RESEARCH

A Framework to Address the Food, Energy and Water Nexus among Indian Megacities and Their Rapidly Expanding Peripheries

ADITYA BANDLA,[1] GOURVENDU SAXENA,[1, 2] RAJAT MISHRA,[1,3] SANJAY SWARUP [1, 2, 4, 5]

[1] Singapore Centre on Environmental Life Sciences Engineering, National University of Singapore, Singapore

[2] Synthetic Biology for Clinical and Technological Innovation, National University of Singapore, Singapore

[3] NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore

[4] Department of Biological Sciences, National University of Singapore, Singapore

[5] NUS Environmental Research Institute, National University of Singapore, Singapore

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[1] Singapore Centre on Environmental Life Sciences Engineering, National University of Singapore, Singapore

[2] Synthetic Biology for Clinical and Technological Innovation, National University of Singapore, Singapore

[3] NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore

[4] Department of Biological Sciences, National University of Singapore, Singapore

[5] NUS Environmental Research Institute, National University of Singapore, Singapore

All authors contributed equally to this work

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Abstract

India is growing fast, with its fast-expanding cities that are rapidly growing into megacities. This not only puts tremendous pressure on the existing resources of these cities but also poses a grand challenge to the urban planner on how to decongest the flow of resources to the continuously growing population. A major part of this challenge comes from the food, energy and water (FEW) nexus, which in part can be addressed by developing the peri-urban areas to provide the means of such resources. In this article, we have explained a generalized framework to develop the tools for sustainable resource management in the peri-urban areas of the Indian megacities and discussed the tripartite approach to implement it. The first part of the approach is to develop smart environmental surveillance, which will provide the first snapshot of environmental parameters in the region. The second part is to integrate the large datasets with the regional ecosystem characteristics to understand the interactions between the living organisms and the environment. Last in the approach is to extract simplified knowledge from the interactions about the ecosystem and translate them into activities. The outcome of this approach is a peri-urban ecosystem, which will be able to cater to the sustainable means of food and energy in return for the used/storm water from the cities. Such a framework can be extended to megacities in other developing countries and implemented to first understand the peri-urban ecosystem and then to implement the management tools.

Keywords: Peri-urban agriculture; environmental surveillance; AI, storm water; ecology; self-cleaning capacity; resilience agriculture; land-use; human impacts.

Introduction

Urbanization is unfolding at an unprecedented rate across the world, more so in India. Currently, India is home to 5 out of 31 global megacities and will be home to 7 megacities by 2030 (Habitat 2016), when cities will account for nearly 70% of India's GDP (McKinsey Global 2010). Sustaining this growth requires that basic demands for water, food and energy are reliably met in a cost-effective and sustainable manner. Peri-urban agriculture is being advocated for meeting the heavy urban demands of fresh vegetables and fruits. However, the dependency of Indian cities on peri-urban freshwater resources means that water demands for peri-urban agriculture cannot be sustainably met for longer time periods. Peri-urban regions that lie in between cities and rural regions are most impacted by such resource flows, as transporting freshwater across large distances not only involves a substantial expenditure of energy but is also not eco-friendly. Hence, transboundary flows of water, food and energy between urban and peri-urban areas will define the growth and livability of Indian cities in the coming decades.

The peri-urban agriculture is currently practiced using untreated or partially-treated wastewater channeled outwards from India's urban centers (Leslie et al 2017). Such a practice poses grave health risks due to the spread of diseases and toxins. There is a pressing need to secure safe-to-use water for peri-urban agriculture, which in turn can contribute towards food supply for India's urban population, while reducing the energy required to store and transport these perishables.

While cities, in general, depend on large-scale water imports to meet their demands, many are also experiencing urban flooding events, frequencies of which are projected to increase in the near future as a consequence of climate change (Grimm et al 2008, McDonald et al 2014). Urban storm water is a valuable source of freshwater that remains largely untapped. Quantifying water inventories across selected cities in the world has shown that volumes of storm water could fulfill a substantial proportion of a city's water demand (Goonetilleke et al 2016). Indeed, such practices have contributed to Singapore's transformation from a water-stressed country to a water-secure country. An Indian context would entail capturing urban storm water as a resource to meet urban water demand, with the excess being channeled to peri-urban areas for farming or utility purposes, depending on the quality of water.

Although storm water capture contributes to a diversified water portfolio, the conventional approach of using grey infrastructure has been found to be unsustainable (Palmer et al 2015). Supplementing networks with green components, using ecological principles, has been useful to capture storm water in a cost- and energy-efficient manner. Low-lying points in the urban landscape serve as collecting points for storm water sediments and microbes, which in turn underpin the integrity and quality of water (McLellan et al 2015). Here, we first describe how multi-functional urban surface water infrastructure networks are being used in Singapore to capture and treat urban storm water, and then present a research framework to understand microbial diversity and ecosystem service potential. Finally, we detail how smart-sensing approaches can be used to further inform and improve ecologically sound practices within an urban freshwater context.

A generalized framework to develop and manage a sustainable urban watershed

In order to develop an eco-friendly watershed and ecological-principles-based management action plans, the understanding of the waterway's ecosystem, including microbial communities (Saxena et al 2015), higher life forms and their functions, which provide ecological services to the watershed is critical. Here we present a framework to develop an understanding of the watershed ecosystem and how they interact with the local environmental factors of the watershed (Fig 1). The suggested framework has a tripartite workflow, which leads to the identification of important life forms and environmental parameters. It will help in developing sustainable water-resources management at catchment and peri-urban scale.

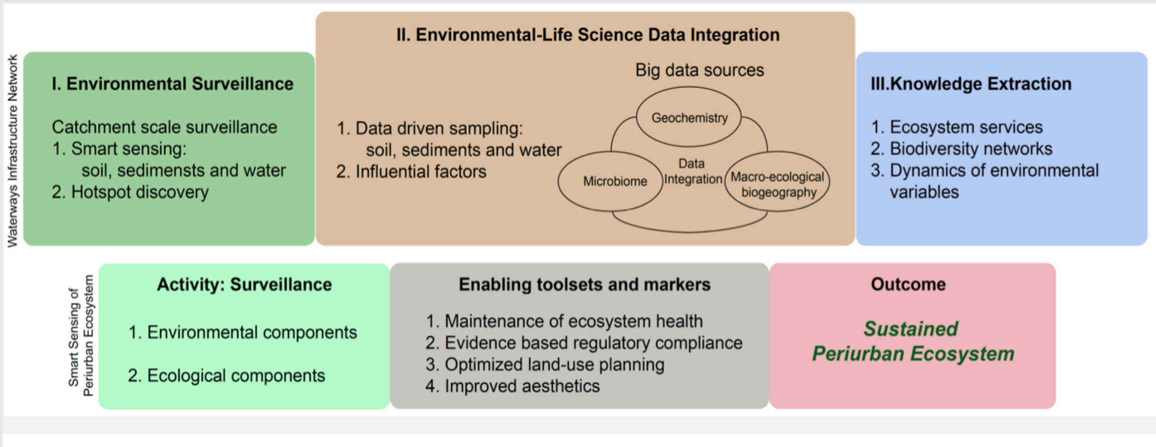

Fig 1 A generalized framework to develop sustainable water resources management using tripartite approach. I. Environmental surveillance provides first snapshot of environmental parameters in the catchment. II. The integration of big data provides interactions between the living organisms and the environment. III. Simplified knowledge can be extracted from the interactions about the ecosystem, which can be translated into activities and final outcome of sustained peri-urban ecosystem.

The first phase in this framework is to develop data-informed optimal sampling design and infrastructure for smart sampling, through environmental surveillance (I). The goal of this process is to measure the spatial and temporal variation in the levels of environmental parameters in response to different urbanization factors, such as land-use types, elevation and soil type. This can be achieved by installing a city-wide Wireless Sensor Network (WSN) to monitor environmental parameters of interest. In general, WSNs are comprised of multiple static nodes across the survey area (Jiang et al 2009). However, in the recent years, hybrid WSNs are becoming more prominent where both static and actuated nodes are deployed for better spatial coverage (Dunbabin and Marques 2012). Another critical component for this phase is the sampling strategy based on elevation, land-use pattern (using digital elevation and land-use maps) and environmental parameters of interest. It encompasses the outlining of land-use type based regions such as commercial or residential, a broad range of environmental parameters that are of interest and the spatial and temporal resolution of the data collection process. However, in the cases where no prior information is available, deciding a sampling strategy can be difficult. In such cases, taking a top-down approach is advised where using hybrid WSNs becomes a necessity. With the help of hybrid WSNs, large spatial and temporal changes can be captured across various survey areas and later narrowed down to the specific questions to meet the overall objective.

Next is Environmental-Life Sciences Data Integration (II). The objective in this phase is to summarize the data from the first phase and produce a subset of important environmental parameters and spatial regions that sufficiently describe the catchment, capturing the variability present in the ecosystem. The soil, sediment and water samples are then collected from the subset of spatial regions to analyse the physicochemical parameters, composition and functions of microbial communities and higher life forms. Soil from the catchment acts as a source of environmental chemicals and life forms that colonize waterways ecosystems (Cruz-

Martínez et al 2009, Fellman et al 2009, Hullar et al 2006). Within waterways ecosystems, while sediments are a sink for most chemicals and the favourable niche from microbial communities (Saxena et al 2015), water acts as a medium of transport for chemicals and dispersal agent for both microbial communities (Saxena et al 2015) and higher life forms. Therefore, soil, sediments and water samples should be analysed for environmental variables and life forms.

Modern ecological approaches and data analytics, such as ecogenomics can be deployed to describe the microbial communities through high-throughput next generation sequencing (NGS) and environmental parameters through sensitive and broad-range technologies (Saxena et al 2015, Saxena et al 2018). In a project where a large number of samples are needed to be processed and analysed, the processing of samples should not be in batches (e.g., if multiple people are processing the samples in multiple days, same day samples or same location samples should not be processed in one batch by one person), rather it should be randomized to minimize batch effects (Leek et al 2010). Therefore, a metadata file is created to capture any non-biological source of variations due to sample processing. This file records parameters, such as, the date, time of sample collection and each step-in sample processing, local environmental observations during the sampling, issues during sample transportation, details of sample processing (information *viz.*, where, who did which step, reagents/kits) and any other information which might be useful to identify and remove the batch-effects in the analysis.

The samples are first analysed for the set of environmental parameters, which describe the watershed. These environmental parameters include, but are not limited to, pharmaceuticals, organics, emerging pollutants, persistent organic compounds, metals, nutrients and other physicochemical variables, such as pH, temperature, salinity, conductivity, oxidation-reduction potential, turbidity and total organic carbon (Saxena et al 2015). Chemical parameters can be analysed by high-throughput, sensitive and broad range technologies, such as ion-exchange chromatography (ions), liquid/gas-chromatography for organics and pharmaceutical, inductively-coupled plasma mass spectrometry for metals and chemical sensors and probes from in-situ measurements of physicochemical parameters (Saxena et al 2018).

Life forms are analysed from the same samples using next-generation sequencing (Pompanon and Samadi 2015). It provides deep-sequence data to classify the microbial taxonomic groups at the level of species and functional genes at the level of enzyme names with high precision (Saxena et al 2018). Higher life forms can be qualified and characterized by sequencing variable region of the 18S ribosomal gene (Pompanon and Samadi 2015). This characterization can be complemented with transcriptomics and metabolomics analysis (Rocha-Martin et al 2014) for strategic locations and highly dynamic environmental hotspots and hot-moments. The transcriptomics and metabolomics data will provide the changes in microbial communities' active taxonomic groups and their functions in response to the changes in the hotspot characteristics, including the higher life forms. The data on the microbial communities, higher life forms and environmental parameters obtained from the study can provide deep insights into the living and chemical landscape of the urban watershed. It provides the spatial distribution and temporal shifts of taxonomic groups, invertebrates and plants along with the changes in levels of major environmental descriptors.

This information is then processed using Environmental-Life Sciences Data Integration approaches to reduce the complexity of microbial communities from thousands of species and functional genes to a few important microbial species and functional genes. The reduced list of species and functions will sufficiently explain the microbiome variation (Saxena et al 2015). The number of environmental pressures influencing the microbial communities can also be reduced to a few key parameters that significantly explain the variation in the microbial communities (Saxena et al 2015). The variation in the important taxonomic-groups and environmental variables can then be used to describe the variation in higher life forms. The most influenced life forms can be used as the first line of ecosystem health reports. These can later be used to develop management practices to enhance the ecosystem services provided by the microbial communities, in response to, for example, chronic pressures, such as land-use history, or pulse disturbances, such as rain.

Once the regulation of selected parameters is developed into management practices, the ecological health of watershed can be monitored by smart sensing and informed sampling. This is where the hybrid WSNs used in the first phase of this framework can be re-used for long-term monitoring. However, for this phase, the static and actuated nodes can be equipped with specific sensor payloads based on the knowledge from ecological models. This will facilitate real-time monitoring, with a strong emphasis on detection of any deviation from the developed ecological model. These deviations can be used as signs of early microbial outbreaks in water resources. Once such deviations are detected, these robots can be used to sample the survey area and help in developing an improved knowledge base for ecological modelling. Moreover, the large amounts of datasets that will be produced during this phase will potentially open the doors for big data analytics on environmental datasets (Hampton Stephanie et al 2013). Hence, it will be feasible to develop highly accurate ecological models using the smart sensing and machine learning techniques discussed in this phase and further improve the management of water resources.

Summing up

The first phase in our framework is to develop data-informed optimal sampling design through the use of hybrid WSNs, which are networks with both static and actuated sensor nodes. Such a systematic approach will help in narrowing down the research questions of the overall objective. Based on the ecological model learned using the framework, the hybrid WSNs can be mounted with specific sensor payloads for monitoring anomalies. Moreover, the large amount of data collected during this phase will facilitate the use of big data analytics for environmental data, thereby developing more accurate ecological models.

References

Cruz-Martínez K, Suttle K The Isme Journal 3:B, Brodie EL, Power ME, Andersen GL, Banfield JF (2009). Despite strong seasonal responses, soil microbial consortia are more resilient to long-term changes in rainfall than overlying grassland. 738

Dunbabin M, Marques L (2012). Robots for Environmental Monitoring: Significant Advancements and Applications. IEEE Robotics & Automation Magazine 19: 24-39.

Fellman J B, Hood E, D'Amore D V, Edwards R T, White D (2009). Seasonal changes in the chemical quality and biodegradability of dissolved organic matter exported from soils to streams in coastal temperate rainforest watersheds. Biogeochemistry 95: 277-293.

Goonetilleke A, Liu A, Gardner T (2016). Urban Stormwater Reuse: An Agenda for Sustainable Development. Global Sustainable Development Report.

Grimm N B, Faeth S H, Golubiewski N E, Redman C L, Wu J, Bai Xet al (2008). Global Change and the Ecology of Cities. Science 319: 756-760.

Habitat UN (2016). World cities report 2016. Urbanization and development. Emerging Futures. Nairobi: UN Habitat.

Hampton Stephanie E, Strasser Carly A, Tewksbury Joshua J, Gram Wendy K, Budden Amber E, Batcheller Archer Let al (2013). Big data and the future of ecology. Frontiers in Ecology and the Environment 11: 156-162.

Hullar M A J, Kaplan L A, Stahl D A (2006). Recurring Seasonal Dynamics of Microbial Communities in Stream Habitats. Applied and Environmental Microbiology 72: 713-722.

Jiang P, Xia H, He Z, Wang Z (2009). Design of a Water Environment Monitoring System Based on Wireless Sensor Networks. Sensors 9.

Leek J T, Scharpf R B, Bravo H C, Simcha D, Langmead B, Johnson W Eet al (2010). Tackling the widespread and critical impact of batch effects in high-throughput data. Nature Reviews Genetics 11: 733.

Leslie M-R, Anu R, Priyanie A (2017). Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India. Environmental Research

Letters 12: 075005.

McDonald R I, Weber K, Padowski J, Flörke M, Schneider C, Green PAet al (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. Global Environmental Change 27: 96-105.

McKinsey Global I (2010). India’s urban awakening: Building inclusive cities, sustaining economic growth. McKinsey & Co.

McLellan S L, Fisher J C, Newton R J (2015). The microbiome of urban waters. International Microbiology 18: 141-149.

Palmer M A, Liu J G, Matthews J H, Mumba M, D'Odorico P (2015). Water security: Gray or green? Science 349: 584-585.

Pompanon F, Samadi S (2015). Next generation sequencing for characterizing biodiversity: promises and challenges. Genetica 143: 133-138.

Rocha-Martin J, Harrington C, Dobson D A, Gara F (2014). Emerging Strategies and Integrated Systems Microbiology Technologies for Biodiscovery of Marine Bioactive Compounds. Marine Drugs 12.

Saxena G, Marzinelli E M, Naing N N, He Z L, Liang Y T, Tom Let al (2015). Ecogenomics Reveals Metals and Land-Use Pressures on Microbial Communities in the Waterways of a Megacity. Environ Sci Technol 49: 1462-1471.

Saxena G, Mitra S, Marzinelli E M, Xie C, Wei T J, Steinberg P Det al (2018). Metagenomics Reveals the Influence of Land Use and Rain on the Benthic Microbial Communities in a Tropical Urban Waterway. mSystems 3.