Perspective

Guiding urban water management towards 1.5 °C

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Abstract

Reliable access to clean and affordable freshwater is prerequisite for human well-being, but its provision in cities generates environmental externalities including greenhouse gas (GHG) emissions. As policy-makers target opportunities to mitigate GHGs in line with the Paris Agreement, it remains vague how urban water management can contribute to the goal of limiting climate warming to 1.5 °C. This perspective guides policy-makers in the selection of innovative technologies and strategies for leveraging urban water management as a climate change mitigation solution. Recent literature, data and scenarios are reviewed to shine-a-light on the GHG mitigation potential and the key areas requiring future research. Increasing urban water demands in emerging economies and over-consumption in developed regions pose mitigation challenges due to energy and material requirements that can be partly offset through end-use water conservation and expansion of decentralized, nature-based solutions. Policies that integrate urban water and energy flows, or reconfigure urban water allocation at the river basin-level remain untapped mitigation solutions with large gaps in our understanding of potentials.

Introduction

The Paris Agreement targets limiting global mean temperature change from pre-industrial levels to 1.5 °C. Achieving the ambition requires a global transformation to net-zero GHGs by mid-century across all sectors of society[1]. Simultaneously, there is the drive to construct, operate and refurbish urban water infrastructure in line with the Sustainable Development Goals (SDGs). Lifecycle analyses of cities in different regions of the world estimate that extraction, distribution and treatment of urban water creates between 0.5-2.5 kg of equivalent lifecycle CO_2 emissions per m^3 of freshwater delivered to end-use[2–6]. The CO_2 intensity range suggests mid-century urban water demands, projected to reach 550-1100 km^3/yr[7], could create between 0.3-2.8 $GtCO_2/yr$ (0.2-2.6 % of global annual GHGs). Enhanced mitigation action in the urban water sector will be needed to achieve the net-zero goals of the Paris Agreement.

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Urban water actions that reduce GHGs will be different across geographies due to differences in development status, water resource availability and urban form. Energy used for water pumping and treatment is the main source of urban water sector GHGs in developed economies[8]. An estimated 4 % of electricity generated globally in 2010 was delivered to the global water sector, and this share could grow to 6 % by mid-century under implementation of the SDGs[9].

Cities employing energy-intensive wastewater reuse and desalination processes supplied by fossil power generation are associated with the largest GHG footprints[4]. Importantly, one quarter of urban dwellers live in water-stressed cities[10], which are at risk from increased water supply costs due to energy-intensive water sources and GHG emissions pricing consistent with the Paris Agreement[9]. Similar risks are posed by a growing global demand for advanced wastewater treatment in response to pharmaceuticals, petrochemicals, and plastics found in urban wastewater[11]. GHG mitigation from urban water systems reduces risks from future GHG emission pricing; thus, under the Paris Agreement urban planners and policy-makers are expected to integrate increasingly ambitious GHG mitigation solutions throughout the urban water sector.

Despite a number of studies outlining individual urban water solutions for reducing GHGs, there is an absence of synthesis distilling the innovations and challenges in the context of achieving net-zero emissions by mid-century in line with the Paris Agreement's goal of 1.5 °C. This perspective fills this knowledge gap by reviewing recent observations and analyzing quantitative scenarios generated by engineering and economic models. The perspective links the major innovations, and identifies where future research and partnerships will be most fruitful. The main opportunities, policy linkages and implementation challenges are categorized across five solution themes in Table 1. The following sections detail each solution theme and discuss the implications for policy-making.

Solution Theme	Prospective Urban Policies	Implementation challenges	Mitigation Potential	Literature
Save water at end-use to avoid embodied energy and materials	Incentives for wastewater reuse, water conservation and low-carbon materials / processing chemicals Education to support understanding differences between curtailment and technological efficiency Water and energy standards for appliances and distribution system auditing Smart meter implementation and incentive programs Water pricing including GHG costs Subsidies to protect low-income populations from GHG price impacts in water stressed regions	Anticipated demand growth combined with energy-intensive water treatment in rapidly developing, water stressed regions Costs for ICT enabled smart metering technology Lack of wholesale water markets and carbon prices Rebounds after implementation of conservation and efficiency measures	~ 0.5-1.1 $GtCO_2$/yr avoided by 2050	Attari, S. Z. (2014)[12] Britton, T. C., et al. (2013)[13] Dieu-Hang, T., et al. (2017)[14] Dworak, T. et al. (2007)[15] Escriva-Bou, A., et al (2018)[16] Flörke, M. et al. (2013)[17] Gonzales, P. et al. (2017)[18] Grafton, R. Q. et al. (2018)[19] Gurung, T. R., et al. (2016)[20] Hsien, C., et al. (2019)[5] Kajenthira, A., et al. (2012)[21] Meron, N., et al. (2020)[4] Mo, W., et al. (2014)[2] Parkinson, S., et al. (2019)[9] Rothausen, S. et al. (2011)[8] Sambito, M. et al. (2017)[3] Slagstad, H. et al. (2014)[6] Stillwell, A., et al. (2011)[22] Vassolo, S. et al. (2005)[23]
Tap the energy and nutrient potential of wastewater	Incentives and establishment of markets for nutrient capture and distribution Incentives for renewable energy and energy efficiency targeting wastewater treatment	Investment, energy and material requirements for pumping, distributing and/or transporting recovered resources Social acceptance of wastewater reuse	~ 0.2-0.7 $GtCO_2$/yr avoided by 2050	Bertrand, A., et al. (2017)[24] Gomez Sanabria, A., (2018)[25] Guo, X. et al. (2018)[26] McCarty, P. L., et al. (2011)[27] Qadir, M. et al. (2020)[28] Song, X. et al. et al. (2018)[29] Stillwell, A. S. et al. (2014)[30] Tubiello, F. N. et al. (2013)[31]
Integrate decentralized and nature-based solutions	Spatially-explicit capacity expansion planning considering energy and net-zero GHG paths Prioritizing parks, wetlands and reforestation projects in urban and peri-urban areas for combined water storage, wastewater/stormwater management and carbon sequestration.	High investment costs for distributed technologies and system reconfiguration ICT requirements for managing water quality at decentralized suppliers Recovering nutrients and flexible energy services for nature-based solutions	?	Engström, R., et al. (2018)[32] Engström, R., et al. (2017)[33] Guo, T., et al. (2013)[34] Kavvada, O, et al. (2018)[35] Lafortezza, R., et al. (2018)[36] Liu, L. et al. (2020)[37] Wu, D., et al. (2020)[37]
Market system flexibility in real-time	Incentives for water efficiency solutions that enable automated response to electricity pricing Including demand response in power sector capacity markets	ICT investment requirements Harmonizing water and electricity market time and spatial scales Reliability of the control strategies and their ability to fully replace conventional storage	?	Kernan, R, et al. (2019)[38] Kernan, R., et al. (2017)[39] Menke, R., et al. (2016)[40] Muhanji, S. O., et al. (2021)[41] Oikonomou, K., et al. (2020)[42] Santosh, A., et al. (2014)[43] Wang, D., et al. (2013)[44]
Reprioritize users to support decarbonization	Establishment of a basin system operator to coordinate urban water savings across basin-connected cities and with other sectoral water uses	Existing user prioritization and transboundary policies	?	Vinca et al. (2020)[45]

Table 1: Solution themes for guiding urban water management towards 1.5 ℃. Each theme is linked to prospective urban policies and implementation challenges. The global mitigation potential is measured relative to a business-as-usual scenario in which no mitigation actions are taken in the urban water sector, and has been estimated based on the literature indicated.

Save water at end-use to avoid embodied energy and materials

If the urban freshwater supply-chain creates GHGs, a low-risk mitigation pathway is to reduce urban water withdrawals and wastewater generation at end-use. This strategy avoids the embodied energy and materials associated with the development and operation of urban water infrastructure[16]. The scale of potential urban water savings is dependent on how inflexible current water uses are to behavioural changes and the accessibility of financing for implementing technological solutions[15].

Urban water uses are diverse, covering all water-related activities in the domestic, commercial and industrial sectors of cities. Sectoral water use trends vary across cities due to differences in incomes, industries, and urban form[17,46]. Recent analysis of Spain finds cities therein are on average using 69 % of urban water in households, 11 % for commercial services, 10 % for industry, and the remaining 9% for public space maintenance[47]. The manufacturing sector generally features wide differences in water intensities across products[23]. In the domestic sector, water heating is a particularly energy-intense aspect of the urban water system[16]. Co-designed industry standards and labelling schemes targeting combined water and energy efficiency are needed at the appliance- or process-level[14]. Ratcheting-up standards over time will help guide technology manufacturers and end-users towards solutions aligned with ambitious sustainability goals. Additionally, improving public understanding of key differences between curtailment (behavioural change) and efficiency (technological change) will accelerate water saving efforts[12], leading to GHG savings through avoided development and operation of urban water infrastructure.

Water savings achieved through conservation and efficiency can be negated by increased water use elsewhere in the system[18]. This rebound effect has the potential to impact GHGs, with net changes determined by the relative GHG-intensity of the shifted water demands. If rebounds occur in sectors with higher energy use, there is the potential for increased GHGs. Rebounds are managed by setting and tracking absolute water saving targets at both the end-user and river basin (aquifer) levels[19]. Multi-scale water budgeting helps prevent reallocation of saved water to other uses, but requires a framework for monitoring and control.

Digital technologies including smart water meters support real-time tracking of water resource use, identification of leaks, user demand feedback, and dynamic resource pricing[13]. Research on savings potentials in the EU highlights behavioural changes induced by simple metering have the potential to provide 10-25 % reduction in urban water demands[15]. The incremental cost and GHG footprint from developing smart water metering is likely minimal, as modern appliances are already incorporating information and communications technology (ICT) for alternate reasons (e.g., increased end-user controllability). The highly-resolved data from smart meters and ICT-enabled appliances supports distribution system monitoring and optimization of water supply planning[20]. These enhancements bring further opportunities for energy, GHG and cost savings at the municipal- or utility-level.

Urban water withdrawals from rivers and aquifers and the associated material and energy footprint for pumping and distribution infrastructure can further be avoided through the direct reuse of urban wastewater for applications that do not require potable quality[21,22]. For example, industrial processing, power plant cooling, and park/garden irrigation can be supported with urban wastewater[23,30]. Pumping distances and GHG impacts are minimized by focusing on applications located within the same building, industry or neighbourhood[35]. In the reverse direction, the expansion of distributed low-carbon thermal power generation in response to the Paris Agreement has the potential to create a new source of waste-heat. This heat can be repurposed to offset thermal energy requirements in co-located advanced water treatment[43]. The cross-sector efficiency benefits will be realized in the future through the integrated planning of distributed power and water projects serving urban areas.

Tap the energy and nutrient potentials of wastewater

Recent inventories estimate that 4 % of anthropogenic methane emissions are caused by the degradation of organic material in domestic wastewater[25]. The emissions can be captured as biogas at wastewater treatment plants using mature technologies[29]. Globally, there is potential to generate between 70-530 TWh of renewable electricity each year[25,28], which if fully exploited could support more than half of the existing global water sector electricity requirements[9]. Emerging microbial fuel cell technologies demonstrate even greater electricity conversion efficiencies, and are making the prospect of energy positive wastewater treatment a promising target for the future[27].

Recent work further estimates that 13.4% of global agricultural demand for nitrogen (14.4%), phosphorous (6.8%) and potassium (18.6%) can be recovered from domestic wastewater flows[28]. Synthetic fertilizers delivering these nutrients are often produced from fossil fuels, with annual global emissions from these sources estimated at 0.68 $GtCO_2eq$[31]. By combining the nutrient availability estimates with the reported emission intensity ranges for each fertilizer it is estimated here that 0.03-0.09 GtCO2eq yr^{-1} can be mitigated through nutrient recovery from urban wastewater. This excludes the additional GHG impacts resulting from the collection and distribution of nutrients to agricultural regions.

Thermal energy recovery in urban wastewater systems represent additional GHG mitigation potential. Heat exchangers installed on wastewater pipes and in sewers can be used to repurpose thermal energy in domestic and industrial wastewater flows for low-grade building heating services[24]. Similarly, building cooling services can be recovered from urban water systems by exchanging heat with low-temperature water found in the freshwater distribution system[26]. Recent technical assessment of similar technologies embedded within the Paris water supply systems estimates a 75% reduction in GHGs typically resulting from building heating and cooling[26]. Additional research is needed to generalize these results for other cities, particularly for more extreme climates where there could be challenges with reliability.

Integrate decentralized and nature-based solutions

Many urban water systems were originally designed at a time when water resources were assumed to be more plentiful and predictable. Opportunities for resource recovery and reuse were neglected. The result is a propensity for unidirectional system designs, where wastewater treatment plants are typically located across an elevation gradient that reduces energy use during pumping from consumers[48]. Nevertheless, energy used for pumping urban water can still be greater than that used in the treatment processes[34]. Moreover, the configuration makes pumping recycled wastewater back to consumers particularly energy-intensive, because it must be moved in reverse across the elevation gradient. When wastewater systems are distributed throughout cities and communities, there is less need to pump/transport recovered resources over great distances and elevations. There is also potential to use smaller distribution pipes. Decentralization can therefore reduce the energy and material footprint of resource recovery from wastewater treatment.

Reconfiguring urban water systems for decentralization drives massive investments into new infrastructure and the replacement of existing distribution systems. For regions lacking existing infrastructure, there is the opportunity to integrate decentralization from the bottom-up. Challenges for decentralization include missing out on economies-of-scale, both in terms of capital cost, maintenance and process energy efficiency[34]. Capacity investment planning trade-offs have not been assessed comprehensively from the perspective of future GHG price implications of the Paris Agreement. The GHG impacts of system reconfiguration have been demonstrated for the city of Houston, Texas in the United States[49]. The data-driven analysis of hybrid system designs finds energy savings on the order of 80% compared with a baseline centralized configuration. Direct comparison between the degree of centralization and lifecycle energy use for a given urban area is needed to understand and manage GHG trade-offs.

Water quality tracking is another important consideration for decentralized water treatment systems, posing risks to human health. City-scale distributed monitoring of water quality in real-time will help manage water quality risks[37]. These functions could be co-developed with smart metering and ICT targeting conservation and energy flexibility.

Nature-based solutions (NBS) are also relevant for urban water management, and include urban design choices such as green roofs, permeable concrete, parks and wetlands[36]. These systems retain precipitation and reduce wastewater and stormwater flows. NBS can mitigate GHGs from urban water systems by avoiding the development and operation of conventional water infrastructure providing similar services. A recent cost-benefit analysis of NBS options for municipal planners in New York City indicates some options are no-regret (i.e., negative cost) due to combined savings on energy and water infrastructure[32]. Despite the potential benefits, NBS remain largely passive; there is limited potential to recover nutrients, energy resources and flexibility. The associated trade-offs for GHG mitigation have not been assessed. Required is lifecycle analysis with the scope to compare the material and operational impacts of NBS versus conventional water system solutions.

Market system flexibility in real-time

Urban water systems must be reliable and resilient; thus, the pumps, pressure valves and intermediate storage tanks contained therein are designed to handle extreme conditions, including peak demands, droughts and storm surges. The drive for reliability results in operating capacity that sits idle under normal operating conditions. This idle capacity can be engaged for real-time energy flexibility.

Specifically, the operation of pumps, pressure valves, and storage tanks can be deferred for short periods or initiated earlier than planned to modulate electricity usage in response to real-time prices or requests from the electricity system operator[39,40]. These real-time requests help manage the variability from loads and generation on the grid[38]. Supplying these services with urban water systems avoids development of dedicated energy storage infrastructure. Future energy storage investments could be directed towards the digitization and modernization of flexible urban water supplies.

Urban water managers at the municipal- or utility-level can play an important role in enabling effective demand response programs by: i) acting as a service aggregator that compiles real-time information on urban water assets to estimate systemic flexibility; ii) brokering the interactions with the real-time energy market operators; and iii) dispatching the resulting control requests to achieve the electricity demand response[44]. Managing the latter at a municipal- or utility-level could be important for ensuring control requests do not threaten the simultaneous goals for water quality.

Third party operators have emerged as alternative demand response service aggregators in the water sector, particularly for large consumers such as wastewater treatment plants[50]. These electricity customers receive revenue from participating as a balancing reserve in electricity markets. Balancing services might alternatively be configured using real-time pricing of electricity[51]. Customers utilize automated control technologies to respond to real-time price changes in an intuitive way.

Challenges with real-time pricing include potential impacts to affordable access and data privacy. Operational decision-making in urban water systems would also need to be harmonized with the same time frames used in the electricity market[41,42]. Moreover, significant investment into ICT-based technologies will be needed to track and dispatch urban water sector demand response. To reduce these costs, energy flexibility considerations should be co-integrated with smart metering technologies targeting water conservation and system monitoring. Further cost-sharing with the electricity sector might be sought to account for the multi-sector benefits of enhanced ICT in the urban water sector. Multi-sector system studies will be needed to quantify the scale of the offered energy flexibility, and to assess an appropriate benefit-sharing mechanism with the electricity sector.

Reprioritize users to support decarbonization

Urban water savings can in principle be reallocated to other uses within the same river basin. These managed rebounds are particularly appealing where and when basin water resources offer limited room for expanded use because of a lack of precipitation, excessive consumption upstream, or user prioritizations. In non-cooperative transboundary basins, existing geopolitical disputes are leading to sub-optimal coordination of sustainable development across regions[52]. These water management inefficiencies are anticipated to create GHGs indirectly, through the constraints they impose on water use across multiple sectors. The potential benefits of reallocation for decarbonization include: i) more flexibility with hydrologically-connected hydropower assets to generate low-carbon electricity and to support grid-integration of other low-carbon renewables (e.g., wind and solar); ii) additional water to support manufacturing and operation of low-carbon technologies, including for cooling of concentrating solar power and for carbon capture, utilization and storage (CCUS) processes; and iii) displacement of alternative energy-intensive water sources (e.g., desalination) from operating downstream.

Long-term river basin scenarios generated for the Indus Basin with the Nexus Solutions Tool (NEST) provide new insights into the potential scale of GHG mitigation cost benefits from reallocation[45]. The configuration of the Indus Basin in relation to the urban areas it contains means urban water savings translate to more water for hydropower generation in the lower Indus Basin, and for meeting future urban demand growth in the delta regions facing water stress without switching to unconventional and energy-intensive water resources. Marginal benefits of enhanced basin-scale coordination are likely less important in regions that do not face water scarcity, and this requires future research. Research is also needed to understand if integration of CCUS in the urban industrial sectors will be constrained by the availability of water resources. A combination of urban water efficiency solutions and re-prioritization might compete as cost-competitive water supply options, with implications for GHG mitigation costs.

Discussion

If urban water demand can be governed so that it reduces in developed economies and grows slowly in developing regions, there is more room to reduce absolute GHG emissions from the urban water sector. If urban water related GHGs increase, enhanced mitigation actions will be needed in other sectors of the economy to reach the net-zero ambitions of the Paris Agreement. Reducing future water demands and wastewater flows relative to those observed today hedges against risks from uncertainties in future costs of alternative technological solutions, and is the strategy with the least uncertainty and complexity for urban water managers to promote for GHG mitigation.

Urban water planners can further mitigate GHGs through the integration of low-carbon materials and decentralized technologies for water treatment and resource recovery. Moreover, urban water managers can support decarbonization of electricity by cooperating with utilities on the implementation of demand response programs. Purchasing zero-carbon electricity will be critical for supporting the widespread roll-out of advanced water treatment in line with the SDGs. Redistribution of water-intensive manufacturing activities away from energy-intensive water sources present additional GHG mitigation opportunities, but come with uncertain costs and impacts for other resources.

Integrated water-energy efficiency standards for appliances and manufacturing processes combined with GHG-aware water pricing represent important future policy levers for driving urban water users towards low-carbon, water-efficient decision-making. Yet, increased municipal water costs could pose challenges for low-income populations. Subsidies will protect these consumers under a real-time, GHG-aware water pricing strategy consistent with the Paris Agreement.

Urban water managers seek an economic characterization of GHG mitigation opportunities, so they can prioritize efforts while minimizing costs for consumers. Marginal abatement cost curves have previously been proposed for this purpose, particularly for coordinating climate action at the municipal-level; however, the static view and limited scope neglects the effects from project sequencing and opportunities to reduce GHGs through cross-sector and basin-scale water reallocation. Quantifying the climate change mitigation potential of urban water instead requires a comprehensive characterization of existing systems from supply to end-use over a timeframe consistent with project lifecycles[53,54].

High-resolution mapping of urban water systems and associated energy use should be used by utilities and municipalities to inform the design of economically optimized pathways for sequential water system transformations at a river basin-scale (Figure 1). In this context, urban water sector mitigation opportunities are coordinated with other municipal and regional mitigation solutions[54]. A basin pathways approach enables intelligent prioritization of efforts that aim at reducing GHGs, while maintaining water quality and enhancing environmental flows both to surface and groundwater systems[45]. Basin-scale models can be co-developed and shared with urban stakeholders to enable their widespread use in urban planning[55].

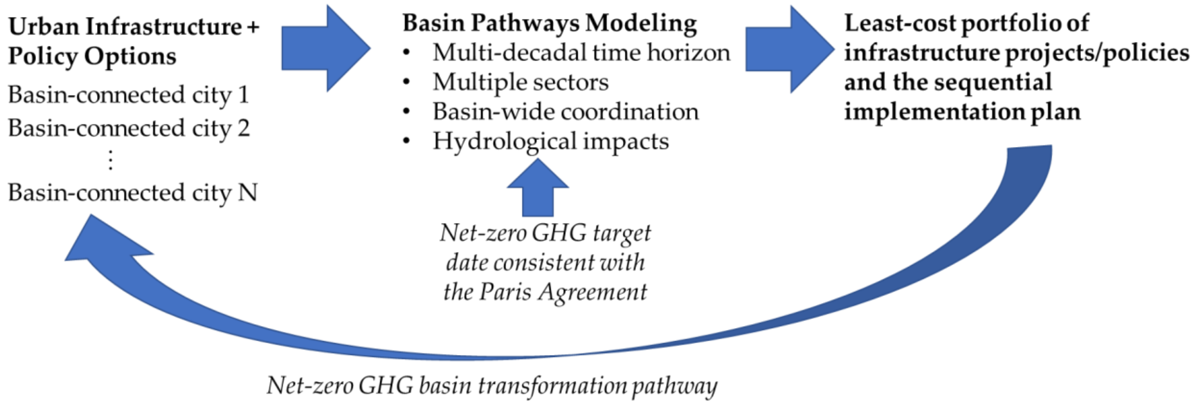

Figure 1: Basin pathways modeling incorporating urban infrastructure and policy options across basin-connected cities informs the economic optimization of net zero GHG transformations under constrained water resources. Multiple sectors, decades and spatial scales are represented simultaneously to identify a least-cost portfolio of projects and policies and the sequential implementation plan.

Potential synergies with the electricity sector that could be beneficial to explore include establishment of an independent system operator at the basin-scale. Similar to a grid operator orchestrating electric load balancing, the basin operator's objective is to coordinate water allocations across basin-connected users. Comparable organizations are already helping manage scarce water resources in heavily urbanized catchments of the Western United States[56]. The basin operator could leverage a market approach to plan and direct the development of decentralized solutions and the reprioritization of users to support both water quality and decarbonization goals[57]. Basin-connected cities become market participants that remain flexible to manage their own portfolio of water-related projects[58], as well as their interactions with electricity markets. Interconnection policies are defined by the basin system operator to ensure decentralized systems have the required ICT infrastructure for maintaining and reporting real-time water quality and GHGs. Time horizons for urban water supply, river basin and distribution operations are harmonized with electricity markets such that opportunities for cross-sector demand response and resource recovery are co-optimized.

Despite the breadth of previous work linking urban water, energy and GHG flows, important knowledge gaps exist in the scientific literature that limit estimation of the total GHG mitigation potential. First, urban water systems represent an attractive new source of electricity flexibility that could provide short-term and long-term services beneficial to decarbonization. More research is needed to develop control strategies and to size the potential flexibility at city-scales. Second, buildings represent a key focal area for coupled water-energy management. Future research should focus on quantifying the global potential to offset building cooling and heating requirements through the capture and re-utilization of thermal energy found in urban water flows. Third, carbon sequestration within vegetation incorporated into nature-based urban water solutions applied at large-scale (as well as associated urban cooling benefits) represent important aspects for future analysis to explore. For example, reforestation of urban and peri-urban areas to alleviate urban stormwater risks could offset GHG emissions occurring elsewhere in the urban water system that are difficult to mitigate (e.g., material requirements). Finally, future studies are needed to understand how the integration of urban water management with river basin management opens new doors for GHG mitigation through coordinated, multi-scale planning.

Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study

Author contributions

S.P. was the sole author of this manuscript

Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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