ACS ES&T Water

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Decarbonizing Water: The Potential to Apply the Voluntary Carbon Market toward Global Water Security

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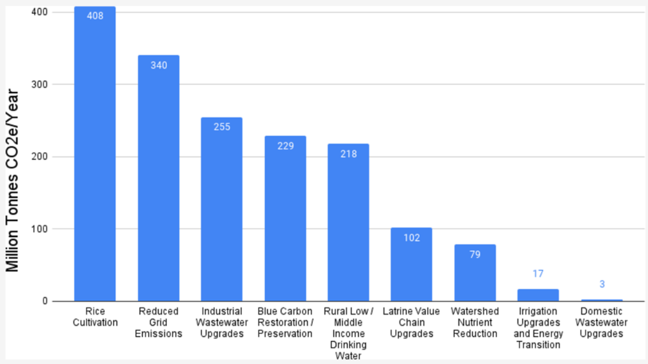
Cite This: *ACS EST Water* 2024, 4, 2655−2666

ABSTRACT: The increase in global water insecurity is one of the first perceivable effects of climate change. Two billion people are now without access to safe drinking water, and four billion experience water stress at least once a year, primarily in low per-capita emission countries. This nexus between climate change and water insecurity has significant implications for the global economy, with the water sector contributing 10% of global emissions. Though traditionally a local issue, climate finance mechanisms like the voluntary carbon market (VCM) present opportunities for a global, sustainable, performance-based funding stream to address water insecurity. Since 2010, water-related carbon projects have yielded over 45 million emission reduction credits. Our analysis estimates a global potential of over 1.6 billion tCO2e per year across various water project subsectors. At a $10 per credit average, this could attract over $160 billion in investments over the next decade, enhancing global water security. However, barriers like high intervention costs and limited technologies hinder widespread implementation, creating a tension between standardized and bespoke credits. We present case studies, spanning drinking water initiatives to the wastewater treatment sector that illustrate VCM's role in channeling private sector capital for water security in climate-vulnerable regions.



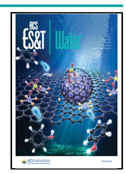
KEYWORDS: *water security, voluntary carbon market, carbon credits, climate finance*

1. INTRODUCTION

Today, two billion people live without access to safe drinking water, primarily in countries among those with the lowest per capita carbon emissions,[1] and four billion experience water stress for at least one month a year,[2] with an unequal distribution of risk globally. There has also been an increase in the number of violent conflicts related to water, with more than 500 of such conflicts logged by the Pacific Institute since 2020.[3] The global energy system is responsible for roughly 10% of freshwater withdrawals, so the energy transition will have an impact on water security as well.[4] Meanwhile, there are significant opportunities to reduce carbon emissions related to both direct and indirect water use. Water and wastewater activities account for 4% of global electricity consumption, and that figure is expected to double by 2040.[5] Water management is responsible for 10% of global greenhouse gas emissions, primarily related to energy use for water treatment and transport, as well as emissions from wastewater decomposition and surface water bodies, the decomposition of organics in reservoirs, and the destruction of wetlands, including peatlands.[6] To contextualize, the airline industry accounts for 2% of global emissions.[7]

The linkages between climate change and water insecurity are clear, as are the implications for the global economy. A recent report by the World Wildlife Fund suggested that as much as 60% of the global gross domestic product (GDP), or $58 trillion, is threatened by water insecurity.[8] This estimate includes both the direct value of water, including its use in industry, households, and agriculture, and its indirect value, including environmental regulation, sustenance of biodiversity, and mitigation of extreme weather events. However, water as a form of natural capital has proven challenging to value and manage. It is mobile, heavy, nonrival, has multiple uses, and its value varies depending on time and place.[9] These characteristics have limited the markets for managing water. While water management is typically a local challenge, climate finance mechanisms, including the voluntary carbon market (VCM),

Received: February 19, 2024
Revised: May 16, 2024
Accepted: May 17, 2024
Published: May 30, 2024



https://doi.org/10.1021/acsestwater.4c00149
ACS EST Water 2024, 4, 2655−2666

offer the potential to provide new sources of recurring revenue to create sustainable, performance-based funding streams and incentivize safe water services globally. Dedicated climate financing from the private sector provides an opportunity to fund reliable, sustainable, and affordable water supply systems.[10]

Carbon markets facilitate the reduction of greenhouse gas emissions worldwide through economic incentives. A voluntary carbon credit is a financial commodity, currently worth about $10 for many nature-based projects,[11] and over $1000 for some direct air capture projects,[12] which represent the reduction or removal of one tonne of carbon dioxide. Many corporations are interested in buying carbon credits through the VCM to compensate for a proportion of their remaining emissions, to achieve sustainability targets linked to environmental, social, and governance (ESG) criteria, or to contribute to/accelerate global net zero. High-integrity carbon markets mean that (1) credits must represent real, verified emission reductions and removals and apply robust environmental and social safeguards; (2) credits must be used by companies in addition to—not instead of—decarbonization as part of their net zero transitions; and (3) associated claims must be credible.

The VCM is designed to financially incentivize voluntary action supporting climate change solutions. VCM projects include both nature-based solutions (NBS), such as improved forest management and reforestation, and technology-based solutions, such as renewable energy installations and improved cookstoves. The two largest registries, Verra and the Gold Standard, also are home to almost all water-related programs. As of October 2023, Verra had issued a total of more than 511 million credits, roughly half of which are related to nature-based solutions,[13] while the Gold Standard reported that 20 million credits had been retired by the end of the third quarter of 2023, more than at the same point in either of the previous two years, and that credit issuances were on track to exceed those of 2022.[14]

Market research conducted in 2022 projected a 20-fold increase in the demand for carbon credits by 2035, with prices rising to an estimated $80−$150 per tonne from the current $25.[15] However, the VCM has recently faced several challenges, calling into question the additionality, permanence, and volume of credits issued, primarily those associated with "Reducing Emissions from Deforestation and forest Degradation" (REDD+) programs. Yet, there are also clear signals that the VCM may recover, including the strengthening of activities led by the Voluntary Carbon Markets Integrity Initiative (VCMI) and the Integrity Council for Voluntary Carbon Markets (ICVCM). Further, recent research suggested that corporations purchasing carbon credits decarbonize twice as fast as companies not participating in the VCM, belying suggestions that carbon credits enable greenwashing.[16]

This review, adapted from a recent report preprinted by the University of Colorado Boulder by these authors,[17] presents the trends and opportunities in applying the VCM toward global water security. We summarize carbon credit-generating water programs under the major registries, including drinking water treatment, wastewater treatment, and irrigation efficiency projects. We develop a global estimate of the potential carbon credits generated from water projects. Overall, across project types, these estimates should be interpreted as broadly reflective of the general potential of various water-related projects to participate in the VCM.

2. METHODS

In this analysis, some project types (blue carbon, rice cultivation, and industrial wastewater treatment) had existing literature estimating emission reduction and removal volumes that we adapted here. For other project types (irrigation and energy sourcing), we extrapolated globally from regional studies. Finally, for some project types (reduced centralized treatment grid emissions, and rural drinking water treatment), we applied novel analysis and generated estimates based on disparate literature values and the application of relevant methodologies. Given these novel contributions, the description of this analysis, while not dominant in overall potential emission reductions and removals, occupies a greater fraction of this report.

2.1. Review of Registered Projects. We reviewed the four major carbon credit registries: Gold Standard, Verra, American Carbon Registry (ACR), and the Climate Action Reserve (CAR). Each registry was polled using the search criteria **water**, **wastewater**, and **irrigation**. While additional relevant terms surfaced during the searches, we noted that the term **water** alone was sufficient to extract projects of significance. Excluded project types included the construction of hydropower plants, renewable energy projects designed for community power generation not explicitly linked to water infrastructure, and efficient cookstoves for water boiling. While it is acknowledged in other sections of this document that projects like hydropower plants offer emission reduction benefits for water utilities, the predominant emphasis of current projects within the registries is on renewable energy generation for communities. Hence, we adopted a conservative approach and omitted these projects. Additionally, projects such as household biogas plants that predominantly relied on cow dung and reforestation efforts not directly linked to water systems were also excluded from the analysis. After review, we excluded projects from the American Carbon Registry (ACR) and Climate Action Reserve (CAR) registries from our analysis due to data gaps and a limited number of related projects. Only seven out of the 80 projects in the search results registered to ACR were found to be relevant, with the number of credits issued and their issuance dates not available on the public registry. Considering the data gaps and the limited number of projects, these seven projects were excluded from our analysis. Our search of the CAR registry returned only five results, and the methodology for each project was not available on the public registry.

2.2. Typology. Based on a review of existing and potential water-related carbon credit programs, we proposed a typology for these projects. The proposed taxonomy first categorizes climate mitigation strategies into two core types: carbon removal and emission reduction. The emission reduction category is further segmented into key subsectors: wastewater, drinking water, and agriculture. In the carbon removal category, we focus on nature-based projects, particularly those related to coastal blue carbon. Each subsector is subsequently delineated into relevant project types, informed by outcomes from registry reviews and literature, as detailed in other sections of this report. Notably, wastewater treatment is identified as a project type in the agriculture subsector. While acknowledging that projects of this type could theoretically fall under the wastewater subsector, their closer association with agricultural processes justifies their placement within the agriculture subsector.

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ACS EST Water 2024, 4, 2655−2666

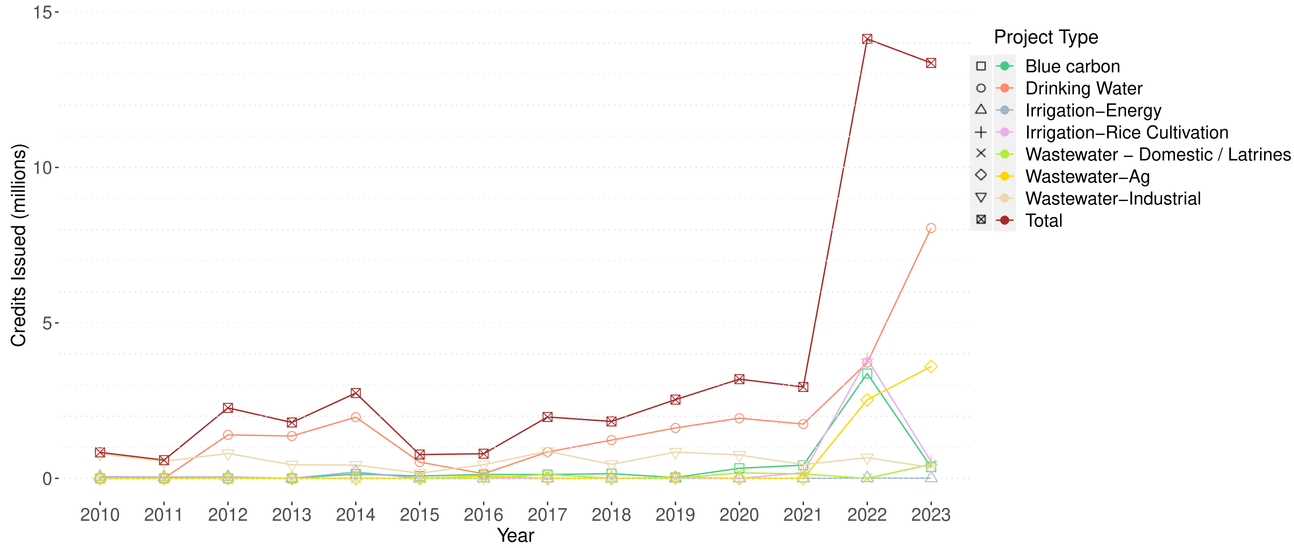

Figure 1. Total carbon credits issued by project type per year since 2010.

2.3. Reduced Centralized Treatment Grid Emissions. We estimate global water supply from utilities based on a random selection of utilities' water production from the International Benchmarking Network (IB-Net)[18] and "the World Health Organization (WHO) and United Nations International Children's Emergency Fund (UNICEF) Joint Monitoring Program (JMP)" data on populations with access to piped water services.[19] Water loss estimates and electricity use for developed countries were estimated from utility data from a sample of eight high-income countries in IB-Net. While those for developing countries were estimated from utility data from a sample of 15 low- and middle-income countries in IB-Net. In addition to the JMP data, grid emission factors from the "United Nations Framework Convention on Climate Change" (UNFCCC) Harmonized Grid Emission factor data set[20] were used to estimate water losses.

2.4. Drinking Water Treatment in Medium- and Low-Income Settings. To estimate the total potential global supply market for these kinds of credits, we apply the Gold Standard's "Methodology for Emission Reductions from Safe Drinking Water Supply"[21] in places where rural populations are currently without safely managed drinking water.[1] Potential savings are relative to the fraction of nonrenewable biomass[22] and rural population solid fuel use in a country.[23] Optimally, improved drinking water services could provide up to 5.5 L of clean water daily per person and would displace water boiling on low-efficiency (e.g., 0.2) wood-burning stoves.

3. RESULTS AND DISCUSSION

3.1. Review of Registered Projects. Our review of the major carbon credit registries yielded a total of 434 water-related projects that have issued a total of more than 45 million credits since 2010. These projects and issuances are summarized in Figure 1. The projects identified in these search results were subsequently categorized into the classifications identified in the typology presented in Figure 2.

3.2. Typology. Here, we present a proposed typology based on existing and potential water-related carbon credit programs. Figure 2 categorizes the programs into the core climate mitigation strategies, key subsectors, and relevant project types. It also provides key characteristics related to each project type.

3.3. Water-Sector Project Types. In our analysis of the global potential of carbon credit generation in the water sector, we consider the major possible project types of domestic and industrial wastewater treatment technology upgrades, replacement of pit latrines (and open defecation) with upgraded centralized treatment, provisioning of treated drinking water as an alternative to water boiling, reduction of nutrients in watersheds as an alternative to wastewater treatment upgrades, irrigation efficiency upgrades, and irrigation energy transition.

Across the subsectors of reduced grid emissions, wastewater treatment upgrades, coastal blue carbon, rural drinking water treatment, latrine value chain upgrades, watershed nutrient reduction, and irrigation, we estimate a total global potential for carbon credits generated through water projects of more than 1.6 billion per year, as indicated in Figure 3.

3.3.1. Reduced Centralized Treatment Grid Emissions. *3.3.1.1. Piped Water Loss Reduction.* Using data from IB-Net[18] and JMP data on populations with access to piped water services,[19] we estimate that water utilities around the world supply 1.3 billion cubic meters of water per day. Power for treatment and pumping typically comes from the national electricity grid, which is powered primarily by fossil fuels in most countries. This means that the more water that is pumped and treated, the greater the emission of greenhouse gases (GHGs). We estimate that water losses in developed countries are typically around 11%. In contrast, the estimate for developing countries is about 26%. This loss of water also wastes the electricity used for pumping and treatment. Reducing water losses reduces electricity consumption and so lowers CO_2 emissions from the power grid. The emissions reduction potential can be estimated from the volume of water that could be saved if water losses were reduced to an efficient level. The efficient level differs from system to system (based on factors such as water scarcity and energy costs), but a reasonable rule of thumb for a typical utility is that physical water losses should not exceed 10%[24] of the water input volume, according to experts.

To quantify emissions, we estimate annual global water losses at 95 billion cubic meters in the business-as-usual

https://doi.org/10.1021/acsestwater.4c00149
ACS EST Water 2024, 4, 2655−2666

Carbon Type	Sub Sector	Project Type	Examples	GHG reduction source	Proportion of credited projects in the major registries	Geographic scope of existing projects	Sustainable development co-benefits	Total Global potential (Million Tonnes CO2e/Year)	DMRV Opportunities	The registry having the highest number of projects with issuances
Emission Reduction	Agriculture	Irrigation- rice cultivation	Alternate wetting and drying for rice cultivation	Methane	16%	China-100%	Affordable and clean energy; Decent work and economic growth; Sustainable production and consumption; Industry, innovation and infrastructure	408.2	Internet/satellite connected sensors can allow for real time monitoring and improve data quality.	Verra (25)
		Irrigation- energy transition, irrigation-efficiency	Use of solar pumps; Use of micro-irrigation systems	Fossil fuel	3%	India- 75%	Affordable and clean energy; Decent work and economic growth; Sustainable production and consumption; Industry, innovation and infrastructure	17	Internet/satellite connected sensors, databases can reduce the time and cost of MRV and improve the quality of data.	Gold Standard (8)
		Nutrient reduction	Implementing conservation tillage to reduce nutrient runoff to watersheds	Fossil fuel	-	-	Sustainable production and consumption	79	Remote sensing, drones, machine learning can improve the quality of monitoring data.	-
		Wastewater treatment	Animal manure management systems; Biogas power generation plant	Methane, fossil fuel	8%	China-83%	Affordable and clean energy; Decent work and economic growth	Grouped with Industrial wastewater treatment	Internet/satellite connected sensors can allow for real time monitoring and improve data quality.	Gold Standard (12)
	Drinking water	Community safe water supply	Borehole rehabilitation; Piped water networks	Biomass	36% (Community + Household)	Sub Saharan Africa-71% (Community+Household)	Safe drinking water; Good health and well-being; Quality education; Gender equality; Decent work and economic growth	218 (Community + Household)	Internet/satellite connected sensors, GIS can reduce the time and cost of MRV and improve the quality of data.	Gold Standard (334)
		Household interventions	Water filter distribution; household safe water supply	Biomass			Safe drinking water; Good health and well-being; Quality education; Gender equality; Decent work and economic growth		Internet/satellite connected sensors, GIS can reduce the time and cost of MRV and improve the quality of data.	
		Reduced grid emissions for utilities	Piped water loss reduction; Utility pumping efficiency	Fossil fuel	-	-	Sustainable cities and communities; Clean water and sanitation	137.8	Internet / satellite connected sensors.	-
	Wastewater	Industrial wastewater treatment	Biogas utilization	Fossil fuel, methane	30%	Thailand-66%, Vietnam-11%, US-11%, China 7%	Sustainable production and consumption; Good health and well-being	823.2 (Industrial + Domestic)	Smart sensors, cloud computing apps can allow MRV to be done in real time.	Verra (24), Gold Standard (24)
		Domestic wastewater treatment,	Biogas utilization	Fossil fuel, methane	3%	80%-China	Improved sanitation; Sustainable cities and communities		Internet/satellite connected sensors, GIS can reduce the time and cost of MRV and improve the quality of data.	Verra (4)
		Latrines	Treatment and disposal of sludge from latrines	Methane	-	-	Improved sanitation; Sustainable cities and communities	319.2	Service value chain monitoring	-
Carbon Removal	Nature-Based	Blue Carbon	Projects that sequester CO2 from coastal wetlands such as mangroves and seagrass	Sequestration of CO2	5%	-	Sustainable cities and communities; Clean water and sanitation; Good health and well-being	841	Remote sensing, drones, machine learning can reduce the time and cost of monitoring	Verra (8)

Figure 2. Proposed typology and key characteristics of water-related carbon credit programs.

(BAU) scenario. Developing countries contribute 72 billion cubic meters, while developed countries contribute 23 billion cubic meters. We then calculate the optimal scenario with 10% water losses,[25] resulting in a global water loss of 47 billion cubic meters, 44 billion cubic meters less for developing countries, and 3 billion cubic meters less for developed countries. The associated reduction in GHG emissions, based on local emission factors for water pumping, is estimated at 52.8 million tCO2e per year globally. In developing countries, the reduction potential is 51.8 million tCO2e per year, and in developed countries, it is 0.9 million tCO2e per year.

In developing countries, water losses have remained stubbornly high for decades, despite the financial and service benefits of loss reduction. Utilities cannot generate their own funds for investment, their cash-strapped public owners cannot fund them adequately, and they cannot borrow commercially. For these reasons, the total financing gap for meeting SDG 6 is estimated to be $106.1 billion.[26] VCMs can relieve this pressure, enabling a loss reduction that would otherwise not have occurred. We consider all water loss reduction in developing countries to be additional, while water loss reduction in developed countries is not.

While the United Nations Clean Development Mechanism (CDM) and Gold Standard do not have approved specifications for carbon credits from the reduction of physical water losses, the International Water Association (IWA) introduced the Leakage Emissions Initiative (LEI), which aims to establish a standard carbon balance for drinking water utilities[27] that could easily be adopted for verification and certification.

3.3.1.2. Utility Pumping Efficiency. Utilizing IB-Net data, we calculate that water utilities worldwide use 837 terawatt h of electricity annually. Of that, 70 to 80%[28] goes into pumping for the distribution of treated water. The remainder is split between raw water pumping and treatment processes. As previously stated, the higher the energy needs, the more GHGs are emitted. Electricity is wasted when pumps are outdated, oversized, or suboptimally placed. Water utilities can improve pumping efficiency by replacing old pumps, better maintenance, better design, and better operational planning. The potential to increase pumping efficiency differs between

https://doi.org/10.1021/acsestwater.4c00149
ACS EST Water 2024, 4, 2655−2666

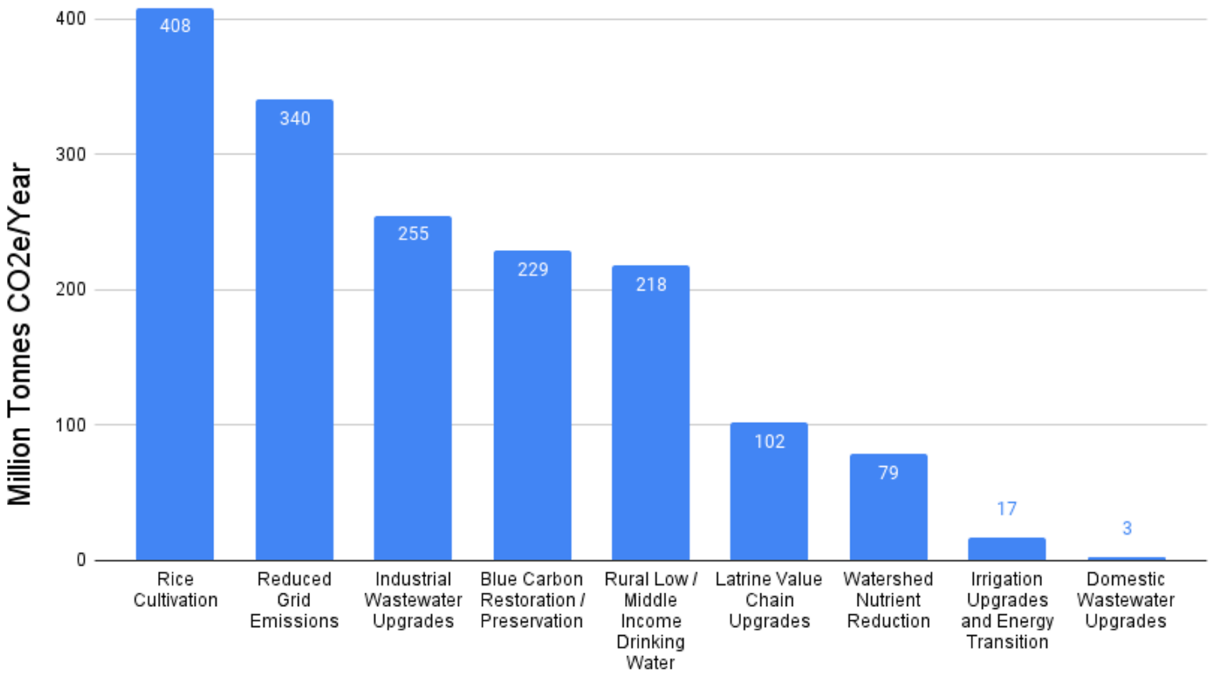

Figure 3. Estimated potential global emissions reductions and removal by the water sector.

developed countries and developing countries. In developed countries, pumping efficiency measures typically reduce water utilities' energy consumption by 14.5%.[28] We estimate that in developing countries, pumping efficiency measures typically reduce water utilities' energy consumption by 30%. This number is an estimate based on eight pumping efficiency case studies in developing countries, namely, China, Brazil, Cambodia, and Ghana, that showed an average energy savings of 46%. We use the conservative estimate of 30% energy savings in our calculations.

We estimate that the annual global emission from energy used for pumping is 311 million tCO2e. Developing countries produce 259 million tCO2e annually, and developed countries produce 52 million tCO2e annually. Using the reduction percentages for pumping efficiency measures, we quantify the global potential of reduced emissions at 85 million tCO2e per year, 27% lower than in the BAU scenario. The reduction potential in developing countries is 78 million tCO2e per year, while in developed countries, it is 8 million tCO2e per year. Emission reductions from pump efficiency can be registered and verified under the Gold Standard or Verra using the CDM methodology "AM0020: Baseline methodology for water pumping efficiency improvements—Version 2.0".[29]

3.3.1.3. Energy Sourcing. Water utilities can reduce emissions by adopting distributed energy sources like solar photovoltaic, hydropower, and biogas generation. Solar panels can be installed on land, rooftops, or floating pontoons and offer a cost-effective way to generate electricity. In specific cases, biogas generation through anaerobic digestion can entirely replace electricity consumption in wastewater treatment plants.[30]

Considering the range of distributed renewable generation options open to water utilities and the ability to use solar power in the day to pump into storage for nighttime supply, we estimate that 80% of electricity used in treatment plants and pumping could be replaced with renewably generated electricity. We compute BAU emissions, postintervention emissions, and reduction potential based on this assumption. The electricity used by utilities in providing water services is around 615,043 million kW h (estimate based on water production, population with access to piped water, and energy efficiency data from a sample of utilities in IB-Net[18]). Adding the annual electricity used in wastewater services (221,740 million kW h)[31] yields an estimated annual electricity consumption by utilities of 836,783 million kWh. Using the reduction percentages above, we quantify the emissions reduction potential as 422 M tCO2e per year. Emission reductions from renewable energy can be registered and verified under the Gold Standard or Verra using the CDM methodology "AMS-I.F.: Renewable electricity generation for captive use and mini-grid-Version 5.0".[32]

3.3.2. Utility Demand-Side Management. Studies indicate that demand-side management programs in developed countries typically deliver water savings of 10 to 20%.[33,34] In developing countries, significant reductions in consumption from demand-side management initiatives seem possible. A demand-side water management program in Pakistan achieved a 23% cut in consumption.[35] In Namibia, a water demand management strategy that included water pricing policies, information campaigns, legislation, and technical measures reduced consumption by 38% between 1992 and 1999.[35] Using data from IB-Net, we estimate that Emissions from water production can be estimated using water produced, energy efficiency, and grid emission factors. In developed countries, these emissions are about 65 million tCO2e per year, while in developing countries, they total roughly 324 million tCO2e per year. We estimate the emissions reduction potential from demand-side management at 107 million tCO2e per year, of which 99 million tCO2e per year would come from developing countries and 8 million tCO2e per year from developed countries.

Demand-side interventions through low-flow technologies can be registered and verified under the Gold Standard or Verra using the CDM methodology "AMS-II.M.: Demand-side energy efficiency activities for the installation of low-flow hot water savings devices—Version 2.0".[36]

3.3.3. Mitigating Methane Emissions from Wastewater Treatment. Methane is responsible for more than a third of total anthropogenic climate change. It is the second most common GHG, accounting for 14% of global GHG emissions.[37] Methane emissions from wastewater account for 7 to 10% of global methane emissions.[38] Methane emissions from wastewater can be reduced in two ways: methane capture and reuse or methane avoidance. Methane avoidance involves ensuring aerobic treatment of wastewater and sludge so that only CO2, not methane, is emitted. Methane capture and reuse can be achieved by installing biogas capture systems at existing open-air anaerobic lagoons or by initiating anaerobic sludge digestion through new construction or retrofitting existing treatment systems. The anaerobic digesters process wastewater biosolids and produce biogas, which can displace fossil fuels.

Methane emissions from municipal wastewater treatment can be reduced by about 9% by improving operational efficiency and implementing advanced technologies that help prevent methane release and harvest biogas.[38] This would potentially reduce methane emissions by about 3.21 million tCO2e per year in developing countries and 1.49 million tCO2e per year in developed countries.

Given the diversity of industrial wastewater sources, a more general estimate is provided for the potential reduced emissions associated with upgrading industrial wastewater systems. A 2020 study (using a 2015 baseline) estimates that upgrading industrial wastewater treatment to anaerobic with biogas recovery followed by aerobic treatment could save about 254 million tCO2e per year globally.[39] As identified elsewhere in this report, such upgrades also require increased electricity demand and associated emissions.

Emissions reduction from methane recovery or reuse can be registered and verified under the Gold Standard or Verra using the CDM methodology "AMS-III.H.: Methane recovery in wastewater treatment—Version 19.0"[40], while technology upgrades can be verified with "AMS-III.I.: Avoidance of methane production in wastewater treatment through the replacement of anaerobic systems with aerobic systems—Version 8.0".[41]

3.3.4. Distributed Sanitation Management. On-site sanitation systems emit around 310 million tonnes of CO2e per year.[42,43] Most of these emissions come from on-site containment systems, pit latrines, and septic tanks. These account for 252 million tCO2e per year. The rest occur largely in treatment and disposal. An estimated 97% of emissions from on-site sanitation occur in developing countries (estimate based on the distribution of on-site sanitation users between developed and developing countries[19]). One recent study suggested that 50% of GHG emissions from Kampala, Uganda, may come from its on-site sanitation value chain.[44]

In many developing cities, desludging is either infrequent and ad hoc or not conducted at all.[45] Increased regularity and coverage of desludging can reduce emissions by shifting fecal sludge from conditions in which it decomposes anaerobically on-site and thus produces methane to centralized sludge treatment plants that use sealed digesters to create methane, capture it, and allow it to be used as biogas, substituting for fossil fuels.

We estimate that under the BAU scenario, on-site sanitation systems produce a total of 310 million tCO2e per year, of which 252 million tCO2e per year come from the containment stage, 159,000 tCO2e per year from emptying and transport operations, and 58 million tCO2e per year from the treatment stage. Under the intervention scenario, on-site sanitation systems emit 205 million tCO2e per year. This is broken down into 204 million tCO2e per year in containment, 344,000 tCO2e per year in operations, and zero in treatment. In developing countries specifically, the potential reduction is 102 million tCO2e per year. In developed countries, it is 2.5 million tCO2e per year.

3.3.5. Blue Carbon. Blue Carbon is a subsector of the carbon markets derived from nature-based solutions.[46] Blue carbon projects focus on the conservation and restoration of coastal and marine ecosystems, such as mangroves, seagrasses, and salt marshes, to mitigate climate change by sequestering and storing significant amounts of carbon dioxide.

Globally, the conservation of existing blue carbon ecosystems stores more than 304 million tCO2e per year across 185 million hectares, while the restoration of these ecosystems could remove more than 841 million tCO2e per year, the equivalent of roughly 3% of global emissions.[47] One recent study suggested that about 20% of global mangrove forests could be protected using VCMs alone.[48] However, the supply of blue carbon projects remains significantly below demand. A recent estimate suggested that demand for blue carbon credits exceeds $10 billion per year.[49] As of late 2022, there are eight mangrove projects operating under a Verra methodology, 15 planned, one seagrass project, and five seagrass projects planned.[49]

It is worth mentioning that, while there are other wetland restoration projects beyond the scope of blue carbon, we observe that these projects are frequently included within broader forest initiatives. Therefore, we do not categorize them as distinct water projects. There is ongoing work to develop separate methodologies for these types of projects.[50]

3.3.6. Watershed Restoration Alternatives to Wastewater Treatment. Energy use by water and wastewater treatment accounts for 4% of global emissions.[5] In the United States alone, water and wastewater treatment plants currently account for about 2% of energy use and the equivalent of 45 million tonnes of CO2e per year.[51] Recent estimates suggest that these US and global values could almost double over the coming years as utilities are obligated to increase treatment levels, even as states transition to renewable energy sources. Furthermore, freshwater quality globally is impaired by nonpoint source pollution from land-use change, agricultural and forestry practices, soil erosion, and urbanization, as well as from large-scale, short-and medium-term shocks associated with wildfires and other impacts of climate change. Fertilizer application, and subsequent runoff into streams, is also a dominant source of water quality impairment.[52]

Distributed land-based water quality interventions, including riparian restoration, stream bank erosion control, livestock exclusion, irrigation upgrades, and fertilizer reduction, have been used to improve instream water quality in lieu of building the electricity-consuming gray infrastructure. Program developers have proposed that carbon financing could provide a novel incentive to accelerate this transition. A recent study suggested that, across the contiguous United States, green alternatives are less expensive, less energy intensive, and less carbon intensive than gray infrastructure alternatives and could save $15.6 billion, 21.7 terawatt-hours of electricity, and 29.8 million tonnes of CO2-equivalent emissions per year while sequestering more than 4.2 million tonnes CO2e per year over

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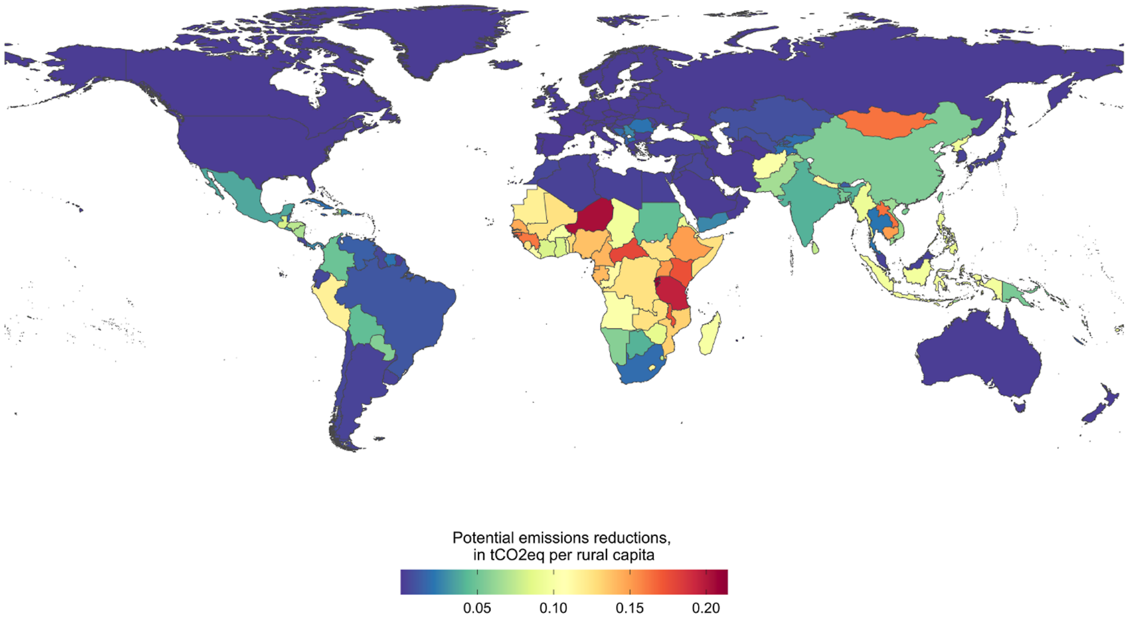

Figure 4. Estimated potential emissions reductions per rural capita replacing demand for woody biomass fuels with treated drinking water services.

40 years [?]. While incentivizing the adoption of green infrastructure remains challenging due to utility and regulator risk aversion, green solutions may have the potential to reduce or remove about 34 million tonnes of CO2e per year in the United States alone.

Extending this opportunity globally, there are many examples of watershed and water quality trading programs in Canada, Australia, New Zealand, the United Kingdom, The Netherlands, Honduras, India, China, and Kenya. Extending the findings of the US study globally and assuming that an indicative 10% of irrigated croplands outside of the United States could be used to generate instream water quality benefits and thereby avoid facility-based treatment, the global potential for this approach could be close to 80 million tonnes of CO2e reduced or removed per year.

3.3.7. Drinking Water Treatment in Medium- and Low-Income Settings. Globally, two billion people do not currently have access to clean drinking water,[1] either by consuming contaminated water or, in about 20% of cases, boiling their drinking water using wood, other biomass, or fossil fuels to address microbial contamination.[53] Since 2007, the Gold Standard and the CDM have provided methodologies that enable project developers to produce carbon credits based on avoided use and demand for fuel to boil water.

These crediting methodologies rely on a concept known as suppressed demand, which presumes a wood fuel demand associated with treating water by boiling. In reality, only a minority of households boil their water, while most drink untreated water, causing a significant health burden.[54] Early criticism of these programs and finance mechanisms came from the donor-supported water and sanitation community and focused on two weaknesses of the model: First, the tenuous technical concept of suppressed demand linking a conceptual demand for nonrenewable biomass burning to boiling water, and second, the lack of rigor in the measurement of functionality and use of water interventions yielding proportional carbon credit issuance.[55−57] From a limited technical perspective, the suppressed demand criticism is valid. However, this legal construct was created not to reduce emissions in low-income countries but instead to recognize that energy use and associated health and economic livelihoods are suppressed in low-income communities.[58] As per capita emissions in high-income countries are still more than 23 times the emissions in least developed countries,[59] there is a strong equity argument for mitigating this disproportionate cause and effect of climate change. A number of adjustments have been made to the eligible methodologies in response to this critique, and new technologies have been introduced to the sector that enable improved digital monitoring, reporting, and verification.[60] Today, there are hundreds of programs globally that generate revenue that is attributable to and reinvested in water services. These programs earn revenue only upon continued delivery of clean water, in contrast to many donor-and government-supported programs that pay up front for capital investments with no direct accountability for functionality and sustainability.

Globally, we estimate a total potential carbon credit generation of more than 218 million tCO2e per year from averted fuel use (Figure 4).

3.3.8. Irrigation Efficiency. About 70% of global freshwater use from surface and groundwater sources is employed in agricultural activities[8] across more than 822 million acres.[61] A recent study estimated global energy demand for irrigation to be more than 6.6 GJ per year.[62] Using continent-level estimates for irrigated cropland[61] and representative national carbon intensity of electricity estimates[63] (China applied to Asia, the United States applied to the Americas, the United Kingdom applied to Europe, Kenya applied to Africa, and Australia applied to Oceania), we estimate that the total amount of emissions associated with irrigation today is more than 85 million tCO2e per year. A recent US-level irrigation energy intensity study combined with US carbon intensity suggests an even higher energy and emissions demand, at more than 22 million tCO2e per year.[64] Extrapolation of these US estimates suggests a global irrigation emissions potential of more than 315 million tCO2e per year. The wide range between these estimates may be attributable to an underestimate of water demand in the global model and

https://doi.org/10.1021/acsestwater.4c00149
ACS EST Water 2024, 4, 2655−2666

consideration only of on-farm irrigation energy use, excluding transport by irrigation utilities.

Estimates of the potential energy and associated emissions savings associated with irrigation upgrades are sparse. A detailed evaluation of low-energy precision application (LEPA) irrigation technologies in Kansas identified a nearly 20% reduction in energy demand (while no reduction in overall water use).[65] Applying this estimate of 20% globally indicates a potential GHG savings of between 17 and 63 million tCO2e per year.

3.3.9. Rice Cultivation. In low-to middle-income countries, rice plays a vital role in diets, constituting over a quarter of per capita caloric intake. However, this staple crop comes with a substantial environmental footprint, accounting for 30 to 40% of the world's annual freshwater consumption and contributing about 10% of global methane emissions.[66] These methane emission are primarily due to field flooding during rice cultivation; the anaerobic conditions created by flooding during cultivation foster the activity of methane-producing bacteria.[67] China is the largest producer of rice and holds a pivotal position in global emissions. Approximately 20% of the world's harvested rice area is in China, making it a significant emitter.[68]

Innovative approaches are being implemented to reduce such emissions. Effective strategies involve the adoption of alternating wetting and drying cycles and intermittent flooding. These not only help to reduce methane production but also result in significant water savings.[69] A 2020 study (using a 2015 baseline) estimated that improvement of water management in rice cultivation, and the use of alternative hybrids and soil amendments could save about 408 million tCO2e per year globally.[39]

Both Gold Standard and Verra have methodologies for the reduction of methane emissions from adjusted water management practices in rice cultivation. The Gold Standard has a methodology dedicated to rice cultivation,[70] developed with inputs from the International Rice Research Institute. Verra, on the other hand, has a broader methodology for improved agricultural land management.[71]

3.4. Energy Transition. The ongoing global transition from fossil fuels to renewable energy sources will have a significant impact on the emissions associated with centralized water treatment and transport, as well as implications for energy generation. Hydropower directly harnesses water for energy generation, while solar and wind, although indirectly affecting water use through manufacturing and cooling processes, contribute to a broader effort to decouple energy production from extensive water consumption. Moreover, a noteworthy aspect of this transition is the potential reduction in energy demand for critical water-related sectors, such as irrigation and water and wastewater treatment. However, significant sources of existing emissions from the water sector, namely, wastewater management and drinking water treatment in low-income settings, may both result in reductions in emissions and increase electricity demand as basic services are extended. In many of these low-income settings, where the majority of the population is underserved, climate financing provides the funds to extend services. Consequently, we anticipate increases in emissions from factors such as methane emission from wastewater treatment, and as gray infrastructure is constructed to connect more people to the grid.[72] Although no studies have been done yet, we expect emission reductions from energy transition to balance out the emissions generated from infrastructure expansion.

3.5. Sustainable Development Goal Cobenefits. Carbon credits generated from water projects offer significant cobenefits aligned with multiple United Nations Sustainable Development Goals (SDGs). Beyond contributing to SDG 6 (Clean Water and Sanitation), these projects address SDG 13 (Climate Action) by mitigating greenhouse gas emissions and often enhancing climate resilience in water systems. These projects also positively impact SDG 1, 10, 14, and 15. The two major registries we searched listed the SDG cobenefits of projects.

Recent research reveals that projects with the potential for the greatest cobenefits obtained a price 30.4% higher than projects with minimal cobenefit prospects and project quality indicators like the Gold Standard, which signal a heightened likelihood of cobenefits, resulted in a substantial price premium, ranging from 6.6 to 29%.[73]

3.6. Parallel Water Credit Markets. Some water sector and VCM stakeholders have suggested a potential for standalone water credits, developed and marketed separately from the VCM. However, existing examples of these so-called water credits, developed to demonstrate compliance with the US Clean Water Act[74] or the Water Benefit Certificates under the Gold Standard,[75] have failed to show significant, scaled demand outside of a large market. The emerging methodologies and projects generating biodiversity credits may reveal if parallel crediting to carbon credits can generate significant demand and stable pricing.

3.7. Regulation, Governance, and Additionality. Additionality in the VCM emphasizes that the emissions reductions claimed by a project must be additional, meaning they go beyond what would naturally occur without the project's intervention. In the context of governance and regulation, it is crucial to recognize that if a regulation already mandates certain emission reductions, a project subject to that regulation may not be considered additional.

However, in the context of the water and wastewater sectors, the concept of additionality becomes nuanced when considering the enforcement of regulations in low-income countries. While a certain service may be mandated, such as clean drinking water access, the actual enforcement may be limited in lower-income settings, leading to a scenario in which the essential service is required but not readily available. In these cases, projects aiming to improve access to drinking water and safe sanitation could still be considered additional as they address a crucial need that regulatory frameworks may struggle to fulfill. Robust carbon credit governance frameworks must therefore carefully consider socioeconomic context and enforcement capacity when assessing additionality in projects within the water and wastewater sectors.

3.8. Cost of Credit Generation. This analysis has not attempted to estimate the cost of the various interventions that would result in emission reductions and removals, so it should not be assumed all projects, technologies, or interventions would be economically viable without additional funding, subsidies, or policy support. The cost of carbon credit generation within the water sector can, in many cases, exceed the pricing available upon sale of these credits. For example, the abatement costs of emissions from latrines have been estimated at roughly \$50 per tCO2e to nearly \$950 per tCO2e,[76] dramatically exceeding, even at the low end, most of the current pricing of carbon credits.

https://doi.org/10.1021/acsestwater.4c00149
ACS EST Water 2024, 4, 2655−2666

3.9. Credit Demand. Demand, in both volume and pricing terms, for voluntary carbon credits varies. Some buyers optimize for large volumes at low prices, while others prioritize cobenefits and direct promotion of the activities generating credits. As described earlier, market research conducted in 2022 projected a 20-fold increase in the demand for carbon credits by 2035, with prices rising to an estimated $80-$150 per tonne from the current $25.[15] If these forecasts for both volume demand and pricing hold, then many carbon credit-generating water programs may become viable without requiring bespoke pricing. However, it remains likely that many water programs will seek and require above-average pricing, and there will remain buyers willing to pay for these cobenefits.

3.10. Claims. Carbon credit buyers can prove their commitment to environmental sustainability by directing their investments toward projects that specifically enhance water treatment, water security, water quality, and watershed restoration.[77]

The Voluntary Carbon Markets Integrity Initiative Claims Code of Practice, launched at COP28 and developed in collaboration with the Integrity Council for the Voluntary Carbon Market, has been designed to support corporate buyers and address "integrity on the demand side by guiding companies and other nonstate actors on how they can credibly make voluntary use of carbon credits as part of their climate commitments and on how they communicate their use of those credits. It provides clarity, transparency, and consistency on what these commitments and claims mean and will give confidence to all those engaging with VCMs.

3.11. Benefit Sharing. Benefit sharing in the VCM refers to the equitable distribution of environmental, social, and economic advantages that arise from carbon credit projects. It emphasizes the inclusion of local communities, indigenous groups, and other stakeholders in the project's success. Prioritizing community engagement and obtaining support from local communities ensures that the benefits extend beyond carbon and that the development is sustainable.

Common mechanisms include revenue sharing, job creation, and community infrastructure projects. Implementing robust benefit-sharing provisions enhances transparency, social acceptance, and the long-term viability of carbon credit initiatives and aligns with the broader goals of environmental conservation and community well-being within the VCM. Recently, some countries have formalized requirements for benefit sharing in the tax code.

However, water security projects within the VCM are intrinsically benefit-sharing initiatives due to their direct and positive impact on local communities and ecosystems. These projects, which often involve sustainable water resource management, watershed protection, and improved water infrastructure, inherently contribute to the well-being of communities by ensuring reliable access to clean water. Furthermore, as described above, water security projects in the VCM are often costly due to the complexity of infrastructure development, sustainable management practices, and ecosystem restoration. Therefore, given the substantial financial investments required, additional revenue sharing beyond the inherent benefits provided needs to be determined on a case-by-case basis, in consultation with all stakeholders in particular impacted communities.

3.12. Digital Monitoring, Reporting, and Verification Technologies. Monitoring, reporting, and verification (MRV) is fundamental to carbon markets and involves the measurement of emission reductions caused by an activity and the reporting of those reductions to an authorized third party that then verifies them in order for carbon credits to be issued. The current MRV process is primarily a manual one, relying on the physical input of data, making it costly, time-consuming, and susceptible to error.[78]

Digital monitoring, reporting, and verification (DMRV) plays a pivotal role in the VCM by enhancing transparency, accuracy, and efficiency in tracking emissions reductions and the impact of carbon offset projects. DMRV leverages digital technologies and data analytics to remotely monitor and report on project activities, providing real-time or near real-time insights into emission mitigation efforts. This digital approach not only reduces the administrative burden associated with manual monitoring but also enables more frequent and reliable reporting. Additionally, it enhances the credibility of carbon credits by improving the accuracy of emissions measurement and verification processes. By employing digital solutions, the VCM can achieve greater accountability and streamline the verification of emission reductions, thus contributing to the market's effectiveness and encouraging trust among stakeholders.

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Notes

The authors declare the following competing financial interest(s): Authors Thomas, Johnson, MacDonald and Fankhauser are also affiliated and part time compensated by Virridy, a social enterprise engaged in carbon financed water treatment programs globally.

ACKNOWLEDGMENTS

This report was prepared by the Mortenson Center in Global Engineering and Resilience at the University of Colorado Boulder and Castalia Advisors and supported by the Resilient Water Accelerator, WaterAid, HSBC, the Voluntary Carbon Markets Integrity Initiative, the Gold Standard, the Moore Foundation, and the Autodesk Foundation. The views and opinions expressed in this report are only those of the authors. We thank the expert stakeholders who participated in interviews and provided resources.

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https://doi.org/10.1021/acsestwater.4c00149
ACS EST Water 2024, 4, 2655−2666