source controls. “Our system bridges traditional knowledge with modern day knowledge” (R3). Yet another respondent noted that “People see it and they think it’s simple, but actually a lot of engineering goes into this kind of work, and many things have to be correct for it to work properly.” (R1). Others noted that the smaller scale of PGI interventions enable them to be maintained by local laborers and community partners without the need for extensive training and expertise, leading to wider sense of shared ownership in the daily maintenance and operations:

> “The basic orientation was that the villagers should have ownership of this project. They should feel that we need to maintain it because we are getting the benefits out of it. If [someone else] is maintaining it they won’t look at it as frequently, they won't look at the [nallah], and won’t take care of the [nallah]. Every natural system requires care” (R3).

Simplicity also appears to drive many design considerations in PGI, with some innovators citing a preference for the use of locally available materials and natural processes as opposed to that which require energy intensive mechanical processes or advanced technology. Considering the importance of this characteristic to PFA’s, the successful diffusion of future PGI interventions will likely rely on strategies that are relatively simple to explain, install, and maintain.

Trialability

In this study, trialability refers primarily to the establishment of pilot scale interventions that demonstrate *proof of concept* at critical early stages in the innovation process. This allows innovators to engage in the performance testing of various design parameters before committing to a full-scale rollout. These pilot interventions are often funded entirely by the innovators themselves and often outside the purview of official sanction; “If you want something to get done, you do it with your own funding. If you wait for the government to provide funding, your enthusiasm will be lost" (R3). While these pilots operate at small scales by necessity, there is clearly a focus on larger adoption and diffusion in the future; "If we can show [impact] at a nallah that is feeding the Ganga [Ganges] then it can be replicated on so many drains and in so many cities, and in a short span of time, we can rid the Ganga of its pollution problems" (R2).

Demonstrating the positive impacts on in-stream and downstream health to local communities and decision-makers is the primary focus of pilot scale interventions. For this reason, the characteristic of trialability in PGI also encompasses a process of post-implementation water quality monitoring (Table 5). Contaminants of highest concern among innovators included physical parameters such as total suspended solids (TSS) and solid waste, nutrient pollutants such as Nitrogen (N) and Phosphorus (P), as well as qualitative measures such as smell and wildlife bioindicators. Despite recognizing the utility of *trialability* as a key driver of success for the future of their innovations, these non-state actors often find their resources strained once an intervention has been built, and struggle to find funding support for ongoing monitoring and research efforts that might help bolster the case for diffusion to state-level decision-makers and adopters. "We are an NGO, we have very limited funds, this was only a demonstration" (R2).

Observability

Given their placement in highly populated urban environments, PGI interventions are often subject to a high level of public visibility and scrutiny at the earliest stages of their development. When discussing the characteristic of observability, innovators often pointed to the positive qualitative effects that result from improved water quality in the nallah or from improvements to the spatial and ecological conditions surrounding urban context. Examples cited include the reduction in foul odors emanating from the nallah, the return of aquatic and avian biodiversity; “Birds are coming back, less fish are dying, there’s no smell” (R1).

One respondent emphasized the importance of *observability* as a means of gaining public approval for projects that may initially be met with local resistance from residents and decision makers; “At first they’re against it...But gradually as they get results, they gain confidence” (R3). Additional ancillary impacts that were observable included increased shelf-life for vegetables and fish harvested from adjacent agricultural land and downstream lakes. One respondent recalled that shortly after installing a full scale PGI intervention, that cattle once again began drinking from the water downstream, noting that “They didn’t need a laboratory certification that proved they could” (R3). Several innovators also noted that improving the social, ecological and spatial conditions of the nallah even resulted in increased property values in the adjacent neighborhoods by up to 20 percent.

However, the characteristic of *observability* in this context also presents a double-edged challenge: with the rewards of observable success on the one hand, and the risks of observable failure on the other. Even those interventions that are initially successful on a trial basis can quickly deteriorate if proper maintenance, management, and community engagement is not sustained, which could result in a decline in public faith in these efforts. “There is so much uncertainty around what to expect, that everyone fears to invest” (R5).

Despite these anecdotal accounts focusing on the role of *observability* in the demonstration of value and performance to the public, survey results show that innovators and PFA’s both rate this characteristic with lower importance than other factors, with 41.6% of PFA’s and 66% of innovators rating this characteristic as "least important". This is further emphasized when PFA's were asked to weigh this characteristic in relation to the performance criteria of cost and water quality improvement (Table 6).

Table 6. PFA's were asked "How would you weight the importance of the following criteria regarding the implementation of stormwater/wastewater infrastructure (note that values must sum to 100)"

	Min	Max	Mean	SD	N
"Cost of installation + maintenance"	25%	65%	40%	11.18	31
"Water quality improvement"	10%	60%	36%	12.03	31
"Enhancement of urban context (Visual, spatial, etc)"	10%	50%	24%	11.04	31

Reinvention

Reinvention concerns the degree to which potential adopters can refine, adapt or modify the innovation to suit their needs (Hays, 1996; Rogers, 1995). Regarding the future diffusion of PGI, we expect reinvention processes may entail an iterative process of implementation by which micro or macro level actors adopt individual components or alter PGI design principles over time. This process assumes that innovators have a desire to share knowledge and expertise across organizational boundaries, and a willingness for continued evolution that occurs outside their explicit purview and control. Survey results suggest that existing PGI practices are highly ranked for this characteristic among both innovators and PFA's. However, it was found that none of the PGI innovations are explicitly open-source in their approach to diffusion, and interviews suggest a more complicated set of conditions regarding the potential for reinvention may be at play.

One respondent suggested that reinvention was encouraged, stating "This is an open system. There is nothing to hide" (R3), while others appear to be more proprietary over their innovations, "We don't tell the authorities any more technically than they need to know" (R1). This may be driven by both the protection of hard-won insights, and the assurance of quality control "Lots of people copy us...and do a bad job...if we're involved, the budget will be reasonable, the time will be short." (R1). This suggests that the process of reinvention between other non-state actors or organizations of a similar size may not be uniformly desired or encouraged amongst PGI innovators at present. It also suggests a level of implicit competition between non-state actors as they attempt to develop a successful (and scalable) approach that will eventually "catch-on" and be adopted on a wider basis at a city or national scale by macro-level actors. In PGI the process of reinvention may be largely an internal process engaged in by the innovators themselves as they iterate and improve on their designs. These issues will be further addressed in the next section examining adopter characterization.

3.3.2 Adopter Characterization

As this study occurs at an early stage of a diffusion process of PGI, it is important to understand how innovators characterize the targeted adopters for future PGI interventions and diffusion efforts. Rather than a top-down diffusion process (e.g. large entities as the source of innovations, and individuals as the target adopters), PGI diffusion will necessarily occur from the bottom up (from small networks of non-state actors up to the municipal, regional, or national scales).

PGI innovators identified local municipalities as the primary adopter for future interventions (rating highest for involvement in the funding, building and maintenance). For funding, respondents also recognize the involvement of the private sector (in the form of corporate social responsibility, CSR) as well as funding from national and state government sources. For the building and maintenance of future interventions, innovators suggest moderate levels of involvement amongst civil society organizations, public private partnerships (PPP) and individuals.

> "The most feasible way forward is that the city has to take ownership over these spaces. It is incredibly naive to think that a movement of this intensity can be sustained through every neighborhood in the city given the investment of time and resources by [ourselves and our partners]." (R4)

Yet as mentioned above regarding *reinvention*, some PGI innovators suggest a desire to retain some oversight in the process of diffusion efforts across broader spatial and organizational extents, even as macro-level actors become increasingly involved. Several innovators cited frustration with their experiences with local decision makers who actively resisted their work, and even suggested that municipal actors may be invested in the perpetuation of problems rather than focused on their solution (Richa Pinto, 2017). 'The city would much rather spend money every month *not* fixing the problem than fixing the problem" (R1).

Without exception, all respondents mentioned the role of ineffective bureaucracies and corruption as a major impediment to the implementation of alternative approaches to any form of SUWM in Indian megacities. This observation is consistent with evidence from the economic development literature showing that corruption has a significant negative effect on innovation writ large, producing a “sanding-the-wheels” phenomenon (Lee et al., 2020). “India suffers because the money that should be spent on infrastructure actually goes into the pockets of [corrupt] people” (R1).

Other respondents also highlighted the lack of disciplinary perspectives at the municipal level, noting that the structure of many city planning bureaucracies is heavily skewed towards an “engineering mindset” regarding urban hydrology and infrastructure that leads to a “complete lack of passion” (R2). “In a sense our city is regressive, because we don’t have designers and planners in key decision-making positions” (R4).

These observations align with broader challenges to diffusion green infrastructure in other contexts globally, namely the role of politics and the need for coherent design standards aligned to specific contexts (Zuniga-Teran et al., 2020). In addition to innovation characteristics that impact individual attitudes toward adoption, diffusion and adoption processes are also highly influenced by the broader organizational norms of the social systems involved in the process, impacting their internal readiness for adoption (Rogers, 2003). Results of this study suggest that the target adopters identified by innovators may not ultimately be the most feasible targets due to their hierarchical structure, lack of internal readiness and high levels of corruption. In contrast, we found positive attitudes toward PGI approaches among a range of non-municipal and non-governmental actors, and suggest that such organizations may prove to be more receptive for future targeting efforts by innovators.

3.3.3 Communication

Communication in this study refers to communications made by innovators with the public, and across organizations. This is an important consideration as a lack of awareness of available alternative approaches among potential adopters has been previously identified as a significant barrier to adoption of GI in other contexts (O'Donnell et al., 2017). In this study, innovators emphasized the importance of social media and peer reviewed journal publications as their primary modes of communication. One innovator expanded on the relevance of social media, noting that "Technical reports don't really reach the public… Social media is essential if you're doing a citizen-led scheme" (R1). While another mentioned the need to leverage local media channels to increase public visibility, "We have identified journalists and reporters who are passionate about public space projects...we pitch certain stories to them that they print" (R4). The DOI literature identifies this phenomena as a primary effect of media exposure, whereby information about a given innovation is disseminated directly to potential adopters, thus acting as a major channel for diffusion processes (Rogers & Shoemaker, 1971; Wejnert, 2002). While 'word of mouth' was rated lower in innovator survey responses, one innovator alluded to its importance during the interview process, noting that "It's a constant interaction and engagement...there's not a time where you switch off. Even in your social gatherings and your informal meetings you're talking to people about these projects." (R4). PFA's survey responses suggest a preference for social media (24.3%) and peer reviewed journal publications (29.4%) and further suggest that a higher degree of familiarity with PGI innovations that currently have social media presence (Figure 12, Table 7).

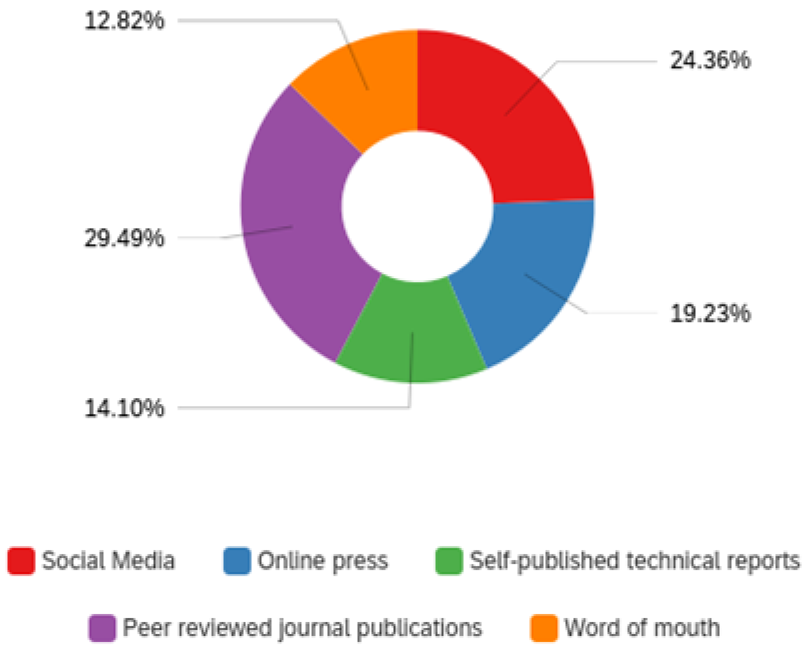

Figure 12. Preferred communication channels among PFA's
(answer to the survey question: "Where do you currently seek out information about new technologies and research in your field?") N=31.

Table 7. PFA responses to the question: "Before [learning about it in this survey], were you aware of this project?" N=40

PGI innovation case study	**Social Media Presence?**	**Recognition among PFA's[1]**		**PFA's preference[2]**
		Yes	*No*	
Green Bridges Initiative (GBI)	No	16%	84%	19%
Hauz Khas Urban Wetland (HKUW)	Yes	44%	56%	21%

Assi Nadi Experiments (ANE)	No	34%	66%	21%
Irla Nullah Re-invigoration Project (INRP)	No	23%	77%	17%
Strategic In-stream Systems (STRAINS)	No	36%	64%	22%

[1] PFA's answer to the question: "Before seeing this today, were you aware of this project?"

[2] PFA's answer to the question: "Is there a particular approach that you felt was particularly suitable for adoption in your city or locality? Please click on the image for all that apply."

A majority of PFA's reported that they were "extremely likely" (26%) or "very likely" (55%) to recommend or support the adoption of PGI innovations in their particular city or locality, with the highest preference for STRAINS (22%) followed by HKUW and ANE (21%), GBI (19%), and INRP (17%) (Table 6). These results emphasize that the barriers to PGI diffusion extend beyond the adoption attitudes of PFA's toward the innovations themselves, including questions of maintenance, scale, and pollutant removal efficiency (Table 8).

Table 8. Selected PFA responses to survey question: "Please briefly explain why (or why not) [your preferred] PGI innovation(s) are relevant to your city or locality?" (N=31)

Innovation Characteristics	Selected responses
Trialability, simplicity	"In my opinion a lot needs to be worked on the maintenance and management side of these systems"
Simplicity, compatibility	"They are natural fits into the ecosystem, with no mechanical parts more efficient in terms of O & M"

Observability, relative advantage	"Cannot judge the efficacy of these measures unless we know the water quality parameters (before and targeted). All of these look like lightweight intervention that look good good in public places. I recommend more heavyweight measures."
Observability	"Given the drastic effect of solid waste and untreated sewage its essential to monitor and reduce stress on smaller streams and nallahs which form a network and ultimately pour into the river channel. The approach would ensure property protection which would make the owners and residents more involved and also an aesthetic living condition."
Reinvention	"it's easily replicated with minor modifications."
Simplicity, relative advantage	"Not yet convinced they are easy to maintain"

We suggest that innovators might work to better emphasize the *simplicity* of their approaches to maximize the likelihood of adoption amongst a range of possible actors. We suggest that in addition to targeting *vertical* adoption efforts (promoting their innovations to municipal and state-level actors) innovators might work toward intentionally *lateral* modes of adoption (via public private partnerships, civil society organizations, and other NGO's) if wider diffusion is desired. Finally, we posit the important role of peer-reviewed journal articles and social media as high-impact channels of communication between innovators and PFA's.

3.3.3 Possible diffusion pathways for PGI, limitations and future research

This study was exploratory rather than confirmatory, considering various PGI innovations from a range of Indian megacity contexts to further build a typology and to generate opportunities for further exploration. Directly surveying and interviewing PGI innovators and PFA's using the DOI framework proved useful, and allowed insights into a range of unique processes, challenges, perceptions and aspirations that were not commonly documented in publicly available materials and technical reports. Further studies will reveal additional insights that may ultimately impact the diffusion of experimental Green Infrastructure innovations in this and other contexts in the global south.

Analysis of our survey and interview data suggests that future diffusion of PGI will occur both vertically (i.e. from smaller actors upward to larger municipal and institutional actors) as well as laterally across networks of non-state actors operating in the Indian subcontinent. Successful adoption is likely to depend on innovators' ability to effectively leverage public support and media for the dissemination of information. Building a cooperative rather than an adversarial relationship between PGI innovators and municipal actors may also play an important role, with a mutual understanding of the *relative advantage* and *simplicity* of PGI (IE its ability to work in concert with existing infrastructures to meet shared goals of improving in-stream water quality and protecting downstream receiving waters). We expect that informal introduction of novel wastewater treatment practices by small networks of non-state actors at demonstration scales will continue to enable their selective legitimization at local scales while contributing to their increasing normalization and adoption over time.

It should be noted that while this study was intentionally focused on a range of cases from across the Indian subcontinent, there may be a resulting geographical bias to the perspectives and insights. It should therefore be noted that the scope, infrastructural context, and diffusion strategies of PGI projects in south Asia may not align with analogous GI projects occurring within megacities or regions elsewhere in the world. A further limitation is the relatively small survey sample size for both innovators and PFA's.

Future research should therefore focus on inter-organizational communication between various actors, and take a more detailed account of PFA's needs and perspectives using similar semi-structured interview approaches. We suggest that this research could be driven by a particular focus on how potential PGI adopters from a range of positions view the innovation characteristics of *relative advantage, compatibility and simplicity*, as well as how they perceive risks of adoption. Conducting analogous studies in other contexts could further elucidate the processes and challenges of informal SUWM innovation. Finally, this study provides a viable foundation for a larger longitudinal study of the five cases presented here, documenting the perspectives of innovators at a nascent stage in the development process. We recommend that future research should be conducted to periodically assess the diffusion status of each innovation while comparing and contrasting the relative challenges related to diffusion over time.

3.4 Conclusion

This study contributes to the literature on GI by integrating various perspectives on informal innovations currently arising in the unique and challenging context of Indian megacities. Using a mixed methods approach and the DOI framework as a lens, it reveals several useful insights related to the values, goals and perceptions of both PGI innovators and PFA's.

Regarding the perception of currently available PGI innovations, we found that innovators and PFA's were largely aligned in their assessment of two characteristics considered most important (namely *relative advantage* and *compatibility*), but not aligned on the characteristic of *simplicity* or other moderate to less important innovation characteristics (*trialability, observability, and reinvention*) Results suggest perception of *relative advantage* may ultimately be the primary driver of positive adoption attitudes amongst PFA's.

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Appendix A: Survey and Interview Content

Table 9. Questionnaire design for PGI innovators (web-based Qualtrics survey)

Survey Stage	Question(s)	Response/choices
Characteristics of the Innovation according to DOI theory	“In your opinion, to what degree did/will the attributes listed below lead to the success of this particular innovation?” It provides more/different benefits than other available approaches ● It fits well with the existing context ● It is simple to install, and maintain ● It can be quickly tested and evaluated ● It is highly visible to many people ● It can be easily modified and replicated elsewhere	Rating scale 1 to 5; 1=no degree at all, 5= large degree
	“Please rank the relative importance of these attributes” ● Relative advantage ● Compatibility ● Simplicity ● Trialability ● Observability ● Reinvention	Forced ranking question (highest to lowest)
Innovator/Adopter characterization	1) Which of the following best describes you or your organization? > 2)“In your opinion, to what degree do you view the following organizations as likely ‘adopters’ of this particular innovation now or in the future?” ● Individuals, private citizens ● Other non-state actors (NGO’s civil society organizations) ○ (Optional) Please specify: ● Public/Private partnerships (PPP), Corporate sector ● Local municipalities ● City-wide planning/development authorities ● State governments ● Federal government ● Other > (Please specify)	Rating scale 1 to 5; 1=no degree at all, 5= large degree

Performance	”In your opinion, what is the degree of importance of the following performance characteristics of this particular innovation?” ● Improving local water quality ○ Subset of various pollutants (TP, TN, BOD, TSS) ● Improving water quality downstream (for example, environmental benefits to receiving waters such as lakes and rivers) ● Public “placemaking” via visual or other characteristics of the local context) ● Other > (Please specify)	Rating scale 1 to 5; 1=no degree at all, 5= large degree
Communication	”What do you think are the most effective ways of sharing information with others who might want to implement this innovation?” ● Social Media, online press ● Print media ● Self-published technical reports ● Peer reviewed journal publications ○ Optional > Please specify which journals ● Informal networks (Word of mouth, relationship building with individuals and organizations, etc) ● Other > (please specify)	Rating scale 1 to 5; 1=no degree at all, 5= large degree

Table 10. Lines of questioning for semi-structured interviews with PGI practitioners

Determinants of Diffusion from DOI theory	Open-ended questions:
Relative Advantage	Please describe in broad terms, the existing regime (infrastructural, bureaucratic, social) that your project operates within. What does your approach offer that existing technologies and approaches can’t? Who is the targeted adopter? What challenges have you faced in convincing adopters to accept this approach as a legitimate alternative?
Compatibility	Please describe the specific biophysical context in which these interventions are taking place. ○ Channel dimensions ○ Flow ○ Seasonal variation How and where do you imagine this approach being ‘upscaled’ throughout a larger catchment area? What are the critical factors that would enable this to occur?
Simplicity	Please describe the design features and functions (materials used, mechanisms of decontamination, maintenance required)
Trialability	Please describe the costs associated with the intervention, including how/who is providing funding currently. Which water quality parameters are most important to track in your opinion? How are water quality impacts being monitored and communicated (parameters and results)
Observability	In addition to water quality impacts, what other benefits have you observed at a local scale? Have you faced local resistance? If so, please describe How are your efforts and ideas communicated?

Table 11. Questionnaire design for potential future adopters (PFA's), a web-based Qualtrics survey

Survey Stage	Question(s)	Response/choices
Demographics	"Please indicate your age range"	Multiple choice (ranges)
	I am: ● Employed by an NGO, non-profit, or civil society organization ● Employed by the private sector ● An academic researcher ● A private citizen currently residing in India ● A national, state, or municipal decision maker	Multiple choice
	"Select a category that best describes your expertise" ● Engineering ● Architecture/Planning ● Water policy or research ● Governance ● Local Advocacy ● Other (please specify)	Multiple choice or short answer
	"Please indicate the city in which you reside or work."	Multiple choice or short answer
PGI introduction and case study descriptions	Photos and brief text descriptions of each case study, followed by: "Before seeing this today, were you aware of this project?" ● Yes ● No	Binary choice

	"How likely are you to recommend or support the adoption of PGI innovations for your particular city or locality?"	Rating scale 1 to 5; 1=not at all likely, 5=extremely likely
	"Is there a particular approach that you felt was well suitable for adoption in your city or locality? Please click on the image for all that apply" ● Example #1>#5	Multiple choice (multiple answer)
	"Is there a particular approach that you felt was particularly suitable for adoption in your city or locality? Please click on the image for all that apply."	Text entry
PGI Innovation Characteristics	"To what extent do you agree or disagree with the following statements as they relate to the PGI innovations you saw in the previous sections?" ● They provide more/different benefits than other available approaches that I am aware of ● They provide more/different benefits than other available approaches that I am aware of ● They seem simple to install, and maintain ● They seem easy to quickly test and evaluate ● They are highly visible to the public ● They seem like they could be easily modified and replicated	Rating scale 1 to 5; 1=strongly disagree, 5=Strongly agree
	What is the importance of each of the following characteristics on your willingness to support or adopt PGI in your city/locality in the future? Please click and drag to arrange each into the boxes below (max 3 choices per box). ● Relative advantage ● Compatibility ● Simplicity ● Trialability ● Observability ● Reinvention ● Other (please specify)	Forced ranking question (Most important>Moderately important>Least important)

Performance	"How would you weight the importance of the following criteria regarding the implementation of stormwater/wastewater infrastructure (note that values must sum to 100)" ● Cost of installation + maintenance ● Water quality improvement ● Visual and spatial enhancement of urban context	Constant sum (total must be 100)
Adopter involvement	"In your opinion, who should be involved in funding, building, and maintaining PGI interventions in the future?" Involvement in: Funding> Building>Maintenance ● Individual, private citizens ● Local municipality ● State Governments ● National government ● Private entities ● Public Private Partnerships ● NGOs ● Civil Society Organizations ● Other (please specify)	Side by side matrix with single answer ranking scale of 1-3 (High>Moderate>Low)
Communication	"Where do you currently seek out information about new technologies and research in your field? Click all that apply ● Social Media, online press ● Online press ● Self-published technical reports ● Peer reviewed journal publications ● Word of mouth ● Other > (please specify)	Multiple choice (multiple answer)

Appendix B: Overview of five PGI Case-studies

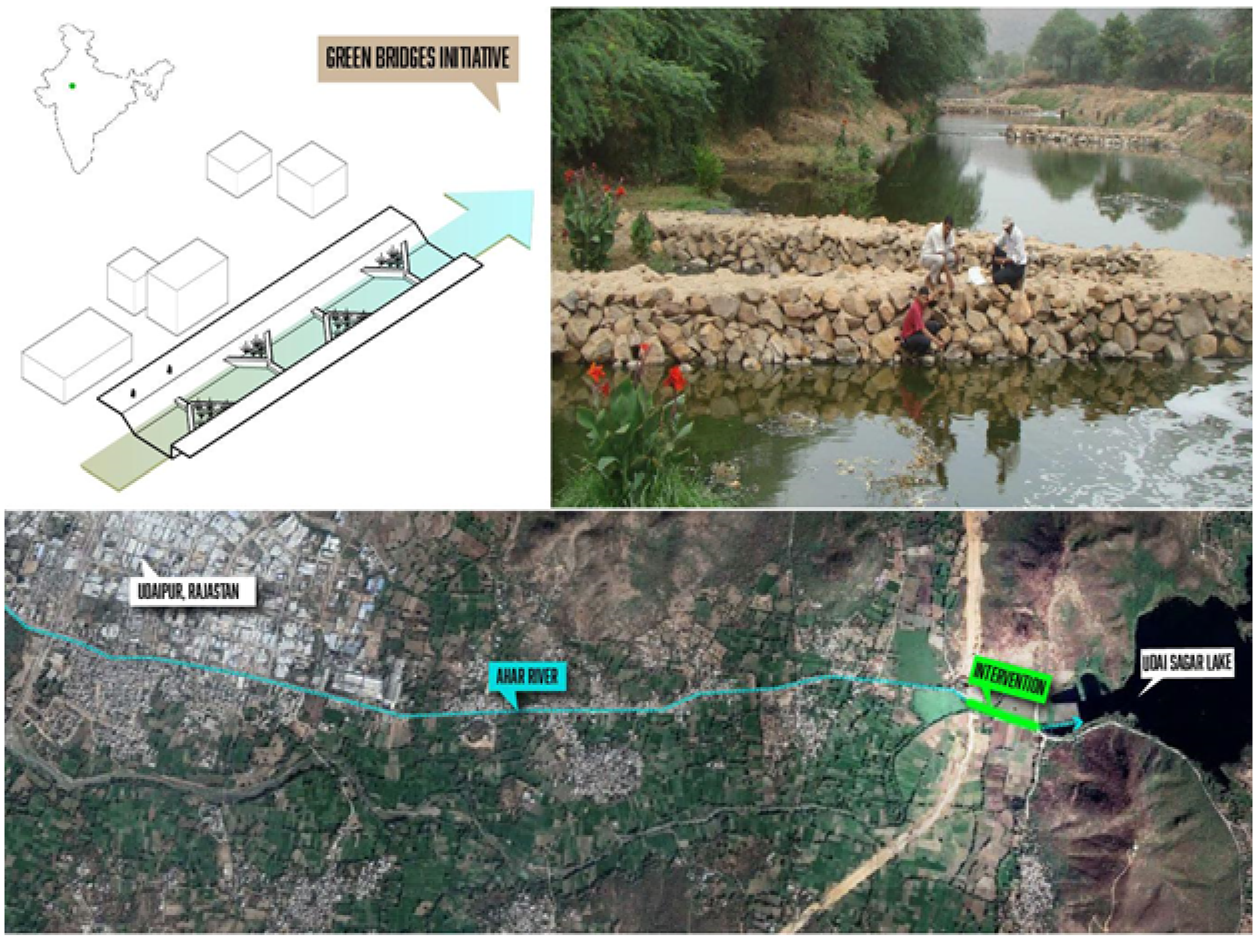


Figure 13. Green Bridges Initiative (GBI)

Green Bridges Initiative (GBI) typically consists of an alternating series of wedge-shaped in-stream treatment modules (composed of natural materials) arrayed along the length of an open channel or urban stream. The system is designed to increase retention time and bring contaminated water in contact with various filtration materials (including sand, coconut coir, soil and plants) and beneficial bacteria (Badal okays Buddha Nallah, 2010; D. Das, 2010; Green Bridge draws, 2011).

Figure 14. Hauz Khas Urban Wetland (HKUW)

Hauz Khas Urban Wetland (HKUW) consists of (1) a horizontal flow wetland condition within a 50 meter section of an upstream channel flowing into the lake (composed of sand, gravel, and plants), as well as (2) numerous 'floating island' remediation units (comprised of aquatic plants set within buoyant plastic frames) on the surface of the lake near the inlet (Delhi, Let's Save Our

Lakes | The Stories Of Change, 2018; Three city lakes, 2011). The project allowed private individuals to sponsor a floating island for the project at a cost of 5,000 INR (66 USD).

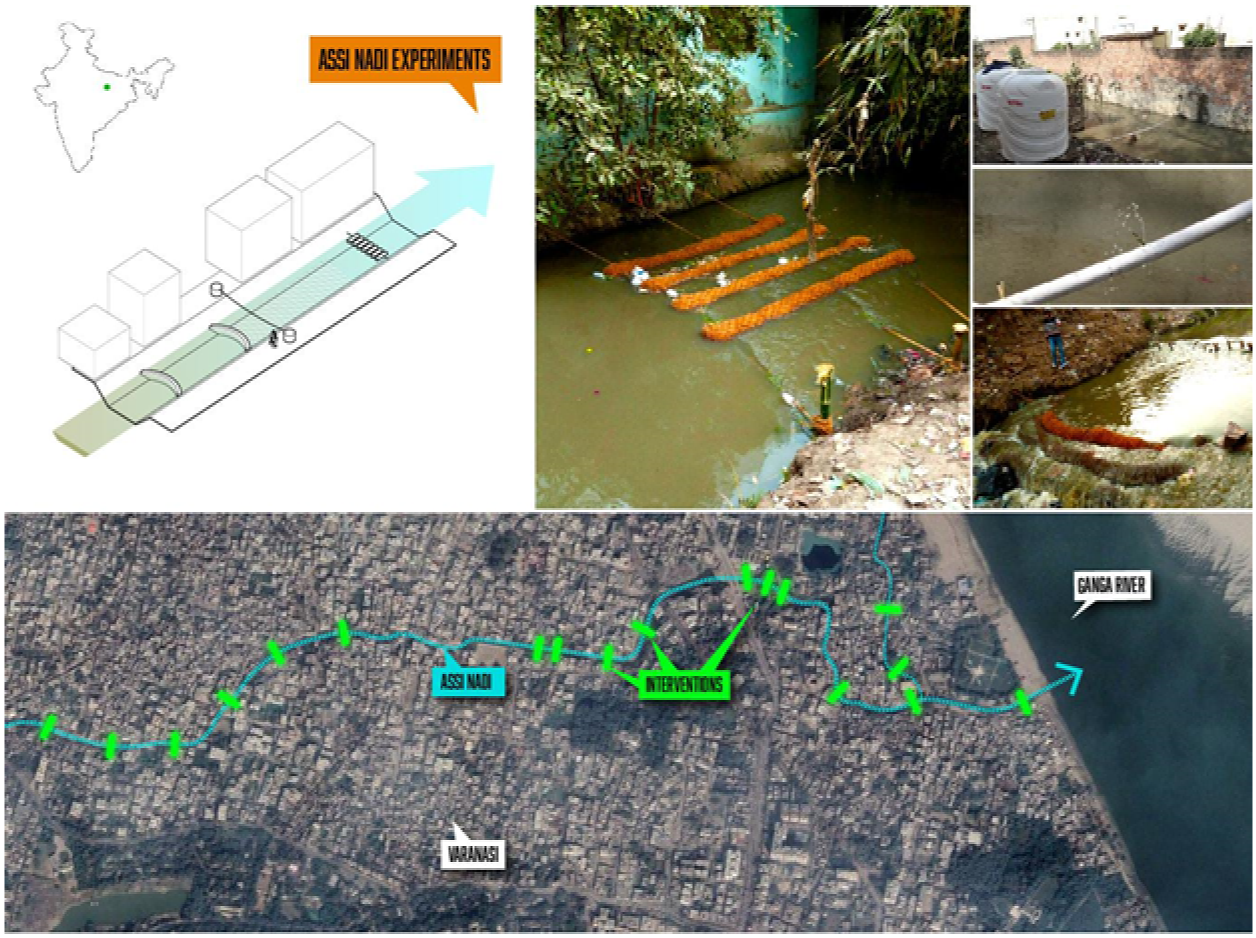


Figure 15. Assi Nadi Experiments (ANE)

Assi Nadi Experiments (ANE) undertook an ‘acupunctural’ approach along a 3.5 km section of the Assi nadi channel in Varanasi without investment in any permanently built structures (Bhatnagar, 2017). Instead, a series of informal structures were introduced into the waterways to intentionally disrupt the flow of water, debris and contaminants. This included the manual installation of temporary soil bag weirs for increasing retention time and settling out suspended solids, and the introduction of biofilter media and coconut coir logs coupled with beneficial bacterial dousing to accelerate the processes of organic decomposition.

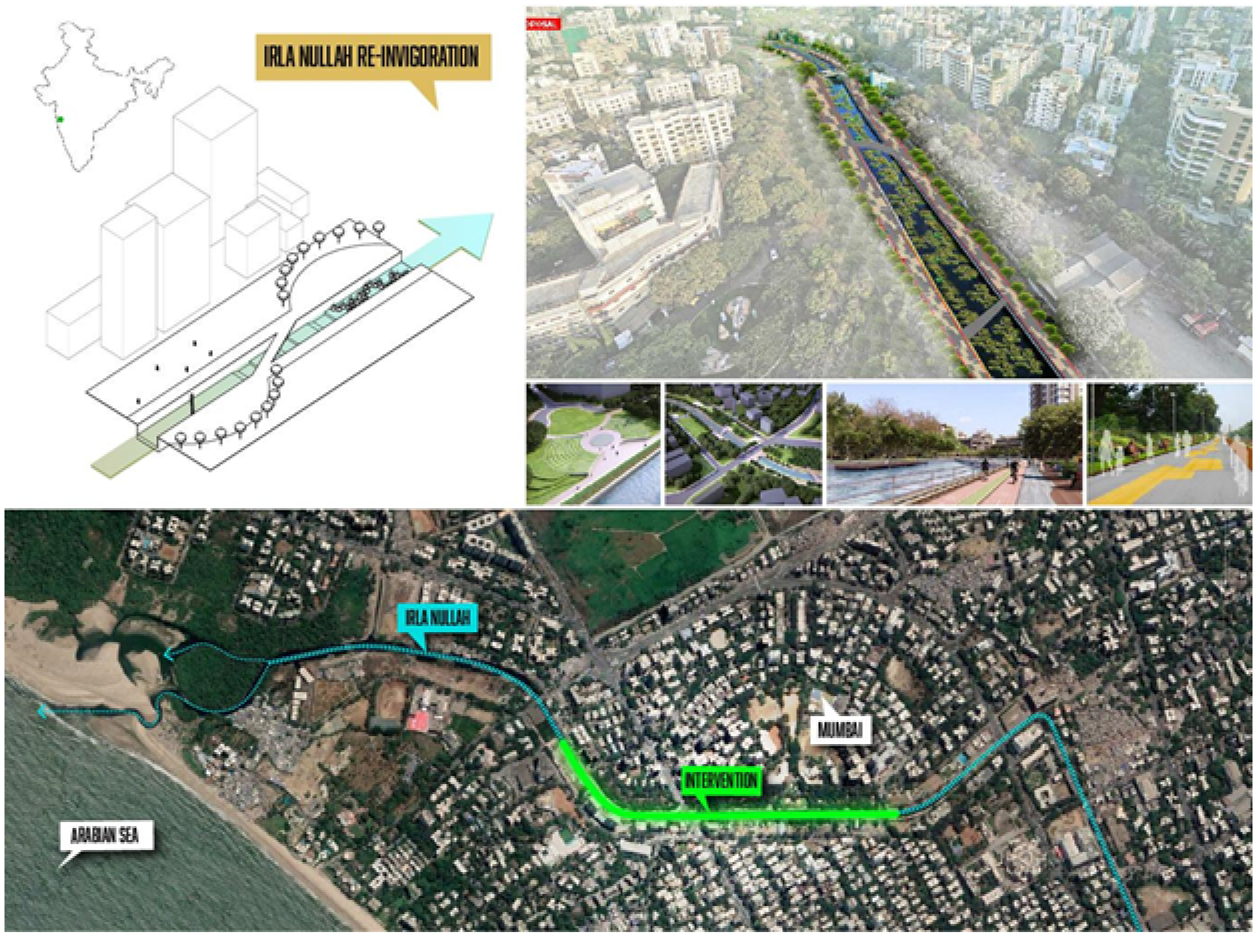


Figure 16. Irla Nallah Re-invigoration Project (INRP)

The goal of Irla Nallah Re-invigoration Project (INRP) is the creation of a 10 KM tree-lined, flood-free walkway along Irla Nallah in Mumbai (Amrita Nayak Dutta, 2014; P. K. Das & Akhtar, 2018). To date, a 1.5 km “phase one” section of the plan has been completed, which includes desilting, in-stream structures and near-stream improvements for pedestrian and bike access, which has led to an increase in local awareness about the health of the Irla, and a 20% increase in local property values (Lewis, 2013).

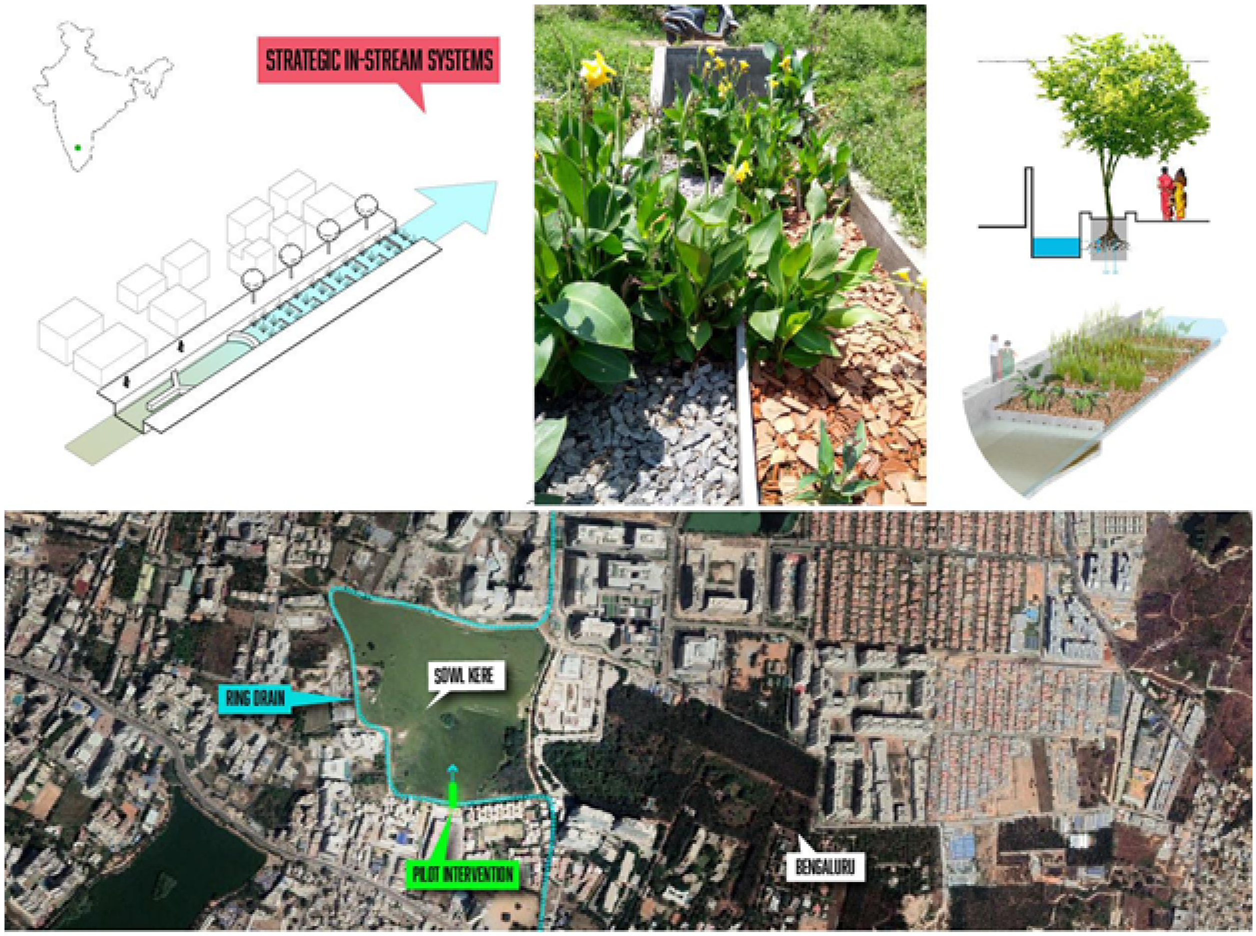


Figure 17. Strategic Instream Systems (STRAINS)

Strategic Instream Systems (STRAINS) proposes a modular system comprising three basic stages for (1) diverting and collecting solid waste, (2) slowing and settling sediment and suspended solids, and (3) biofiltration using locally available aggregate materials and stress-tolerant aquatic plants (Jamwal et al., 2019). Proposed tree planting along the nallah provides social and ecological benefits.

Chapter 4 Assessing Performance of Local Substrates for Treatment of Dry Weather Flows in Open Drains: Results of a Pilot Study in Bangalore, India.[3]

Abstract: The efficacy of two filter materials (gravel and terracotta rubble) were tested in a semi-controlled pilot study deployed to treat dry weather flows (DWF) from an open storm water drain in Bangalore, India. The filtration treatments were operated at a similar hydraulic loading rates (HLR's) of 265mm/day by diverting greywater flows from surrounding land uses for a period of 15 months. High variability in the quality of influents was observed. The average COD, BOD_5, TN and TP levels of 1528 mg/l, 439 mg/l, 28.6 mg/l and 9.8 mg/l, respectively, corresponded to high strength wastewater. Differences in porosity led to the difference in hydraulic retention time (HRT) with 0.8 days for the gravel treatment and 1.01 days for terracotta. Significant differences in the quality of effluents were observed for 4 out of 12 parameters tested. A statistically significant Mass Removal Rate (MRR) was higher in the terracotta substrate for total nitrogen (TN), dissolved chemical oxygen demand (DCOD), total phosphate (TP), and orthophosphate, A K_{BOD5} of 0.89 in was significantly higher in gravel than

[3] Currently under review as Phillips, D., & Jamwal, P. (2021). *Assessing performance of local substrates for treatment of dry weather flows in open drains: Results of a pilot study in Bangalore, India*. Ecological Engineering.

terracotta (0.70). Neither substrate was effective at removing Fecal Coliform levels, particularly in the later stages of the study, and Ammonia-N levels showed periodic increases in both setups, a suspected result of incomplete nitrification-denitrificatoin. Despite these exceptions, the data suggests both substrates are suitable for use in treating inflows rich in organic matter in-situ despite highly variable inflow quality and lower HRT. While outflows did not meet discharge standards specified by India's Central Pollution Control Board (CPCB), results suggest that significant reduction in common contaminants in dry weather flows (DWF) can be achieved within open drains, and are expected to inform future interventions and modelling studies promoting sustainable urban water management in the megacity context. Suggested removal efficiencies for using PGI as LID objects in modelling studies are included, and future research trajectories in this domain are discussed.

4.1 Introduction

Contamination of urban streams by direct inflows of domestic greywater remains a significant challenge in the Megacities of the global south, where much of the freshwater used at the household level for everyday purposes such as cooking, cleaning, laundry, and bathing eventually discharges to urban streams (Morel & Diener, 2006; Radin, Al-Gheethi, & Kassim, 2018). Inadequate household level greywater management practices and persistent capacity gaps in centralized wastewater infrastructure leave the majority of these dry weather flows (DWF) untreated. These inflows contribute to the degradation of lakes and rivers, as evidenced by the regular occurrence of anomalies such as hyper-eutrophication, harmful algal blooms, declines in the lake health, mass fish kills, and toxic foam events that threaten public health and local livelihoods (Benjamin, Chakrapani, Devashish, Nagarathna, & Ramachandra, 1996; Pattusamy, Nandini, & Bheemappa, 2013; Ramachandra, Vinay, M., V., & Bharath, 2016)

Provisional Green Infrastructure (PGI), refers to *"Informal nature-based retrofits to existing grey infrastructure networks by non-state actors for the purpose of improving water quality within highly unpredictable, space-constrained, and contaminated urban environments"* (Phillips et al., 2020). PGI proposes to work in conjunction with existing grey infrastructures through the intentional introduction of modular in-stream structures and materials. These interventions temporarily interrupt contaminated dry weather flows in open drains ("nallahs") to promote various physical and biological processes that are beneficial to the health of downstream water bodies. Many PGI interventions contain design features that operate in a similar fashion to modified horizontal flow constructed wetlands (CW's). These systems use various materials and processes to promote decontamination without the need for electricity or complex technology. The primary organic matter removal mechanisms being advanced by horizontal flow interventions such as PGI includes adsorption, sedimentation and microbial metabolism.

Previous studies suggested that critical parameters impacting removal of pollutants in horizontal flow constructed wetland (HFCW) conditions include hydraulic loading rate (HLR), hydraulic retention time (HRT), substrate composition, aspect ratio, and the presence or absence of aquatic plants (Akratos & Tsihrintzis, 2007; Coleman et al., 2001; Vymazal, 2011; Weerakoon, Jinadasa, Herath, Mowjood, & van Bruggen, 2013). A review by Vohla et al (2011) suggested the material characteristics of substrates can greatly impact the efficiency of pollutant removal in greywater. Other studies suggest that substrates with high porosity provides additional capacity as well as space and a favorable environment for attached microbial growth, yielding increased organic matter removal (Jamwal & Phillips, 2019; Pisoeiro, Galvão, Ferreira, & Matos, 2016). Many previous studies used synthetic wastewater in highly controlled conditions over short time periods, which limits the applicability and scalability of results to real-world settings. Additionally, other research has promoted materials that may be cost-prohibitive or unavailable in resource-constrained contexts. The purpose of ongoing applied research in material performance assesses the viability of incorporating low-cost, locally available aggregate materials that exhibit desirable properties, while being easily sourced by non-expert stakeholders.

This study builds on a previous laboratory study that assessed performance of local aggregate materials (e.g., gravel, terracotta, cinder slag) in the biological treatment of synthetic wastewater (Jamwal & Phillips, 2019). That study demonstrated that terracotta can produce stable biofilms even at relatively high HLR’s and both gravel and terracotta filter material had potential for treating greywater. The present study was conducted over a longer duration (15 months) and tested the removal efficiency of these materials using wastewater from an urbanized catchment in Bangalore, India. It was expected that a semi-controlled field experiment could reflect the dynamic challenges of the in-stream context, namely the high degree of variability in pollutant loading rate (throughout a typical day, month, or season), and the comparatively low HRT's that are possible in an in-stream setting.

This research demonstrates important aspects that should be considered for the future development and implementation of PGI in cities. As the performance of many GI interventions are only evaluated at limited temporal and spatial scales, they reveal little about effects scaled over long time periods and larger areas (e.g., catchment, region) (Golden & Hoghooghi, 2018). This study serves as a primary data source for PGI performance characteristics in a real-world setting that can inform hydrological modelling studies. By combining field-based testing with modelling studies, it should be possible to evaluate the cumulative impact that small scale PGI interventions might have if effectively upscaled.

4.2 Methodology

4.2.1 Experimental design at Sowlkere (Bangalore, India)

The study was located near the inlet of a small urban lake Sowlkere (12°55'304644"N, 77°40'57.2232"E), which is in a lower elevation gradient of the Koramangala-Challaghatta subcatchment in Bangalore's southeast periphery (Fig 18).

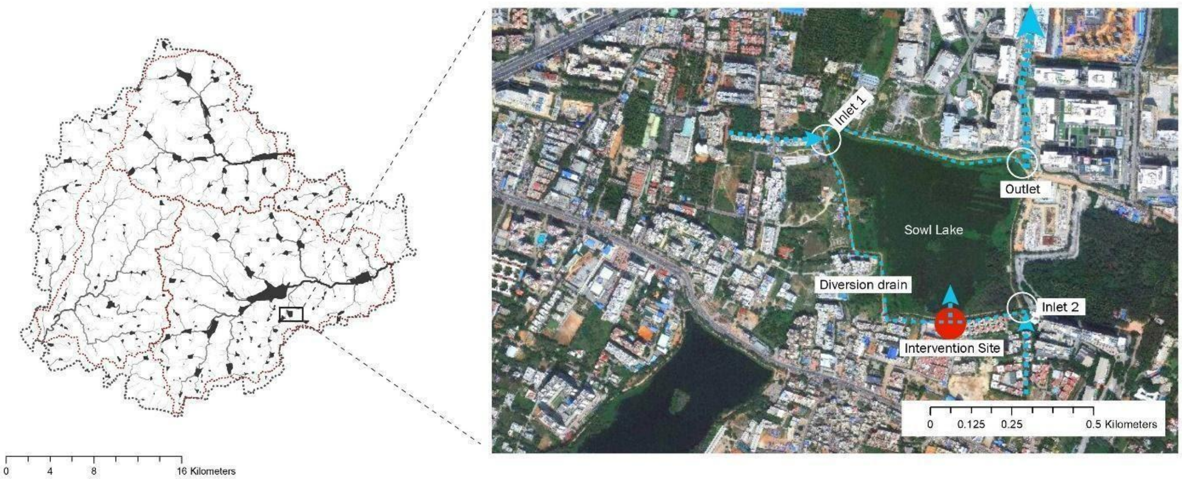


Figure 18. Semi-controlled field experiment is located near the inlet of a small urban lake known as Sowlkere

The design was conceived as a small-scale ‘model nallah’ condition, which mimics the dimensions and materials of a typical concretized stormwater channel found throughout the city. A Horizontal Subsurface flow (HSSF) filtration system (FS) was built with an overall dimension of 8mx2mx1m (length x width x height) and subdivided into two independent cells (Cell A, and Cell B) each filled with a different filter material (Figure 1b). This iteration assessed the performance of two substrates: gravel (4-5 cm) and terracotta rubble (10-15 cm, typically used as a roofing material). Gravel is a high-density material with low porosity and terracotta is a lightweight porous material (Yang et al., 2017). The gravel and terracotta filtration design had a porosity of 40% and 50%, respectively. Porosity refers to the total volume of void space in a filtration setup after filled with aggregate material (equation 1).

$$Porosity = \frac{Pore\ volume}{Bulk\ volume} x100 \qquad (1)$$

4.2.2 System operation and maintenance

The Hydraulic Loading Rate (HLR) of the filtration systems was 265mm/day and mean Hydraulic retention Time (HRT) was 0.8 days (19.25 hrs) for gravel and 1.01 (24.16 hrs) days for terracotta. HRT is determined by dividing the pore volume of the filtration system with the outflow (Reed & Brown, 1995).

The system operated at a mean flow rate of 3000 liters per day (SD±27); flow rate was measured using a bucket flow method. The system received a constant supply of greywater from a sewage manhole to which urban wastewater was flowing from nearby commercial and residential land-uses and was held constant. A mesh was inserted in the inflow pipe connecting the manhole to the system to impede large solids. This mesh was cleaned twice a day and silt was removed from the system (both pipes and filtration channel) regularly. The wastewater flow into each substrate treatment was controlled using a valve. It is assumed that flow remained constant between sampling campaigns and was given daily visual inspections by local park staff to ensure that water remained flowing into the system. Figure 19 shows the layout of the filtration setups. Figure 1c shows visual reductions in the outflows from both systems.

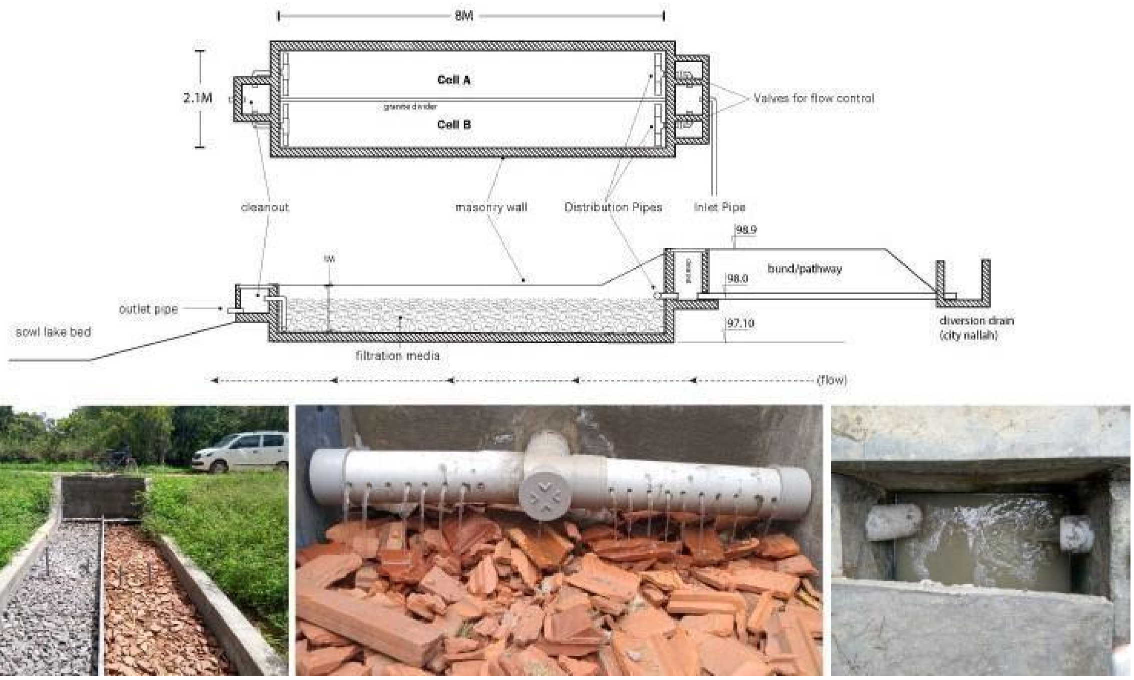


Figure 19. Semi-controlled experimental "model nallah" field setup at Sowl Kere in Bangalore.

4.2.3 Water sampling and analytical methods

Greywater quality was monitored fortnightly for a period of 15 months (July 2019 to October 2020). An average of 10 samples were taken per month (minimum 6 and maximum 12) during the 15 month duration of the study. This consisted of fortnightly sampling campaigns with composite samples taken at the system inlet, midpoint, and outlet (two composite samples at each point). System midpoint samples were omitted due to field sampling techniques which invalidated their accuracy (sampling device was resuspending sediment into the water column, leading to very unstable readings). Samples were collected at the inlet and the outlet of the two treatments (Fig 20). Samples were collected in sterile borosilicate glass bottles and plastic bottles (LDPE, medical-grade USP class VI) and were tested for physical, chemical and biological parameters listed in Table 1. Samples were preserved at a pH < 2 whenever necessary and stored < 4˚C during transportation to ATREE's Water and Soil Laboratory and until analyzed. All the water quality parameters were tested according to methods described in APHA standard methods for the examination of water and wastewater (American Public Health Association, 2005). The pH, temperature and conductivity of samples were measured onsite with a YSI Pro 1030 sensor (YSI, Yellow springs USA). Nitrate-N was measured using Hach Nitrate Pocket Colorimeter (Hach Company, Loveland, USA). Ammonium-N, Total nitrogen (TN), Orthophosphate-P and Total phosphorus (TP) were analyzed photometrically (Merck KGaA, Darmstadt, Germany). Biochemical Oxygen Demand and Chemical Oxygen Demand were analyzed by methods described in APHA standard methods. Fecal coliforms were detected and enumerated by Colliret 18 (IDEXX Laboratories, Westbrook, USA).

Figure 20. Outflow from gravel and terracotta setups and b) inflow and outflow samples from two setups

Removal efficiencies were calculated as a percentage reduction in the concentration from influent to the effluent samples using Equation (2).

$$Removal\ Efficiency(RE) = \frac{Ci - Co}{Ci}\ x\ 100 \qquad (2)$$

where C_i= Concentration of contaminant in the influent (mg/L), and C_0= concentration of the contaminant in the effluent (mg/L).

Table 12. List of parameters for which samples were analyzed

Parameters	
Physical	Temperature (°C)
	pH
	Electrical conductivity (µS/cm)
	Total Suspended Solids (TSS) (mg/L)
Chemical	Nitrate-N (mg/L)
	Ammonium-N (mg/L)
	Total Nitrogen (mg/L)
	Orthophosphates-P (mg/L)
	Total Phosphorus (mg/L)
	Chemical Oxygen Demand (mg/L)
Biological	Biochemical Oxygen Demand (mg/L)
	Fecal coliform (MPN/100mL)

The first-order plug-flow model was used to model the removal of TN, TP, BOD_5 and COD. The removal rate constant K was calculated by linear regression using the integrated first-order plug-flow equation (3) (Sooknah & Wilkie, 2004):

$$ln\, ln\, \left(\frac{C_i}{C_o}\right) = K_T t \quad (3)$$

where C_i and C_o are influent and effluent concentrations in mg/L respectively

K_T is the temperature-dependent first-order rate constant, day^{-1}, and

t is the Hydraulic Retention Time (HRT). K_T is the rate constant at temperature T. For comparison rate constant is estimated at 20 ºC. The temperature dependence of rate constant is given by equation 4

$$K_T = K_{20}\theta^{(T-20)} \quad (4)$$

K_{20} is the removal rate constant at temperature 20 ºC and

θ is the modified Arrhenius temperature correction factor, θ = 1.06 for TSS, TP and BOD_5 (Kadlec & Reddy, 2001).

The mass loading rate (MLR), mass removal rate (MRR) and % MRR of TSS, BOD, COD, TN and TP was estimated using Equation (5) and Equation (6).

$$Mass\ Loading\ Rate\ (MLR)\ (g\ /\ m2\ /\ day)\ =\ C\ \times\ Q/As \quad (5)$$

$$Mass\ Removal\ rate\ (MRR)(g\ /\ m2\ /\ day)\ =\ (\ MLRi\ -\ MLRo) \quad (6)$$

$$Mass\ Removal\ Rate\ (\%) = \frac{(MLR_i - MLR_o)}{MLR_i} \times 100 \quad (7)$$

Where C (g/m^3) is the concentration of contaminant and Q is the flow rate (m^3/day) and A_s is the surface area (m^2).

MLR_i (g/m^2/day) is the mass loading rate at the inlet and MLR_o (g/m^2/day) is the mass loading rate at the outlet.

4.2.4 Statistical analysis

Data gathered after the system achieved steady state (water balance) was used to test the significant difference for various trials of both systems. Tests for significant difference in water quality between influent and effluent of the wetlands and water quality between gravel and terracotta were determined by paired t – test at a significance level of 0.05.

4.3 Results and Discussion

4.3.1 Inflow characteristics

Grey water from open drains was diverted and fed to the gravel and terracotta setups at fixed flowrates. The mean outflow from the gravel system was 2049 litres/day (SD=101) and 1993 liters/day (SD=103) for terracotta. Table 13 presents the average levels of physical, chemical and biological parameters in greywater inflows. Given that the open storm water drain receives greywater from restaurants, households and commercial establishments, high variations occurred in all chemical constituents. It is expected that seasonal monsoonal rainfall also influenced the concentration of inflow contaminants, with lower concentrations during precipitation events due to dilution. The pH varied between 5.5 and 7.95 (6.7 avg) indicating both acidic and alkaline conditions.

Table 13. Water quality characteristics of greywater inflow

Parameter	Average	Range
Temp C	26 ± 1.74	21-29
pH	6.7 ± 0.71	5.5-8
Conductivity	1420 ±420	522-2228
TSS (mg/l)	682±754	20-2800
BOD_5 (mg/l)	420±234	19-704
DCOD (mg/l)	542±484	22-1853
COD (mg/l)	1460 ±1162	100-4130
TN (mg/l)	28 ±21	7-83
NO3-N (mg/l)	3.3 ±1.9	0.2-7.1
Ammonia-N (mg/l)	3.9±6.7	0.07-22.0
TP (mg/l)	9.5±6.4	3.1-22.2
Ortho-P (mg/l)	3.3±2.3	0.2-9.1
Fecal Coliform (MPN/100ml)	6±1	3-7

A comparison to wastewater quality in other countries, shows the test site greywater was very concentrated with high constituent levels, with the exception of TP (Boano et al., 2020) . The maximum TSS, BOD_5 and COD levels were 2800 mg/l, 704 mg/l and 1853 mg/l, respectively. The average BOD_5 /COD ratio was 0.41 indicating an organic nature of the inflows; however, a sudden drop in BOD_5 /COD ratio suggests a reduction in biodegradability at high

COD levels (>2000mg/l). A negative correlation between BOD_5 /COD ratio and TSS levels ($p<.05$) indicated the non-biodegradable nature of suspended solids at high TSS levels (Figure 21).

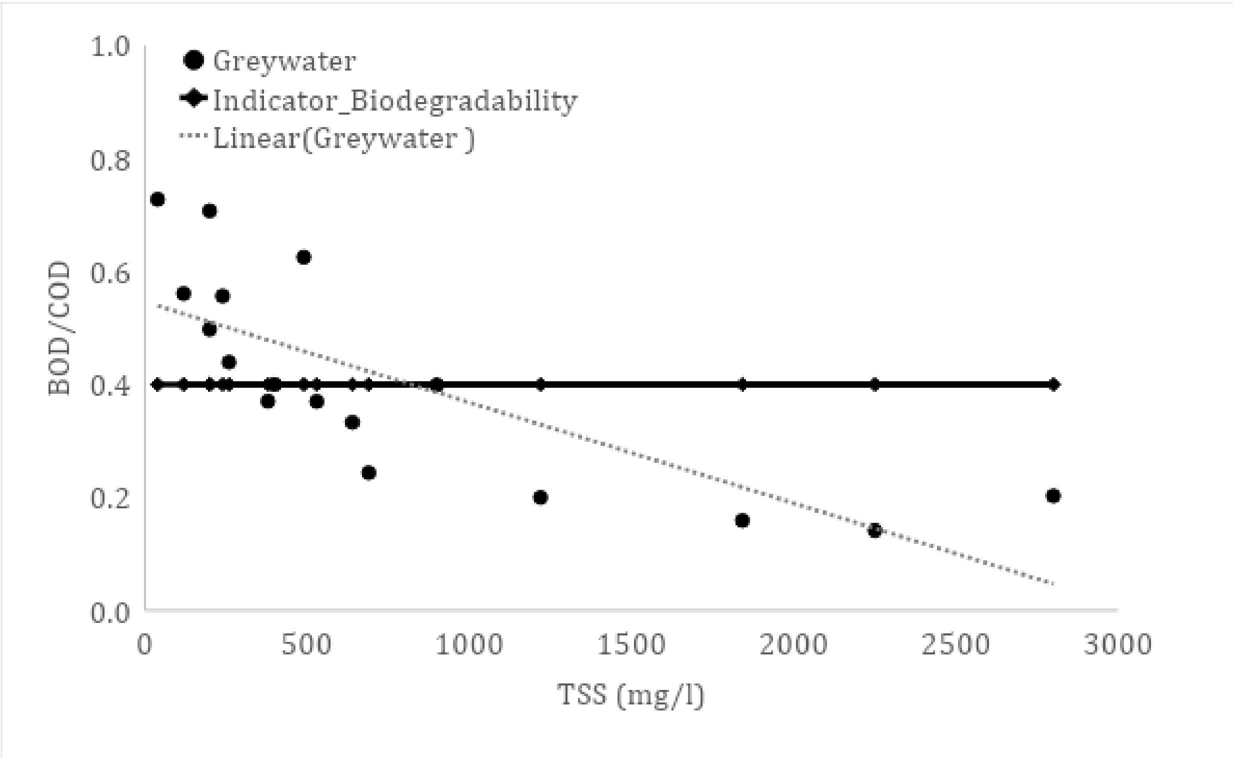


Figure 21. Correlation between BOD5 /COD ratio and TSS levels in greywater inflows
($y = -0.0001x + 0.4931$, $R^2 = 0.35$)

Significant positive correlation between the nutrients (TN and TP) and COD levels suggest they have common sources (Figure 22). High COD levels suggest discharges from commercial activities, hotels, and roadside cafeteria discharge into the open storm water drains with common discharges of commercial cleaning products, and other chemicals associated with industrial commercial and residential activities. In addition, an average dissolved chemical oxygen demand DCOD/COD ratio observed in inflows is 0.43 indicating presence of significant fraction of oxidizable matter in dissolved form. A positive correlation between conductivity and

DCOD (R^2= 0.53 p<.05), DCOD and BOD_5 (R^2= 0.43, p<.05) levels indicates contribution of both organic matter and readily oxidizable chemical constituents to the DCOD levels in greywater.

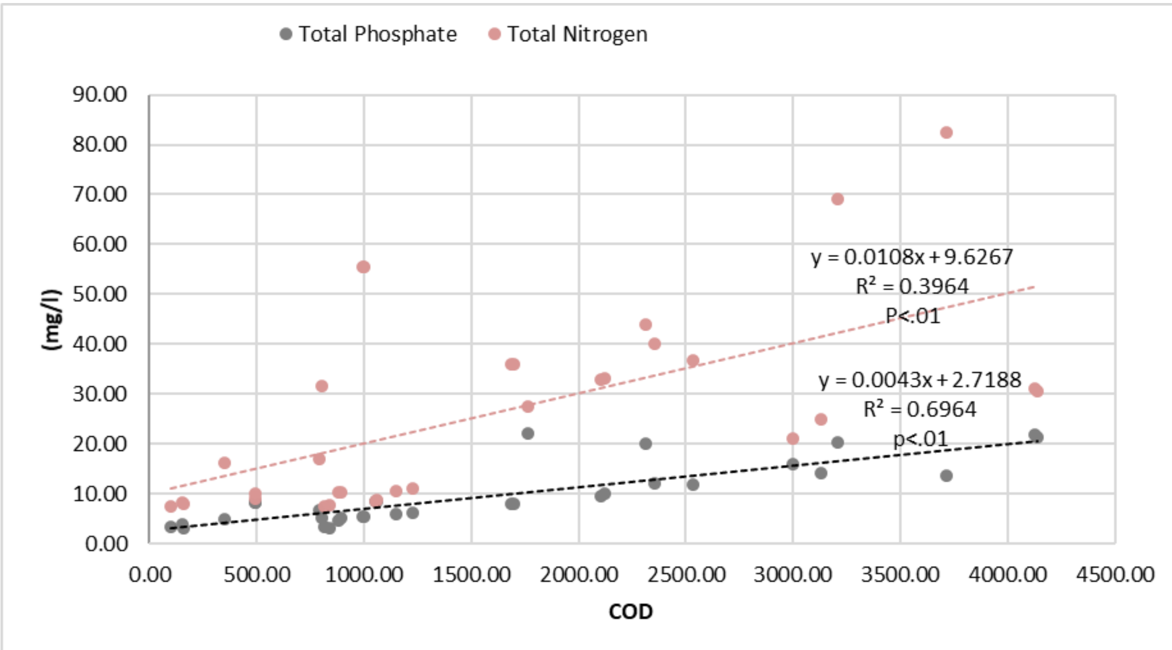
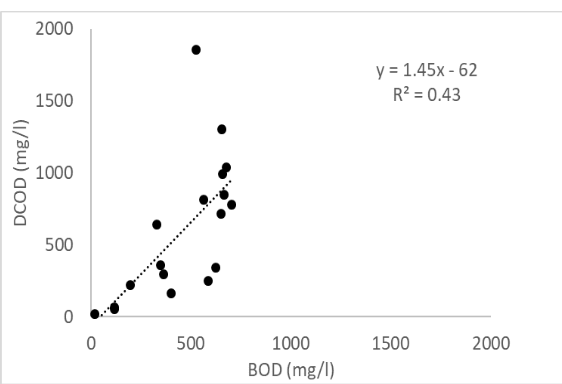


Figure 22. Correlation between nutrients (TN and TP) and COD levels



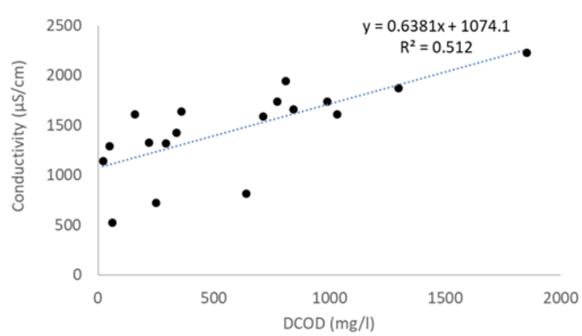


Figure 24. Relationship between DCOD and BOD5, Conductivity and DCOD

4.3.2 Effluent quality and contaminant removal efficiency

No significant reduction in the pH and conductivity levels was observed at the outlet of the two treatments. Figure 25 shows variations in TSS levels at the inflows and outflows of both setups. Significant reduction in TSS levels were observed with 79% and 74% removal in gravel and terracotta, respectively. Mean difference in these ranges were not statistically significant ($p=.07$), suggesting that both substrates are suitable for TSS removal in-situ.

Ammonia increases observed from inlet to outlet are likely influenced by the relatively short HRT in the system (19-24 hours). There may not have been sufficient residence time in the system to allow later stage nitrification processes to occur (ammonia-N conversion to nitrites via ammonia oxidizing bacteria). Literature suggests that decontamination efficiencies are significantly influenced by HRT, with higher removal rates observed as HRT increases (Bayley, Davison, & Headley, 2003; Velvizhi, 2019). (Li, Zhang, Yang, & Kamagata, 2013) showed that variation in HRT's significantly influences specific ammonium-oxidizing rates (SAOR), and shorter HRT's favor the growth of faster growing nitrite-oxidizing bacteria (NOB's). While it is expected that removal efficiency of this system for all parameters of concern will increase as residence time increases, it is important to note that Ammonia-N is particularly sensitive to HRT, and may increase. This is particularly relevant for in-stream systems where HRT may be substantially lower and less stable than HRT's for conventional approaches.

Table 14. Effluent quality and percent reduction in contaminant levels from both the setup

Parameter	Inflow ± SD	Gravel ± SD	Terracotta ± SD	% reduction GR	% reduction TR	P-Value	N
pH	6.7 ±0.71	6.6 ±0.2	6.6 ± 0.5	-	-	0.28	26
Conductivity	1420 ±420	1657 ±416	1661 ±517	-	-	0.46	26
TSS	682 ±754	102 ±88	136 ±140	79.7 ±21.3	74.55 ±29	0.07	30
BOD5 (mg/L)	420 ±234	94 ±37	91 ±41	79.8 ±16.1	77.7 ±17.8	0.15	30
DCOD (mg/L)	542 ±484	266 ±218	321 ±270	23.6 ±123.3	21.6 ±126.3	0.02*	30
COD (mg/L)	1460 ±1162	490 ±278	519 ±304	63.9 ±32.1	65.7 ±20.6	0.15	30
TN (mg/L)	28 ±21	24 ±11	21 ±10	14.1 ±58.7	24.7 ±45.4	0.01**	30
NO3-N (mg/L)	3.3 ±1.9	2 ±1	2 ± 2	33.2 ±77.8	4.2 ±199	0.20	30
Ammonia-N (mg/L)	3.9±6.7	9 ±13	6 ±7	-108.5 ±385.21	-99 ±313.1	<0.01**	30
TP (mg/L)	9.5±6.4	6 ±3	5 ±3	49.8 ±19.9	59 ±20.9	<0.01**	30
Ortho-P (mg/L)	3.3±2.3	4 ±2	3 ±2	-5 ±78.8	25.3 ±30	<0.01**	30
FC (MPN/100ml)***	6±1	5.9 ±1.05	5.7 ±1.06	7 ±9.2	2 ±7.4	<0.01**	25

[*] the difference is statistically significant $p<0.05$, ** the difference is statistically significant $p<0.01$,

**In case of Fecal Coliforms log removal is estimated

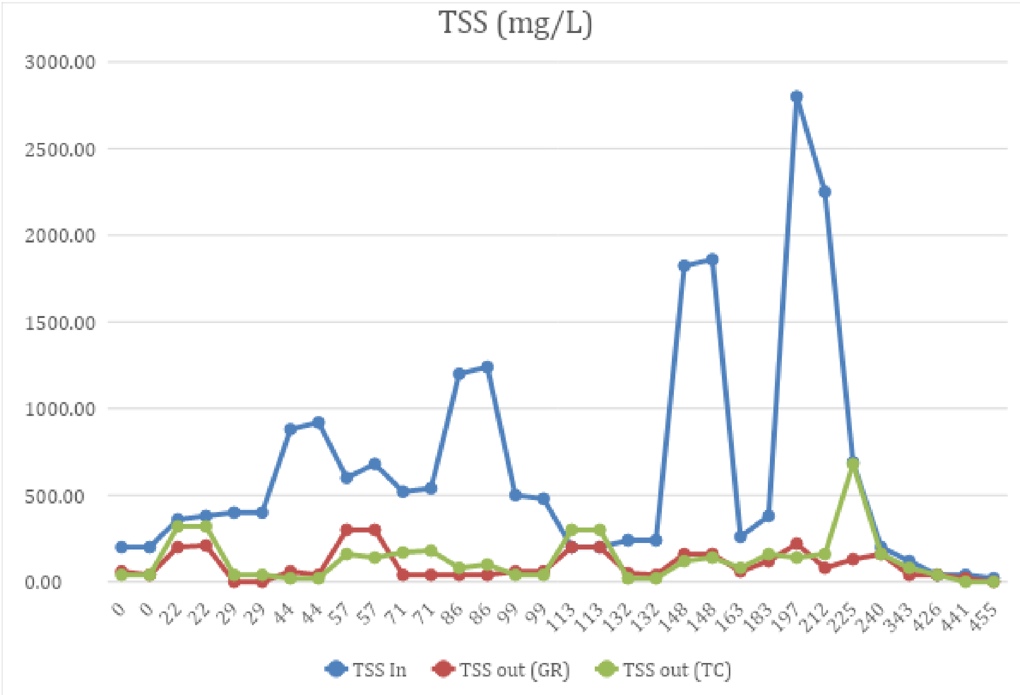


Figure 25. TSS levels in the inflows and outflows from both treatments (N=30, p=.07, .01 respectively)
(See Appendix A for charts showing variance)

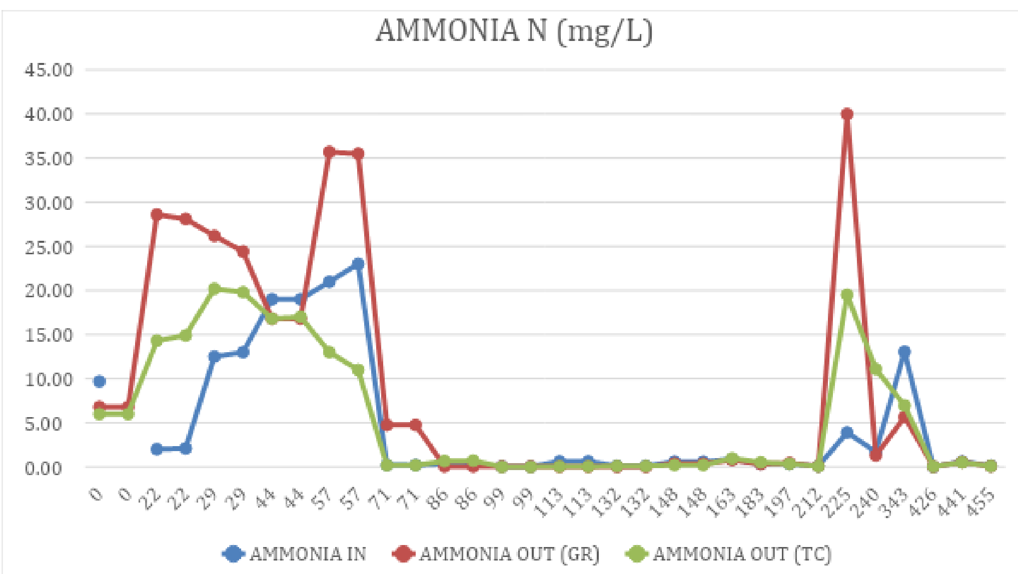


Figure 26. Ammonia-N levels in the inflows and outflows from both treatments (N=30, p=.07, .01 respectively). (See Appendix A for charts showing variance)

Physical processes such as sedimentation contribute to the removal of suspended particles from wastewater (Boano et al., 2020). Considering that suspended particles are both of organic and inorganic nature, their removal directly contributed to the removal of organic matter, nutrients and pathogens (attached to the suspended solids). TSS contributed to 59% (average DCOD/COD ratio of 0.41) of total COD levels in inflow samples therefore contributing significantly to COD removal.

Figure 6 presents the BOD_5 and COD levels in the inflows and the outflows of both systems. While significant reduction in BOD_5 levels were observed at the outlet, no significant difference was observed between the effluent BOD_5 levels. An average of 77% and 78% BOD_5 removal was observed in gravel and terracotta substrates, respectively. The BOD removal could be attributed to both the physical and the biological degradation processes occurring within the systems (Tanner, Clayton, & Upsdell, 1995). In addition to removal of suspended organic matter by sedimentation, microbial degradation of both dissolved and particulate organic matter contributes to BOD_5 removal. Microbes attached to the biofilm plays an important role in degradation of organic matter. They also help in uptake of nutrients thereby reducing the nutrient content in outflows (Saeed, Majed, Khan, & Mallika, 2019). Conversely, the two treatment systems increased ammonia (gravel to a greater degree) suggesting ammonification is occurring (discussed below). There is not time for nitrification to occur due to the short residence time and heterotrophic bacteria are more competitive than nitrifiers.

The organic matter degradation in filtration systems is modelled using first order kinetics equations (Reed, 1993). Using equation 3 and 4, BOD_5 and COD decay rate constants for gravel and terracotta setups was estimated. The average temperature during the sampling period was 26.3 ºC (21-29 ºC). For comparison, the decay rates for both setups were estimated at 20ºC.

Despite the similar BOD_5 removal efficiencies and effluent quality, significantly higher decay rates were observed in the gravel setup as compared to the terracotta setup. As mentioned above, ammonification was also higher in the gravel, suggesting it may have a greater surface area allowing for greater bacterial colonization. An average K_{BOD5} at 20 ºC for gravel and terracotta setup was estimated as 0.89d^{-1} and 0.70 d^{-1} respectively. While a significant difference was observed in the K_{BOD5}, no difference was observed in the K_{COD} and K_{DCOD} for both the setups (Table 15). The estimated decay rates are well within the range mentioned in literature with highest values reported for K_{BOD5} as 6.11d^{-1} (Gajewska et al., 2020). Decay rate constant depends on the biodegradability of the organic matter (glucose vs. ligand) and the hydraulic retention time (Abdelhakeem, Aboulroos, & Kamel, 2016). In this study while both treatments were exposed to the same inflows, the difference in the pore volumes contributed to different HRTs. The HRT estimated for gravel setup was less (0.8 days) than terracotta setup (1.01 days). The increased residence time also allowed for greater levels of bacterial metabolism and degradation. This resulted in high K_{BOD5} values in gravel setup as compared to terracotta setup. K_{COD} at 20 ºC of 0.62 d^{-1} and 0.45 d^{-1} was observed for gravel and terracotta setups but the difference was not statistically different. Terracotta material is reported to support stable biofilms that contributes significantly to the removal of inorganic pollutants, which might have contributed to high variability in decay rate constants (Jamwal & Phillips, 2019). A decrease in effluent BOD_5 /COD ratio (0.23) and increase in DCOD/COD ratio (0.6) indicating removal of biodegradable organic matter and conversion of suspended non-biodegradable fraction to dissolved fraction during the treatment process (Saeed et al., 2019). Table 15 list the average decay rate constants for water quality parameters for both setups.

Table 15. Volumetric decay rate constants for gravel and terracotta setups

Decay rate constant at 20°C (d^{-1})	Gravel	Terracotta
K_{BOD5}	0.89[a]	0.70[a]
K_{COD}	0.62	0.45
K_{DCOD}	0.40	0.29
K_{TN}	0.03	0.05
K_{TP}	0.24	0.29

[a] the difference is statistically significant $p<0.05$

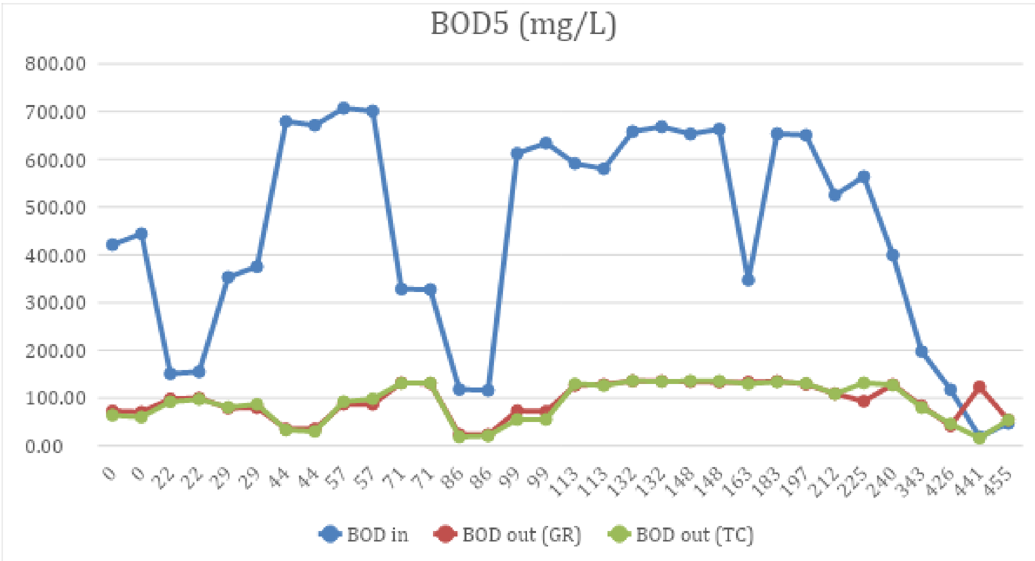


Figure 27. BOD5 (N=30, P=.15) levels in the inflows and outflows
(See Appendix A for charts showing variance).

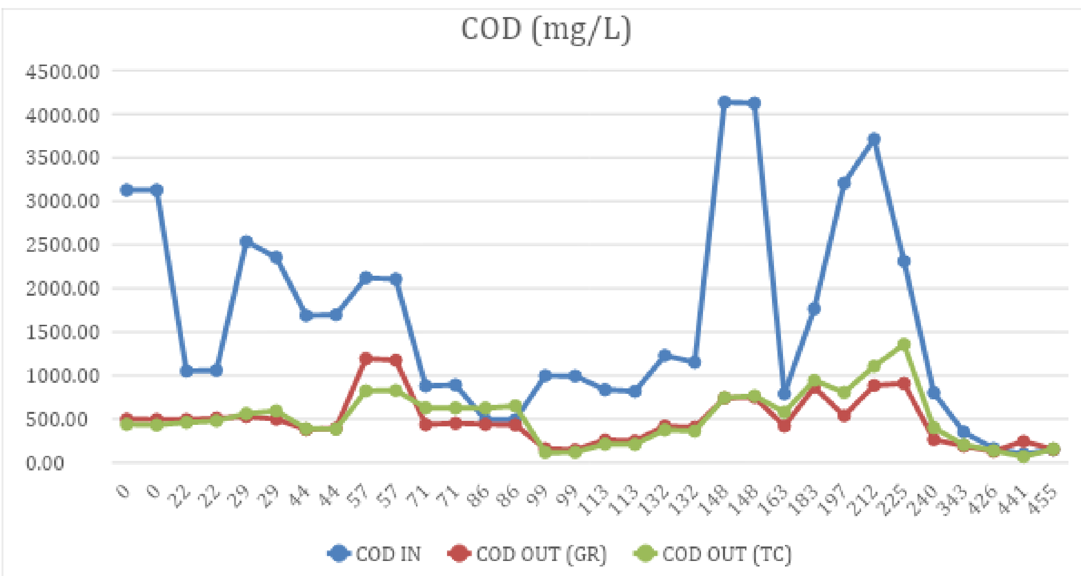


Figure 28. COD (N=30, P=.15) levels in the inflows and outflows
(See Appendix A for charts showing variance).

An average of 14% and 24% reduction in TN levels occurred in gravel and terracotta, respectively (p=.01). Both physical and chemical processes facilitate the reduction of TN (Lee, Fletcher, & Sun, 2009). Sedimentation processes remove the TN present in suspended particles whereas the dissolved constituents such as Ammonia-N and Nitrates-N are removed by subsequent nitrification and denitrification processes. We observed 20 % and 22 % reduction in Nitrates-N levels in gravel and terracotta. Contrary to TN and Nitrates-N, significant increases in Ammonia-N levels occurred in effluents, with the highest in gravel. Plants prefer Ammonia-N as compared to nitrates-N as a nutrient source. Absence of plants and slower bacterial metabolism by nitrifiers led to increased ammonification (Gajewska et al., 2020). For complete transformation (conversion of Ammonia-N to nitrogen gas) and removal of TN 8 days of hydraulic retention time is suggested in the literature (Lee et al., 2009).

Average TP levels of 9.2 mg/l and 7.1 mg/l occurred in the outflow from gravel and terracotta, respectively. The percent TP removal for both setups was significantly different with 59% (SD 20.9) TP reduction observed in terracotta (p<.01). While significant reduction occurred, no significant difference was observed in the decay constant K_{TP}. Increased TP reduction could be attributed to the higher retention time and presence of stable biofilms that improve the efficacy of the physical and chemical processes in the terracotta treatment. Terracotta aggregate material offers greater surface area for biofilms to grow thereby enhancing the TP through adsorption and uptake by bacteria for biofilm formation (Jamwal & Phillips, 2019).

While both substrates were efficient in removing TSS and organic matter, no significant reduction was observed in FC levels, particularly in the later stages of the study. Various factors, such sediment removal, sunlight intensity, natural die-off and grazing contribute to FC removal in constructed wetlands (Anderson, Whitlock, & Harwood, 2005; Nguyen, Le, Garnier, Janeau, & Rochelle-Newall, 2016). The effectiveness of processes listed above depends on the hydraulic retention time and acclimatization/survival of FC to the new environment. Figure 29 shows an average of 1 log order FC removal during the initial four months of operation followed by sudden drop in FC removal. The drop could be attributed to either increased survival or growth of FC in the treatments as surfaces became colonized by periphyton communities and both TSS and nutrients increased (Reed, 1993). Similar FC removal rates were observed for constructed wetland units operated at high HLR (880mm/day) for 8 years in Rabat (Morocco) (Boano et al., 2020). Various studies report the persistence of FC in organic sediments and low die-off rates in wastewater (Anderson et al., 2005; Burton, Gunnison, & Lanza, 1987).

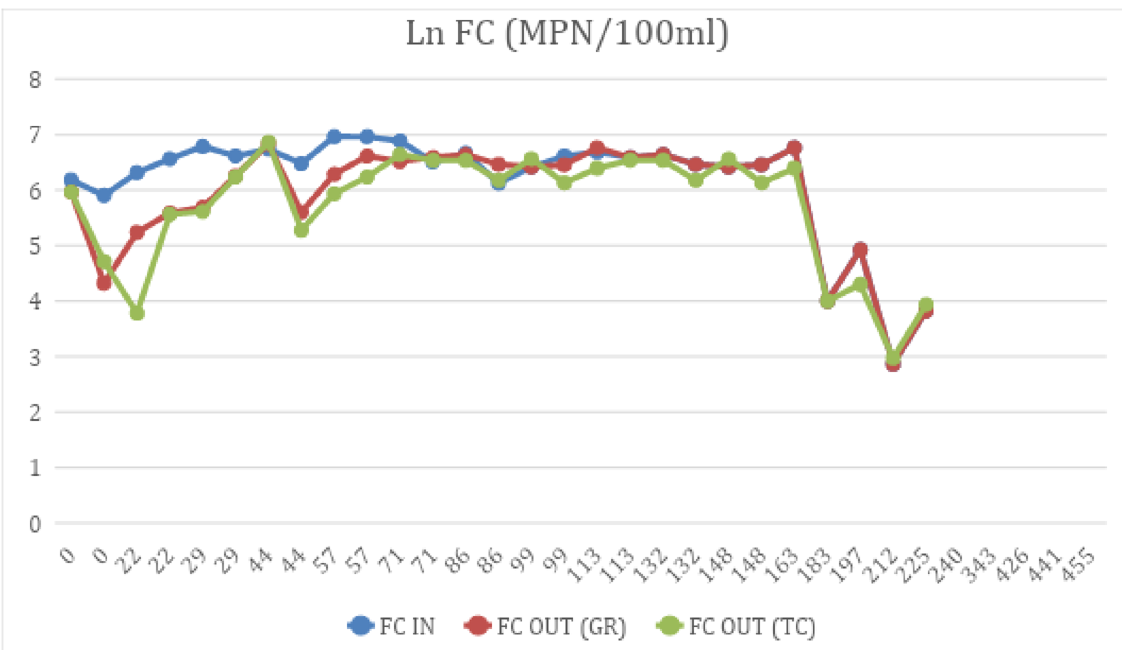


Figure 29. FC (LN) levels in inflows and effluent of gravel and terracotta setup
(See Appendix A for charts showing variance)

4.3.4 Contaminant load removal efficiency

Considering the setups were deployed in an open space devoid of shading, we expected high evaporative losses from the system. The water balance estimates a loss of 129 L/day of water from each system. The data is in sync with the daily average evaporation rates reported by the Indian meteorological department (IMD) for Bangalore city (10mm/day). Equation 4, 5 and equation 6 is used to estimate mass loading rates (MLR) (inflows and outflows) and mass removal rate respectively. Finally, percent mass removal rate is estimated using equation 7.

The treatments were operated at identical HLR (265 mm/day) and contaminant loadings (highly variable) with average rates listed in Table 16 ($g/m^2/day$). Unlike several previous studies in this domain, this study's exposures demonstrated high variability in the inflow pollutant loads (See table 16).

Table 16. Average daily contaminant loading rates

Loading rate	Average loading rate ± Std dev	Max	Min
TSS ($g/m^2/day$)	256 ± 283	1050	8
BOD_5 ($g/m^2/day$)	157 ± 86	264	7
COD ($g/m^2/day$)	547 ± 435	1548	37
DCOD ($g/m^2/day$)	157 ± 131	491	6
TN ($g/m^2/day$)	7.6 ± 5.8	22	2
TP ($g/m^2/day$)	2.6 ± 1.7	6	0.8

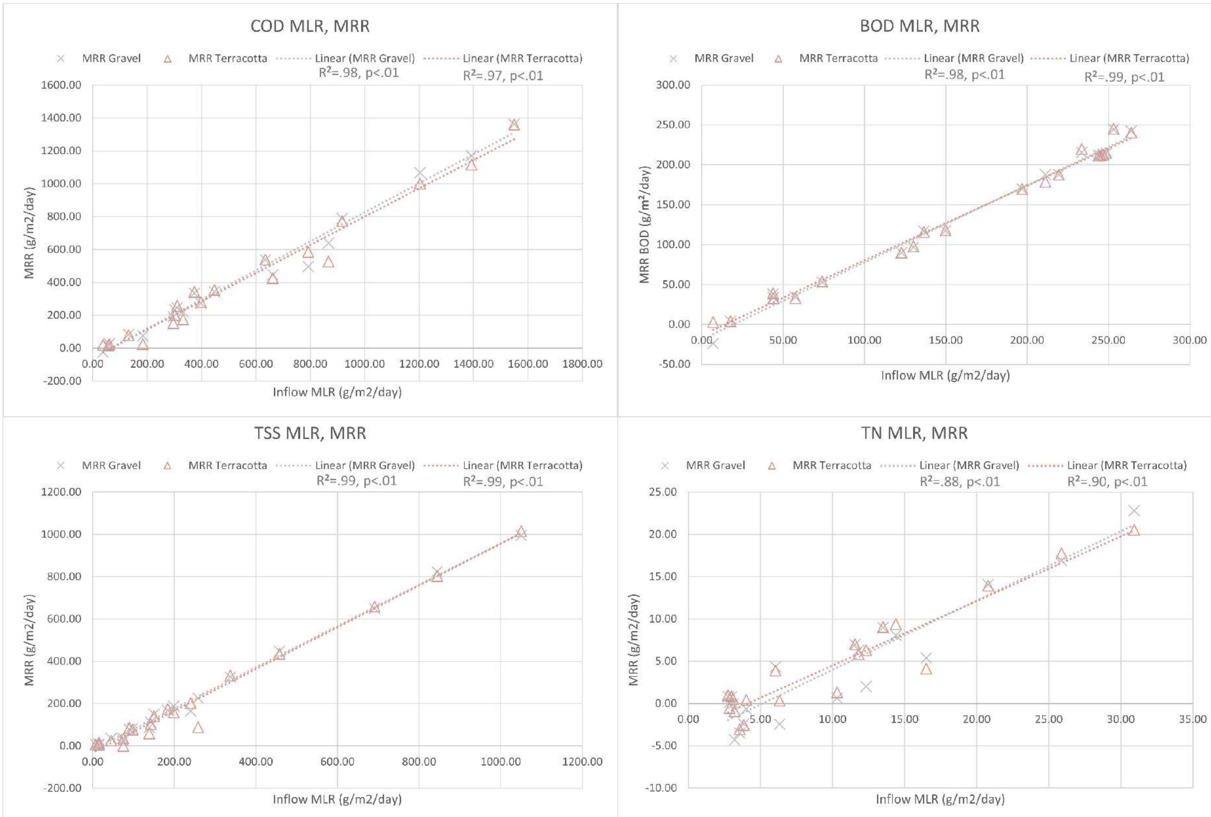


Figure 30. Relationship between contaminant mass loading rate and the mass removal rate.
A linear relationship was observed between MRR and MLR for all pollutants (Table 6). For all parameters, there was a linear relationship with high regression coefficients indicating constant rate of change of MRR with respect to MLR. The relationships are similar to the literature, suggesting a slope of the curve (representing percentage MRR) close to 1, except for cases where HRT is less than or equal to1 (Ghosh & Gopal, 2010). This also suggests low HRT physical removal processes are dominant whereas at high HRT, biological processes contribute to a high rate of MRR change (Tanner et al., 1995).

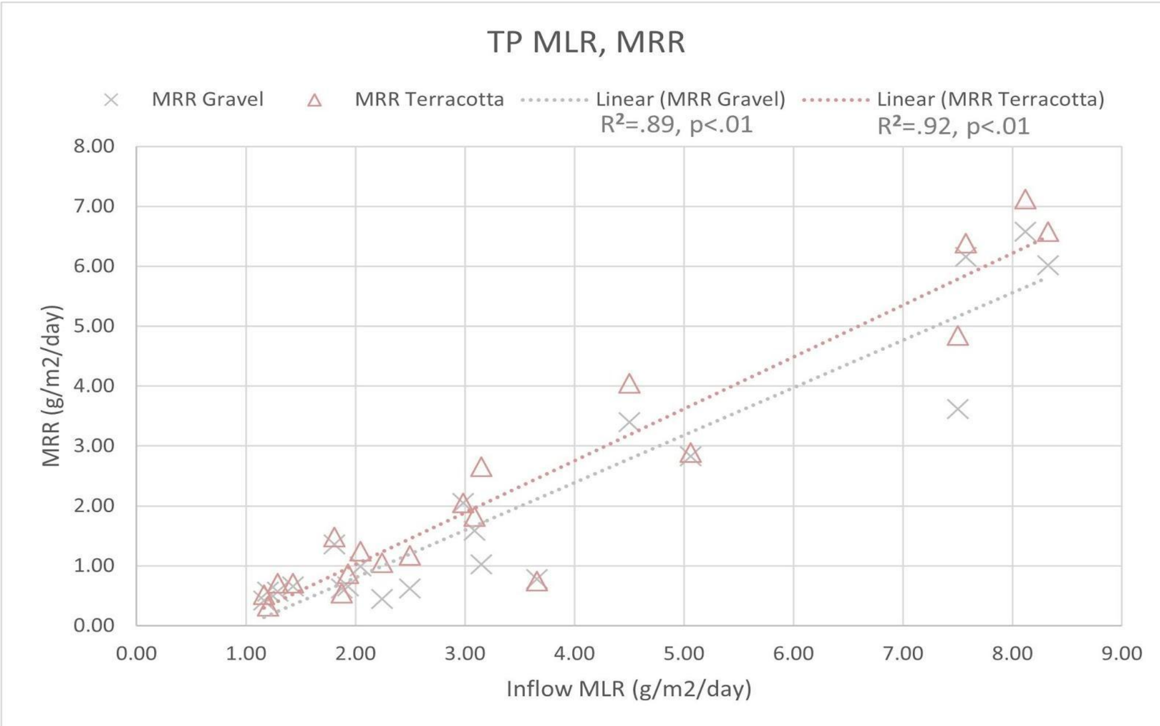


Figure 31. Relationship between contaminant mass loading rate and mass removal rate (Phosphorus)

The data suggests similar mass loading rate removal efficiency ($p>0.05$) provided by both treatments. Despite operating at lower HRT, the gravel setup provided similar load removal efficiencies indicating its suitability for treatment of dry weather flows in open storm drains.

The treatments demonstrated their effectiveness at removing BOD_5 and COD, as their MLRs comply with effluent discharge standards (Fig 31). Except for TSS, the relationship between effluent levels (COD, BOD_5) and mass loading rate was best described by a polynomial equation. The data fitting in the polynomial model revealed that both setups at their present design are capable of meeting effluent discharge standards when exposed to BOD_5 and COD loading rate of 28 g/m^2/day and 138 g/m^2/day, respectively. However, it should be noted that targeting specific inflow qualities for PGI interventions may prove impractical in the field, and the value of future studies such as this one may be in their ability to suggest likely removal efficiencies given a broad range of inflow characteristics.

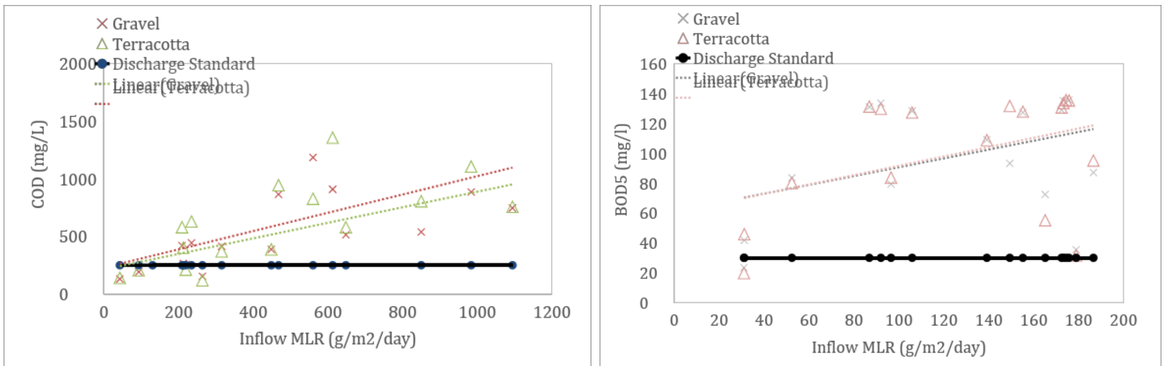


Figure 32. Mass removal rate for COD AND BOD5 compared to CPCB standards

4.4 Conclusions and future research

This study demonstrates the applicability of inexpensive, locally available aggregate substrates (gravel and terracotta rubble) in treating the highly variable DWF in open stormwater drains without the use of specialized or mechanical technology. Results suggest that gravel substrates may be marginally better for the removal of organics, with a statistically higher decay rate constant for BOD_5. Whereas terracotta rubble substrates performed better for the removal of Total Phosphorous and Ortho-P, and may be a more suitable choice where greywater flows contain an excess of phosphorus-laden contaminants such as detergents.

Limitations of this field study include the lack of an initial stage ("forebay") for primary settling of suspended particles, which led to periodic clogging and increased maintenance. Future designs and field tests for PGI should include this critical component as the first stage of the system to prevent silt buildup. Further, as this study built a semi-controlled channelized environment with valve-controlled inlets, it may not have fully captured the pollutant and flow dynamics of an open drain that may be expected in the field. Full scale pilots within open drains are therefore necessary to add robustness to these results.

For similar treatment designs as this, an average BOD_5 and COD MLR of 28 $g/m^2/day$ and 138 $g/m^2/day$, respectively could be considered to result in effluents meeting national discharge standards set by the CPCB (30mg/l and 250mg/l respectively). If inflows have constituents of higher concentrations, these standards may not be met; however, significant reductions of many constituents can still be expected. Higher MLR will likely require the installation of larger or multiple interventions in series throughout the larger catchment area to meet discharge standards. It is suggested that a minimum of 18 hours of retention time are provided to achieve similar effluent quality on a per-unit basis. Finally, it is suggested that varying the depth of the treatment units at intervals along the length of the system may provide additional opportunities for both anaerobic and aerobic digestion to occur, including anoxic denitrification to increase the removal efficiency of Ammonia-N.

The broader aim of this research is to assess the likely performance of multiple PGI interventions in terms of their cumulative impact on the transport and loading of contaminants into downstream receiving waterbodies for the purpose of improving or forestalling the eutrophication of urban lakes. Therefore, instead of strict compliance with the water quality standards at the immediate downstream sampling point of an individual system, the inlets of lakes will likely be used as critical assessment points for water quality parameters, such as TSS, Phosphorous, and Nitrogen. Results reported here can be used to guide simulated hydrological modelling studies for application in analogous study areas in the Bangalore watershed that incorporate PGI as Low Impact Development (LID) objects. We suggest that efficiencies for individual PGI treatment objects may be informed by the field-verified results presented in Table

3. These include reductions for TP ranging from 48-59%, TN from 14-24%, and TSS ranging from 74-79%.

Future research in this domain should focus on 1) developing and comparing the performance of various hypothetical upscaling scenarios using computer modelling platforms such as the US EPA's Stormwater Management Model (SWMM); 2) Considering how additional design parameters impact the performance of in-situ interventions. For example, how the removal efficiency of pollutants is impacted by the addition of various upstream control measures for diverting solid waste and lowering flow velocity, alternative materials and configurations, as well as the water quality and maintenance implications of introducing plants into the system. Beyond informing localized decision-making processes, this study adds to the broader discourse on GI innovation in the Global South and addresses persistent questions related to the effective siting and upscaling of GI retrofits to maximize their water quality impacts.

4.5 References

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4.6 Appendix A: Supplementary Data and results

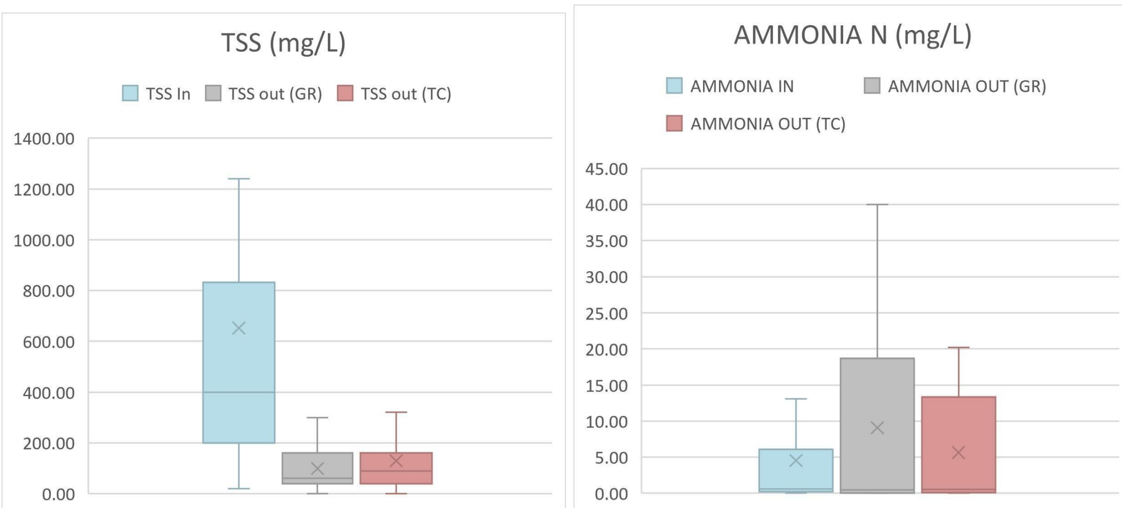


Figure A1 TSS and Ammonia-N concentrations in inflow and outflow

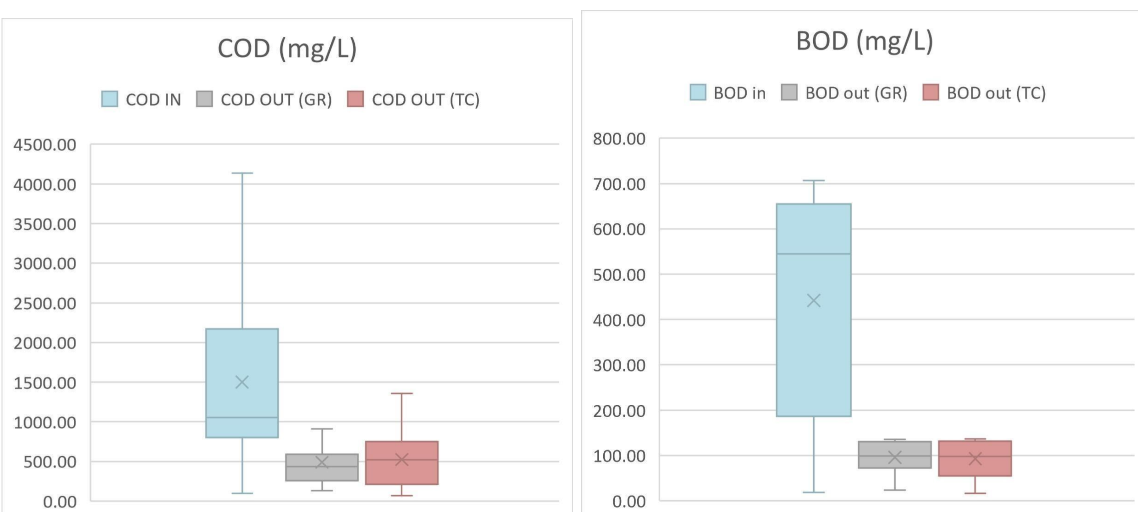


Figure A2 COD and BOD concentrations in inflow and outflow

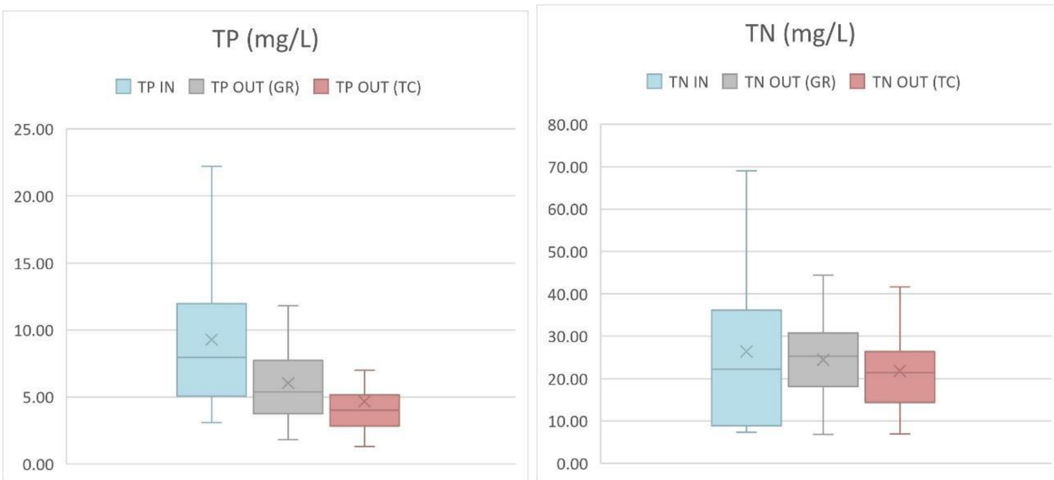


Figure A3 TP and TN concentrations in inflow and outflow

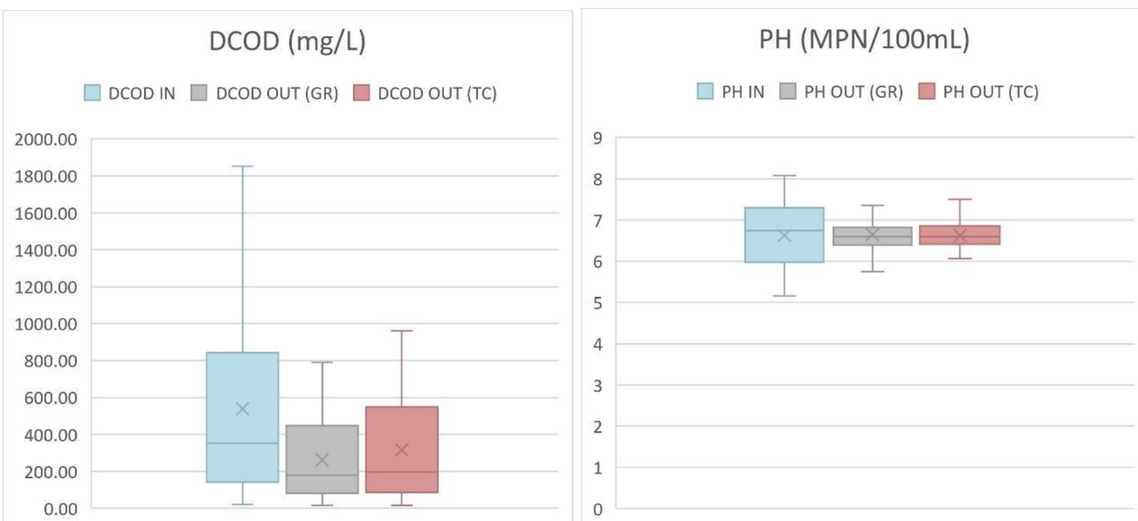


Figure A4 DCOD and PH concentrations in inflow and outflow

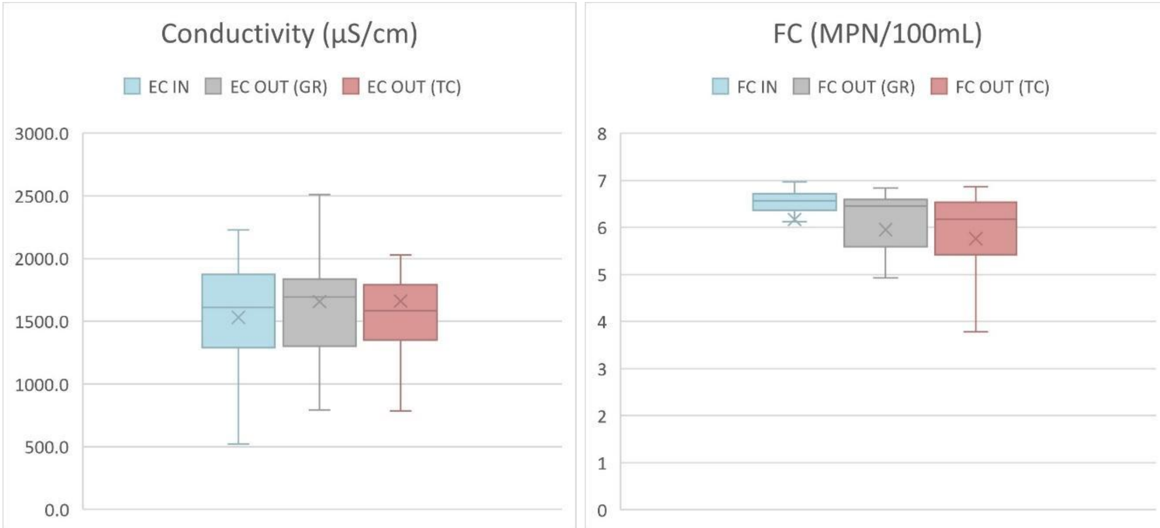


Figure A5 Conductivity and FC concentrations in inflow and outflow

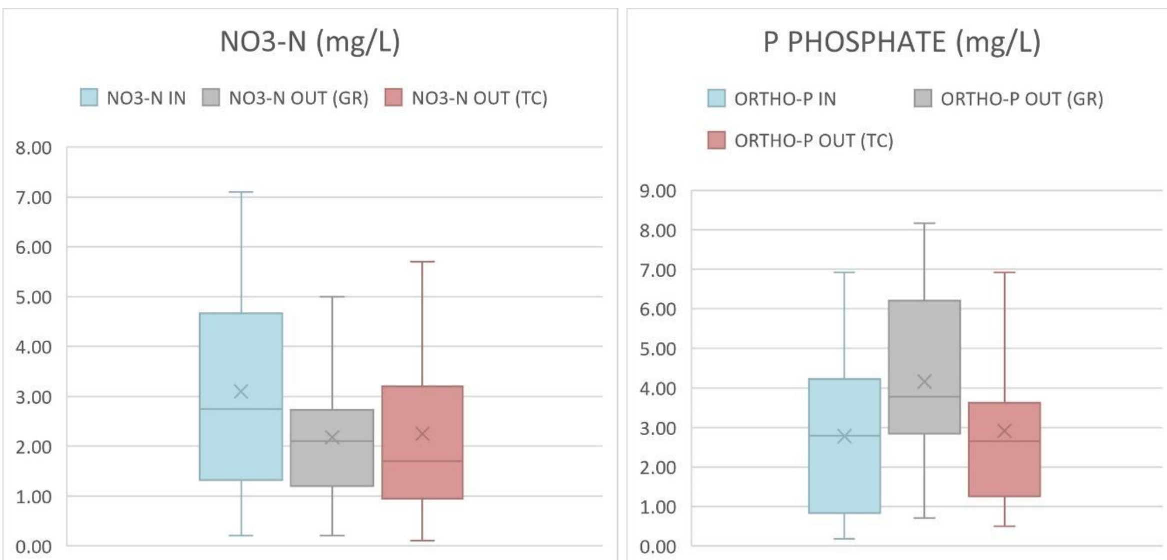


Figure A6 N03-N and P Phosphate concentrations in inflow and outflow

Chapter 5 Assessing Catchment Scale Performance of In-stream Green Infrastructure Interventions Using SWMM-based TOPSIS.[4]

Abstract: Provisional Green Infrastructure (PGI) refers to a range of low-cost intervention strategies that are currently being developed and deployed by non-state actors in the context of Indian megacities to supplement the inefficient operation of large scale grey infrastructures while providing other localized multi-functional benefits. This study addresses how variations in the location and configuration of PGI interventions at the watershed catchment scale impact their cumulative performance in terms of contaminant removal efficiency, cost, and public accessibility using Stormwater Managment Model (SWMM) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) In this study, we consider upscaling scenarios for PGI in the context of an 5.4 sq. km. urbanized watershed in the periphery of Bangalore, India: 1) Downgradient dispersed 2) Downgradient centralized 3) Upgradient dispersed 4) Upgradient centralized. In addition to these PGI upscaling scenarios, S0 was employed as a 'control' scenario (in which no interventions are made), and 5 assumed the construction of a conventional wastewater treatment plant (WWTP). TSS removal efficiencies ranged from 53% to 97% and were higher in upgradient locations. TP removal efficiencies ranged from 59% to 90% and were less sensitive to location, but were substantially improved in scenarios with dispersed configurations. Costs (combining initial capital investment, operational and maintenance) associated with PGI upscaling (4.2-6.3 million INR) were substantially lower

[4] Currently under review as Phillips et al (2021). *Assessing catchment-scale performance of in-stream Green Infrastructure interventions using SWMM-based TOPSIS.* Landscape and Urban Planning.

than for S5 (37.5 million INR). Public accessibility scores for upgradient scenarios were considerably larger than downgradient or scenarios with 95.5% and 81% for S3 and S4 respectively. Results further suggest that dispersed configurations of PGI interventions are optimal wherever such an approach is feasible. In cases where dispersed configurations prove unfeasible, centralized configurations should be placed preferentially in upgradient locations in the watershed (second or third order nallahs), and in locations with higher pollutant concentrations and lower flow rates such as channels with shallower slopes. Authors emphasize PGI should not be viewed as a functional replacement for conventional wastewater treatment infrastructures, but rather as a supplementary stop-gap function in contexts where functional separation of wastewater and stormwater are unlikely to occur, or where existing large scale WWTP's operate below their designed capacity.

5.1 Introduction

Rapid and often unplanned urban growth in the Global South continues to radically alter the patterns and processes of land use, land cover and hydrology. In the context of Indian megacities, growing urban populations and informal development patterns, coupled with a lack of effective policy, capital investment and frequent power failures, results in persistent capacity gaps in conventional wastewater treatment facilities, leaving an estimated 60 percent of all wastewater flows entirely untreated before being discharged into local streams, rivers, and lakes (Schellenberg et al., 2020). Excess inflows of nutrients and sediment into these downstream receiving waters is associated with a range of adverse ecological, economic, and human health impacts, including eutrophication, harmful algal blooms, fish kills, toxic foam events, degradation of recreational amenity, and reductions in groundwater recharge capacity (Benjamin et al., 1996; Lele et al., 2013; Majumdar, 2012).

Throughout many Indian megacities the separation of sewers from surface drainage systems is relatively rare, even when they have been designed for functional separation (Parkinson et al., 2007). Open channel conveyance networks, (often referred to as "nallahs") are therefore subject to combined inflows of both stormwater and wastewater flows (Fig. 33). Dry Weather Flow (DWF) in open channels is often composed of a mixture of industrial discharge, leaks from adjacent piped sewage networks, as well as direct inflows of partially or entirely untreated domestic grey and blackwater sources. Inflows of untreated domestic greywater in DWF contribute substantially to total suspended solids (TSS) and Total Phosphorus (TP) loading, with TP inputs especially high in Indian provinces that have not yet banned the use of phosphorus in laundry and dishwashing detergents (*Detergents Threaten India's Waterbodies*, n.d.). Contamination of TSS and TP tends to be more highly concentrated during the dry season than in the wet season, as flows and contaminants are not diluted by stormwater runoff during monsoonal precipitation events (Boks, 2018). Additionally, cities with lower per capita water consumption tend to produce more concentrated sources of greywater, with TSS ranging from 50-1500 mg/L and TP ranging from 1-200 mg/L (Morel & Diener, 2006). These unique conditions underscore the importance of understanding the performance of Low Impact Development (LID) practices in relation to DWF conditions, and is the primary focus of this study.

Figure 33. Open channel networks (nallahs) in the Binnamangala catchment
(near Bangalore, India). a) secondary (upgradient) channels at the scale of neighborhoods carry Dry Weather Flows (DWF) to b) primary channels (downgradient) and in turn into local receiving waters such as c) Nelamangala lake, which is often choked with silt, solid waste, and emergent macrophytes such as water hyacinth (indicating high levels of nutrient pollution).

Provisional Green Infrastructure (PGI)

PGI refers to a range of low-cost intervention strategies that are currently being developed and deployed by non-state actors in the context of Indian megacities to supplement the inefficient operation of large scale grey infrastructures (Phillips et al., 2020). In resource scarce, space-constrained environments where source control measures may prove unfeasible, PGI targets the in-stream context to provide physical, chemical, or biological treatments to flows that have already been captured and transported within a conveyance network (Fig 34). PGI is intended for use in urban streams that contain a minimum of blackwater and industrial effluents, and is highly suitable for DWF conditions containing domestic greywater sources. While preliminary field-testing have demonstrated the localized positive impacts of these interventions on individual sites (Bhatnagar, 2017; Jamwal & Phillips, 2021; Joshi & Patil, 2018), there is currently a lack of understanding regarding how these measures should be effectively upscaled throughout a watershed catchment area, and the factors driving performance, future implementation, broader policy and decision-making. The purpose of this study therefore is to introduce new decision support tools and methods for deploying PGI in megacity watersheds in a manner that balances the need for water quality performance with other important factors to provide multi-functional benefits.

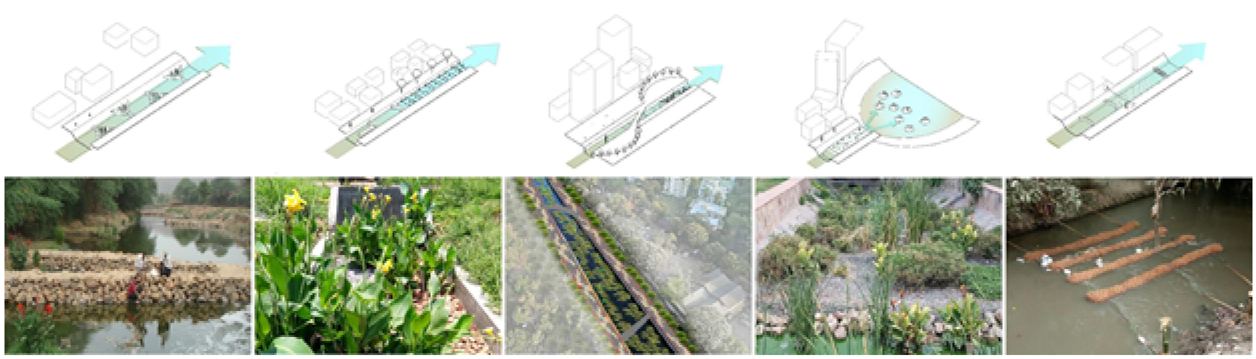


Figure 34. Five PGI case studies from across the Indian subcontinent
(from left to right) 1) Green Bridges Initiative (Shristi Eco Research Institute) 2) Strategic In-stream Systems (ATREE, Commonstudio) 3) Irla Nallah Re-invigoration project (PK Das & Associates), 4) Hauz Khas Urban Wetland (Evolve Engineering), and 5) Assi Nadi Experiments (INTACH). See also Phillips et al (2020).

These questions of upscaling reflect similar challenges observed in the deployment of established LID practices in the Global North. The catchment scale impacts of LID implementation are currently under-studied and therefore not well understood (Golden & Hoghooghi, 2018; Palla & Gnecco, 2015) (Fig. 35). Emerging research in GI is beginning to address how variations in the spatial distribution of LID interventions at various scales influence various quantitative performance metrics (e.g. nutrient processing, reduction of peak flow behaviour) (Carson, 2019; Jayasooriya & Ng, 2014). Because the physical implementation of LID interventions throughout an entire catchment area is both time and cost-prohibitive, addressing critical questions related to upscaling necessitates the use of geospatial analysis, speculative design, and dynamic water quality modeling tools simultaneously and iteratively. Modeling software such as the U.S. EPA Stormwater Management Model (SWMM) can be used to rapidly simulate the probable effects of LID practices at multiple spatial scales (Rosa et al., 2015) and has been used in a variety of analogous studies (Boks, 2018; Endreny & Collins, 2009; Hurley & Forman, 2011; Liu, Cibin, et al., 2016; Loperfido et al., 2014; Palla & Gnecco, 2015).

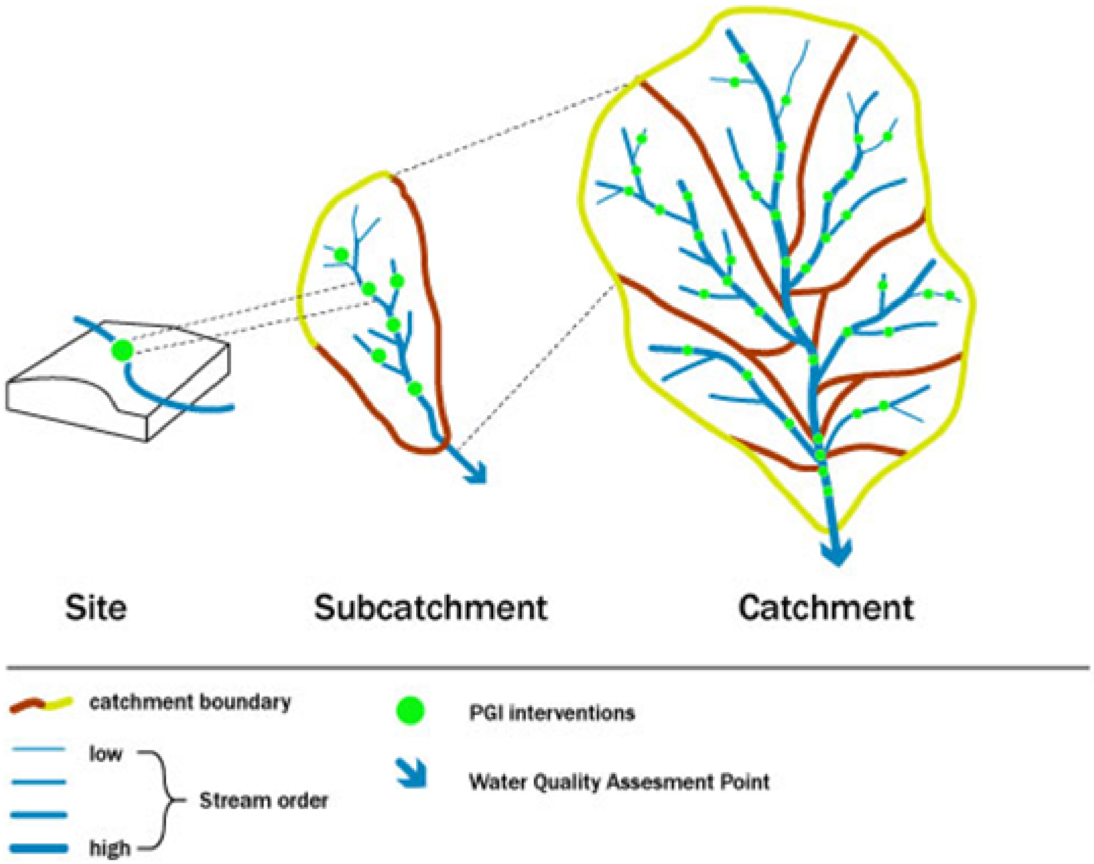


Figure 35. Conceptualizing the scaling effects of PGI interventions on downstream receiving waters from individual sites (left) to nested catchment scales (not to scale). Diagram by Daniel Phillips, adapted in part from (Golden & Hoghooghi, 2018).

Previous studies highlight the mixed results and ongoing debates regarding the relative effectiveness of *centralized* as opposed to *dispersed* deployment strategies for LID at the catchment scale (Carson, C, 2019; Endreny & Collins, 2009; Hurley & Forman 2011) . Other studies in this domain have emphasized the need to supplement hydrological modelling processes with various Multi-Criteria Decision Analysis (MCDA) tools to arrive at speculative solutions that balance various stakeholder needs and additional performance criteria (Gogate et al., 2017; Luan et al., 2019). MCDA tools such as Analytical Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) enable the inclusion and weighting of additional criteria such as cost effectiveness, or social and community benefits to optimize potential outcomes from a range of optional upscaling scenarios (Yoon & Hwang, 1995). Morel & Diener (2006) need to address highly contaminated DWF in developing countries with a range of small scale or de-centralized solutions at the household level but do not address the surface water network at large. Although conventional water treatment infrastructures are likely to outperform smaller scale in-situ interventions in terms of cumulative contaminant removal (Sato et al., 2007), decentralized approaches may become more salient to stakeholders and decision-makers when factors such as cost effectiveness and issues of public access and amenity are taken into account (Phillips & Lindquist 2021). Additionally, the use of walkshed analysis as a critical metric of performance is employed to suggest how the benefits and services of nature-based interventions such as PGI might be more equitably distributed to a broad range of urban residents, especially those who are most at risk of suffering the negative environmental impacts of unplanned development (Goldenberg et al., 2018; Boulton et al 2020). Given these important considerations, we pose the following research question: *How are critical performance criteria influenced by both the location and configuration of PGI at the scale of a watershed?*

The purpose of this study is therefore to evaluate and compare the performance of various PGI upscaling scenarios in a peri-urban catchment located in the metropolitan periphery of Bangalore, India in terms of contaminant removal, cost effectiveness and public accessibility. Drawing upon previous lab and field-based experiments that inform the performance criteria for individual interventions (Jamwal & Phillips, 2019), scenarios for centralized vs. dispersed deployment in both primary (downgradient) and secondary (upgradient) surface channels are compared to a control scenario (in which no interventions are made) and a scenario which includes the installation of a conventional wastewater treatment plant (WWTP). Performance is evaluated using SWMM 5.1 and outcomes are further weighted using a three criteria TOPSIS model that seeks to identify appropriate criteria and optimized scenarios for PGI upscaling. Additional weighting schemes are also presented to evaluate various tradeoffs in terms of cost, performance, and public access. In addition to filling gaps of knowledge in this under-studied domain of GI research, the study is intended as a replicable decision-support tool that can be deployed in service of localized implementation of PGI.

5.2 Materials & Methods

This mixed-methods study combines field data, survey data, literature review, and a SWMM-based TOPSIS assessment process to produce an optimized solution (and ranked options) from a series of speculative upscaling scenarios in the context of an urbanized watershed catchment. The general process is presented in Figure 36. This process allows for a range of spatially explicit criteria to be used in a flexible and iterative manner, rapidly evaluating economic, ecological, and spatial "tradeoffs" of multiple alternatives in terms of their relative impact.

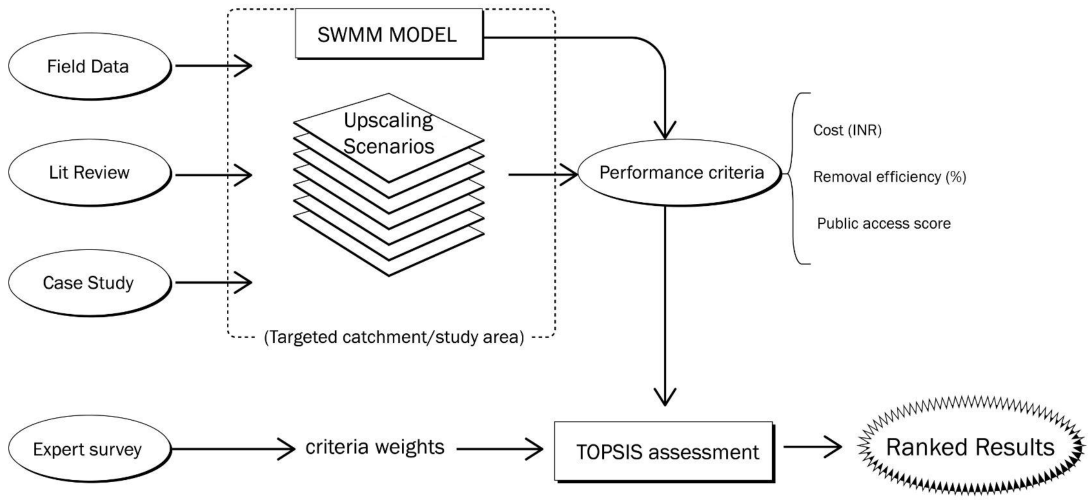


Figure 36. Overview of mixed methods process including scenario development, performance criteria weighting and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) assessment. The outputs of the process include ranking of alternative scenarios according to ideal and least ideal options given a defined weighting scheme for each input criteria

5.2.1 Study Area: Binnamangala catchment (Bangalore, India)

The urban catchment known as Binnamangala, in the peri-urban town of Nelamangala was selected as the study area for the development of PGI upscaling scenarios (Fig 5). This area is known as a "satellite town" of Bangalore, India (a megacity of over 10 million inhabitants) and is projected to experience steady population increases and continued development as the metropolitan boundary of the adjacent megacity continues to expand outward. The study area is defined by a watershed boundary of 5.42 square kilometers, and characterized primarily by built up residential areas (44%), and agricultural land uses (29%) with a minimum of industrial land uses (1.4%). The surface water quality and flow characteristics are influenced by the widespread adoption and use of domestic scale soak-away pits for blackwater discharge, and thus the majority of DWF is primarily composed of domestic greywater flows (Biswas & Jamwal, 2017). These factors render it an ideal context for the application of PGI, as these small scale in-stream treatment interventions are not intended for higher strength blackwater and industrial effluents. Wet Weather Flows (WWF) are intentionally excluded from this study as the catchment is ungauged and historic time series of flow rates are therefore unavailable. Another reason for excluding WWF's is to enable the assessment of performance of PGI during periods when baseflow contamination is undiluted by stormwater and therefore more highly concentrated. The downstream assessment point represents the inlet of Nelamangala lake, a 20 hectare waterbody with recreational, economic, and ecological importance to the local community. As this waterbody has undergone significant water quality degradation after recent urban development in the region, the goal of upstream PGI interventions is to reduce excessive inflows of sediment and nutrients and thus prevent or forestall adverse impacts such as eutrophication.

Binnamangala is home to an estimated 23,455 total residents distributed across 14 "wards" (municipal subdivisions) ranging from 6.9 to 31.3 hectares. Ward-wise population data was derived from a 2017 census by the Bruhat Bengaluru Mahanagara Palike (BBMP; municipal authority of Bangalore). An average of 75 liters per capita per day (lpcd) water consumption was assumed using estimates from Raj (2013) for Bangalore city, which due to supply inefficiencies is significantly lower than the requisite standard 150-200 lpcd. Per estimates provided by Morel and Deiner (2006) Greywater discharge was estimated at 80% of total lpcd consumption, and multiplied by ward population size to yield ward-level average dry weather flow (DWF) (Fig 37, Table 17).

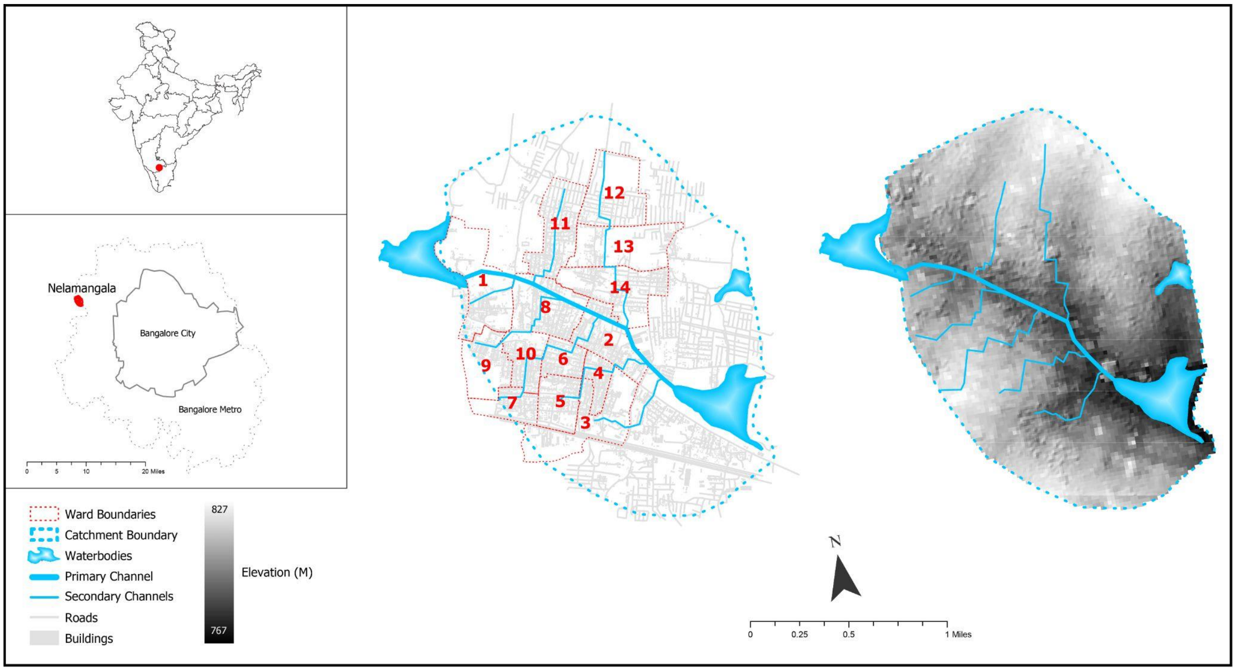


Figure 37. Regional context and catchment characteristics for the Binnamangala study area, including 14 wards, employed as stylized sub-sewershed boundaries.

Table 17. Characteristics by Ward

Wards	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Area (HA)	31.3	23	18.8	28.8	7.0	9.1	13.4	12.6	16.9	10.5	21.8	24.6	25.6	25.4
Population	1305	1608	1084	2101	2240	793	2534	2879	2600	2761	1200	250	500	1600
DWF (lpd)	78300	96480	65040	126060	134400	47580	152040	172740	156600	165660	72000	15000	30000	96000
Average Baseflow (lps)	0.94	1.15	0.78	1.51	1.61	0.57	1.824	2.07	1.87	1.98	0.86	0.18	0.36	1.15

5.2.2 SWMM Model

Stormwater Management Model (SWMM) is typically used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Epa & ORD, 2014). Other studies suggest that SWMM can also be a useful tool in designing for dry weather flow conditions related to sanitary wastewater (Boks, 2018; Lowe, 2010). Modelled flows are either generated from simulated rainfall onto discrete "subcatchment" areas with specific characteristics, or introduced directly to any node object in the network as baseflows with pre-defined pollutant concentrations. This study employs the latter approach, where baseflows are introduced directly to nodes and further transported through conduits representing open channels, and in-stream storage/treatment objects representing PGI interventions, (other object types such as pumps and regulators were not used). Importantly, SWMM 5 also allows users to introduce treatment functionality at nodes or storage objects to evaluate the cumulative effects of treatment throughout a network.

The SWMM modeling in this study was conducted using PCSWMM Version 7.4.3220 with SWMM engine 5.0.013 (CHI, 2021). It consists of 83 junctions, 83 conduits and 1 outfall representing the inlet of Nelamangala lake, which also serves as the assessment point for pollutant loading of TSS and TP. Ward boundaries in this study are employed as stylized sub-sewersheds (as field data for hydrologically accurate sewersheds was unavailable). Ward-level daily DWF averages (based on population) were converted to liters per second (lps) and assumed to be equally distributed across all junctions contained by ward boundaries (Table 1, Fig 6). The creation of a synthetic DWF time series also necessitated the creation of time patterns representing hourly (diurnal), and daily fluctuations. This is achieved within the SWMM environment by the addition of multipliers that augment baseflow patterns at defined intervals. An hourly and daily time pattern was defined based on field data and references from the literature (Rodríguez et al., 2011). As household level monitoring was unavailable, assumptions for TSS and TP concentrations within DWF (150 mg/L and 15 mg/L respectively) were based on typical high value estimates suggested by Morel & Diener (2006) for developing countries.

Channel transects for the main nallah channel were derived from averaging field measured channel morphology. Minor (second order) nallah transects were assumed as standard 1X1 meter rectangular open channels. Although the the entirety of the second order nallahs, and 25% of the main nallah channel are assumed to be concretized, a manning's roughness coefficient of 0.15 was assumed (as opposed to a typical value of 0.011-0.02 for constructed channels (French, 1985)). This value was employed to reflect the presence of accumulated solid waste, sediment, and spontaneous emergent macrophyte growth within the conveyance network (a common condition in the megacity context). Invert elevations for conduits and nodes were derived from subtracting assumed channel depth values from a bare earth Digital Elevation Model (DEM) at a 30 meter spatial resolution (Fig 38).

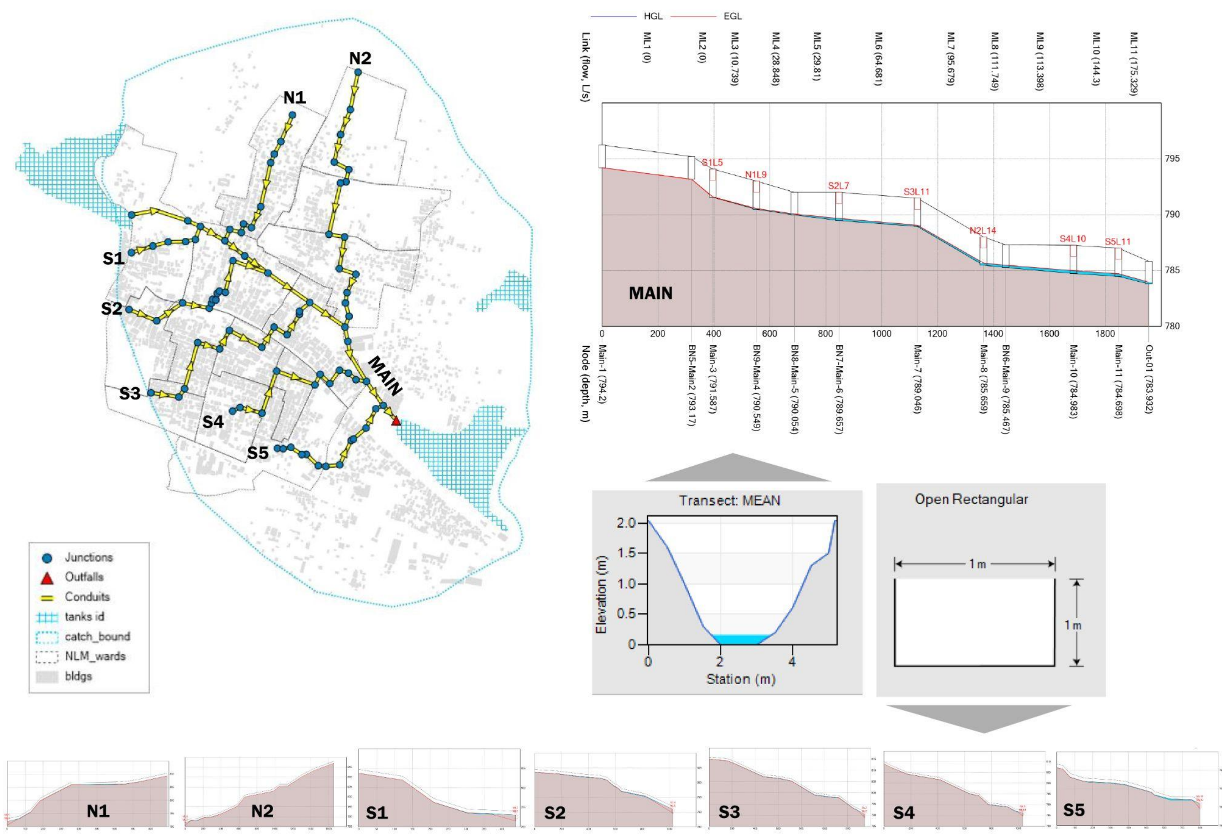


Figure 38. SWMM model characteristics including profiles for primary (downgradient) and secondary (upgradient) channels (N1-N2, S1-S5).

As the study area catchment was ungauged and long term hydrologic data was unavailable, calibration and validation of hydrologic response was not possible, and instead relied on synthetically derived DWF time series. This requires a degree of stylization and is unable to reflect other hydrological phenomena such as groundwater interflow, evaporation, and commercial or industrial inflows that may contribute substantially to baseflows and contamination.

5.2.3 Simulation scenarios

The model employs a varying number of storage unit objects (representing PGI interventions) situated in the path of existing conduit flow. The size and configuration of the storage unit nodes is used to reflect various upscaling scenarios for in-stream PGI interventions. Five scenarios were developed by varying the location, size and configuration of PGI interventions at the watershed scale. Locations include both "downgradient" interventions (situated in the larger, first order nallah through which flow is accumulated at lower elevations in the watershed) and "upgradient" configurations (situated in smaller scale second order nallahs at higher elevations). Configuration variables include both *centralized* (larger continuous interventions covering a large surface area of the channel) and *dispersed* (representing multiple smaller interventions arrayed at intervals along the length of a conveyance channel). These scenarios were compared to a control scenario (S0) (in which no interventions are made) and a non-PGI scenario (S5) that assumes the construction of a conventional WWTP at a downstream location in the watershed (Fig 39). The storage size of centralized PGI nodes was set using a functional storage curve with a constant value of $700m^3$ (assuming a 15m width X 46m length, 1m depth. Dispersed scenarios included a storage area for each PGI intervention ranging from $25m^3$ to $150m^2$ for S5 and S1 respectively.

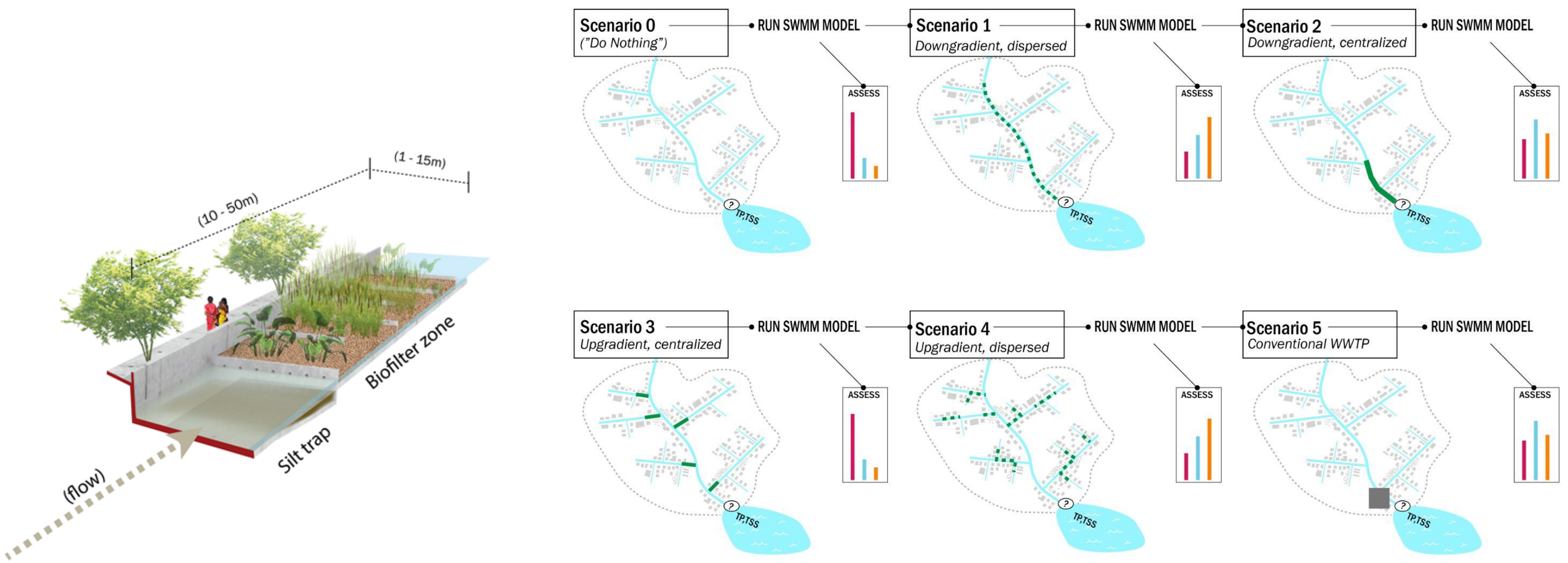


Figure 39.
PGI interventions are introduced into the SWMM model as storage nodes (See appendix A for storage parameters incorporated into the modelling process for each scenario) and deployed in various locations and distributions throughout the catchment area (upgradient vs. downgradient, dispersed vs. centralized). Five PGI implementation scenarios were incorporated into the modelling process and compared to a control scenario (in which no interventions were made) and a scenario incorporating a conventional wastewater treatment plant (WWTP).

5.2.4 Contaminant removal

Primary removal mechanisms for TSS in PGI interventions include gravitational settling due to increased retention time, as well as filtration through substrates (Winston et al., 2017). Removal of TP is driven by adsorption to PGI substrate media, microbial metabolism, and biological uptake/conversion (via phytoremediation) (Vohla et al., 2011).

Despite the fact that pollutants evolve (i.e. decay) throughout the entire distribution network, the SMMM modelling system is only able to represent pollutant loss at nodes, expressed either as a fractional removal equation or as an outlet concentration equation (Rossman & Huber, 2016). Although removal and concentration equations are used in other studies (Baek et al., 2020; Heineman et al., 2013; Hurley & Forman, 2011; Palla & Gnecco, 2015), we acknowledge that pollutant removal equations in SWMM are limited in their ability to account for a range of physical, biological, and chemical processes involved in decontamination. Ideally these modelling processes would be based on additional design parameters, hydraulic variables, and intrinsic chemical properties and reaction rates that a general purpose water management model such as SWMM does not currently permit. Therefore we rely largely on empirical relationships developed from site specific monitoring data (Rossman & Huber, 2016) and other references available in the literature. In this study, *TSS* removals in each of the storage nodes are expressed using the following outlet concentration equation (including conventional notation for the SWMM model):

$$C = TSS * exp(- Vs * DT/Depth) \tag{1}$$

where *C* is the TSS concentration at the outlet of the storage node, *TSS* is the TSS concentration at the inlet of the storage node, 0.0002 is specified as the mean settling velocity (V_s) of suspended particles (m/s) within the storage unit (Chebbo & Gromaire, 2009).

TP removal in this study is expressed as a fractional removal which draws upon field data from a previous study which assessed multiparameter removal efficiencies of pilot-scale PGI intervention over a period of 15 months (Jamwal & Phillips, 2021). In that study, a statistically significant increase in TP removals was observed using terracotta rubble (TR) as a substrate material (59%±20.9) as compared to gravel substrate (49.8% ±19.9). Our current study assumes that TR is employed as a filtration substrate, as its porosity and specific surface area are shown to promote adsorption of TP as wastewater passes through the storage node, while creating a suitable substrate for the growth of specialized aquatic plants which further aid in the uptake of bioavailable orthophosphates. Therefore the fractional of TP removed in each PGI storage node (R) is expressed as:

$$R=0.59*TP \tag{2}$$

where TP is defined as the concentration of TP at the inlet to the storage node.

Finally, the overall contaminant removal performance of each scenario is based on a relative removal of pollutants as compared to S0 (control scenario without interventions). Total pollutant loading is assessed at the system outfall node located in the lowest elevational gradient of the conveyance network. Reductions of pollutant loads at this assessment point is employed as a proxy for the improvement of surface water quality to forstall (or improve) eutrophication levels in Nelamangala lake. Pollutant removal is expressed as a percentage, drawing upon a simple method employed in previous research concerned with TP as a pollutant modeling variable (Hurley & Forman, 2011).

$$= \left[1 - \left(\frac{Total\,pollutant\,load\,(tons\,TSS + tons\,TP)\,at\,outfall\,with\,PGI\,interventions\,present}{Total\,pollutant\,load\,(tons\,TSS + tons\,TP)\,at\,outfall\,without\,interventions}\right)\right] \times 100$$

(3)

5.2.5 TOPSIS Assessment of scenarios

TOPSIS is a mode of MCDA that is employed to identify an ideal solution and/or rank a series of alternatives into a subjective preference order based on weights given to input criteria. The process of TOPSIS assessment includes: 1) formulating a standard data matrix R through non-dimensionalization and standardization of the data for each scenario; 2) determining the optimal and least optimal values of each indicator in the matrix to identify the ideal solution r^i and negative ideal solution r for each scenario; 3) according to the weight of each indicator w_j determined by a subject matter expert or decision-maker, calculating the weighted Euclidean distance from the ideal solution (S^i) and negative ideal solution (S) of a given scenario; and 4) calculating the closeness coefficient (C) for each scenario. The greater the value of C, the closer the corresponding scenario is to the ideal solution (Eq. 4-7).

$$R = r_{ij}, r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{4}$$

$$S_i^+ = \sqrt{\sum_{j=1}^{n} ((r_{ij} - r_j^+) \times w_j)^2} \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} ((r_{ij} - r_j^-) \times w_j)^2} \tag{6}$$

$$C_i^* = \frac{S_i^-}{(S_i^+ + S_i^-)} \tag{7}$$

where r_{ij} is the normalization matrix, i denotes the i-th scenario, j represents the j-th indicator; X_{ij} is the indicator value; S_i^+ is the distance of the ith scenario from the ideal solution; S_i^- is the distance of the i-th scenario from the negative ideal solution; r_j^+ is the ideal solution of the j-th indicator; r_j^- is the negative ideal solution of the j-th indicator; w_j is the weight of the j-th indicator and C_i^* is the closeness coefficient of i-th scenario to the ideal solution.

The criteria selected for weighting in the TOPSIS assessment include 1) Cost 2) Pollutant removal efficiency and 3) Public access score. Comparative weightings given to the three TOPSIS criteria described above were determined through an online survey of water experts working in the Global South (Phillips & Lindquist, 2021), resulting in weights of 40%, 36% and 24% for the criteria of cost, removal efficiency and public access respectively.

5.2.6 Cost criteria

The cost criteria include a combined total for initial installation (including civil work, material and labor) and five years of operation and maintenance (O&M) costs. While any number of factors may influence the actual cost of PGI interventions in the field, the following estimates were generated using input from PGI practitioners (Phillips & Lindquist, 2021) and the author's previous experience building pilot-scale demonstrations elsewhere in the city of Bangalore (Phillips, Jamwal & Gowda, 2022). This includes an estimated 6000 indian rupees (INR) (~$80 USD) per square meter of in-stream intervention with annual O&M estimated at 3000 INR (~$40 USD) per square meter installed. Costs of S5 (conventional WWTP) were estimated using the installation and O&M cost assumptions provided by the Central Pollution Control Board of India (CPCB) per Schellenberg (2020) and Sato et al (2007) for a combined up-flow anaerobic sludge blanket (USAB) and waste stabilization pond (WSP) treatment plant with a operating capacity of 5 million litres per day (MLD).

5.2.7 Pollutant removal criteria

Fractional TP removal efficiencies for S5 were set as 90% of inflow concentrations at the outfall node, drawing on reported performance estimates for USAB's suggested by Tian et al (2015). TSS removals for S5 follow Schellenberg et al (2020) typical performance metrics observed for USAB's in India (secondary treatment), assuming a TSS outlet concentration of <30mg/L. Pollutant removal efficiencies for PGI interventions utilized equations 1-3. Additionally, scenario performance was calculated as total simulated pollutant loading to outfalls (expressed in tons) for a one month duration of dry weather operation for each scenario (as compared to control). Total contaminant removal efficiencies used in TOPSIS analysis are expressed as the mean of TSS and TP removal (as a percentage).

5.2.8 Public access criteria

Public access score is employed as a proxy for value ascribed to the ancillary benefits reported by PGI practitioners (Phillips & Lindquist, 2021). These include anecdotal evidence of increases in local property values, benefits for local biodiversity, and reduction in odors. As observed by Bringula et al (2014) public access and visibility is a vital aspect of the long-term success and sustainability of small scale interventions made in public waterways serving to increase local awareness, engagement and ownership over the operation and maintenance of these systems. This model therefore assumes that a) such multifunctional benefits can be expected with the introduction of PGI and b) these benefits will result in increases of local engagement with the semi-public spaces contained within the immediate bufferzone of the existing conveyance channel (where PGI interventions are introduced). Public access scores in the TOPSIS model are therefore defined as the percentage of total calculated households living within a 10 minute walk of PGI interventions. Walksheds were generated using the network analyst toolset in ArcGIS Pro 2.8.0. (ESRI, 2021). A service area ("walkshed") for each scenario was calculated incorporating point data from PGI interventions as destination facilities along the existing vehicular street network. The output of this process is a spatially explicit walkshed polygon, with the public access score expressed as the percentage of total buildings having a centroid within a given walkshed polygon. Public access score of S5 was set at 0 as conventional WWTP construction was assumed to have negligible nearstream public amenity value.

Using the abovementioned criteria, five scenarios were modelled and evaluated, results are presented and discussed in the following section.

5.3 Results & Discussion

We present the results of, first, relative contaminant removal efficiencies for both TSS and TP. Next, public access scores for each scenario are visualized and discussed. Finally, normalized values for all criteria are presented relative to each scenario, followed by the the results of a post-hoc TOPSIS sensitivity analysis.

5.3.1 Water quality performance

Figure 40 shows the synthetic DWF timeseries for a typical weekly interval, representing diurnal variations in flow (34.4 - 208.3 lps) with a mean value of 96 lps during model operation.

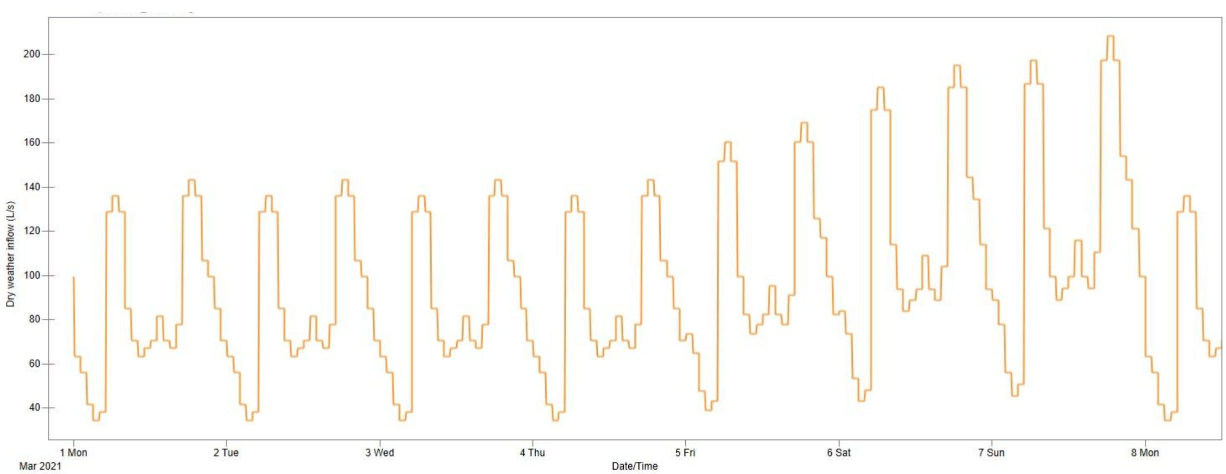
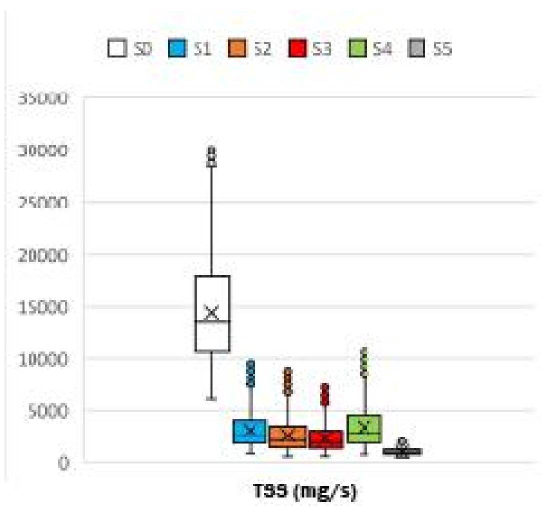


Figure 40. Synthetic DWF timeseries representing one week of flows. Timeseries reflects interaction of two time patterns: 1) hourly (diurnal) patterns and 2) daily patterns which indicate higher flow on weekends.

Removal efficiencies for both TP (90%) and TSS (97%) were highest in S5. Costs are also highest in this scenario as it includes the building of a large scale, conventional USAB facility. TP removal among PGI scenarios was highest in decentralized configurations S1 (87%) and S3 (86%). TP loading was similar in centralized scenarios (S2, S4), with higher peaks in the pollutographs and smaller removal efficiencies compared to all other scenarios (Fig. 41). This suggests that dispersed configurations of PGI in both upgradient and downgradient locations may be more effective at detaining TPl.

TSS removal across PGI scenarios ranged from 53% (S1) to 66% (S5), as compared to 93% under S5 (WWTP). TSS removal was most efficient in S3 and S4, suggesting that TSS removal may be increased when interventions are placed in upgradient locations in the watershed. This is likely due to the increased flow rates observed at lower gradients in the watershed which may decrease the hydraulic retention time and impact the settling rate of suspended particles. Because this SWMM modelling process and pollutant removal equations are sensitive to these flow dynamics, we believe this may explain increases in TSS removal efficiencies for upgradient scenarios (Figs 41). The model did not account for the accumulation of solid waste and debris within the channels, factors which may impact the adsorption, fate and transport of contaminants in throughout a highly informal conveyance network.



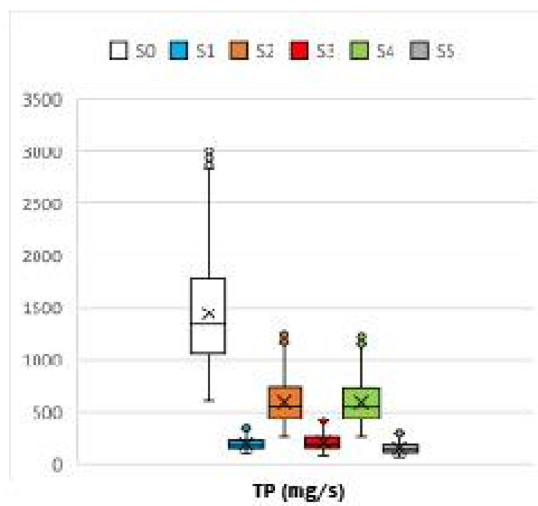


Figure 41. TSS and TP loading at the model outfall node for all scenarios over the duration of the model run, including control scenario in which no interventions are made (S0)

In summary, TSS removal efficiencies were higher in upgradient locations. TP removal efficiencies were less sensitive to location but were substantially improved in scenarios with dispersed configurations. Combining removal efficiency scores for TSS and TP into a single weighted value for the purpose of TOPSIS assessment results in the following water quality performance metrics (see Fig. 44): S5 (93%), S3 (75%), S1 (70%), S4 (62%), S2 (58%).

5.3.2 Public accessibility

Public accessibility scores for upgradient scenarios were considerably larger than downgradient scenarios with 95.5% and 81% of buildings within a 10 minute walk of PGI interventions for S3 and S4 respectively, followed by S1 (73%), S2 (38%). In this growing urban context, dispersed PGI implementation maximizes possibilities for public visibility and engagement, especially when placed in areas of higher overall population density (Fig 43). Results of water quality modeling also suggest that increased removal efficiencies may be expected when placed in these locations, offering more immediate treatment opportunities closer to water quality “hotspots”, where pollutants are most concentrated.

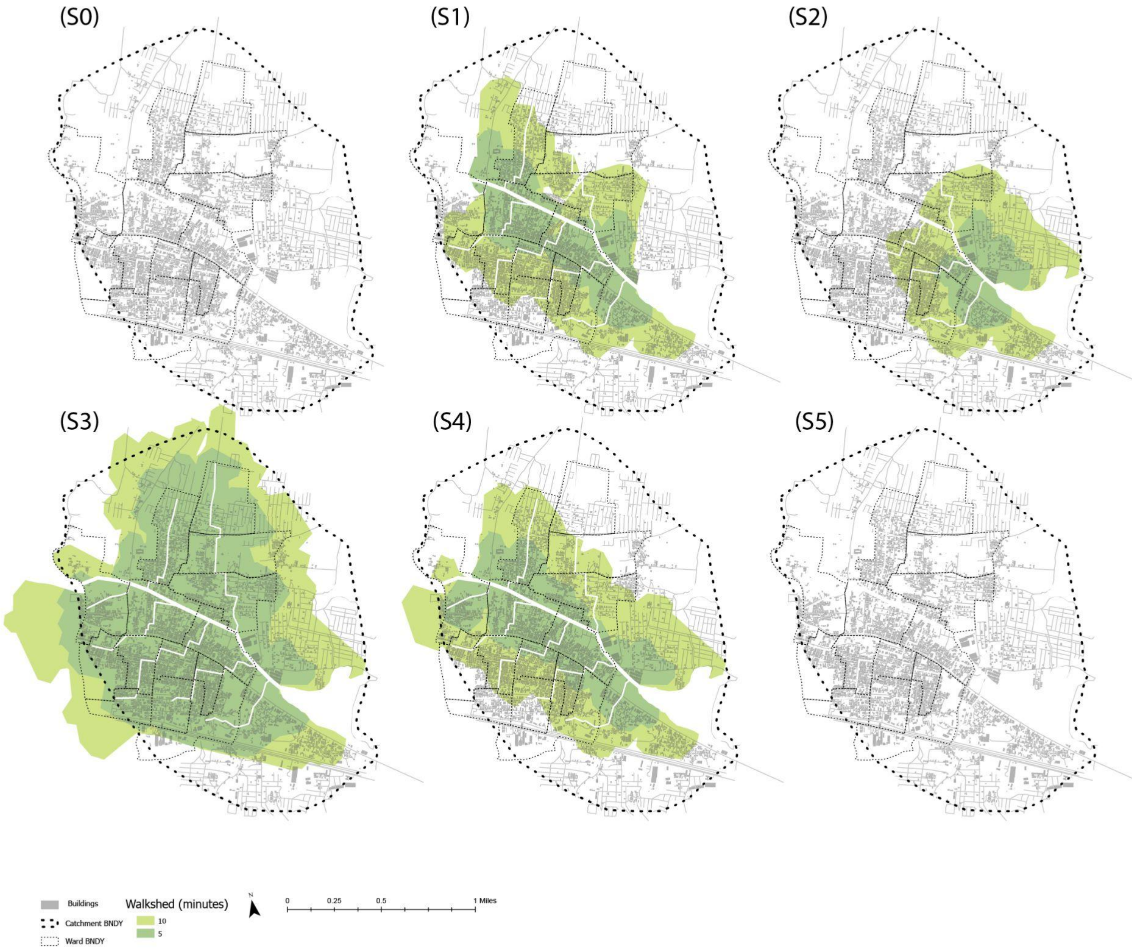


Figure 43. Results of public access analysis, with 5 and 10 minute "walksheds"
Walkshed are shown as green polygons, indicating public access to the ancillary benefits of PGI interventions.

It is important to note that public access criteria are given the least weight (24%) in the TOPSIS analysis according to subject matter experts and therefore had the least influence on ranked results. As suggested in similar studies by Gogate (2017) and Luan (2019), additional post-hoc analysis demonstrates how various weighting schemes impact scenario performance outcomes and are discussed further below.

5.3.3 TOPSIS results and weightings

Normalized scores for all three performance criteria relative to each scenario are presented in figure 44 and detailed results are presented in Table 18. S1 and S2 had the lowest costs (6.2 million INR) and S5 the highest (48.75 million INR). S3 yielded the highest public access score (93%) followed by S4 (81%) and S1 (73%). Overall water quality performance (mean removal efficiency for TSS and TP) is highest in S5 (93%) and lowest in S2 (58%). When ranked outcomes are driven by expert opinion (with 40%,36% and 24% for cost, water quality performance, and public access respectively)) S1 (downgradient location, dispersed configuration) followed by S4 (upgradient location centralized configuration) are the highest ranked. (Table 18, 19).

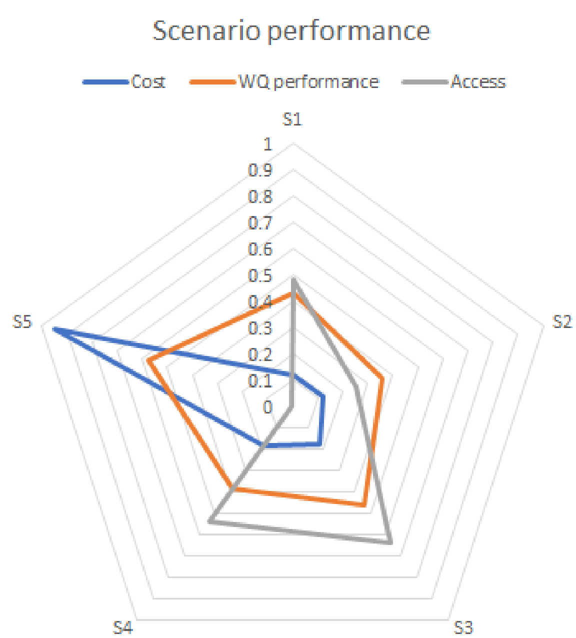


Figure 44. Normalized comparison of performance for all scenarios in terms of cost, overall water quality performance, and public access score.

Table 18. Results of all scenario simulations

	S0: Do Nothing	**S1:** Downgradien t Dispersed	**S2:** Downgradient Centralized	**S3:** Upgradient Dispersed	**S4:** Upgradient, Centralized	**S5**: Conventional WWTP
Total # of PGI interventions	--	7	1	39	7	--
Total M^2 PGI	--	700	700	975	525	--
Construction (million INR)	--	4.2	4.2	5.85	3.15	50
5 yr. O&M (million INR)	--	2.1	2.1	2.925	1.575	25
1 month O&M (million INR)	–	0.175	0.175	0.243	0.262	0.937
Cost Effectiveness (1 month)	–	0.76	0.71	0.89	0.93	3.70
Access score	--	73%	38%	96%	81%	0%
			TSS			
Max. TSS (mg/s)	30300	9493	8845	7350	11040	2055
Min. TSS (mg/s)	6062	824.9	494.5	518.3	716.9	415.5
Mean TSS (mg/s)	14420	3104	2609	2303	3392	983.9
Total TSS loading (tons)	42.1	9.1	7.6	6.7	9.9	2.9
% Removed (TSS)	--	53%	57%	63%	66%	97%
			TP			
Max. TP (mg/s)	3030	346.8	1241	438.1	1238	303
Min TP (mg/s)	606.2	98.69	253.3	77.54	254.4	60.62
Mean TP (mg/s)	1438	184.3	590.7	200.8	589.6	143.8
Total TP loading (tons)	10.8	5.0	4.6	3.9	3.7	0.4
% Removed	--	87%	59%	86%	59%	90%

Post-hoc sensitivity analysis further extends the interpretation of the TOPSIS results to consider relative effects of various weighting schemes. Rather than a deterministic set of outputs such as those discussed previously and explored by Gogate et al., (2017), and Luan et al, (2019), this approach yields a more robust set of probabilistic outcomes as demonstrated by Zeng et al. (2021). while accounting for variables that may be subject to future change. For example, if local expert opinions were to shift toward a higher level of priority regarding issues of public access, or if new policies required a higher degree of cost effectiveness. Importantly, it also begins to suggest various thresholds regarding sentiment of decision-makers at the municipal, state or national level and how their priorities might need to shift in the future to allow for the adoption of novel approaches such as PGI.

When cost and pollutant removal are combined into a single metric of cost effectiveness (cost per ton of pollutant removal considering initial construction and one month of O&M), PGI scenarios become rapidly more advantageous as compared to conventional approaches such as UASB (Fig. 45). As cost effectiveness factor carries more weight, the ranking of S5 (representing a conventional USAB) quickly drops from the highest ranked to the lowest ranked scenario, while S4 shifts from the lowest ranked, to the highest. As the weightage of access score increases, the ranking of S3 substantially rises, while S2, S1 and S4 trend downward, suggesting that upgradient locations and dispersed configurations of PGI may be increasingly advantageous if broader public accessibility is desired.

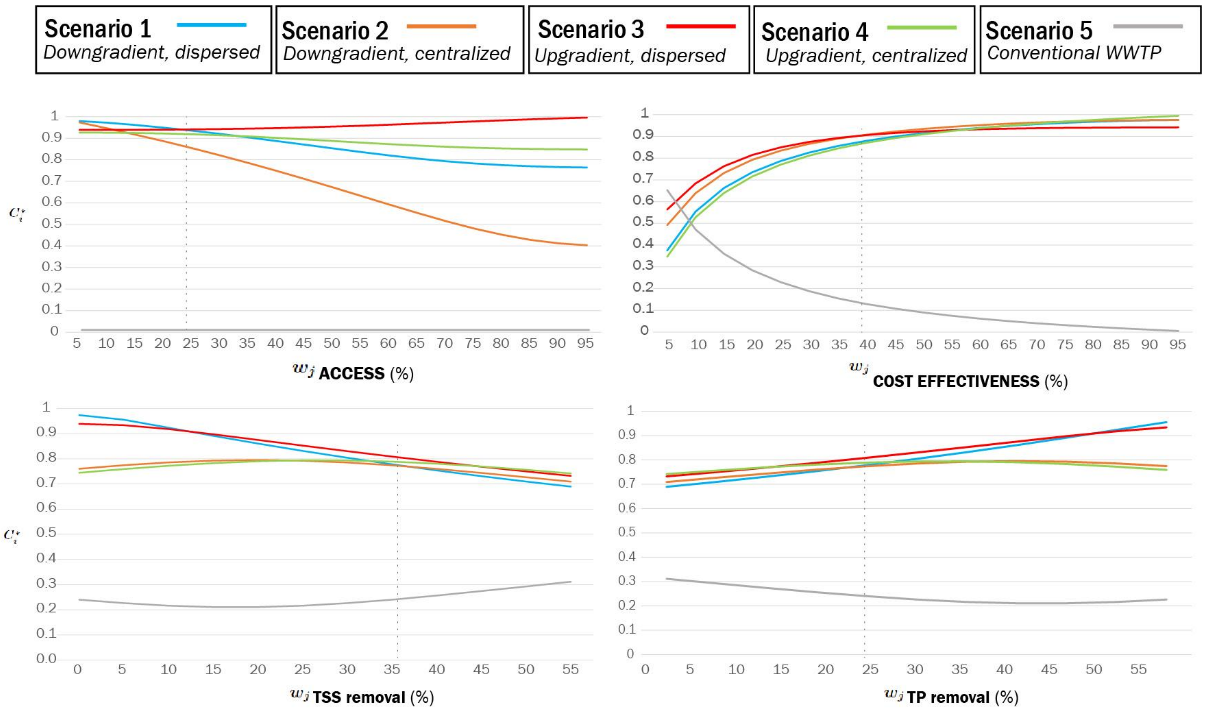


Figure 45 Comparison of closeness coefficient of each scenario under various TOPSIS weighting schemes. Ci* indicates closeness coefficient (proximity to an "ideal" solution on a 0-1 scale). Dashed vertical lines indicate the weights ascribed by subject matter experts (N=31) (Phillips & Lindquist, 2022).

As the importance of TSS removal is given more weight, dispersed configurations show a downward ranking trajectory, while centralized configurations show the opposite. S3 and S4 (both upgradient scenarios) are more highly rated when TSS is highly weighted. Rankings largely converge as TP and TSS are given equal weight, with S4 emerging as the highest ranked. Weighting of TP removal shows the inverse of TSS suggesting that S1 and S3 (dispersed configurations of PGI) may be more effective if the importance of TP capture is given more weight.

When equal weights are given to all criteria, S1 is the highest ranked, followed by S3 (upgradient dispersed).

Given expert driven weights for cost, removal efficiency, and public access for the study area in question, dispersed configurations of PGI interventions are optimal wherever such an approach is feasible. In cases where dispersed configurations prove unfeasible, centralized configurations may be placed preferentially in upgradient locations in the watershed (first or second order nallahss), and in locations with higher pollutant concentrations and lower flow rates such as channels with shallower slopes. These results broadly support similar findings by Fry & Maxwell (2017) suggesting that LID effectiveness varies significantly depending on location and configuration. Liu et al. (2016) suggested that optimizing GI placement for reducing runoff volume results in negative tradeoffs for water quality benefits. Di Vittorio & Ahiablame (2015) conducted modelling at the catchment scale in the Deer Creek Watershed of Missouri, USA, determining that land-based interventions GI targeting the reduction of peak flow behavior are more effective when sited near the catchment outlet. Carson (2019) and Hurley & Forman (2011) conducted modelling studies in the cities of Atlanta and Boston respectively, concluding that centralized configuration of bioretention areas are more effective at reducing pollutant concentrations (including TP) for downstream receiving waters. Boks (2018) applied modelling to evaluate various sewage treatment plant (STP) upscaling scenarios in a rapidly urbanizing watershed of Guwhati, India, which suggested that surface water quality showed greater improvement with a decentralized approach. Given the range of mixed and often contradictory results in this domain, the effective upscaling of LID interventions remains a largely context-specific phenomena. As such future research should include field-measured hydrological data to further calibrate and validate modelled results. Examine broad spatial patterns and their relationship to LID performance following recent examples by Wang et al (2021).

It is important to note that whereas the majority of LID studies and applications focus on source control (preventative measures), this study addresses treatments applied to flows that have already been (intentionally or unintentionally) captured and transported within a conveyance network. Currently few published studies focus on DWF applications for SWMM modelling software, and still fewer still are applied to the context of the Global South. We suggest that this is an opportunity area for future research to add robustness to the findings of this study. Specific targeted aims should be paired with careful consideration of localized hydrology, geology, climate land-use land-cover types, and underlying infrastructural conditions within the catchment. Limitations of this study include a) omission of wet weather flow (WWF) conditions, which substantially impact the concentration and loading of contamination as DWF is significantly diluted by monsoonal rain events throughout the year; b) the model does not account for factors such as the role of temperature, evaporative losses, leakage from or to adjacent infrastructures, which impacts DWF patterns and processes.

5.4 Conclusion

The strategic upscaling of LID at the catchment scale remains a complex challenge for designers, planners, and decision makers. This study demonstrated and evaluated how the integration of SWMM modelling and TOPSIS analysis can address this challenge, and provided actionable insights for future implementation efforts in the context of this and other Indian megacities. Five alternative scenarios for upscaling of PGI throughout an urban catchment to address DWF conditions were assessed based on quantitative data reflecting cost, pollutant removal, and public access criteria. Weighting for criteria was driven by subject matter expertise, and sensitivity analysis assigned alternative weightings were assigned to criteria in order to assess their possible impact on ranked outputs.

Tradeoffs exist in the process of upscaling and include economic, technical, performance, and social factors. The placement of interventions solely targeting water quality improvements may not be optimized for benefits to other important variables. Rather than a replacement for WWTP's, we suggest that PGI be deployed (in a supplementary role) in tandem with conventional wastewater treatment infrastructures to address persistent capacity gaps and provide ancillary benefits to urban contexts where the separation of wastewater and stormwater flows is not likely to occur. Finally, we suggest that this SWMM based TOPSIS approach be incorporated and modified for use in future upscaling studies to actively inform decision-making processes for sustainable urban water management in the Global South.

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Chapter 6 Final Conclusions and Future Research Trajectories

6.1 Summary of key insights

In *Chapter 2: Provisional Green Infrastructure: Trans-disciplinary approaches to address contamination in urban streams* my co-authors and I defined PGI as a speculative innovation typology emerging from the Indian megacity context, and suggested ways in which this term might be useful in setting research agendas in this nascent domain of practice. Scouring the grey literature and other sources we identified five relevant precedents for PGI distributed across major population centers throughout the subcontinent and analyzed their form, function and mode of implementation from a design, engineering and public engagement perspective. For the first time in the discourse of SUWM, we proposed the "in-stream" context as an incubator for GI innovation in the Global South. Importantly, we suggest how this context - defined by unpredictability, space-constraints, and acute levels of contamination requires different approaches to the conception and implementation of GI compared to other contexts in the Global North. Finally we define two primary modes of upscaling as "organizational" upscaling (the broader diffusion and adoption of PGI approaches by various state and non-state actors) and "spatial" upscaling (the spatially explicit manner in which PGI interventions are deployed throughout an urban watershed catchment to maximize cumulative water quality benefits). This is largely a framework that sets a foundation for PGI research, and the cases are further explored in Chapter 3.

In *Chapter 3: Informal diffusion of Green Infrastructure innovations in Indian Megacities: Perspectives from innovators and potential future adopters,* we address the topic of “organizational” upscaling by digging deeper into the networked communities of practice driving PGI innovation, employing semi-structured interviews with individual practitioners and broader surveys of potential future adopters (PFA’s). Here we employed the DOI framework to assess the alignments and misalignments of perceived innovation characteristics amongst these two levels of actors, and suggest ways in which their needs and goals might be better aligned. We suggest that future diffusion of PGI will likely occur both vertically (i.e. from smaller actors upward to larger municipal and institutional actors) as well as laterally across networks of non-state actors operating in the Indian subcontinent. We note that this is somewhat inverted from the conventional diffusion dynamics of innovations, where innovations are developed by higher level actors and promoted for adoption by individuals or smaller firms. This bottom-up mode of innovation is an area for future research and may exhibit its own set of diffusion characteristics. We further suggest that successful adoption is likely to depend on innovators’ ability to effectively leverage public support and media for the dissemination of information. Finally we emphasize that building a cooperative rather than an adversarial relationship between PGI innovators and PFA’s may also play an important role in future diffusion, with a mutual understanding of the *relative advantage* and *simplicity* of PGI (i.e. its ability to work in concert with existing infrastructures to meet shared goals of improving in-stream water quality and protecting downstream receiving waters).

In *Chapter 4 Assessing performance of local substrates for treatment of dry weather flows in open drains: Results of a pilot study in Bangalore, India* we employed a field-scale pilot study of a PGI intervention using live wastewater to assess various contaminant removal efficiencies over the course of 15 months. This study demonstrated the applicability of inexpensive, locally available aggregate substrates (gravel and terracotta rubble) in treating the highly variable DWF in open stormwater drains without the use of specialized or mechanical technology. Results of this study suggest that gravel substrates may be marginally better for the removal of organics, with a statistically higher decay rate constant for BOD_5. Whereas terracotta rubble substrates performed better for the removal of Total Phosphorus (TP) and Ortho-P, and may be a more suitable choice where greywater flows contain an excess of phosphorus-laden contaminants such as detergents. We also observed that the input concentrations for urban wastewater in open drains are often of a high strength and highly variable throughout the course of a given day, week, and month. This paired study observed reductions for TP ranging from 48-59%, TN from 14-24%, and TSS ranging from 74-79%. While these removal efficiencies were substantial, it was found that PGI interventions alone are not sufficient to lower the concentration of many contaminants to a level that would satisfy current water quality standards set by the Central Pollution Control Board (CPCB) for discharge into lakes and should therefore be considered as a supplementary (rather than a "standalone") approach.

In *Chapter 5: Assessing catchment-scale performance of in-stream Green Infrastructure interventions using SWMM-based TOPSIS* we utilized the site-scale insights and data generated by our pilot study to inform the development of a series of catchment-wide upscaling simulations in a rapidly urbanizing peri-urban region of Bangalore, India. Five alternative scenarios for upscaling PGI throughout an urban catchment to address DWF conditions were assessed based on quantitative data reflecting cost, pollutant removal, and public access criteria. Weighting for criteria was driven by subject matter expertise (taken from previous surveys of PFA's), and alternative weightings were assigned to criteria to assess impact on ranked outputs. Results identified that alternative scenario 1 (incorporating seven PGI interventions of $100m^2$ each) performed reasonably well across all weighting schemes, suggesting that a downgradient, dispersed approach to catchment scale PGI deployment minimized tradeoffs between cost-effectiveness, removal efficiency and public access. This insight provides a generalizable theory (i.e. that PGI is most effective with a downgradient, dispersed deployment) which can be further tested and iterated in future studies and implementation efforts. Importantly, this study demonstrated how the integration of GIS, SWMM modelling and TOPSIS analysis can address various tradeoffs of design implementation and therefore provides actionable insights for future diffusion and upscaling efforts in the context of Indian megacities.

6.2 Implications for PGI praxis in the Global South

The Sustainable Development Goal (SDG) 6 of the United Nations is to "provide universal access to safe drinking water and sanitation for all by 2030" (Griggs et al 2013). It also explicitly mentions that water quality has to be improved by addressing both biological and chemical contaminants. The need for alternative surface water management approaches is particularly urgent in urbanising India, where immense development pressure, ongoing capacity building gaps and delays in conventional waste-water infrastructure—combined with persistent widespread contamination—continue to place immense stress on local ecosystems, such as lakes, wetlands, and even groundwater sources, while threatening human health. As stormwater drains have become conduits of pollution, low-cost and low-resource green infrastructure approaches offer immense potential to address the pollution loads in these drains, especially in expanding megacities and emerging towns, where the volume of waste water continually outweighs the total capacity of STPs.

Against this backdrop, PGI is capable of responding to a unique range of spatial, social, political, and economic conditions. This research marks the early stages of a larger transdisciplinary effort aimed at examining the viability of bottom-up approaches to these challenges, emphasizing "provisional" (decentralised, low-tech, low-cost, low-maintenance, and culturally responsive) designs. Results of this initial phase of research suggests that PGI may be applicable to both peri-urban towns, where grey and black water are segregated at the source (household), and also in those regions of large cities where STPs are inefficient and work below capacity. The goal of future research in this domain will be to further codify and actively inform the praxis of PGI. Our aim is to share these multi-level insights and decision support tools with PGI practitioners and PFA's to promote awareness and implementation of alternative SUWM strategies in the megacity context.

6.3 Implications of hydrology-integrated methods in Landscape Architecture discipline

This section briefly addresses how the transdisciplinary methods and frames of approach employed throughout this dissertation might continue to inform my research and teaching in the field of landscape architecture (LA), and the implications to the discipline more broadly.

Historically, the use of digital tools in LA has been primarily leveraged to support the representation, morphology or construction of proposed projects. This often takes the form of maps, renderings and construction documents. In many design fields for example, 'parametric design' is primarily concerned with issues of data-responsive form-making. The research approach described here suggests the possibilities for incorporating a wider array of parameters, data and digital toolsets to influence the likely social-ecological performance of a design at the early phases of the design process. Whereas (Felson & Pickett, 2005) have advocated the role of "design experiments", a significant limitation to this approach is that evaluating the performance of a landscape intervention is typically carried out post-construction. By contrast, the incorporation of powerful hydrodynamic modelling tools such as SWMM introduces a paradigm in which performative design testing can occur in the *pre-construction* or even conceptual phase of a project (Grose, 2014). This is important as it offers a way for various stakeholders and decision-makers to assess the tradeoffs that may exist between various scenarios before any shovels meet the ground. From a pedagogical and epistemological perspective, there are opportunities to further advance the discipline of landscape architecture by engendering a more meaningful interface with other disciplines including urban hydrology, environmental ecotoxicology, civil engineering, and urban planning. Introducing these methods and tools to LA students in accessible ways at an early stage in their education offers immense potential for bridging the gap between design and science.

6.4 Future research trajectories

The nascent discourse of catchment-scale LID research continues to be marked by many challenging questions regarding the most effective way to "upscale" GI interventions to minimize negative tradeoffs and maximize multifunctional benefits (Golden & Hoghooghi, 2018; Tuomela et al., 2019). This includes questions of technical design parameters, as well as both the organizational and spatial upscaling of PGI over medium and longer timescales. Theresearch presented here adds robustness to this field of inquiry while identifying several possible trajectories for further research. Therefore it is suggested that future research in this domain might be driven by the following questions:

- What are the barriers to wider adoption and from the perspective of PFA's?

- How might PGI be deployed in tandem with conventional WWT infrastructures to offset the costs of initial construction and maintenance while achieving acceptable standards of water-quality at the catchment scale?
- How does PGI influence localized behaviours and perceptions of urban streams? What are the relevant "feedback-loops" that drive restoration and/or degradation?
- What is the role of local community participation in the maintenance and operation of PGI at local scales? How might we promote a deeper sense of ownership and care of infrastructural commons such as open drains?
- What factors influence the success or failure of individual PGI innovations in the medium and long term?
- What additional design parameters that might enhance the performance of PGI from a water quality perspective (plants, substrates, configurations, etc)?

While this list is not exhaustive, it illustrates the continued need to bridge practice and science in order to drive processes of landscape change toward resilient futures. By using small scale experiments as an evidence base for city-wide scenarios or models, future research should attend to perennial questions of scale and efficacy which are currently topics of debate within the field of GI. Finally, it is important to further explore the notion of "the provisional" as it relates to the megacity context, and how the notion of PGI might fit into the broader discourse of GI praxis. Rather than offering a "silver bullet" cure to the urban stream syndrome, PGI serves as a catalyzing invitation to begin the larger, more comprehensive project of cooperatively managing urban streams and drains as the common pool resources that they are (Jumbe et al., 2008; H. Nagendra, 2016; Harini Nagendra, 2014). The development of appropriate, performative and feasible design solutions that are well maintained and aligned with local norms and institutions will likely maximize the potential for positive socio-ecological reverberations that extend well beyond the context of the stream channels themselves.

6.5 References

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Chapter 7: Coda: We're Not "Solving" Wicked Problems Through Design and Science—Is That OK?

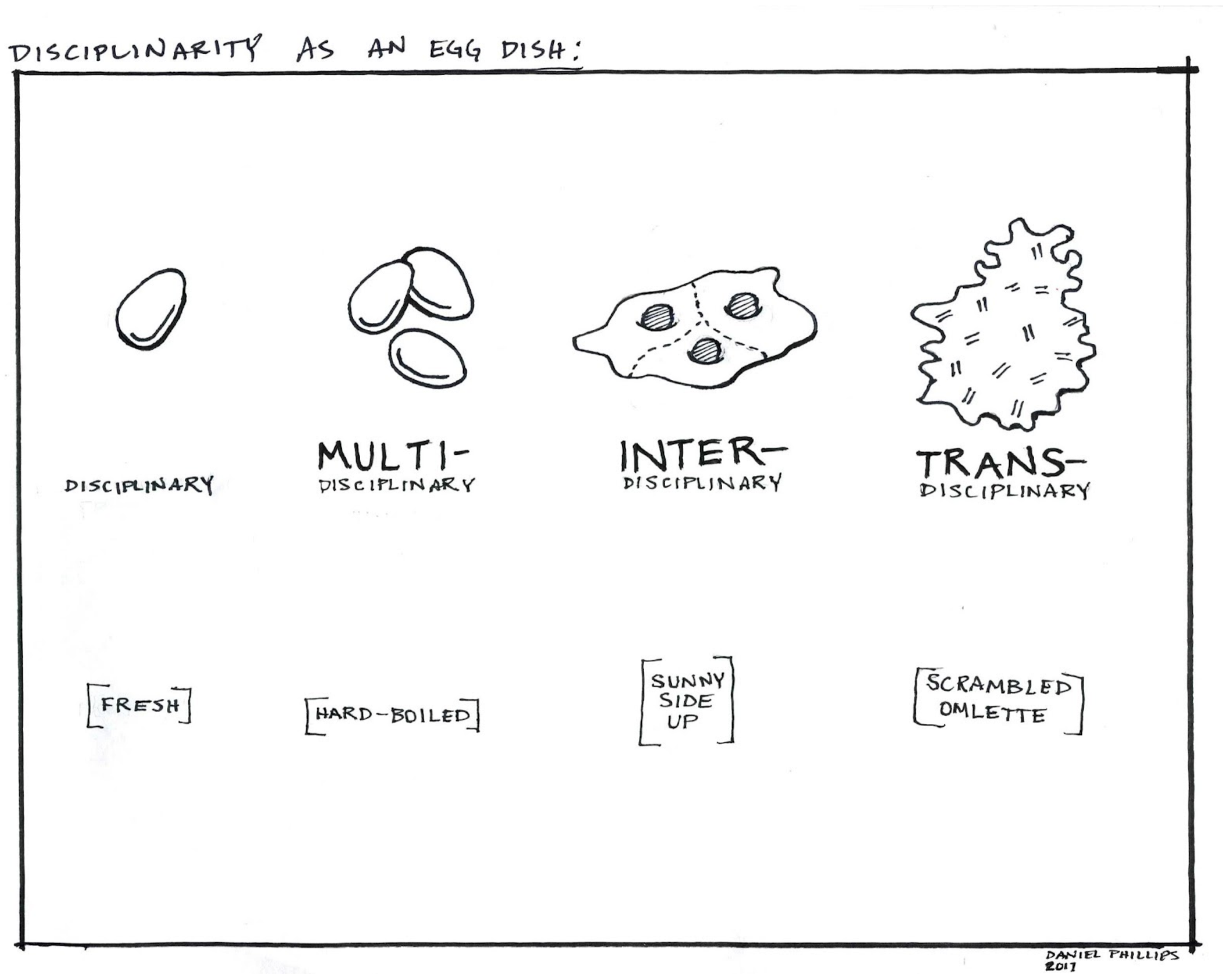

Figure 45. Transdisciplinarity as an egg dish, adapted by Daniel Phillips from Cedric Price's "City as an Egg" diagrammatic analogy

Designers and scientists alike are drawn to the process and potential of transdisciplinary projects through a desire to deepen the scope and impact of our work. Though landscape architects and planning practitioners claim to be capable of achieving socio-ecological impact, too often their proposals and built projects lack the necessary grounding in solid science to demonstrate and measure that impact. Conversely, many modes of academic research can lack immediate and relevant applications in the real-world. How this divide between design and science might be more effectively bridged is a topic of frequent debate and discussion within many disciplines. A fiery piece by Flemming (2019) entitled "Design and the Green New Deal", struck a resonant chord within the discourse of landscape architecture, arguing that the discipline's very *reason for being* warrants a timely re-examination. Indeed, it serves as a call to action for all of us who hope to make meaningful change in the world through our research and practice to think bigger, get political and offer our skill sets and capacities to the pressing issues of the day. Polemics like these form a gathering recognition that many responses to issues like climate change, environmental justice and urban resilience will inevitably find expression in spatial projects throughout the landscapes we occupy. Yet these challenges are all arguably "wicked" in nature. So how should they be approached?

The notion of "wicked challenges", often attributed to the work of Rittel and Webber (1973) forms an important heuristic device around which many contemporary transdisciplinary projects have orbited. Wicked challenges are framed in distinction to challenges that could be labeled "simple" and "complex". Whereas simple challenges (e.g., filling a cavity in a tooth) are those in which both the question and answer are well understood, complex challenges (e.g., landing a man on mars) are those in which the question is understood but not the answer is not yet known. Wicked problems (e.g., Brexit, climate change, addressing the urban stream syndrome) are defined by uncertainties on both sides, and therefore rely heavily on the ways in which the challenge is effectively *framed*. Wicked challenges are further characterized by the fact that they have “no stopping rule”—that is, every proximate answer leads to more questions—and that every wicked problem can be said to be a “symptom of another problem” (Farrell and Hooker 2013).

Addressing wicked problems therefore requires the development of new tools and frameworks for approaching them. Throughout this dissertation, the Design-in-Science (DIS) framework, originally formulated by Nassauer and Opdam (2008) has offered such a framework. This approach calls for increased transdisciplinary research between and across disciplines such as engineering, landscape ecology and landscape planning. The central aim of the DIS framework, arguably, is to find ways to reconcile the *agency* of design with the *authority* of science to better address wicked challenges that occur within human dominated ecosystems. The DIS framework has since become a prominent node in a constellation of related approaches referred to variously as *“participatory landscape planning”* (Hulse, Branscomb, and Payne 2004; Johnson and Campbell 1999; Johnson et al. 2002) *“designed experiments”* (Felson and Pickett 2005), *research-through-designing* (Lenzholzer, Duchhart, and Koh 2013), *“ecology with design”* (M. J. Grose 2014; M. Grose 2017), *“Design-Related-Research”* (Nijhuis and Bobbink 2012) and *Transdisciplinary Action Research* (Thering and Chanse 2011; Stokols 2006). Importantly, the framework defines and employs *Design* (as both a noun and a verb) as an operative “boundary concept”, and proposes an “iterative loop” of evidence-based (and evidence-generating) design inquiry (Fig 46).

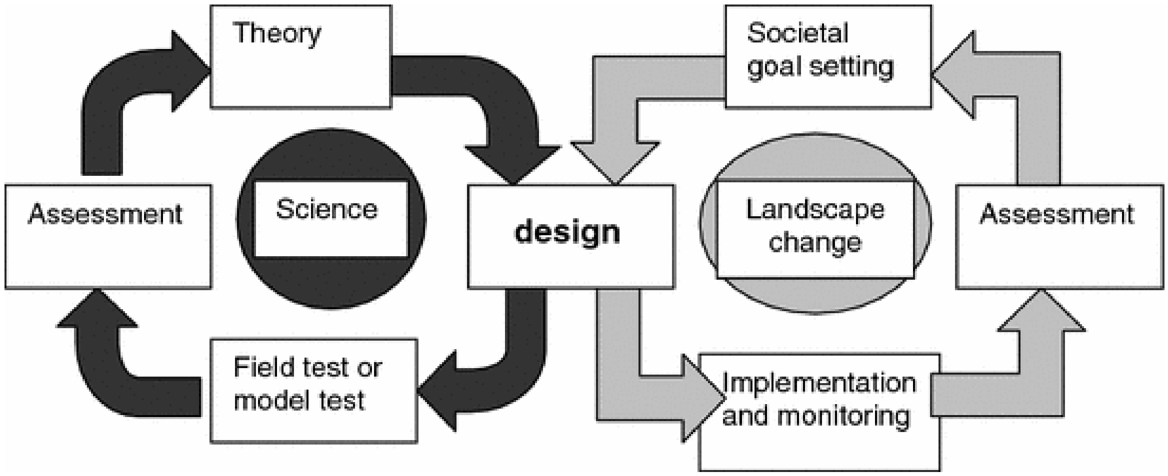

Figure 46. Design as a link between science and landscape change (Nassauer and Opdam 2008)

The DIS framework as a tool for addressing "wicked" problems

To understand the value of DIS as a useful tool for confronting wicked challenges, it may also be instructive to explore the reflexive modes of inquiry it implies. First, it should be recognized that *Science* (in a post-positivist era), and *Design* (understood as a mode of thinking and action rather than merely a professional practice) are not as far apart in their core cognitive processes as they used to be (Farrell and Hooker 2013; Innes and Booher 2016). Luckily, we are moving gradually away from the hubris that defined our past epistemologies—namely that designers "solve" problems, and that scientists discover immutable "truths".

It was Karl Popper who famously observed that the foundations of science are not anchored to a stable bedrock of proven truth, but rather, driven just deep enough into the swamp of possibility to continue one's research (Popper 1959). In confronting our collective fallacies as designers and scientists, we are increasingly finding middle ground and focusing on the processes we might share—the ability to frame and ask questions, to *task the void* in pursuit of new insights, and advise (or take) action in line with the insights we discover. To do this, each are increasingly reliant on the mixing of Inductive, Deductive, and Abductive modes of reasoning to arrive at plausible assumptions about the nature of the problem at hand (Deming and Swaffield 2010).

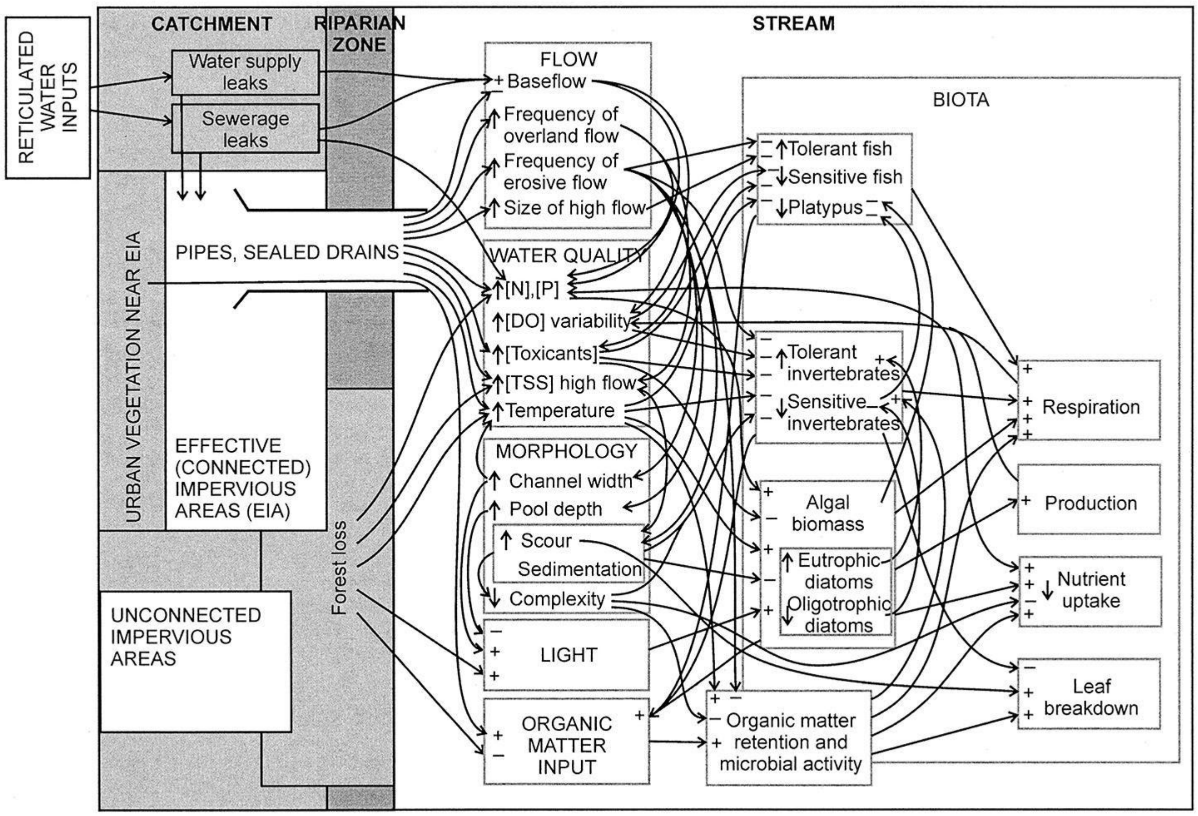

Figure 47. A wicked problem: The "urban stream syndrome" from Walsh et al (2005)

This interplay is especially important when it becomes necessary, on the one hand, to tease out from a wicked problem a series of more tame ones, and on the other hand, to recognize that in every tame one, a series of those which are wicked always exist. As stated by Nassauer and Opdam (2008), "Undoubtedly effective transdisciplinarity will require that new norms, not solely dependent on disciplinary conventions, evolve for credible research" (634). Situating *Design* in *Science*, therefore, isn't marked by an erosion of boundaries between these disciplines, but rather by an attempt to seek moments of permeability and alignment across boundaries that are mutually beneficial and *actionable*.

Strategic alignments between design, science, and policy can minimize the tradeoffs that occur regarding the credibility, saliency and legitimacy of new knowledge. To further illustrate the interplay of design and science, I will sketch out a series of brief speculative scenarios, with attempts to highlight the various epistemologies involved.

In the first scenario, we might imagine an alignment of science and policy, but without design. Policy makers with a high degree of agency and influence in the regime-level decision making processes, solicit scientific research to gain deeper knowledge about a specific phenomenon that they are trying to better understand or plan for. The question at hand might be related to where the next wastewater treatment plant should be built. The scientist, or team of scientists in question, deploy(s) a rigorous purpose-built methodology resulting in new data that is not only highly credible, but highly salient (as it was driven by a specific purpose or policy implication at its outset). Yet without the critical role of design, and design thinking, the team might never attempt to divergently reframe or challenge the nature of their task itself. What if the goal shouldn't be just about defining service areas for existing technologies? What other (unexpected) opportunities might we be overlooking? What about the urban streams themselves? By excluding design from the equation, the science/policy team never pose or ponder relevant "what if" scenarios that could be attenuated to local phenomena or needs. Further, if the process of collecting data is not attentive to normative dimensions of everyday landscapes and people within them, the resulting prescriptions might risk not being adopted, or worse—actively resisted within the context they are being proposed. Here, questions of *legitimacy* are paramount—defined as the degree to which various public stakeholders perceive the process to be “unbiased and meeting standards of political and procedural fairness” (Cash et al. 2002, 5). Despite being both *credible* and *salient*, eschewing participatory modes of design engagement may stifle this team’s potential to affect broader landscape change.

In a second scenario, there exists a strategic alignment of design and policy, but without science. Designers, informed by a particular program or brief, propose a series of speculative responses, perhaps even drawing upon general ecological principles as an evidence base in science. The process is transparent, participatory, and imaginative. Policymakers place trust in the creative process and the capacity to think beyond rigid conceptual frames to imagine and propose a series of ‘what if’ scenarios that are both salient and legitimate. This could be further exemplified in urban planning and design practice when a beautifully conceived solution is installed in the “right” place but fails to build sufficient capacity and rigorous methodologies to monitor the quantitative and qualitative impacts of their efforts over time. The project becomes easily dismissed as “greenwashing”, where designs or landscape changes *appear* ecological without actually functioning ecologically. Further, they fail to generate any new knowledge that can be used or replicated elsewhere.

In a third scenario, we have a strategic alignment of science and design, but without policy. This team works together within a protected niche—fuelled by independent funding from public grants and private institutions and have internal capacity to control the parameters and goals of their research and inquiry. Seasoned interdisciplinary teams use lab and field-based tests to frame, test and refine research and eventually build a compelling public value proposition that is both legitimate and credible. But they fail to translate these insights into relevant and *feasible retrofits* to the existing status quo. In this scenario the proposed responses may never move beyond the stage of a brilliant hypothetical that never actually comes to pass. Or alternatively, they propose localized responses that can only survive with constant inputs from the initiators themselves, and thus fail to effectively upscale in a way that is sustainable.

Finally, we have a strategic alignment of design, science, and policy at a time when a relevant window of opportunity opens up in an existing regime. Regime level actors are hungry for new ideas, and front line innovators have built the transdisciplinary capacity necessary to propose viable alternative responses. Scientists consult the evidence base to form valid and plausible assumptions about the basic viability of responses. Designers work in collaboration with scientists to frame built works as a mode of hypothesis testing that feeds larger, generalizable insights. These insights fuel the upscaling of more widely distributed intervention which are informed by collaborations with various local civil society organizations and stakeholders on the ground (Figure 48).

Figure 48. The author and collaborators Priyanka Jamwal and Shubha Ramachandran setting up a small scale wastewater demonstration project in Bangalore, India.

A key takeaway is this: When it comes to addressing wicked challenges, designers, policymakers and scientists alike should challenge themselves to work more synthetically to frame built works as a mode of hypothesis testing that feeds larger, more generalizable insights. Staging small-scale, safe-to-fail interventions create insights for design iteration and also allows critical engagement of stakeholders at early stages in the development of projects. Over time, a compelling evidence base on which to base the form and function of new landscape patterns can emerge. Small interventions, once merely speculative or provisional, become more widely replicated and accepted.

Figure 49. Urban rapid prototyping via socio-ecological interventions in Rome, Italy, The Commonstudio

Transdisciplinarity is especially relevant to contemporary discussions surrounding the science and practice of green infrastructure in cities. Embedded within the semantics of framing “problems” is an implicit suggestion that *cures* to complex urban ills might exist. Yet, one of the very conditions that defines the city as an ecosystem are the many irreversible histories it contains. The re-framing of socio-ecological challenges and their many reverberations as wicked problems allows us to collectively confront, and perhaps even *accept* their ultimate insolubility. For example, there will always be a preponderance of pavement in human-dominated ecosystems. Restoring the function of these constructed ecologies to pre-urban, or pre-human states of health will always prove to be a logical impossibility. Even in a future world without *us*, the biophysical constructions we call cities will continue to impact the patterns and processes of the landscapes and watersheds in which they have emerged.

As designers, scientists, and policy makers, we *cannot* hope to ever truly “solve” these wicked problems, but through our combined efforts, we can try to better understand their nature. And that’s ok! If we refuse to resign ourselves to cynicism, we can allow this realization to become the fuel that drives the process of relentless incrementalism and continued experimentation. With few exceptions that’s how the process of changing the world has always occurred—aggregated efforts which compound across vast scales of space and time. My hope is that projects, methods and partnership models such as the ones I’ve had the pleasure of engaging with over the past 5 years, will continue to demonstrate the power and potential for new modes of cross-cultural, cross-disciplinary engagement which bridge the “design-science divide” and point to new horizons of action—even if those actions are initially tiny in their scope. They serve to make these challenges we face a bit less wicked, and maybe that’s enough.

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