

Asia-Pacific Tech Monitor

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Technologies for the Sustainable Use of
Natural Resources



APCTT
Asian and Pacific Centre
for Transfer of Technology



*The shaded areas of the map indicate ESCAP members and associate members.**

The Economic and Social Commission for Asia and the Pacific (ESCAP) is the most inclusive intergovernmental platform in the Asia-Pacific region. The Commission promotes cooperation among its 53 member States and 9 associate members in pursuit of solutions to sustainable development challenges. ESCAP is one of the five regional commissions of the United Nations.

The ESCAP secretariat supports inclusive, resilient and sustainable development in the region by generating action-oriented knowledge, and by providing technical assistance and capacity-building services in support of national development objectives, regional agreements and the implementation of the 2030 Agenda for Sustainable Development.

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Asia-Pacific Tech Monitor

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ASIAN AND PACIFIC CENTRE FOR TRANSFER OF TECHNOLOGY

C-2, Qutab Institutional Area

Post Box No. 4575

New Delhi 110 016, India

Tel: +91-11-6901-3710

E-mail: apctt.techmonitor@un.org

Website: <http://www.apctt.org>

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Foreword

I extend my warmest wishes for a Happy and Prosperous New Year 2026.

This edition of *Asia-Pacific Tech Monitor* explores the theme “Technologies for the Sustainable Use of Natural Resources.” The Asia-Pacific region, endowed with diverse ecosystems and natural resources, is also confronting mounting pressures from climate change and rapid population growth. Challenges such as biodiversity loss and ecosystem degradation underscore the urgent need for sustainable resource management. The priority is to strive for a balance—fostering socio-economic growth while preserving ecological integrity for present and future generations.

Innovative and emerging technologies are pivotal in driving this transformation. Artificial intelligence and machine learning are revolutionizing environmental monitoring through real-time water quality analysis and satellite-based coastal mapping. Digital twins and living labs enable participatory governance by blending traditional knowledge with modern innovation, while blockchain enhances transparency in critical mineral supply chains. Smart tools—such as sensors, IoT platforms, mobile applications, and data-driven systems—are advancing local water management and nature-based solutions, collectively shaping community development.

However, significant barriers remain. Infrastructure gaps, limited technical capacity, governance challenges and financial constraints hinder the scaling of these solutions. With innovation, enabling policies, inclusive governance, and coordinated regional action are essential—through stronger cooperation and stakeholder engagement, strategic investments in infrastructure, capacity-building initiatives, and frameworks that balance innovation with environmental and social safeguards.

Against this background, this edition features insightful articles on technological applications in water management, coastal monitoring, climate adaptation, hydrogen energy financing, critical mineral governance, and nature-based solutions. Each contribution is enriched with real-world examples from across the region, offering readers a comprehensive perspective on technology’s transformative role in sustainable use and management of natural resources.

In the year ahead, we reaffirm our commitment to strengthening collaboration and delivering timely insights, emerging trends, and feature articles on technology cooperation and transfer. Through the Tech Monitor and its diverse thematic focus, we strive to work together to harness technology and cooperation for a resilient and sustainable future for the Asia Pacific region.

Preeti Soni
Head, APCTT

Technology Market Scan

ASIA-PACIFIC

CHINA

R&D spending reports steady growth in 2024

China's research and development (R&D) expenditure rose 8.9 percent year-on-year to more than 3.6 trillion yuan (about \$506.41 billion) last year, as per the National Bureau of Statistics. Over the 2021-2024 period, the country's R&D spending rose at an average annual rate of 10.5 percent – one of the fastest paces among major economies – making China the world's second-largest R&D investor, said Zhang Qilong, an NBS senior statistician.

R&D intensity, which looks at expenditure as a share of GDP, edged up 0.11 percentage points to 2.69 percent last year. In 2024, China's spending on basic research, applied research, and experimental development grew by 10.7 percent, 17.6 percent, and 7.6 percent, respectively, compared with the previous year.

Enterprises have accounted for more than 75 percent of the country's total R&D spending for many years running, and their contribution to the overall increase in such spending reached 77.1 percent, cementing their role as the main engine of China's R&D spending expansion.

<https://www.chinadaily.com.cn/>

INDIA

State Mining Readiness Index (SMRI) 2025

The Ministry of Mines on Thursday released the State Mining Readiness Index (SMRI) along with state rankings. The index for tracking how well states are performing in facilitating mining activity and implementing reforms. The move also fulfils an announcement made in the Union Budget 2025-26.

The index assesses states across several indicators, such as auction performance, early mine operationalisation,

exploration focus, and sustainable mining practices for non-coal minerals. These parameters are to measure readiness, efficiency, and the overall progress of states in the mining sector.

Under the SMRI, States have been divided into three categories based on their level of mineral endowment.

- In Category A, which includes mineral-rich states, Madhya Pradesh, Rajasthan, and Gujarat have secured the top three ranks.
- In Category B, Goa, Uttar Pradesh, and Assam are the leading performers.
- In Category C, Punjab, Uttarakhand, and Tripura hold the top positions.

This classification allows comparison among states with similar geological capacities rather than absolute rankings.

The Ministry stated that the index is meant to act as a benchmarking tool to measure performance across states. It aims to encourage competition among them and identify areas needing policy attention. The framework is also expected to help the government assess the impact of mining-related initiatives and reforms at the state level.

The release of the SMRI is part of the Centre's plan to improve governance and bring uniformity in how mining operations are monitored and managed across India. By linking rankings with measurable outcomes, the Ministry hopes to promote a more structured and transparent system for resource development.

The index provides a single reference point for tracking state performance in the mining sector. It is intended to promote accountability and help strengthen the overall framework of mineral governance in India.

<https://www.angelone.in/>

INDONESIA

Waste-to-energy technology

The Government of Indonesia officially launched a new milestone in

national waste management through the issuance of Presidential Regulation (Perpres) Number 109 of 2025 concerning Urban Waste Handling through Waste Processing into Renewable Energy Based on Environmentally Friendly Technology.

This policy marks a major change in the direction of national environmental and energy development towards a modern, efficient, and sustainable waste management system. The regulation is an answer to the national waste emergency, which has been a source of pollution, environmental damage, and public health threats.

Minister of the Environment/Head of the Environmental Control Agency (KLH/BPLH), Hanif Faisol Nurofiq, said that through this Presidential Regulation, the government emphasises that waste is no longer just an environmental burden, but a renewable energy resource that can be processed into electricity, biogas, biofuel, renewable fuel oil, and various other derivative products with environmentally friendly technology.

"Handling waste into renewable energy is a real step towards transforming the national waste management system based on environmentally friendly technology. We want to ensure that waste generation in the regions can be processed in accordance with good environmental rules and the energy produced can be used as part of clean energy, so that what enters the Final Processing Site (TPA) later is only residue," said Hanif.

Hanif said that Presidential Regulation 109/2025 brought a number of important improvements compared to the previous policy, Presidential Regulation Number 35 of 2018.

First, if the previous regulation focused on accelerating the construction of Waste Power Plants (PLTSa) in 12 priority locations, this new regulation expands the target to all regions that meet the criteria according to the regulations.

Second, this Presidential Regulation emphasises the government's role in the development of Waste Processors

into Electric Energy (PSEL), including investment support and the selection of PSEL Development and Management Business Entities (PSEL).

Third, the government introduced a breakthrough in accelerating licensing and funding mechanisms so that projects run more efficiently and sustainably.

Fourth, this Presidential Regulation also provides a guarantee of investment certainty through the determination of a fixed electricity tariff of USD 0.20 per kWh for 30 years, as well as the obligation of PT PLN to buy electricity from processed waste. The scheme is expected to attract investors, strengthen the sustainability of the project, and position PSEL as an important part of the national clean energy transition.

Fifth, local governments are obliged to prepare land and ensure that the supply and transportation of waste to PSEL facilities run sustainably.

Through cross-ministerial collaboration, green investment support, and active participation of local governments, we are setting a new direction towards a clean, healthy, and sustainable Indonesia

The government targets the implementation of this Presidential Regulation to be focused on metropolitan cities and big cities with daily waste generation above 1,000 tons, as well as landfills that have exceeded capacity or are limited in land.

The technology used is expected to be able to significantly reduce the volume of waste while producing clean energy to support national energy needs and the Net Zero Emission 2060 target.

<https://wartaekonomi.co.id/>

JAPAN

First national AI strategy

Japan is preparing its first national AI basic plan to boost AI adoption in public institutions and beyond. The draft sets out four core policies to balance innovation with risk management, with final Cabinet approval expected later this year. The plan targets low AI usage rates in the country, around 20% for individuals and 50% for corporations. Policies include

accelerating AI adoption, strengthening development capacity, leading in AI governance, and fostering continuous social transformation toward an AI-integrated society. Government bodies and municipalities are expected to lead by example, improving efficiency and enhancing defence capabilities.

High-quality data, a key factor in AI accuracy, is a national strength. The plan stresses the importance of human-AI collaboration, calls for robust copyright and liability frameworks, and identifies risks such as errors, disinformation, and threats to national security. Authorities plan thorough investigations of rights infringements and aim to help shape international AI rules.

The draft will be presented at the AI strategy headquarters meeting, chaired by Prime Minister Shigeru Ishiba, before being refined by an expert panel and finalised within the year.

<https://dig.watch/>

MALAYSIA

Measures to support high value sectors

Malaysia has announced several measures under its Budget 2026 to support high value sectors, including investing MYR 550 million (\$130 million) in the semiconductor ecosystem. Under the National Semiconductor Strategy (NSS), Bank Pembangunan Malaysia Berhad (BPMB) will provide MYR 500 million in soft loans to support high-value-added activities such as research and development (R&D), especially by local companies that support the electrical and electronics (E&E) ecosystem.

Meanwhile, a total of MYR 200 million (\$47.35 million) under the Strategic CoInvestment Fund (CoSIF) will provide matching grants to small and medium-sized enterprises (SMEs) and mid-tier companies that strengthen the supply chains of key sectors, through Equity Crowdfunding (ECF) and Peer-to-Peer (P2P) financing platforms.

An allocation of MYR 180 million (\$42.61 million) under the NIMP Industry Development Fund (NIDF) to finance industry development programs

in high-impact sectors such as pharmaceutical, semiconductor, artificial intelligence (AI), digital and sustainability. It was also highlighted that government-linked investment companies (GLICs) will continue to catalyse domestic investment.

Under GEAR-uP, GLICs will increase their domestic investment to MYR 30 billion (\$7.1 billion), up from MYR 25 billion (\$5.92 billion) this year. KWAP will provide MYR 1.2 billion (\$280 million) under Dana Pemacu to undertake co-investments with private fund managers (co-GP) to finance emerging companies or markets in sectors, such as energy transition, food security and the digital economy.

Under Khazanah's Mid-Tier Company Program, MYR 250 million (\$59.19 million) is provided to strengthen the capacity of mid-tier companies. It is noted that start-ups have contributed MYR 1 billion (\$240 million) to gross domestic product (GDP) and generated 82 thousand job opportunities.

It is noted that in line with the aspirations of the Malaysia Venture Capital Roadmap, KWAPs' Dana Perintis and Khazanah's Jelawang Capital have increased their investments to MYR 750 million (\$178 million) from MYR 550 million (\$130 million).

The government also proposes to improve the existing Venture Capital Tax Incentive through special tax rates and dividend tax rates for ten years. Since its introduction, MyCIF has attracted over MYR 6 billion (\$1.42 billion) in ECF and P2P capital into micro, small, and medium-sized Enterprises (MSMEs), nurturing local companies to expand their footprint globally.

For agri-entrepreneurs, he said Agrobank will provide MYR 1.1 billion (\$260 million) in financing for entrepreneurs to grow their businesses and support automation and mechanisation in agricultural projects. KPKM NextGen Agropreneur Program will also provide start-up grants and agricultural project development grants with a fund of MYR 20 million (\$4.73 million), he added.

To encourage automation for higher crop productivity, the government also proposes the Agricultural Sector Automation Incentive for crops,

livestock, apiculture, aquaculture and deep-sea fishing to include selected livestock through closed-house farming.

<https://technode.global/>

MONGOLIA

Critical minerals policy and strategic development

The draft law to support critical mineral projects introduces the principle that the Government will approve the list of critical minerals. Professional institutions will conduct studies to determine which minerals in Mongolia are in global demand yet undersupplied, and how to attract investment into those deposits. The draft also outlines how Mongolian citizens will benefit once such deposits are developed, investments are made, and extraction begins.

Currently, Mongolia's legal framework does not define the "benefits" of the mining sector. We tend to view benefits only in economic terms — for example, by focusing on the percentage of royalties and their distribution. Yet, beyond that, there is the concept of social benefit in its classical sense. The number of professionals trained and employed through a project affects not only the employees themselves but also their families and the local economy. Building schools, kindergartens, and infrastructure in mining communities should likewise be considered social benefits.

If the benefits of resource use are clearly defined, it would enable broader discussions with investors and project implementers. Hence, the draft law attempts to clarify what constitutes the "benefit" of a mining project — and many proposals have already been submitted. In short, laws should be clear, intelligent, and adaptable — but always under the guiding principle of sound reasoning.

Another key issue is defining the "impact area". Project implementers often compensate households affected by mining operations. However, current laws provide no clear definition of what an impact zone is or who qualifies as an impacted resident. This draft seeks to establish such a definition. If agreed upon through thorough consultation, this would make future negotiations

more effective and transparent. The draft also aligns with other laws to prevent legal conflicts. The new draft addresses this by introducing coordinated amendments to the Law on Land.

Another conceptual area concerns "resource taxation". In mining, projects typically recover their initial investment before generating profit — a process that can take years. For example, Mongolia has not yet received profit from Oyu Tolgoi, and may not until 2039. Despite this, the government committed to holding a 34% stake, which also requires additional investment as the project expands. Instead of maintaining such obligations, it would be more efficient to collect a fixed tax from sales revenue, directing it straight to the National Wealth Fund.

<https://en.mininginsight.mn/>

NEW ZEALAND

Crown Minerals Amendment Act 2025

The Crown Minerals Amendment Act 2025 was enacted on 5 August 2025. The Act removes the ban on new oil and gas exploration beyond onshore Taranaki and signals the Government's intent to reinvigorate investment in petroleum exploration.

The Act amends the decommissioning regime to provide an appropriate balance between minimising risk to the Crown and the need to increase investment confidence, by introducing Ministerial discretion to assign liability to former permit holders or those who held an interest in a permit.

The Act also makes other changes to the Crown Minerals Act 1991, including:

- Changing the purpose of the Act from 'manage' to 'promote' prospecting for, exploration for, and mining of Crown-owned minerals for the benefit of New Zealand.
- Introducing the ability for the Minister for Resources to issue a Government Policy Statement on petroleum and minerals.
- Allowing for new methods to allocate petroleum permits.

- Providing greater flexibility under the existing exemption and deferral powers for decommissioning to consider exemptions for either the whole or parts of particular items of infrastructure.
- Providing greater flexibility and clarity around what types of financial securities may be accepted.
- Extending the confidentiality period for speculative prospectors who were impacted by the ban.
- Introducing a new Tier 3 permit category for small-scale, non-commercial gold mining.

<https://www.mbie.govt.nz/>

REPUBLIC OF KOREA

AI infrastructure development

The Republic of Korea is accelerating its AI development through a major partnership with NVIDIA, deploying over 260,000 GPUs across government, cloud providers, and industrial leaders. The Ministry of Science and ICT is investing in sovereign AI infrastructure, while companies, including Samsung, SK Group, Hyundai, and NAVER Cloud, are building AI factories and expanding GPU capacity to support physical and enterprise AI workloads. The initiative seeks to boost innovation in manufacturing, automotive, and telecoms, supporting large-scale AI model training, validation, and deployment.

The Republic of Korea's organisations are developing sovereign large language models through public-private partnerships with LG AI Research, SK Telecom, NC AI, Upstage, and NVIDIA. The infrastructure will allow start-ups, researchers, and enterprises to access high-performance computing for AI applications and industrial digital twins.

The Republic of Korea is also advancing AI-enabled quantum computing and scientific research. The Korea Institute of Science and Technology Information (KISTI) is creating a Centre of Excellence using NVIDIA supercomputers, NVQLink for quantum processors, and PhysicsNeMo for physics-based AI models.

The goal is to strengthen research collaboration, AI innovation, and economic growth. Start-ups gain support through NVIDIA Inception and N-Up AI programs, accessing computing infrastructure, AI tools, and investment guidance to speed growth and industrial AI adoption.

<https://dig.watch/>

SINGAPORE

Water technology research

The Government has allocated \$220 million under the Research, Innovation and Enterprise 2025 (RIE2025) Urban Solutions & Sustainability (USS) domain to drive new initiatives in water technologies and resource circularity. This draws from the National Research Fund, under the five-year RIE2025 tranche. These initiatives will help the country achieve the Singapore Green Plan 2030 targets while optimising limited resources.

Of this, the National Environment Agency (NEA) will administer a new \$80 million Closing the Resource Loop (CTRL) Funding Initiative that supports the Green Plan and the Zero Waste Masterplan. The funding will support research and development (R&D) on sustainable resource recovery solutions for key waste streams such as e-waste, plastics and food, and finding useful and safe applications for treated waste residues.

The new \$80 million CTRL Funding Initiative will build upon the R&D work carried out under the earlier Waste-to-Energy (WtE) programme and the Closing the Waste Loop (CTWL) Funding Initiative. CTRL will contribute to the country's efforts to pursue a circular economy approach under the Zero Waste Masterplan to achieve a sustainable, resource-efficient, and climate-resilient Singapore.

Another \$87 million has been allocated to support R&D efforts in three water technology focus areas: (i) Desalination and Water Reuse; ii) Used Water Treatment; and iii) Waste Reduction and Resource Recovery under the RIE2025. The funding will go towards supporting the Nanyang Environment and Water Research Institute (NEWRI) and Separation Technologies Applied

Research and Translation (START) under the Centre of Excellence (CoE) Programme. These Centres of Excellence have amassed considerable capabilities in R&D, attracting talent and investments from all over the world, and enriching Singapore's water industry.

The investments in these Centres of Excellence will go towards developing high-impact solutions for Singapore's national water needs. It will also be an economic multiplier and will spur private sector R&D spending, job creation and technology spin-offs in the water industry and adjacent sectors.

In RIE2025, PUB will require START to build on its existing achievements and deepen its expertise in separate technologies for desalination through the design and operation of a Desalination Integrated Validation Plant (IVP). The IVP will integrate the most promising technologies, configure and optimise them at the system level to validate if lower energy consumption and superior performance can be achieved. If successful, the IVP will reduce the system-level energy consumption of desalination to < 2kWh/m³, taking PUB one step closer to attaining net-zero carbon emissions by mid-century.

<https://gwf-wasser.de/>

SRI LANKA

Green Energy Acceleration Plan 2025-2030

The launch of the five-year renewable energy development plan, "Green Energy Acceleration Plan 2025-2030", was presented by the Ministry of Energy, under the patronage of Prime Minister Dr Harini Amarasuriya. The plan outlines key strategies for identifying and implementing renewable energy methods and digital innovations, ensuring their efficient and environmentally sustainable use. It also highlights the economic benefits of renewable energy and its potential to strengthen the country's financial stability.

Prime Minister Dr Harini Amarasuriya stated, "The Ceylon Electricity Board and the Sri Lanka Sustainable Energy Authority have taken the lead in steering Sri Lanka towards sustainable energy solutions."

The Ministry of Energy has introduced a valuable five-year action plan, the Green Energy Acceleration Plan 2025-2030. This initiative will promote sustainable energy consumption, identify renewable energy sources, and provide a comprehensive understanding of energy conservation and storage methods.

The primary objective of this plan is to reduce electricity demand and lower the initial cost of electricity in Sri Lanka by identifying and promoting the use of renewable energy sources. The goal is to expand renewable energy production over the next five years and provide affordable electricity to all Sri Lankans.

The aim to reform energy acts in three key areas: Ensure the provision of affordable and reliable energy through renewable sources such as solar, wind, and hydropower while minimising carbon emissions; Educating the public on the significance of renewable energy and digital technologies and their role in accessing modern and reliable energy; and introducing advanced energy conversion methods to modernise the energy sector, aligning Sri Lanka with global advancements in the field.

It encompasses various aspects, including the identification and development of energy sources, public awareness initiatives, implementation timelines, allocated funding, and necessary legal frameworks. To ensure the success of this project, it is essential to leverage both local and international partnerships.

<https://www.news.lk/>

THAILAND

First climate change act approved

Thailand's first Climate Change Act sets up national oversight, carbon pricing, an ETS, carbon tax, climate fund, and strict reporting rules to drive the country toward Net Zero. Thailand has taken a historic step by introducing its first-ever Climate Change Act, a landmark law set to transform the country's economic and environmental systems.

The Cabinet approved the principles of the Climate Change Act on December

2, 2025, making it Thailand's first master law on climate governance. It establishes a national framework for managing greenhouse gas emissions, fulfilling commitments under the United Nations Framework Convention on Climate Change (UNFCCC) and driving Thailand toward the goals of carbon neutrality (Net Zero) and net-zero emissions.

1) Four national-level governance bodies established

The legislation mandates the creation of four major committees:

1. National Climate Change Policy Committee,
2. Climate Fund Committee,
3. Climate Fund Evaluation Committee, and
4. Greenhouse Gas Management Organisation

The Climate fund will collect revenue from carbon-related mechanisms — such as carbon taxes, fees, and carbon credit trading — and allocate it to clean energy investment, community adaptation projects, and greenhouse gas reduction programmes. Public and private sectors will be required to collect and report emissions, carbon sinks, and net reductions. A national greenhouse gas registry will be established to ensure transparency.

The Act requires a national master plan and action plans to ensure unified climate targets across all ministries and agencies, with short-, medium-, and long-term emission reduction pathways. The law lays the foundation for a Thai ETS, enabling businesses to buy, sell, transfer, and hold allowances for greenhouse gas emissions. A national registry and allocation rules will govern the system.

The Act accommodates CBAM measures, meaning imported goods may face carbon charges based on emissions from their countries of origin — aligning Thailand with emerging international standards. The draft law introduces a carbon tax for products or activities with significant emissions — a key instrument enforcing the polluter pays principle. Certified domestic carbon credits will be recognised as legal property. They can be bought, sold, transferred, or used to offset

emissions, with mandatory registration under the Greenhouse Gas Management Organisation.

Beyond mitigation, the Act requires national, provincial, and local adaptation plans to address climate risks, such as floods, droughts, and extreme weather, which will be supported by government resources.

<https://www.nationthailand.com/>

UZBEKISTAN

Tax-free zone for AI and data centre projects

Uzbekistan offers tax breaks, cheap electricity, and renewable-energy support, with most sites planned in Karakalpakstan to help build the country's AI ecosystem by 2030. Uzbekistan has announced a major package of incentives to attract more than €85 million in foreign investment into artificial intelligence (AI) and data infrastructure.

The programme, introduced by presidential decree, aims to position the far-western Karakalpakstan region as a site for large data centres and high-tech projects, backed by generous tax incentives and government-supported infrastructure development.

Investors will receive significant tax breaks and access to low-cost electricity, while companies will be required to invest their own capital and adopt energy-efficient solutions, including renewable power and battery storage.

Ongoing upgrades to the country's fibre-optic networks and telecom infrastructure are gradually improving the country's digital capacity, according to assessments by Uzbekistan's Ministry of Digital Technologies and a UNDP study on Uzbekistan's digital economy. These developments, combined with relatively low operating costs and Uzbekistan's position between larger Eurasian markets, make the country a potential practical location for data-centre and compute operations for firms looking to broaden their geographic footprint.

Karakalpakstan is an autonomous region in Uzbekistan's northwest and one of the areas most affected by the Aral

Sea crisis. The Aral Sea, once among the world's largest inland lakes, began shrinking in the 1960s after large-scale irrigation projects diverted the rivers that fed it. The government's decision to anchor high-tech and AI-related projects in the region is seen as an attempt to offset these long-term challenges by fostering new industries, attracting investment, and creating a more resilient economic base.

According to Kamola Sobirova, Advisor to the Minister of Digital Technologies, the region offers a rare combination of energy availability, climate conditions, and land resources needed for large-scale data and AI infrastructure. Cooling systems can account for up to 70 per cent of a data centre's power consumption, she noted, and the region's position within the north-western part of the national power grid — where electricity production exceeds consumption by roughly 10–15 per cent — ensures a more stable supply environment.

Although traditional data centres often rely on large volumes of water for cooling, projects planned in Karakalpakstan are expected to adopt low-water or water-free cooling solutions, given the region's well-documented water scarcity and the emphasis on energy-efficient technologies in recent investment announcements. The area's relatively cool climate, with an average annual temperature of 12 to 14°C, also enables the use of natural "free cooling," reducing dependence on water-based systems.

The initiative is also expected to drive socio-economic development by creating skilled jobs, attracting investment into IT and digital services, and stimulating the growth of supporting industries, such as logistics, cooling systems, and equipment maintenance.

<https://www.euronews.com/>

VIET NAM

New law strengthens technology transfer

The National Assembly passed the amended Law on Technology Transfer, marking an effort to refine the legal framework, encourage innovation, enhance enterprises' capacity to absorb

new technologies, and create further advancements for technology transfer, in line with the Party's guidelines and state policies.

One of the key highlights of the law is the addition of clear definitions of green technology and contactless technology transfer, a form of transfer through electronic or digital environments, reflecting the strong development of digital transformation and online technology cooperation models.

The law introduces many new priority policies: particularly encouraging the transfer of high technology, strategic technology, advanced technology, green technology, and clean technology from abroad to Vietnam; promoting the diffusion of technology from foreign-invested enterprises (FIEs) to domestic enterprises; and strongly supporting technology transfer activities in disadvantaged areas, mountainous regions, islands, and in the agricultural and rural sectors.

The law emphasises investment, tax, land, and credit incentives for FIEs' projects that involve technology transfer,

human resource training, or the development of research, design, and manufacturing capabilities in Vietnam.

To create flexibility and reduce risks when businesses adopt new technologies, the amended Law on Technology Transfer introduces three mechanisms for the first time: temporary technology transfer, allowing testing within a defined scope and timeframe to assess suitability before widespread investment; results-based technology transfer: the value and obligations between parties are established based on the ability to meet technical, economic, and environmental criteria; and controlled testing in technology transfer activities, consistent with the sandbox model currently applied in many innovation fields.

To improve management efficiency, the law adds regulations such as tightening the technology assessment process in investment projects, especially for technologies with restricted transfer or those posing a risk of adverse environmental impact; clearly defining the responsibilities of provincial

People's Committees in receiving, assessing, and licensing technology transfer; strengthening inspection, supervision, and evaluation of the effectiveness of technology transfer using state budget funds; and encouraging the public disclosure of technology transfer information on the national digital platform for science, technology, and innovation management.

Regarding support for businesses and promoting the commercialisation of research results, the law has many support policies such as supporting businesses in technological innovation through the National Technology Innovation Fund and the system of science and technology funds; the state investing in the development of a network of innovation centres, start-up support centres, and intermediary organisations of the sci-tech market; and allowing the state to purchase and disseminate technology for national defence, security, or public purposes.

The law will take effect from April 1, 2026.

<https://vir.com.vn/>

Technology Scan

Focus: Technologies for the sustainable use of natural resources

ASIA-PACIFIC

AUSTRALIA

Spatial digital twin

Five years since its launch, the NSW Spatial Digital Twin (SDT) continues to prove its worth as a transformative platform for government planning. The NSW Spatial Digital Twin has evolved into a robust ecosystem supporting a growing number of use cases across sectors, including education, infrastructure development, housing supply, emergency response and local government.

The value of the digital twin is not just about the technology itself but about unlocking the value of the State's data. An example of this is the release of the NSW Land Subdivision Pipeline into the Spatial Digital Twin, providing a forward view of new land development. This data empowers planners, developers and councils planning for communities and demand for infrastructure. It also informs the community of what neighbourhoods will look like in the future. It has been significant in supporting housing supply, unlocking new land, and finding efficiencies in the planning process.

One of the greatest benefits of the Spatial Digital Twin has been the ability to fully customise it to suit different needs across government. The NSW Department of Education leveraged a fully customised version of the Spatial Digital Twin to manage its school assets across the state. The tool allows them to manage their current assets and complete a rapid, early assessment of sites suitable for development, unlocking significant value.

Land information is not just about planning and development. During recent flooding events in NSW, the Spatial Digital Twin was used to identify land suitable for temporary housing and streamline the process for activating it. This provided much-needed relief for the impacted community.

<https://www.spatialwa.wa.gov.au/>

CHINA

Intelligent mining technology

The mining sector is currently witnessing a digital transformation as mine operators embrace autonomous vehicles, AI-driven monitoring systems, robotics and smart drill rigs, as well as more environmentally responsible practices, aimed at enhancing efficiency and safety. A major focus is on sustainable resource extraction and decarbonisation, with firms investing in technologies to lower emissions, manage water, and rehabilitate mined land, with several countries leading a global shift towards more intelligent and responsible mining.

As both the world's largest producer and consumer of coal, in recent years, China has made remarkable progress in upgrading its mining sector, with intelligent production capacity now representing more than 50% of total coal output. The number of mines adopting intelligent systems has increased significantly, and China now leads the world in the deployment of technologies, such as 5G-enabled industrial internet, autonomous vehicles and digital management platforms.

Underpinned by robust policy support from the Chinese authorities, this transformation promotes intelligent, safe, and sustainable mining. New regulations mandate the adoption of advanced technologies to protect workers and reduce risks, with environmental sustainability a key priority. For example, autonomous trucks and drills are enabling continuous, round-the-clock operations, reducing the need for personnel to work in hazardous conditions, while AI-powered predictive maintenance systems are helping to prevent equipment failures, minimising costly downtime and ensuring more reliable, efficient mining operations.

A pivotal player of this evolution is technology pioneer Huawei, whose innovative solutions are helping to address mining's most pressing challenges. Its 5G-Advanced (5G-A) networks deliver

the high-speed, low-latency connectivity required for real-time data exchange between autonomous trucks, drills, and central control systems. This connectivity enables 24/7 operations, significantly boosting productivity while minimising human exposure to hazardous environments.

Huawei's AI-driven platforms are also transforming mine management, with predictive maintenance and cloud-based management systems enabling seamless coordination of complex mining processes. Huawei's autonomous vehicle solutions, such as those deployed at the Yimin open-pit mine, demonstrate the practical benefits of these technologies, with improved safety, greater operational efficiency, and reduced environmental impact.

In May 2025, the Yimin open-pit coal mine in Inner Mongolia became the world's first mine to deploy a fleet of 100 autonomous electric mining trucks, marking a significant milestone in the digital transformation of the mining sector. This achievement was the result of a joint innovation project between Huaneng Inner Mongolia Eastern Energy Co., Ltd., Huawei, and other partners, aimed at creating a zero-carbon, intelligent mine transportation system.

Huawei has been at the forefront of integrating AI and digital solutions into mining operations, and at the heart of the Yimin mine is the integration of a 5G-Advanced (5G-A) network, enabling seamless vehicle-cloud-network synergy. Huawei played a pivotal role by providing its Commercial Vehicle Autonomous Driving Cloud Service (CVADCS), which leverages crowd-sourced mapping for real-time location updates and route optimisation.

This technology not only reduces waiting times and maximises fleet efficiency, but also supports the safe, continuous operation of trucks in harsh environmental conditions, including the extreme -40°C temperatures often found at the Yimin mine, frequent dust storms, and fog. The Yimin mine is also the first in China to operate autonomous mining trucks without

driver cabins, significantly improving personnel safety by removing workers from hazardous environments entirely.

The 5G-A network deployed by Huawei ensures robust, low-latency connectivity, supporting high-definition video backhaul and real-time cloud dispatching. With 500 Mbps uplink and 20 ms latency, the network underpins the smooth operation of the autonomous fleet, setting a new benchmark for intelligent mining worldwide.

<https://www.mining-technology.com/>

Sea wind and wave detection satellite

China's first satellite designed to detect sea winds and waves has been officially named MAZU, officials announced Sunday at the 10th World Mazu Culture Forum in Fujian province. The satellite is scheduled for launch in 2027. The satellite will provide technical support for real-time monitoring of ocean wind and wave conditions, marine and weather forecasting, ocean resource development, and disaster prevention and mitigation at sea. It is part of China's national early warning initiative MAZU, unveiled in July.

Lin Mingsen, former director of the National Satellite Ocean Application Service under the Ministry of Natural Resources, said that "marine satellites, with their high resolution, speed, wide coverage, and comprehensive data advantages, can play a vital role in ocean disaster prevention and mitigation."

MAZU stands for "Multi-hazard", "Alert", "Zero-gap", and "Universal", coinciding with the name of an ancient Chinese sea goddess worshipped in south-eastern China's coastal areas for her death while rescuing people from a shipwreck in the 10th century. The core MAZU spirit lies in "virtue, kindness, and great love," which in the maritime context is expressed through "sea rescue".

<https://www.ecns.cn/>

INDIA

A novel spatially aware AI model

Now, researchers from the Indian Institute of Technology, Bombay,

have developed a spatially aware domain adaptation network (SpADANet), which refers to an AI model designed to 'adapt' across different storms, even with a limited number of labelled samples from ground zero. The findings of the study, published recently in the IEEE Geoscience and Remote Sensing Letters, demonstrate that SpADANet achieves more than 5% improvement in damage classification accuracy compared to existing methods across different hurricanes.

"The existing models consider the problem of domain gap in a statistical sense, but often ignore the spatial context. Spatial context is basically the arrangement and relationship of any spatial object (like buildings) within an image, which is the heart of SpADANet," explains Pratyush Talreja, a PhD Candidate and Prime Minister's Research Fellow at IIT Bombay and also the first author of the study.

Further, the researchers have even optimised the model to run with limited computing power, and it can be used on tablets and phones as well. This feature makes it a handy tool in the field and addresses a genuine bottleneck in disaster response, particularly for regions with limited resources. While the researchers tested the model on hurricanes in the US, they are confident that the framework can be applied globally for damage assessments with appropriate local imagery. SpADANet can generalise effectively across varied environments, but modest amounts of locally labelled data enhance its adaptation performance and reliability, says Talreja.

"Agencies like NDMA (National Disaster Management Authority in India) face three main constraints: lack of labelled data, limited computing resources, and regional differences (domain gap) in the image characteristics. SpADANet can help overcome these barriers as it learns from fewer labels, adapts to new regions, and can run on modest hardware once trained. With continued collaboration between the researchers and the government agencies, such AI models can soon become part of near-real-time disaster response systems," highlights Talreja.

SpADANet is developed using ResNet as the background model, which is a

type of deep neural network with proven superior image pattern recognition abilities.

Labelling satellite imagery is slow and expensive, as each image needs a human eye to mark whether a building is destroyed or lightly damaged. The findings, therefore, emphasise the effectiveness of domain-aware learning in real-world disaster response settings. While the results look encouraging, the ways that SpADANet employs to perform domain adaptation are also novel.

After introducing self-supervised learning, the researchers further enhanced the model using a new module called the Bilateral Local Moran's I (BLMI). Moran's I is a widely used statistical method to spot groups of similar patterns that appear close together in an image. BLMI builds on this idea to help the model understand how nearby pixels relate to each other. In other words, the model does not judge a patch solely by its colour or shape, but also by how neighbouring patches relate to one another, enabling SpADANet to recognise damage patterns based on location and context.

In essence, SpADANet makes sure each damage category, like 'no damage', 'minor damage', 'major damage', 'destroyed', matches properly across different hurricanes. It learns to recognise that a "destroyed" building in one storm should look like a "destroyed" building in another, even if the lighting, materials or layouts differ. This means a destroyed roof in one hurricane is treated the same way as a destroyed roof in another to avoid mix-ups across geographies. The BLMI module strengthens the model's ability to read spatial patterns, and the self-supervised learning step helps it adapt to a new hurricane smoothly, even when only a few labelled examples are available.

However, researchers highlight that factors such as the availability of standardised datasets and data-sharing limitations from the agencies may pose a short-term barrier to immediate large-scale implementation. Their next step in this research is integrating multimodal data, such as combining images with LiDAR data. In a warming world, where both frequency and intensity of hurricanes continue to increase, a faster, cheaper damage assessment tool like

SpADANet can prove critical for a timely and reliable damage assessment.

The Indian model is developed independently for hurricane damage assessment using ResNet as the background, adding spatial awareness and self-supervised learning to achieve domain adaptation.

<https://researchmatters.in/>

JAPAN

Sulfated yeast rises to the challenge

A research group led by Professor Masayuki Azuma and Associate Professor Yoshihiro Ojima at Osaka Metropolitan University's Graduate School of Engineering successfully achieved selective recovery of metals with S-yeast, a sulfated yeast. The study was published in *Environmental Research*.

When testing the removal of copper (Cu) from a solution, S-yeast's metal adsorption capacity was found to absorb approximately 2.3 times more than the phosphate-modified baker's yeast (P-yeast) previously created in their past studies. Furthermore, S-yeast can desorb Cu using hydrochloric acid, then adsorb it again, effectively providing a possible sustainable and cost-effective solution to metal recovery. Additionally, it was found that S-yeast adsorbs more zinc, cadmium, lead, and rare earth elements than P-yeast.

"We hope these research findings lead to applications in efficient and environmentally-friendly rare earth recovery technology. Moving forward, we plan to advance toward practical implementation by scaling up material production and conducting evaluations using actual waste liquids," stated Professor Azuma.

<https://phys.org/>

REPUBLIC OF KOREA

Smart measurement to enhance flood forecasting accuracy

A research team from the Republic of Korea has developed an artificial

intelligence (AI)-based automatic water level measurement system to improve the accuracy of flood forecasting and the reliability of hydrological data in Southeast Asian countries. The Korea Institute of Civil Engineering and Building Technology (KICT) announced on the 29th that a team from its Water Resources and River Research Division has developed an AI-based automatic water level measurement system called the 'Smart Staff Gauge'. A staff gauge is a measuring instrument installed in rivers and streams with a graduated scale to allow for direct observation of the water level.

The research team developed the Smart Staff Gauge, a low-cost, highly field-applicable, contact-type automatic water level measurement system that applies AI technology and can precisely measure both river water levels and inland inundation levels simultaneously. The newly developed Smart Staff Gauge overcomes the limitations of conventional manual staff gauges. It performs an integrated process of automatic water level measurement, data transmission, anomaly analysis, and flood prediction. A key feature is its integration of AI technology, which manages the quality of water level data in real-time and can predict future water level changes and the possibility of flooding.

The Smart Staff Gauge's measurement device uses both resistance-type sensors, which measure changes in electrical resistance between sensors, and laser-type sensors, which detect the position of a float to measure the water level. The newly developed device is capable of precise water level measurement within an error range of ± 2 mm. It operates on solar power, eliminating the need for an external power source. Installed on the main stream of the Mekong River in Laos during the flood seasons from 2023 to 2024, the Smart Staff Gauge measured water levels with an accuracy of within ± 2 mm. It recorded an accuracy level equivalent to manual observation, successfully demonstrating the effectiveness of its AI-based hydrological data quality control and prediction capabilities.

Furthermore, the Smart Staff Gauge can be installed at less than half the cost of existing foreign-made equipment and

is easy to maintain. As the collected data is transmitted automatically, it is highly useful for developing countries with limited personnel and budgets. It can be installed not only in rivers but also in flood-prone areas such as roads and underpasses, and it is highly scalable, allowing for integration with disaster response systems that include LED warning signs, sirens, and CCTVs.

The research team plans to further advance the Smart Staff Gauge technology to suit various field conditions and expand its development into a modular product suitable for urban areas, including underground spaces. They also intend to seriously pursue global market entry through cooperation with domestic local governments, as well as international organisations, and foreign cities.

<https://www.dongascience.com/>

THAILAND

Smart aquaculture IoT solution

HydroNeo is a Thailand-based aquaculture technology company. Since 2020, it has grown into a leading provider of smart water monitoring and farm management systems, and is nowadays trusted by farmers in six countries across Asia. HydroNeo's IoT-based system enables shrimp and fish farmers to monitor key parameters such as dissolved oxygen, pH, and temperature in real time, while automating operations to improve energy efficiency, reduce costs, and support more sustainable farming through digitalisation.

HydroNeo's vision is simple: to empower farmers to make decisions with confidence, no more guessing. Farming becomes more efficient, predictable, profitable, and better for everyone: the animals, the farmers, and the environment. What makes HydroNeo's journey unique is that they are farmer themselves. They understand farmers' daily struggles and test their solutions directly in real ponds. From there, they built technology step by step, ensuring it truly serves the needs of farmers upgrading their operations rather than forcing them to adapt to technology on a green-field.

It also highlights why aquaculture farms today must modernise with technology, not as a luxury, but as a smart investment to strengthen financial performance, improve sustainability, and secure the future of farming.

<https://enaca.org/>

Smart water management

In a quiet district along the Thai-Lao border, a new kind of digital transformation is taking shape – one powered by solar panels, smart sensors, digital tools, and most importantly, by the people who use them. Bung Khla Sub-district, home to Moo 1, 2, and 3 (*Moo means villages in Thai*) in Bueng Kan Province, has recently emerged as a pioneering innovation site for a smart, community-led water management solution under the P-LINK Project – *People’s Livelihoods Initiative through water-energy-food Nexus in the Mekong Region*. Rooted in South-South and triangular cooperation, the community is stepping into the future with smart water technology, designed not just to function, but to last.

Also known as the ROK-UNOSSC Facility (Phase 3), this initiative brings together the United Nations Office for South-South Cooperation (UNOSSC), the Republic of Korea’s Ministry of Science and ICT (MSIT), the Mekong River Commission, Thailand’s Office of the National Water Resources (ONWR)/Thailand National Mekong Committee Secretariat (TNMCS), the Mekong Institute (MI), ROK Science and Technology Policy Institute (STEPI) and Korean start-up WI.Platt, all working closely with local government and communities to deliver results. At the core of the project is a smart water system—a major upgrade to the community’s existing infrastructure. Installed across three villages, the system includes:

- AI-powered leak detection and water pressure sensors
- Automated chemical dosing systems to improve treatment consistency
- Solar-powered energy units for sustainability

A centralised real-time monitoring room outfitted with digital dashboards. These tools allow local operators to monitor water quality, track system performance, and detect problems

quickly – something that was not possible before.

“Before this project, we relied mostly on manual checks and didn’t have tools to detect leaks or monitor water quality in real time,” said Mr Piya Panumas, Director of Public Works at Bung Khla SAO. “Now, we can see what’s happening in the system right away and respond faster. Since installation, the water looks clearer and more consistent. I really hope everyone in the village will take care of it together.”

They have installed a digital water metre and a mobile app for real-time leak detection via IoT. Smart systems only reach their full potential when people are equipped to use them. This is why the project placed strong emphasis on training, local capacity, and ownership.

While full automation remains limited by cost and uneven internet access, this semi-digital approach already marks a significant step forward in efficiency and service delivery. The smart water system has already begun to reduce water loss, improve supply quality, and support clean energy use. As ONWR/TNMCS’s Director of Foreign Affairs Division, Dr Winai Wangpimool noted, “There are real production costs to ensure water is clean and safe. It is crucial that water reaches households as efficiently as possible.” As results are tracked over the coming months, stakeholders are already looking at scaling the model across Thailand and the wider Mekong region.

The Bung Khla pilot is more than a technical upgrade – it is a human story about what happens when innovation is grounded in cooperation and driven by community. For Moo 1, 2, and 3, it is not just about water flowing downstream. It is about progress flowing forward.

<https://unsouthsouth.org/>

EUROPE

GERMANY

Diving robot collects underwater trash

German researchers have developed a groundbreaking AI-powered underwater

robot that could transform how we tackle marine pollution by collecting ocean debris with its giant four-fingered robotic hand. To address one of the world’s greatest environmental problems, marine litter, the engineering team at the Technical University of Munich (TUM) built the robot as part of the EU project SEACLEAR.

The autonomous diving robot uses an integrated AI system with ultrasound and cameras to detect underwater litter. Once identified, it then picks up the waste and brings it to the surface. Demonstrating its capabilities for the first time in the port of Marseille in France, the diving robot collected various debris from the seabed, including objects as heavy as 551 lbs (250 kilograms). With ocean litter ranging from e-scooters and lost fishing nets to old tyres from the harbour basins and broken glass, the system is engineered to handle both heavy-duty lifting and delicate precision.

According to Stefan Sosnowski, PhD, Chair of Information Technology Control at TUM, waste disposal using autonomous underwater waste collection becomes profitable at depths of 52 feet (16 metres) or more. That’s why the entire system consists of an unmanned service boat with a dinghy, a drone, a small underwater search robot and the TUM diving robot. The service boat supplies the robots with power and data connections through cable. At the same time, it also sends ultrasonic waves into the depths to generate a rough map of the seabed. The small 20-inch (50-centimetre) search robot then quickly and efficiently scans the seabed.

Powered by eight mini turbines, the submarine then dives to the locations where the litter is detected and collects the objects. It uses a which to load them onto an additional autonomous dinghy that serves as a floating waste container. “Since we first have to identify the rubbish and grasping objects requires a high degree of precision, we have a camera and sonar on board that enable orientation even in murky water,” Sosnowski stated. Identifying underwater rubbish is no easy task, as there’s little image data available to train neural networks. Nevertheless, the team have managed to label more than 7,000

images as potential objects which don't belong on the seabed. Once the waste is detected, the AI transforms the images into 3D models. "This is important for deciding where the object can be gripped securely," Sosnowski elaborated. He stated that the autonomous gripper's four-fingered hand can exert a force of 4,000 Newtons (N) and lift objects weighing up to 551 lbs (250 kilograms). Its grip is, however, regulated by special sensors that measure how much force can be applied without causing damage. This, for instance, prevents plastic buckets from breaking or glass bottles from shattering.

Although the boat operates autonomously, researchers kept it tethered during the experiment. The onboard battery lasts only two hours, and the cable boosts AI performance while also helping pull heavy objects to the surface. Meanwhile, the 264-lb (120-kilogram) submarine is encased in buoyancy foam, keeping it suspended in water when the mini turbines are off. This lets the robot move freely and stay on course. "This is important for approaching objects precisely," Sosnowski concluded.

<https://interestingengineering.com/>

UK

AI supercharges science on the Antarctic seafloor

Using the latest AI technology, scientists from the British Antarctic Survey have dramatically sped up the process of detecting animals found in photographs and videos taken of the seafloor—from taking several hours to a few seconds per image. The use of this tool, in combination with expert scientists, is fast enough that it could even be used on research vessels in Antarctica to label photographs in real time as they are taken. This major increase in speed and efficiency enables researchers to cover a much larger area of the seafloor when trying to decide which parts of Antarctica need special protection.

The Antarctic seafloor is home to more than 94% of all the species known from the Southern Ocean, most of which live nowhere else on Earth and are adapted to sub-zero temperatures. As climate

change and human activities threaten these specially evolved animals, it is important to gather information to help us understand where these animals live and which species are at greatest risk.

"This new AI technology will massively speed up how marine biologists analyse the data they collect. Before we developed this tool, image analysis was performed by hand, taking up to eight hours per photo. By having the AI work alongside the human experts, we can cut this down to a few seconds per photo," said Dr Cameron Trotter, machine learning research scientist at the British Antarctic Survey and lead author of the study, which is posted to the *arXiv* preprint server. "This allows us to analyse far more data than ever before, speeding up our understanding of these unique and globally important ecosystems."

Training AI tools to understand the Antarctic seafloor, along with the creatures that call it home, is extremely challenging. The model was trained on images taken on board Germany's polar research ship, the *RV Polarstern*, of the Alfred Wegener Institute, in the Weddell Sea. Dr Trotter added, "The images we used to train the AI are extremely high-resolution and packed full of weird and unusually shaped animals, often living on top of each other, some of which have never been seen before."

Scientists labelled each animal in 100 images, which captured a range of seafloor species, representing a range of conditions. Learning from these labelled images, the AI can now find and label the same types of animals in photographs taken in regions across the Southern Ocean. It can identify many of the most commonly seen seafloor creatures, including starfish, corals, sponges and fish.

"This is a game-changer for the way in which we analyse the seafloor, unlocking vast quantities of data crucial for the conservation of Antarctic ecosystems," said co-author Dr Rowan Whittle, a paleobiologist at the British Antarctic Survey. "Traditionally, scientists have relied on destructive dredging and fishing methods to collect biodiversity data, but the use of photography and AI allows rapid data collection, while not causing any disturbance to this vulnerable environment."

Researchers are already using this technology in their research, with a backlog of more than 30,000 images from the Antarctic Peninsula and Weddell Sea currently being analysed. The findings have strong potential for discovering species, as well as providing policymakers with crucial information that will help protect the creatures found in this vulnerable ecosystem.

<https://phys.org/>

NORTH AMERICA

USA

AI-Powered geothermal discovery

Zanskar Geothermal and Minerals has announced a major breakthrough in geothermal energy with the discovery of the first commercially viable geothermal system in over 30 years. This achievement was made possible by leveraging artificial intelligence (AI), signalling a new era in renewable energy exploration and development. The new geothermal system, "Big Blind", is located in a remote part of western Nevada.

Remarkably, there were no prior surface or geological signs indicating geothermal activity there, highlighting how AI has revolutionised exploration. Traditionally, geothermal exploration involved extensive drilling and many non-productive wells, leading to high costs and environmental disruption. By incorporating AI, Zanskar analysed large datasets to more accurately predict promising geothermal sites, significantly reducing unproductive drilling, cutting exploration expenses, and minimising environmental impact. This success builds on Zanskar's previous projects at Pumpnickel in northern Nevada and Lightning Dock in New Mexico, which utilised technology-driven approaches to geothermal development. However, Big Blind stands out due to its location in an area previously considered unlikely for geothermal activity.

This discovery underscores the vast untapped potential of geothermal resources in overlooked regions. Zanskar now plans to obtain permits to move Big Blind from discovery to development,

aiming to create a power-generating geothermal facility within this decade. This is part of a broader strategy to harness advanced technologies to unlock new geothermal sources and expand the U.S. renewable energy portfolio. Such projects are expected to promote cleaner energy, decrease greenhouse gas emissions, and strengthen energy security. The implications extend beyond Zanskar and Nevada.

Amid rising energy demands, fossil fuel price volatility, and environmental challenges, Zanskar's discovery represents a promising step toward diversifying and strengthening energy systems. Big Blind not only demonstrates technological ingenuity but also provides a practical pathway to commercially viable geothermal power. This landmark find suggests that ongoing integration of AI and technology could reveal many hidden geothermal resources globally, opening new opportunities for sustainable energy production. It also signals hope for a future in which clean, renewable geothermal energy can notably reduce reliance on carbon-intensive sources, advancing the global fight against climate change and fostering a sustainable energy system for future generations.

<https://neuron.expert/>

Efficient ways to extract rare earth elements

A team of scientists at The University of Texas at Austin has created a cleaner and more efficient way to extract rare earth elements, which are vital for technologies such as electric vehicle batteries and smartphones. The technique could strengthen domestic production

and lessen dependence on expensive imports. The new process makes it possible to separate and collect rare earth elements from sources that were previously too difficult or inefficient to use, offering a potential solution to supply challenges heightened by global trade tensions.

"Rare earth elements are the backbone of advanced technologies, but their extraction and purification are energy-intensive and extremely difficult to implement at the scales required," said Manish Kumar, professor in the Cockrell School of Engineering's Fariborz Maseeh Department of Civil, Architectural and Environmental Engineering and the McKetta Department of Chemical Engineering. "Our work aims to change that, inspired by the natural world."

The study, recently published in *ACS Nano*, describes how the team engineered artificial membrane channels, tiny pores within membranes, that imitate the highly selective transport systems of natural proteins in living organisms. In biology, such channels guide ions as they move between cells. Each channel has unique properties that allow only ions with specific traits to pass through while blocking others. This fine-tuned selectivity is essential for many biological functions, including the way the human brain processes information.

The researchers' artificial channels use a modified version of a structure called pillararene to enhance their ability to bind and block specific common ions while transporting specific rare earth ions. The result is a system that can selectively transport middle rare earth elements, such as europium (Eu³⁺) and terbium

(Tb³⁺), while excluding other ions like potassium, sodium, and calcium.

Rare earth elements are split into several classes (light, middle and heavy), each with different properties that make them ideal for specific applications. Middle elements are used in lighting and displays, including TVs, and as magnets in green energy technologies, such as wind turbines and electric vehicle batteries.

Using advanced computer simulations, they discovered that the channels' selectivity is driven by unique water-mediated interactions between the rare earth ions and the channel. These interactions allow the channels to differentiate between ions based on their hydration dynamics—how water molecules surround and interact with ions.

Kumar and his team have been working on this research for more than five years. He is an expert in membrane-based separations, applying that knowledge to clean water generation as well. The researchers envision their technology being integrated into scalable membrane systems for industrial use. The goal is to make it easier to conduct ion separations in the U.S., using clean energy. They're working on a platform for these channels that allows users to select a variety of ions to gather. This could include other critical minerals like lithium, cobalt, gallium, and nickel.

This is a first step towards translating nature's sophisticated molecular recognition and transport strategies into robust industrial processes, thus bringing high selectivity to settings where current methods fall short.

<https://scitechdaily.com/>

Technologies for the Sustainable Use of Natural Resources

AI and Digital Governance for Critical Minerals in the Asia-Pacific

Vlado Vivoda

Sustainable Minerals Institute, The University of Queensland, Australia
Email: v.vivoda@uq.edu.au

Abstract

The race for critical minerals is increasingly a race for data—data that can illuminate deposits, monitor impacts and strengthen supply-chain transparency. Artificial intelligence (AI) and digital technologies are reshaping how these minerals—essential for energy transitions, digitalisation, mobility and defence—are governed across the Asia-Pacific. Tools such as machine learning, geospatial analytics, digital twins (DTs) and Internet-of-Things (IoT) sensors are transforming exploration and extraction, while blockchain systems and Digital Product Passports (DPPs) support traceability, circularity and robust measurement–reporting–verification (MRV). Drawing on regional developments, this article argues that policy integration and capacity-building are crucial to align digital innovation with environmental, social and governance (ESG) objectives and to build more transparent and efficient critical-minerals supply chains.

Introduction — data and minerals in the sustainability era

Critical minerals have emerged as the backbone of the twenty-first-century economy, powering batteries, energy technology, semiconductors, defence platforms and advanced digital systems (Christmann & Lefebvre, 2022; International Energy Agency, 2025). Their growing importance for energy transitions, digital connectivity and strategic autonomy has made the governance of these materials a defining issue for the Asia-Pacific. Yet rapidly growing demand has heightened regional vulnerabilities—including price volatility, environmental pressures and the concentration of refining capacity—while opacity in some supply chains further amplifies these structural risks (Vivoda et al., 2025a).

Across this landscape, artificial intelligence (AI) and digital technologies are

reshaping how subsoil resources are discovered, developed and governed. Machine-learning (ML) models analyse geological, hyperspectral and geophysical datasets to identify mineralisation patterns with high precision. Digital-twin (DT) platforms create dynamic virtual replicas of mines and processing plants, allowing operators and regulators to test operational scenarios and optimise performance. Internet-of-Things (IoT) sensors enable real-time monitoring of water use, tailings stability and emissions, while blockchain and Digital Product Passports (DPPs) record provenance and environmental attributes across the supply chain (Calvão & Archer, 2021; World Economic Forum, 2021).

This digital transformation aligns with the objectives of the *Asia-Pacific Tech Monitor* special issue and the strategic direction of the Asian and Pacific Centre for Transfer of Technology (APCTT, n.d.). For mineral-rich economies such as Australia, China, India, Indonesia, Mongolia, and the Philippines, AI offers new tools for enhancing efficiency while

embedding transparency and accountability in governance systems. For resource-importing states such as Japan and the Republic of Korea, AI-enabled traceability and DPPs are increasingly essential for securing reliable mineral inputs and meeting emerging European Union (EU) and U.S. supply-chain transparency requirements in batteries, electronics and advanced manufacturing.

Governments across the region are increasingly embedding digital technologies into their minerals strategies, using AI, geospatial analytics and automation to modernise exploration, safety systems and environmental management. In China, major advances in intelligent mining are emerging, where fully integrated AI, 5G networks, autonomous haulage, hazard-warning platforms, and remote-operation systems are transforming safety, efficiency, and mine control capability (Leng & Xie, 2024). Japan's *Green Innovation Fund* supports AI-enabled recycling of rare-earth magnets (Ministry of Economy, Trade and Industry, 2023). The Republic of Korea is making similar progress, using digital lifecycle management systems mandated under the *Resource Circulation Act* to support AI-enabled traceability and recycling across its battery and manufacturing sectors (Ministry of Environment, 2023). In India, the *National Mineral Policy* incorporates remote sensing and hyperspectral analytics (Ministry of Mines, 2019).

Regionally, ASEAN has articulated a coherent vision through the *ASEAN Minerals Development Vision* (ASEAN, 2025), which positions the region as a leading destination for sustainable minerals investment by emphasising high-quality digital data, strong governance, responsible production, decarbonisation, and human-capital development, supported by successive five-year cooperation plans.

While digital technologies can support improved oversight and

decision-making, they do not automatically resolve underlying governance challenges. The AI infrastructure itself—data centres, transmission networks and chip manufacturing—is material-intensive, driving further demand for copper, power and water. In settings where institutional capacities vary, AI tools may influence existing patterns of data access, capital allocation or environmental exposure in uneven ways (Vivoda et al., 2025b). Governance systems must therefore account for the “material footprint of the digital” to ensure net-positive outcomes (United Nations Environment Programme, 2024).¹ The central challenge is therefore how digital intelligence can be aligned with principles of security, sustainability and justice—a minerals governance trilemma that calls for cooperation among international organisations, governments, industries and communities (McMaster, 2024).

This article explores how AI-enabled systems can enhance exploration, strengthen environmental performance and accelerate circular-economy models. It proceeds in four parts: (i) data-driven exploration; (ii) smart extraction and ESG-aligned operations; (iii) traceability, circularity and resource recovery; and (iv) policy pathways for embedding digital innovation within resource-governance frameworks. It concludes by summarising the strategic imperatives for regional cooperation.

Data-driven exploration — from intuition to prediction

Exploration has traditionally been one of the most uncertain and capital-intensive stages of the mineral value chain. Success rates remain low, and early-stage activities often occur in environmentally sensitive or poorly mapped areas, heightening ecological and social risks. In the Asia-Pacific—home to vast but unevenly characterised mineral systems—such uncertainty has often fuelled land-use tensions, slowed

permitting processes and led to inconsistent exploration outcomes.

Advances in AI and digital geoscience are reshaping this landscape. AI-enabled models increasingly allow geoscientists to integrate multiple datasets into probabilistic prospectivity maps, supporting a shift from intuition-driven fieldwork toward more data-intensive and predictive exploration workflows (Xiong et al., 2018).

Machine learning as the new engine of discovery

ML techniques—including random forests, gradient boosting, convolutional neural networks and support-vector machines—are now widely applied to analyse geochemical, geophysical, structural and spectral datasets. By revealing patterns that are not easily detectable through traditional interpretation, these models can generate mineral-prospectivity maps with higher precision (Cracknell & Reading, 2014; Rodriguez-Galiano et al., 2015).

Australia is at the frontier of these developments. Commonwealth Scientific and Industrial Research Organisation’s (CSIRO) *Deep Earth Imaging* program has developed advanced imaging, inversion and data-fusion techniques that dramatically improve understanding of Australia’s subsurface structures, integrating diverse geophysical and geological datasets to support more accurate and less invasive exploration (Filatoff, 2024). *Digital Earth Australia* provides analysis-ready satellite imagery and spatial data that enable continent-scale monitoring of terrain, land cover and environmental change across Australia (Geoscience Australia, n.d.). Industry innovators such as SensOre use proprietary ML–geoscience workflows to generate lithium, nickel and gold prospectivity targets across Western Australia, several of which have advanced into joint ventures, tenement acquisitions and drilling campaigns (SensOre, 2021).

Similar approaches are emerging across the region. In China, AI-assisted remote sensing, deep-learning approaches and 5G-enabled drone systems are

increasingly used across geological surveying and the broader mining sector to improve mapping, monitoring and operational safety. These systems not only improve discovery outcomes but also reduce environmental impact by narrowing search areas and limiting the need for broad reconnaissance surveys. In Southeast Asia—where forested or mountainous terrain often constrains ground-based mapping—AI-supported satellite analytics are increasingly important for supporting sustainable exploration planning.

Hyperspectral sensing and geospatial analytics

A second pillar of data-driven exploration is the rapid expansion of satellite- and drone-based remote sensing, which can detect lithological patterns, alteration zones and surface mineralogical signatures. When combined with machine-learning classification, multispectral and hyperspectral datasets can help identify prospective geological structures, map lateritic profiles and characterise terrain where ground access is limited (Drury, 2001; van der Meer et al., 2012).

Across Southeast Asia, remote-sensing methods are increasingly used to support geological mapping, land-use monitoring and environmental assessment near mining areas. Indonesia and the Philippines rely on satellite imagery to track landscape change in mining regions, particularly where mining-related deforestation or land disturbance must be assessed (Ordoñez & Silva, 2023; Rakuasa et al., 2025). China and Viet Nam apply multispectral and hyperspectral imagery—predominantly Sentinel-2 and ASTER—in academic and government-supported geological studies to identify alteration zones and map mineralised terrain (Ge et al., 2018; Tran et al., 2023). These approaches improve baseline geological knowledge where dense vegetation, rugged landscapes or limited sampling constrain conventional fieldwork.

In Japan and the Republic of Korea, public agencies and private firms make extensive use of satellite constellations

¹ The “material footprint of the digital” refers to the minerals, energy, water and land required to produce, operate and dispose of digital infrastructure—from sensors and servers to batteries, chips and communication networks.

Box 1: The invisible front line—geological espionage

As the value of critical minerals rises, geological data has become a battleground for intelligence agencies.

- Australia: In 2025, the Australian Secret Intelligence Organisation (ASIO) Director-General Mike Burgess highlighted that the mining sector is a top target for foreign espionage. The agency noted specific cases where “commercial secrets” and geological IP were stolen to devalue Australian projects before acquisition attempts (Burgess, 2025).
- China: In July 2025, China’s Ministry of State Security (MSS) released a public warning accusing foreign intelligence agencies of “stealing rare earth technology” and smuggling samples. The MSS detailed tactics, including the mislabelling of rare-earth exports as “ceramic parts” to bypass controls (MSS, 2025).

Implication: Digital governance systems must be cyber-resilient. A DT of a mine is not just an operational tool; it is a blueprint of national strategic assets that may require military-grade cybersecurity.

and commercial geospatial services for land-use, terrain and environmental monitoring, capabilities that increasingly intersect with mineral prospectivity analysis and resource-mapping activities (Kim, 1999; Japan Aerospace Exploration Agency, 2014).

In Iran and Mongolia, where large distances and challenging terrain limit field operations, drones equipped with automated navigation and multispectral sensors enable high-resolution surface mapping at significantly lower cost than traditional campaigns. Unmanned aerial vehicle (UAV)-based mapping has been demonstrated at major operations such as the Erdenet copper mine, generating detailed orthophotos and terrain models that directly support geological interpretation and environmental assessment (Murison, 2018; Honarmand & Shahriari, 2021).

Together, these tools illustrate how remote sensing is becoming an essential component of modern mineral exploration—particularly in regions where conventional surveys are difficult, expensive or environmentally disruptive.

Digital twins of the subsurface

DTs are emerging as a powerful exploration tool. They create interactive simulations of the subsurface by combining geological, geophysical, geochemical, hydrological and environmental datasets into unified, dynamically updating models. This allows governments and companies to test drilling options, assess hydrogeological impacts and

evaluate potential ore bodies with reduced invasive activity.

Several Asia-Pacific countries are advancing national or sectoral digital-twin initiatives. Australia’s geological and environmental digital platforms integrate land, water and resource datasets to support transparent decision-making (Geoscience Australia, n.d.). China has developed integrated geological information systems that link digital-twin technologies with multi-source data for exploration planning (Tan et al., 2025).

For policymakers, these systems offer evidence-based planning tools that enable evaluation of exploration proposals against biodiversity, water resources, cultural heritage and climate considerations. By improving the quality of early-stage information, DTs help reduce conflict, permitting delays and regulatory uncertainty.

Moving toward integrated regional platforms

The next frontier is regional integration of exploration data, enabling countries to share non-commercial geological information, harmonise standards and build collective capacity. ASEAN’s *Minerals Development Vision* (ASEAN, 2025) and the *ASEAN Minerals Cooperation Action Plan* (ASEAN, 2021) emphasise this direction, highlighting the importance of strengthening digital geological databases, building geoscience training capacity, and improving information-sharing mechanisms across member states.

Beyond ASEAN, broader regional initiatives already support cross-border data exchange. These include

the implementation of the Integrated Geospatial Information Framework (IGIF) across APEC economies, and UNESCAP’s *Asia-Pacific Plan of Action on Space Applications for Sustainable Development* (United Nations & World Bank, 2018; ESCAP, 2018). Emerging AI tools could build on these foundations to enable shared prospectivity mapping, regional baseline datasets and environmental early-warning systems. A proven operational model for such data integration is the Critical Minerals Mapping Initiative (CMMI). This partnership between the geoscience agencies of Australia, Canada and the United States harmonises geological schemas and merges national databases to support seamless, cross-border critical-mineral assessment (Geoscience Australia et al., 2021).

Smart extraction and ESG-aligned operations

While AI-driven exploration reduces uncertainty and environmental disruption at early stages of mineral development, the largest sustainability gains arise during extraction and processing, where energy use, water demand and waste generation are highest (Liang et al., 2024). Across the Asia-Pacific, governments and mining companies are increasingly adopting AI, IoT, automation and DT systems to improve environmental performance, enhance safety and strengthen the reliability of ESG reporting. These tools support a shift toward data-driven operational governance, where environmental and social outcomes are assessed through

continuous monitoring rather than periodic declarations.

AI, automation and safer mining systems

AI-enabled automation is now widely used in Australia, China and selected mining operations in Southeast Asia, improving both worker safety and production efficiency. Autonomous haulage systems, automated drilling platforms and real-time fleet-optimisation technologies reduce fuel use, minimise equipment downtime and support more consistent operating conditions. Australia's Pilbara iron-ore sector remains a global reference point, where autonomous trucks and remotely operated rail and port systems are managed through integrated digital command centres (Jang & Topal, 2020). Similar automation and AI-enabled optimisation frameworks are increasingly extending to lithium, nickel and rare-earth operations, reflecting the broader trend in the mining industry toward AI-driven productivity and process-control improvements – a trend substantiated by recent evidence on the role of AI in improving efficiency across exploration, extraction and processing stages (Vespignani & Smyth, 2024).

China has advanced a broad smart mining model that integrates 5G connectivity, automated equipment, real-time gas and ventilation monitoring, AI-assisted hazard detection and remote-operation systems (Zadeh, 2025). These technologies improve safety, reduce operational disruptions and give regulators more timely access to production and environmental data, supporting the evolution of digital compliance frameworks.

Industrial Internet of Things (IIoT) technologies are increasingly central to modern mining, integrating sensors, wireless networks and real-time analytics to improve safety, productivity and environmental oversight. Recent work shows that IIoT platforms enable predictive maintenance, automate routine processes and support operational decision-making by providing continuous data on equipment performance, ventilation, geotechnical conditions and energy use (Zvarivadza et al., 2024). Wearable devices, drones and proximity-detection

sensors complement fixed monitoring systems, helping to reduce accidents and optimise production. Together, these capabilities illustrate how sensor-rich IIoT architectures are becoming foundational to data-driven mining operations.

IIoT networks for real-time environmental monitoring

A defining feature of ESG-aligned extraction is the ability to monitor environmental conditions continuously. IIoT sensor networks—installed on equipment, in tailings facilities, at water monitoring points and across processing infrastructure—generate high-frequency data that support near-real-time operational decisions.

Water use—one of the most sensitive aspects of both hard-rock and brine-based extraction—is increasingly monitored using sensor-based and remote-sensing tools. In Australia, mining operations routinely apply groundwater and surface-water monitoring systems, combining automated loggers, flow meters and digital water-balance modelling to support forecasting and regulatory compliance (AusIMM, 2024). In China, national reforms under the Ministry of Natural Resources have expanded the deployment of water-quality and hydrological monitoring stations in mining-affected regions, integrating sensor data into provincial environmental platforms designed to track pollution and ecological impacts (Li et al., 2024; Yin et al., 2025).

Tailings management is another critical application. The Asia-Pacific has experienced several significant tailings incidents—including the 2012 Philex spill in the Philippines and the 2019 Basamuk spill in Papua New Guinea—reinforcing the need for predictive monitoring. AI-ready systems now integrate data from satellite imagery, ground-based sensors, moisture probes and piezometers to identify potential instability and strengthen early-warning capability. Mining companies in Australia have adopted digital tailings monitoring aligned with the Global Industry Standard on Tailings Management (GISTM) (Global Tailings Review, 2020), while China is developing integrated multisensor and data-driven tailings-risk assessment

methods, as demonstrated in recent work applying environmental-risk indexing and multi-indicator analysis to dense tailings-pond regions in the Yellow River Basin (Wang et al., 2024).

Air-quality monitoring—particularly for dust control in mining and quarrying regions—is also advancing. Across the Asia-Pacific, regulators and operators are increasingly using combinations of fixed IIoT particulate sensors, mobile monitoring units and UAV-based surveys to map dust dispersion and optimise suppression measures, as demonstrated in large-scale pilot applications in China's coal and metal-mining provinces (Li et al., 2023).

Digital twins for resource optimisation and reduced environmental footprint

DTs enable operators and regulators to model the interactions between ore bodies, processing systems, waste streams and surrounding environmental conditions. These virtual models update with incoming sensor data, allowing scenario testing, performance optimisation and improved anticipatory decision-making.

In Australia, companies including Rio Tinto, BHP, Fortescue and South32 have incorporated digital-twin components into operational control systems, particularly in iron ore, copper and emerging critical-mineral operations. These systems support ore-blending analysis, equipment-performance simulation, water-balance forecasting and energy-use optimisation, helping reduce waste, improve reliability and align with national decarbonisation and efficiency objectives.

DT approaches are also expanding in China, where research and industry initiatives are developing mine-planning platforms that integrate geological, geotechnical, hydrological and environmental datasets. Recent work documents the use of DT-based models for open-pit design, slope-stability assessment, and mine-water management in Chinese coal, iron-ore and metal mines (Qu et al., 2023). These systems allow mining enterprises and provincial authorities to visualise operational and

environmental conditions, assess cumulative impacts and strengthen risk management across multiple stages of the mining value chain.

AI-enhanced MRV and the rise of evidence-based Environmental, Social and Governance (ESG) systems

The central challenge for ESG governance in the region is the durability and transparency of environmental data. Traditional reporting systems rely heavily on self-reporting, periodic audits and paper-based documentation. AI-enabled measurement, reporting and verification (MRV) systems shift compliance toward continuous, verifiable and auditable data flows, supporting stronger regulatory oversight and improving confidence among investors and downstream manufacturers.

Key developments include:

- **Digital and blockchain-based traceability:** Australia has trialled digital traceability platforms for critical minerals, including systems that combine blockchain, IoT sensors and digital-product-passport architectures to record extraction data, processing parameters and environmental metrics, providing verifiable provenance for material shipments and supporting emerging transparency expectations in global battery and electronics supply chains (Hidayat, 2025a).
- **Automated biodiversity and land-use monitoring:** AI-assisted image recognition is being applied to classify vegetation cover, detect disturbance and track rehabilitation progress using satellite and drone imagery. A project in Queensland, Australia, illustrates how these tools can strengthen environmental oversight where terrain or staffing capacity limits field-based monitoring (Murray et al., 2022).
- **ESG-integrated process optimisation:** Advanced metallurgical and process-control systems increasingly use data-driven and real-time optimisation to reduce reagent consumption, improve recovery and minimise waste generation. Recent work on circular hydrometallurgy

highlights how real-time digital control, mechanochemistry and intensified leaching systems can enhance efficiency and reduce environmental impacts across hydrometallurgical circuits, including those used for laterite processing and battery-metal recovery (Kalupahana et al., 2025). These approaches reflect growing regulatory and industry emphasis—particularly in China and Southeast Asia—on improving efficiency and reducing the footprint of hydrometallurgical operations.

As international buyers—especially in battery, EV and electronics value chains—tighten expectations for traceability and emissions verification, these evidence-based ESG systems are becoming essential for securing market access and meeting procurement requirements. Such continuous verification is increasingly required by downstream battery and EV manufacturers, making digital ESG systems a competitive necessity rather than a voluntary enhancement.

Traceability, circularity, and resource recovery

As demand for critical minerals accelerates across the Asia-Pacific, governments and industries face growing pressure to ensure that materials are sourced responsibly, used efficiently and recovered at the end of life. For countries such as Japan, the Republic of Korea, China and Australia—and for emerging ASEAN battery producers—circularity has become both an industrial priority and a strategic requirement. Digital technologies, including AI, blockchain-based traceability, IoT-enabled tracking and DPPs, now play a central role in building transparent supply chains and supporting the shift from linear resource flows toward more circular systems.

While Section 3 examined how digital tools are reshaping extraction, this section focuses on post-extraction governance: how materials are tracked, processed, reused and recycled, and how policy frameworks can support more efficient and sustainable resource utilisation.

The rise of traceability: From static certification to dynamic data transparency

Traditional certification and assurance schemes have long relied on periodic audits and paper-based documentation. These approaches can be slow and fragmented, making it difficult to meet the increasingly stringent traceability expectations of electric vehicle (EV), electronics and defence manufacturers.

Digital traceability systems introduce a different model:

- **Blockchain platforms** can maintain tamper-resistant records of material origin, processing steps and custody changes.
- **Digital Product Passports (DPPs)** consolidate environmental and material information across the supply chain, improving consistency and auditability.
- **IoT sensors and digital tags** support real-time tracking of material movements from mine to refinery to manufacturing plant.
- **AI analytics** can identify inconsistencies, detect risks and strengthen overall supply-chain assurance.

The Republic of Korea has introduced digital lifecycle-management systems under its *Resource Circulation Act*, enabling battery manufacturers and recyclers to exchange material-flow and recycling data through integrated national platforms (Ministry of Climate, Energy and Environment, 2024). China has also advanced digital transparency requirements, with major battery producers developing data systems to meet the EU Battery Passport's 2027 rules, including carbon-footprint disclosure, material-traceability records and third-party verification standards (Hidayat, 2025b).

In Southeast Asia, Indonesia has already moved toward digital traceability through the expansion of its national Mineral and Coal Information System (Simbara), which now tracks nickel and tin flows from mines to smelters and integrates real-time data on production quotas, permitting and shipments to strengthen oversight and governance (Nangoy, 2024). Traceability systems are also critical for disrupting transnational criminal networks. The United

Nations Interregional Crime and Justice Research Institute (UNICRI) (2025) highlights that opaque mineral supply chains in Southeast Asia are targeted by organised crime for money laundering and illicit trafficking.

Australia's critical minerals and battery industries are also advancing digital reporting and traceability frameworks, with companies increasingly integrating ESG data, emissions information and processing records into digital passports. These systems support access to international markets where verifiable environmental performance and supply chain transparency are becoming mandatory requirements under emerging global regulations.

DPPs and the future of mineral governance

The introduction of the EU Battery Regulation in 2023 (European Union, 2023)—which mandates a Digital Battery Passport (DBP) for all electric-vehicle and industrial batteries placed on the EU market—has become a global reference point for supply-chain transparency. Under this system, producers must disclose structured data on material provenance, carbon footprint, recycled content, processing steps, performance characteristics and end-of-life pathways. These requirements are already influencing regulatory planning and industry practices far beyond Europe, as access to EU markets increasingly depends on the ability to supply verifiable, standardised digital information.

At the international level, the Global Battery Alliance (GBA) has piloted a Battery Passport framework with major industry partners, demonstrating how lifecycle data can be aggregated across borders while maintaining commercial confidentiality (GBA, 2024). These pilots show that digital product-passport systems are not speculative: operational models exist, and the technical foundations for interoperability are already in place.

Industry reporting indicates that battery manufacturers in China are actively preparing for these emerging requirements by upgrading data-management systems, strengthening supply-chain documentation and aligning internal processes with anticipated EU compliance

expectations (Hidayat, 2025b). These developments signal a broader shift across the Asia-Pacific, where firms supplying global markets increasingly recognise that digital traceability is becoming an essential condition for competitiveness rather than a voluntary enhancement.

AI-enabled circularity and predictive waste-stream modelling

Circularity begins early in the value chain, and AI-driven tools are increasingly used to forecast material flows, optimise recovery processes and support closed-loop manufacturing. Several developments across the Asia-Pacific illustrate this shift.

Japan has developed one of the world's most advanced rare-earth magnet and battery-recycling ecosystems. Automated sorting, disassembly and material-characterisation systems are widely used, and national recycling facilities employ digital tools to assess battery condition and optimise recovery pathways (Xu et al., 2016; Antony Jose et al., 2024). China's major battery-recycling enterprises, including Brunp and GEM, deploy automated disassembly, advanced process-control technologies and analytical systems to improve recovery rates of lithium, nickel, cobalt and manganese, strengthening circularity in EV and electronics value chains (He et al., 2024; Ali et al., 2025).

Australia is developing its domestic lithium-ion battery recycling capability, with research and pilot initiatives focused on improving disassembly, separation, and chemical-processing pathways. Current activity includes using advanced technology in dismantling and crushing batteries to produce black mass domestically, with further processing occurring offshore (Commonwealth Scientific and Industrial Research Organisation, 2024). These efforts align with the country's *National Battery Strategy* and growing domestic processing capability (Department of Industry, Science and Resources, 2024).

Finally, AI enhances urban mining by supporting the identification, quantification and prediction of secondary resource flows. Studies show that

machine-learning techniques improve material classification, sorting efficiency and recovery modelling across several Asia-Pacific contexts. In Japan, deep-learning approaches have been used to identify and sort electronic components more accurately, raising correct-selection rates by around 70% in pilot tests (Markazi et al., 2025). Across Australia, research groups apply ML frameworks to optimise metal-recovery processes from e-waste, including parameter prediction for leaching and process modelling (Commonwealth Scientific and Industrial Research Organisation, 2024). Broader regional work using GIS and remote sensing demonstrates how spatial data and ML-based analysis help map urban material stocks, forecast waste availability and guide decisions on recycling system design—laying the groundwork for more efficient, technology-enabled urban-mining strategies (Murthy & Ramakrishna, 2022).

Policy frameworks driving circularity

Circularity in minerals depends on coherent policy frameworks that support efficient material use, recovery and recycling. Several Asia-Pacific economies have established legislative and strategic initiatives that point in this direction:

- **Australia's *National Battery Strategy*** includes measures that encourage traceability, recycling infrastructure and integration of recovered materials into domestic battery value chains (Department of Industry, Science and Resources, 2024).
- **China's *Circular Economy Promotion Law*** embeds lifecycle management, extended producer responsibility and digital monitoring of key waste streams (National People's Congress, 2008).
- **Japan** has long prioritised closed-loop systems for motors, batteries and electronics through its circular-economy and recycling legislation, supported by technology-development programmes and partnerships between government and industry (Ministry of Economy, Trade and Industry, 2023).
- The **Republic of Korea's *Resource Circulation Act*** sets recycling

obligations for designated products and promotes digital and automated systems to improve material recovery (Ministry of Environment, 2023).

- **Malaysia's National Mineral Industry Transformation Plan 2021-2030** outlines a strategic shift toward sustainable mining, emphasising the development of a comprehensive digital mineral inventory to manage resources and prevent leakage (Ministry of Natural Resources and Environmental Sustainability, 2021).
- **ASEAN's Minerals Development Vision** and associated cooperation plans emphasise improved recycling, shared infrastructure and capacity-building to support sustainable resource management across the region (ASEAN, 2025).

A common theme across these frameworks is the recognition that reliable data underpins effective circularity. Without traceable and verifiable information on material origin, composition, processing and end-of-life outcomes, recycled materials struggle to compete with primary production or to satisfy the transparency requirements of global clean-technology supply chains.

Policy pathways for the Asia-Pacific

The accelerating adoption of AI, geospatial analytics, DT and blockchain tools offers the Asia-Pacific an opportunity to support proactive, data-driven and sustainability-centred systems. To capture this opportunity, the region would benefit from policies that enable digital integration, strengthen regulatory capacity, and support regional cooperation.

Build interoperable digital governance systems

Across the region, digital resource-governance tools are expanding—but mostly in isolation. Interoperability is essential for efficient cross-border supply chains, ESG reporting and market access. Because geological and operational datasets are increasingly considered strategic assets, regional frameworks for cybersecurity and secure data exchange will be essential to underpin

interoperability. Governments can advance this by establishing:

- common data structures for DPPs and traceability systems;
- shared metadata standards for geological, environmental and social datasets;
- verification and audit rules for digitally generated MRV;
- minimum requirements for cybersecurity and ledger integrity.

Technical integration must also navigate the complex reality of data sovereignty. As many nations view geological data as a strategic national security asset, protocols are needed to allow for verification and interoperability without requiring the full disclosure of sensitive proprietary datasets. Beyond national security, governance systems must also respect Indigenous data sovereignty, which is increasingly recognised as a foundational principle for ethical resource governance in Australia, Canada and elsewhere. Frameworks such as the *CARE Principles* (Collective Benefit, Authority to Control, Responsibility, Ethics) are becoming vital for ensuring that First Nations communities retain control over geological and environmental knowledge derived from their traditional lands (Carroll et al., 2020). Meaningful progress in this space requires sustained political will, trust, coordination, co-investment and technical alignment.

Embed AI-enabled MRV into regulatory regimes

Regulators can raise environmental standards and improve investor confidence by integrating AI-enabled MRV into permitting and compliance systems. Actionable steps include:

- requiring continuous reporting of water use, emissions and tailings indicators;
- shifting impact assessments and rehabilitation plans to digital formats linked to real-time monitoring;
- using DTs to evaluate mine plans, cumulative impacts and climate risks;
- incorporating verified MRV data into national ESG and sustainability reporting frameworks.

These measures move compliance away from periodic audits toward continuous assurance, transparency, and accountability, thus reducing uncertainty for governments, communities and financiers.

Enable responsible circularity and traceability

As global markets adopt stricter sustainability rules—particularly the EU battery passport and emerging U.S. transparency requirements—Asia-Pacific countries may benefit from policies that support credible, digital-first circularity systems. Priority actions include, but are not limited to:

- developing national traceability platforms compatible with international reporting standards;
- expanding producer-responsibility policies for batteries and electronic waste;
- supporting recycling, refurbishing and recovery innovation through incentives and pilot programmes;
- creating regional recycling and processing hubs linked through harmonised digital standards.

These measures reduce pressure on primary extraction, improve resilience and enable participation in high-value global value chains. It is important for policymakers also to guard against a “digital divide” where high-cost traceability barriers exclude artisanal and small-scale miners (ASM). Inclusive digital platforms that allow smaller operators to participate in formal supply chains are essential to prevent the criminalisation of this vital livelihood sector (United Nations Interregional Crime and Justice Research Institute, 2025).

Invest in people, institutions and digital infrastructure

Digital systems are effective only when institutions can govern them. However, a critical bottleneck remains the regional scarcity of talent at the intersection of geoscience and data science. Building this dual capability is as vital as the technology itself. Stakeholders in the Asia-Pacific can invest in:

- AI, digital MRV and geospatial training for regulators and geological agencies;
- centres of excellence dedicated to digital resource governance and sustainability analytics;
- secure and accessible data repositories that integrate public and private environmental information;
- reliable digital infrastructure in mining regions, including connectivity, data security and sensor networks;
- community capacity-building so local stakeholders can interpret and engage with environmental data.

Strengthened institutional capability ensures that digital transformation benefits communities as well as industry.

Deepen regional cooperation and knowledge exchange

Digital minerals governance is inherently regional. The Asia-Pacific can accelerate progress by expanding:

- partnerships for joint learning and technical assistance;
- regional pilots that test digital MRV, traceability and circularity systems;
- shared training and technology-transfer programmes among geological surveys and regulators;
- multi-country research initiatives on AI-enabled monitoring and environmental modelling;
- coordinated approaches to supply-chain security, sustainability and circular-economy development.

APCTT, through its long-standing work on technology transfer and digital governance, can serve as a convening platform for piloting regional MRV, traceability and interoperability initiatives. Such cooperation positions the region to actively influence global norms and build a more resilient, sustainable mineral future.

Conclusion

A region that can see its mineral systems clearly, measure its impacts honestly and coordinate its responses digitally will be far better placed to navigate the turbulence of the energy transition. The Asia-Pacific is already moving in

this direction. AI-enabled prospectivity models, hyperspectral analytics and subsurface DTs are reducing uncertainty and unnecessary disturbance in exploration. In parallel, automation, IoT networks and digital MRV are turning mines into continuously monitored systems rather than opaque black boxes. At the other end of the chain, traceability platforms, DPP-aligned reporting and AI-supported recycling are beginning to stitch primary production, manufacturing and resource recovery into a more circular whole.

Yet technology alone will not determine whether this transition delivers security, sustainability and justice. The same tools that can democratise access to information can also entrench asymmetries between well-resourced operators and under-resourced regulators, or between advanced economies and smaller states. APCTT and ESCAP are well-positioned to convene the regional architecture needed for this transition—linking standards, capacity building, pilot projects and knowledge-sharing to accelerate the uptake of interoperable digital systems. Technology exists, the policy models are emerging, and the region now has a clear opportunity to move from pilots to scaled, interoperable solutions. If governments and industry treat data as a public good, design digital systems for interoperability from the outset and foreground circularity alongside security, the region can move decisively beyond a narrow focus on extraction and build a more coherent, transparent and equitable minerals governance architecture fit for the demands of the energy transition.

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Remote Sensing Data Analytics for Sustainable Coastal Monitoring in the Asia-Pacific

Case Studies of Malaysian Peninsula Coastal Regions

Saima Khurram¹, Amin Beiranvand Pour^{1*}, Milad Bagheri^{1,2}, Effi Helmy Ariffin¹, Mohd Fadzil Akhir¹, Saiful Bahri Hamaah³

¹Institute of Oceanography and Environment (INOS), Higher Institution Center of Excellence (HICoE) in Marine Science, Universiti Malaysia Terengganu (UMT), 21030 Kuala Nerus, Terengganu, Malaysia

²School of Distance Education, Universiti Sains Malaysia, Gelugor 11800, Pulau Pinang, Malaysia

³National Water Research Institute of Malaysia (NAHRIM), Marine Technology department, 43300 Seri Kembangan, Selangor, Malaysia

Corresponding Author: beiranvand.amin80@gmail.com; beiranvand.pour@umt.edu.my

Abstract

Coastal regions across the Asia-Pacific are increasingly exposed to sea-level rise, erosion, and rapid urbanization, heightening the need for scalable and data-driven monitoring frameworks. This article explores how remote sensing data analytics and deep learning techniques, such as U-Net, DeepLabV3+, and hybrid convolutional models, can enhance sustainable coastal observation and management. By integrating multispectral satellite imagery (e.g., Landsat and Sentinel series) within geospatial and machine learning environments, automated shoreline mapping and multi-decadal change detection can be achieved with high precision. Case studies from Malaysia's Peninsular coast demonstrate how combining AI-based segmentation with the Digital Shoreline Analysis System (DSAS) provides actionable insights into erosion, accretion, and human impacts. The study underscores how AI-powered satellite informatics can support coastal resilience, adaptive management, and sustainable resource governance across the Asia-Pacific region.

Introduction

The coastal areas of the Asia-Pacific are some of the most dynamic and vulnerable natural environments in the world, experiencing unprecedented threats in the form of a climate-induced sea-level rise (Noor et al., 2022), intensified tropical cyclones (Kopf et al., 2025), and human-induced pressures related to intensive urban and economic development (Arbinolo et al., 2021). According to the Intergovernmental Panel on Climate Change (IPCC), the rate of mean sea level rise has been increasing globally. It has deep consequences on coastal cities and ecosystems that are at a low

altitude (IPCC, 2021). Countries in the Southeast, such as Malaysia, Indonesia, Thailand, and the Philippines, face a compounded risk, such as coastal erosion, saltwater intrusion, loss of protective mangroves, and damage to critical infrastructure (Hens et al., 2018). Although useful, traditional in-situ methods of monitoring prove to be spatially sparse, expensive to maintain, and have limits on the ability to capture the large-scale changes and long-term variations that take place over long coastlines (Garcia-Soto et al., 2021; Kennedy, 2013). This data gap inhibits the capacity of policymakers and planners to make sound decisions towards sustainable coastal management. As a result,

an urgent requirement exists regarding alternative, consistent, and comprehensive monitoring systems.

Satellite remote sensing has transformed the field of environmental monitoring through the provision of synoptic, multi-temporal, and freely available data at different spatial and temporal resolutions (Amitrano et al., 2021). Mission archives such as Landsat (since 1972) and Copernicus Sentinel (since 2014) provide decades of imagery, which allows examining traditional shoreline transformation. Nevertheless, manual extraction of shorelines out of such large data is meticulous and subjective. The paradigm shift has been initiated by the incorporation of advanced data analytics, especially deep learning (DL). U-Net and DeepLabV3+ are convolutional neural networks capable of processing the accurate segmentation of coastline on complex satellite images, which allow much better efficiency and accuracy than manually tackling the problem (Khurram et al., 2025).

Coastal challenges in the Asia-Pacific

A digital horizon: coastal resilience at the crossroads

The Asia-Pacific coastal areas are leading the frontier of global environmental change with mounting challenges of climate-induced sea-level rise, storm intensity, and unsustainable coastal development. According to the state of the climate in the South-West Pacific 2023 report by the WMO (World Meteorological Organization), from January 1993 to May 2023, the global mean sea-level rise (GMSL) was approximately $3.4 \text{ mm} \pm 0.3 \text{ mm/year}$. This is increased by land subsidence of major deltas in the Mekong (Viet Nam), Irrawaddy (Myanmar), and Chao Phraya (Thailand) due to compaction of

the river sediment and groundwater extraction (Becker et al., 2024). The combination of sea-level rise and land subsidence enhances the relative sea-level rise at the site, which in turn aggravates the rate of coastal flooding, erosion, and saltwater intrusion (Restrepo-Angel et al., 2021).

Recent assessments have estimated that coastal flooding is already inflicting approximately US\$26.8 billion of loss every year in Asia and the Pacific, which is expected to increase to USD144-198 billion by 2050 unless there is significant adaptation (Monioudi et al., 2025). In urban deltas (like those in Bangladesh, Viet Nam, and Indonesia) where the sea-level rise is coupled with subsidence, tens of millions of the population are at a high risk of displacement (IPCC, 2022) (Figure 1). Human-driven subsidence, in addition to sediment starvation and coastal erosion, has raised the risk of relative sea-level rise significantly and led to the loss of vast territories over the past few decades in the Mekong Delta alone (Baldan et al., 2025).

The danger of extreme weather also contributes to such risks. The Asia-Pacific region is one of the most affected areas in the world by tropical cyclones,

and in warmer ocean environments, the storms are expected to get stronger and more precipitous (Chen et al., 2021). The most notable examples of such events include Typhoon Rai (2021) in the Philippines and Cyclone Mocha (2023) in the Bay of Bengal, which demonstrate the rising destructive power of tropical cyclones, especially when they are combined with high base-level sea levels and lead to compound coastal-flooding dangers (Bevacqua et al., 2020). Moderate storm surges can be devastating to coastal defences and drainage systems, coupled with heavy rainfall or even when coupled with a high tide. According to the Asia-Pacific Disaster Report 2023 (ESCAP, 2023), the vital factors contributing to overwhelming exposure to flood risk are climate extremes and a fast pace of coastal urbanisation. There is also a threat to coastal buffer ecosystems, like mangroves, although Southeast Asia is home to one of the highest mangrove forest proportions in the world. These mangrove ecosystems are disappearing at an incredibly fast pace due to the expansion of aquaculture, land reclamation, and pollution (Friess et al., 2019). In the Global Mangrove Watch data, an overall loss of about 5,245 km² of mangrove forests was experienced during 1996-2020,

and hotspots of the loss were found in Southeast Asia (Indonesia, Malaysia, Myanmar) (Bunting et al., 2022). Confirmed by NOAA (National Oceanic & Atmospheric Administration) (2024), the current global coral bleaching (since the beginning of 2023) has already affected over 80 per cent of the world's coral reefs, greatly affecting their ability to provide natural protection of the coastline.

Most of the megacities in the region, including Jakarta, Manila, Bangkok and Ho Chi Minh City, which are built on reclaimed or submerged land behind crumbling flood-defences, are estimated to be chronically flooded in moderate emission scenarios (Ruan et al., 2024). Some areas of Jakarta, in particular, are sinking up to 3-10 cm per year, which is a more immediate risk than world-scale sea-level rise (Abidin et al., 2015). The process of urbanization and the increase of impervious surfaces decrease the infiltration and drainage capacity of the soil and increase flood peaks during monsoon rains (Yosua et al., 2024). Another hazard that is serious but less evident is saltwater intrusion. The impact of a rise in sea level, coupled with decreased upstream discharge and excessive groundwater extraction, allows

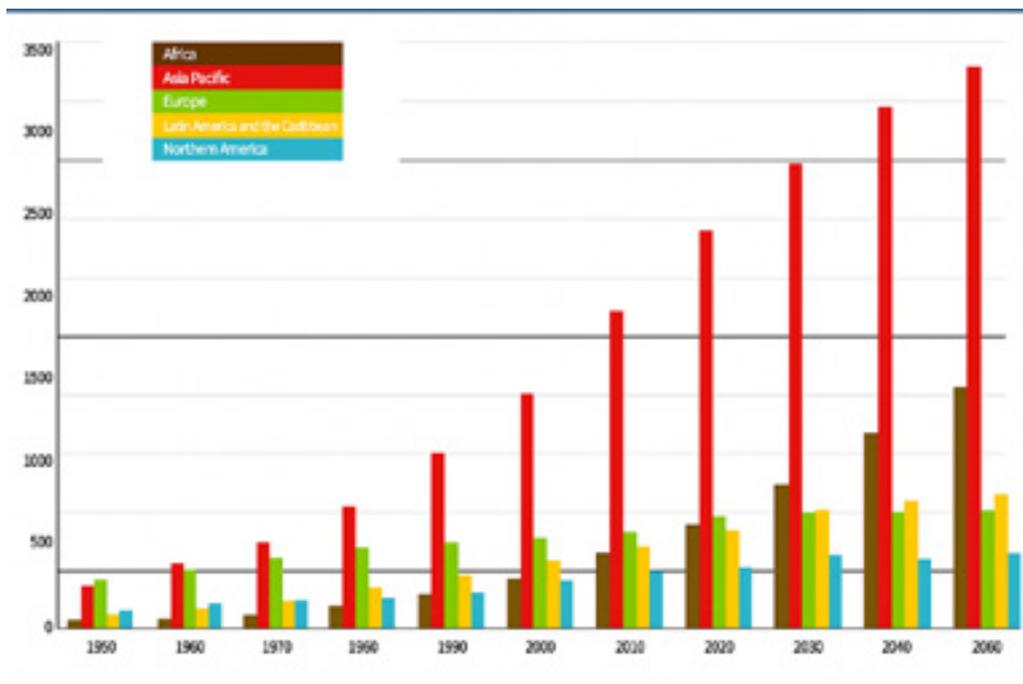


Figure 1. Projected population growth for the Asia-Pacific region from 1950 to 2050 (by Rollins, A. M. 2019).

estuaries and aquifers to become more vulnerable to groundwater. This is already affecting the rice production in the Mekong Delta in Viet Nam (IPCC, 2022) and the water/ soil quality in coastal Bangladesh (Ashrafuzzaman et al., 2022). It is stated with high certainty in IPCC (2022) that in the continued warming of low-lying coastal areas like deltaic plains, there is a growing risk of salinization, especially when the elevation of the land is low and the sediment input is inadequate, which hinders adaptation. In spite of a great level of scientific development, there are still large gaps in data and monitoring. In most of the countries in the region, observation capabilities are still low with sparse networks of tidal gauges, intermittent subsidence surveillances, and limited to rough height measurements that limit accurate coastal risk evaluation (WMO, 2023). Additionally, it is mentioned in the Asia-Pacific Disaster Report, 2023 (ESCAP, 2023) that the elimination of data, model, and early warning systems gaps is necessary to make operational the anticipatory coastal planning.

The fragile pulse of the Malaysian peninsula

The east coast coastal belt, Kelantan-Terengganu-Pahang, is an ecological and economic hotspot of Peninsular Malaysia, as well as the southern belt of Johor. They support fisheries, tourism, agriculture, and biodiversity. Yet they are the locations of sea-level rise, mangrove loss, estuarine flooding, and saltwater intrusion. These problems do not spread in equal measure - neither do their solutions. What is required is a spatially intelligent, real-time way of diagnosing, identifying, and guiding interventions. This is where AI works with satellites.

The Asia-Pacific region is a considerable bearer of coastal hazards in climatic conditions. WMO reports that the rate of rise of sea levels along the coasts of the Pacific and Indian Ocean in Asia is currently higher than that of the world, posing a threat of coastal flooding (WMO, 2024). According to the State of the Climate in Asia 2023 report, the hydro-meteorological hazard events (mostly

floods and storms) affected over 9 million people in 2023 (WMO, 2023). The spatial distribution of the patterns of coastal risk is different in the Malaysian Peninsula, as shown in Figure 2, which plots the National Coastal Vulnerability Index (NCVI). It reflects very-high vulnerability regions (in red) that are focused on the western shores of Selangor and Kedah, and the eastern shores of Kelantan and Terengganu, which proves the skewed distribution of exposure to erosion and flood hazards across the peninsula (Amiruddin, 2023).

The long coastline in the Peninsula, which borders the Strait of Malacca and the South China Sea, is very susceptible in Malaysia. Key challenges include:

- Erosion: Malaysia has a considerable portion of its coastline that has been identified as eroding and poses a danger to communities, agriculture, and tourism infrastructure.
- Sea-Level Rise: It is projected that it will increase further, and the threat of inundation and freshwater aquifers being contaminated with saltwater will persist.

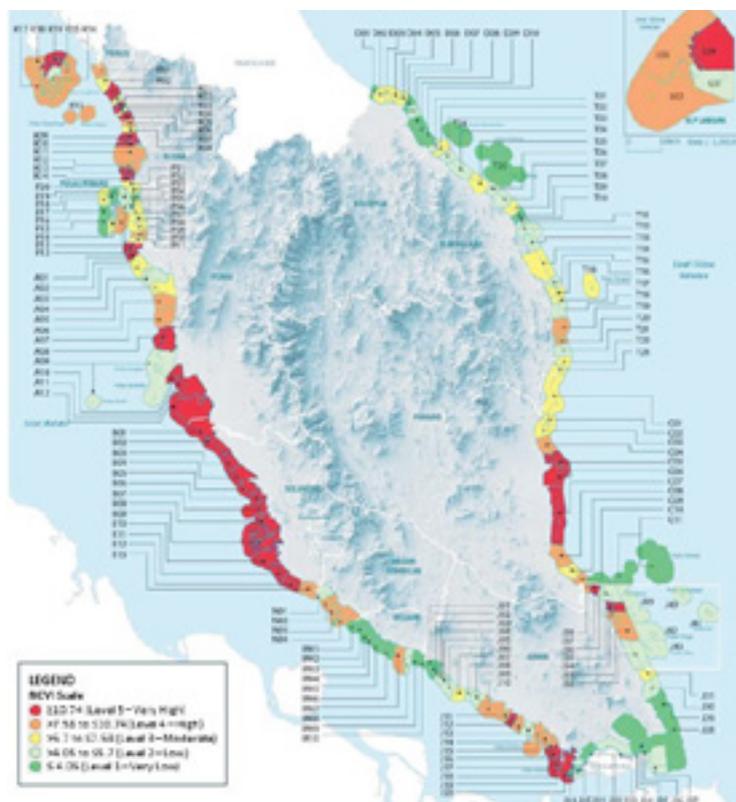


Figure 2. National Coastal Vulnerability Index (NCVI). Malaysia (by Amiruddin 2023).

- **Land Use Change:** Rapid urbanisation, agricultural and aquaculture deforestation, development of ports and other infrastructures have greatly changed the sediment transport regimes and decreased the natural coastal buffer, including mangroves (Billah et al., 2023).
- **Extreme Events:** Monsoon floods and tropical storms are likely to happen in the region and result in rapid and drastic changes in the coastal areas.

The accruing effects of these factors portray the urgency of high-resolution monitoring systems, frequent, and accurate monitoring systems to provide information on adaptation and mitigation plans.

Evolution of remote sensing in coastal monitoring

Historical context

Remote sensing as a science has transformed into a pillar of coastal science since the introduction of Landsat 1 in 1972, and it started as an experimental procedure. The earlier spectral algorithms, like the Normalized Difference Water Index (NDWI), were able to perform simple land-water mapping but failed in complicated settings that were hit by turbidity, vegetation, and shadowed buildings. As the fields of big data, machine learning, and deep learning, and cloud computing have advanced, the field has passed through another stage of multi-sensor integration, significantly enhancing the spatial accuracy and time continuity of monitoring the dynamics of the coasts.

Optical, radar, and altimetric sensors are currently integrated into an interoperable global system. Sentinel-2 is (10 and 20 m spatial resolution) multiple-spectral imagery of the shoreline and habitat, whereas SAR activities like Sentinel-1 and ALOS/PALSAR can also offer coverage at all times. The revolution of measurements of sea-level anomalies, tides, and land subsidence has been brought by altimetry missions (TOPEX/Poseidon, Jason series, Sentinel-6 Michael Freilich) and laser altimetry

measurements by ICESat-2, playing an important role in flood-risk and coastal-planning research.

Recent research (ESA, European Space Agency, 2020) emphasizes the significance of harmonised, cross-sensory data that amalgamate optical reflectance, radar backscatter, and elevation data into single structures - transforming the disaggregate data into a coherent understanding of shoreline change, sediment transportation, and risk of inundation. The cloud-computing revolution by the use of Google Earth Engine and Copernicus Data Space Ecosystem can now process petabytes of imagery over the world in long-term and near-real-time. This combination of multi-sensor observation and cloud analytics has changed coastal monitoring into a planetary observatory, which observes the dynamic connection between land, sea, and society.

Deep learning implementation at shoreline analytics

Deep learning is a paradigm shift from rule-based to data-driven analysis. CNNs (Convolution Neural Network) are able to learn spatial hierarchies of features because they can be used to classify complex coastal scenes better than threshold-based algorithms. Zhao et al. (2022) and Khurram et al. (2025) showed that U-Net and DeepLabV3+ are more effective in accuracy and generalizability than traditional classification.

Core models

U-Net: U-Net possesses a contracting-expanding architecture with skip connections that results in the high localization accuracy of the land-water interface.

DeepLabV3+: It uses atrous (dilated) convolution and spatial pyramid pooling, which allows it to capture multi-scale contextually relevant information; hence, it can work across varied coastal morphology.

Hybrid models: CNNs further improved by Conditional Random Fields (CRFs) or attention mechanisms yield more classification edges and less misclassification.

Case Study: multi-decadal shoreline change monitoring in Kelantan, Malaysia

Kelantan had the most active and erosive behavior along its coastline of the four eastern and southern states of Malaysia over the 34 years. The shoreline dataset derived by U-Net and processed with the help of DSAS displayed extensive and intense retreat and localized areas of accretion (Figure 3). The highest linear regression rate (LRR) of erosion was around -64.9 m/year around the Tumpat estuary near Kota Bharu, where erosion was sustained due to the interaction of monsoonal waves, strong littoral drift, and fluvial flooding (the most recent was the 2014 flood).

Though erosional trends prevailed, Kelantan did show some examples of high accretion rates, up to +47.6 m/year especially in areas of sheltered embayments and depositional conditions caused by large sediment loads in the Kelantan River system. The entire Net Shoreline Movement (NSM) ranged between approximately 1,885m (Movement landward) and +1,629m (Movement seaward) and indicated a great deal of variability along the coast. The shoreline moved by over 1.5-1.9 km in various transects, and this revealed both erosion and deposition of sediments (Figure 4). As shown in Table 1, key coastal parameters, satellite sensors, and deep-learning methods effective in the Asia-Pacific region is summarized.

The spatial analysis suggests hot spots of erosion occur at the mouths of the major rivers and bare coastal areas, and the accretion on the coast prevails in the sediment-laden or structurally protected sections. The results prove that the Kelantan shoreline is subject to the products of the interplay of high-energy monsoonal processes, riverine discharges of sediments, and episodic flooding, which makes it highly vulnerable to anthropogenic and climatic disturbances. In general, the deep learning-based DSAS system was able to adequately model these fine-scale transitions to offer a strong quantitative foundation to define essential erosion areas that

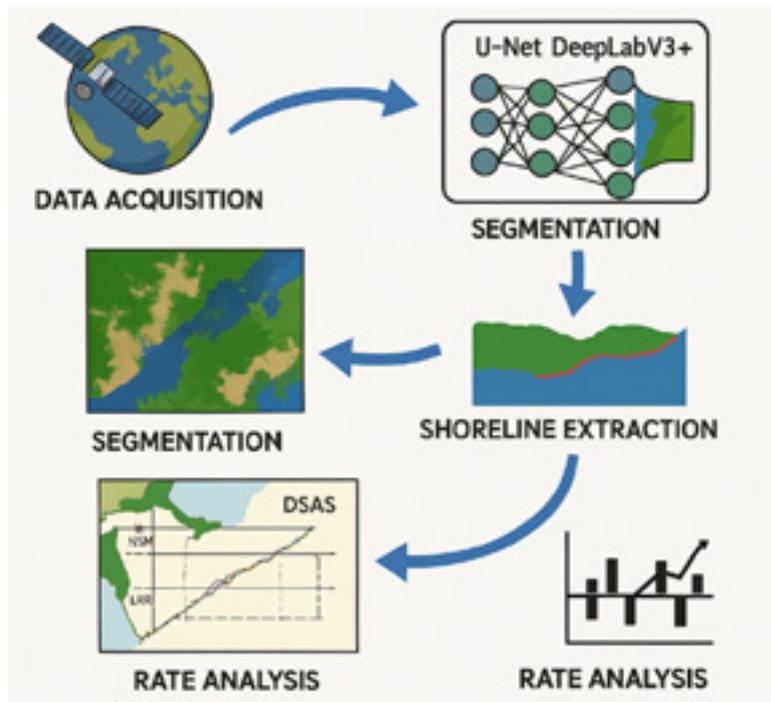


Figure 3. Schematic workflow of the application of remote sensing multi-decadal shoreline change monitoring in Kelantan, Malaysia.

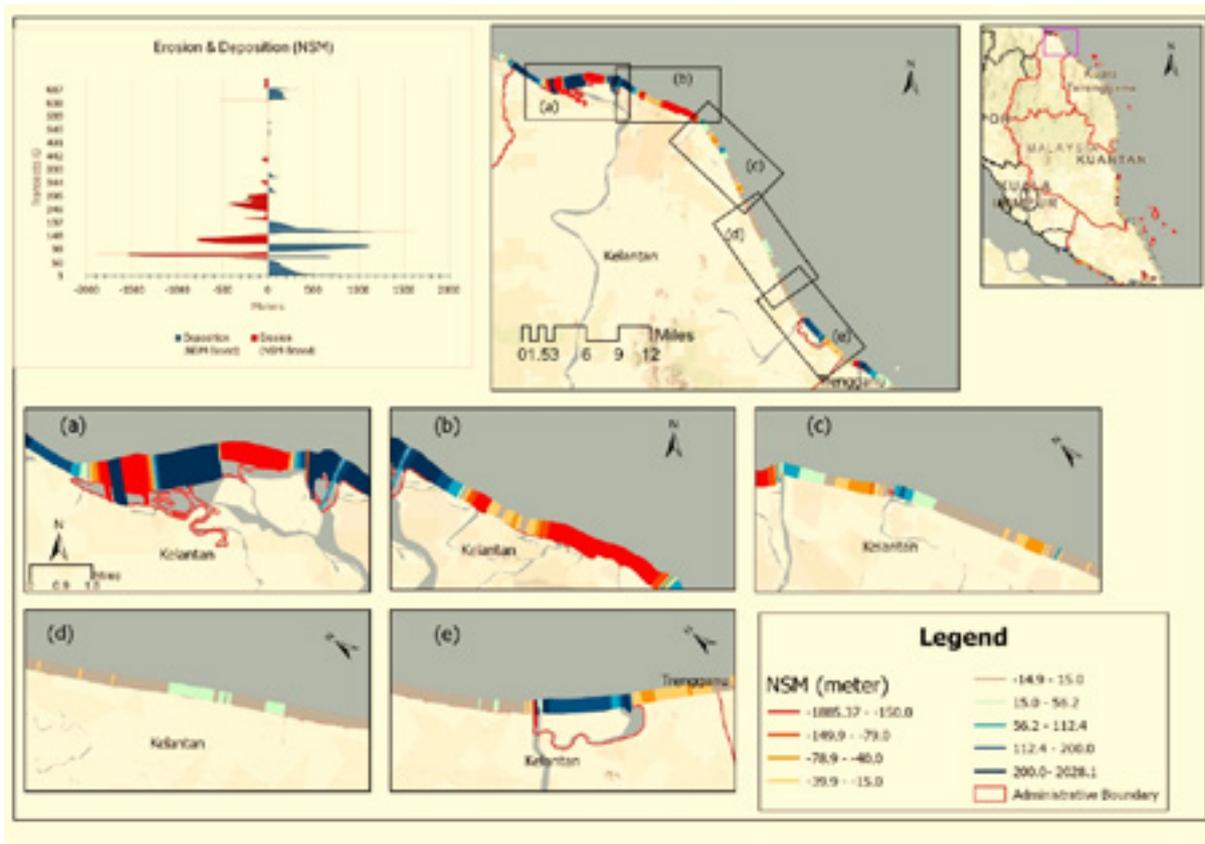


Figure 4. Spatial distribution of shoreline change analysis in Kelantan state: NSM results (1990 - 2024) (by Khurram et al. (2025)).

Table 1 summarizes key coastal-monitoring parameters, the satellite sensors commonly applied, and deep-learning approaches that have proven most effective in the Asia-Pacific context.

Monitoring Parameter	Satellite Sensors / Products	Data Analytics & Deep Learning Approaches
Shoreline Position & Change	Landsat 5-9, Sentinel-2, Sentinel-1	U-Net, DeepLabV3+ for segmentation; DSAS for change rate calculation
Coastal Erosion & Accretion	Multi-temporal composites from the above missions	CNN-based change detection; DSAS (EPR, Linear Regression Rate)
Land Use/Land Cover (LULC) Change	Landsat, Sentinel-2	Random Forest, Support Vector Machines (UI Din and Mak, 2021); U-Net for semantic segmentation
Sea Level Rise & Inundation	Satellite Altimetry (TOPEX/Jason series, Sentinel-3, Sentinel-6)	Integration with Digital Elevation Models (DEMs); ML for flood risk modeling
Mangrove Forest Extent & Health	Sentinel-2 (Red Edge bands), Landsat	Spectral Indices (NDVI, EVI); CNN models for species classification and health assessment
Urban Sprawl & Impervious Surface	Landsat, Sentinel-2, Very High-Resolution (VHR) data (e.g., WorldView)	Spectral Unmixing; DeepLabV3+ for precise urban feature extraction

should be given priority when developing future coastal protection and adaptive management projects.

Coastal management and wider applications

Mapping risk and enhancing resilience

The use of AI-based geospatial analytics can reveal the interrelationship of coastal risks in terms of interrelating climatic, hydrological, and human components. The overall impact of the stresses of the environment is identified across the researched coasts, as processes of coastal erosion, habitat loss, flooding, and salinity intrusion are interdependent.

Hotspots in erosion: For a long time, the shoreline has been steadily receding, in some cases several meters a year, in many vulnerable areas, which stresses the need to focus on specific adaptation and sediment management.

Degradation of the ecosystem: The reduction of the mangrove cover and fragmentation of the habitats highlight the

necessity to adopt nature-based solutions where the restoration of the ecosystem must be incorporated as a component of climate protection.

Flood exposure: A Predictive model of floods assures that intact natural buffers can cut off the extent of inundation by half, supporting their usefulness in safeguarding livelihoods.

Salinity intrusion: The inland movement of saline intrusion into agricultural deltas is an indication of growing water and food security concerns rising sea levels.

Collectively, such insights can prove that AI-enabled remote sensing is superior to conventional monitoring it is a decision-support and early-warning system. This will help the nations to develop their robust and resilient coasts in the long term, as it will enable them to develop predictions and governance of the coasts.

From data to decisions: the governance edge

The AI-satellite framework has its value of transformation based on its policy translatability. Scientific knowledge is made into an action plan:

- Zoning and setback control based on real-time coastal-risk overlay based on AI classification and DSAS change indicators.
- Restoring mangrove corridors that give the greatest ecological and socio-economic benefits through rehabilitation (Alongi et al., 2023).
- Community dashboards: Community dashboards that combine IoT sensors for tides and Earth-observation data to keep people informed of floods;
- Evidence-based climate-adaptation policy, and use of infrastructure investment as spatially justified risks evaluation (ESCAP, 2024; WMO, 2025)

This is an adaptive, predictive, and participatory paradigm of digital environmental governance that fills the old dichotomy between information creation and operationalization of the decisions. Achieving this is possible by integrating machine intelligence into national coastal-management processes, where Malaysia is able to shift to engineering in a proactive mode, and resilience planning.

Building resilient shores: Malaysia's evolving coastal strategy

To institutionalize this data-driven resilience model, Malaysia should undertake these coordinated reforms:

1. **Establish a national coastal intelligence unit** that consolidates AI-remote sensing analytics within federal and state planning agencies, delivering dynamic dashboards for shoreline monitoring and zoning alerts (Khurram et al., 2025).
2. **Risk-informed development**, which entails, before issuing a permit to any coastal development, that all aquaculture, tourism, and infrastructure must take into account certified AI-generated erosion and flood overlays (ES-CAP, 2024).
3. **Invest in nature-based infrastructure**, escalating mangrove restoration and seagrass restoration as cost-effective climate shields that stabilize sediments, reduce waves, and enhance carbon sequestration (Alongi, 2020; UNEP, 2024).
4. **Empower local data stewardship** coaching communities in the coastal areas in conducting citizen-science validation and in engaging local people in participatory mapping with access to open-source applications such as Google Earth and QGIS (Fraisl et al., 2022).
5. **Regionalize the framework across ASEAN**, expand the Malaysian AI-satellite model to the entire Southeast Asian coast, and help in developing common resilience principles and cross-border sediment-management plans (ADB, Asian Development Bank, 2024).

Coastal futures, digitally defended

In the Anthropocene, defending coasts is less about concrete and more about cognition. The integration of artificial, spatial, and ecological intelligence enables nations to anticipate, rather than

merely react to, environmental transformation. Malaysia's leadership in operationalizing this AI-remote sensing model could redefine coastal management across the Asia-Pacific, where scientific foresight becomes the cornerstone of sustainability. The satellites are already in orbit; the algorithms, in code. What remains is the collective will to turn intelligence into action (Horton et al., 2020).

Conclusion

This study demonstrates that remote sensing data analytics offers an effective, scalable solution for sustainable coastal monitoring in the Asia-Pacific, as shown in the Malaysian Peninsula case studies. By integrating multi-temporal satellite imagery with deep learning techniques, accurate shoreline and land-water dynamics were mapped to reveal patterns of erosion and accretion. The approach enhances monitoring efficiency, supports climate-resilient coastal management, and aligns with global sustainability goals. Overall, remote sensing-based analytics provide a robust framework for data-driven decision-making toward protecting vulnerable coastal environments. Coastal agencies should integrate remote sensing-based monitoring into routine management frameworks, combine optical and radar data for improved accuracy, and develop open-access geospatial platforms to support community and policy-level decision-making for long-term coastal sustainability.

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International Experience of Hydrogen Energy Financing

Yarygina Irina*, Arlashchenkova Ekaterina

Economy and Banking Department

Moscow State Institute of International Relations (MGIMO) under the Ministry of Foreign Affairs of the Russian Federation, Russian Federation
76, Prospect Vernadskogo, Moscow, Russian Federation, 119454

Email: jiz4@yandex.ru

* Corresponding author

Abstract

The paper examines international experience in hydrogen energy financing, following the rapid expansion of the global hydrogen market, fuelling interest in hydrogen energy elsewhere. The purpose of the paper is to determine the sources of financing and features of the financial mechanisms of hydrogen programs aimed at boosting economic growth and combating climate change. The study provides the development preconditions of the global hydrogen market, identifies the factors of investment attractiveness of hydrogen projects, and presents the mechanisms for their financing. The analysis reveals the predominance of public financing and multilateral global initiatives underpinning the emerging hydrogen market. The results of the paper determine the methods of risk management for hydrogen energy projects and reveal the experience of China, suggesting the economic viability of hydrogen projects. The paper reveals the necessity for comprehensive risk management of hydrogen projects and concludes on the necessity of expansion of financing through the participation of institutional investors in the programs for the new types of energy production that are safe for the global environment.

Introduction

Research displays the soar of the contemporary hydrogen market, followed by skyrocketing investments in hydrogen projects. In 2023, global accumulated investments in the field reached 29 billion USD, with the forecast indicator being assessed at the level of 320 billion USD till 2030, the International Energy Agency (IEA) reckons (IEA, 2024).

Increased investments in the hydrogen industry require a profound understanding of international practice, sources of financing, analysis of the factors influencing investment decision-making and public development programs, including stimulus and subsidies.

Practice suggests that decarbonization of the global energy balance is the driving force of facilitating renewables as a substitute for fossil fuels, which account for a major part of greenhouse

emissions in the energy sector, agriculture and industrial production International Renewable Energy Agency (IRENA, 2022). In view of the following, it is worthwhile to harness the potential of hydrogen in hard-to-abate sectors, such as aviation, marine and rail transport, in remote areas. Besides, wider integration of hydrogen into energy-consuming industries of metallurgy (direct reduced iron) and chemicals (ammonia, methanol and plastics) has the potential to fuel economic growth. Raising investment in the hydrogen industry is crucial for advancing hydrogen technologies and hydrogen commercialization.

Investment attractiveness factors

International research suggest that hydrogen projects are associated with

high risks, with less than 10% of their total amount reaching final investment decisions, as indicated in the International Federation for Information data.

Key factors reducing the investment attractiveness of hydrogen projects are as follows:

1. Immaturity of the hydrogen market, lack of clarity, unstable demand and limited utilization, which complicates long-term marketing policy;
2. Absence of business practice and expertise in contiguous industries;
3. Absence of commercial ties and trade routes;
4. Capital intensity and high sensitivity to cost of financing fluctuations amidst macroeconomic turbulence;
5. Absence or insufficient infrastructure; and
6. Innovations and high technological risk triggering delays in delivery or project budget deficits.

Key sources of financing for hydrogen projects (HP) are provided by banks, intergovernmental financial institutes, institutional investors, joint-stock companies, including debt financing, grants and mixed financing (OECD, 2024).

Standard HP's funding mechanisms

According to OECD data, Bank lending and public grants account for more than half of hydrogen projects' financing, indicating the emergence of the hydrogen industry. Current financial structure suggests heavy governmental support and scarce private investment, whose share makes up only 15% of the total investments, well behind the public finance. In the context of the present research, bank lending shall be an umbrella term for financing from state-owned banks, commercial banks, international development banks and international organizations. A large share of bank lending is compiled by multilateral development banks (MDBs), export credit agencies (ECAs), international

Table 1: Global financial initiatives for hydrogen energy

Initiator	Project
World Bank	Scaling Hydrogen Financing for Development, Green Hydrogen Support Program, Hydrogen for Development Partnership, IBRD PROBLUE
African Development Bank	Sustainable Energy Fund for Africa (SEFA), Alliance for Green Infrastructure for Africa
Asian Development Bank	ADB Institute, Green Hydrogen Innovation Center
International Development Bank	Green Hydrogen Bank
European Investment Bank	Regional Integration of the Green Hydrogen Chain
International Energy Agency (IEA)	Clean Energy Ministerial, Global Ports Hydrogen
Green Hydrogen Organization (GHO)	Developing Finance Priority Actions
International Renewable Energy Agency (IRENA)	Energy Transition Accelerator Financing Platform Coalition
Organization for Economic Co-operation and Development (OECD)	Clean Energy Finance and Investment Mobilization
United Nations Industrial Development Organization (UNIDO)	Green Hydrogen Financing, Regional Integration of the Green Hydrogen Supply Value, Global Program for Hydrogen in Industry
World Economic Forum (WEF)	Acceleration Clean Hydrogen Initiative

(Source: Composed by the authors based on (OECD, 2024).)

economic organizations and specialized institutions. Approximately 75% of financial initiatives for hydrogen energy are led by international development banks and international organizations, OECD assesses (Table 1).

The enlisted financial institutions secure strategic financing for the emerging hydrogen industry, mitigating project risks and catalysing private capital. Apart from that, comprehensive tailor-made analysis and sector-specific expertise aligned with peculiarities of national hydrogen strategies are crucial for creating a benign investment climate for hydrogen projects (IRENA, 2024).

Public grants have come to be one of the most widespread financial practices for hydrogen projects, implying financial resources from the government in exchange for a share in a project. Public

grants aim at reducing hydrogen cost through partial compensation for capital expenditures, which account for up to 40% of the total costs, and thus, boosting hydrogen economic competitiveness. Yet, public grants may hamper the economic efficiency of a renewables project, the World Bank reckons (World Bank, 2024). Governmental intervention and supervision enhance efficiency of financial input. Yet, heavy governmental regulation of the project poses a threat to management efficiency.

Investors of hydrogen industry

It is worth mentioning the diversity of numerous hydrogen industry investors (Table 2).

International research (OECD, 2024) suggests that China has succeeded in the commercialization of hydrogen in transport and other areas, which leads us to the hypothesis that hydrogen projects can achieve profitability at the stages of production, transport and distribution.

Expenses itemizing of 3 projects in China (Climate Policy Initiative, 2024) was studied to reveal the key characteristics of the financial performance of similar projects. The calculations suggest that the average cost of equipment is 65 thousand USD, operational costs (OPEX) - 2 million USD, construction costs – 50 thousand USD, and financing – 10 million USD. The average financial indicators are provided in Table 3.

The data provided demonstrates that borrowed capital, represented by bank lending, is the key source of financing.

Table 2: Hydrogen industry investors and their role

Investor	Example	Role
Government bodies	State-owned companies	Both lender and shareholder
State-owned and commercial banks	State bank of India, HDFC (India), ICICI (India), Kreditanstalt für Wiederaufbau (Germany), Bank of Baroda (India)	Both lender and shareholder
International financial organizations and development banks	World bank, European Hydrogen Bank	Lender
Investment funds	Clean H2 Infra Fund, Hy23, Environmental Fund of Namibia, Amazon's Climate Pledge Fund	Both lender and shareholder
Insurance companies	Marsh (USA), Munich Re (Germany)	Lender
Industrial conglomerates	Japan Steel Works (JSW), ACWA Power (Saudi Arabia), Industrial and Port Complex of Pecém (CIPP) (Brazil), Scatec (Norway), Lhyfe (France), Posco Holdings (Republic of Korea) etc.	Shareholder

(Source: Composed by the authors based on OECD, 2024; UNIDO, 2024; GHO, n.d.; Climate Policy Initiative, 2024; IEA, 2021)

Table 3: Financial indicators of hydrogen projects in China

Indicator	Meaning
Discount rate	8%
Equity financing/Debt financing	30%/70%
Interest rate	5%
Income tax rate	20%
Operation period	20 years
Payback period	5 years
Internal revenue rate (IRR)	15,38%

(Source: Composed by the authors based on (Taghizadeh-Hesary F. et. al., 2022).)

A large share of bank lending pinpoints high sensitivity of financing to interest rate fluctuations. The global average discount rate for renewable energy projects is 6-10%; meanwhile, in China, it remains at the rate of 8%. Interest rate and income tax rates are 5% and 20%, respectively (Yarygina I. et.al., 2023). Capital intensity of hydrogen projects determines their high sensitivity to income tax fluctuations. Operation and payback periods are calculated as 20 and 5 years, respectively (Taghizadeh-Hesary F. et. al., 2022).

The average IRR for focus groups in China makes up 15,38%, well above the discount rate of 8% in the amount. (IRENA, 2024). Thus, the conducted research proves the economic viability of hydrogen projects.

Institutional investors as a factor in hydrogen energy financing

Actually, institutional investors are defined as special financial institutions

that manage savings in the interests of private investors, maintain an acceptable level of risk, with the intent of obtaining the maximum investment return, backed by the terms and conditions of an agreement.

Institutional investors comprise collective investment institutions, pension funds, and insurance companies and participate in the process of direct (on their name) or indirect (as agents) financing and perform the following economic functions:

- they are responsible for the efficient distribution of financial resources among economic entities;
- accumulate savings of the population and reduce transaction costs;
- diversify risks and participate in environmental protection.

The term “institutional investors” is interpreted in the Russian economic literature relatively broadly and includes both non-deposit and deposit intermediaries. Some authors limit themselves to listing most financial intermediaries as institutional investors. At the same time, experts of the Bank for International Settlements (BIS) define insurance companies, pension funds and various collective investment schemes as institutional investors. In a number of studies of Russian economists, the institutional investors are considered as non-bank financial intermediaries who invest funds, which are accumulated during their activity, in financial market instruments in order to gain profit.

We consider that retail banks cannot be classified as classic institutional investors, since their activity is related to attracting deposits and placing them in loans, while institutional investors are mostly focused on long-term investments, required for hydrogen projects.

It is worthwhile mentioning that the term “collective investment” is also widely used in the Russian Federation and relates to non-state pension funds and specialized companies. Sometimes, so-called collective investors are involved in raising funds from a large number of individuals for their subsequent investment as institutional investors. The general approach of financing the hydrogen economy does not prevent from using different forms of financing, but our attention is specifically drawn to institutional investors and their possible contribution to hydrogen energy financing.

Having a wide range of investment options, institutional investors do not limit themselves to financial assets available on domestic markets. The increasing efficiency of information technologies and the easing of regulatory restrictions have contributed to their global activity. The trend towards global investments and integration of national capital markets into the international context has

accelerated investments in foreign assets (local currencies) and purchase of securities, depositary receipts, shares of investment funds, etc.

It is worthwhile mentioning that Russian pension funds invest up to 30% of their assets in social projects. It is important to note that green energy and new technologies projects are considered to be of social significance globally. Thus, the origin of hydrogen projects itself accelerates the cross-border supply of services, provided by institutional investors and gives way to life insurers and pension funds to accumulate international resources for sustainable economic development locally and globally.

The contemporary research shows that the main international trend manifests itself in developing resources for green projects and requests improvement of hydrogen production and environmental protection. For example, the International Energy Agency (IEA) estimates that the prevention of major climate changes by reducing carbon emissions requires an additional \$500 billion to be invested annually, in addition to the \$10.5 trillion of investments in 2010-2030. At the same time British Petroleum experts consider that in the near future, approximately two thousand hydroelectric power plants will operate worldwide (IEA, 2024). It is worthwhile mentioning that electrolysis of water is one of the ways to produce hydrogen. We should consider it for strategic development and planning.

Actually, institutional investors have accumulated a significant amount of capital and a variety of instruments well known to financial professionals that can help to smooth out the consequences of a significant slowdown in global economic growth and ensure energy production. Acceleration of institutional investors’ activity will be a positive trend that will contribute to the green energy transition and sustainable development.

Due to financial flexibility and mobility, institutional investors play a significant role in the global financial architecture, which is confirmed by their cooperation with supranational institutions. Management of the global capital flows and contributes to energy production, as well as environmental policy implementation, changes the role of institutional

investors in the global economy, turning them into systemic financial institutions. Actually, institutional investors control more than 80 percent of the US stock market capitalization. At the same time, private investors, meeting a policy of strategic investments, control 10 percent of the UK market. It means that institutional investors possess control over business (Fitch, 2023).

The results obtained allowed us to draw the following conclusions. There are several trends for institutional investors in the hydrogen economy: growing competition, passive portfolio management strategies, and demand for new investment instruments to set up securities portfolios.

The trend of growing competition is supported by increasing regulatory requirements for the volume of funds and structure of assets, as well as the constant growth in the number of mutual funds, offering similar services to the population in different sectors of the economy.

There are also some specific challenges for each type of institutional investor that are determined by specific market activity of insurance companies, non-state pension funds, and collective investment institutions. The main challenge for the insurance companies is the reduction of insurance schemes (tax optimization) and the non-state pension funds activity. As one of the elements of scientific foresight, forecasting allows us to display possible scenarios for the development of institutional investors’ activity in the Russian green energy sector. The current market environment has proved that the authorities should be interested in developing domestic non-bank financial intermediaries, which help to transform savings into investments.

The activity of institutional investors in hydrogen production is insignificant. Federal loan bonds and deposits in leading Russian banks accumulate the main share of investments. At the same time, based on the analysis of investment strategies and market behavior of key players, we conclude that there is a great potential for institutional investors in the hydrogen production that promotes the development of indirect financing (Yarygina I. et al., 2022)/

The following measures help to realize the potential of institutional investors in the global market and develop their activities in green energy production, namely, in environmentally friendly hydrogen. It is economically reasonable to improve taxation of insurance companies and requirements for the structure of the insurance company's investment portfolio, as well as legislation, by creating a unified code of responsible investments. It is also very important to promote cooperation between insurance, production and management

companies, as well as increase information transparency of non-state investment funds. Clarification of the rights and obligations of participants of the non-state investment funds market, primarily in strategic spheres of the economy, will certainly contribute to the activity of institutional investors in different spheres of the economy, namely, in new types of energy production. The above-mentioned measures contribute to financial resources accumulation in the interest of sustainable economic growth and environmental protection.

Risk mitigation strategies for hydrogen projects

In view of the substantial risks inherent in hydrogen projects, it is indispensable to crystallize a comprehensive approach to risk management to enable their economic viability and investment appeal. Key risk factors impacting hydrogen projects' attractiveness and their possible mitigation tools are listed in Table 4.

According to the information presented in Table 4, global practice demonstrates

Table 4: Key risk factors impacting hydrogen projects and their mitigation ways

Risk mitigation tools / Risks	Uncertain market demand	Country risks	Technological risks	Environmental, Social, Governance-risks	Macroeconomic risks
ECAs' cover	+	+			+
Contractors-all-risk insurance (SAR)		+	+	+	
Contracts for difference (CFD)	+				+
Due diligence	+	+	+	+	+
Syndicated loan		+		+	+
Interest rate swaps		+			+
Liquidated damages			+		
Credit-default swaps (CDS)	+	+			+
Foreign currency guarantee		+			+
Loan loss reserve (LLR)	+	+			+
Off-take guarantee	+	+			+
Performance guarantee	+		+		
Foreign investment insurance	+	+			
Partial credit guarantee	+	+			+

(Source: Composed by the authors based on (Bjerde, A. et al., 2024; Climate Policy Initiative, 2024; Cordonnier, J. and D. Saygin, 2023; Pillay K. et al., 2025).)

Table 5: Risk allocation matrix by hydrogen project type (SPP)

Project type/ Risk	Developing and permitting risk	Construction and completing risk	Technological/ Performance risk	Feedstock risk	Market risk	Operational risk	Regulatory risk
Green hydrogen (Electrolyzer + Renewables)	PUB	PRI	PRI	PRI	PRI	PRI	PUB
Green hydrogen (Electrolyzer + Grid Power Purchase Agreement (PPA))	PUB	PRI	PRI	PUB	Shared	PRI	PUB
Blue hydrogen (steam methane conversion (SMC) + carbon capture, storage and utilization (CCUS))	PUB	PRI	PRI	PRI	PRI	PRI	PUB
Public supported hydrogen SPP (offtake or subsidy)	PUB	PRI	PRI	Shared	PUB	PRI	PUB
Merchant hydrogen SPP (no contracted offtake)	PUB	PRI	PRI	PRI	PRI	PRI	PUB
Integrated hydrogen hub (production + storage + pipeline)	PUB	PRI	PRI	PRI	PRI	PRI	PUB

(Source: Composed by the authors based on OECD, 2024; GHO, 2022; Hovy P, 2015; Fitch Ratings, 2023).

deal structuring and calculations of indicators of source origin.

Global practice suggests that state-private partnership (SPP) secures benign and enabling factors and hydrogen projects (Global Infrastructure Hub, 2020), by providing favourable conditions for their implementation. Deploying SPP in innovative projects provides equal distribution of risks between all the parties involved, thus securing efficient economic contribution of both public (PUB) and private (PRI) parties. The results of our study of SPP hydrogen projects are provided in Table 5.

The provided data are typical. In a variety of cases, peculiarities of hydrogen production and distribution require adjusted indicators. It is worthwhile to pinpoint that up to 85% of hydrogen projects have secure financing within the framework of public and intergovernmental development projects (OECD,

2024). Meanwhile, the involvement of private actors is curbed due to existing economic constraints. On the contrary, national financial architecture is determined by the maturity of the hydrogen market, with inherent risks hampering the inflow of private capital to the developing industry.

Conclusion

Analysis of global hydrogen energy financing demonstrates that the industry is emerging, yet at a strategically significant stage of development. Skyrocketing inflow of investments reflects both joint efforts for decarbonization and the unleashing potential of hydrogen for hard-to-abate industrial sectors. Notwithstanding the strategic role of hydrogen in tackling climate issues, private investments are curbed by market immaturity, technological constraints and high capital intensity of hydrogen projects. Consequently, the

current financial architecture of the hydrogen market is dominated by public finance and multilateral global initiatives, well above private investments.

The analysis underpins the necessity to develop a comprehensive approach to risk mitigation and project management to unlock private investments and unleash the potential of the hydrogen industry. The study suggests that, along with the SPP mechanism deal, structuring and financing from intergovernmental development organizations come as a crucial aspect of risk mitigation within the framework of long-term economic programs.

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Digital Twin-Based Living Lab Model for Social Problem-Solving

Bridging Technology, Education, and Sustainability in the Asia-Pacific Region

Changbeom Choi¹, Eun Joo Kim², Sang Hwa Jung^{3*}

¹ Professor, Department of Computer Engineering, Hanbat National University, Daejeon, Republic of Korea (cbchoi@hanbat.ac.kr)

² Principal Researcher, Division of Global Innovation Strategy Research, Science and Technology Policy Institute, Sejong, Republic of Korea (ejkim@stepi.re.kr)

^{3*} Head of Center, River Experiment Center, Korea Institute of Civil Engineering and Building Technology, Andong, Republic of Korea (sanghwa.jung@kict.re.kr). Corresponding author

Abstract

As climate change triggers a surge in water-related disasters—ranging from severe flooding to water pollution—across the Asia-Pacific region, there is an urgent need for innovative research and development frameworks that transcend the limitations of conventional closed-laboratory research. This study proposes a digital-twin-based living lab model currently established by the Korea Institute of Civil Engineering and Building Technology (KICT) at the Andong River Experiment Center (REC) in the Republic of Korea. This model integrates a computing continuum architecture with zero-shot learning artificial intelligence to address tangible challenges, such as the detection of riverine floating debris and flood prediction. Furthermore, this study analyzes how these experiential education programs operated by the REC for students and citizens drive the popularization of science and technology, while contributing to the achievement of UN Sustainable Development Goals (SDGs) 4 and 13. Finally, we present a roadmap for technology transfer and cooperation to enhance the climate resilience of UN ESCAP member states.

Introduction

Water resource management in the 21st century has been confronted with an unprecedented landscape of uncertainty. Conventional frequency analyses, which are based on meteorological data accumulated over the past century, no longer serve as reliable indicators for predicting future rainfall patterns. The Asia-Pacific region is one of the areas globally most vulnerable to natural disasters. In this region, rapid urbanization combines with accelerating climate change, significantly amplifying the unpredictability of water management.

According to reports by the UN ESCAP (2023), water-related disasters such

as floods, droughts, and typhoons are evolving beyond environmental shocks into complex social disasters that threaten regional economies and exacerbate poverty (Seddik and Sovacool, 2025). In particular, the discord between the intense, concentrated rainfall characteristics of the monsoon climate zone and aging water resource infrastructure makes disaster response increasingly challenging.

Decision-making based on rigorous scientific data and precise simulations is essential to establish effective climate adaptation policies. However, a significant number of developing member nations - Lao People's Democratic Republic (Lao PDR), Cambodia, Nepal,

and Bangladesh - face profound difficulties in implementing preemptive disaster management because of the absence of high-cost experimental facilities, a shortage of specialized personnel, and issues regarding data reliability.

Against this backdrop, the Andong River Experiment Center (REC) of the Korea Institute of Civil Engineering and Building Technology (KICT) proposed an experimental solution that combines physical infrastructure with digital technology. The REC has evolved beyond a simple research facility into a Living Lab—an ecosystem in which various stakeholders participate in verifying technologies and solving social problems in an environment that closely mimics a natural river.

The objectives of this study are to introduce REC's Digital Twin-Based Living Lab model in detail and identify how this model simultaneously achieves technological innovation and social education. Specifically, this study focused on 1) computing continuum technology that bridges physical experiments and virtual models, 2) concrete case studies of river debris and flood management using artificial intelligence (AI), 3) the achievements of educational programs designed for the popularization of science, and 4) strategies for diffusing these technologies throughout the Asia-Pacific region.

Andong REC

Technologically supporting the sustainable use of natural resources requires verification at a scale identical to that of actual rivers, specifically through prototype empirical experiments. The REC of KICT is an empirical research facility specifically established to resolve such engineering challenges.

Located in Andong-si, Gyeongsangbuk-do, the Republic of Korea, the center is



Figure 1: View of the River Experiment Center (REC) (Source: River Experiment Center, KICT)

a hydraulic experimentation facility capable of reproducing the hydraulic and hydrological phenomena of actual rivers on a real scale. It was constructed on a site with a total area of 192,051 m² site. Although most hydraulic experiments rely on reduced-scale models—thereby necessitating the acceptance of errors such as the scale effect¹—the REC has a large-capacity pumping station capable of supplying water at a maximum flow rate of 10 m³/s (10 tons per second) and three large-scale experimental channels. This infrastructure enables the replication of natural river flows without distortion. This implies the capability to artificially generate flood events, optimizing the facility for simulating extreme rainfall events that are becoming more frequent owing to climate change.

The success of large-scale experiments and the accuracy of digital twins depend entirely on the quality of the input data (Fuller et al., 2020). The REC is equipped with state-of-the-art instrumentation, including Acoustic Doppler Current Profilers (ADCP), underwater laser particle-size analyzers, 3D laser scanners, and ultra-precision Real Time Kinematic (RTK) GPS, to ensure this quality. These

instruments measure variables, such as bed fluctuation, vegetation resistance, and flow velocity distribution, down to the millimeter scale. This provides the foundational data necessary to replicate reality within digital space, serving as a critical element in bridging the gap between physical reality and digital models.

Theoretical background and technical framework

In the water sector, a Living Lab refers to an open ecosystem in which technology suppliers (researchers) and demanders (citizens and the government) interact in a real-world environment to achieve innovation (Hossain et al., 2019). The REC functions not as a closed laboratory, but as an open outdoor testing ground. It serves as a platform that simulates various disaster scenarios and shares the results with the local community and educational sector, thereby enhancing the social acceptance of new technologies (Song and Sung, 2025).

The digital twin of the REC operates on a computing continuum architecture (Beckman et al., 2020), which

integrates resources across three distinct layers to optimize performance and responsiveness.

- **Edge Layer (Field Site):** Internet of Things (IoT) sensors and intelligent closed-circuit televisions (CCTVs) installed throughout the river channels collect raw data. Lightweight AI models are deployed directly on these edge devices to perform initial analysis (for example, initial recognition of debris objects), enabling immediate data processing at the source.
- **Fog Layer (Local Center):** The data collected from the edge is transmitted to a local server. Here, data pre-processing and short-term predictive modeling are performed. This layer acts as an intermediary, reducing the latency and filtering data before reaching the central cloud.
- **Cloud/High-Performance Computing (HPC) Layer (Central Analysis):** Complex tasks such as computational fluid dynamics simulations and long-term climate change predictions are performed using HPC resources. The results of these intensive calculations are input back to the edge layer, thereby enabling

¹ Scale effect denotes the deviation of experimental results in a reduced-scale model from those in the full-scale prototype, leading to potential distortions in the experimental results compared to real phenomena.

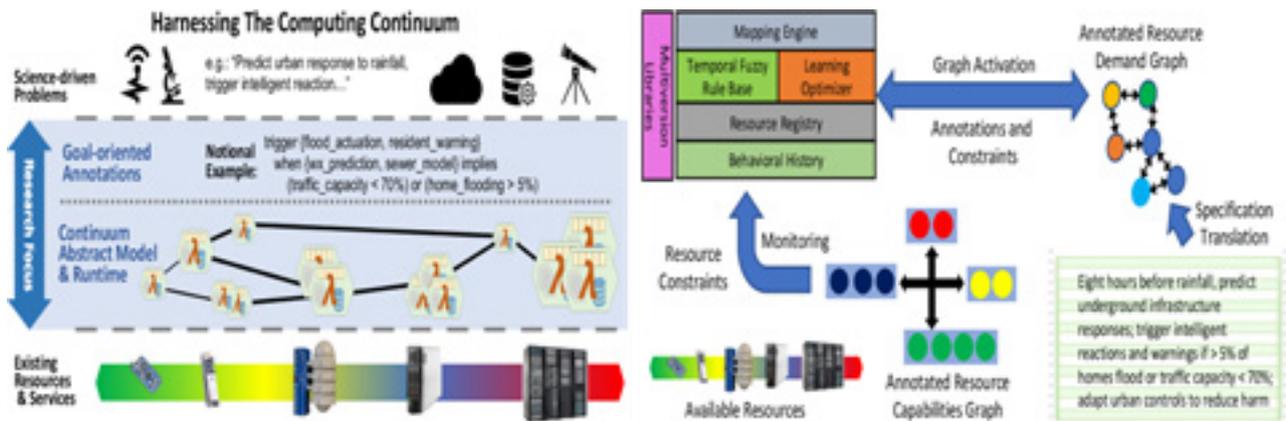


Figure 2: Computing continuum (Beckman et al., 2020)

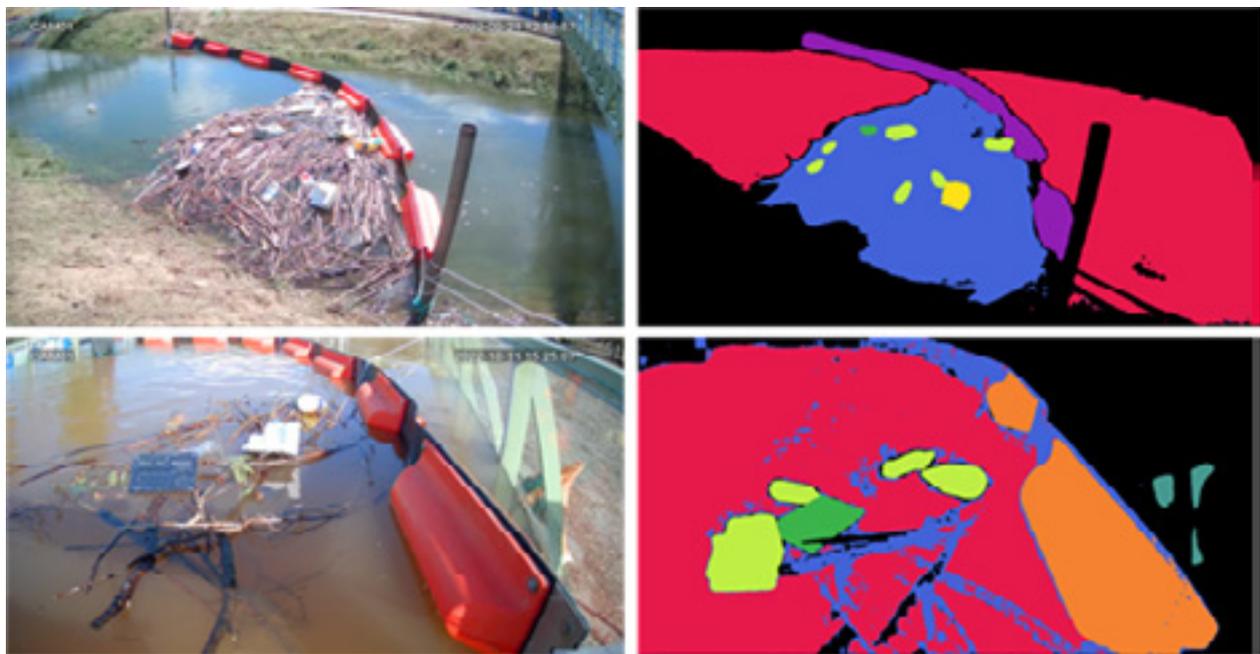


Figure 3: Waste detection using VLM (zero-shot learning) (Source: SimLab of Hanbat National University)

real-time response mechanisms (Buyya & Srirama, 2019).

A critical challenge in disaster management is that disaster data have a low frequency of occurrence, which makes it difficult to obtain sufficient training datasets for AI. To overcome this problem, the REC introduced zero-shot learning techniques. This approach combines large language models with vision models to identify new types of river debris or anomalies that the system has not previously learned using only text prompts for identification. This methodology significantly decreases the costs associated with data labeling, opening

the possibility of low-cost AI solutions suitable for developing nations (Li et al., 2017).

The adoption of digital twin technology for water disaster management in the Asia-Pacific reveals a stark digital divide. While advanced economies such as Singapore and Japan leverage city-scale, real-time integrated platforms (Smart Nation and Digital Government Office (SNDGO), 2022; Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2022), developing member States are hindered by systemic infrastructure and capacity bottlenecks. Consequently, a distinct multi-tier

structure has emerged wherein mid-tier nations employ partial solutions—such as early-stage digital twin applications in basin-scale flood modelling systems in Thailand (Hydro-Informatics Institute (HII), 2021)—while lower-tier nations continue to struggle with fundamental data fragmentation and sensor maintenance (World Meteorological Organization (WMO), 2021).

Crucially, the direct transfer of high-end digital twin models to developing economies has proven unsustainable, as the primary barrier is not hardware availability but operational continuity. High-fidelity models depend on continuous,

high-precision data streams, yet resource-constrained environments frequently suffer from equipment malfunctions and data gaps (World Bank, 2020). Moreover, long-term projects often fail due to a shortage of the local technical expertise required for regular sensor calibration and system repair.

To successfully expand digital twin adoption, stakeholders must therefore shift from a strategy of “high-end replication” to “context-appropriate adaptation.” This approach necessitates deploying low-cost sensor networks augmented by AI-based data enhancement to overcome hardware limitations, while simultaneously adopting modular architectures that allow for scalable growth rather than demanding immediate, full-system integration (Fuller et al., 2020). Finally, investment must be reoriented from capital-intensive facilities toward sustainable training programs focused on basic hydraulic measurement and model operation.

Considering these pronounced disparities in digital twin readiness, particularly the persistent challenges related to data continuity, sensor maintenance, and institutional capacity in lower-tier economies, the need for empirically grounded and operationally feasible implementation models becomes evident. Accordingly, the Andong River Experiment Center offers a rigorous case study through which the integration of large-scale physical hydraulic experiments with digital twin methodologies can be examined for their applicability to real-world water disaster management.

Case studies for social problem-solving

Case 1: AI-based automated detection system for floating river debris

Plastic waste in Asian rivers represents a severe problem; during floods, it obstructs bridges and drainage outlets, causes overflows, and eventually flows

into the ocean, thereby destroying marine ecosystems. Traditional visual monitoring is limited in its ability to cover vast areas and is highly labor-intensive.

To address this issue, the REC research team, in collaboration with Hanbat National University, is developing an intelligent-monitoring system that integrates the YOLO v5 object detection algorithm with vision language models.

- **Experimental setup:** Various floating objects, such as plastic bottles, Styrofoam, and driftwood, were introduced into the experimental channels. Video footage was secured using CCTVs and drones. Data were collected for 3 years (2023-2025) under various environmental variables (daytime, nighttime, illumination, light intensity, angle of light), including changes in lighting conditions and adverse weather scenarios, to ensure robustness of the system under varying conditions.
- **Real-time detection:** The developed AI model successfully detected and classified floating debris, with an average accuracy exceeding 90% (Source: SimLab of Hanbat National University).
- **Volume estimation and decision support:** Beyond simple detection, the system utilized pixel segmentation technology to calculate the volume of trash in real time. This capability enables local governments to implement data-driven administration, such as optimizing the dispatch schedules of collection trucks and prioritizing the management of locations with a high debris influx (van Lieshout et al., 2020).

Case 2: Flood simulation and vegetation management guidelines

Vegetation in natural rivers (trees and grasses) is ecologically vital; however, during floods, it acts as an obstacle to water flow, causing water levels to rise. Balancing vegetation conservation with flood safety (hydraulic control) is a persistent challenge in river management.

The REC conducted real-scale vegetation channel experiments for 5 years

(2021-2025) in cooperation with the Aalto University in Finland and Deltares in the Netherlands.

- **Methodology:** Vegetation zones with varying densities and arrangements were created, and flood flows were discharged through the zones. Variations in the flow velocity and water levels were measured in 3D.
- **Application:** The data were used to calibrate the roughness coefficients of the numerical models. The accuracy of the floodwater level prediction models was significantly improved by precisely calculating the flow resistance caused by vegetation.
- **Outcome:** The experimental results, regarding the flow resistance of density variation, provide a scientific basis for establishing vegetation management guidelines that minimize flood risk while preserving ecosystems. By quantifying changes in the roughness coefficient based on vegetation, this work continues to be researched under the national research and development projects of the Korean Ministry of Environment (e.g. Nature-based Solution project) and is cited as a benchmark case for climate-adaptive river management in Korea.

Science popularization and educational impact

The living lab at the KICT REC functions as a comprehensive platform that integrates research and development with Education and Civic Engagement. This integration plays a pivotal role in the diffusion of the social value of technology.

The REC operates systematic educational programs targeting elementary, middle, high schools in the Gyeongsangbuk-do region, as well as university students from across the nation.

- **Experiential Learning:** Students step out of the classroom and into the real-scale river experiment site. They operate drones to scan the terrain and virtually experience the downstream impacts of dam construction simulated through digital twin. For instance, on November 19, 2025, the REC hosted 39 students from Andong Seohu, Namseon, and Gilju



Figure 4: Andong Integrated Education X AI Digital Collaboration Program (Source: River Experiment Center, KICT)



Figure 5: Demonstration of drone-based river monitoring systems at the REC Open Lab event (Source: River Experiment Center, KICT)



Figure 6: Simulation for workload planning integrated with AI (Source: SimLab of Hanbat National University)

Elementary Schools. These students participated in drone operation and digital twin simulations (Figure 4).

- **Connecting theory to reality:** These programs demonstrate how abstract scientific principles are applied to solve actual social problems (floods and droughts), thereby cultivating students' scientific interests and problem-solving capabilities.
- **Sustainable Development Goal (SDG) Contribution:** This contributes directly to UN SDG 4 (Quality Education). REC helps bridge the educational gap by providing opportunities to experience cutting-edge technology, particularly for students in regional cities.

The REC regularly hosts Open Lab events. Local residents are invited to observe demonstrations of flood prevention technologies and communicate directly with researchers, thereby increasing their understanding of water management policies. This represents the practice of Citizen Science, where citizens function not merely as beneficiaries, but also as active monitors and participants (Buytaert et al., 2014).

Regional strategy: Cooperation and diffusion in the Asia-Pacific region

The REC aims to share its established infrastructure and accumulated

knowledge with UN ESCAP member countries to enhance the climate resilience of the entire region. However, this strategy focuses on technology transfer, recognizing that it is difficult for developing nations to immediately construct large-scale experimental facilities that require massive budgets. This approach involves packaging validated low-cost IoT sensor packages and open-source analysis software, coupled with joint research and workforce training to enhance social problem-solving capabilities.

Therefore, a three-phase cooperation roadmap is proposed.

- **Phase 1: Standardization and baseline establishment**

Utilizing real-scale experimental facilities at the REC, we will verify and standardize the performance of AI flood prediction models and low-cost sensor networks specifically specialized for the Asian-Pacific monsoon climate including India, Bangladesh, Pakistan, Viet Nam, Thailand, Philippines, Indonesia, China, the Republic of Korea, and Japan. This establishes a reliable baseline for the technologies deployed across the region.

- **Phase 2: Remote access and platform sharing**

We will open a cloud-based laboratory that will allow countries lacking physical experimental facilities to remotely access the digital twin

system at the REC. Member nations can input their local river data and run simulations. This approach reduces cross-border travel costs and maximizes the efficiency of research collaboration.

- **Phase 3: Education and operational model export**

Beyond simple technology transfer, we will provide structured operational know-how and educational curricula from the REC. By offering invitational training for policymakers and engineers and localized custom education, we will support capacity building to enable member countries to independently construct sustainable water management ecosystems (Antonesi et al., 2025).

Furthermore, the REC implements an empowerment program that fosters regional cooperation and shared growth by partnering with local government bodies, including municipal education offices. Under this initiative, the REC opens its research infrastructure to the regional community to co-organize hands-on learning activities and capacity-building workshops. This collaborative framework not only advances SDG 4 by broadening access to quality Science, Technology, Engineering, and Mathematics (STEM) education but also supports SDG 13 by equipping local stakeholders with the technical and institutional expertise to address climate-related water challenges. By synthesizing education, public-sector

collaboration, and open infrastructure, the program offers a practical pathway for regions to enhance both climate resilience and long-term sustainable development.

Lessons learned and recommendations

Experience across the Asia-Pacific region indicates that the primary barrier to digital twin adoption is not technological capability, but operational sustainability.

- **Data scarcity vs. Model precision:** High-fidelity models frequently fail in developing member States because necessary field data—specifically regarding water levels, flow velocity, debris movement, and vegetation roughness—is either non-existent or fragmented (Hrachowitz et al., 2013).
- **Infrastructure fragility:** Projects relying on expensive, high-maintenance sensor networks are often discontinued within one to two years due to systemic constraints, including unstable power grids, hardware malfunctions in harsh environments, and a critical shortage of technical staff (Rogers & Tsirkunov, 2019).
- **The “Over-Engineering” trap:** attempting to deploy full-scale, high-end systems immediately often leads to resource exhaustion. Sustainable operations must take precedence over advanced technical features to ensure long-term viability.

To address these challenges, member States and technical partners should adopt a context-appropriate, phased deployment strategy.

- **Adopt a “Remote Validation” model:** Countries lacking domestic experimental facilities should utilize regional hubs, such as the Andong River Experiment Center, to generate high-quality calibration data. These large-scale physical experiments provide a reliable substitute for missing field data, reducing model uncertainty without requiring expensive local infrastructure.
- **Shift to lightweight and hybrid technologies:** Governments should move away from fragile, capital-intensive hardware toward robust solutions

like CCTV-based monitoring combined with edge-AI modules. This approach offers high operational impact with minimal reliance on continuous internet connectivity or specialized maintenance.

- **Structure systems with layered architecture:** Digital twins should be distributed across layered resources utilizing edge devices for immediate processing, local servers for data aggregation, and reserving national/cloud HPC only for complex simulations. This prevents over-investment in high-end infrastructure.
- **Implement phased and modular deployment:** Avoid “all-or-nothing” implementation by beginning with specific, high-value modules (e.g., flood-level prediction or roughness calibration). This step-by-step scaling builds capability before expanding to fully integrated systems.
- **Standardize through regional collaboration:** Developed modules should be standardized and shared through APCTT and ESCAP networks. Collaborative development will reduce duplication and allow member States to adopt “plug-and-play” solutions tailored to common hydrological problems.
- **Institutionalize through community engagement:** Technology cannot survive in a vacuum. Establishing student programs and “Open Laboratories” fosters public understanding and institutional acceptance, increasing the likelihood that digital twins will be integrated into long-term disaster management protocols.

Conclusion

The most powerful weapon tool humans possess is scientific evidence of the colossal threat of climate change. We must move away from uncertainty-driven assumptions or overly conventional engineering designs and adopt an attitude that acknowledges the complexity of nature by measuring and analyzing it with precision.

The Andong River Experiment Center is at the forefront of this scientific inquiry. The water and plants flowing here are not merely the subjects of the experiment; they constitute a testing ground

that reveals optimal solutions for the co-existence of humanity and nature.

Furthermore, the case of the Andong REC demonstrates how the convergence of digital twins and living labs can solve complex social problems during a climate crisis. Technical innovation based on the computing continuum has heightened the precision of disaster management, whereas education and civic participation through the Living Lab have proven the social value of science and technology.

An organic connection among Technology, People, and Cooperation is essential for a sustainable future in the Asia-Pacific region. The KICT REC is poised to become a pillar in building a network that makes Asia safe and resilient to floods and droughts by actively sharing its proven technology platforms and educational programs with ESCAP member nations. We propose that policymakers and research institutions participate in this cooperative model to implement cross-border climate action (SDG 13).

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Nature-Based and Tech-Enabled: Thailand's Integrated Approach to Water and Climate Resilience

Jittiporn Chantarojsiri, Nisakorn Yingkajohn, Royboon Rassameethes, Montree Pinkaeo

Hydro-Informatics Institute, Ministry of Higher Education, Science, Research and Innovation (MHESI), 901 Ngam Wong Wan Road, Lat Yao, Chatuchak, Bangkok 10900, Thailand, Tel: +66-2-158-0901.

Emails: jittiporn@hii.or.th; nisakorn@hii.or.th; royboon@hii.or.th; montree@hii.or.th

Abstract

Accelerating climate change and ecosystem degradation make sustainable resource use an urgent global priority. This paper examines Thailand's Hydro-Informatics Institute (HII) and its integrated approach to advancing data-driven Nature-based Solutions (NbS) for water resilience. The framework combines traditional ecological knowledge with modern Science, Technology, and Innovation (STI), aligned with Thai Royal Development concepts, such as "Three Forests, Four Benefits" and "New Theory Agriculture."

The Mae La Oup River Basin Network Community in Chiang Mai illustrates the model's efficacy. Confronting land tenure ambiguity and water scarcity, the community adopted participatory Community Water Resource Management (CWRM) in 2009. Interventions included community-led land use maps, 394 check dams, and solar-powered greenhouses with post-harvest technologies (Hydro-Informatics Institute, 2021).

Results show improved ecological and economic resilience: diversified farming supported by smart technology raised household incomes while reducing flood and drought risks. The study concludes that converging NbS, technology, and community empowerment provides a scalable pathway to achieve the SDGs and strengthen regional climate adaptation.

Introduction

Sustainable use of natural resources has become an urgent global imperative amid accelerating climate change. Intensifying temperature anomalies, hydrological shifts, the increasing frequency of extreme weather events, and ecosystem degradation are placing unprecedented pressure on natural systems and communities, further increasing the vulnerability of societies and economies worldwide (Intergovernmental Panel on Climate Change, 2022).

These challenges highlight the need for strategies that enhance resilience while

preserving ecosystem integrity. Ensuring that natural resources are managed responsibly is not only essential for environmental protection but also for safeguarding livelihoods, food security, and long-term resilience.

Within this context, Nature-based Solutions (NbS) have gained prominence as an integrated approach that leverages natural processes to address societal challenges, including climate adaptation, disaster risk reduction, and sustainable water management. NbS encompasses the protection, restoration, and sustainable management of ecosystems to generate environmental, social, and economic co-benefits (International Union for Conservation

of Nature, 2020). By working with nature rather than against it, NbS offers cost-effective, scalable, and inclusive pathways toward sustainability.

To maximize the effectiveness of NbS, the integration of modern technology is indispensable. Advanced tools, such as automated telemetry stations, remote sensing, geographic information systems (GIS), hydrological modelling, and data-driven decision-support platforms, enhance the ability to track ecosystem dynamics and evaluate impacts. These technologies also improve the precision, efficiency, and monitoring capacity of NbS initiatives, helping to optimize long-term planning (UN Environment Programme, 2021).

Integrating traditional ecological knowledge with digital technologies facilitates the development of Nature-based Solutions that are not only scientifically robust and practically implementable but also precise, scalable, and cost-effective.

In Thailand, the Hydro-Informatics Institute (HII) serves as a primary catalyst for advancing data-driven Nature-based Solutions (NbS). Leveraging hydro-informatics platforms, climate resilience initiatives, and community-based water resource management, HII bolsters national endeavours to deploy adaptive, evidence-based strategies that fortify natural resource governance. The integration of NbS with innovative technologies strengthens institutional capacity, fosters regional collaboration, and delivers tangible impacts for communities. Through strategic partnerships and knowledge dissemination, HII demonstrates the efficacy of a science-based, technology-enabled, and nature-centred paradigm in enhancing sustainable resource management amidst climate change. These initiatives underscore Thailand's broader commitment to sustainability, climate adaptation, and the deployment of innovation to mitigate environmental challenges.

Conceptual framework

Nature-based Solutions

Nature-based Solutions (NbS) are underpinned by the principle that healthy ecosystems, when protected, restored, and sustainably managed, provide essential services capable of addressing societal challenges. This framework emphasizes working synergistically with natural processes—rather than relying solely on engineered interventions—to enhance resilience, support biodiversity, and deliver long-term socio-economic benefits (IUCN, 2020). To operationalize this concept within water resource management and climate adaptation, three core principles, Watershed Restoration, Wetland Utilization, and Rainwater Management, are applied.

1. **Watershed restoration:** This approach prioritizes the rehabilitation of degraded catchments through reforestation and soil conservation. By restoring natural vegetation and stabilizing slopes, these interventions improve hydrological functions, specifically infiltration and flow regulation, thereby securing water supplies and mitigating flood risks (Browder et al., 2019).
2. **Wetland utilization:** Recognizing wetlands as multifunctional assets that simultaneously provide ecological services and safeguard human settlements, this principle leverages their natural capacity for water retention and filtration. Wetlands act as critical buffers against hydrological extremes, effectively managing floodwaters and improving water quality, which offers a resilient complement to engineered infrastructure (Ramsar Secretariat, 2018).
3. **Rainwater management:** Focused on mimicking natural hydrological cycles, this principle employs green infrastructure and decentralized storage to manage rainfall. Techniques such as permeable surfaces and community-based rainwater harvesting integrate natural hydrological processes into urban and rural planning, thereby reducing surface runoff and enhancing groundwater recharge.

These strategies are particularly critical in rapidly urbanizing environments to mitigate localized flooding and disaster risks, while simultaneously bolstering water availability and promoting sustainable usage (UN-Habitat, 2020).

The effectiveness of NbS is maximized by bridging traditional ecological knowledge with modern science, technology, and innovation. The integration of data-driven tools—such as hydrological modelling and Geographic Information System (GIS)—ensures that these nature-centred solutions are scientifically robust, scalable, and optimized for long-term sustainability. By aligning ecological processes with human needs, NbS provides a clear pathway toward climate resilience and sustainable water governance.

Science, Technology, and Innovation for community water resource management

HII's Science, Technology, and Innovation (STI) for Community Water Resource Management or CWRM, grounded in active participation from local villagers, strengthens local ownership and enhances community capacity to manage water resources sustainably under diverse conditions, including floods and droughts (Hydro and Agro Informatics Institute, 2016). HII works closely with local villagers by providing training in technologies that are appropriate to the local context. This approach ensures that modern scientific tools are adapted to community needs and combined with indigenous knowledge, enabling villagers to manage water resources effectively while preserving their cultural traditions.

The integration of science, technology, and information systems has enabled communities to systematically collect essential data, diagnose root causes of local water challenges, and develop planning strategies that are best suited to their circumstances (Hydro-Informatics Institute, 2021). This participatory approach ensures that solutions are not only technically sound but also socially accepted and locally relevant.

Information technology: Information technology plays a central role in

strengthening CWRM. Geographic Information Systems (GIS) provide communities with powerful tools to capture, analyse, and visualize geographic information, enabling them to map resources, monitor water flows, and plan for disaster preparedness. Global Positioning System (GPS) receivers complement this by offering precise location data, which is invaluable for land and water surveys. Together with satellite imagery and land use maps, these technologies allow villagers to better understand their local context, clarify land use patterns, and create visual guides for comprehensive future planning. Automated telemetry stations further enhance local capacity by continuously measuring water levels, precipitation, temperature, and humidity, transmitting data in real time for use in water modelling, forecasting weather, and disaster warning systems (Hydro and Agro Informatics Institute, 2018).

Water data, mapping, and security:

Effective community water resource management relies on the systematic use of water data, water maps, and water diagrams. These tools provide essential information for analysing local hydrological conditions and developing resource management plans. By combining quantitative data with spatial mapping and flow diagrams, communities are better equipped to cope with flood and drought risks, strengthen water infrastructure, and enhance their capacity to manage local resources (Hydro and Agro Informatics Institute, 2017). Such integrated approaches ensure that decision-making is based on a shared and accurate understanding of water availability and distribution.

Equally important is the pursuit of water security, which encompasses the reliable availability of sufficient water for consumption, agriculture, and other essential uses throughout the year. Improving water security requires increasing water capital—through measures such as storage, reuse, and conservation—and ensuring adequate water reservations to buffer against seasonal variability and climate extremes. By securing water resources in this way, communities can safeguard livelihoods, reduce vulnerability

to disasters, and promote sustainable development.

Tools and innovation for water management: Practical tools and innovations for water management, such as echo sounders, are used to determine water depth and monitor reservoirs, while hydropneumatics pumping stations enable the delivery of water from lower to higher grounds over long distances (Office of Research Administration, 2024). Wastewater treatment systems, such as household grease traps and solar-powered aerators, provide low-cost solutions for improving water quality. Water balance analysis has become a crucial practice, allowing communities to calculate demand and supply, identify risks of scarcity, and plan agricultural activities accordingly. Water reuse strategies, such as circulating canal water into farm ponds and paddy fields, reduce external demand and increase water value. Visual water diagrams, which illustrate flows from upstream to downstream, help communities understand hydrological dynamics and manage resources more effectively.

Innovation in agriculture is also closely linked to water resource management. Crop calendars provide farmers with timely information on planting, sowing, and harvesting periods, supporting climate-adaptive agricultural planning. Pond networks distribute water from upstream reservoirs to downstream ponds, strengthening local storage and distribution systems. Monthly water balance analysis, combined with surveys of natural streams recorded in GIS, enables farmers to identify the root causes of water stress and adopt appropriate solutions, such as rainwater harvesting and allocation for cropping (Hydro and Agro Informatics Institute, 2017). These practices are essential for coping with seasonal variations in rainfall and extreme weather events, thereby strengthening adaptability and resilience in agricultural communities.

Thai Royal Development Frameworks on Sustainable Agriculture and Natural Resource Management: Community-driven innovations are further strengthened by the application of royal initiatives, particularly the “Three Forests and Four Benefits” principle, which entails planting three types of forests

for economic, conservation, and community-use—to generate four distinct benefits: wood/fuel, food/income, environmental protection, and water security. Additionally, the “New Theory Agriculture” promotes efficient land and water use through the systematic division of farmland into functional zones. This is exemplified by the 30:30:30:10 model (30% water storage, 30% rice cultivation, 30% mixed crops, and 10% housing). Together, these frameworks provide holistic approaches that ensure water–food–income security and reduce climate vulnerability, thereby promoting economic self-reliance and sustainable resource management (Grossman et al., 2016, Grossman et al., 2017).

The innovative solutions implemented by these communities have led to reduced flood and drought risks, improved water security, and strengthened reforestation efforts. Collectively, these initiatives contribute to resilient and sustainable livelihoods, ensuring that communities are better prepared to face the challenges of climate change.

Good practice case: Mae La Oup River Basin Network Community, Galayani Vadhana District, Chiang Mai Province, Thailand

The Mae La Oup River Basin Network Community is in Moo 3, Jam Luang Sub-district, Galayani Vadhana District, Chiang Mai Province, Thailand, covering 78.35 square kilometers, of which 79.05% is forest, 20.40% is agricultural land, and only 0.05% is designated for settlement. This network consists of 221 households with a total population of 810 people, primarily from the Paka-Kyaw ethnic group, who have inhabited the area for centuries (Hydro-Informatics Institute, 2021).

Despite their long-standing presence, the Paka-Kyaw community has historically lacked formal land title deeds. This absence of legal recognition created ambiguity regarding the boundaries between arable land and conserved

forests. Over time, population growth and migration intensified the demand for natural resources, leading to forest encroachment. The situation was further exacerbated by external capitalists who hired local people to clear forested areas; this accelerated environmental degradation and directly resulted in worsening water shortages (Hydro and Agro Informatics Institute, 2017). Consequently, long-term conflicts over water allocation emerged as households competed for limited resources to sustain agricultural production. These tensions highlighted the community's vulnerability to resource scarcity and underscored the need for collective management strategies

Community water resource management in Mae La Oup River Basin, Galayani Vadhana District, Chiang Mai Province, Thailand: Integrating indigenous knowledge and modern technology

In 2009, Community Water Resource Management (CWRM) was introduced to the Mae La Oup River Basin Network Community. Recognizing the importance of indigenous knowledge within the Paka-Kyaw community, the Hydro-Informatics Institute (HII) placed special emphasis on facilitating the sharing of community-led local traditions and practices, and provided training in local languages enabling them to combine their deep knowledge of the landscape with modern tools, such as satellite imagery, Geographic Information Systems (GIS), and Global Positioning System (GPS) technology, to produce community land use maps. These efforts promoted the application of cultural wisdom while simultaneously transferring modern technologies to strengthen community-based resource management (Hydro-Informatics Institute, 2021).

Through participatory surveys by representatives of the local villagers, the community mapped and delineated vivid boundaries of preserved forest, usable forest, rehabilitating forest, crop rotation areas, and arable land. The resulting maps were formally endorsed by the

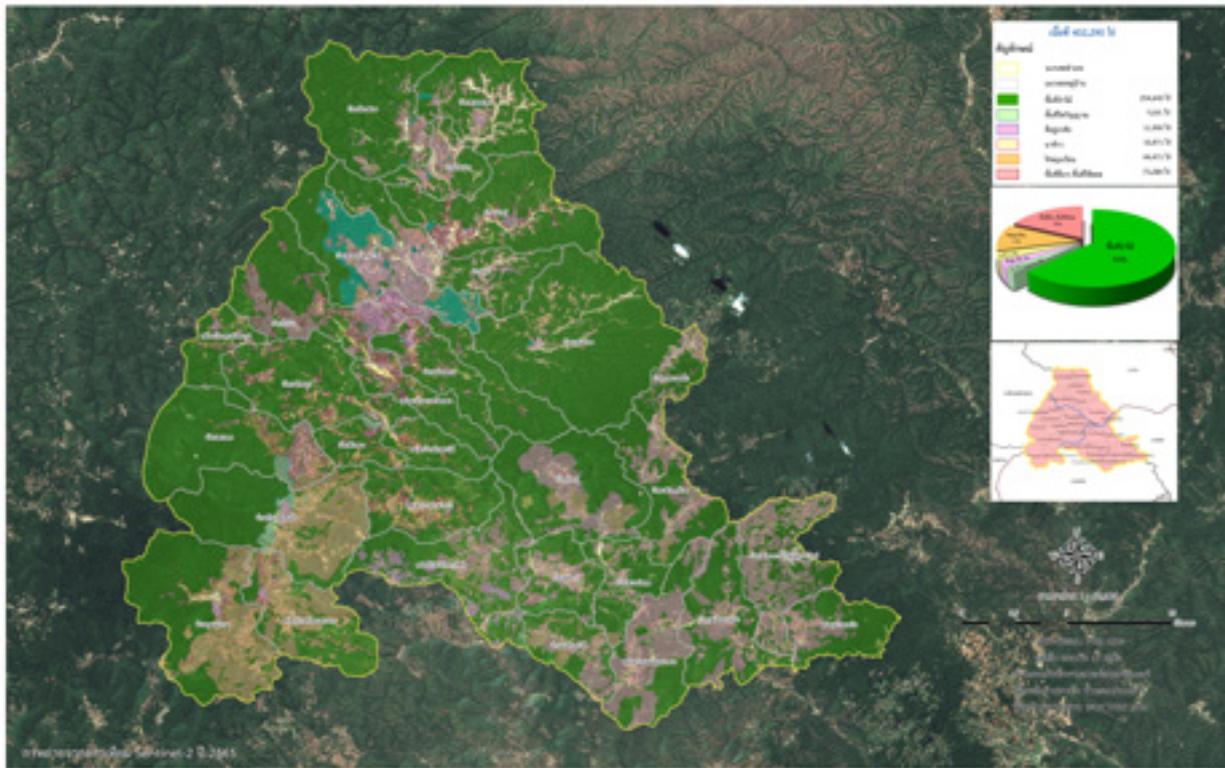


Figure 1: Example of Land-use Map in Mae La Oup River Basin, Galayani Vadhana District, Chiang Mai Province, Thailand

community and became the basis for issuing land use titles, thereby securing tenure rights and empowering collaborative upstream reforestation and sustainable land management.

Villagers were trained by HII to apply science and technology in preparing detailed water maps, conducting water balance analyses, and designing nature-based check dams and distribution systems suited to local hydrological conditions. Building on this technical capacity, the community constructed a series of three-level filter-system check dams tailored to the surrounding topography. The check dams were designed based on the location of the stream in the forest, using local materials, such as stone and wood. The primary and secondary levels function to slow water flow, trap sediment, and promote upstream reforestation, while the tertiary level enhances water storage for dry season use. To date, a total of 394 check dams have been completed, securing year-round water availability across 20 brooks (Hydro-Informatics Institute, 2021).

In 2009, the community faced severe natural disasters triggered by heavy rainfall, which caused soil erosion and landslides. These events not only damaged local infrastructure and agricultural land but also heightened awareness of the risks associated with unsustainable resource use. The experience reinforced the importance of integrated watershed management and community-driven approaches to strengthen resilience against climate variability and environmental hazards.

To address landslide risks, a 920-meter "canal street" was constructed along ridge areas. In normal conditions, it functions as a road, while during the rainy season it serves as a flood-control canal, channelling excess water to retention ponds. This innovation completely solved the landslide problem and strengthened community resilience against flash floods (Hydro-Informatics Institute, 2016). Indigenous knowledge guided the design of water storage dams and local irrigation systems, while traditions, such as the River Goddess Worship Ceremony (Natee Khunnam) and traditional rhymes,

were revived to reinforce environmental stewardship.

Strengthening water security requires attention to both physical infrastructure and social governance. The installation of solar-powered pumps and storage facilities in Mae La Oup River Basin, together with pipelines extending to higher elevations, has reduced dependence on seasonal rainfall and enabled more reliable agricultural planning and crop diversification. Equally important, the project emphasized community-driven management. By entrusting the operation and maintenance of these systems to local stakeholders, the initiative fostered a strong sense of ownership that is essential for the long-term sustainability of community water resources (Yingkajohn, 2025).

From 2024, a notable technological advancement introduced through the project is the development of automated, climate-smart greenhouses designed to provide stable growing conditions year-round. Constructed with mesh roofing and equipped with comprehensive IoT-enabled control systems,

these greenhouses autonomously regulate irrigation, temperature, and humidity. All operational functions are managed through the Tuya Smart application, a comprehensive mobile application that centralizes the control, monitoring, and automation of smart devices, allowing farmers to monitor and adjust environmental parameters in real time. Powered entirely by solar energy and utilizing mist irrigation to decrease temperature during summer for off-season cultivation, the system maintains ideal conditions for high-quality cultivation (Yingkajohn, 2025). As a result, farmers are able to produce vegetables and herbs consistently throughout the year, significantly increasing productivity while reducing vulnerability to climate-related impacts.

Complementing the improvements in water access, the initiative placed strong emphasis on integrating renewable energy into both water distribution systems and post-harvest agricultural processes in the Mae La Oup River Basin. By deploying hybrid systems that combine solar and hydropower, the project ensured a stable and reliable energy supply for agricultural processing and storage, which is an essential advancement for remote communities with limited access to conventional energy infrastructure. Practical applications of these systems include solar-powered electric dryers used for efficient dehydration of crops, such as chili and vegetables, as well as solar-driven cold storage units that maintain low temperatures needed to preserve product quality. These cold storage facilities reduce post-harvest losses and support off-season marketing, directly contributing to increased farmer income. Together, these innovations demonstrate how renewable energy infrastructure simultaneously strengthens environmental sustainability and reinforces economic resilience within the community. Value-added processing has lifted product worth by 1.6 times, while extended shelf life enables off-season sales that raise prices by up to 1.3 times (Yingkajohn, 2025).

With improved water resource management supported by various IoT technologies, the community transitioned from monocropping and nomadism to integrated agriculture, boosting household

incomes through organic farming and agroforestry.

Outcomes and lessons learned

The implementation of these integrated interventions has yielded significant tangible outcomes, particularly regarding economic security and production efficiency. Household income from production saw an annual increase of approximately 28,800 THB (USD 893). Most notably, the strategic transition from monoculture to diversified farming systems proved highly lucrative; farmers reported an average annual income of 88,600 THB (USD 2,747), a substantial rise from the 14,400 THB (USD 446) typically generated by rice monoculture alone. Beyond primary production, value-added processing initiatives increased product value by 1.6 times, while improvements in shelf-life extension facilitated off-season sales, allowing farmers to command prices up to 1.3 times higher. These technical advancements also significantly reduced post-harvest product damage, ensuring more efficient market delivery. On a social level, the project successfully fostered community and youth engagement, expanding networks for knowledge exchange to support continuous, collaborative development (Yingkajohn, 2025).

Community empowerment was applied in Mae La Oup through training in technology, while ensuring that villagers themselves took the lead in surveying, planning, decision-making, and implementation. HII acted as a mentor, providing knowledge and financial support to foster sustainable development. As Ani et al. (2017) note, empowerment occurs when communities can identify problems, access resources, improve skills, and mobilize collective action for mutual benefit. It is a process of expanding the ability of individuals and groups to make choices and pursue common goals. Empowerment begins with individuals recognizing their own capacity and freedom, which can then be shared to build collective strength. For sustainability, empowerment must evolve from external initiation into self-reliant, internally driven actions.

Policy recommendations and scaling up

By the end of 2020, the Mae La Oup River Basin Network Community had expanded its practices to reach 8,648 people across 465.05 square kilometres, covering seven subdistricts: Jam Luang, Mae Daet, Wat Jan, Mae Najorn, Mae Suek, Ban Tab, and Tha Pha. Working Groups on Land Management and Regulation were established, alongside the "AePaWaDou" Youth Network, which now engages 105 members in 8 communities. The success of the Mae La Oup model has also extended to the Mae Jam River Basin, where good practices have been transferred to three subdistricts in nine villages (Hydro-Informatics Institute, 2021). Further scaling opportunities have emerged as visitors learn from the community's good practices, inspiring networks across Thailand to adopt similar approaches.

Since 2003, HII has initiated Community Water Resource Management (CWRM) project starting with two pilot communities in the very first year. Mae La Oup Network stands as one of the notable achievements within this journey, exemplifying how local empowerment and sustainable practices can evolve into national models. Over time, these good practices have self-expanded and multiplied. By the end of 2024, 60 CWRM core communities and 1,847 villages were established across 19 river basins, covering the entire country (Nunta & Kanyawarak, 2024).

HII has expanded its nature-based science adaptation concept not only across Thailand but also to neighbouring countries. In Lao PDR, HII partnered with the Department of Technology and Innovation, Lao PDR, to transfer knowledge and techniques on Community Water Resources Management concept to strengthen capacity of the local community in Sangthong Village, Vientiane Capital for climate-resilient adaptation. This initiative was started as bilateral project between two agencies, and further supported by the local private sector, the Coca-Cola Foundation, as part of their Corporate Social Responsibility program, demonstrating how community-based water resource management can be scaled regionally through

cross-border collaboration and public-private-people partnerships.

Conclusion

The Mae La Oup experience underscores the critical role of integrating Nature-based Solutions (NbS) with modern technology to achieve sustainable development and climate resilience. By combining indigenous knowledge, scientific tools, and community empowerment, the model demonstrates how local action can reduce disaster risks, restore ecosystems, and secure livelihoods. Its success highlights that resilience is not only ecological but also social, rooted in community governance and collective capacity.

As HII's Community Water Resources Management model expands nationally and regionally, it provides a replicable framework for countries seeking to strengthen climate adaptation strategies. The convergence of NbS and technology offers pathways to achieve the Sustainable Development Goals (SDGs), particularly those related to water security, ecosystem restoration, and inclusive governance. Importantly, it shows that sustainable development is most effective when communities are empowered to lead, supported by institutions, and connected through regional collaboration.

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Living Labs for Climate Adaptation: Civic Participation, Co-creation, and Experimental Innovation

Taedong Lee¹, Juyeon Park²

¹ Underwood Distinguished Professor, Department of Political Science, Yonsei University, Seoul, South Korea (tdlee@yonsei.ac.kr)

² Department of Political Science, Yonsei University, Seoul, South Korea (juyeon.park0202@yonsei.ac.kr)

Abstract

In the era of climate crisis, the importance of local climate adaptation strategies is growing. Given that the impacts of climate change vary across regions, a bottom-up approach involving various stakeholders is crucial. This article introduces living labs, where diverse stakeholders collaborate to define problems and experiment with solutions, as a viable approach for climate adaptation. Through the case studies of the three living labs: corporate climate adaptation, ESG information disclosure framework, shade infrastructure against heat waves, and climate disaster text message. We explore the applicability and effectiveness of living labs and discuss their implications for sustainable development and enhancing the resilience of local communities in the Asia-Pacific region.

Introduction

In 2015, sustainable development became an international agenda. Under the overarching vision of harmonizing the environment, economy, and society, the Sustainable Development Goals (SDGs) are being pursued at various levels. Among them, climate change has become a serious issue worldwide; hence, designing an appropriate response to it is becoming significant. Both climate mitigation, reducing greenhouse gases (GHGs), and climate adaptation, strengthening resilience and adaptive capacity to climate risks are crucial. As the impacts of climate change vary across regions, effective responses require tailored strategies reflecting local characteristics and needs. This necessitates an integrated and transformative approach involving diverse fields and interests. In other words, it demands us to go beyond top-down approaches to establish and implement bottom-up climate adaptation.

This article introduces living labs as a method for enhancing sustainability and

realizing bottom-up climate adaptation policies. It is an approach that creates social value through user-driven innovation, representing an experimental environment where diverse stakeholders jointly define problems and develop solutions. By fostering collaboration, living labs pursue not only public benefit but social acceptability, making them highly suitable for addressing complex, multi-layered challenges. As a form of social innovation, living labs can contribute to going beyond mere technical solutions and enhancing practical resilience to the climate crisis, as well as community resilience and autonomy.

The structure of the article is as follows: the next chapter addresses the concept of the necessity of living labs. The subsequent chapter presents the methodology of living labs, focusing on how living labs facilitate participatory and innovative approaches to local climate adaptation. Then, two case studies follow: the corporate climate adaptation living lab and the shade living lab. In this section, we explore how living labs can be utilized both in a corporation and local

government context. In conclusion, we discuss implications for sustainable development in the Asia-Pacific region.

Concept and necessity of living labs

Living labs are public innovation platforms where diverse actors collaborate to define problems and experiment with solutions within real-life environments (Bergvall-Kåreborn and Ståhlbröst 2009; Voytenko et al. 2016). This approach contributes to enhancing the suitability of climate adaptation measures and fostering a sense of shared responsibility by actively utilizing the knowledge and creativity of citizens who were previously marginalized in the policy process (Nesti 2018, Shin and Lee 2025).

Arias et al. (2025) analyzed over 80 living lab cases across Europe, confirming that living labs have evolved into innovation platforms integrating citizen participation, co-design, interdisciplinary collaboration, and institutional structures. They emphasized that social value, inclusivity, and locally tailored contexts play a decisive role in living lab design and outcomes. Campos and Marín-González (2023) have also argued that living labs should be designed to integrate social value, ethics, and inclusivity.

While living labs are generally citizen-led, they possess a multi-layered structure and incorporate diverse institutional support. Universities and research institutions provide a knowledge and technology base, while government and private companies handle financial and administrative support (Evans et al. 2015). Civil society groups also play crucial roles in operation and collaboration coordination (Mukhtar-Landgren et al. 2019).

Features of living labs can be summarized in several ways. First, in terms of participation, living labs transform policy recipients from mere beneficiaries into co-designers of solutions. Citizens and

communities can reflect their practical needs, ensuring adaptation strategies are designed to fit the local context. Second, in terms of innovation, living labs provide a structure to experiment with technical and social solutions in real-world environments and improve them based on experimental results. Third, living labs facilitate the exchange of knowledge and experience among diverse stakeholders, enabling the combination of new policies, technologies, and social practices. This contributes not only to short-term problem-solving but also to strengthening long-term adaptive capacity.

In summary, living labs provide an innovative process. They offer participant-centred problem definition, experimental solution development, and continuous improvement. They establish themselves as a crucial approach that enhances the effectiveness and feasibility of community-tailored adaptation strategies. Particularly in today's situation, where rapid climate change coexists with social vulnerability, living labs are able to improve the efficiency of climate adaptation and provide a practical platform for diverse stakeholders to manage climate risks.

How do living labs facilitate participatory and innovative approaches to local climate adaptation?

Figure 1 conceptually presents the development of living lab techniques,

consisting of four steps: planning, co-creation, experiment and verification, and realization. Among these, the planning steps include diagnosing climate vulnerability and identifying the target group for living labs. It serves as a crucial step to determine the overall direction of living labs. It is essential to clearly define the type of entity and specify objectives, since methods and procedures depend on the nature and purpose of the implementing entity. This is followed by a preliminary diagnosis to lay the foundation for living labs operation, such as investigating the baseline status of the project or targeted problem and developing the operation plan. When designing new climate adaptation projects or restructuring existing projects, a review of the relevant legal basis is mandatory. In particular, local governments are directly constrained by statutes and ordinances. It entails a thorough prior analysis of the relevant legal and institutional framework.

The second step, co-creation, encompasses co-design (problem discovery and identification) and prototype development (ideation and prototyping). From this step onward, the participation and interaction of key stakeholders (such as citizens, civil society organizations, experts, public officers, and corporate workers) become fully engaged. During the co-design process, workshops are conducted to discover problems and select and refine the identified problems. Workshops are generally structured according to the following three-process flow.

- **Sharing findings from real-life context investigations:** Share observed problems with stakeholders to establish shared problem recognition and support redefining problems in user-centred language.
- **Organizing and structuring problems:** Based on investigation results, categorize discussed issues by theme and type to derive a concrete list of problems.
- **Problem prioritization:** Evaluate the importance and urgency of the derived problems to establish priorities.

Based on this process, an idea workshop generates solutions, followed by prototype development to visualize and concretize these ideas.

The third step, experiment and verification, involves reviewing the effectiveness and suitability of prototypes through pilot experiments. For example, in a corporate climate adaptation living lab, the developed solution is evaluated for its applicability and potential to deliver tangible results. Living labs' core element is experiment, which involves (1) assembling specific tools and participants, (2) inducing change, and (3) measuring that change (Karvonen and van Heur 2014). Therefore, it is indispensable to set clear evaluation criteria for experiments. During verification, stakeholder surveys, priority assessments (e.g., AHP: Analytic Hierarchy Process), and comparisons of pilot application outcomes are employed.

The final step, realization, consists of assessing the feasibility of the derived

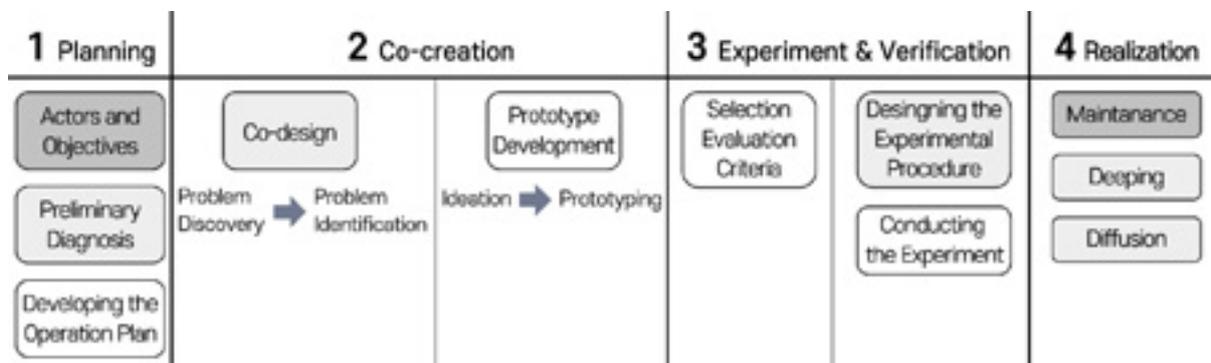


Figure 1. Development of Living Lab Techniques

* Source: Lee and Shin et al. (2025)

** The above content systematizes practical methodologies, based on the experience accumulated by the Yonsei University Climate Adaptation Living Lab R&D.

solutions and connecting them to institutionalization or commercialization. It is achieved by three stages: maintenance (continuous development of solutions), deeping (refining co-created outcomes), and diffusion (Shin and Lee 2025). Living labs should not remain confined to the laboratory level; if experiments validated at the local or small-scale level fail to scale up into broader systems, the creative efforts of diverse stakeholders may face limitations (Hakkarainen and Hyysalo 2013). That is, even if living labs start with local-level experiments, they can be realized as tangible products, services, and institutions through processes of scaling and transition (Lee et al. 2014; Von Wirth 2019).

Remember that the guidance provided in this article is not the definitive answer. Certain steps may be omitted, or it may be necessary to return to a previous step. The essence of living labs lies not in rigidly adhering to frameworks and steps, but in the engagement of multiple stakeholders and the realization of solutions through experiment and verification. Therefore, it is recommended to use the guidance as one practical milestone on the journey toward enabling a collective response to the climate crisis and advancing toward a sustainable future.

Case studies on climate adaptation living labs

This chapter introduces two living lab cases and explores how living labs actually support developing solutions and advancing them to the level at which they can be institutionalized. The three cases are conducted by the Yonsei University Climate Adaptation Living Lab R&D in South Korea (Lee and Shin et al. 2025). They have distinct environments, targets, and risk structures, yet both share the commonality of enhancing the coherence and effectiveness of climate adaptation policies.

The first case is the corporate climate adaptation living lab. It structured the private sector's climate risk and adaptation capabilities and laid out the groundwork for building a corporate climate adaptation disclosure system. The second case is the shade living lab conducted

in collaboration with Seodaemun-gu (local government in Seoul) from 2023 to 2025 (Lee and Shin, 2025). It empirically reviewed heatwave climate adaptation policies based on the living environment and derived policy design requirements.

Corporate living lab

The climate crisis has become a key factor in exerting structural and persistent impacts on corporate management. The necessity of ESG (Environmental, Social, Governance) management is emphasized, with environmental responses serving as a core pillar of corporate sustainability. However, the trend in ESG disclosures has largely focused on mitigation. Unlike mitigation, corporate climate adaptation lacks a robust institutional foundation and reporting standards, necessitating the development of evidence-based indicators tailored to industry-specific characteristics. Given this context, living labs are deemed a proper research methodology. They reflect real-world environments while enabling collaborative problem-solving through stakeholder interaction.

To conceive the corporate climate adaptation disclosure system, a research institute-led living lab platform is set up to structure corporate climate adaptation information and ensure the effectiveness of disclosure indicators. This platform was designed as an experimental collaborative structure where corporations collectively design and review the entire process. Figure 2 describes the co-creation process of a corporate living lab. The living lab comprised five steps: problem identification and agenda setting; co-inquiry and knowledge integration; ideation; prototype development; and verification and institutionalization.

Figure 2 describes the co-creation process of a corporate living lab. The living lab comprised five steps: problem identification and agenda setting; co-inquiry and knowledge integration; ideation; prototype development; and verification and institutionalization. First, ESG officers in private companies were recruited considering diversity by industry and size. A preliminary assessment of each company's climate risk awareness level and adaptation capacity laid out the groundwork for living lab discussions. Subsequently, systematic training

on international standards and climate risk assessment techniques was provided to strengthen the companies' capabilities, enabling their participation in the design process. During the co-creation, companies, researchers, and experts jointly conducted an in-depth analysis of climate risk factors, identifying candidate adaptation disclosure indicators.

The resulting indicators underwent in-depth verification by an expert group. It included detailed discussions on the feasibility of applying industry-specific frameworks and methods for integrating qualitative (such as social values) and quantitative (such as market values) indicators. This verification procedure played a crucial role in ensuring the disclosure framework reflects the realities of corporate operating environments and climate data infrastructure. Through this process, the corporate climate adaptation disclosure framework was derived. This globally applicable framework was constructed by synthesizing empirical data collected from living labs, analysis of international disclosure standards, and review results of quantitative evaluation systems (ND-GAIN: Notre Dame Global Adaptation Initiative) and VESTAP: Development of the Korean Climate Change Vulnerability Assessment Tool).

Table 1 presents the framework for corporate climate adaptation disclosure. The research team categorized corporate climate adaptation information into two major categories: climate risk and corporate climate adaptation capacity. It is found on the quantifiability of future indicators, data accessibility, and operational simplicity of the disclosure framework. Climate risk refers to the physical and transition risks faced due to climate change, consisting of climate exposure and climate sensitivity. Climate exposure indicates how directly a company is exposed to current and future climate risks, while sensitivity signifies how significantly or easily the impacts of climate change affect a company's operations.

Meanwhile, the corporate climate adaptation capacity refers to the resources, capabilities, strategies, systems, and policies a company possesses to identify, manage, and mitigate climate risks. It is composed of climate readiness and

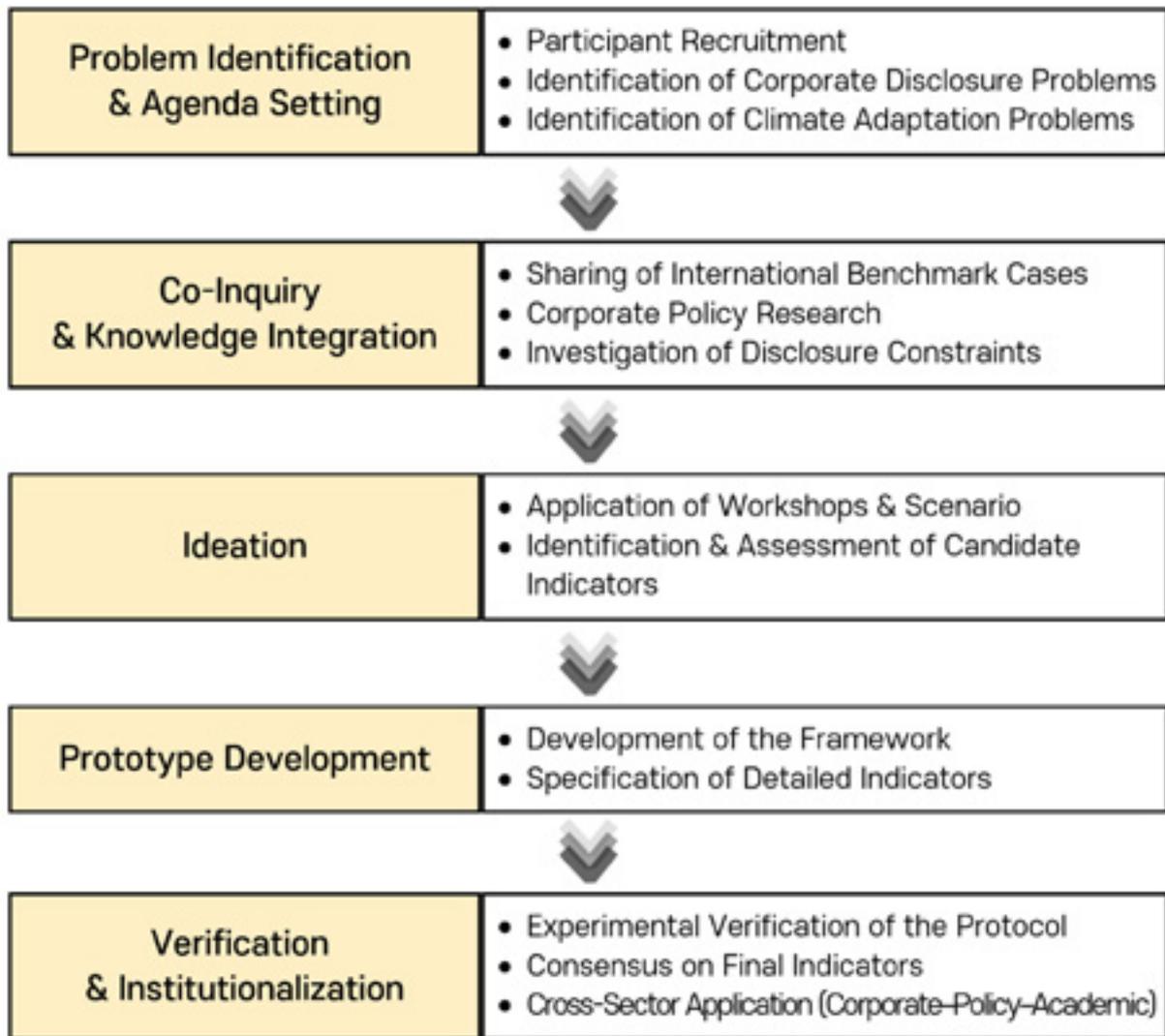


Figure 2. Co-creation Process of Corporate Living Lab

* Source: Lee et al. (2025)

climate responsiveness. Readiness means the level of preemptive readiness a company has to respond to when confronted with climate risks. Climate responsiveness denotes the company's ability to respond immediately and effectively when an actual climate crisis occurs, encompassing its execution capability and resilience.

Shade living lab

Climate change has intensified exposure to heatwaves in urban spaces, and as an adaptation policy, outdoor shade has been widely adopted by local governments. However, existing projects have shown policy limitations, being implemented in a fragmented manner

with insufficient evidence regarding their power-saving effects and lacking verification of practical impacts. Recognizing these issues, Seodaemun-gu (Seoul, South Korea) introduced a living lab approach to analyze the feasibility, effectiveness, and resident acceptability of the outdoor air conditioner shade project.

Figure 3 depicts the process of the shade living lab. During the planning, a preliminary investigation reviewed the project's legal basis, effectiveness, and feasibility. The investigation revealed that Seodaemun-gu's ordinance system lacked a legal foundation for supporting the shade project, and there were almost no scientifically verified

cases demonstrating power-saving effects. This initial analysis suggested that the living lab should be an experimental policy design process integrating policy, technology, and resident participation.

Based on this, the living lab established a participatory structure encompassing diverse stakeholders. Participants included citizens with outdoor unit installation experience, government officials responsible for climate and energy policy, energy diagnosis experts, outdoor unit management and cleaning specialists, and shade manufacturers and installers. The living lab adopted an issue-focused workshop approach, creating a structure to translate each

Table 1. Framework for Corporate Climate Adaptation Disclosure

Major Category		Subcategory	Indicators
Corporate Climate Risk	Climate Exposure	Physical Risk	Climate Risk Modeling
			Climate Impact Assessment
		Transition Risk	Policy and Regulatory Risk
			Market and Reputation Risk
	Climate Sensitivity	Infrastructure Sensitivity	Human Infrastructure
			Physical Infrastructure
		Corporate Value Chain Sensitivity	Supply Chain Sensitivity
			Revenue Sensitivity
Corporate Climate Adaptation Capacity	Climate Readiness	Risk Mitigation and Management	Climate Adaptation Awareness
			Green Infrastructure Development and Operation
			System Efficiency Improvement
		Corporate Value Creation	Social Value Creation
			Market Value Creation
		Climate Adaptation Implementation	Adaptation Impact Assessment
			Scale of ESG Investment
			Financial Planning for Climate Risk
		Climate Responsiveness	Climate Disaster Response Capacity
	Climate Disaster Management		
	Employee Safety Management		
	Corporate Governance		Internal Rules and Regulations
			Stakeholder Engagement
			Climate Disclosure

* Source: Lee et al. (2025)

stakeholder’s expertise and experience into concrete policy elements. Key issues identified during this process were summarized as: (1) lack of ordinance and policy basis, (2) reduced effectiveness due to formal linkage programs, (3) absence of criteria for users, (4) insufficient verification of effectiveness, and (5) safety risks.

During the co-creation, three experiments were designed to address these issues. The first was a cleaning and management experiment, examining how maintenance affects energy efficiency and safety. Results revealed accessibility and safety issues with outdoor units in high-rise apartments, frequent overheating and fire risks

observed, and the need for safe cleaning methods and management training.

The second was an installation experiment requiring residents to install the shade themselves to evaluate installation difficulty, safety, and structural constraints. While most participants reported being able to install it themselves,

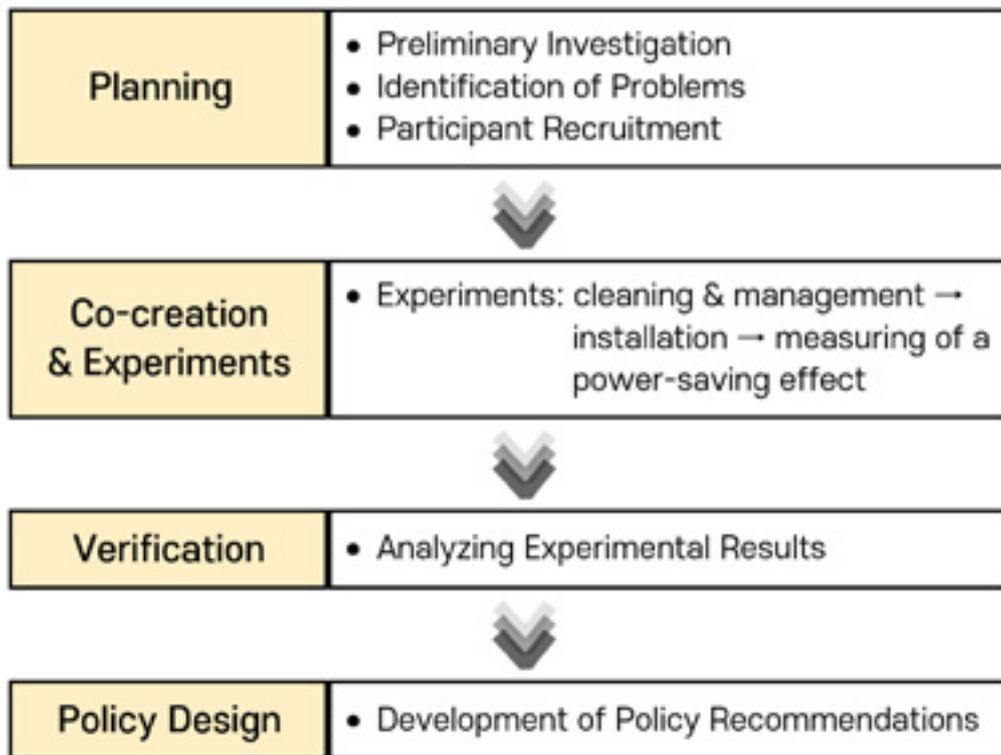


Figure 3. Process of Shade Living Lab

significant risks were identified in confined installation spaces or on high-rise external balconies. This suggests the need for installation guidelines and prior training, and that professional installation support may be required for certain housing types.

The most critical experiment was to verify the power-saving effect in 2025 (Lee and Shin et al. 2025). Of the 29 resident researchers, 22 provided valid data, enabling an analysis. The researchers were residents of Seodaemun-gu, selected from 13 out of 14 administrative districts, living in various housing types (apartments, villas, detached houses, etc.). They measured and recorded their daily electricity consumption and reported it via SNS (Social Networking Services). This experiment was conducted during summers and was based on actual measurements of changes in outdoor unit power consumption. The analysis confirmed that the shade has a practical effect, but its effect is limited to specific residential types.

In the final step, policy design directions were derived based on the experimental

results. First, shade support is not a universal policy applicable to all households; therefore, differentiated application by housing type is essential. Second, the outdoor unit cleaning and management program should be linked to transforming it into a comprehensive policy. Third, evidence-based policy design must be strengthened, incorporating the effectiveness of verification as an essential procedure. Fourth, the SNS-based real-time feedback model proved effective for resident participation and communication methods.

Climate disaster text message living lab

The Republic of Korea is sending a climate disaster text message (Lee et al. n.d). However, there is insufficient verification on whether it actually increases risk awareness and induces behavioral change. Despite the increasing frequency and intensity of climate disasters, the current alert system has been criticized for failing to reflect recipients' situations and characteristics, causing alert fatigue and lacking concrete action guidelines. Based on this

problem awareness, the research team determined that a living lab approach involving both citizens and experts is necessary to improve disaster text message (Lee et al. n.d.).

Figure 4 illustrates the process of the climate disaster text message living lab. In the first living lab, a focus group interview (FGI) was held with 7 citizens of diverse ages (20s, 30s, 40s, 50s, and 60s) to review heatwave disaster messages and identify problems at Seoul (Yonsei University) in 2024. Citizens emphasized that messages lack relevance because they fail to reflect actual risks and situations, and that repeated messages from multiple agencies lead to fatigue. They also pointed out that abstract expressions like "be careful of the heat" made it difficult to know when, what, and how to act, arguing that more specific, action-oriented information was needed.

In the second step of the living lab, the technical and institutional feasibility of the citizen suggestions was reviewed by 2 citizens (of the first step living lab participants) and 3 experts

* Source: Lee and Shin et al. (2025)



Figure 4. Process of Climate Disaster Text Message Living Lab

* Source: Lee et al. (n.d.)

(from the climate change research institute, news media, and disaster message management institute). Experts explained the authority and legal responsibilities of each message-issuing agency, the structure of communication systems, and the limitations of information provision, discussing how citizen ideas could realistically be implemented. While citizens stated they trusted the messages from the Korea Meteorological Administration (KMA), which provides weather and climate change related information, the most, experts worried that if the KMA provided action guidelines, it could lead to role conflicts or responsibility issues between agencies (such as local governments). Through these discussions, the research team and participants jointly designed a two-stage structured message, where the KMA provides risk information, and health/disaster management agencies provide action guidelines.

In the final living lab, the prototype messages were delivered to all participants. They thoroughly examined messages without time constraints, evaluating the clarity of phrasing, the effectiveness of action guidelines, the safety of provided links, and the placement and role of hashtags. The research team supplemented the context of opinions through phone interviews when necessary. This remote review process compensated for the time, power, and participation constraints of in-person meetings, verifying whether the message content would function naturally and effectively within the actual context of disaster alerts.

Implications for sustainable development

This article focuses on the concept and practice of climate adaptation living labs, discussing how living labs facilitate participatory and innovative approaches to local climate adaptation. Three living lab cases introduced in this study empirically demonstrate that living labs can simultaneously provide the institutional framework of evidence-based approaches and multi-stakeholder engagement. These position living labs as experimental and verification platforms for localized climate adaptation.

Living labs can function as a core policy and socio-technical mechanism for sustainability transition, going beyond simple participatory programs. Their operation mechanism serves as a catalyst for the enhancement of contextuality, coherence, and feasibility by enabling stakeholders to experience climate risks in real-life, reframe problems, and co-create solutions. Furthermore, living labs hold significant theoretical implications as they facilitate the interaction between societal, technological, institutional, and behavioral changes - core elements of the transition perspective emphasized sustainability. From a policy perspective, the co-creation process of living labs has stakeholders directly engage in review, experimentation, and discussion from the initial stage. This institutionally implements the core principles of sustainability policy - inclusiveness and co-production - and strengthens long-term sustainability by building trust in climate policies.

The Asia-Pacific region is experiencing the world's fastest urbanization and industrialization, with an extremely uneven spatial distribution of climate risks and stark socioeconomic vulnerabilities. Besides, significant disparities in policy capacity, financial conditions, and data accessibility make applying a uniform adaptation model difficult. Considering these regional characteristics and constraints, the living lab approach can promote climate adaptation policies in the Republic of Korea and some other Asia-Pacific countries such as the Philippines, Indonesia, and Viet Nam. First, through real-life experiments, it can derive locally customized adaptation strategies reflecting differences in residential environments, corporate structures, and social vulnerabilities. Second, the co-creation structure is well-suited for building multi-stakeholder participation-based adaptation systems. Third, accumulating evidence-based data can ensure policy credibility and alignment with international standards, thereby contributing to the institutionalization of climate adaptation policies.

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Application of Biosensors and Artificial Intelligence for Biomonitoring Aquatic Ecosystems Towards Achieving Sustainable Water Utilization

A.N. Grekov¹, R.V. Gorbunov², N.A. Grekov³, V.A. Ryazanov⁴, K.A. Kuzmin⁵, M.A. Pasyukov⁶, V.V. Trusevich⁷

A.O. Kovalevsky Institute of Biology of The Southern Seas of Ras, Sevastopol, Russian Federation

Emails: ¹grekov@ibss-ras.ru; ²gorbunov@ibss-ras.ru; ³ngrekov1@ya.ru; ⁴rez_blk@ibss-ras.ru; ⁵kuzminka@ibss-ras.ru; ⁶sevmixa@ibss-ras.ru; ⁷trusev@list.ru

ABSTRACT

In modern conditions of progressive water pollution intensity resulting from increased discharges of untreated or partially treated waters and frequent technogenic accidents, the development of automated methods and means for operational detection of pollutants and assessment of their danger to aquatic ecosystems and humans has become imperative. This article describes the development of an automated biomonitoring system based on behavioral responses of bivalve mollusks combined with machine learning algorithms for real-time identification of pollutants. The system has been successfully deployed for both marine and freshwater environments, utilizing hall sensors and magnets attached to mollusk shells to detect valve movement patterns. The system incorporates artificial intelligence for anomaly detection using unsupervised machine learning algorithms, including isolation forest (iForest), elliptical envelope, one-class support vector machine (SVM), and local outlier factor (LOF). Laboratory and field tests demonstrate high sensitivity, reliability, and effectiveness in detecting dangerous pollution levels within seconds to minutes. The system represents a significant advancement in continuous automated environmental monitoring for sustainable water utilization across marine and freshwater aquatic ecosystems.

Introduction

In the aquatic environment, we face the simultaneous impact of a complex mixture of many thousands of pollutants on ecosystems (Zhang et al., 2022). While chemical analysis can identify the concentration of pollutants, it cannot assess the actual toxicological threat these substances pose to living organisms. Existing aquatic environment monitoring systems, which rely primarily on physicochemical methods, remain labor-intensive and costly. They generate fragmented data, cover only a traditionally narrow spectrum of pollutants, fail to ensure timely detection

of sudden releases, and cannot rapidly assess the associated ecological or human health risks. (Feio et al., 2021; Zolkefli et al., 2020; Kokkali and van Delft, 2014). Furthermore, the number of chemical compounds polluting the aquatic environment is so great that it is difficult to control (Rodriguez-Mozaz et al., 2004). Threshold level indicators, used in modern environmental practice, characterize only quantitative characteristics of substance content, are established for a relatively small number of chemicals, and aimed ensuring the safety of certain categories of water users. They are not aimed at protecting aquatic ecosystems and do not determine the

level of danger to the "health" of biota as a whole (Depledge and Galloway, 2005).

Assessing the actual impact of pollution on the aquatic environment is possible using biological monitoring methods. Living organisms respond quickly and accurately to pollution, providing a comprehensive assessment of the state of the aquatic environment in real time, regardless of the composition and origin of xenobiotics. Biological early warning systems (BEWS) are increasingly playing a role in solving the problem of organizing continuous automated biomonitoring of surface waters in environmental practice worldwide (Bae and Park, 2014). These systems utilize living organisms as sensors embedded in electronic circuits and recording various physiological, biochemical, and behavioral indicators (Dvoretzky and Dvoretzky, 2023). These systems, unlike physical and chemical monitoring methods, allow for the acquisition of integrated toxicological characteristics of the environment in real time and the assessment of water quality as a habitat for aquatic organisms (Kramer and Foekema, 2001). Such systems, while not providing information on the content of specific pollutants, provide real-time information on unfavorable aquatic environments. Moreover, given their high reliability, ease of maintenance, high level of automation, and low cost, they are the most suitable means for effective environmental monitoring over large water areas.

One challenge is the correct interpretation of incoming signals with high fault tolerance (Meti and Sangam, 2017). In global practice, BEWS utilizes mollusks, fish, crustaceans, algae, and other organisms as biosensors. Prominent examples of aquatic biomonitoring systems using mollusks include the Musselmonitor (Kramer and Foekema, 2001) and Dreissena Monitor (Borcherding, 1992; Borcherding, 2006).

These systems evaluate the behavioral responses of mollusks, including the extent of valve opening, the nature of their movement, the number of valve movements, and the percentage of open mollusks. The Aqua-Tox-Control and bbe Fish Toximeter systems use fish to assess the ecological state of the aquatic environment by analyzing their behavioral responses (swimming speed, depth of swim in the water column, turning speed, and circling motion) (Mons, 2008; Kuklina et al., 2013). The cardiac activity characteristics of the narrow-clawed crayfish *Astacus leptodactylus* were used as biomarkers in a bioelectronic system for continuous monitoring of the quality of purified water at the State Unitary Enterprise Vodokanal in St. Petersburg (Kholodkevich, 2007; Kholodkevich et al., 2006).

This article describes the developed aquatic monitoring system using machine learning algorithms and mussel-based biosensors for both marine and freshwater environments and presents the results of laboratory and field tests demonstrating the versatility and effectiveness of the technology across different aquatic ecosystems.

RESULTS

The structure and operation of the system

Continuous and effective environmental monitoring of aquatic areas in the seas, oceans, and freshwater bodies requires the development of an automated monitoring system that would alert to changes in aquatic environmental parameters using the behavioral responses of bivalve mollusks. This system should include a network of biosensor monitoring systems deployed in aquatic environments and a universal monitoring center. Through long-term research in various environments (sea and freshwater), the "ECOBIMONITOR" system was developed (Shatokhin et al., 2021; Grekov et al., 2020; Grekov et al., 2019). It is based on the behavioral responses of bivalve mollusks, along with software packages that enable real-time identification of pollutants, primary data processing, and internet transmission

(Trusevich et al., 2010). This system is an upgrade to a prototype developed in 2008 (Trusevich et al., 2010).

The system operates by recording the activity of bivalve mollusks, specifically the extent to which their valves are open. For bivalves, motor activity is an indicator of normal functioning (Trusevich et al., 2021). Knowledge of the behavioral responses of mollusks in their natural (normal) habitats allows us to assess their reactions under adverse conditions and generate alarm signals. Marine *Mytilus galloprovincialis* (Lam, 1897) and freshwater *Unio pictorum* (Linnaeus, 1758) bivalves were used in the tests. The developed system consists of above-water and underwater sections connected by a cable (fig. 1).

The underwater portion of the system consists of a mussel colony unit and a battery, connected to the anchor by a chain. The mussel colony unit is a sealed container designed for a depth of up to 20 meters. It contains: a) a control unit, b) 16 Hall sensors hermetically mounted in the device's housing, c) 16 permanent magnets on remote plates, d) mussel attachment points, e) a light sensor, f) a temperature sensor, and g) a pressure sensor. The above-water portion of the system is a sealed container installed in conjunction with a buoy. The container contains: a) a backup battery, b) a GSM module, c) a control unit, and d) a flashing beacon.

The ends of the cable-rope (KG 3×1.5-70 grade) connecting the above-water and underwater sections are fitted with sealed connectors. This allows for servicing the system even from small vessels. Furthermore, the cable-rope connection between the system components is made through thimbles, allowing for variable installation depth of the underwater section and providing additional reliability during long-term operation. A flashing beacon is integrated into the container's hull and provides visibility of up to 2.5 nautical miles.

The mussels are attached to the underwater section of the system using polymer adhesive (fig. 2). One mussel flap is secured to the device's platform, while the other flap is attached to a freely moving plate with permanent magnets attached to it. The plates are 3D printed using individual templates taken from

the mussels. Changes in the distance between the flaps during their movement, and consequently the distance between the Hall sensor and the magnet, lead to changes in the sensor's output voltage.

The underwater module's control software sequentially measures the voltages of all Hall sensors, the light sensor, and the pressure sensor, and also reads the digital temperature sensor. This data, represented as digital codes and combined with a digital marker in a specific sequence, forms a measurement frame. The measurement frame is transmitted to the surface portion of the system via an RS-232 interface and a tethered cable.

The surface module's controller, implemented using the MSP-430FR5994, receives a frame of measurements. After receiving 20 frames of measurements, the controller generates a data packet and transmits it via the GSM module to the system's internet server. The data packet contains data on physical parameters (valve opening distance, water temperature, and illumination) obtained during calibration using codes, the system's serial number, and the current time and date. It also contains additional primary measurement information in the form of digital codes and is used for debugging and diagnostics of the system.

To determine actual mussel activity values, it is necessary to obtain individual calibration coefficients for all the system's measurement channels. This procedure can also be performed in the field immediately before installation. The device's design allows for calibration of the measurement channels without disassembling the device in the field, maintaining its hermetic seal.

Behavioral responses of freshwater mollusks

The freshwater system developed for water supply intake monitoring at Sevastopol's Vodokanal in the Chornaya River (Southern Federal District) provides critical insights into mollusk behavior and system performance in freshwater environments (Trusevich et al., 2010). Prolonged, continuous,

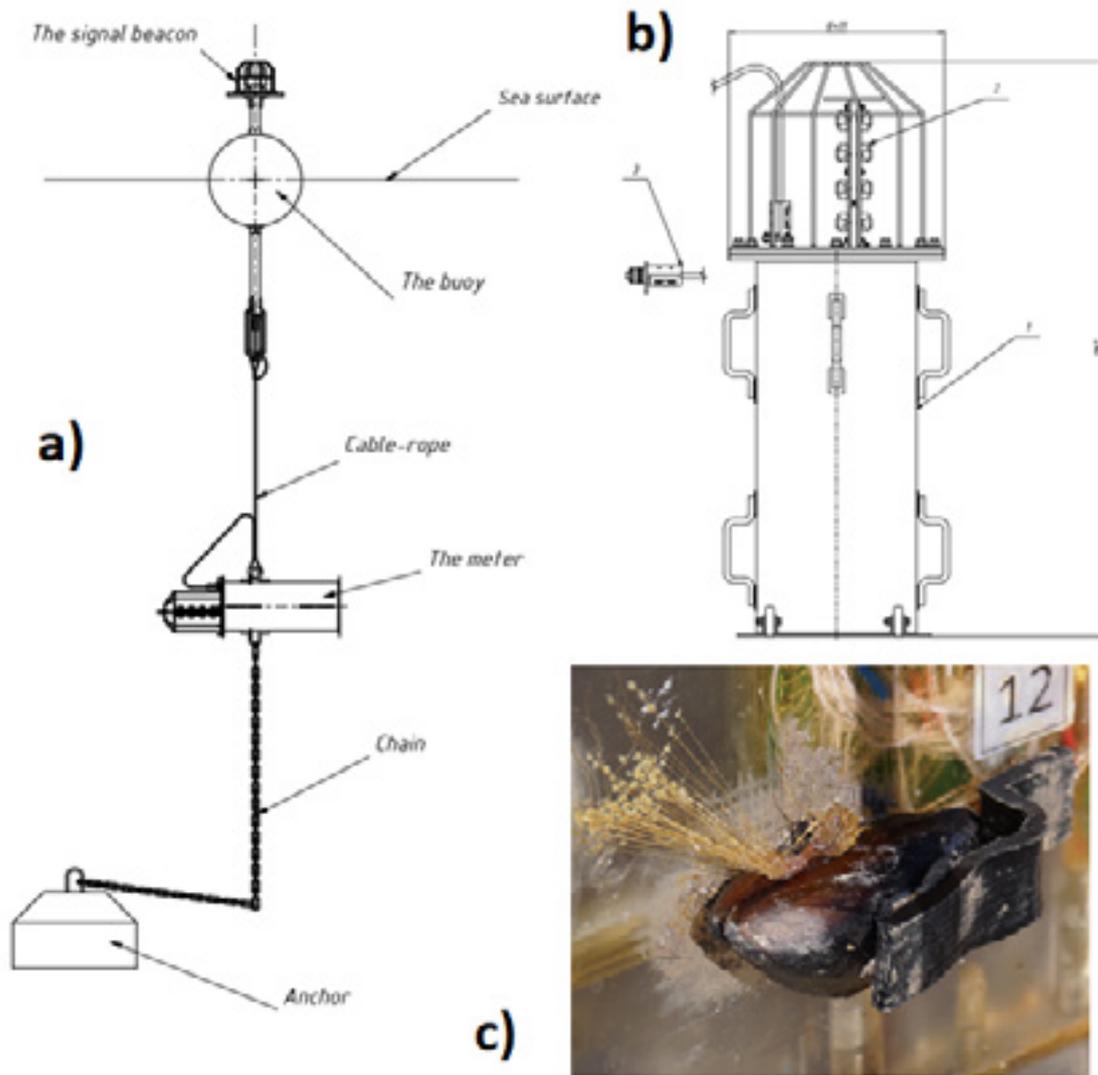


Figure 1. General diagram of the device (a), diagram of the underwater part of the device (b) and attachment of the mussel to the block of colonies (c). 1 – sealed container with batteries; 2 – block of mussel colonies; 3 – watertight connector (Source: Authors)

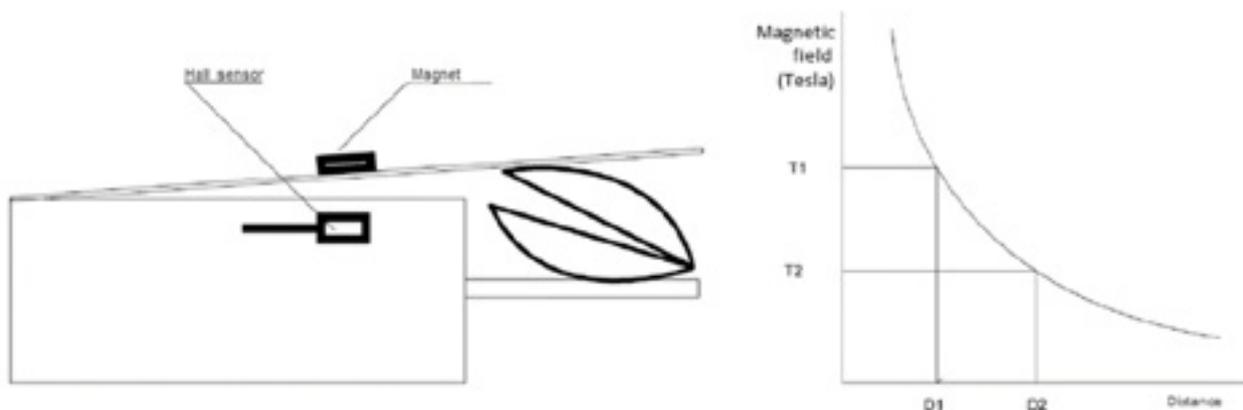


Figure 2. Scheme of attachment of a mussel to a block of colonies (a) and characteristics of the magnetic field in the measurement range (b) (Source: Authors)

year-round research of baseline characteristics of mollusk behavior showed that under normal conditions, valve movements follow a strict daily rhythm. With the onset of dusk, the frequency of adductions (rapid valve closing and subsequent opening within 0.5-1 minute) increases sharply and continuously, with gradually decreasing frequency, until dawn. During daylight hours, the frequency of valve closures ranges from 1 every 2-3 hours to 2-3 per hour. The frequency increases sharply to 10-15 or more times per hour in the initial phase of the nighttime portion of the daily cycle (Trusevich et al., 2021). The ability of the organism to maintain a normal daily rhythm indicates the level of adaptation of the animal to its habitat. Any deviations from normal conditions indicate significant changes in environmental parameters.

In the daily rhythm of freshwater mollusks, two groups of movements can be distinguished: a) adductions (valve closures) – rapid, brief movements of valve closure and opening lasting from 0.5 to 1.5-2 minutes (Trusevich et al., 2021), which mainly facilitate the removal of metabolic products and pseudo-feces, and b) slow, occupying most of the day, shallow oscillations that facilitate filtration and respiration processes. The amplitude and frequency of valve opening are completely individual and vary widely depending on the physiological state of the mollusks and fluctuations in environmental factors.

Mollusks react sharply to many sudden changes in the surrounding environment. Tapping on the aquarium, sudden sounds, vibrations, sudden shadows, and the like cause mollusks to instantaneously (within 2-3 seconds) close their valves for a short time (1-2 minutes) (Trusevich et al., 2021), which appears to be a manifestation of protective reflexes. However, with frequent repetition of these non-damaging effects, the magnitude of the mollusk reaction decreases rapidly and disappears. Such brief synchronized responses of mollusks practically do not affect the overall rhythm of valve movement, and during the operation of automated water environment monitoring systems, they should be excluded by the controlling computer programs as false signals.

Sensitivity of freshwater mollusks to pollutants

Laboratory experiments assessing the sensitivity of mollusks to pollutants in freshwater environments have been conducted since 2017 in 120-liter aquariums installed on the riverbank with continuous water flow from the main riverbed at 4 liters per minute. Experiments were conducted synchronously in flowing and non-flowing variants. In the non-flowing variant, the calculated concentration of the pollutant was introduced into the aquarium through a tube from a distance of 3 meters. Uniform mixing was achieved using an aquarium micro compressor. In the flowing variant, the calculated concentration of the toxicant solution was supplied by a peristaltic pump directly into the flow of incoming water in the aquarium, thus maintaining the necessary concentration of the toxicant throughout the experiment.

The mollusks were tested for sensitivity to: ammonia – 1; 2; 10 MAC; copper sulfate – 0.062; 0.125; 0.25; 0.5; 1; 2 MAC; detergent sodium dodecyl sulfate (SDS) – 1; 2; 3; 5 MAC; lead acetate – 10; 20; 30; 50 MAC; cadmium sulfate – 20; 30; 100 MAC; potassium bichromate – 10; 20; 100 MAC; nickel sulfate – 20; 100 MAC (in terms of metal ions), in accordance with MAC values established by Russian Hygienic Standards (Trusevich et al., 2017).

Results showed that signs of mollusk reaction to the appearance of polluting chemical agents in water depend on the nature and concentration and manifest in increased frequency and duration of adductions, decreased amplitude of valve opening, and/or complete closure of valves during negative influences. Negative effects are detected for several hours after the removal of polluting components from aquarium water. Mollusks react sharply to ammonia and detergents even at relatively low concentrations – 2 mg/l (2 MAC) according to Russian Hygienic Standards (SanPiN 1.2.3685-21). Copper ions present the highest stress factor for mollusks, with sensitivity thresholds as low as 0.006 mg/l (Trusevich et al., 2017). In the waters of the Chornaya River, which have a high content of humic substances and

other components of organic and mineral suspension, the toxic action of heavy metals on mollusks is greatly reduced. The first signs of lead impact at 2-hour exposure are only detected at 100 MAC (0.6 mg/l), nickel at 100 MAC (2 mg/l), cadmium at 20 MAC (0.02 mg/l), and chromium at 20 MAC (1 mg/l). This is explained by the fact that salts of heavy metals and other chemically active substances, upon entering water environments with high humic acid content, practically instantaneously form complex compounds of varying stability levels and are largely converted to sediment in bottom silts, while the greatest danger to living organisms comes from free ions of chemically active elements (Trusevich et al., 2017).

It is important to note that mollusk reaction in the flowing water variant of the experiments is significantly lower than in the non-flowing variant. Consequently, when assessing the toxicity of a substance, significant discrepancies can arise between flowing and stagnant water conditions. These conclusions are fully consistent with data from numerous foreign researchers.

Organization of a system for monitoring the aquatic environment

Active research, which began in 2020, is currently underway to develop sensor networks for water quality monitoring, including those based on the principles of the Internet of Things (Trusevich et al., 2010). The creation of a unified automated aquatic environment monitoring system with a single monitoring center is a critical requirement for implementing the operational control program, as it will ensure the detection of emergency situations and the adoption of measures to prevent negative impacts on aquatic ecosystems. The proposed system consists of three elements: a server with a database, the biosensor systems described in the previous section, and user or operator information panels (fig. 3).

The system server is implemented using scripts stored on remote computers in the Data Center. These scripts enable the following capabilities:

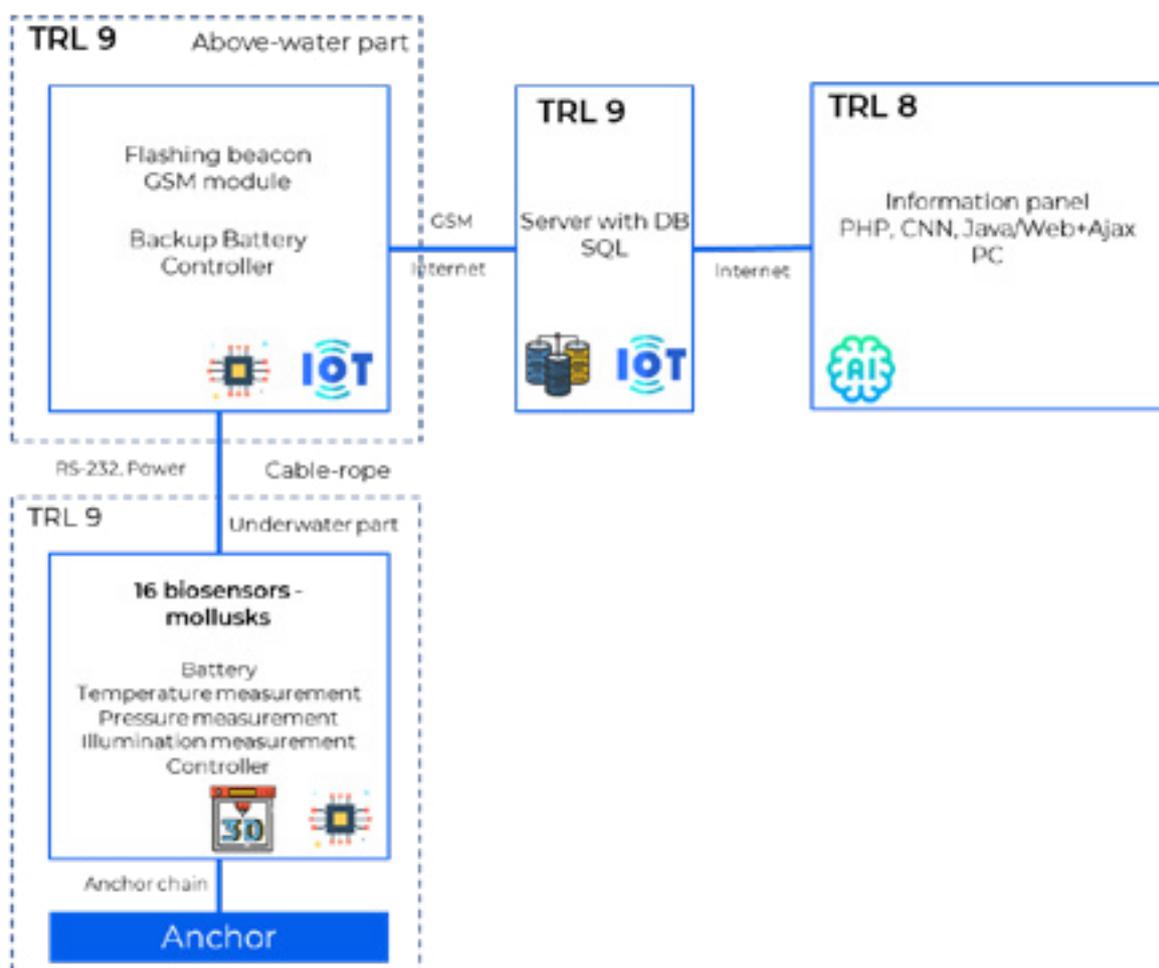


Figure 3. Diagram of the aquatic environment monitoring system (Source: Author)

importing current calibration coefficients for each system to the server; receiving data from the system and storing this data on the measurement data server; providing system operators with access to measurement data, primary data, calibration coefficients, and data received from the system online. The server software, responsible for processing incoming measurement data, extracts data from the POST request received from the system. Based on the received system serial number, this software finds the corresponding data on the server and appends the new data to the primary measurement data files and physical characteristics files.

The systems transmit primary and pre-processed measurement data to the server and upload calibration coefficients. Using specialized software on the dashboard, the operator can access

the server and monitor the status of any operating system (or determine why one is currently down). The software automatically monitors physiological parameters and behavioral responses of mussels, such as valve opening range, closure frequency, and duration of closure, among other things. After analyzing these parameters, the program can identify significant deviations from normal values and generate alerts that may indicate pollution in the monitored aquatic area.

To manage the system, the operator must periodically (but no more than once every 24 hours) monitor and analyze the system’s status: to identify unusual behavior patterns; to detect measurement channels that are not functioning properly; and to study long-term degradation patterns (possible responses to long-term, low-level pollution).

Laboratory and field tests of the device

Before long-term trial operation, the system’s functionality was verified in laboratory and field conditions for both marine and freshwater environments.

Laboratory tests (marine environment): During the first stage, a prepared mussel colony block with attached marine mussels was placed in a tank containing seawater, where the mussels adapted for 24 hours, and data on their normal valve activity was transmitted to the server. The seawater was enriched with oxygen by blowing air through it using a micro-compressor. The lighting was not changed during the tests, and no impacts on the tank were allowed to confirm the “NORMAL STATE” signal in the program interface. At the beginning of the tests, 5 grams of a 10%

ammonia solution were added to the tank using a syringe. Within 10 minutes, a “POLLUTION” warning signal appeared on the operator’s computer monitor. A second portion of the prepared solution, 5 grams at a 10% concentration, was then added to the tank. Within 10 minutes, a “DANGEROUS POLLUTION” warning signal appeared on the operator’s computer monitor. Changes in motility parameters were monitored on the operator’s computer monitor using a valve activity analysis program. After the warning signals were generated, the water in the tank was replaced with clean water, and the time it took for the mussels to regain motility was recorded.

Field testing (marine environment): Tests in the marine environment were conducted by exposing the mussels to a measured level of pollution in the immediate vicinity of a mussel colony block located at the operating depth. An environmentally safe solution of table salt, detergent, and white clay was first prepared. The underwater module of the complex was installed at a depth of 3 meters, where the mussels adapted for 2 hours, and data on their normal valve activity was transmitted to the server. The prepared solution was poured through a 40 mm diameter plastic pipe at a distance of 1 m from the underwater module. The operator monitored the mollusks’ motor activity using a valve activity analysis program. Within 15 minutes, the «DANGEROUS POLLUTION» warning signal was automatically generated.

Additionally, the system was tested for mechanical impacts, leakage, and hydrostatic pressure, as well as for measuring mussel valve opening, temperature, illumination, and pressure, and for monitoring battery voltage.

Field trial operation (marine environment): From August to December 2021, the first unit of the system was deployed in the coastal waters of Sevastopol at the mariculture aquafarm for trial operation. From June to October 2022, the system was reinstalled. After 120 days, 14 of the 16 mussels remained in the operating position (two mussels died).

Freshwater system performance: The freshwater system deployed for two years in continuous functioning at water intake monitoring points in Sevastopol

demonstrated high sensitivity, reliability, and efficiency in detecting dangerous water pollutants in real time. The system successfully operated under natural conditions in the Chornaya River, showing the ability to continuously monitor freshwater quality while maintaining operational stability over extended periods.

Anomaly detection using machine learning

Anomaly detection in our system is implemented using machine learning algorithms. The study assessed the feasibility of anomaly detection in bivalve data using unsupervised machine learning algorithms (Grekov et al., 2023). Four machine learning algorithms were tested for the anomaly detection procedure: elliptical envelope, isolation forest (iForest), one-class support vector machine (SVM), and local outlier factor (LOF).

By tuning the hyperparameters of the four algorithms, their performance estimates were obtained, and the response time of the methods for anomaly detection was assessed. Since an F1 score of one was obtained for three algorithms with different hyperparameters, the methods were compared in terms of response time and anomaly detection. The F1 score is the harmonic mean of precision and recall and provides a better estimate of misclassified cases than the accuracy score.

For three anomalies, the iForest machine learning algorithm demonstrated the best anomaly response rate when averaging data over 15 minutes. The same set of averaging times was tested for all models: no averaging, 1 minute, 5 minutes, 15 minutes, and 30 minutes. The elliptical envelope and one-class SVM algorithms also demonstrated good performance, but their anomaly detection rates were lower than those of the iForest algorithm. This artificial intelligence component significantly enhances the system’s ability to identify subtle environmental changes and distinguish genuine pollution events from natural behavior variations, thereby improving the reliability and responsiveness of the monitoring network.

Conclusion

The developed system enables early detection of dangerous levels of pollution in both marine and freshwater bodies. The system automatically and in real time receives digital data on mussel movements using Hall sensors and magnets attached to their shells. Individual responses of 16 mussels are simultaneously recorded. A synchronized response by a group of mussels (at least 70% of the total) triggers an alarm. The developed software analyzes mussel movement trends, identifies synchronized mussel responses to environmental influences, automatically triggers an alarm, and transmits data online (all in real time). The system’s latency to respond to pollution ranges from a few seconds to several minutes, depending on its nature and concentration.

10 years of use of the system in both marine and freshwater environments confirm its high effectiveness in assessing water quality and pollution levels in seas, freshwater bodies, and rivers. The design features of the developed system allow it to be used both as a permanent water monitoring station and as a portable option for active monitoring in specific regions and areas. The system’s demonstrated performance in diverse aquatic ecosystems – from seawater to river freshwater – underscores its versatility and robustness for sustainable water utilization applications.

The key advantages of the proposed system include: a highly automated monitoring process, the ability to create large automated aquatic monitoring networks, enabling real-time detection of pollution sites and assessment of their hazard to humans and other living creatures, high reliability, ease of operation, durability, and a relatively low cost. The use of native mollusks allows for the scalability of the complex and the entire system to other regions. Integration of artificial intelligence and machine learning algorithms further enhances the system’s capability to detect anomalies with high precision and minimal false positives, supporting effective environmental management and the achievement of sustainable water utilization goals.

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Tech Events

28 February - 2 March 2026

12th International Conference on Environment and Renewable Energy (ICERE 2026)

Nha Trang, Viet Nam
Contact:
Ms. Alice Lin
Conference Secretary
Tel: +86-18148151445
Email: icere@ieet.ac.cn
<https://icere.org/>

6-8 March 2026

16th International Conference on Renewable and Clean Energy (ICRCE 2026)

Osaka, Japan
Contact:
Ms. Rachel Cao, Conference Secretary
Tel: 86-132-9000-0003
Email: icrceconf@126.com
<https://www.icrce.org/>

9 Mar 2026

2026 Asia-Pacific Climate Summit (APCS)

Bali, Indonesia
Contact:
APCS-2026 Secretariat
Tel: +91 8895188931
Email: info.isfecc@gmail.com
<https://isfecc.org/Conference/2364/APCS/>

9-10 March 2026 (Pre-events)

11-13 March 2026 (Main Conference) 2026 12th Better Air Quality Conference (BAQ)

Bangkok, Thailand
Contact:
Conference Secretariat - Clean Air Asia
Co-organized by: Asian Development Bank (ADB), Climate and Clean Air Coalition
CCAC), ESCAP, UNEP
<https://cleanairasia.org/baq/>

26-27 March 2026

2026 8th International Conference on Renewable Energy, Resources and Sustainable Technologies (EnergyTech)

Tokyo, Japan
<https://energytechconference.com>

28-30 March 2026

2026 7th Asia Conference on Renewable Energy and Environmental Engineering (AREEE)

Singapore
Contact:
Vera Liao
Conference Secretary
AREEE Conference Secretariat
Tel: +86-17311381986
Email: areee@iacsitp.com
<https://www.areee.org/>

23 April 2026

Digital Transformation Summit Malaysia 2026

Kuala Lumpur, Malaysia
<https://events.coinpedia.org/digital-transformation-summit-malaysia-2026-7462/>

14-17 May 2026

RENEWABLE ASIA – 2026

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Vasanthnagar, Bangalore -
560052, INDIA.
Tel: 080 - 46000603/6
Mobile: +91 98451 99545
Email: info@renewable-asia.in
<https://renewable-asia.in/>

3-5 June 2026

ENERTec Asia 2026

Kuala Lumpur, Malaysia
Contact:

Ms. Esther Lim

Email: esther.lim@informa.com
<https://www.enertecasia.com/>

9-11 June 2026

Asia Pacific Green Hydrogen 2026

Sarawak, Malaysia
Contact:
Conference Secretariat
Email: secretariat@borneobiz-connect.com
<https://hydrogenapac.com/>

22-26 June 2026

World Hydrogen Energy Conference (WHEC) 2026

Singapore
Contact:
Conference Secretariat
Email: info@whec2026.org
<https://whec2026.org/>

7-9 July 2026

2026 Asia Climate Summit

Hong Kong, China
Contact:
International Emissions Trading Association (IETA)
The Great Room, 63 Robinson Road, Afro-Asia
Level 6, 7 and 8, Singapore 068894
Email: singapore@ieta.org
<https://www.ieta.org/events/asia-climate-summit-ac-s-2026>

7-10 July 2026

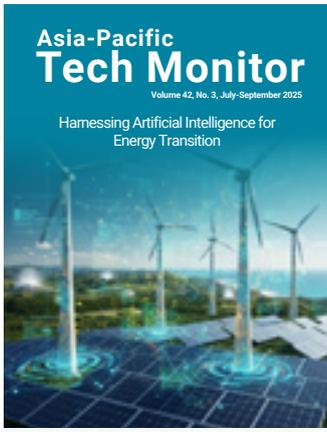
ITU AI for Good Global Summit 2026

New York, USA
<https://aiforgood.itu.int/ai-events-calendar/>

8-9 July 2026

Carbon Capture APAC Summit 2026

Melbourne, Australia
<https://www.carboncaptureapac.com>



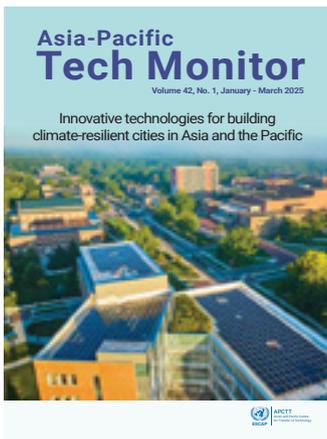
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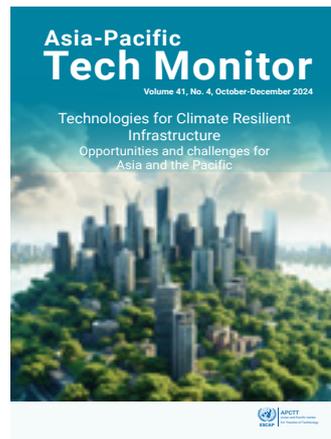
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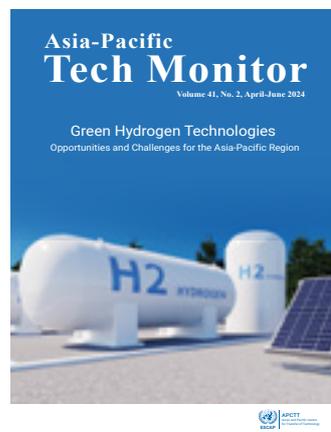
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