Provisional green infrastructure: transdisciplinary approaches to address contamination in urban streams

Priyanka Jamwal, Durba Biswas and Daniel Phillips

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 more widely recognized as a 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 generalizable 'upscaling' opportunities for deploying in-stream interventions across various organizational and spatial domains.

Key words | green infrastructure, megacities, stormwater drains, typology, wastewater treatment, water quality

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HIGHLIGHTS

- Provisional green infrastructure (PGI) is introduced for the first time as a relevant innovation typology describing a range of sustainable urban water management research and practices throughout the context of the Global South.
- Discusses emerging precedents for PGI intervention in megacities across India.
- Provides a framework for assessing future organizational and spatial 'up-scaling' efforts.

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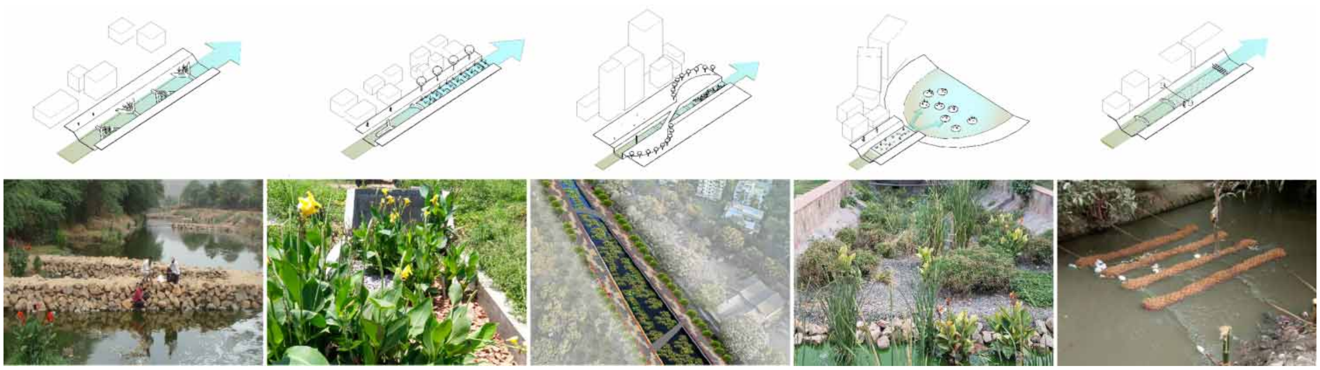
GRAPHICAL ABSTRACT



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 *et al.* 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, best management practices, and sustainable urban drainage systems (Benedict & MacMahon 2001; Mell 2010; Marlow *et al.* 2013). These practices are comprised of many individual tactics including bioretention cells, porous pavements, and constructed wetlands, and are associated with the wider definition of green infrastructure (GI) (US 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).

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 phenomenon, 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 phenomenon which render them highly *unpredictable*, *space-constrained*, and acutely *contaminated*.

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

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	Roy (2005); Kraas (2007)
	Illegal and 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 Barr & Mehta (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 *et al.* (2016b)
	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 Lele & Menon (2016)
	Lack of enforcement of existing standards and laws (often exacerbated by corruption, bribery, cronyism, nepotism)	Kraas (2007), Tortajada (2016), Jamwal Lele & Menon (2016)
	Lack of separation between stormwater and wastewater conveyance networks.	Parkinson Tayler & Mark (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), Jumbe *et al.* (2008), Ramachandra *et al.* (2016a); Jamwal (2017)

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.

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 *et al.* 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 *et al.* 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 (Figure 1).

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,

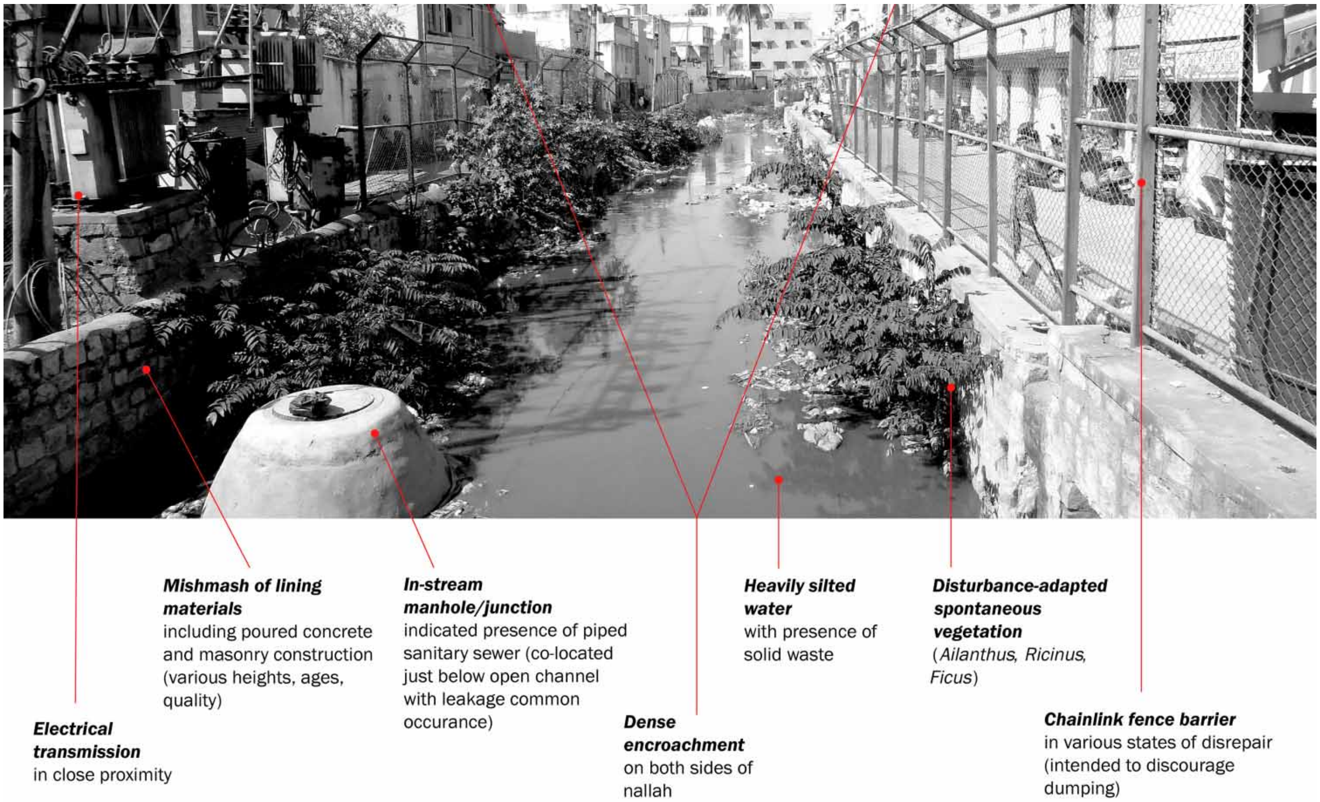


Figure 1 | Identifying typical characteristics of a megacity nallah (Shivaji Nagar Neighborhood, Bangalore). Photo/diagram: Daniel Phillips.

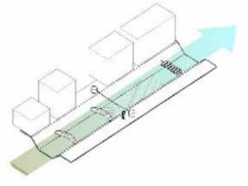
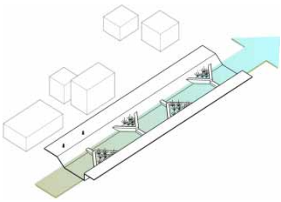
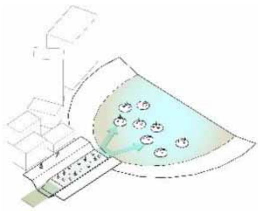
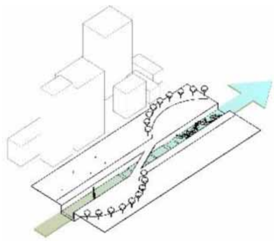
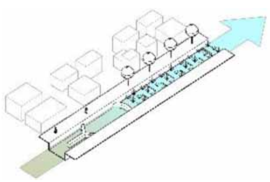
modified, maintained or removed with minimal disturbance to the form and function of the underlying infrastructure into which they are placed. Table 2 identifies five case studies currently under development by various non-state actors across many regions in India.

Selected case studies in PGI

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, PGI tactics are often informally initiated, developed, funded and demonstrated by non-state actors at small local scales, and are rarely documented in the refereed literature (Table 2).

The first precedent describes the self-determined efforts of the Indian National Trust for Art and Cultural Heritage (INTACH) undertaken along the Assi Nadi in Varanasi, India. The Assi is one of 33 local 'nadis' which drain directly to the receiving waters of the Ganges river (an ecosystem of extreme cultural and religious significance). The project undertook an 'acupunctural' approach along a 3.5 km section of the channel without investment in any permanently built structures. 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. Initial water quality monitoring results conducted by the team were promising, citing an 87.3% reduction in biological oxygen demand (BOD), and a 50% reduction in both chemical oxygen demand (COD) and total suspended solids. Communities along the Assi were reported to have noticed significant reduction in odors after the interventions were made (Bhatnagar 2017). The project was rapidly conducted after obtaining a non-objection certificate from local authorities, enabling INTACH to undertake self-funded and self-directed tactical actions within the watershed, all of which were neither officially sanctioned, nor explicitly forbidden by the municipality.

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	Temporary pilot built
	**Green Bridges**	Udaipur	Shrishti Eco-Research Institute	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

Green Bridges is a long-term initiative of the Shrishti Eco-Research Institute (SERI) based in Pune, India. This approach is described as a 'horizontal eco-filtration system – a grafting of ecological systems to treat the pollution flowing through streams and rivers' (Joshi 2015, p. 13). The system 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 (Sule 2010). Recent demonstration projects in the context of the Ahar River (Udaipur), and the Medi Kuntha (Hyderabad) have reported significant increases in dissolved oxygen levels, and reduction in COD and BOD, leading to fewer downstream anomalies such as fishkills (Joshi & Patil 2018). Importantly, SERI tracks multiple parameters for each project they initiate, including measures of saprobic to aerobic biodiversity, native species recurrence, space footprint, economic efficiency, carbon footprint, nitrogen balance and community ownership of project (Joshi 2015).

The Hauz Khaus Urban Wetland is a project undertaken by Evolve Engineering, a small private firm in the city of Delhi, India. As with many megacities throughout the country, Delhi's rapid growth has led to persistent capacity gaps in urban wastewater treatment which leaves many local lakes polluted from domestic, industrial and diffuse sources. This intervention is situated near the inlet of Hauz Khas lake, a roughly 6 ha (15 acre) waterbody located within a heavily urbanized catchment area of 10 km^2 (Singh & Bhatnagar 2012). The project was pursued according to a memorandum of understanding with the Delhi Development Authority but without any government funding for its implementation. It consists of (1) a horizontal flow wetland condition within a 50 m section of an upstream channel flowing into the lake (composed of sand, gravel, 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. The project allowed private individuals to sponsor a floating island for the project at a cost of 5,000 INR (66 USD) (Satija 2018). The impact of this work remains largely anecdotal and qualitative, with claims regarding reduction in foul odors and algal blooms in the period after interventions were undertaken.

In the context of Mumbai, the Irla Nallah Re-invigoration project was launched in 2012 by an interdisciplinary team that includes PK Das & Associates (a private design firm) and the National Environmental Engineering Research Institute (NEERI), among other local partnerships (Das 2018). The proposed interventions were developed as part of a larger urban revitalization project known as the *Juhu Vision*, which includes a goal of 'creating a 10-km tree-lined, flood-free walkway along Irla Nallah' (Das & Akhtar 2018, p. 12). An estimated 40% of Juhu's 250,000 inhabitants live adjacent to the nallah, and stream reinvigoration is being promoted as an alternative to the municipal plans to cover the channel with concrete, resulting in lengthy legal litigation in the high court (Lewis 2013; Siddhaye 2010; Das 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, but lack of cooperation from the Municipal Corporation of Greater Mumbai has hindered its success (Richa Pinto 2017).

Strategic In-Stream Systems (STRAINS), is a PGI tactic currently under development by a transdisciplinary team (Commonstudio, ATREE (Ashoka Trust for Research in Ecology and the Environment), Biome Trust), situated primarily in Bangalore, India. This approach is intended for mid-sized nallahs which contain primarily mixed effluents or grey water (Figure 2). 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. The development of this project to date has included iterative design, laboratory and field-based material performance testing using various aggregates and plantings, physical and virtual hydrological modeling, city-wide suitability analysis, and relationship building with local partners. 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 *et al.* 2019).

Although the tactical interventions described above 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. We posit that many of the challenges associated with the future upscaling of PGI tactics may be met through the development of a coherent transdisciplinary framework that effectively combines input from social sciences, hydro-ecological engineering, urbanism, and landscape planning.

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, and at what scales can different types of 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

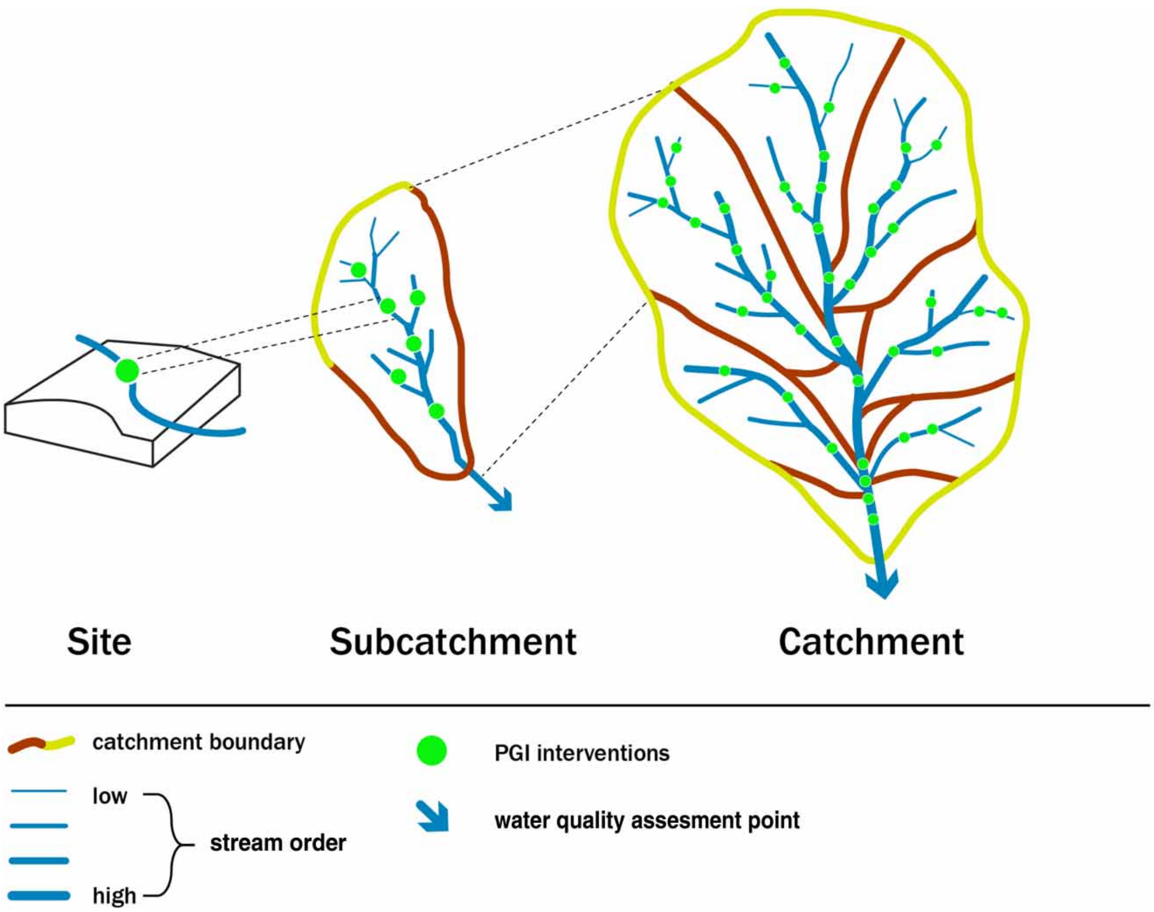


Figure 2 | Conceptualizing the scaling effects of PGI interventions on downstream receiving waters from individual sites (left) to nested catchment scales (not to scale). Diagram by Daniel Phillips, adapted in part from Golden & Hoghooghi (2018).

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 (subcatchment and catchment level) to achieve cumulative water quality benefits.

Organizational upscaling

Future research in PGI should examine the process of organizational upscaling by drawing upon the diffusion of innovations (DOI) theory, originally proposed by Rogers (1962, 1995). DOI has already been employed as a framework for research in many domains from agriculture to education, management, health care and public health, information technology, and sociology – amassing a significant body of research (Baptista 1999; Wejnert 2002; Oldenburg & Glanz 2008; Karakaya *et al.* 2014). 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) and DOI theory 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*. Later, *reinvention* was proposed by other scholars as a sixth characteristic, defined as 'the degree to which an innovation is changed or modified by

Table 3 | Innovation characteristics of 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

a user in the process of its adoption and implementation' (Rogers 1995, p. 17). This simple framework of innovation elements and sub-elements (Table 3) can be applied to a given 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 phenomenon (Baptista 1999).

These elements of DOI are expected to be particularly relevant to understanding the processes and potential organizational upscaling of PGI, offering a useful framework to compare and contrast the unique characteristics of individual PGI innovations, and evaluate the perceptions amongst PGI innovators about which among these characteristics may be most relevant to the upscaling of PGI within the megacity context. DOI theory therefore provides a useful and well-established framework in which to identify key aspects of PGI innovators, innovations, and their intended organizational context at an early stage in their development. We therefore suggest that the DOI theory provides a useful framework for future case-study analysis in PGI innovations.

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 influence various quantitative performance metrics (nutrient processing, reduction of peak flow behavior, flood risk etc.) (Jayasooriya & Ng 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 modeling 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 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 Figure 2). Catchment-scale analysis in GI has been recently characterized by Golden & Hoghooghi (2018) as an *emerging science*, and is poised to answer complex questions related to the upscaling of established and emerging approaches (including PGI).

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 US EPA Stormwater Management Model (SWMM) can be used to rapidly simulate the probable effects of PGI interventions at multiple spatial scales (Rosa *et al.* 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 subcatchment 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.

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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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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