The use of geomembranes for pumped-storage reservoirs

A. Peters and A. Blystra, River Connectivity Systems, USA

Energy storage is fundamental to ensuring the reliability, stability, and resilience of the grid, essential for meeting the energy demands now and in the future. Pumped storage stands out as a proven energy storage solution. There are 43 pumped-storage plants operating in the USA today, and they offer unparalleled scalability, rapid-response capabilities, and long-term reliability at a competitive cost. With a history of successful operation spanning decades, and approximately 60 sites proposed at various stages of permitting and development, this technology is a critical component for the US energy sector. However, its development involves some complex engineering and regulatory challenges.

In designing a reservoir for a pumped-storage development, it is paramount to ensure water retention, dam safety, and minimal seepage to achieve effective energy storage and operational efficiency. A liner system provides the essential interface between the dam materials and the reservoir water to safeguard the surrounding environment and maintain the stability and longevity of the facility.

Various materials such as dense asphaltic concrete, conventional concrete and clay have been considered for pumped-storage reservoir liners. However, geomembrane liners stand out for their promising advantages, including reduced construction costs, accelerated schedules, and significant improvements in dam safety, efficiency and longevity. With a proven track record spanning more than 50 years, in applications with static loading, such as agricultural reservoirs, potable water systems and landfill projects focused on groundwater protection, the successful use of geomembranes has showcased their ability to withstand consistent conditions without significant degradation. This durability and reliability make geomembranes a compelling choice for reservoir liners, offering both cost-effectiveness and long-term performance benefits.

However, the dynamic conditions in pumped-storage projects present unique challenges; the frequent and significant water level fluctuations test the durability and adaptability of geomembrane liners far beyond traditional static applications. To date, only Mount Elbert in Colorado, one of the 34 licensed pumped-storage projects in the USA, has a geomembrane liner.

In an industry that places much emphasis on precedence and proven practices, the limited use of geomembrane liners at pumped-storage projects reveals a significant knowledge gap that hampers the advancement of liner technology in this sector. This scarcity of precedence inhibits effective comparative analysis of the engineering, environmental and economic impacts of various liner systems, particularly in terms of their effects on construction timelines and costs. The empirical validation of the benefits offered by geomembrane liners for pumped storage settings is still lacking, highlighting the critical need for extensive research. Stakeholders require confidence, evidence and modelling to address concerns of the impact of rapid reservoir drawdown and refilling, dam safety and the integrity of cost-effective geomembrane liners in pumped-storage applications.

River Connectivity Systems, supported by the US Department of Energy's Office of Science, Water Power Technologies Office under Award Number DE-SC0023779, and in collaboration with the University of Illinois, the Fabricated Geomembrane Institute, Argonne National Laboratory, and Oak Ridge National Laboratory, is proposing further research to address this gap, and to model and analyse loading conditions on geomembranes in pumped-storage applications. The anticipated results of this research will equip engineers, developers, geomembrane manufacturers and regulatory agencies with essential design standards and guidelines to reduce seepage and prevent leakage, to protect the existing groundwater regime, and to prevent slope failure during rapid drawdown.

Seepage and leakage management in pumped-storage systems

The management of seepage is critical for maintaining the efficiency and structural integrity of pumped storage systems. Effective seepage control not only reduces the need for costly replacement water, but also enhances the system's stability. Modern pumped-storage projects typically adopt closed-loop systems, where the reservoirs are initially filled and periodically replenished from surface or groundwater sources. This setup requires meticulous management of water losses caused by seepage and evaporation. Implementing solutions such as covers over reservoirs can mitigate significant evaporation losses.

The geological foundation of the reservoir, whether soil or rock, significantly influences its hydraulic conductivity. Soil type variations and the presence of joints and fractures in rocks can lead to significant fluctuations in hydraulic conductivity. Without robust liner systems, a reservoir could lose more than five per cent of its operational water volume annually to seepage. This loss could amount to millions of cubic metres of water each year, highlighting the crucial role of liner systems in conserving water and ensuring both the efficiency and safety of the entire system.

In 1977, the Mt Elbert pumped-storage project's upper reservoir was initially equipped with a low hydraulic conductivity compacted soil liner (CSL). This 1.5 m-thick liner was constructed from the soil integral to the dam's core, and was designed to contain the reservoir water efficiently. The CSL was methodically compacted in 15 cm lifts with tamping rollers, extending across the reservoir's entire area, and reaching up to 1 m above the maximum water surface level. Despite these precautions, post-filling assessments revealed excessive seepage through the CSL. This unforeseen leakage raised groundwater levels to a degree that risked reactivating a previously dormant landslide on a natural slope located between the upper reservoir and the lower lake. The implications of such a reactivation posed a significant threat to the structural integrity of the powerplant below [USBR, 2002[1]]. To address the critical seepage issue, the US Bureau of Reclamation embarked on a project to secure integrity of the reservoir. A 45 mm-thick reinforced chlorinated polyethylene (CPE-R) geomembrane was selected for its robustness, and was installed over an area of 1.17 km^2. This choice was made to reduce water loss and stabilize the surrounding groundwater levels, effectively addressing the seepage concern.

The installation of the geomembrane marked a turning point. Subsequent observations from wells around the reservoir confirmed that groundwater levels had stabilized, indicating the geomembrane's success in creating a watertight barrier. The effectiveness of the geomembrane was underscored by its achievement of a field hydraulic conductivity significantly below the 0.9×10^{-6} cm/second previously measured for the CSL, confirming its superior performance in minimizing leakage [Morrison *et al*., 1982[2]]. The Mt Elbert project serves as a pivotal case study in the application of geomembrane technology for resolving seepage issues in pumped-storage reservoirs. With the implementation of a CPE-R geomembrane across a substantial area, not only was the immediate risk posed by elevated groundwater levels and potential landslide reactivation mitigated, but also a benchmark was established for future endeavours in reservoir liner technology.

Leakage management at Taum Sauk

The Taum Sauk pumped-storage project in Missouri has an upper reservoir located approximately 244 m above the powerplant, characterized by a kidney-shaped rockfill dam about 28 m high, with a 3 m-high concrete parapet wall above the rockfill. At full capacity, it stores about $1500 \times 10^6 \text{m}^3$. Initiated in 1960 and completed in 1963, the project employed a shotcrete layer on the waterside of the embankment to prevent water loss. After the completion, the shotcrete-lined embankment experienced increasing leakage each year, compromising the reservoir's water containment and highlighting concerns over the embankment's stability and the efficiency of the pumped storage operations. In response to the escalating leakage, grouting was performed to seal cracks and reduce water loss. Despite these efforts, by 2003, the reservoir was losing approximately $135.6 \times 10^3 \text{m}^3$ of water daily as a result of seepage [Tomich and Hand[3]], as shown in Fig. 2.

To tackle the leakage problem, Geosynthetics Inc (GSI) was contracted in 2004 for around \$2.4 million to install a geomembrane liner across the embankment and part of the reservoir floor. The project involved laying down $120.7 \times 10^3 \text{m}^2$ of an 80 mm-thick HDPE textured geomembrane, with a geosynthetic drainage composite underneath. In addition, LLDPE geomembrane cushion layers were placed over five rock outcroppings on the slope interiors. This intervention markedly reduced the leakage rate from an average of 1.4 to approximately 0.14 m^3/s, enhancing the facility's efficiency to around 70 per cent post-geomembrane installation, as reported by FERC in 2005.

On 14 December 2005, the Taum Sauk project's upper reservoir embankment experienced a catastrophic failure as a result of overtopping, triggered by a failure to shut down the pumping mechanism. Despite this severe incident, the geomembrane installed earlier proved its effectiveness by keeping the embankment's base dry beneath it, as evidenced in photographs documenting the event.

Installation of the geomembrane at Mt Elbert.

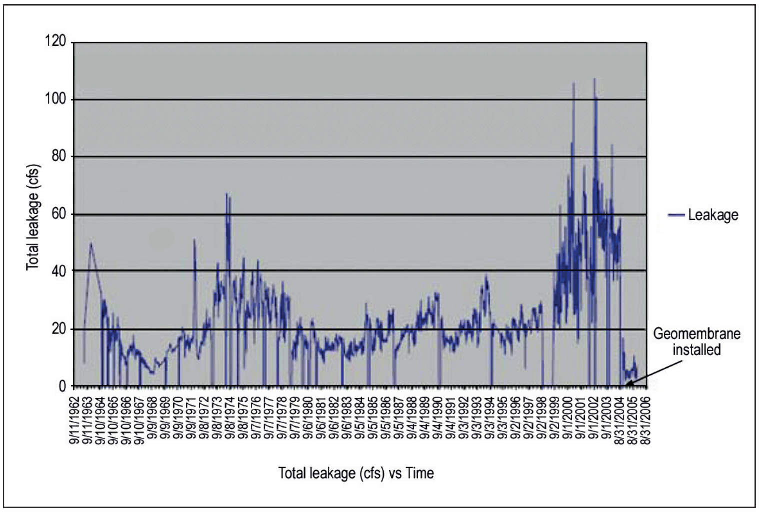
This incident highlighted both the vulnerability of the infrastructure to operational failures, and the protective value of the geomembrane in mitigating water-related damage. The subsequent reconstruction of the upper reservoir was based on the use of roller-compacted concrete, and it was decided not to incorporate a geomembrane liner in the new design.

Seepage concerns at the Upper Stillwater dam

The Upper Stillwater dam, a major water retention facility near Duchesne, Utah, illustrates the challenges of managing seepage in large-scale hydraulic structures. This 61 m-high RCC gravity dam on Rock Creek was completed in 1987, and is known for the substantial design measures to harness and manage water flow effectively. Despite its overall strong performance, the dam has encountered persistent leakage issues, which, while not currently compromising the dam's structural integrity, have sparked public concern and could pose future risks. These leaks primarily stem from cracks within the RCC and at the interfaces between the dam's horizontal layers or lifts. Notably, the flow through these lift joints can lead to efflorescence, mineral deposits left by evaporating water, and potential uplift pressures that challenge the dam's stability.

One contributing factor to these issues is the absence of contraction joints in the initial design, which would have allowed for natural expansion and contraction without causing damage. Also, the natural processes of foundation deformation and the cooling of the concrete post-construction, have exacerbated the formation of cracks. The resulting leaks often follow an almost horizontal trajectory along the interfaces between RCC layers, as shown in Fig. 3, illustrating a distinct pattern of seepage through the structure.

Time history of leakage from the Taum Sauk upper reservoir. Data in imperial units: 1 ft^3/s = 0.28 m^3/s.



Downstream face of the Upper Stillwater RCC dam.

Protecting the existing groundwater

It is possible that pumped-storage reservoir water could contain contaminants which could pollute the groundwater system. However, a reservoir liner can prevent such pollution from occurring. Another concern that has been raised by regulatory agencies is that reservoir seepage could affect the groundwater regime by altering flow paths and groundwater elevations. Changes to an existing groundwater regime can also be eliminated or minimized by the installation of a liner. An example of changes to the groundwater regime is the seepage at Mt Elbert, that raised the groundwater level mentioned above.

Challenges of rapid drawdown (RDD) at pumped-storage projects

Managing the stability of embankments during rapid drawdown events at pumped-storage schemes is critical because of the dynamic changes in pore-water pressures. These pressures, including shear-induced, transient seepage-induced, and unsaturated transient seepage-induced porewater pressures, are pivotal factors during RDD. Accurate calculation and management of these pressures is therefore essential for assessing and ensuring the stability of both the upstream slope of the embankment and surrounding natural slopes. This is crucial to prevent any compromise to the containment system and the powerplant's operational integrity.

The San Luis dam failure in 1981 exemplifies the potential consequences, if these challenges are not adequately addressed. This failure was notable following a reservoir drawdown of about 55 m over 120 days, equating to a rate of 45 cm/day, significantly below the US Army Corps of Engineers' limiting rate of 0.9 m/day. Despite being within perceived safe limits, the dam experienced a catastrophic slope failure, critically affecting the filling capacity of an essential reservoir in the California aqueduct system. This incident, documented by Stark and Duncan [1991[4]], highlights the necessity for rigorous geotechnical analysis and preparedness, especially as efficiently projects often involve drawdown rates far exceeding those at San Luis dam, with rates ranging from 15 to more than 30 m/day.

Moreover, the design and maintenance of embankment linings play a vital role in mitigating these risks. A well integrated liner system, particularly geomembranes, can significantly reduce seepage, thereby limiting the shear-induced and transient seepage-induced pressures that contribute to slope instability. This was evidenced in the Taum Sauk project, where the addition of a geomembrane liner minimized embankment erosion risks, particularly in scenarios of overtopping caused by filling mechanism malfunctions.

Effectively controlling seepage through the embankment and dam can significantly mitigate the stability concerns associated with rapid drawdown conditions. This control ensures that the pumped-storage facility can safely accommodate rapid drawdown scenarios to meet fluctuating power consumption needs without compromising structural stability. The implementation of geomembranes at facilities like the Mt Elbert project further underscores the strategy's effectiveness. Here, the installation was primarily motivated by the need to control seepage that had elevated groundwater levels and posed a landslide reactivation risk above the downstream powerplant.

Types of liners in service at pumped-storage reservoirs

Pumped-storage projects incorporate various types of liners, each chosen based on the specific needs of the project, environmental considerations, and expectations for long-term durability. The liner types commonly used are:

- *Compacted soil liners (CSLs)*: Initially, containment efforts in pumped-storage projects predominantly used CSLs. These liners are favoured for their use of readily available materials and simplicity in construction. However, CSLs sometimes struggle with variations in hydraulic conductivity that can be influenced by environmental conditions. Early studies in the 1980s, notably by Kirk Brown and colleagues, highlighted CSL vulnerabilities to chemical degradation and increased hydraulic conductivity, which posed environmental risks.
- *Composite liner systems (CLS)*: These insights (mentioned above), along with regulatory pressures from the USEPA, prompted a significant shift from traditional CSLs to more advanced liner systems. Composite Liner Systems (CLS) typically consist of a geomembrane placed in intimate contact with the underlying CSL. This design ensures that leakage occurs only over areas with geomembrane defects, providing an improved barrier against environmental contamination.
- *Geosynthetic clay Liners (GCLs)*: Introduced as an advanced sealing technology, GCLs consist of two layers of geotextiles enclosing a sodium bentonite clay core, offering exceptional low permeability and self-healing capabilities after puncture. Their effectiveness is maximized when used in conjunction with other liner types, such as geomembranes, to form a composite barrier system that addresses both mechanical durability and hydraulic impermeability. This combination enhances the hydraulic performance and barrier integrity against hydrostatic pressure, marking a significant advancement in containment technology.
- *Concrete liners:* These are used for their durability and strength, and are especially valuable in structures where natural impermeable materials are scarce. A prime example of concrete liners in action is the Cabin Creek pumped-storage project in Colorado. Here, a concrete-faced rockfill dam with an upstream slope inclination of 1.3 H:1V was constructed, to overcome the challenge of lacking impervious materials. The concrete liner, varying in thickness from 45 cm at the base to 31 cm at the crest, features meticulously designed vertical and horizontal contraction joints to enhance its structural integrity. Notably, the Cabin Creek dam underwent rigorous visual inspections,

showing minimal settlement and effective compaction, thus underscoring the liner's resilience and effectiveness in water containment.

- *Dense asphaltic concrete (DAC) and high asphaltic concrete (HAC) liners*: These are vital for pumped-storage projects because of their impermeability and flexibility, which are crucial in adapting to the dynamic pressures from rapid drawdown events. However, the capability of these materials to manage differential movements and environmental stresses is an important factor in their application.

Based on research by Callari and Cazuffi [2020[5]], DAC is utilized as a bottom liner for embankments, reservoir sides, the reservoir bottom and water conveyance channels at pumped-storage schemes. A DAC bottom liner is composed of aggregates, sands, fillers, bitumen and additives. This system typically includes several layers: a DAC layer, a support binder, a bituminous drainage layer for leak control, a mastic sealing for UV-protection and pore sealing, and a non-bituminous filter and drainage layer, followed by stabilizing and protection layers.

The DAC liner system offers low hydraulic conductivity to water, assuming watertight joints between asphalt strips, and provides good stability against rapid drawdown. It also exhibits resistance to mechanical traffic, ice abrasion and rock falls. However, despite these benefits, DAC systems have limitations in leak detection. They cannot incorporate a leak detection layer below or between the DAC liners, thus the rate and magnitude of leakage cannot be directly monitored. This is a significant disadvantage, as understanding these factors is crucial for assessing the stability of water retention structures.

The hydraulic conductivity of intact asphalt ranges from 10 ($1.0 \times 10 + 1$) to 0.00001 (1×10^{-5}) mm/s [Feng *et al.*, 2021[6]]. In comparison, an intact geomembrane's conductivity ranges from 1×10^{-10} to 1×10^{-11} mm/s [Koerner, 1998[7]], which is significantly lower than that of a DAC liner. Furthermore, DAC liners are vulnerable to cracking or breaches from seismic activities or other structural stresses, as evidenced by the failure at Baldwin Hills dam. In contrast, geomembranes offer greater flexibility and can be equipped with leak detection systems for continuous, remote monitoring, enhancing their suitability for seismic-prone areas.

The use of geomembrane liners presents a transformative approach to enhancing the efficiency and sustainability of water containment systems. These liners, crafted from materials such as Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE), and Chlorosulphonated Polyethylene (CSPE), offer unique properties tailored to meet the demands of modern hydropower infrastructure.

PVC is a versatile thermoplastic that becomes flexible when modified, offering resistance to weather, punctures, abrasion and chemicals. However, it requires protection against UV light to maintain its integrity over time. HDPE is celebrated for its high density and molecular weight, providing substantial resistance to a wide range of chemicals and harsh environmental conditions, thus serving as a durable, low-maintenance option for long-term applications. CSPE stands out with its superb chemical, UV, and temperature resistance, and its flexibility and ease of installation make it ideal for creating seamless joints, enhancing its suitability for various water containment tasks.

Geomembranes are notably more adaptable to settlement than traditional materials like concrete, making them ideal for pumped-storage environments with dynamic soil conditions. They feature significantly lower hydraulic conductivity than DAC liners, reducing the risk of seepage and bolstering containment efficacy.

Moreover, the rapid deployment capability of these materials was demonstrated at Mt Elbert, where a geomembrane installation was completed in just 84 days, far quicker than conventional materials that might require multiple construction seasons.

From an economic standpoint, geomembranes often represent a more cost-effective solution upfront, particularly when considering their lower long-term maintenance requirements compared to materials like HAC. However, the environmental impact of producing and deploying these synthetic liners requires careful consideration to ensure that the choices made are sustainable.

Challenges and future research needs

Despite the potential and increasing adoption of geomembranes at projects such as Mt Elbert and Taum Sauk, significant data gaps persist regarding their performance under daily cyclic loading and rapid drawdown conditions. Addressing these gaps is imperative, necessitating comprehensive research to tackle issues related to durability, joint and seam strength, and overall lifecycle fatigue failure of geomembrane systems. Such studies are essential for establishing robust design standards and cost-efficiency metrics, thereby solidifying geomembranes as a preferred solution in the pumped-storage sector. Under a contract with the Department of Energy, River Connectivity Systems is leading an initiative aimed at creating a tool tailored for engineers and developers to streamline the understanding, design and manufacturing processes of geomembranes for pumped-storage projects. Leading this research endeavour is Dr Timothy Stark at the University of Illinois at Champaign-Urbana, whose expertise is pivotal for the project's success.

In a collaborative effort to ensure the highest standards, Argonne National Laboratory will oversee Quality Assurance and Quality Control (QA/QC) and contribute expertise in cost estimation. Complementing this, Oak Ridge National Laboratory will conduct a comprehensive potential failure modes analysis and risk assessment, adding a critical layer of reliability and safety to the project. In addition, a partnership with Rye Development allows for the use of one of its early-stage pumped-storage projects as a practical model, supplying essential data such as reservoir geometry and other key parameters. This collaboration ensures that the tool is not only theoretically sound, but also practically applicable. This comprehensive approach aims to bridge the gap between current challenges and innovative solutions in the pumped-storage sector, paving the way for more efficient, sustainable and reliable energy infrastructure development. ◊

Acknowledgement

This material is based on work supported by the US Department of Energy, Office of Science, Water Power Technologies Office under Award Number DE-SC0023779. The authors are grateful for the support of Timothy Stark, University of Illinois Department of Civil and Environmental Engineering, Vladimir Koritarov and Mustafa Altinakar, Argonne National Laboratory, USA.

References

1. **USBR**, "Water Operation and Maintenance" Bulletin 199 '20-Year Performance of the Buried Geomembrane Lining at Mt. Elbert Reservoir', US Bureau of Reclamation; 2002.
2. **Morrison, W.R., Gray, E.W., Paul, D.B., and Frobel, R.K.,** "Installation of Flexible Membrane Lining in Mt. Elbert Forebay Reservoir", US Bureau of Reclamation, Report No. REC-ERC-82-2, 1981.
3. **Tomich, J. and Hand, E.,** "Memo warned of dam danger at Taum Sauk", in St. Louis Post Dispatch, Jan. 15, 2006.
4. **Stark, T.D., and Duncan, J.M.,** "Mechanisms of Strength Loss in Stiff Clays", *Journal of Geotechnical Engineering, ASCE,* Vo. 117, No. 1, January, 1991.
5. **Callari, C., and Cazuffi, D.,** "Embankment dams with bituminous concrete upstream facing: Review," Bulletin No. 114, International Commission on Large Dams; 2020.
6. **Feng, S, et al.,** "Studying Hydraulic Conductivity of Asphalt Concrete Using a Database", *Journal of Transportation Engineering,* Vol. 3, March 2021.
7. **Koerner, R.M.,** "Designing with Geosynthetics" 4th Edition, Prentice Hall, London, UK; 1998.

Bibliography

Duncan, J. M., Wright, S. G., and Wong, K. S., "Slope stability during rapid drawdown", Proceedings, Seed Memorial Symposium, Vol. 2, BiTech Publishers, Vancouver, BC, Canada; 1990.

FERC, "Taum Sauk Upper Dam Breach, FERC No. P-2277 – Technical Reasons for the Breach of December 14, 2005", Federal Energy Regulatory Commission Independent Panel of Consultants, Washington DC, USA; 2006.

Giroud, J.P., "Leakage Control Using Geomembrane Liners", Geosynthetics International, 5th Victor de Mello Lecture, J. Soils and Rocks, Brazilian Society for Soil Mechanics and Geotechnical Engineering, Vol. 39, No. 3, 2016.

Koerner, R.M. and Koerner, G.R., "The Intimate Contact Issue of Field Placed Geomembranes with Respect to Wave (or Wrinkle) Management," GSI White Paper No. 27, Geosynthetics Institute, Folsom, PA, USA; June 2023.

Stark, T.D., Hernandez, M.A., and Rohe, D.S., "Geomembrane Factory and Field Thermally Welded Geomembrane Seams Comparison," Geotextiles and Geomembranes Journal, 48(4), August, 2020.

Stark, T.D. and Saud-Medina, F., "Geomembrane Defect and Wrinkle Leakage Calculator," Proceedings, Geosynthetics 2021 Conference, IFAI, Kansas City, February, 2021.

USBR, "Mt. Elbert Forebay Reservoir Membrane Lining, Fryingpan-Arkansas Project, Colorado", US Bureau of Reclamation, Water and Power Resources Services Specifications. No. DC-7418; 1980.

USBR, "Design Summary for Mt. Elbert Forebay Reservoir Membrane Lining, East Slope Power System - Fryingpan-Arkansas Project, Colorado", US Bureau of Reclamation for Specification No. DC-7418, Water and Power Resources Services; 1981.


A. Peters


A. Blystra

Andrew Peters has 32 years' experience in developing and commercializing products and technology. He started his career as a research fishman for the National Oceanographic and Atmospheric Administration and has a background in business development and operations in the marine and commercial fishing industry. Over the past 13 years he has used his combined expertise to commercialize the use of fish guidance and exclusion nets, and debris and safety booms in the energy sector. His accomplishments include a patent on an innovative boom design, and two patents pending, as well as the publication of numerous technical papers with corresponding or supporting presentations to organizations including ICOLD, CEATI, American Society of Dam Safety Officers, National Hydropower Foundation, American Fisheries Society, the Joint Committee on Fish Science, and many others.

Andrew Blystra, PE, received a BS in Civil Engineering from Michigan Technological University, an MS in Geotechnical Engineering from the University of Illinois at Chicago and did additional graduate work in Engineering Geology at UIC and Western Michigan University. He has more than 50 years of engineering experience, primarily related to hydro and pumped-storage projects throughout the USA, Canada and South America. His hydropower experience includes safety inspections and evaluations, permitting and licensing, design and operation. He has conducted more than 60 independent consultant safety inspections of FERC-licensed hydro projects, including the Ludington and Smith Mountain-Leesville pumped-storage projects. He was a member of design teams working on conceptual and final designs of pumped-storage schemes in California, Nevada and Pennsylvania. He has worked for the US Army Corps of Engineers, the Federal Energy Regulatory Commission, consulting firms, and has his own consulting engineering practice. He joined River Connectivity Systems as a Partner and Senior Engineer in 2024.

River Connectivity Systems, 578 Azalea Ave NE,
Bainbridge Island, WA 98110, USA.

AECOM

Delivering sustainable legacies

AECOM draws upon our network of dam and hydropower experts to provide technical excellence for the most complex project.

Dennis J. Hogan, P.E.
Global Dams & Hydropower
Market Sector Leader
dennis.hogan@aecom.com

Cordeaux Dam, New South Wales, Australia, Dam Owner & AECOM Partner: WaterNSW

aecom.com

Delivering a better world