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PREFACE

This volume examines integrated approaches to environmental engineering and sustainable development in the context of accelerating ecological and climatic pressures. The chapters collectively emphasize the need for interdisciplinary frameworks that combine chemical, biological, ecological, technical, and socio-economic perspectives to address complex environmental challenges.

Chapter 1 establishes the foundations of integrated environmental engineering, highlighting how chemical, biological, and ecological processes can be harmonized to promote sustainability. Chapter 2 explores the integration of micro hydropower into rural energy systems, analyzing technical feasibility, economic viability, and social implications to advance decentralized and inclusive energy solutions.

Chapter 3 presents a systematic review of multi-functional green urban infrastructure, focusing on water and economic security in Mekong Delta cities facing drought and salinity intrusion, with adaptive policy pathways for Can Tho City. Together, these contributions offer practical and conceptual insights into resilient infrastructure, sustainable resource management, and climate-responsive governance.

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CHAPTER 1
FOUNDATIONS OF INTEGRATED ENVIRONMENTAL ENGINEERING: CHEMICAL, BIOLOGICAL, AND ECOLOGICAL APPROACHES TO SUSTAINABILITY

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INTRODUCTION

Environmental Engineering has evolved from early sanitary engineering to an interdisciplinary domain integrating chemistry, biology, ecology, material science, and systems engineering (Metcalf & Eddy et al., 2014). Modern environmental challenges — including microplastics, climate-altering gases, pharmaceutical residues, antimicrobial resistance, nutrient imbalances, and ecosystem degradation — require engineers who understand physical unit operations alongside chemical transformations and biological interactions (UNEP, 2019; Thompson et al., 2004). This chapter provides an integrated overview of the chemical and biological foundations underpinning environmental engineering, aligned with current scientific advances (Chapra, 2020; Bitton, 2014). Environmental Engineering intersects with:

- Chemical Sciences reaction kinetics, thermodynamics, redox processes, adsorption, and pollutant transformation (Kannan, 2017; Weiner, 2013).
- Life Sciences microbiology, biochemistry, genetics, ecological networks, and toxicology (Madigan et al., 2018; Girling, 2015).
- Environmental Systems treatment technologies, resource recovery, and risk mitigation (Rittmann & McCarty, 2020; Tchobanoglous et al., 1993).

These intersections support technologies that treat water, regenerate soils, degrade pollutants, and restore ecosystems.

1. CHEMICAL FOUNDATIONS OF ENVIRONMENTAL SYSTEMS

Understanding chemical principles is essential to predicting contaminant fate, designing treatment systems, and evaluating environmental risks. Emerging pollutants such as PFAS, microplastics, and endocrine-disrupting chemicals demand advanced chemical literacy (Manahan, 2017; Ravindra, 2019).

Environmental Chemistry Principles

- **Conservation of Mass:** Governs the design of mass-balance models predicting pollutant behavior in water and treatment systems (Chapra, 2020).

- **Thermodynamics:** Determines reaction spontaneity and equilibrium, influencing redox reactions, sorption, and mineral precipitation (Libes, 2021; Weiner & Matthews, 2017).
- **Reaction Kinetics:** Controls the rate of pollutant transformation under varying environmental conditions (Noyes, 2013; Schwarzenbach et al., 2017).
- **Phase Partitioning:** Predicts distribution of pollutants among air, water, soil, and biota using coefficients like Henry's constant and K_ow (Schnoor, 1996; Wania & Mackay, 1996).
- **Acid–Base Chemistry:** Regulates pH, alkalinity, and nutrient speciation (Clesceri et al., 1998; Henze et al., 2008).
- **Redox Chemistry:** Governs transformations of metals, nutrients, and organics, affecting mobility and toxicity (Rittmann & McCarty, 2020; Sposito, 2008).

Chemical Speciation

Speciation determines chemical toxicity, solubility, and environmental behavior. For example, arsenite [As (III)] is more mobile and toxic than arsenate [As(V)], affecting groundwater remediation strategies (Weiner & Matthews, 2017). Nitrogen, carbon, and carbonate species critically influence biogeochemical cycles, water chemistry, and scaling potential (Henze et al., 2008; Stumm & Morgan, 2012). Tools like PHREEQC and Visual MINTEQ model these equilibria (Parkhurst & Appelo, 2013).

Aqueous Chemistry and Water Treatment

- **Hardness and Alkalinity:** Impact coagulation, scaling, and process stability (Weiner & Matthews, 2017).
- **Coagulation–Flocculation:** Uses metal hydroxide flocs to remove suspended solids, organic matter, and pathogens (Clesceri et al., 1998; Zhao et al., 2020).
- **Oxidation–Reduction Processes:** Include chemical oxidants and advanced oxidation processes for micropollutant degradation (Dotson et al., 2018).

Atmospheric Chemistry

Air chemistry controls smog formation, acid deposition, and climate dynamics. Tropospheric ozone, secondary organic aerosols, and greenhouse gases significantly affect human health and radiative forcing (Seinfeld & Pandis, 2016; Hallquist et al., 2009; IPCC, 2021).

Soil Chemistry

Soil regulates nutrient cycling, pollutant immobilization, and ecosystem productivity. Organic matter, clays, and oxides sorb hydrophobic pollutants, while pH and redox gradients influence metal mobility. Cation exchange capacity governs nutrient retention and leaching risks (Schnoor, 1996; Sposito, 2008).

2. LIFE SCIENCES FOUNDATIONS

Biological sciences underpin pollutant transformation, nutrient cycling, and ecosystem restoration.

Environmental Microbiology

- **Microbial Metabolism:** Aerobic and anaerobic pathways drive organic matter degradation and nutrient transformations (Madigan et al., 2018; Conrad, 2020).
- **Enzymatic Transformation:** Enzymes degrade hydrocarbons, chlorinated solvents, pesticides, and emerging contaminants (Grady et al., 2011; Haritash & Kaushik, 2009).
- **Biofilms:** Structured microbial communities enhance treatment stability and enable simultaneous aerobic–anaerobic reactions (Flemming & Wuertz, 2019).
- **Microbial Kinetics:** Monod-based models guide reactor design and process optimization (Rittmann & McCarty, 2020).

Biogeochemical Cycles

- **Nitrogen Cycle:** Nitrification, denitrification, and anammox processes remove nitrogen efficiently in wastewater systems (Henze et al., 2008; Kartal et al., 2010).

- **Carbon Cycle:** Photosynthesis, respiration, methanogenesis, and methane oxidation drive carbon flux and energy recovery (Grady et al., 2011; Angelidaki et al., 2018).

Ecology and Ecosystem Engineering

Nature-based solutions—such as constructed wetlands, riparian buffers, and urban forests—leverage ecological processes to improve water quality, sequester carbon, and enhance resilience (UNEP, 2019; Mitsch & Jørgensen, 2020).

Environmental Toxicology

Toxicology evaluates chemical impacts on organisms and ecosystems. Key metrics include NOEL, LOEL, LD_{50}/EC_{50}. Persistent and emerging contaminants bioaccumulate, requiring advanced removal strategies (Girling, 2015; Newman, 2019; Thompson et al., 2004; Wang et al., 2022).

Integrated Chemical–Biological Processes

Modern environmental engineering integrates chemical and biological processes for efficient contaminant removal.

Water and Wastewater Treatment: Biological processes (activated sludge, biofilms) degrade biodegradable pollutants, while chemical oxidation (AOPs) removes refractory compounds. Hybrid designs optimize nutrient removal and effluent quality (Metcalf & Eddy et al., 2014; Lackner et al., 2014; Weiner, 2013).

Solid and Hazardous Waste Treatment: Composting and anaerobic digestion convert organic waste to humus and biogas, while chemical stabilization and bioleaching manage hazardous materials (Tchobanoglous et al., 1993; Appels et al., 2008; Johnson, 2014).

Air Pollution Control: Biofilters, biotrickling filters, and bioscrubbers leverage microbial oxidation, often coupled with chemical pretreatment, to remove VOCs and odorous gases cost-effectively (Bitton, 2014; Lebrero et al., 2013).

3. ENVIRONMENTAL BIOTECHNOLOGY

3.1 Bioremediation

Bioremediation leverages the inherent metabolic capabilities of microorganisms to transform, detoxify, or completely mineralize environmental contaminants, making it one of the most sustainable and cost-effective approaches for environmental cleanup. Microbial communities possess a remarkable enzymatic repertoire that allows them to degrade a wide spectrum of pollutants, including hydrocarbons, pesticides, chlorinated solvents, phenolic compounds, and certain heavy metals. Aerobic bacteria typically oxidize organic contaminants using oxygenases and dehydrogenases, producing intermediates that enter central metabolic pathways such as the tricarboxylic acid (TCA) cycle. In contrast, anaerobic microorganisms play a critical role in the reductive transformation of highly chlorinated solvents and metals through processes such as reductive dechlorination and metal reduction (Rittmann & McCarty, 2020; Lovley, 2013).

The versatility of microbial metabolism enables adaptation to complex environmental matrices, including soils, sediments, groundwater, and engineered bioreactors. Recent advances highlight the importance of multi-species consortia, where synergistic interactions enhance degradation efficiency beyond what single strains can achieve. For instance, pesticide-degrading bacteria may work in conjunction with fungi capable of breaking down recalcitrant organic structures through extracellular oxidative enzymes (Jugder et al., 2016).

Hybrid technologies that integrate physicochemical and biological processes are increasingly used to improve remediation outcomes. Pretreatment with oxidation (e.g., Fenton, ozone), adsorption, or thermal desorption can reduce the molecular complexity of pollutants, making them more bioavailable and easier for microbes to metabolize. bioelectrochemical systems and engineered bioreactors further enhance degradation kinetics by optimizing redox conditions and electron transfer processes (Kumar et al., 2022). These innovations demonstrate how bioremediation is shifting from natural attenuation toward highly engineered, performance-optimized systems tailored for diverse contaminants.

3.2 Resource Recovery

Resource recovery represents a paradigm shift from waste treatment to resource generation, aligning environmental engineering with circular-economy principles. Biological processes are central to this transition, enabling the conversion of organic waste streams into valuable energy carriers and bioproducts. Anaerobic digestion remains the most widely implemented technology, producing biogas composed predominantly of methane and carbon dioxide. With appropriate upgrading, biogas can be refined into biomethane, a renewable substitute for natural gas (Appels et al., 2008).

Beyond energy recovery, microbial pathways enable the production of hydrogen through dark fermentation, photofermentation, and microbial electrolysis cells, offering carbon-neutral energy options. Nutrient recovery is another growing focus: phosphorus, a finite global resource, can be precipitated as struvite in wastewater treatment systems, creating a slow-release fertilizer suitable for agricultural use (Hall & Hall, 2020; Rahman et al., 2021).

Bioplastics such as polyhydroxyalkanoates (PHAs) are synthesized by bacteria under nutrient-limiting conditions and can be generated directly from waste substrates including food waste, agricultural residues, industrial effluents, and municipal organics (Kourmentza et al., 2017). These bioproducts replace petroleum-based plastics and close material loops, reinforcing sustainability goals. Overall, resource recovery bioprocesses support waste valorization, reduce dependence on virgin materials, and promote environmentally resilient economic systems.

3.3 Genetic and Synthetic Biology

Genetic and synthetic biology are transforming environmental biotechnology by enabling precise control over microbial functions used in remediation and resource recovery. CRISPR-based gene editing tools allow rapid modification of microorganisms to enhance their degradative capabilities, improve stress tolerance, or enable the assimilation of novel substrates. One emerging application is the development of CRISPR-enabled biosensors capable of detecting trace levels of pollutants—such as per- and polyfluoroalkyl substances (PFAS) or pesticide residues—with high specificity and sensitivity (Yeh et al., 2020).

Engineered microbes can be designed to express tailored metabolic pathways that degrade persistent organic pollutants or convert waste into high-value products. Synthetic consortia, which combine engineered strains with natural microbial partners, leverage division of labor to optimize complex biotransformations (Bernstein & Carlson, 2012). These systems enable more robust performance than single-strain designs and can be customized for pathways such as chlorinated solvent degradation, aromatic compound breakdown, or nutrient recovery (D'Agostino & Mabury, 2017).

4. GREEN CHEMISTRY & SUSTAINABLE ENGINEERING: DESIGNING FOR PEOPLE AND PLANET

In our everyday lives from the clothes, we wear to the medicines we rely upon — countless chemical processes quietly operate behind the scenes. Historically, many of these processes prioritized cost and efficiency, often at the expense of human health and the environment. Green Chemistry emerged as a transformative alternative to that paradigm. Its core aim is simple: rather than dealing with pollution or hazardous waste after it appears, design chemical processes and products from the start to be safer, less wasteful, and more efficient (Anastas & Warner, 1998; Mulvihill et al., 2011). The promise isn't just cleaner chemistry it's a fundamentally better way to live. As society's challenges have grown from resource scarcity to climate change and toxic waste green chemistry alone is insufficient. Sustainable Engineering complements it by designing whole production systems, supply chains, and waste cycles with human health and ecological integrity in mind (UNEP, 2019; Ruiz-Mercado et al., 2016).

From Laboratory to Life Cycle

Modern sustainable engineering emphasizes life-cycle thinking. Engineers assess environmental impacts from raw material extraction through production, use, and end-of-life management (Cespi, 2025; Qazalbash et al., 2024). This approach reveals hidden impacts; for example, a solvent may appear benign in lab experiments but become hazardous when produced or disposed of improperly.

Integrating life-cycle assessment (LCA) into green chemistry research ensures that lab innovations translate into real-world sustainability (Ruiz-Mercado et al., 2016).

Innovation That Cares for Communities

Sustainable engineering considers people as well as the planet. It addresses questions such as: Who is exposed to pollutants? When and where do emissions occur? What are the long-term consequences? By designing processes with lower emissions, less waste, and fewer toxic by-products — alongside opportunities for reuse, recycling, or valorization — engineers can reduce health risks and environmental degradation (Meshram, 2024; Santos et al., 2025). For example, rethinking polymer lifecycles under green chemistry principles can produce plastics that degrade safely or are fully recyclable, minimizing plastic waste and dependence on virgin fossil feedstocks (Alhassani et al., 2025).

Efficient Use of Resources

Process intensification is central to sustainable engineering. Compact reactors, flow chemistry, and membrane-based separations reduce energy and material consumption (Mulvihill et al., 2011). Combining renewable feedstocks, energy-efficient design, and clean production reduces reliance on finite resources and greenhouse-gas emissions, advancing circular economy goals (Santos et al., 2025).

A Roadmap Toward a Better Future

Integrating green chemistry, sustainable engineering, and circular economy principles can reshape how we produce, consume, and dispose of materials. This approach promises cleaner air and water, reduced health risks, and a resilient economy. Yet it requires cooperation across disciplines, rethinking economic models to prioritize sustainability, and ensuring transparency in supply chains. When implemented, these strategies can enhance quality of life for current and future generations, aligning human development with planetary health (Anastas & Warner, 1998; UNEP, 2019).

4. CLIMATE CHEMISTRY

Climate chemistry focuses on the chemical transformations that govern the behavior of greenhouse gases and their effects on Earth's climate system. Greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons trap infrared radiation in the atmosphere, driving global warming and altering weather patterns (Seinfeld & Pandis, 2016). Beyond their atmospheric presence, these gases interact with natural systems: for example, CO_2 dissolves in oceans, forming carbonic acid, which lowers pH and affects marine life—a phenomenon known as ocean acidification (Gattuso et al., 2015). Similarly, methane undergoes oxidation in the atmosphere, producing CO_2 and water vapor, thereby influencing radiative forcing and contributing to climate feedback loops (Kirschke et al., 2013).

Understanding these chemical processes is essential for designing effective climate mitigation strategies. Carbon capture and storage (CCS), including amine scrubbing and mineral carbonation, relies on chemical principles to remove CO_2 from industrial emissions and convert it into stable forms, either as dissolved bicarbonates or solid carbonates (Liu et al., 2020). Biological sequestration, such as algal cultivation, uses photosynthetic organisms to capture CO_2 while generating biomass that can be converted into biofuels, fertilizers, or high-value bioproducts, merging climate mitigation with resource recovery (González-Fernández & Muñoz, 2017). Another promising approach is biochar production, in which organic residues are pyrolyzed to create a stable carbon-rich material that improves soil fertility while locking carbon in long-term storage (Lehmann & Joseph, 2015). By integrating chemical knowledge with technological and ecological solutions, environmental engineers can design interventions that address both emissions reduction and sustainable resource management. Climate chemistry thus bridges the gap between understanding atmospheric reactions and applying practical solutions to safeguard ecosystems and human communities.

Nature-Based Solutions

Nature-based solutions (NBS) harness the power of natural ecosystems to address environmental challenges while providing social and economic benefits.

Unlike conventional "grey" infrastructure, NBS integrate plants, soils, and microorganisms into engineered systems to restore ecological balance and enhance resilience (Cohen-Shacham et al., 2016). For instance, constructed wetlands treat wastewater by combining microbial degradation, plant uptake, and sedimentation, removing nutrients, organic matter, and metals while creating habitat for wildlife. Similarly, urban forests and green roofs mitigate heat islands, manage stormwater, and sequester carbon, directly improving air quality and human well-being (Shackleton et al., 2021).

Coastal and riparian ecosystems, including mangroves, marshes, and floodplains, act as natural buffers against flooding, storm surges, and erosion. Their vegetation traps sediments, stabilizes soils, and supports fisheries, linking climate adaptation with biodiversity conservation. NBS emphasize low-energy, adaptive, and self-sustaining approaches, reducing the need for intensive mechanical or chemical interventions. By integrating ecological processes into infrastructure design, environmental engineers can create multifunctional systems that simultaneously address water quality, climate resilience, carbon storage, and community well-being. As global environmental pressures increase, NBS offer scalable, cost-effective, and socially inclusive strategies for sustainable development (UNEP, 2019).

Nanotechnology in Environmental Engineering

Nanotechnology has emerged as a transformative tool in environmental engineering, offering unprecedented opportunities for pollution control, water treatment, and environmental monitoring. Nanomaterials, due to their extremely high surface area-to-volume ratios and tunable chemical properties, exhibit enhanced adsorption, catalytic activity, and reactivity compared to conventional materials (Khan et al., 2021). For example, titanium dioxide (TiO_2) nanoparticles are widely applied in photocatalysis, where light-induced electron–hole pairs generate reactive oxygen species that degrade persistent organic pollutants such as dyes, pharmaceuticals, and endocrine-disrupting compounds (Fujishima et al., 2008).

Carbon-based nanomaterials, including carbon nanotubes (CNTs) and graphene oxide, have been incorporated into membranes and filtration systems, providing high selectivity, fouling resistance, and improved permeability for the removal of heavy metals, organic pollutants, and emerging contaminants (Mahmoud et al., 2017).

Nanoscale zero-valent iron (nZVI) represents another breakthrough in environmental remediation, particularly for contaminated groundwater. Its high reactivity enables the reductive degradation of chlorinated solvents, pesticides, and heavy metals, effectively immobilizing or detoxifying hazardous substances in situ (Zhang & Elliott, 2006). Despite these benefits, the use of nanomaterials requires careful risk assessment. Their small size allows them to interact with cellular structures, potentially inducing oxidative stress or cytotoxicity in aquatic and terrestrial organisms. Consequently, "safe-by-design" principles, life-cycle assessment, and controlled application strategies are critical to ensure that nanotechnology advances environmental remediation without introducing new ecological or human health risks (Khan et al., 2021; Li et al., 2020).

Microplastics and Emerging Contaminants

The persistence of microplastics and emerging chemical contaminants has become a pressing environmental concern. Microplastics — defined as plastic particles smaller than 5 mm — originate from the fragmentation of larger plastic debris or from industrial and personal care products. Their small size and hydrophobic surfaces allow them to adsorb pollutants such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and heavy metals, creating vectors for chemical transport across ecosystems (Thompson et al., 2004; Galloway et al., 2017). Furthermore, biofilms that develop on microplastics can harbor pathogenic microorganisms and antibiotic-resistant genes, posing risks to aquatic organisms and potentially to human health through trophic transfer. Emerging contaminants, including pharmaceuticals, personal care products, endocrine-disrupting chemicals, and per- and polyfluoroalkyl substances (PFAS), often resist conventional water and wastewater treatment, persisting in rivers, groundwater, and sediments (Gomes et al., 2022).

Addressing these challenges requires advanced mitigation strategies that combine physical, chemical, and biological methods. Adsorption using activated carbon or engineered nanomaterials can remove hydrophobic and persistent pollutants efficiently. Membrane filtration, including nanofiltration and reverse osmosis, provides size-selective removal of both microplastics and dissolved contaminants. Advanced oxidation processes (AOPs) generate highly reactive radicals that degrade recalcitrant organic compounds, while engineered biodegradation employs specialized microbial consortia capable of metabolizing otherwise resistant pollutants (Zhang et al., 2020).

Integrating these approaches enhances treatment efficacy and environmental safety. Moreover, monitoring the environmental fate, transport, and ecological impacts of microplastics and emerging contaminants is essential for developing targeted regulatory strategies and sustainable mitigation practices. Collectively, advances in nanotechnology, adsorption, membrane processes, AOPs, and bioremediation illustrate how environmental engineering is evolving to address complex pollution challenges, bridging chemical, biological, and technological solutions (Khan et al., 2021; Galloway et al., 2017).

Future Directions

The future of environmental engineering lies in integrating advanced materials, digital innovation, and ecological principles. Digital twins—virtual replicas of treatment plants or ecosystems—enable real-time simulation, predictive modeling, and optimization of operations. Paired with AI-driven monitoring systems, these tools support fault detection, energy optimization, and adaptive management of water and waste infrastructures. Material science advances continue to drive innovation, with metal–organic frameworks (MOFs) and graphene-based sorbents emerging as highly efficient materials for gas capture, adsorption, and catalysis. Hybrid treatment systems that combine physical, chemical, biological, and nature-based components will become common as environmental challenges grow more complex. Circular-economy principles encourage resource recovery from wastewater, solid waste, and industrial by-products, closing loops and reducing reliance on virgin materials (UNEP, 2019).

As climate change accelerates, environmental engineers must also prioritize resilience by integrating decentralized systems, renewable energy, and adaptive ecological infrastructure. The emphasis is shifting from pollution control to systems transformation, with sustainability embedded at every design stage.

CONCLUSION

Environmental engineering integrates chemical, biological, ecological, and technological knowledge to address the interconnected challenges of pollution, resource depletion, and climate change. The field has evolved from traditional sanitation and end-of-pipe treatment to a multidisciplinary, sustainability-focused discipline. Progress in green chemistry, bioremediation, synthetic biology, NBS, nanotechnology, and advanced materials is enabling cleaner, safer, and more efficient systems (Anastas & Warner, 1998; Rittmann & McCarty, 2020). Global initiatives led by UNEP (2019) highlight the need for integrated, nature-aligned approaches to ensure long-term environmental and societal resilience. As emerging contaminants, climate pressures, and resource scarcity intensify, the future of environmental engineering will depend on innovative solutions that harmonize technology with natural processes, advancing both human development and planetary health.

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CHAPTER 2
INTEGRATING MICRO HYDROPOWER INTO RURAL ENERGY SYSTEMS: TECHNICAL, ECONOMIC, AND SOCIAL PERSPECTIVES

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INTRODUCTION

1. INTEGRATING MICRO HYDROPOWER INTO RURAL ENERGY SYSTEMS

1.1 Global Energy Transition

Energy is the foundation of economic and social development. However, the world's dependence on fossil fuels has created a complex global energy crisis. Surging oil and gas prices, geopolitical instability, and environmental impacts such as greenhouse gas emissions have exacerbated this situation. The International Energy Agency (IEA) noted that the global energy crisis that began in 2021 and was exacerbated by geopolitical conflicts in 2022 caused energy prices to soar, inflation to rise, and millions of households to fall into energy poverty. These impacts are not only economic but also social and political, highlighting the vulnerability of fossil-based energy systems to external shocks.

Furthermore, the energy sector accounts for nearly 75% of total global greenhouse gas emissions, making it a major contributor to climate change. IRENA's World Energy Transitions Outlook report emphasizes that to achieve the 1.5°C target set by the Paris Agreement, the world must accelerate the energy transition through electrification, efficiency, and the use of renewable energy, including hydropower, solar, and biomass. However, despite global commitments such as COP28, fossil fuels still dominate the energy mix, making the chances of achieving climate targets increasingly slim each year.

The urgency of the energy transition is also driven by the limited reserves of fossil fuels and their environmental impacts. Recent research emphasizes that the shift to renewable energy is not only about reducing emissions, but also about ensuring energy security and sustainable economic growth. Innovative technologies, supportive policies, and market mechanisms are key factors in accelerating this transition. Thus, the global energy transition is no longer an option but a strategic imperative for planetary sustainability and human well-being.

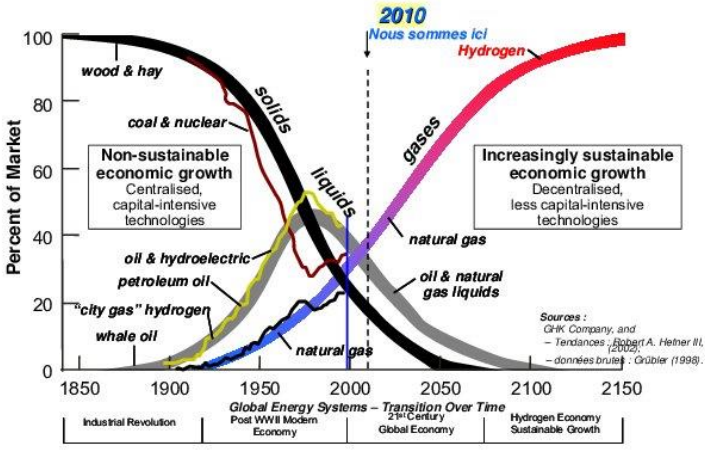

Figure 1. Global Energy System Transition

This figure depicts the evolution of the global energy system from 1850 to a projected 2150, showing the shift in dominant energy sources as economic and technological developments progressed. Early in the period, solid fuels such as wood, straw, and coal dominated the energy market, supporting centralized and capital-intensive economic growth. Entering the 20th century, a transition occurred to liquid energy sources such as petroleum and hydroelectricity, which became the backbone of the modern economy after World War II. This shift marked the beginning of energy diversification and increased system efficiency.

Since the beginning of the 21st century, the graph shows a decline in the share of oil and coal, replaced by cleaner natural gas. This period has been referred to as the transition phase to the 21st-century global economy, where energy technologies are moving toward decentralization and reduced capital intensity. Projections beyond 2050 show hydrogen dominating as the primary energy source, supporting a sustainable, low-emission energy system. This shift aligns with global commitments to achieve net-zero targets and reduce dependence on fossil fuels. The energy transition depicted in the graph has major implications for the development of renewable technologies, including micro-hydropower. With the increasing focus on sustainability, technologies such as microhydropower plants (MHP) are becoming relevant to support rural electrification and reduce carbon emissions.

These systems offer a decentralized solution that aligns with the global trend toward clean energy while supporting inclusive economic growth in remote areas. Therefore, investing in microhydro technology and its integration with future energy systems is a crucial strategy for achieving long-term sustainability.

1.2 The Role of Small-Scale Hydropower

Amidst the global push toward clean energy, small-scale hydropower has emerged as an effective solution, particularly for remote areas. This technology harnesses natural water flows without the need for large dams, resulting in a relatively low environmental impact. According to a UNIDO report, small-scale hydropower plants offer a practical and affordable solution to increase energy access in rural communities, while creating local economic opportunities and reducing carbon emissions. However, their global potential remains underutilized, with only about 34% of the total potential being utilized. [unido.org]

The technical advantages of MHP (Microhydro Power Plants) lie in their simple design, low operational costs, and ability to operate sustainably. From a social perspective, micro hydro projects often involve local community participation in planning and maintenance, enhancing project ownership and sustainability. Case studies in Indonesia demonstrate that community involvement in micro hydro projects not only provides electricity but also drives local economic growth, improves quality of life, and strengthens communities' capacity to manage energy resources independently. [hydropower.org]

Furthermore, micro hydro is particularly relevant for remote areas where national electricity grid access is limited. By utilizing local water resources, this technology can reduce dependence on expensive and polluting diesel generators. Research in Ghana and Indonesia confirms that micro hydro is a technically and economically feasible solution for expanding rural electrification, while supporting the Sustainable Development Goal (SDG 7) for access to clean and affordable energy.

1.3 Objective and Scope

This chapter aims to provide a comprehensive analysis of the technical and economic assessment (techno-economic assessment) of a micro hydro power generation system with specific parameters: a head of 18 meters and a discharge of 41.6 liters per second. The primary focus is on evaluating technical feasibility through hydraulic calculations, turbine selection, transmission system design, and energy generation estimation. From an economic perspective, the analysis includes investment cost estimates, revenue projections, and financial indicators such as Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Payback Period to determine project feasibility.

The scope of discussion includes:

- Global and national studies related to the energy transition and the role of micro-hydro power plants.
- Technical design methodology, including the selection of key components (turbines, penstocks, transmission lines).
- Economic analysis based on actual data and realistic assumptions.
- Environmental and social impacts, including CO_2 emission reductions and benefits to local communities.

1.4 Global Policy Landscape and Developing Countries' Role

Accelerating the energy transition is inseparable from global and regional policy frameworks that encourage clean energy investment. At the global level, countries' commitments under the Paris Agreement encourage the penetration of An effective approach is a "just energy transition"—a just transition that considers fiscal capacity, development needs, and inclusive energy access. In Southeast Asia, regional cooperation is strengthening the ASEAN Power Grid initiative and the development of distributed renewable resources to expand electricity access in rural areas. In the Indonesian context, harmonizing electricity policies, energy mix targets, and fiscal incentives play a key role in attracting investment in community-scale micro hydropower plants, reducing reliance on diesel, and strengthening regional energy security.

1.5 Barriers and Enablers for Small-Scale Hydropower

Key barriers to micro hydropower include initial funding, local technical capacity, and ensuring operational sustainability. On the other hand, there are enablers such as community-participatory approaches, green financing schemes, and simple technical standards that facilitate replication. Local operator training programs, the procurement of readily available standard components, and fair tariff models for the village scale have been shown to accelerate adoption. The presence of local manufacturing industries (penstock pipes, small turbines, V-belts, electrical panels) also reduces logistics costs and shortens the supply chain, making micro-hydro power plants a competitive option for remote areas with hilly topography and year-round water sources.

2. LITERATURE REVIEW

Renewable Energy Overview

Renewable energy is energy derived from natural resources that can be sustainably renewed, such as sunlight, wind, water, biomass, and geothermal energy. Unlike fossil fuels, which are limited and produce high carbon emissions, renewable energy offers an environmentally friendly solution to mitigate the impacts of climate change and increase global energy security. Solar energy harnesses solar radiation through photovoltaic (PV) technology and thermal systems. Solar panels have become one of the fastest-growing technologies due to their decreasing costs and increasing efficiency. Wind energy uses turbines to convert the wind's kinetic energy into electricity. Onshore and offshore wind turbines now account for a significant portion of the global energy mix, although their intermittent nature requires integration with energy storage systems. Biomass is an energy source derived from organic materials such as agricultural waste and wood. Although renewable, biomass combustion can produce emissions if not managed sustainably. Geothermal energy harnesses heat from the Earth's core to generate electricity and heat. This technology has the advantage of stable availability throughout the year, but is limited to areas with high geothermal activity. Furthermore, ocean energy, such as wave and tidal energy, is also being developed, although it is still in the early stages of commercialization.

Globally, renewable energy will contribute more than 30% of electricity generation by 2023, with hydropower, wind, and solar as the main contributors.

Hydropower Classification

Hydroelectric power plants (HPPs) are classified based on their power capacity:

- Large Hydropower: >10 MW, typically requiring large dams and complex infrastructure.
- Small Hydropower: 1–10 MW, suitable for areas with moderate river flows.
- Mini Hydropower: 100 kW–1 MW, used for small communities or local industries.
- Micro Hydropower: <100 kW, ideal for remote areas with limited water resources.

Micro Hydropower (PLTMH) is becoming a popular solution for rural electrification due to its low operational costs, simple design, and minimal environmental impact. The turbines used are generally impulse-type (Pelton, Turgo) for high heads and low discharges, or reaction-type (Francis, Kaplan) for low heads and high discharges.

Design Principles for Micro Hydropower

MHP design is based on three main parameters: head, discharge, and site selection.

- Head (the height of the water fall) determines the available potential energy. The greater the head, the more energy can be converted into electricity.
- Discharge (flow rate) is the volume of water per unit time. A stable discharge throughout the year is important to ensure continuous operation.
- Site selection takes into account topography, accessibility, and environmental impact. An ideal location has a sufficient slope to generate adequate head, a constant water flow, and low geological risk.
- The theoretical power calculation is done using the formula:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta$$

where

P is the power (W),

ρ is the water density (kg/m^3),

g is the gravitational acceleration (m/s^2),

Q is the discharge (m^3/s),

H is the net head (m), and

η is the system efficiency.

In addition, the design must account for head losses in penstocks, valves, and connections. Turbine selection depends on the head and discharge combination: Pelton is for high head and low discharge, while Crossflow is for intermediate conditions. Geological studies and Hydrological analysis is necessary to avoid the risk of flooding and landslides and ensure project sustainability.

Economic Feasibility Indicators

The economic feasibility analysis of a micro-hydro power plant project generally uses the following financial indicators:

- Net Present Value (NPV): Measures the difference between the present value of cash inflows and outflows. A positive NPV indicates the project is financially feasible.
- Benefit-Cost Ratio (BCR): The ratio between total benefits and total costs. A BCR > 1 indicates a profitable project.
- Payback Period (PP): The time required to recoup the initial investment from annual net income. The shorter the PP, the more attractive the project.
- Internal Rate of Return (IRR): The rate of return that makes the NPV equal to zero. An IRR higher than the discount rate indicates the feasibility of the investment.

Advances in Turbine Technology for Micro Hydro

Developments in micro turbine design over the past decade have focused on efficiency, ease of fabrication, and durability.

Modular Pelton turbines with CNC runners and adjustable nozzles allow for seasonal flow adjustments without significant efficiency loss. For medium heads, the new generation Crossflow features blade profiles optimized through CFD simulations, reducing secondary losses. Micro Francis turbines for heads of 10–30 m feature short draft tubes to minimize pressure loss. The trend toward open-source hardware manufacturing and standardized documentation facilitates local workshops in developing components with consistent quality. At the control level, the use of simple microcontroller-based electronic governors allows load regulation to maintain stable frequency despite flow fluctuations.

Small-Scale Hydropower and Distributed Energy Systems

The integration of microhydropower plants (MHP) into distributed energy resources (DER) strengthens the reliability of the local grid. In rural microgrids, MHP can act as a baseload, with solar PV as a supplement during the day and batteries as energy storage for peak evening loads. The advantage of MHP is its relatively stable output profile, reducing the need for large battery capacity. In a smart microgrid scheme, priority load control (e.g., water pumps, public lighting, and essential services) is combined with prepaid metering to ensure sustainable operational cash flow. This synergy results in a lower effective cost of electricity compared to a single diesel- or PV-only system, especially in forested areas with year-round water access.

Comparative Assessment: Micro Hydro vs. Solar PV for Rural Electrification

Micro Hydro generally exhibits a competitive LCOE when the head is ≥10 m and the flow is stable, due to a high-capacity factor (often >50%) and a mechanical equipment lifespan of 20–30 years. Solar PV has the advantages of rapid installation and drastically reduced costs, but daily intermittency and the need for large batteries increase lifecycle costs. In locations with high rainfall, for high-energy communities, micro hydro power plants (MHP) serve as the backbone of the system, while solar power plants (PV) serve as a supplement.

Comparative studies show that for small communities (<100 kW), a micro hydro power plant (MHP) + PV + small battery configuration provides the best balance between reliability, cost, and social sustainability. This method is based on Discounted Cash Flow (DCF) to consider the time value of money. In renewable energy projects, this indicator is often complemented by sensitivity analysis to variables such as electricity tariffs, investment costs, and capacity factors. Recent studies confirm that although classical methods (NPV, IRR, PP) remain dominant, additional approaches such as Levelized Cost of Energy (LCOE) and Real Options Analysis (ROA) are beginning to be used to accommodate market uncertainty and project risks.

3. METHODOLOGY

Site Selection and Data Collection

Site selection is a crucial stage in the planning of a Micro Hydro Power Plant (MHP). This study focuses on Mondrowe Waterfall, Nias Island, Indonesia, which has hydropower potential with a head of 18 meters and a discharge of 41.6 L/s. The location was selected based on topographic criteria, the availability of permanent water sources, and accessibility for infrastructure development. Data collection was conducted through field surveys to measure hydrological parameters, including flow rate using volumetric methods and head measurements using elevation gauges. Additionally, topographic data was obtained from contour maps and satellite imagery to validate the land slope and penstock route. Geological analysis was also conducted to identify landslide and flood risks, which could impact project sustainability. This approach aligns with research emphasizing the importance of integrating hydrological, topographic, and geological data in MHP site selection to minimize technical and environmental risks and ensure long-term project feasibility.

Design Approach

The technical design of the MHP includes turbine selection, penstock design, transmission system, and generator. Based on the site characteristics (high head and low discharge), a Pelton turbine was selected due to its high efficiency under these conditions.

A Pelton turbine operates on the impulse principle, where pressurized water is directed through a nozzle to produce a jet that rotates the turbine blades.

Theoretical power calculations were performed using the equation:

$P = \rho \cdot g \cdot Q \cdot H \cdot \eta$

With

ρ=1000" " kg/m^3,

g=9.81" " m/s^2,

Q=0.0416" " m^3/s,

H=18" " m, and system efficiency

(η) assumed to be 75%.

The penstock is designed to minimize head losses due to friction and connections. The pipe material is selected based on its resistance to pressure and corrosion. The pipe diameter is calculated using the Warnick equation for design flow rate, while head losses are calculated using the Darcy-Weisbach method. The transmission system uses a type B V-belt with a 2:1 ratio to connect the turbine (750 rpm) to the generator (1500 rpm). Generator selection takes into account power capacity (5 kW), output voltage, and compatibility with the local distribution system. This approach follows MHP design standards recommended by international studies, which emphasize turbine selection based on head and flowrate, as well as optimizing the penstock and transmission for maximum efficiency.

Economic Analysis Framework

An economic analysis is conducted to assess the financial feasibility of the MHP project. The Discounted Cash Flow (DCF) method is used, with the following key indicators:

- Net Present Value (NPV): The difference between the present value of cash inflows and outflows.
- Benefit-Cost Ratio (BCR): The ratio of benefits to costs.
- Payback Period (PP): The time required to recoup the investment.
- Internal Rate of Return (IRR): The rate of return that makes NPV = 0.

The data used includes initial investment costs (civil works, turbine, generator, installation), operation and maintenance costs, and projected revenue from electricity sales. Electricity tariffs refer to national regulations for renewable energy. This approach aligns with feasibility studies of micro-hydro power plants (MHP) in Indonesia and globally, which show that NPV, IRR, and BCR are key parameters in determining the feasibility of renewable energy projects, with sensitivity to variables such as electricity tariffs and capacity factors.

Environmental Impact Assessment

Environmental impacts are evaluated by estimating CO_2 emission reductions resulting from the replacement of fossil-fueled power plants. Based on the emission factor of a coal-fired power plant (0.9 kg CO_2/kWh), a 5 kW MHP with an annual production of 42,360 kWh can avoid approximately 38 tons of CO_2 per year.

Recent studies have shown that although micro-hydro power plants have a carbon footprint during the construction phase, their emissions intensity is much lower than that of fossil-fueled power plants, thus contributing significantly to net-zero targets and climate change mitigation.

Assumptions and Design Criteria

The analysis model uses the following assumptions:

- Project lifespan: 20 years; turbine lifespan: 20–25 years; generator lifespan: 15–20 years.
- System availability: 90%; average capacity factor: 50–60% depending on the season.
- O&M: 8–12% of CAPEX per year for the first 3 years, then 5–8% annually.
- Electricity tariff: Refers to the low-voltage category for local household/MSME customers, with the option of feeding into the village mini-grid if available.
- Design standards: Refers to the IEC general guidelines for electrical machines and practical mechanical engineering standards (shaft, belt, bearing dimensions) to facilitate calculations for local workshops.

Methodological Flowchart

Methodological flowchart: (1) Hydrological survey (discharge, head, seasonal variability), (2) Topographic study for pipe routing and elevation, (3) Turbine selection based on specific speed and selection maps, (4) Penstock design (diameter, material, connections, support), (5) Transmission and generator design (turn ratio, capacity, electrical protection), (6) Energy estimation and capacity factor, (7) Economic analysis (DCF, NPV, BCR, PP, IRR, LCOE), (8) Environmental and social assessment, (9) O&M plan and community governance, (10) Sensitivity and risk analysis. Each stage feeds into the next, ensuring reconciliation between technical and economic assumptions.

4. TECHNICAL DESIGN AND ANALYSIS

4.1 Hydraulic Calculations

Hydraulic calculations are the initial stage in MHP design to determine net head, head losses, and nozzle water velocity. Theoretical power is calculated using the equation:

$P = \rho \cdot g \cdot Q \cdot Hnet \cdot \eta$

where:

ρ = 1000 kg/m^3 (water density)

g = 9.81 m/s^2 (gravity)

Q = 0.0416 m^3/s (flow rate)

H_net = net head after losses

η = system efficiency

Head losses are calculated using the Darcy-Weisbach equation:

$$h_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2g}$$

where

f = coefficient of friction (from the Moody diagram),

L = pipe length,

D = pipe diameter,

V = flow velocity.

Calculation example:

Gross head = 18 m

Pipe diameter = 0.15 m

Pipe length = 30 m

Discharge = 0.0416 m^3/s

$$V = \frac{4Q}{\pi D^2} = \frac{4(0.0416)}{3.14(0.15)^2} = 2.35\, m/s$$

With f = 0.015, then:

$$h_f = 0.015 \cdot \frac{30}{0.15} \cdot \frac{(2.35)^2}{2(9.81)} \approx 2.43\, m$$

Total losses including valves and elbows ≈ 3 m, so:

$$H_{net} = 18 - 3 = 15\, m$$

Water velocity exiting the nozzle:

Total losses including valves and elbows ≈ 3 m, so:

$$V_n = \sqrt{2gH_{net}} = \sqrt{2(9.81)(15)} \approx 17.15\, m/s$$

This approach complies with the MHP design standards recommended by international studies to minimize energy losses and improve system efficiency.

4.2 Turbine Selection and Performance

Turbine selection is based on the specific speed (Ns), which is calculated as:

$$N_s = N \cdot \sqrt{P}/H^{5/4}$$

Where N= turbine speed (rpm), P= power (kW), H= net head (m).

With $N = 750\, rpm$, $P = 5\, kW$, $H = 15\, m$:

This value is suitable for a Pelton turbine, which is ideal for high heads and low discharge.

Pelton turbine efficiency ranges from 70–85% at full load. Assuming 75% efficiency, the actual power is:

$$P = 1000 \cdot 9.81 \cdot 0.0416 \cdot 15 \cdot 0.75 \approx 4.6\,kW$$

International studies show that impulse turbines like Pelton offer advantages in operational flexibility and long life, making them a prime choice for microhydro power plants in mountainous areas.

4.3 Transmission System Design

The transmission system uses a type B V-belt to connect the turbine (750 rpm) to the generator (1500 rpm) with a 2:1 ratio. The pulley diameter is calculated as follows:

$$i = \frac{N_2}{N_1} = \frac{1500}{750} = 2$$

If the turbine pulley is 0.25 m, then the generator pulley is 0.125 m.

Belt length:

$$L = 2C + 1.57(D_1 + D_2) + \frac{(D_1 - D_2)^2}{4C}$$

where C = center distance (1 m), D_1 = 0.25 m, D_2 = 0.125 m:

The shaft is designed to withstand the following torque:

$$T = \frac{9550 \cdot P}{N} = \frac{9550 \cdot 4.6}{750} \approx 58.6\,Nm$$

The shaft diameter is calculated using shear strength theory:

This approach aligns with mechanical design standards for power transmission in micro-hydro power plants, which emphasize belt and shaft selection to avoid mechanical failure.

4.4 Expected Energy Output

Annual energy is calculated based on average power and operating hours:

$E = P \cdot t$

With P = 4.6 kW, P = 4.6 kW, kWP = 4.6 kW, and 24-hour operation for 353 days:

$t = 24 \cdot 353 = 8472$ hours

$E = 4.6 \cdot 8472 \approx 39.571$ kWh/year

$t = 24 \cdot 353 = 8472$ hours, $t = 24 \cdot 353 = 8472$ hours

If the electricity tariff is Rp1,352/kWh, annual revenue is Rp53.5 million. Feasibility studies of micro-hydro power plants show that small capacities (≤10 kW) can provide a return on investment within 2–3 years, especially in remote areas with high electricity costs.

4.5 Illustrations of Micro Hydro Power Plant Systems

Schematic Diagram of a Micro Hydro Power Plant System

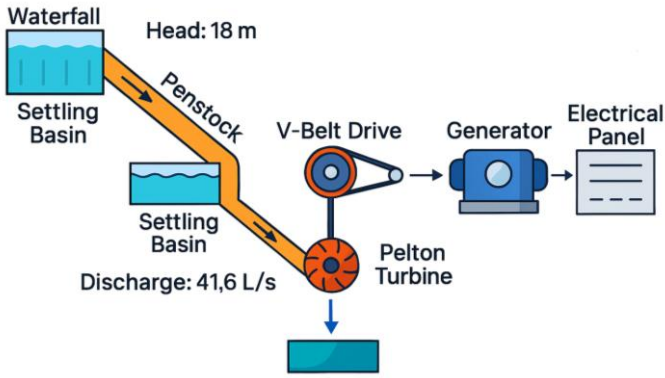

Figure 2. Micro Hydro Power Plant (MHP) System

This image shows the workflow of a Micro Hydro Power Plant (MHP) designed to harness the potential energy of water from Mondrowe Waterfall. The process begins with the waterfall, which flows into a settling basin to settle sediment and maintain water quality. From the settling basin, water flows through an orange penstock, which directs the high-pressure water flow to the turbine. The annotation in the image indicates a head of 18 meters and a discharge of 41.6 liters per second, which are key parameters for determining output power.

The pressurized water rotates a Pelton Turbine, depicted by the red turbine icon. This turbine is connected to a generator via a V-belt drive, which transmits mechanical energy into electrical energy.

The electricity generated by the generator is then channeled to an electrical panel to regulate power distribution to the loads. The water element is colored blue, while the mechanical and electrical components are colored in contrasting colors for easy differentiation. The arrows indicate the direction of energy flow from the water source to the distribution system.

This schematic illustrates the basic principle of a microhydro power plant: converting the potential energy of water into electrical energy through an impulse (Pelton) turbine, which is ideal for locations with high head and low discharge. With its simple design and high efficiency, this system is suitable for remote areas requiring a renewable energy source.

Table 1. Main Specifications of PLTMH System

Component	Specification
Net Head	15 m
Flow Rate	0.0416 m^3/s
Turbine	Pelton, 750 rpm
Generator	5 kW, 1500 rpm
Penstock	Diameter: 150 mm, Length: 30 m
V-Belt	Type B, Length: 2.6 m
Shaft	Diameter: 20 mm, Material: S45C Steel

Table 1 presents the key technical specifications of the micro-hydro power plant (PLTMH) designed for Mondrowe Waterfall. The system operates with a net head of 15 meters and a flow rate of 0.0416 m^3/s, which are critical parameters for determining the available hydraulic energy. A Pelton turbine is selected due to its suitability for high-head and low-flow conditions, operating at 750 rpm to ensure optimal efficiency.

The turbine is coupled to a generator rated at 5 kW and 1500 rpm, enabling the conversion of mechanical energy into electrical power for local distribution. Water is conveyed through a penstock with a diameter of 150 mm and a length of 30 meters, designed to minimize head losses while maintaining structural integrity under high pressure. ,

Power transmission between the turbine and generator is achieved using a V-belt (Type B) with a length of 2.6 meters, providing a simple and cost-effective solution for speed adjustment.

Finally, the shaft, constructed from S45C steel with a diameter of 20 mm, ensures durability and resistance to torsional stress during operation. These specifications collectively demonstrate a robust and efficient design tailored for rural electrification, aligning with international standards for small-scale hydropower systems.

4.6 Seasonal Flow Variability and Operational Strategy

River discharge at the waterfall site generally varies seasonally. The proposed operational strategy is as follows:

- Multiplex nozzles: two nozzles with different openings; during high discharge, both nozzles are active; during low discharge, one nozzle is active to maintain effective head and turbine efficiency.
- Load management: prioritizing essential loads (lighting, health facilities, water pumps). Non-essential loads are operated during peak discharge (rainy season) or when the solar power plant generates additional energy.
- Bypass and filter: Installing a trash rack and an easy-to-clean settling basin to prevent cavitation caused by hard particles and maintain turbine reliability throughout the year.

4.7 Penstock Detailing and Support Structure

A 150 mm, 30 m long penstock requires:

Anchor blocks at bends and sharp elevation differences to withstand dynamic forces during start/stop.

- Simple expansion joints in long pipe segments to accommodate thermal expansion and transient pressures.
- Anti-corrosion coating (e.g., epoxy paint) on steel pipes; if using HDPE, ensure the pressure rating matches the head + a safety margin of 1.5–2.0.
- Air valve at the top of the line to prevent airlock and water hammer when filling the penstock.

4.8 Generator, Electrical Panel, and Protection Scheme

A 5-kW synchronous generator at 1,500 rpm is connected to a distribution panel with:

- A simple AVR to maintain voltage.
- Protection: MCB/MCCB according to the rated current, Earth leakage (RCD) for safety, and surge protection if connected to a solar power plant.
- Load controller: An electronic load controller (ELC) that switches to dump loads (e.g., water heaters or resistor banks) when the load decreases to maintain a frequency of 50 Hz.

This scheme ensures frequency stability in the microgrid without relying on the mains grid.

4.9 Reliability and Maintainability

System reliability is improved through:

- Preventive maintenance: weekly settling basin cleaning, nozzle inspections, V-belt checks (tension and wear), bearing lubrication, and electrical panel inspections.
- Critical spare parts: Type B V-belts (2–3 spares), nozzle tips, standard bearings, AVR brushes (if applicable), and pipe joint gaskets.
- Mean Time Between Failure (MTBF) is targeted at >2,000 hours for major mechanical components with a quarterly maintenance schedule. Operator log sheets serve as the basis for performance evaluation.

5. ECONOMIC ASSESSMENT

Capital Cost Breakdown

The initial investment cost analysis includes the following main components: civil works, mechanical equipment, turbine, generator, and installation costs. This estimate is based on feasibility studies of micro-hydro power plants in Indonesia and international references that emphasize the importance of cost breakdowns in determining the feasibility of renewable energy projects.

Table 2. Capital Cost Breakdown

Component	Quantity	Unit Price (IDR)	Total Cost (IDR)
Penstock (6 Inch)	6 pipes	1,000,000	6,000,000
Elbow 90°	2 pieces	250	500
Elbow 45°	2 pieces	250	500
Gate Valve	1 piece	3,000,000	3,000,000
Pelton Turbine	1 unit	31,500,000	31,500,000
Generator (5 kW)	1 unit	15,000,000	15,000,000
Civil Works	-	-	25,000,000
Installation & Tools	-	-	7,000,000
Total			**88,500,000**

Plus, taxes and shipping costs, the total initial investment is estimated at IDR 124,437,500. International studies indicate that microhydro power plants cost between USD 2,000 and USD 3,000 per kW, making this estimate in line with global standards for microhydro projects.

Revenue Projection

Annual revenue is calculated based on the energy generated and the electricity tariff. With an average power of 4.6 kW and 24/7 operation for 353 days, the annual energy is:

$$E = P \times t = 4.6\,kW \times 8472\,hours = 39.571\,kWh/year$$

If the electricity tariff is IDR 1,352/kWh (low voltage R-1 category), then:

Revenue = IDR 39,571×1,352≈IDR 53.5 million/year

This revenue can increase if electricity tariffs increase or if the project is connected to a Feed-in Tariff scheme for renewable energy. Feasibility studies of microhydro power plants in Southeast Asia have shown that annual revenue from microhydro projects can cover operational costs and provide a significant profit margin.

Financial Indicators

The feasibility analysis uses the following indicators:

• Payback Period (PP)

$$PP = \frac{\text{Investment Cost}}{\text{Annual Net Income}}$$

With an investment cost of Rp124,437,500 and net income (after 10% O&M costs) of Rp51,547,968:

$$PP = \frac{124.437.500}{51.547.968} \approx 2.41\ tahun$$

- Net Present Value (NPV)

$$NPV = \sum_{t=1}^{n} \frac{CIF_t}{(1+r)^t} - CF_0$$

CIF = Rp57,275,520/, r = 10%, n = 5:
With CIF = Rp57.275.520/ year, r = 10%, n = 5 years:

$$NPV = 57.275.520 \times \frac{1-(1+0.10)^{-5}}{0.10} - 124.437.500$$

$$NPV = 57.275.520 \times 3.7908 - 124.437.500 \approx Rp92.716.746$$

A positive NPV indicates the project is financially viable.

- Benefit-Cost Ratio (BCR)

$$BCR = \frac{\text{Present Value of Benefits}}{\text{Present Value of Costs}}$$

$$BCR = \frac{217.154.246}{124.437.500} \approx 1.75$$

BCR value > 1 indicates a profitable project. International studies confirm that this indicator is the standard for assessing the feasibility of renewable energy projects.

Sensitivity Analysis

A sensitivity analysis was conducted to examine the impact of changes in variables on project feasibility:

- Electricity tariff increases by 10% → Annual revenue becomes IDR 58.8 million, NPV increases by ±12%.
- Investment costs increase by 15% → Total investment becomes IDR 143 million, PP increases by ±2.8 years, NPV decreases by ±18%.

These results indicate that the MHP project is relatively sensitive to investment costs, but remains feasible if electricity tariffs increase or government incentives are provided. Global study emphasizes the importance of sensitivity analysis to anticipate price fluctuations and market risks.

Levelized Cost of Energy (LCOE)

A Simple Approach:

LCOE = (CAPEX + ∑ OPEXt / (1+r)^t) / ∑ Et / (1+r)^t

Assuming: CAPEX of IDR 124.44 million; OPEX of 8% of CAPEX in the first 3 years (≈IDR 9.95 million/year), then 6% of CAPEX (≈IDR 7.47 million/year); r = 10%; initial annual energy of 39,571 kWh and degradation of 0.3%/year (conservative for mechanical components).

A quick estimate gives an LCOE of IDR 1,400–1,700/kWh in the current configuration. This value is competitive compared to diesel costs (including logistics and maintenance), which often exceed IDR 2,500/kWh in remote areas. The LCOE can be reduced by optimizing the capacity factor, reducing penstock losses, or integrating with solar power plants for peak shaving.

Financing Options and Revenue Models

Financing schemes:

- Green credit: preferential interest rates for village-scale renewable energy projects.
- Community revolving fund: initial community contributions and electricity revenues are used as working capital for maintenance and expansion.

- Small-scale carbon credits: additional income from CO_2 emission reductions, although their value needs to be calculated with verification costs.
- Revenue model:
- Tiered tariffs: lower rates for essential needs (lighting, schools, clinics), regular rates for small businesses.
- Productive services: power rental for grinding, light welding, or communal cooling (cold storage) that enhances local economic value.

Comparative Lifecycle Cost: Microhydro Power Plant vs. Diesel and PV-Only

- Diesel: low CAPEX, high OPEX (fuel, oil, spare parts), price volatility, supply risk; lifecycle costs tend to be highest.
- PV-only: medium CAPEX, significant battery costs, battery replacement time 5–8 years; LCOE decreases if daytime loads are dominant, but nighttime loads are difficult to meet without large batteries.
- Micro-hydro power plants: Medium CAPEX, moderate OPEX, long lifespan; energy stability reduces battery dependence. The combination of micro-hydro power plants and photovoltaic (PV) lowers aggregate LCOE and increases system resilience.

6. ENVIRONMENTAL AND SOCIAL IMPACT

CO_2 Emission Reduction

$$39.571 \times 0{,}9 = 35.6\ ton\ CO_2/tahun$$

Micro-hydro power plants (MHP) have a positive impact on reducing carbon emissions compared to coal-fired steam power plants (PLTU). A coal-fired power plant produces an average of 0.9 kg of CO_2 per kWh of electricity generated (IEA, 2022). With a MHP capacity of 5 kW and an annual energy production of approximately 39,571 kWh, the avoided emissions reach:

$$39.571 \times 0{,}9 = 35.6\ tons\ CO_2/\text{year}$$

This demonstrates that microhydro power plants contribute significantly to climate change mitigation and support the Net Zero Emission target. Studies by Likadja et al. (2023) and Pane et al. (2020) confirm that microhydro technology has a significantly lower carbon intensity than fossil-based power plants, making it an environmentally friendly clean energy solution.

Community Benefits

In addition to environmental benefits, microhydro power plants have significant social and economic impacts on rural communities. Stable access to electricity improves the quality of life, enabling the use of household appliances, lighting, and educational facilities. Economically, these projects open up local business opportunities such as rice milling, agricultural processing, and electricity-based small businesses. Research by Suwignyo et al. (2022) and Harianja et al. (2022) shows that the presence of microhydro power plants in remote areas can reduce dependence on expensive and polluting diesel generators. Furthermore, community involvement in the development and management of microhydro power plants increases a sense of ownership and strengthens local capacity to manage energy resources independently.

Sustainability Considerations

The sustainability of microhydro power plants (MHPs) depends on routine maintenance and active community participation. Microhydro systems require regular maintenance on turbines, penstocks, and generators to ensure efficiency and longevity. A community-based management model involving technical training and the formation of management groups has proven effective in maintaining project sustainability. With this approach, microhydro power plants (MHPs) are not only a source of clean energy but also a means of community empowerment, supporting SDGs 7 (Affordable and Clean Energy) and SDG 13.

Biodiversity and Aquatic Ecology Considerations

MHPs pose minimal ecological risks if they do not significantly impound the main stream. The fish-friendly intake design with closely spaced trash racks reduces the risk of biota entering the penstock.

Environmental flow is maintained to ensure healthy downstream ecosystems. During construction, sediment management and minimal land clearing of access routes minimize impacts on flora and fauna. Simple monitoring (monthly checklists, periodic photographs) helps ensure ongoing environmental compliance.

Gender and Inclusivity Perspective

Access to electricity from micro-hydro power plants can strengthen women's roles in the local economy—for example, through electricity-based small businesses (food processing, crafts, digital services). Women's involvement in management committees increases accountability and aligns services with household needs. Inclusive technical training programs (flexible schedules, local languages) ensure equitable knowledge transfer. This approach aligns with the principles of energy justice and strengthens community social resilience.

Community Capacity Building and Governance Model

Suggested governance model:

- Village energy cooperative: a business unit that manages revenue, O&M, and expansion; has simple statutes and oversight mechanisms.
- Maintenance fee scheme: a percentage of revenue is allocated to maintenance funds and reserve investments.
- Transparency: Monthly reports on energy, financial, and technical conditions are published on the village information board.

Stakeholder involvement (village government, farmer groups, schools, clinics) ensures the sustainability and productive use of electricity.

7. DISCUSSION

Technical Feasibility

The design of the Mondrowe Waterfall micro hydro power plant (MHP) demonstrates high technical feasibility, but challenges include head losses due to the length of the penstock and connections, as well as the selection of corrosion-resistant materials.

The implemented solutions include optimizing the pipe diameter using the Warnick equation and selecting a Pelton turbine suitable for high head and low discharge. Studies by Pane et al. (2020) and Suwignyo et al. (2022) emphasize that appropriate turbine selection and efficient penstock design are key factors in maximizing the efficiency of a micro hydro system.

Economic Viability

The economic analysis indicates that this project is financially viable with a positive NPV (Rp92.7 million), a BCR > 1 (1.75), and a Payback Period of ±2.4 years. These results align with research by Likadja et al. (2023), which states that MHPs with a capacity of ≤10 kW offer a rapid return on investment, especially in remote areas with high electricity tariffs. Sensitivity to investment costs and electricity tariffs indicates that the project remains profitable even if electricity prices increase or government incentives for renewable energy are introduced.

Scalability and Replicability

This microhydro power plant model can be replicated in other locations with similar characteristics, such as mountainous areas with a head of >10 m and stable flow. Global studies (Harianja et al., 2022; Suwignyo et al., 2022) confirm that microhydro is a sustainable solution for rural electrification, supporting SDG 7 (Affordable and Clean Energy). With a modular design and community involvement, this project can be scaled to meet the energy needs of small communities while reducing dependence on fossil fuels.

Design Trade-offs and Optimization

At a net head of 15 m and a flow rate of 0.0416 m^3/s, selecting a Pelton system is reasonable for its impulse efficiency. However, if seasonal analysis indicates that the flow rate frequently exceeds 0.06 m^3/s, the Crossflow option can be considered due to its robustness to flow rate variations and ease of local fabrication. Trade-offs: Pelton excels in peak efficiency at low to medium flows; Crossflow excels over a wide operating range.

Optimization can be achieved via a variable nozzle (for Pelton) or a two-stage runner (for Crossflow). On the penstock side, a larger diameter reduces losses but increases CAPEX; the optimal approach seeks the minimum LCOE.

Policy Implications and Local Regulation

To ensure that micro-hydro power plants (MHP) reach more villages, policy harmonization is needed: (1) streamlined licensing for installations ≤100 kW, (2) fiscal incentives (tax/VAT reductions for components), (3) electricity purchasing schemes by village-owned enterprises (BUMDes) or local microgrid operators, and (4) technical training support for village operators in collaboration with local polytechnics/vocational schools. Establishing minimum technical standards (electrical protection, safety, and civil engineering quality) increases security and confidence for social investors.

Replicability in ASEAN and Knowledge Sharing

The island-based and hilly topography of ASEAN makes MHPs highly potential. Knowledge-sharing programs through regional platforms and project banks can accelerate replication: standard technical drawings, lists of materials, calculation templates, operator training modules, and social impact casebooks. Strengthening local manufacturing networks (pipes, small turbines, panels) lowers costs and shortens construction time. Cross-border learning enriches best practices such as ecologically sound intakes, energy cooperative governance, and micro-hydropower–PV–battery integration.

8. CONCLUSION AND RECOMMENDATIONS

The analysis results indicate that the Mondrowe Waterfall microhydro power plant (MHP) is technically and economically feasible. Technically, the system, with a net head of 15 m and a discharge of 0.0416 m^3/s, is capable of generating approximately 4.6 kW of power, using a Pelton turbine suitable for high head and low discharge conditions. Hydraulic calculations, penstock selection, and V-belt transmission design ensure optimal system efficiency and a Payback Period of ±2.4 years, indicating strong financial feasibility.

A sensitivity analysis also confirms that the project remains profitable despite increases in investment costs or fluctuations in electricity tariffs (Likadja et al., 2023).

Recommendations

- Micro hydro power plants (MHPs) should be developed in remote areas with similar water potential to support SDG 7 (Affordable and Clean Energy).
- The government and relevant institutions should provide incentives, such as feed-in tariffs, to accelerate the adoption of this technology.
- A community-based management model should be implemented to ensure long-term operational and maintenance sustainability (Harianja et al., 2022).

With this strategy, MHPs can be an effective, environmentally friendly, and empowering clean energy solution for rural communities.

Strategic Roadmap (Next 10 Years)

- Phase 1 (1–2 years): design refinement, MHP construction, commissioning, operator training, strengthening energy cooperatives, and establishing baseline environmental monitoring.
- Phase 2 (3–5 years): integration of 5–10 kWp solar power plants, implementation of ELC and priority loads, expansion of productive services (milling, cold storage), and development of a tiered tariff model.
- Phase 3 (6–10 years): Replication to other locations, component standardization, access to green financing, and LCOE optimization. Annual evaluations ensure the project is adaptable to changes in discharge and community needs.

Final Recommendations

- Continue penstock optimization (diameter/material) to minimize losses and lower LCOE.
- Implement ELC + dump load for frequency stability and productive use of excess energy (communal water heating).

- Establish a scheduled O&M program, operator log sheets, and critical spare parts reserves.
- Encourage partnerships with universities/vocational schools for technical support and local innovation.
- Leverage green financing schemes and community-scale carbon credit opportunities to strengthen financial viability.

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CHAPTER 3
MULTI-FUNCTIONAL GREEN URBAN INFRASTRUCTURE: A SYSTEMATIC REVIEW FOR ENHANCING WATER AND ECONOMIC SECURITY IN THE MEKONG DELTA CITIES AMIDST DROUGHT AND SALINITY INTRUSION—GLOBAL LESSONS AND ADAPTIVE POLICY PATHWAYS FOR CAN THO CITY

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INTRODUCTION

The Vietnamese Mekong Delta (VMD), a crucial national food basket, faces a compounded crisis due to escalating climate change and intense urbanization, leading to increased frequency of severe droughts and saline intrusion. This research analyzes literature published since 2020 to establish the critical role of Multi-Purpose Urban Green Infrastructure (GI) in enhancing water security and economic resilience for VMD cities, with a specific focus on Can Tho City.

The analysis demonstrates that Nature-based Solutions (NbS)—such as mangrove restoration, permeable pavements, and green roofs—offer a superior, adaptive approach compared to conventional grey infrastructure. These solutions effectively manage complex hydrological challenges while delivering substantial socio-economic co-benefits, including improved air quality, reduced urban heat island effect, and enhanced biodiversity. The review synthesizes global best practices, particularly drawing lessons from integrated planning models like the Netherlands' "Room for the River," highlighting the necessity of integrated governance and adaptive spatial planning for success.

Although a long-term cost-benefit assessment validates GI as a high-return, "no-regret investment," its adoption in Can Tho is currently restricted by institutional fragmentation, a lack of dedicated financing mechanisms, and ambiguous regulatory standards. The study proposes a strategic roadmap for Can Tho, advocating for integrated water-space planning, innovative public-private financing, and targeted capacity building to overcome these barriers, ensuring a successful transition toward a resilient delta city paradigm.

1. FRAMING THE SYSTEMIC CRISIS AND THE PARADIGM SHIFT

The Critical Socio-Ecological Context of the Mekong Delta (VMD): A Dual Crisis of Climate Shocks and Anthropogenic Pressures

The Vietnamese Mekong Delta (VMD) is a region of paramount strategic importance, serving as a critical national food basket that contributes 50% of Vietnam's rice yield, 65% of its aquaculture products, and 70% of its fruit output (Woillez et al., 2022).

Despite its strategic function, this region is now grappling with a severe, compounded environmental crisis that fundamentally threatens its long-term sustainability. This crisis is manifested through a notable escalation in the frequency and intensity of extreme climate events, specifically severe drought and pervasive saltwater intrusion (Tho, 2022). These extreme events inflict substantial annual economic damages, estimated to be between $300 million and $500 million, imperiling the security and livelihoods of millions (Tran et al., 2025).

Crucially, the instability in the VMD transcends mere passive climate vulnerability; it represents a complex socio-economic-ecological systems crisis where local anthropogenic factors significantly amplify global environmental pressures. The situation is further intensified by activities external to the Delta, such as the development of upriver hydropower dams, as well as destructive local practices like extensive sand mining and, most critically, unsustainable groundwater extraction. This over-extraction leads to accelerated land subsidence, which effectively raises the relative sea level and drives saline water deeper inland (Woillez et al., 2022). Furthermore, rapid, often poorly coordinated, large-scale urban development projects contribute to the degradation of natural hydrological systems, diminishing the Delta's inherent capacity to manage seasonal flooding.

This confluence of factors creates a dangerous feedback loop: fast-paced urbanization increases water demand, necessitating over-extraction of groundwater, which triggers subsidence, ultimately amplifying the adverse impacts of sea-level rise, flooding, and salinity intrusion. The recognition of this structural vulnerability, where the development model itself degrades the region's resilience, mandates a shift in focus. Effective adaptation requires not just defensive measures against external climate shocks but a comprehensive, sustainable management approach addressing the underlying local development pathways.

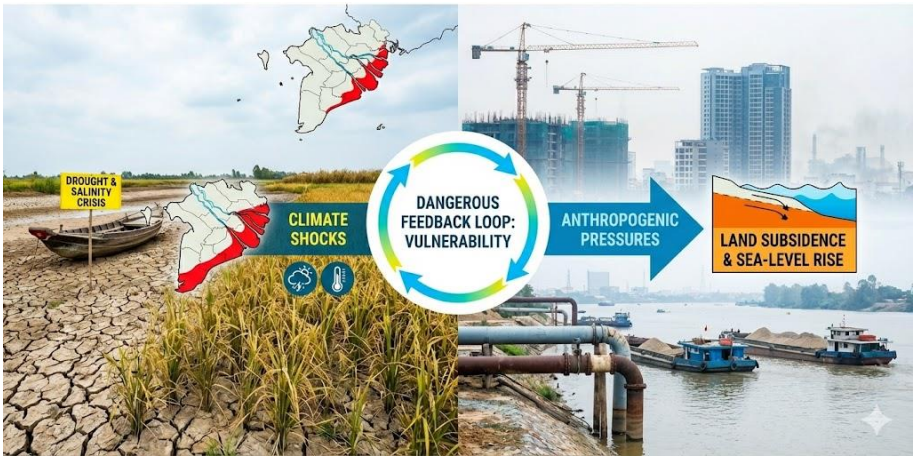

Figure 1. The critical socio-ecological Context of the Vietnamese Mekong Delta

Defining the Threat to Resilience: From Water Security to "Water Economic Security."

The dual crisis directly jeopardizes water security in the VMD's urban centers. Water security, as defined by UN Water, involves ensuring a population's sustainable access to acceptable quantities and quality of water for livelihoods, human well-being, socio-economic development, protection against water-related disasters, and preservation of ecosystems (Vicuña et al., 2018). Within the Delta, drought and salinity not only compromise reliable domestic water supply but also severely undermine industrial and agricultural production—the fundamental economic engines of the region (Lee et al., 2018). The broader economic stakes are colossal. Projected non-action scenarios regarding sea-level rise could culminate in economic damages exceeding 22 trillion USD by the close of the 21st century (Oanh et al., 2020). For a vital economic center like Can Tho City, this instability represents more than temporary inconvenience; it threatens the foundational economy, impacting sectors from food processing and logistics to real estate valuation. This evidence necessitates a conceptual expansion of "water security" to "Water Economic Security," recognizing the essential role of water systems in guaranteeing economic vitality and long-term urban existence. Under this framework, investing in robust water infrastructure is repositioned from a public service expenditure to a strategic capital investment designed to protect the city's future competitiveness.

This critical reframing shifts policy evaluation away from calculating the immediate "cost of intervention" toward measuring the significant "return on investment (ROI) achieved through damage prevention and guaranteed economic growth."

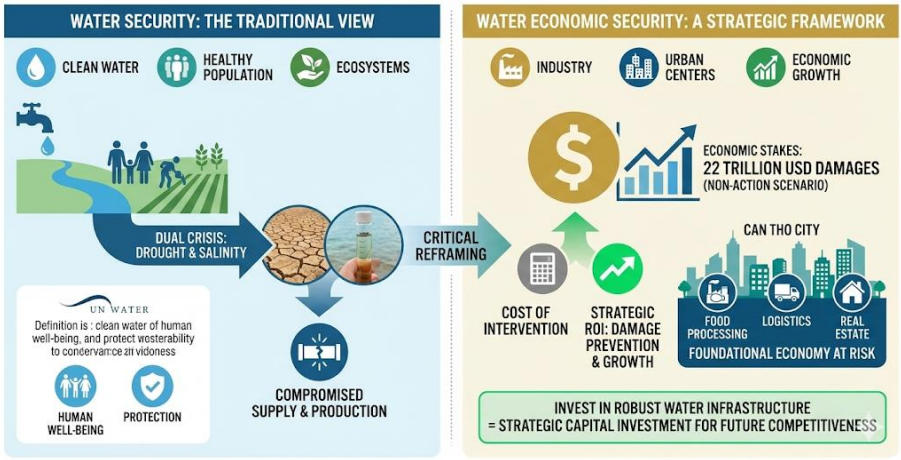

Figure 2. Defining the Threat to Resilience: From Water Security to "Water Economic Security."

The Emergence of Green Infrastructure (GI) as a Strategy for Adaptive Coexistence

Given the magnitude of these complex challenges, reliance solely on conventional, inflexible "grey" infrastructure (such as massive dikes and sluice gates) has revealed severe limitations concerning cost, long-term sustainability, and necessary adaptive flexibility. Green Infrastructure (GI) has consequently emerged as a powerful, complementary, and often superior strategic alternative. GI is defined as a deliberately planned network of natural and semi-natural areas that are strategically designed and managed to provide a wide spectrum of essential ecosystem services (Rodrigues et al., 2025). The guiding principles of GI implementation are strong connectivity, strategic layout, and inherent multi-functionality. The global consensus affirms that the most effective strategy for achieving resilient and sustainable water security is the integration of "green" (natural systems) and "grey" (engineered works) infrastructure—the "green-grey" pathway (Vörösmarty et al., 2021).

Empirical data consistently support the financial efficiency of this combined approach: preserving natural capital to deliver services, such as flood mitigation and water purification, is demonstrably more cost-effective than constructing technical substitutes to replace lost natural functions (Vörösmarty et al., 2021). Furthermore, integrated "blue-green" solutions often exhibit greater flexibility and generate a broader set of supplementary benefits beyond their primary function of protection against inundation (Kapetas & Fenner, 2020).

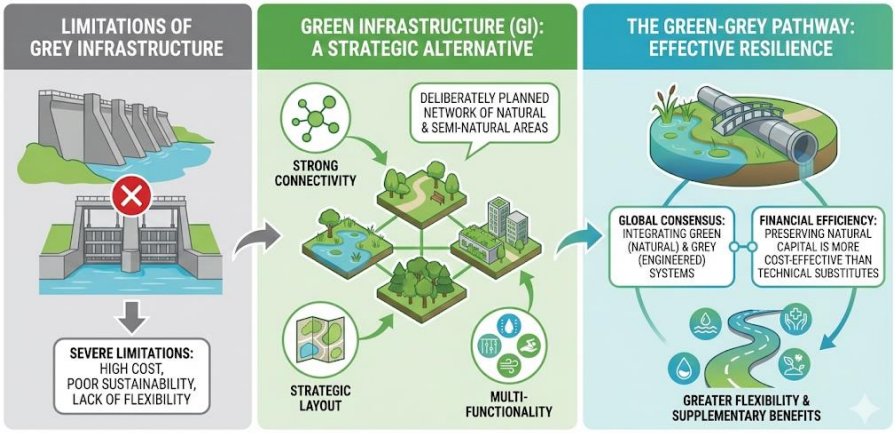

Figure 3. The Emergence of Green Infrastructure (GI) As a Strategy for Adaptive Coexistence

Research Objectives and the Study's Academic and Policy Contributions

This Systematic Literature Review rigorously investigated five core research questions (RQ1–RQ5) outlined in the original study. The study yields two major contributions. Academically, it consolidates a fragmented body of scientific knowledge to identify key global trends and significant research gaps. Practically, it delivers an evidence-based, actionable policy framework intended to guide policymakers in Can Tho, and the broader VMD, in systematically integrating GI solutions into their urban development and long-term climate adaptation strategies.

2. SYSTEMATIC LITERATURE REVIEW: METHODOLOGY AND THEMATIC SYNTHESIS

Methodology: Adherence to Systematic Review Protocol

The methodology for this review strictly adhered to the principles of a Systematic Literature Review (SLR), following the established guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). This meticulous approach ensures that the collection and synthesis of scientific evidence are transparent, objective, and reproducible. The search strategy was constructed using a comprehensive chain of keywords to ensure exhaustive coverage of the intersection between GI, water resilience, climate impacts, development, and policy frameworks within the specific geographical bounds of the Mekong Delta. The search utilized combinations of terms focusing on green infrastructure, water security, climate change adaptation (including drought and saltwater intrusion), sustainable development, the Mekong Delta/Can Tho context, policy frameworks, and international case studies.[1] The subsequent screening and selection process was rigorous, involving multiple stages to eliminate redundancy, assess relevance based on titles and abstracts, and finally, conduct a full-text evaluation for inclusion.

Thematic Synthesis of Evidence: Theoretical Foundations and Geographical Distribution

The selected body of literature demonstrates intellectual breadth, incorporating global meta-analyses on the green-grey pathway, detailed studies from highly relevant deltaic environments such as the Netherlands, and focused regional studies addressing the specific vulnerabilities of the Vietnamese Delta. The theoretical underpinnings of these studies are dominated by the Ecosystem Services Theory and frameworks related to Governance and Sustainable Urban Planning. Ecosystem services theory provides the foundational economic rationale, asserting that conserved natural systems deliver tangible value that makes their protection a financially sound strategy (Rodrigues et al., 2025). Governance theory provides the practical framework for analyzing the institutional prerequisites necessary for the effective, long-term deployment of GI solutions (Tsai et al., 2025).

A Critical Knowledge Gap: The Scarcity of Empirical GI Case Studies in Urban Can Tho

A crucial finding that emerged directly from the systematic search process is the substantial scarcity of published, peer-reviewed, empirical research dedicated explicitly to investigating the application, cost, and functional performance of GI within the dense urban context of Can Tho City. While the literature extensively covers global principles of GI (Rodrigues et al., 2025) and generalized assessments of the Delta's vulnerability (Woillez et al., 2022), the quantity of local studies documenting the efficiency and specific co-benefits of GI interventions in the Delta's urban centers is extremely limited. Existing local references to water management in Can Tho often derive from technical reports or preliminary master plans (Neumann et al., 2011), which, by their nature, do not possess the rigor of peer-reviewed scientific works that quantify GI performance over time. This situation exposes a significant "Research-to-Implementation Gap." There is a noticeable delay in translating established global best practices and theoretical knowledge into verifiable local academic evidence and documented on-the-ground deployment successes. The practical implication of this knowledge asymmetry is substantial: while the international scientific community holds high confidence in the potential efficacy of GI, local decision-makers in Can Tho lack high-certainty data on how these solutions function in their unique, subsidence-prone, seasonally flooded urban environment. This often leads to conservative planning decisions based on risk-aversion, favoring familiar (though ultimately more costly and rigid) grey infrastructure over innovative GI solutions that require localized, bankable proof-of-concept. Therefore, the most critical immediate hurdle for advancing GI in Can Tho is the deficiency of localized empirical performance data.

3. THE FUNCTIONAL MECHANICS OF GREEN INFRASTRUCTURE FOR VMD RESILIENCE

The capacity of GI to confer resilience stems from its multi-functional design, enabling it to solve complex hydrological problems while generating significant socio-economic advantages.

3.1 Nature-Based Solutions (NBS) as the First Line of Defense

For the riverine and coastal cities of the VMD, Nature-Based Solutions (NBS) provide an effective, sustainable, and adaptive initial layer of defense.

The most compelling example is the restoration of mangrove forests. Historically, these forests formed the primary natural buffer protecting coastal areas against salinity intrusion. Past widespread deforestation severely compromised this protective barrier. However, recent large-scale restoration initiatives, such as the addition of 11,184 hectares of mangrove area in the VMD between 2015 and 2020, have successfully demonstrated the feasibility of rehabilitating this natural defense (Tarolli et al., 2024).

Inland, other NBS are highly promising. The strategic, managed following of agricultural land can be used to augment natural freshwater flows during the dry season, thereby effectively holding back the saltwater front (Tran et al., 2025). Crucially, restoring or creating inland wetlands acts as natural freshwater storage. These reserves replenish depleted groundwater aquifers and build hydrostatic pressure—a natural hydraulic barrier—which actively resists the deep penetration of saltwater (Tarolli et al., 2024). This particular solution is highly relevant to the VMD context, where excessive groundwater withdrawal is a primary driver of the crisis.

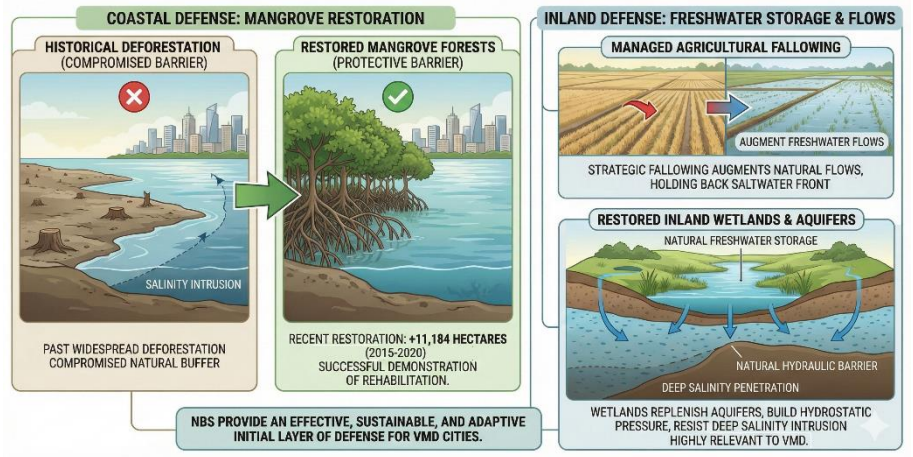

Figure 4. Nature-based Solutions (NbS): Vietnamese Mekong Delta's First Line of Defense

3.2 Integrated Urban GI Components for Hydrological Control

Within the built urban environment, GI components are integrated to manage rainwater and mitigate flood risk through surface regulation. Pervious surface technologies, such as porous pavements, significantly reduce surface runoff volumes, alleviating pressure on conventional drainage networks and minimizing the frequency of combined sewer overflow (CSO) events (Roseboro et al., 2021). Green roofs and walls perform critical functions of stormwater retention and evapotranspiration, simultaneously providing cooling benefits that reduce the debilitating Urban Heat Island Effect. Zonal and linear systems—including urban parks, detention ponds, and bioswales—are intentionally designed to offer temporary water storage during extreme rainfall, acting as natural filtration systems while enhancing public recreational space (Rodrigues et al., 2025). These interventions are essential for transforming impermeable urban areas from flood contributors into adaptive, naturally regulated water management systems.

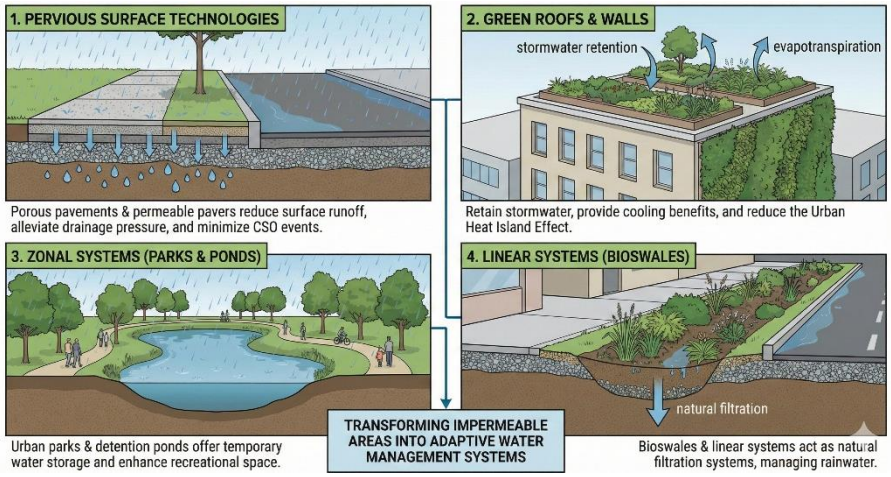

Figure 5. Integrated Urban GI Components for Hydrological Control

3.3 Quantifying Multi-Functional Co-Benefits

The core strength of GI resides in its multi-functionality, delivering synergistic co-benefits that directly enhance sustainable economic development and elevate the quality of urban life.

The creation of aesthetically pleasing and functional green spaces can increase the property values of adjacent areas (Gomes et al., 2021). This property appreciation creates a latent mechanism for increasing municipal tax revenue. By reducing urban heat and absorbing atmospheric pollutants, GI contributes significantly to public health improvements, potentially reducing long-term healthcare costs (Rodrigues et al., 2025). Furthermore, when GI projects are prioritized in low-income or vulnerable communities, they address issues of environmental justice by providing essential protections and improving local amenities (Weber et al., 2022; Weber & Chaiechi, 2022). This reframing allows GI investment to be viewed as a powerful tool for strategic placemaking and economic diversification, transforming it from an environmental cost into a proactive investment in the city's overall economic competitiveness.

Figure 6. Quantifying Multi-Functional Co-Benefits of GI

Table 1. Multi-Functional Green Infrastructure Typologies for Mekong Delta Urban Resilience

GI Typology/NBS	**Primary Water Security Function**	**Secondary Co-Benefit (Economic/Social)**	**Relevance to Can Tho/Mekong Delta**
Mangrove Restoration (NBS)	Salinity intrusion defense, coastal protection	Biodiversity preservation, Carbon sequestration, Sustainable fisheries	Critical for coastal and estuarine zones to restore natural barriers (Tarolli et al., 2024)
Porous Pavements	Reducing surface runoff, mitigating CSO events (Roseboro et al., 2021)	Reducing urban flooding risk, enhancing street aesthetics and safety	High; essential for dense urban stormwater management
Green Roofs/Walls	Stormwater retention, evaporative cooling	Reduced Urban Heat Island Effect, Energy savings (Rodrigues et al., 2025)	High; effective for cooling dense built environments and reducing cooling demand
Wetland/Reservoir Restoration	Natural freshwater storage, Aquifer recharge	Biodiversity habitat, Eco-tourism, Increased hydrostatic pressure against salinity (Tarolli et al., 2024)	High; crucial for actively managing the threat posed by groundwater depletion

4. GOVERNANCE, ECONOMIC FEASIBILITY, AND IMPLEMENTATION BARRIERS

The Economic Case for GI Investment in the Mekong Delta

The economic rationale supporting GI investment in the VMD is exceptionally compelling. A detailed Cost-Benefit Analysis (CBA) specific to the region demonstrated that scenarios involving inaction against sea-level rise could generate economic damages in excess of 22 trillion USD. Conversely, the required investment for a mixed green-grey system, incorporating hard defenses and NBS like mangrove restoration, is estimated to cost approximately 12 to 19 billion USD.

This analysis confirms high Net Present Value (NPV) and robust Benefit-Cost Ratios (BCR) (Oanh et al., 2020). Sensitivity testing verifies that the economic benefits, realized through damage prevention and guaranteed economic stability, significantly surpass the required capital outlay. This data establishes GI as an economically prudent and strategic investment rather than a discretionary expenditure.

Lessons from Global Governance Models in Adaptive Water Management

The success of GI initiatives worldwide is highly dependent on supportive institutional structures and adaptive planning philosophies.

The Netherlands Case Study: Adaptive Delta Management: The Netherlands, through its "Room for the River" program (The Knowledge for Climate Network, 2014), provides the foremost lesson in paradigm shift. Instead of relying solely on increasingly higher, hard defenses, the Dutch adopted an Adaptive Delta Management approach. This philosophy treats flood risk as an integrated spatial and social planning challenge, necessitating flexible policy pathways, interdisciplinary consensus, and multi-level collaborative governance (The Knowledge for Climate Network, 2014). This underscores the critical insight that successful GI deployment is fundamentally a governance problem requiring the fusion of social relations, institutional cooperation, and technical expertise.

Comparative Governance Models and Applicability: Other models demonstrate success under different political contexts.

Singapore's Active, Beautiful, Clean Waters (ABC Waters) program showcases successful, centralized implementation in a highly dense urban setting, characterized by strong coordination driven by the National Water Agency (PUB). This highly coordinated model may offer specific organizational lessons compatible with Vietnam's centralized political system. In contrast, Taipei, Taiwan, highlights the importance of fostering robust community participation for the successful execution of localized GI projects (Tsai et al., 2025), though the Taipei case also illustrates the weakness of long-term financial stability for decentralized maintenance.

The stark contrast between the successful integrated models observed internationally and the acknowledged "fragmentation in governance" and disconnected planning observed in other Vietnamese urban initiatives (Crumpton et al., 2021) strongly suggests that the critical, transferable lesson for Can Tho is the institutional model. The city must replicate the governance integration, not merely the engineering techniques, of these successful global examples.

Table 2. Comparative Analysis of International Green Infrastructure Governance and Policy Frameworks

Case Study	Core Policy/ Program	Governance Model	Key GI Interventions	Mechanisms for Adaptation/ Finance	Relevance to Can Tho/ VMD
The Netherlands	"Room for the River," Adaptive Delta Management (The Knowledge for Climate Network, 2014)	Integrated, Multi-level (central-local), Collaborative, Adaptive Planning.	River widening, dike relocation, creating bypass channels, and coastal nourishment.	Long-term Delta Fund, flexible policy pathways.	Very High: Provides the fundamental blueprint for essential institutional reform and an adaptive planning philosophy.

Singapore	Active, Beautiful, Clean Waters (ABC Waters)	Centralized, high inter-agency coordination, led by the National Water Agency (PUB).	Naturalized waterways, rainwater harvesting, green roofs.	Strong regulatory framework, centralized budget control, and private sector incentives.	High: Offers a model for efficient GI implementation and coordination in high-density urban settings.
Taipei, Taiwan	Greening and GI Initiatives (Tsai et al., 2025)	High community participation, decentralized implementation.	Community gardens, vertical greening, micro-spaces.	Public funding supplemented by social organizations; focus on human capital.	Moderate: Demonstrates the potential of community ownership but highlights the challenge of sustainable long-term financial management.

The Institutional and Financial Impediments to Implementation in Can Tho

Despite the clear economic and technical feasibility, implementation in Can Tho is hindered primarily by institutional inertia. The greatest structural obstacle is the prevalence of fragmented governance. Planning, environmental protection, construction, and transportation departments operate independently, preventing the necessary multi-sectoral planning and coordinated execution required by integrated GI projects (Crumpton et al., 2021). This fragmentation is compounded by short-term planning horizons and an absence of dedicated, long-term financial strategies essential for the sustained maintenance and operation of complex GI systems (Tsai et al., 2025).

Furthermore, technical challenges, such as difficulties in securing land tenure and potential conflicts with existing livelihood activities, remain barriers for large-scale NBS projects like mangrove restoration (Tarolli et al., 2024). The overall conclusion is that, given the strong economic viability established by CBA and the maturity of global technical solutions, the critical bottleneck is institutional capacity, not technical know-how or initial cost. The necessary priority inversion dictates that success depends on shifting the organizational focus from deciding "what technology to use" to determining "how to reorganize the city structure to plan, finance, and maintain GI sustainably."

To address the perpetual challenge of long-term maintenance financing, the economic reality that GI increases adjacent property values (Gomes et al., 2021) suggest a strategic solution: the systematic adoption of Land Value Capture (LVC) mechanisms. Implementing LVC tools—such as specific betterment levies or impact fees on areas benefiting from new green amenities or flood protection—allows the municipality to recapture the financial uplift generated by the GI investment, thereby creating a dedicated, self-sustaining revenue stream for continuous operation and maintenance, overcoming the fragility noted in short-term planning.

5. CONCLUSION AND STRATEGIC POLICY IMPLICATIONS

5.1 Synthesis: GI as a Strategic Imperative for Can Tho's Long-Term Viability

This Systematic Literature Review definitively establishes multi-functional Green Infrastructure as an essential, economically superior strategy for buttressing Can Tho's resilience against intensified drought and salinity intrusion. GI provides a path toward adaptive coexistence, systematically securing water resources while simultaneously driving sustainable economic expansion and enhancing urban living standards. The evidence is conclusive regarding the technical potential and favorable economics; however, the pathway to achieving this transformation is primarily obstructed by pervasive institutional fragmentation and inadequate financial mechanisms for long-term project viability. The transition hinges on the city's commitment to prioritizing profound governance reform and the adoption of an integrated, adaptive planning philosophy.

5.2 Adaptive Policy Frameworks for Urban Can Tho

Based on the synthesis of global lessons and the analysis of local barriers, the following policy framework is recommended, structured around a clear hierarchy of intervention: Governance → Finance → Implementation.

Fundamental Governance Reform

Establish a Politically Empowered Task Force: Create a high-level "Climate Resilience and Green Infrastructure Task Force" with direct reporting lines to the highest municipal authority. This body must have the binding authority to coordinate planning, resource allocation, and project oversight across the previously siloed sectors (Planning, Environment, Construction), thereby dismantling institutional fragmentation (Crumpton et al., 2021).

Mandate Adaptive Planning: Formally integrate the principles of Adaptive Delta Management into all strategic city planning, shifting the management of water resources from a static engineering problem to a flexible, integrated spatial planning challenge (The Knowledge for Climate Network, 2014).

Policy and Regulatory Integration

Formal Regulatory Mainstreaming: Move beyond aspirational goals. Formally mandate quantifiable GI performance standards (e.g., minimum percentage of permeable surface area, mandatory on-site stormwater retention volumes) within the Can Tho City Master Plan and associated zoning and building codes. *Risk-Informed Spatial Prioritization:* Utilize detailed hydrological and salinity risk mapping to establish risk-based spatial planning. This will strategically identify and prioritize zones that require urgent, comprehensive GI and NBS investment to maximize protective benefits.

Sustainable Financing Strategies

Implement Land Value Capture (LVC): Leverage the finding that GI increases property values (Gomes et al., 2021) by implementing LVC mechanisms to sustainably fund operations. This includes applying betterment levies or special assessments to properties that directly benefit from new flood defenses or green amenities. *Diversify Financial Sources and Establish a Dedicated Fund:* Develop a diversified financial portfolio combining public funds, structured Public-Private Partnerships (PPP), and Payment for Ecosystem Services (PES) schemes. Crucially, establish a dedicated, long-term fund, insulated from short-term budgetary pressures, to ensure the continuous operation and maintenance of the GI network.

Capacity Building and Demonstration

Interdisciplinary Skills Development: Launch rigorous training programs aimed at urban planners, engineers, and municipal managers to develop specialized expertise in interdisciplinary GI design, hydrological modeling, the application of CBA techniques, and long-term asset management protocols.

Strategic Pilot Projects: Implement highly visible, strategically placed pilot GI projects—such as a large-scale urban bioswale network or an ecological riverfront park—to build local expertise, demonstrate the tangible co-benefits to the public, and create a verifiable, scalable local knowledge base for future replication (Neumann et al., 2011).

5.3 Limitations of the Review and Directions for Future Local Research

This review's limitations stem from its primary reliance on peer-reviewed English scientific literature, potentially omitting significant research published in Vietnamese or crucial local government "grey literature." The most restrictive limitation is the demonstrated scarcity of localized empirical data regarding GI performance, specifically within urban Can Tho, requiring reliance on analogous global examples.

Future research must focus on filling this critical gap:

Localized Cost-Benefit Analysis (CBA): Conduct primary data-driven CBA studies for specific urban GI typologies (e.g., green roofs vs. porous pavements) tailored to Can Tho's unique environmental and economic context to provide decision-makers with quantified, localized financial certainty.

Political Economy and Institutional Studies: Undertake in-depth research into the political economy of urban development, including the study of institutional resistance, policy conflicts, community willingness, and cultural acceptance of GI solutions to identify practical barriers to scale-up.

Long-Term Monitoring and Evaluation (M&E): Mandate and fund the continuous, rigorous monitoring and evaluation of implemented GI pilot projects. This essential process will measure their actual long-term effectiveness in achieving flood reduction, water quality improvement, and economic co-benefits, thereby building a necessary, robust foundation of local evidence for future policy decisions.

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