Roadmap to Innovation in the Dams Sector

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EXECUTIVE SUMMARY

The Dams Sector provides critical water retention and control services integral to national security, environmental health, and community safety. The sector faces a wide landscape of evolving threats and vulnerabilities, including those posed by natural disasters, cyber threats, and physical threats. Challenges due to changing weather patterns and aging infrastructure enhance these threats. Addressing aspects of these threats and vulnerabilities require innovative scientific and technological (S&T) advancements to enhance the sector's long-term security and resilience. The *Roadmap to Innovation in the Dams Sector* outlines Research and Development (R&D) Focus Areas for the next 3-5 years to enhance the security and resilience of the sector and ensure that dams and related infrastructure can withstand current and emerging risks. By developing new innovative technologies and leveraging and enhancing existing ones, the sector can improve the overall resilience of the nation's dams and related infrastructure.

The R&D Focus Areas identified in this Roadmap include improved design and construction techniques, advanced sensing and monitoring technologies, predictive analytics, modeling and simulation, and physical and cybersecurity tools and methodologies (figure 1). Advancements in these areas aim to help dam owners and operators better prevent, detect, respond to, and recover from a variety of threats and vulnerabilities, ensuring the long-term reliability and safety of sector assets.

The six R&D Focus Areas were identified through extensive stakeholder engagement conducted by the Dams Sector Management Team, including a series of interviews with 35 sector stakeholders and a Dams Sector Innovation Workshop led by the Cybersecurity and Infrastructure Security Agency (CISA) in partnership with the Dams Sector R&D Workgroup. The 2024 effort built upon previous sector-specific R&D evaluations, including a 2012 workshop and R&D priorities highlighted in the *2015 Dams Sector-Specific Plan*, which outlined needs for the safe design, construction, operation, and maintenance of dams and related assets. This Roadmap highlights updated R&D Focus Areas, including specific advancements and capabilities to achieve selected outcomes within each focus area.

For additional information on this roadmap or the Dams Sector in general, contact the Dams Sector Management Team at DamsSector@mail.cisa.dhs.gov.

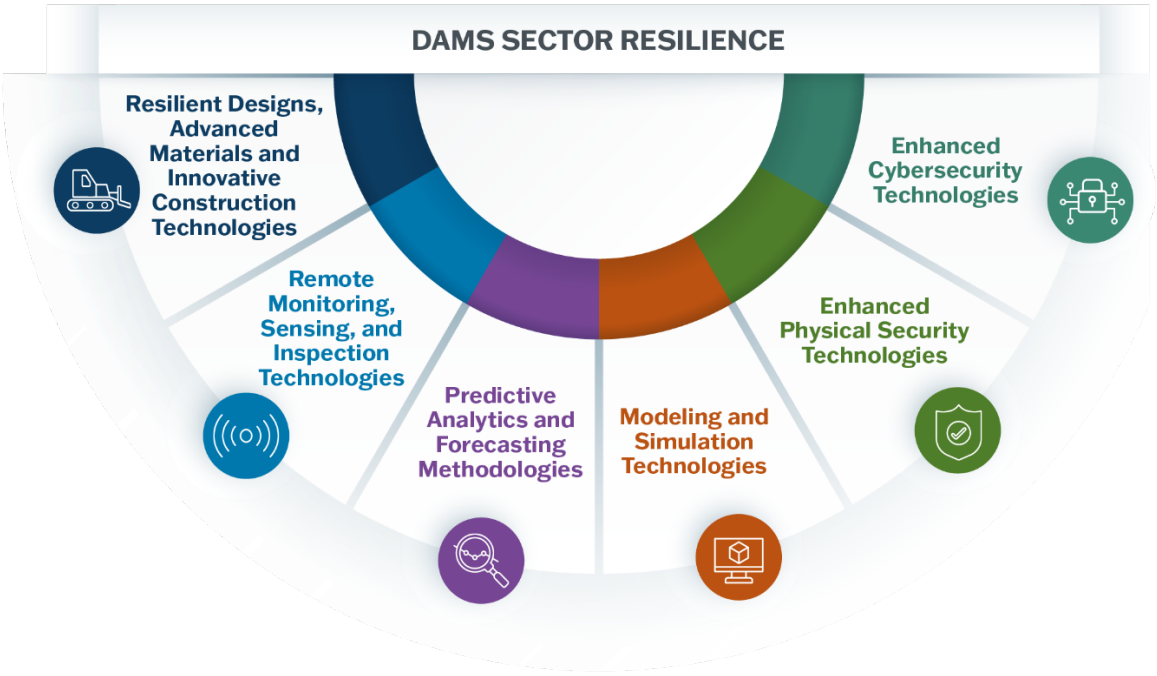

Figure 1. *Dams Sector R&D Focus Areas to improve security and resilience*

Overview of R&D Focus Areas

Resilient Designs, Advanced Materials, and Innovative Construction Technologies

The development of stronger materials and more flexible, adaptive construction approaches are essential to enhancing sector resilience in the face of natural hazards. These advancements aim to enhance the ability of both new and existing dams to withstand threats ranging from earthquakes to extreme weather events, reducing repair and maintenance costs over time. S&T Advancements in this Focus Area include:

- Material and Structural Innovation
- Modular and On-Site Repair Technologies
- Self-Healing and Adaptive Materials
- Vegetation and Erosion Control

Remote Monitoring, Sensing, and Inspection Technologies

Advancements in this Focus Area aim to enable dam owners and operators to effectively monitor the condition of their assets in real-time. These technologies can help detect early signs of degradation, stress, or potential failure, offering the opportunity to address issues before they become critical or too costly. The ability to collect real-time data from sensors placed throughout dam systems can significantly improve situational awareness and facilitate faster, more informed responses to potential risks. S&T Advancements in this Focus Area include:

- Advanced Sensor Technologies
- Nondestructive Inspection and Testing
- Real-time and Remote Monitoring

Predictive Analytics and Forecasting Methodologies

These tools can help dam owners and operators to anticipate and respond to potential risks more proactively, by enhancing the ability to estimate future demands on their assets. Using data-driven insights, dam operators may be better equipped to implement preventative measures, allocate resources effectively, optimize maintenance operations, and mitigate the impacts of natural disasters and other disruptive events before they occur. S&T Advancements in this Focus Area include:

- Digital Twin Platforms and Artificial Intelligence (AI) Integration
- Performance Evaluation and Optimized Maintenance
- Enhanced Natural Hazard and Weather Forecasting

Modeling and Simulation Technologies

Virtual models of dams and their environments enable operators to simulate a variety of scenarios—from extreme weather to physical attacks—to assess how dam infrastructure may respond under stress. These models not only help inform day-to-day operations, but also long-term planning for repairs and rehabilitation. S&T Advancements in this Focus Area include:

- Digital Twin Platforms for Real-Time Data Integration
- Enhanced Models for Material Aging and Degradation
- Improved Hydrological and Atmospheric Models
- Validated Performance Analysis Tools

Enhanced Physical Security Technologies

Dams face a variety of potential physical threats including criminal activities, sabotage, and various types of explosives. To deter, detect, assess, respond to, and recover from these attack scenarios, owners and operators

require advanced detection and deterrence tools to protect sector assets. S&T Advancements in this Focus Area include:

- AI-Enhanced Security Systems
- Counter-Drone Technologies
- Enhanced Surveillance and Intrusion Detection
- Physical Deterrence and Vehicle Barriers

Enhanced Cybersecurity Technologies

With increasing reliance on interconnected digital systems, dams are becoming more vulnerable to cyber intrusions. By developing and making available AI-powered threat detection and improved OT and IT methodologies, the sector can defend against malicious actors looking to exploit security gaps and secure existing vulnerabilities. S&T Advancements in this Focus Area include:

- Advanced Threat Detection and Management
- AI-Based Cybersecurity Applications
- Operational Security and Training
- Secure Data Management
- System Redundancy and Fail-Safes

Roadmap Navigation

The insights in this Roadmap are organized into six Focus Areas, each of which addresses core concepts of potential threats, vulnerabilities, and opportunities for building resilience. Each Focus Area is mapped to corresponding S&T advancements, desired capabilities, and intended outcomes.

Core Concepts

- **Threats** are natural or human-caused occurrences, individuals, entities, or actions that have or indicate the potential to harm life, information, operations, the environment and/or property.
- **Vulnerabilities** are physical features or operational attributes that render an entity open to exploitation or susceptible to a given hazard.
- **Resilience** refers to the ability of individuals, entities, or systems to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions.

Taxonomy

- **Focus Areas** are broad themes in R&D that can address threats and vulnerabilities and enhance the resilience of dams and related infrastructure, including *Resilient Designs, Advanced Materials, and Innovative Construction Technologies; Remote Monitoring, Sensing, and Inspection Technologies; Modeling and Simulation Technologies; Predictive Analytics and Forecasting Methodologies; Security Outcome Technologies;* and *Enhanced Cybersecurity Technologies.*
- **S&T Advancements** are categories within each Focus Area that map to specific capabilities, representing the creation of new technologies and/or methodologies or the enhancement of existing ones. These are listed alphabetically within each Focus Area.
- **Desired Capabilities** are descriptions of aspirational states or functionalities facilitated by the S&T Advancements and the potential technologies or methodologies identified within the S&T advancement category.
- **Intended Outcomes** are anticipated security or resilience capabilities that may be achieved through R&D in the corresponding S&T advancement category.

KEY FINDINGS

The key findings of this Roadmap outline the critical R&D Focus Areas and cross-cutting factors that have the potential to drive advancements in Dams Sector security and resilience over the coming years. Many of the S&T Advancements identified in this Roadmap apply to various stages of resilience-building and across the asset lifecycle (i.e., investigation, design, construction, operation, maintenance, rehabilitation, and decommissioning). As such, this Roadmap organizes the R&D Focus Areas into six functional categories, in no priority order (figure 2).

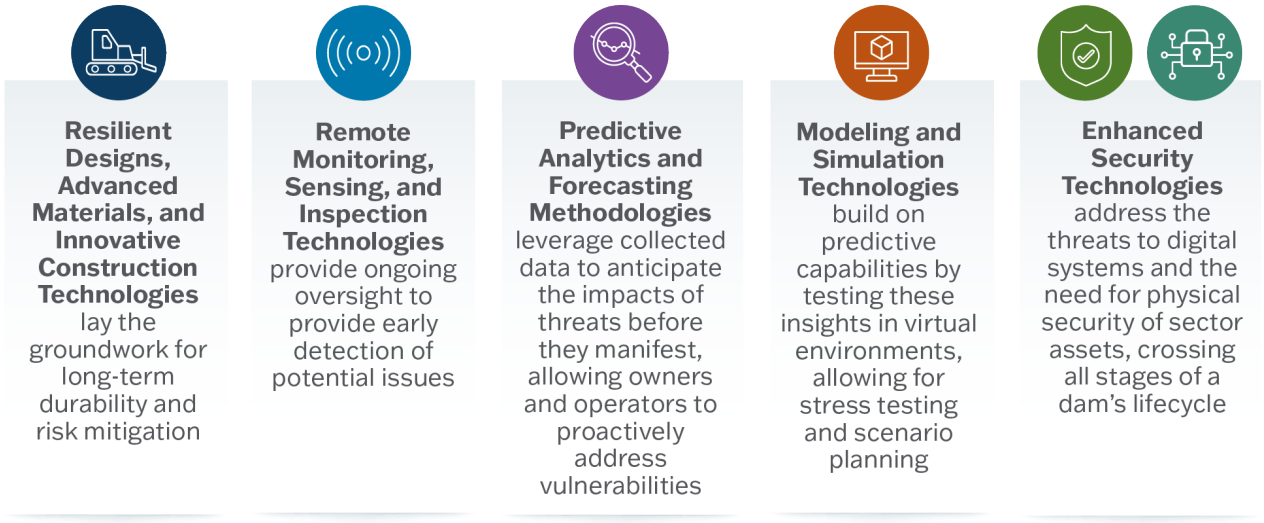

Figure 2. *Order of R&D Focus Areas*

R&D Focus Areas

The following R&D Focus Areas represent the identified desired innovations laid out in this Roadmap:

- **Resilient Designs, Advanced Materials, and Innovative Construction Technologies:** New materials, including self-healing polymers and high-performance concrete, can offer enhanced durability in the construction and repair of Dams Sector assets, extending the lifecycle of the infrastructure and reducing the frequency and cost of repairs. These innovations can be applied across various Dams Sector components and operational needs, providing adaptable solutions to different geographical and environmental conditions.
- **Remote Monitoring, Sensing, and Inspection Technologies:** Innovations in sensor technologies, robotics and autonomous systems, and real-time data integration can provide dam owners and operators with detailed, real-time insights into the condition of their assets. These systems may reduce the need for costly and/or dangerous manual inspections and repairs and can detect emerging issues across both physical infrastructure and operational technology systems.
- **Modeling and Simulation Technologies:** Tools such as digital twins and hydrological models allow operators to simulate various threat and vulnerability scenarios, from extreme weather events to operational malfunctions. This technology supports informed decision-making and planning for a range of vulnerabilities, applying to both physical and cyber resilience strategies.
- **Predictive Analytics and Forecasting Methodologies:** Advanced data analytics and AI tools can be used to forecast potential demands on the system. These tools can help prioritize maintenance and repairs, minimizing operational costs and enabling dam owners and operators to better anticipate disruptive conditions.

- **Enhanced Physical Security Technologies:** AI-based security systems, counter-drone measures for federal facilities, and advanced physical intrusion detection tools can help safeguard dams from physical threats. These technologies can be deployed in multiple security scenarios and include scalable solutions for facilities that vary in size and level of resources.
- **Enhanced Cybersecurity Technologies:** As cyberattacks on critical infrastructure increase, the development of advanced cybersecurity tools, such as real-time threat detection, anomaly monitoring, and AI-driven defense systems, is critical for ensuring the security of sector assets. These tools help protect both operational technology (OT) and information technology (IT) systems, supporting comprehensive cybersecurity coverage.

Cross-Cutting Themes

Several key findings highlight advancements and desired capabilities that apply across multiple R&D Focus Areas and operational needs in the Dams Sector:

- **Affordability and Accessibility:** Cost is a major consideration for dam owners and operators, and the R&D Focus Areas outlined in this Roadmap include scalable and practical solutions. Stakeholders repeatedly expressed the need for cost-effective solutions that reduce maintenance expenses and operational downtime. Technologies such as predictive analytics and AI-driven monitoring tools may reduce overall operational expenses by helping to prioritize repairs, improve maintenance scheduling, and extend asset lifecycles. Modular construction techniques and the use of advanced materials also can contribute to affordability by accelerating repairs and reducing costly long-term maintenance needs.
- **Information Sharing and Data Collection:** To maximize resilience and support both the development and proliferation of effective S&T Advancements, the ability to collect, share, and act on data is of vital importance. Various technologies mentioned in this Roadmap facilitate and rely on real-time data collection across Dams Sector assets, systems, and stakeholders, allowing operators to make informed decisions and collaborate more effectively with partners, including local communities and emergency response teams.
- **Multiple Applications of Advancements:** Many of the technological advancements identified in this Roadmap have multiple applications and may address numerous threats or vulnerabilities such as natural hazards, operational failures, physical threats, and cyberattacks simultaneously. The integration and development of AI, machine learning (ML), and digital twin platforms emerge as recurring themes, foundational to many of the technologies and processes aimed at improving decision-making, maintenance, and incident response. For example, AI-based monitoring systems are applicable to both physical and cybersecurity, while digital twin technologies can model everything from operational failures to extreme weather events. The multi-functional approach of many of the advancements identified in this Roadmap indicate the sector's interest in addressing a wide range of threats and vulnerabilities with fewer, more versatile tools.

By focusing on these cross-cutting technologies and principles, the Dams Sector can improve security and resilience while maintaining operational efficiency and reducing costs. These findings offer a guide for S&T advancements that support the needs of owners, operators, and stakeholders across the sector.

FOCUS AREA: RESILIENT DESIGNS, ADVANCED MATERIALS, AND INNOVATIVE CONSTRUCTION TECHNOLOGIES

Advancements in design, material science, and construction methods are key to enhancing the resilience of dams and related infrastructure. These advancements focus on creating stronger, self-sustaining, and more durable materials that are resistant to environmental and structural threats, thereby extending the lifespan of infrastructure and optimizing maintenance and repair strategies. S&T Advancements in these areas can accelerate repair times and limit the need for maintenance, reducing potential downtime and risk of failure.

This R&D Focus Area has applications for building resilience and addressing threats and vulnerabilities associated with *natural hazards*; *operations, maintenance, repair, and rehabilitation*; *physical threats*; and *cybersecurity.*

S&T Advancements	Desired Capabilities	Intended Outcomes
Material and Structural Innovation	New and cost-effective advanced materials (e.g., high-performance concrete, fiber-reinforced polymers, and corrosion-resistant alloys) for construction, repair, and rehabilitation.	Physical components and systems that exhibit improved performance and require reduced maintenance, thus extending the cost-effective lifespan of dams and related infrastructure.
	Use of longer-lasting and stronger weather-resistant materials that can withstand extreme conditions.	Structural components and systems that are resistant to degradation and damage from environmental threats (e.g., extended periods of drought, frequent flooding, extreme temperatures), extending the cost-effective lifespan of the dam or related infrastructure.
	Use of fireproof and ballistic-resistant materials or coatings for critical components.	Structural components and systems that exhibit robust performance against ballistic threats.
Modular and On-Site Repair Technologies	Use of tools with multiple purposes and devices capable of replacing more expensive components	Ability to conduct faster, fewer, and more affordable repairs, thus reducing downtime associated with maintenance periods, avoiding long lead times for manufacturing parts, and minimizing human safety risks during repair and rehabilitation work.
	Implementation of modular and adaptive components for easier replacement and upgrades.	
	On-site 3D printing of repair parts, including research into standardizing components for faster replacement.	
	Use of advanced manufacturing methods (e.g., robotics) to accelerate repairs and enhance performance.	

S&T Advancements	Desired Capabilities	Intended Outcomes
Self-Healing and Adaptive Materials	Use of self-sustaining, maintaining, and healing materials (e.g., reinforced "self-healing" polymers) for repair and rehabilitation.	Structural components and systems with reduced cost and downtime associated with maintenance as well as improved performance against environmental conditions.
Vegetation and Erosion Control	Advanced tests of vegetation for drought resilience to mitigate erosion and slope failure.	Practical solutions to reduce the risk of erosion and overtopping, strengthening the structural health of the infrastructure and limiting the need for additional intervention or repair technologies.
	Innovative material science solutions to protect earthen dam faces from erosion during overtopping events.	

FOCUS AREA: REMOTE MONITORING, SENSING, AND INSPECTION TECHNOLOGIES

Remote monitoring, sensing, and inspection technologies can provide real-time awareness of potential threats and vulnerabilities to dams and related infrastructure, assessing structural condition and potential risks. The use and development of these technologies can improve the ability of dam owners and operators to detect early signs of structural issues, environmental threats, and security breaches, facilitating timely intervention.

This R&D Focus Area has applications for building resilience and addressing threats and vulnerabilities associated with *natural hazards*; *operations, maintenance, repair, and rehabilitation*; *physical threats*; and *cybersecurity.*

S&T Advancements	Desired Capabilities	Intended Outcomes
Advanced Sensor Technologies	Development of smart sensor technology for continuous environmental monitoring.	Improved response time to and awareness of changing environmental factors, reducing the risk of undetected structural and ecological threats.
	Implementation of multispectral and wave-based sensing methods coupled with AI for decision-making and modeling.	
	Improved satellite technology integrated with AI-enabled monitoring systems to evaluate the structural health of dams and related infrastructure.	
Nondestructive Inspection and Testing	Use of remote testing and monitoring methods such as ultrasonic testing, magnetic resonance imaging, and laser scanning to detect internal defects without causing damage.	Improved inspection and testing capabilities that provide current and detailed identification of defects, equipping owners and operators with the information they need to prioritize repairs before major failures occur.
	Use of sonar and laser systems for detecting cracks in structural components.	
	Use of remote and autonomous technologies (e.g., drones, underwater robots) for inspection and monitoring in remote or hard-to-reach areas.	
Real-time and Remote Monitoring	Implementation of real-time seismic monitoring systems that feed into performance analysis models.	Rapid evaluation of earthquake-related impacts on dams and related infrastructure.
	Deployment of advanced detection and assessment equipment, such as fiber optics or UAS, to monitor structural health and emerging vulnerabilities (e.g., seepage, cracks) at sector facilities.	Continuous structural health monitoring to enable early detection of potential vulnerabilities, resulting in informed decision making on maintenance and repair strategies.
	Use of non-contact sensing technologies (e.g., cameras, lasers) coupled with AI algorithms for real-time monitoring and alert systems.	Enhanced notification systems based on real-time monitoring technology to alert owners and operators and those residing downstream of potential flooding or natural hazards.

FOCUS AREA: PREDICTIVE ANALYTICS AND FORECASTING METHODOLOGIES

The development and integration of Predictive Analytics and Forecasting Methodologies aims to proactively identify vulnerabilities and mitigate potential risks associated with dam operations and environmental threats that could lead to dam failure. Using predictive analytics, owners and operators of dams and related infrastructure can identify maintenance priorities, anticipate and mitigate against potential overtopping or breaches, and enhance detection and early warning systems, protecting downstream communities and infrastructure from potentially adverse effects resulting from asset failure or disruption.

This R&D Focus Area has applications for building resilience and addressing threats and vulnerabilities associated with *natural hazards*; *operations, maintenance, repair, and rehabilitation*; *physical threats*; and *cybersecurity.*

S&T Advancements	Desired Capabilities	Intended Outcomes
Digital Twin Platforms and AI Integration	Use of digital twin platforms and software, which create a virtual representation of the actual system, to test and enhance predictive analytics.	Informed decision-making capabilities facilitated by digital twin platforms that can predict how infrastructure (individual or multiple facilities) might respond to various stressors, including natural hazards, physical attacks, and cyberattacks, improving long-term resilience.
	Use of AI to refine and adjust predictive models that can rapidly and accurately adapt to new data, predicting and simulating potential vulnerabilities or threats to the system and its components.	
	Use of AI-based technologies for modeling of compound hazards to understand their impact on individual and/or interconnected facilities and to explore preventative and/or mitigative measures.	
Performance Evaluation and Optimized Maintenance	AI-driven algorithms and tools that can predict disruptive conditions associated with natural hazards or risks associated with operations, maintenance, repair, and rehabilitation (e.g., aging structures, overtopping, environmental factors).	Improved ability to predict the performance of the system under multiple scenarios, optimizing maintenance and repairs, and ultimately avoiding significant disruptions or catastrophic failures.
	Use of advanced monitoring technology and AI-enabled data analytics to prioritize maintenance needs based on real-time data and smart sensors.	Optimized maintenance schedules and anticipation of necessary repairs to increase cost-effectiveness and improve the overall resilience of the system.

S&T Advancements	Desired Capabilities	Intended Outcomes
Enhanced Natural Hazard and Weather Forecasting	Improved geospatial data collection and analysis tools to help predict impacts of severe weather events.	Improved emergency preparedness for and incident response during natural disasters, as well as improved communication and notification for downstream communities.
	High-resolution precipitation forecasts and tools to monitor rainfall and foresee flooding.	
	Weather projections for use in modeling and simulations.	
	Use of AI and ML- enabled tools to increase the accuracy of forecasting and predict resultant impact on system performance.	Reduced impact of extreme weather events through the use of Forecast Informed Reservoir Operation (FIRO), which supports decision making based on current and forecasted conditions.

FOCUS AREA: MODELING AND SIMULATION TECHNOLOGIES

Advanced modeling and simulation technologies create a dynamic representation of dams, related infrastructure, and their physical and cyber environments, which are integral to predicting and preventing failures. Threats and vulnerabilities addressed by this R&D Focus Area include aging and material stressors; hydrological, hazard, and weather impacts; and potential physical and cyberattacks. By simulating these scenarios, these approaches help optimize maintenance and response times, and enhance overall structural integrity.

This R&D Focus Area has applications for building resilience and addressing threats and vulnerabilities associated with *natural hazards*; *operations, maintenance, repair, and rehabilitation*; *physical threats*; and *cybersecurity.*

S&T Advancements	Desired Capabilities	Intended Outcomes
Digital Twin Platforms for Real-Time Data Integration	Multiscale digital twin models that integrate real-time physical and organizational data.	Improved ability to use real-time data to prepare for and respond to a variety of threats and vulnerabilities, including natural hazards, structural degradation, and physical and cyberattacks.
	Maintaining digital twin models using sensor data and ML for testing and updates.	
	Use of digital twins for simulating potential cyber and physical attacks on dam infrastructure to identify vulnerabilities.	
Enhanced Models for Material Aging and Degradation	3D models to simulate the impacts over time of aging materials and exposure to extreme conditions.	Informed decision-making for risk management and maintenance strategies to enhance infrastructure resilience based on detailed models that replicate structural vulnerabilities associated with the actual system.
	Advanced numerical simulations that more accurately predict material and structural performance under extreme conditions.	
Improved Hydrological and Atmospheric Models	Use of hydrological models to assess impacts of weather events and environmental factors, including research and simulation of non-Newtonian fluids, sediment, and other factors that could impact operations.	Improved understanding of system response to a variety of environmental factors to help inform actions to mitigate risks posed by compound hazards.
Soil and Structural Analysis	Use of advanced soil/structure modeling and simulation tools for improved performance evaluation and optimization of rehabilitation measures.	Optimized repair strategies and identification of emerging vulnerabilities to improve system performance.

FOCUS AREA: ENHANCED PHYSICAL SECURITY TECHNOLOGIES

Dams and related infrastructure are highly susceptible to various physical vulnerabilities and attack scenarios. S&T Advancements in Security Outcome Technologies focus on safeguarding assets from potential security incidents by developing and using detection and deterrence tools. By employing a variety of S&T Advancements in this Focus Area, such as physical deterrence technologies, intrusion and detection systems, and AI for advanced monitoring, dam owners and operators can implement a multi-layered security strategy that reduces the chance of a successful physical attack. The objective of these technologies is to quickly detect threats and prevent unauthorized access to dam assets and information, thereby improving response strategies and safeguarding both dam assets, and the communities that may be impacted by an intentional attack.

This R&D Focus Area has applications for building resilience and addressing threats and vulnerabilities associated with *physical threats* and *cybersecurity.*

S&T Advancements	Desired Capabilities	Intended Outcomes
AI-Enhanced Security Systems	Application of AI and ML algorithms to analyze data from surveillance systems and sensors for improved threat detection.	Faster identification of potential physical attacks using advancements that help optimize response, reducing the likelihood of successful attacks.
	Enhanced security systems with AI-enabled video overlays, including features such as weapons detection, facial recognition, and path reconstruction.	
Counter-Drone Technologies	Practical technologies, legal for use by owners/operators to prevent, deter, and mitigate unauthorized drone operations.	More robust operations by increasing the security and reducing the disruptions associated with unauthorized drone operations.
Enhanced Surveillance and Intrusion Detection	Use of multipurpose advanced sensing and monitoring equipment (e.g., fiber optics, UAS) to monitor sector facilities and detect potential physical attacks by threat actors.	Improved detection and assessment of potential land-side physical threats, enabling appropriate security responses, improved perimeter security, and early-warning systems.
	Implementation of advanced and cost-effective surveillance systems with high-resolution cameras, thermal imaging, and night vision.	
	Development and deployment of tools (e.g., sonar detection networks) to detect and address threats from waterside intrusions (e.g., surface and underwater approaches).	Improved detection and assessment of potential water-side physical threats, enabling appropriate security responses, improved perimeter security, and early-warning systems.

S&T Advancements	Desired Capabilities	Intended Outcomes
Physical Deterrence and Vehicle Barriers	Development and use of less-than-lethal deterrence technologies (i.e., Long Range Acoustic Devices) to improve sector facility security and deter physical threats.	Increased physical security against land-side approaches through strengthened perimeter defenses that prevent unauthorized access and deter intrusions without using lethal force.
	Use of portable and practical barriers made from advanced materials (e.g., self-healing, adaptive, sensor-equipped) to address a broad spectrum of potential vehicle types.	

FOCUS AREA: ENHANCED CYBERSECURITY TECHNOLOGIES

Enhancing the cybersecurity posture of dams and related infrastructure requires comprehensive strategies and technologies to detect anomalies in networks, prevent cyberattacks, secure data, and provide reliable fail-safes for incident response. Advancements in this Focus Area help ensure rapid response and recovery to threats that could disrupt the information technology (IT) and operational technology (OT) systems and functions that dams rely on for day-to-day operations and security. These advancements can also bolster secure information sharing efforts among stakeholders, preventing threat actors from accessing sensitive information that could be weaponized. While many of these capabilities currently exist, advancements are needed to make them available and affordable for Dams Secor facilities with varying resource constraints.

The R&D Focus Area has applications for building resilience and addressing threats and vulnerabilities associated with *cybersecurity*.

S&T Advancements	Desired Capabilities	Intended Outcomes
Advanced Threat Detection and Management	Use of AI and ML for real-time threat detection, anomaly monitoring, and data analysis.	Improved resilience of cyber assets to potential attack through the proactive identification of network threats and intrusions, reducing the risk of a successful cyberattack.
	Use of automated tools for asset management, network mapping, and vulnerability assessment/scanning.	Streamlined management of necessary monitoring functions, speeding up notification and response time, hardening network defenses, and freeing up valuable staff resources for other priorities.
	Use of secure hardware with advanced technologies such as Trusted Execution Environments (TEE) and SCADA.	
AI-Based Cybersecurity Applications	Use of AI-enabled cyber defenses that monitor assets to quickly respond to potential threats and identify vulnerabilities.	Unmanned cyber defenses that intelligently adapt and respond to evolving threats, reducing the likelihood of successful cyberattacks that could lead to downtime, misoperation, or failure.
	Automation of network functions with AI, including traffic management and performance monitoring.	Improved cybersecurity defenses that use real-time data to monitor and adapt to a changing threat environment and provide immediate notification, reducing the risk of a successful cyberattack.
	Application of AI models to augment the cybersecurity of dam facilities, including early threat detection and vulnerability management.	

S&T Advancements	Desired Capabilities	Intended Outcomes
Operational Security and Training	Use of effective white-hat cyberattack exercises to test cybersecurity defenses.	Improved scenario-based training and testing resulting in enhanced preparedness and among staff and systems, reducing the risk of a successful cyberattack.
	Use digital twins and models to train on cyberattack simulations.	
Secure Data Management	Implementation of secure, data-centric solutions with deliberate storage and access control measures.	Reduced risk of cyberbreaches resulting in compromised data, limiting the ability of attackers to weaponize sensitive information.
	Use of improved cloud-based data security with encrypted analytics.	Secure environments for the processing of real-time data and analytics from monitoring technologies.
	Use of a federated data architecture for secure information sharing across organizations.	Secure mechanisms for information sharing among dam owners and operators that is impenetrable to threat actors, enhancing sector preparedness without compromising sensitive data.
System Redundancy and Fail-Safes	Use of systems engineered with redundancy to maintain control during cyber breaches.	Reliable backups and recovery plans in the event of a cyberattack, ensuring the continuous operation of critical functions and reducing potential downtime or dam failure.
	Use of comprehensive recovery and reconstitution plans for shutdown scenarios.	
	Improvement of air-gapping, isolation, and secure bundling to prevent wireless attacks.	Reduced risk of cyber intrusions through a multi-layered security approach.

APPENDIX A: METHODOLOGY

The development of the *Roadmap to Innovation in the Dams Sector* employed a phased approach, drawing on both interviews with Dams Sector subject matter experts (SMEs) and findings from the Dams Sector Innovation Workshop led by CISA and the Dams Sector R&D Workgroup. The Dams Sector Management Team analyzed findings from the interviews, workshop, and open-source research to identify R&D areas for focus and innovation in the next 3 to 5 years.

This Roadmap builds on years of extensive stakeholder engagement and data collection led by the Dams Sector Management Team and the Dams Sector R&D Workgroup. One of the earliest efforts to identify security-related R&D priorities for dams, locks, and levees happened in 2012, when the Dams Sector R&D Workgroup convened partners for a workshop to better understand structural risks and to guide the development of tools that support the safe design, construction, operation, and maintenance of dams and related assets. Building on that workshop, in 2015 the Workgroup collaborated with owners and operators to develop a list of capability gaps that highlighted the pressing need for R&D innovation to enhance sector resilience. In 2018, the Workgroup evaluated and revised the identified capability gaps to reflect the expanding landscape of threats and vulnerabilities faced by the Dams Sector. The Workgroup also developed corresponding R&D priorities. This continuous engagement and evaluation of Dams Sector resilience laid the foundation for this Roadmap, ensuring that it addresses both existing challenges and future needs.

Phase 1: Interviews

In the first phase of the development of this Roadmap, the Dams Sector Management Team conducted interviews with 35 SMEs within the Dams Sector over the course of three months (October-December 2023). The team collected information related to capability gaps through interviews with sector SMEs, including owners/operators, regulators, and safety and security personnel. During the interviews, facilitators asked participants a variety of questions pertaining to future research and technology that could help the Dams Sector improve cyber and physical security and resilience.

In addition to identifying potential R&D Focus Areas, participants identified several constraints in developing and implementing necessary capabilities, which were considered in the development of this Roadmap. Identified constraints included limited funding to implement security measures, protecting and monitoring sector assets situated in remote locations, and limited data on critical topic areas.

Following the interviews, the Dams Sector Management Team analyzed the information gathered during the SME interviews to create a summary report identifying capability gaps and research opportunities.

Phase 2: Workshop

In the second phase, CISA—implementing Sector Risk Management Agency responsibilities for the Dams Sector on behalf of DHS and in collaboration with the Dams Sector R&D Workgroup—hosted the Dams Sector Innovation Workshop. The workshop convened thought leaders across multiple disciplines to discuss R&D areas with the potential to mitigate some of the security and resilience challenges impacting the Dams Sector. The challenges discussed, which drive risk management planning considerations, span a broad spectrum ranging from natural hazards and operational challenges to cybersecurity, criminal activities, and terrorism. Workshop discussions informed the development of this Roadmap.

The facilitation team collected responses from participants using various facilitation methods and styles, categorizing data into broad themes as the discussion evolved.

Following the workshop, CISA analyzed the responses collected through both methods and categorized them by threat, vulnerability, and resilience topics and related S&T Advancements to identify key R&D Focus Areas for the next 3 to 5 years.

APPENDIX B: PARTICIPANTS

We extend our appreciation to the following participating organizations of the subject matter expert interviews and Innovation in the Dams Sector Workshop. These owners and operators, federal and state regulators, members of the research community, trade associations, and others supporting the security and resilience of the Dams Sector were instrumental in developing this Roadmap and will be critical partners in its implementation.

- Argonne National Laboratory
- Arizona State University
- Association of State Dam Safety Officials
- California Department of Water Resources
- Duke Energy
- Electricity Information Sharing and Analysis Center
- Federal Energy Regulatory Commission
- Idaho National Laboratory
- InfraGard
- Lower Colorado River Authority
- Miami Conservancy District
- National Association of Flood and Stormwater Management Agencies
- National Oceanic and Atmospheric Administration
- New Jersey Department of Environmental Protection
- New York City Department of Environmental Protection
- North Carolina Department of Environmental Quality
- Pacific Gas and Electric Company
- Pacific Northwest National Laboratory
- Seattle City Light
- Society of American Military Engineers
- Stanford University
- Texas A&M University
- U.S. Army Corps of Engineers
- U.S. Army Engineer Research and Development Center
- U.S. Bureau of Reclamation
- U.S. Department of Agriculture
- U.S. Department of Energy
- U.S. Department of Labor, Mine Safety and Health Administration
- U.S. Department of Homeland Security
  - Cybersecurity and Infrastructure Security Agency
  - Federal Emergency Management Agency
  - Science and Technology Directorate
- United States Society on Dams
- University of California at Berkeley
- University of California at Irvine
- University of Colorado at Boulder
- University of Kentucky
- University of Mississippi
- Utah State University
- Xcel Energy