

1 **Perspective**

2 **Guiding urban water management towards 1.5 °C**

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8 **Abstract**

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

21 **Introduction**

22 The Paris Agreement targets limiting global mean temperature change from pre-industrial
23 levels to 1.5 °C. Achieving the ambition requires a global transformation to net-zero GHGs by mid-
24 century across all sectors of society¹. Simultaneously, there is the drive to construct, operate and
25 refurbish urban water infrastructure in line with the Sustainable Development Goals (SDGs). Lifecycle
26 analyses of cities in different regions of the world estimate that extraction, distribution and treatment of
27 urban water creates between 0.5-2.5 kg of equivalent lifecycle CO₂ emissions per m³ of freshwater
28 delivered to end-use²⁻⁶. The CO₂ intensity range suggests mid-century urban water demands, projected
29 to reach 550-1100 km³/yr⁷, could create between 0.3-2.8 GtCO₂/yr (0.2-2.6 % of global annual GHGs).
30 Enhanced mitigation action in the urban water sector will be needed to achieve the net-zero goals of the
31 Paris Agreement.

1 Urban water actions that reduce GHGs will be different across geographies due to differences
2 in development status, water resource availability and urban form. Energy used for water pumping and
3 treatment is the main source of urban water sector GHGs in developed economies⁸. An estimated 4 %
4 of electricity generated globally in 2010 was delivered to the global water sector, and this share could
5 grow to 6 % by mid-century under implementation of the SDGs⁹.

6 Cities employing energy-intensive wastewater reuse and desalination processes supplied by
7 fossil power generation are associated with the largest GHG footprints⁴. Importantly, one quarter of
8 urban dwellers live in water-stressed cities¹⁰, which are at risk from increased water supply costs due to
9 energy-intensive water sources and GHG emissions pricing consistent with the Paris Agreement⁹.
10 Similar risks are posed by a growing global demand for advanced wastewater treatment in response to
11 pharmaceuticals, petrochemicals, and plastics found in urban wastewater¹¹. GHG mitigation from urban
12 water systems reduces risks from future GHG emission pricing; thus, under the Paris Agreement urban
13 planners and policy-makers are expected to integrate increasingly ambitious GHG mitigation solutions
14 throughout the urban water sector.

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

23

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	Anticipated demand growth combined with energy-intensive water treatment in rapidly developing, water stressed regions	~ 0.5-1.1 GtCO ₂ /yr avoided by 2050	Attari, S. Z. (2014) ¹²
	Education to support understanding differences between curtailment and technological efficiency			Britton, T. C., et al. (2013) ¹³
	Water and energy standards for appliances and distribution system auditing	Dieu-Hang, T., et al. (2017) ¹⁴		
	Smart meter implementation and incentive programs	Dworak, T. et al. (2007) ¹⁵		
	Water pricing including GHG costs	Escriva-Bou, A., et al (2018) ¹⁶		
Tap the energy and nutrient potential of wastewater	Incentives and establishment of markets for nutrient capture and distribution	Investment, energy and material requirements for pumping, distributing and/or transporting recovered resources	~ 0.2-0.7 GtCO ₂ /yr avoided by 2050	Flörke, M. et al. (2013) ¹⁷
	Incentives for renewable energy and energy efficiency targeting wastewater treatment	Lack of wholesale water markets and carbon prices		Gonzales, P. et al. (2017) ¹⁸
		Rebounds after implementation of conservation and efficiency measures		Grafton, R. Q. et al. (2018) ¹⁹
				Gurung, T. R., et al. (2016) ²⁰
				Hsien, C., et al. (2019) ⁵
Integrate decentralized and nature-based solutions	Spatially-explicit capacity expansion planning considering energy and net-zero GHG paths	High investment costs for distributed technologies and system reconfiguration	?	Kajenthira, A., et al. (2012) ²¹
	Prioritizing parks, wetlands and reforestation projects in urban and peri-urban areas for combined water storage, wastewater/stormwater management and carbon sequestration.	ICT requirements for managing water quality at decentralized suppliers		Meron, N., et al. (2020) ⁴
		Recovering nutrients and flexible energy services for nature-based solutions		Mo, W., et al. (2014) ²
Market system flexibility in real-time	Incentives for water efficiency solutions that enable automated response to electricity pricing	ICT investment requirements	?	Parkinson, S., et al. (2019) ⁹
	Including demand response in power sector capacity markets	Harmonizing water and electricity market time and spatial scales		Rothausen, S. et al. (2011) ⁸
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	Reliability of the control strategies and their ability to fully replace conventional storage	?	Sambito, M. et al. (2017) ³
		Existing user prioritization and transboundary policies		Slagstad, H. et al. (2014) ⁶
				Stillwell, A., et al. (2011) ²²
				Vassolo, S. et al. (2005) ²³
				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
				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
				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
				Vinca et al. (2020) ⁴⁵

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

5

6

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

2 If the urban freshwater supply-chain creates GHGs, a low-risk mitigation pathway is to reduce
3 urban water withdrawals and wastewater generation at end-use. This strategy avoids the embodied
4 energy and materials associated with the development and operation of urban water infrastructure¹⁶.
5 The scale of potential urban water savings is dependent on how inflexible current water uses are to
6 behavioural changes and the accessibility of financing for implementing technological solutions¹⁵.

7 Urban water uses are diverse, covering all water-related activities in the domestic, commercial
8 and industrial sectors of cities. Sectoral water use trends vary across cities due to differences in incomes,
9 industries, and urban form^{17,46}. Recent analysis of Spain finds cities therein are on average using 69 %
10 of urban water in households, 11 % for commercial services, 10 % for industry, and the remaining 9%
11 for public space maintenance⁴⁷. The manufacturing sector generally features wide differences in water
12 intensities across products²³. In the domestic sector, water heating is a particularly energy-intense aspect
13 of the urban water system¹⁶. Co-designed industry standards and labelling schemes targeting combined
14 water and energy efficiency are needed at the appliance- or process-level¹⁴. Ratcheting-up standards
15 over time will help guide technology manufacturers and end-users towards solutions aligned with
16 ambitious sustainability goals. Additionally, improving public understanding of key differences
17 between curtailment (behavioural change) and efficiency (technological change) will accelerate water
18 saving efforts¹², leading to GHG savings through avoided development and operation of urban water
19 infrastructure.

20 Water savings achieved through conservation and efficiency can be negated by increased water
21 use elsewhere in the system¹⁸. This rebound effect has the potential to impact GHGs, with net changes
22 determined by the relative GHG-intensity of the shifted water demands. If rebounds occur in sectors
23 with higher energy use, there is the potential for increased GHGs. Rebounds are managed by setting
24 and tracking absolute water saving targets at both the end-user and river basin (aquifer) levels¹⁹. Multi-
25 scale water budgeting helps prevent reallocation of saved water to other uses, but requires a framework
26 for monitoring and control.

27 Digital technologies including smart water meters support real-time tracking of water resource
28 use, identification of leaks, user demand feedback, and dynamic resource pricing¹³. Research on savings
29 potentials in the EU highlights behavioural changes induced by simple metering have the potential to
30 provide 10-25 % reduction in urban water demands¹⁵. The incremental cost and GHG footprint from
31 developing smart water metering is likely minimal, as modern appliances are already incorporating
32 information and communications technology (ICT) for alternate reasons (e.g., increased end-user
33 controllability). The highly-resolved data from smart meters and ICT-enabled appliances supports

1 distribution system monitoring and optimization of water supply planning²⁰. These enhancements bring
2 further opportunities for energy, GHG and cost savings at the municipal- or utility-level.

3 Urban water withdrawals from rivers and aquifers and the associated material and energy
4 footprint for pumping and distribution infrastructure can further be avoided through the direct reuse of
5 urban wastewater for applications that do not require potable quality^{21,22}. For example, industrial
6 processing, power plant cooling, and park/garden irrigation can be supported with urban wastewater^{23,30}.
7 Pumping distances and GHG impacts are minimized by focusing on applications located within the
8 same building, industry or neighbourhood³⁵. In the reverse direction, the expansion of distributed low-
9 carbon thermal power generation in response to the Paris Agreement has the potential to create a new
10 source of waste-heat. This heat can be repurposed to offset thermal energy requirements in co-located
11 advanced water treatment⁴³. The cross-sector efficiency benefits will be realized in the future through
12 the integrated planning of distributed power and water projects serving urban areas.

13 **Tap the energy and nutrient potentials of wastewater**

14 Recent inventories estimate that 4 % of anthropogenic methane emissions are caused by the
15 degradation of organic material in domestic wastewater²⁵. The emissions can be captured as biogas at
16 wastewater treatment plants using mature technologies²⁹. Globally, there is potential to generate
17 between 70-530 TWh of renewable electricity each year^{25,28}, which if fully exploited could support more
18 than half of the existing global water sector electricity requirements⁹. Emerging microbial fuel cell
19 technologies demonstrate even greater electricity conversion efficiencies, and are making the prospect
20 of energy positive wastewater treatment a promising target for the future²⁷.

21 Recent work further estimates that 13.4% of global agricultural demand for nitrogen (14.4%),
22 phosphorous (6.8%) and potassium (18.6%) can be recovered from domestic wastewater flows²⁸.
23 Synthetic fertilizers delivering these nutrients are often produced from fossil fuels, with annual global
24 emissions from these sources estimated at 0.68 GtCO₂eq³¹. By combining the nutrient availability
25 estimates with the reported emission intensity ranges for each fertilizer it is estimated here that 0.03-
26 0.09 GtCO₂eq yr⁻¹ can be mitigated through nutrient recovery from urban wastewater. This excludes
27 the additional GHG impacts resulting from the collection and distribution of nutrients to agricultural
28 regions.

29 Thermal energy recovery in urban wastewater systems represent additional GHG mitigation
30 potential. Heat exchangers installed on wastewater pipes and in sewers can be used to repurpose thermal
31 energy in domestic and industrial wastewater flows for low-grade building heating services²⁴. Similarly,
32 building cooling services can be recovered from urban water systems by exchanging heat with low-
33 temperature water found in the freshwater distribution system²⁶. Recent technical assessment of similar

1 technologies embedded within the Paris water supply systems estimates a 75% reduction in GHGs
2 typically resulting from building heating and cooling²⁶. Additional research is needed to generalize
3 these results for other cities, particularly for more extreme climates where there could be challenges
4 with reliability.

5 **Integrate decentralized and nature-based solutions**

6 Many urban water systems were originally designed at a time when water resources were
7 assumed to be more plentiful and predictable. Opportunities for resource recovery and reuse were
8 neglected. The result is a propensity for unidirectional system designs, where wastewater treatment
9 plants are typically located across an elevation gradient that reduces energy use during pumping from
10 consumers⁴⁸. Nevertheless, energy used for pumping urban water can still be greater than that used in
11 the treatment processes³⁴. Moreover, the configuration makes pumping recycled wastewater back to
12 consumers particularly energy-intensive, because it must be moved in reverse across the elevation
13 gradient. When wastewater systems are distributed throughout cities and communities, there is less need
14 to pump/transport recovered resources over great distances and elevations. There is also potential to use
15 smaller distribution pipes. Decentralization can therefore reduce the energy and material footprint of
16 resource recovery from wastewater treatment.

17 Reconfiguring urban water systems for decentralization drives massive investments into new
18 infrastructure and the replacement of existing distribution systems. For regions lacking existing
19 infrastructure, there is the opportunity to integrate decentralization from the bottom-up. Challenges for
20 decentralization include missing out on economies-of-scale, both in terms of capital cost, maintenance
21 and process energy efficiency³⁴. Capacity investment planning trade-offs have not been assessed
22 comprehensively from the perspective of future GHG price implications of the Paris Agreement. The
23 GHG impacts of system reconfiguration have been demonstrated for the city of Houston, Texas in the
24 United States⁴⁹. The data-driven analysis of hybrid system designs finds energy savings on the order of
25 80% compared with a baseline centralized configuration. Direct comparison between the degree of
26 centralization and lifecycle energy use for a given urban area is needed to understand and manage GHG
27 trade-offs.

28 Water quality tracking is another important consideration for decentralized water treatment
29 systems, posing risks to human health. City-scale distributed monitoring of water quality in real-time
30 will help manage water quality risks³⁷. These functions could be co-developed with smart metering and
31 ICT targeting conservation and energy flexibility.

32 Nature-based solutions (NBS) are also relevant for urban water management, and include urban
33 design choices such as green roofs, permeable concrete, parks and wetlands³⁶. These systems retain

1 precipitation and reduce wastewater and stormwater flows. NBS can mitigate GHGs from urban water
2 systems by avoiding the development and operation of conventional water infrastructure providing
3 similar services. A recent cost-benefit analysis of NBS options for municipal planners in New York
4 City indicates some options are no-regret (i.e., negative cost) due to combined savings on energy and
5 water infrastructure³². Despite the potential benefits, NBS remain largely passive; there is limited
6 potential to recover nutrients, energy resources and flexibility. The associated trade-offs for GHG
7 mitigation have not been assessed. Required is lifecycle analysis with the scope to compare the material
8 and operational impacts of NBS versus conventional water system solutions.

9 **Market system flexibility in real-time**

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

14 Specifically, the operation of pumps, pressure valves, and storage tanks can be deferred for
15 short periods or initiated earlier than planned to modulate electricity usage in response to real-time
16 prices or requests from the electricity system operator^{39,40}. These real-time requests help manage the
17 variability from loads and generation on the grid³⁸. Supplying these services with urban water systems
18 avoids development of dedicated energy storage infrastructure. Future energy storage investments could
19 be directed towards the digitization and modernization of flexible urban water supplies.

20 Urban water managers at the municipal- or utility-level can play an important role in enabling
21 effective demand response programs by: i) acting as a service aggregator that compiles real-time
22 information on urban water assets to estimate systemic flexibility; ii) brokering the interactions with
23 the real-time energy market operators; and iii) dispatching the resulting control requests to achieve the
24 electricity demand response⁴⁴. Managing the latter at a municipal- or utility-level could be important
25 for ensuring control requests do not threaten the simultaneous goals for water quality.

26 Third party operators have emerged as alternative demand response service aggregators in the
27 water sector, particularly for large consumers such as wastewater treatment plants⁵⁰. These electricity
28 customers receive revenue from participating as a balancing reserve in electricity markets. Balancing
29 services might alternatively be configured using real-time pricing of electricity⁵¹. Customers utilize
30 automated control technologies to respond to real-time price changes in an intuitive way.

31 Challenges with real-time pricing include potential impacts to affordable access and data
32 privacy. Operational decision-making in urban water systems would also need to be harmonized with

1 the same time frames used in the electricity market^{41,42}. Moreover, significant investment into ICT-
2 based technologies will be needed to track and dispatch urban water sector demand response. To reduce
3 these costs, energy flexibility considerations should be co-integrated with smart metering technologies
4 targeting water conservation and system monitoring. Further cost-sharing with the electricity sector
5 might be sought to account for the multi-sector benefits of enhanced ICT in the urban water sector.
6 Multi-sector system studies will be needed to quantify the scale of the offered energy flexibility, and to
7 assess an appropriate benefit-sharing mechanism with the electricity sector.

8 **Reprioritize users to support decarbonization**

9 Urban water savings can in principle be reallocated to other uses within the same river basin.
10 These managed rebounds are particularly appealing where and when basin water resources offer limited
11 room for expanded use because of a lack of precipitation, excessive consumption upstream, or user
12 prioritizations. In non-cooperative transboundary basins, existing geopolitical disputes are leading to
13 sub-optimal coordination of sustainable development across regions⁵². These water management
14 inefficiencies are anticipated to create GHGs indirectly, through the constraints they impose on water
15 use across multiple sectors. The potential benefits of reallocation for decarbonization include: i) more
16 flexibility with hydrologically-connected hydropower assets to generate low-carbon electricity and to
17 support grid-integration of other low-carbon renewables (e.g., wind and solar); ii) additional water to
18 support manufacturing and operation of low-carbon technologies, including for cooling of concentrating
19 solar power and for carbon capture, utilization and storage (CCUS) processes; and iii) displacement of
20 alternative energy-intensive water sources (e.g., desalination) from operating downstream.

21 Long-term river basin scenarios generated for the Indus Basin with the Nexus Solutions Tool
22 (NEST) provide new insights into the potential scale of GHG mitigation cost benefits from
23 reallocation⁴⁵. The configuration of the Indus Basin in relation to the urban areas it contains means
24 urban water savings translate to more water for hydropower generation in the lower Indus Basin, and
25 for meeting future urban demand growth in the delta regions facing water stress without switching to
26 unconventional and energy-intensive water resources. Marginal benefits of enhanced basin-scale
27 coordination are likely less important in regions that do not face water scarcity, and this requires future
28 research. Research is also needed to understand if integration of CCUS in the urban industrial sectors
29 will be constrained by the availability of water resources. A combination of urban water efficiency
30 solutions and re-prioritization might compete as cost-competitive water supply options, with
31 implications for GHG mitigation costs.

1 Discussion

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

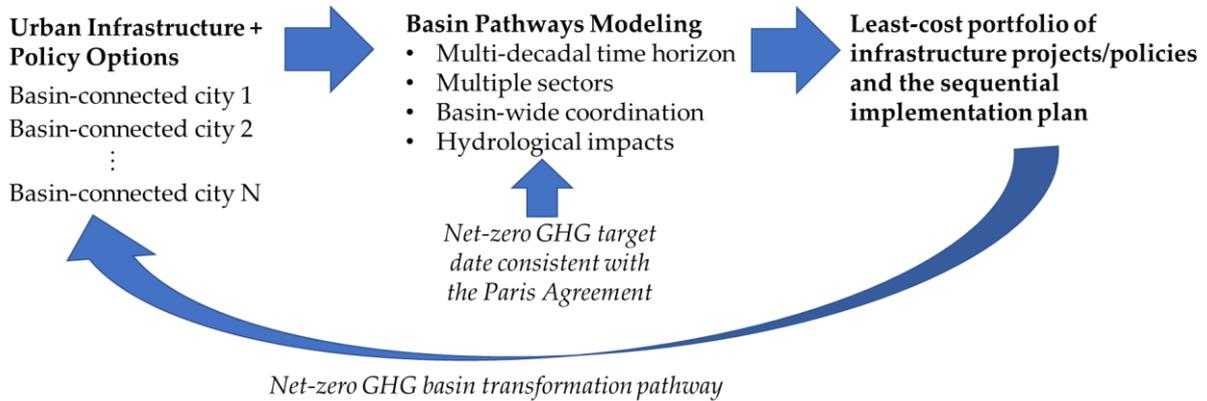
9 Urban water planners can further mitigate GHGs through the integration of low-carbon
10 materials and decentralized technologies for water treatment and resource recovery. Moreover, urban
11 water managers can support decarbonization of electricity by cooperating with utilities on the
12 implementation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

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

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

28 High-resolution mapping of urban water systems and associated energy use should be used by
29 utilities and municipalities to inform the design of economically optimized pathways for sequential
30 water system transformations at a river basin-scale (Figure 1). In this context, urban water sector
31 mitigation opportunities are coordinated with other municipal and regional mitigation solutions⁵⁴. A
32 basin pathways approach enables intelligent prioritization of efforts that aim at reducing GHGs, while
33 maintaining water quality and enhancing environmental flows both to surface and groundwater

1 systems⁴⁵. Basin-scale models can be co-developed and shared with urban stakeholders to enable their
2 widespread use in urban planning⁵⁵.



3
4 **Figure 1:** Basin pathways modeling incorporating urban infrastructure and policy options across basin-connected
5 cities informs the economic optimization of net zero GHG transformations under constrained water resources.
6 Multiple sectors, decades and spatial scales are represented simultaneously to identify a least-cost portfolio of
7 projects and policies and the sequential implementation plan.

8 Potential synergies with the electricity sector that could be beneficial to explore include
9 establishment of an independent system operator at the basin-scale. Similar to a grid operator
10 orchestrating electric load balancing, the basin operator’s objective is to coordinate water allocations
11 across basin-connected users. Comparable organizations are already helping manage scarce water
12 resources in heavily urbanized catchments of the Western United States⁵⁶. The basin operator could
13 leverage a market approach to plan and direct the development of decentralized solutions and the
14 reprioritization of users to support both water quality and decarbonization goals⁵⁷. Basin-connected
15 cities become market participants that remain flexible to manage their own portfolio of water-related
16 projects⁵⁸, as well as their interactions with electricity markets. Interconnection policies are defined by
17 the basin system operator to ensure decentralized systems have the required ICT infrastructure for
18 maintaining and reporting real-time water quality and GHGs. Time horizons for urban water supply,
19 river basin and distribution operations are harmonized with electricity markets such that opportunities
20 for cross-sector demand response and resource recovery are co-optimized.

21 Despite the breadth of previous work linking urban water, energy and GHG flows, important
22 knowledge gaps exist in the scientific literature that limit estimation of the total GHG mitigation
23 potential. First, urban water systems represent an attractive new source of electricity flexibility that
24 could provide short-term and long-term services beneficial to decarbonization. More research is needed
25 to develop control strategies and to size the potential flexibility at city-scales. Second, buildings
26 represent a key focal area for coupled water-energy management. Future research should focus on
27 quantifying the global potential to offset building cooling and heating requirements through the capture
28 and re-utilization of thermal energy found in urban water flows. Third, carbon sequestration within

1 vegetation incorporated into nature-based urban water solutions applied at large-scale (as well as
2 associated urban cooling benefits) represent important aspects for future analysis to explore. For
3 example, reforestation of urban and peri-urban areas to alleviate urban stormwater risks could offset
4 GHG emissions occurring elsewhere in the urban water system that are difficult to mitigate (e.g.,
5 material requirements). Finally, future studies are needed to understand how the integration of urban
6 water management with river basin management opens new doors for GHG mitigation through
7 coordinated, multi-scale planning.

8 **Data availability**

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

11 **Author contributions**

12 S.P. was the sole author of this manuscript

13 **Competing Interests**

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

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