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GEOSYNTHETIC RESEARCH NEEDS FOR HYDRAULIC STRUCTURES

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ABSTRACT

Water is an increasingly expensive commodity as demand for freshwater continues to increase while sources of freshwater are becoming depleted. Geosynthetic systems can play a significant role in conservation strategies of freshwater by providing cost-effective solutions to problems associated with seepage losses. This paper presents benefit/cost analyses conducted to assess the economic implications regarding the use of geosynthetics in hydraulic structures. The analyses indicate that use of geomembranes in dams, canals and reservoirs involves comparatively low construction costs so that conservation of water resources leads to recovery of the costs in a comparatively short period of time. Significant advances have taken place in geosynthetics engineering since geomembranes were first used in hydraulic structures. A good example is the current confidence on the extended service life of geomembranes. However, geosynthetics are certainly underutilized in hydraulic structures, at least when compared with the well-established use of geosynthetics in transportation and waste-containment structures. This paper also provides a summary of the use of geosynthetics in dam structures and a discussion on research needs regarding geosynthetics in hydraulic systems.

INTRODUCTION

Geosynthetics have been used in a large number of applications as they provide inexpensive, long-lasting solutions to problems associated with major geotechnical and geoenvironmental systems. Specifically, geosynthetics used in hydraulic structures provide a barrier for infiltration, erosion and stability control. By using geomembranes in hydraulic applications, the infrastructure of water conveyance and storage can be protected and its effective service life extended.

The economic implications associated with confining water in dams and reservoirs and with transporting water in canals are significant. Sources of water are not replenishing as quickly as they are removed. Minimizing water losses to seepage and evaporation through the use of geosynthetics can provide cost-effective solutions. Accordingly, cost-benefit analyses are presented in this paper to quantify the cost-effectiveness of using geomembranes for water conservation purposes. The analyses consider the application of geosynthetics in both canal liners and dam liners.

Dams are among the most critical civil engineering structures. They provide an important source of water for agricultural, municipal and industrial use. As an example of the use of geosynthetics in hydraulic structures, this paper summarizes the impact that the use of geomembranes had on the construction and rehabilitation of dams.

Many advances have taken place in geosynthetics technology since the first use of geomembranes for waterproofing dams in 1959. However, there are still significant research needs that should be addressed to optimize the design, installation, and performance evaluation of geosynthetics in hydraulic structures. Durability, lifetime prediction, and leakage quantification of geomembranes are among the topics that may benefit from additional research. This paper concludes with the results from a recent survey conducted to identify research needs that are expected to have the most impact on the future use of geosynthetics in hydraulic systems.

ECONOMIC ASSESSMENT

Overview

Water is rapidly becoming an endangered resource. As the population of the world grows at rate of about 100 million people per year, the demand for one of the world's most important resources (water) is on the rise. While the sources of freshwater are finite, the global demand for water is expected to grow 2-3% per year (Lecornu 1998). Also, climate changes can greatly affect the availability of water resources as well as increased demand (Characklis 2003).

The largest component in freshwater demand is for agricultural applications (e.g. irrigation), which has a considerable bearing on food production. Industrial and domestic uses are the other major components of freshwater demand. A substantial amount of the water used for these applications is collected from groundwater supplies (i.e. aquifers). However, the rate of recharge for the groundwater sources is typically less than the amount of removed water, especially as demand increases (International Commission on Large Dams 1999). Water storage through the use of dams and reservoirs constitutes another major source of freshwater. Storage of water from rivers and runoff by using dams provides water supply in drought periods and flood control in rainfall periods. Canals are used for transportation of stored water, typically in agricultural applications.

Seepage losses are an important consideration in the performance of hydraulic structures. No material used in the construction of a dam, canal or reservoir is absolutely impervious to water flow. While some loss of water to seepage is expected, several measures can be implemented to considerably reduce the amount of seepage. The hydraulic conductivity of geomembranes (e.g. 10^{-15} m/s) is several orders of magnitude below that of low-permeability clays (e.g. 10^{-9} m/s). Thus, seepage losses can be minimized by using geomembranes to line reservoirs or canals and to waterproof dams. In 1994, the Bureau of Reclamation began conducting a 10-year field study on the effectiveness of using geomembranes in various canal liner projects (Swihart 1994). In this study, the seepage rates and condition of the liners were monitored. The amount of seepage losses in canals depends heavily on the geologic and soil conditions through which the canals are constructed. However, seepage losses in the canals used in this study prior to installation of the geomembrane liners ranged from 0.43 m^3/m^2-day to 1.6 m^3/m^2-day. This corresponds to 35 to 50% of the total water flow in the canals (Haynes and Swihart 1999). The seepage losses were reduced to less than 0.05 m^3/m^2-day after installation of the liners surveyed in this Bureau of Reclamation study (Swihart and Haynes 2002).

Benefit/Cost Analysis for Canal Liners

As the availability of water decreases, the cost of water increases following the market rules of supply and demand. Water conservation is one among several strategies that can be implemented to increase the supply (Characklis 2003). The use of geomembranes can be particularly useful to reduce seepage losses. The Bureau of Reclamation performed an economic analysis for the Deschutes canal-lining demonstration (Swihart and Haynes 2001). The analysis involves a comparison of the costs of construction and maintenance with the value of water being conserved by lining the canals. The construction cost, durability, maintenance cost and expected seepage reduction for various types of lining systems are presented in Table 1. The authors concluded that a concrete-covered geomembrane canal liner offered the most economical alternative.

Table 1 – Cost Structure for Deschutes Canal-Lining Project (After Swihart and Haynes 2001)

Type of Lining	**Construction Cost** ($/m²)	**Durability** (yrs)	**Maintenance Cost** ($/m²-yr)	**Effectiveness at Seepage Reduction** (%)
Concrete Alone	$19 - $24	40 - 60	$0.05	70
Exposed Geomembrane	$10 - $16	20 - 40	$0.10	90
Geomembrane w/ Concrete Cover	$24 - $26	40 - 60	$0.05	95
Fluid-Applied Membrane	$14 - $44	1 - 20	$0.10	90

An economic evaluation is presented next to estimate the benefit/cost ratio associated with the use of geomembranes in canals. The market value of water reported by Swihart and Haynes (2001) was $0.04/m^3 for the water irrigation districts. Instead, Characklis (2003) estimated that the high-end value of water for agricultural is $0.08/m^3. This range of market values is used to quantify the benefit associated with lining canals to prevent seepage losses.

Water losses prior to installation of a canal liner were defined using data from the Bureau of Reclamation canal-lining demonstration (Swihart and Haynes 2002). The seepage losses after construction were also determined using data reported by the Bureau of Reclamation canal-lining demonstration. Specifically, a reduction of approximately 90% to 95% in seepage losses was reported after installation of a geomembrane lining system (Swihart and Haynes 2002). Consequently, a 90% reduction in seepage losses in the canals was used in this analysis to determine the amount of conserved water.

Table 2 provides the costs and benefits of the canal-lining as estimated in this analysis. The value of the water conserved by avoiding seepage losses by using a liner was estimated to range from $1.36/m^2-yr to $11.66/m^2-yr for water valued at $0.04/m^3. The conserved water has a value of $2.72/m^2-yr to $23.33/m^2-yr when water is valued at $0.08/m^3.

Construction costs for the canal-lining study reported by Swihart and Haynes (2001) were used in the cost analysis conducted herein. Assuming a geomembrane service life of 30 years, the average construction cost for the canal liners ranges from $0.37/m^2-yr to $0.83/m^2-yr. These values do not include maintenance costs and do not consider lining materials other than geomembranes.

As shown in Table 2, this analysis indicates that the total construction cost is recovered and that the value of water conserved is 3.7 to 14 times the initial cost. This benefit/cost ratio is twice as high for a water value of $0.08/m^3. Consequently, this benefit/cost analysis reveals the significance of undertaking geomembrane lining projects in canals. The range of benefit/cost ratios defined by considering the ratios between the lower bound benefits and costs and the upper bound respective values. Swihart and Haynes (2001) reported a benefit/cost ratio on the order of 3.5 for an exposed geomembrane lining. This is consistent with the low end of the analysis presented herein, as the Swihart and Haynes analysis focused on conservative estimates rather than on the expected benefit/cost range.

This benefit/cost evaluation involves significant uncertainty. An important consideration is the assured service life of the geomembrane. Other factors that can affect the analysis include the value of water and the construction costs. Finally, seepage losses are highly dependent on the site conditions (e.g. soil conditions, geologic conditions).

Table 2 - Benefit/Cost analysis for canal linings

Cost		Benefit	
Construction Costs ($\$/\text{m}^2$)	$\$11$ - $\$25$	Pre-Construction Seepage Losses (m^3/m^2-day)	0.21 - 1.8
Service Life (yr)	30	Post-Construction Seepage Losses (m^3/m^2-day)	0.021 - 0.18 (90% Reduction)
Annual Construction Costs Over Lifetime ($\$/\text{m}^2$-yr)	$\$0.37$ - $\$0.83$	Conserved Water Value ($\$/\text{m}^2$-yr) Water Valued @ $\$0.04/\text{m}^3$	$\$1.36$ - $\$11.66$
		Conserved Water Value ($\$/\text{m}^2$-yr) Water Valued @ $\$0.08/\text{m}^3$	$\$2.72$ - $\$23.33$
Benefit/Cost Ratio (Water Valued @ $\$0.04/\text{m}^3$)		**3.7 - 14.0 (Average: 8.9)**	
Benefit/Cost Ratio (Water Valued @ $\$0.08/\text{m}^3$)		**7.4 - 28 (Average: 17.7)**	

*Note: One year in irrigation is 180 days. The canal is not full during non-irrigation season.

Benefit/Cost Analysis for Dam Liners

Contrary to the case of canal liners, the primary objective for waterproofing a dam is not the economic value of water that would otherwise be lost. Instead waterproofing a dam leads to increased stability and erosion control. Nonetheless, an economic evaluation involving quantification of water that would be lost without a geomembrane liner is included herein. This provides an additional perspective that can contribute to the decision of lining dams using geomembranes.

Seepage losses through dams throughout the world have been reported to range from 100 m^3/day to over 8000 m^3/day before installation of a geomembrane liner (Scuero et al. 2003). Seepage loss through a dam depends on factors such as the construction material, the height of water in the reservoir and the condition of the dam. Seepage losses were reported to decrease an average of 88% after the installation of geomembranes.

The benefit/cost analysis conducted herein aims at estimating value of water conserved by using geomembranes as a hydraulic barrier. As in the canal-liner benefit/cost analysis, the market value of water was determined to range from $\$0.04/\text{m}^3$ to $\$0.08/\text{m}^3$. Average seepage losses both before and after installation of a geomembrane were defined using data reported by Scuero et al. (2003). Specifically, the seepage losses before installation were reported to range from 2500 m^3/day to 4000 m^3/day while the seepage losses after installation were reported to range from 100 m^3/day to 500 m^3/day.

The value of the water conserved by avoiding seepage losses by using a liner was estimated to range from $\$35{,}000/\text{m}^2$-yr to $\$51{,}000/\text{m}^2$-yr for water valued at $\$0.04/\text{m}^3$. The conserved water has a value of $\$71{,}500/\text{m}^2$-yr to $\$100{,}000/\text{m}^2$-yr when water is valued at $\$0.08/\text{m}^3$.

Scuero et al. (2003) also reported construction cost information. The construction costs do not include maintenance but do include the installed cost of the geomembrane and of protecting layers. Using these costs and assuming a geomembrane service life of 30 years, the construction costs were calculated to range from about \$1,200/yr to \$120,000/yr. Table 3 summarizes the construction costs and conserved water values (benefits) for this analysis.

While the primary objective of lining the face of dams with geomembranes is not necessarily the cost of water that would be lost by seepage, the results shown in Table 3 are encouraging. The results indicate that from the benefit/cost analysis, the geomembrane system could be very attractive.

Table 3 - Benefit/Cost analysis for dam linings

Cost		Benefit	
Construction Costs (\$)	\$35,000 - \$3,600,000	Pre-Construction Seepage Losses (m^3/day)	2,500 - 4,000
Service Life (yr)	30	Post-Construction Seepage Losses (m^3/day)	100 - 500
Annual Construction Costs Over Lifetime (\$/yr)	\$1,167 - \$120,000	Conserved Water Value (\$/yr) Water Valued @ \$0.04/m^3	\$35,040 - \$51,100
		Conserved Water Value (\$/yr) Water Valued @ \$0.08/m^3	\$71,540 - \$102,200
Benefit/Cost Ratio (Water Valued @ \$0.04/m^3)		**0.43 - 30 (Average: 15.2)**	
Benefit/Cost Ratio (Water Valued @ \$0.08/m^3)		**0.85 - 61 (Average: 30.9)**	

DAMS

Dams are the most critical among the different hydraulic structures that can benefit from the use of geosynthetics. Because of their criticality, a brief overview is presented herein to exemplify the state-of-the-practice on the use of geosynthetics in hydraulic structures.

According to the World Commission on Dams (2000), more than 45,000 large dams have been constructed worldwide. The International Commission on Large Dams (ICOLD) defines a large dam as a dam with a height of at least 15 m or a dam that retains more than 3,000,000 m^3 of water. The average dam is 35 years old (World Commission on Dams 2000). As dams age, deterioration and structural damage are of major concern as they can lead to water loss and even failure.

Seepage of water through a dam is the most common cause of deterioration and structural damage. Dam materials (e.g. concrete) are not only not impervious to water but they actually increase their hydraulic conductivity during service life of the dam.

Dams may be subjected to aggressive environmental conditions. For example, in areas where freeze-thaw conditions are prevalent, concrete dams can be susceptible to cracking. In the case of the Lost Creek Dam, a geomembrane and drainage layer was attached to the upstream face of a concrete dam that had deteriorated as a result of seepage and freeze-thaw cycles (Onken et al. 1998). A geomembrane and geonet system was successful in minimizing the degradation of the dam by diminishing the amount of seepage loss through the dam.

The level of the reservoir affects the volume of water permeating the dam. That is, increased reservoir levels lead to increased seepage flow due to higher hydraulic gradients. If cracks are present, lowering the reservoir level can minimize seepage, at least until a retrofitting solution is selected. This was the case with the Pracana Dam in Portugal (Scuero et al. 1994), where extensive cracking developed in the dam due to expansion of the concrete. Because of concerns regarding the structural integrity of the dam, the reservoir level was restricted to minimize leakage as well as to reduce the stresses exerted on the structure.

The problem of dam deterioration is of major concern. Consequently, solutions are actively sought to slow and possibly halt the deterioration process reported in existing dams as well as to prevent the onset of seepage-induced degradation in new dams. Geosynthetic barriers are attractive candidates to achieve this purpose as they represent comparatively inexpensive but effective solutions to problems associated with dam leakage and deterioration. The hydraulic conductivity of geomembranes (e.g. 10^{-15} m/s) is significantly below that of a typical clay (e.g. 10^{-9} m/s). However, the main mechanism of water infiltration through geomembranes involves flow through defects. Drainage systems have been installed to collect water permeating the geomembrane liner in order to minimize infiltration into the dam structure. Specifically, geonets and geotextiles have been used in drainage applications. For example, a geonet was installed underneath the geomembrane in the Lost Creek Dam project (Onken et al. 1998).

Geomembranes have been typically placed on the upstream face of the dam, preventing water infiltration and preventing degradation of the dam materials. However, geomembranes have been used in place of or in addition to clayey soil as an impervious barrier in the core of a dam. For example, a rock-fill dam of the Zhushou Reservoir (Sichaun Province, China) was constructed using a geotextile/geomembrane composite placed as an additional hydraulic barrier over the clay core of the dam (Tao et al. 2002). The geosynthetic liner was selected because of a shortage of the originally specified core clay material.

Geomembranes have been used for many applications as a solution to seepage problems since 1959. Installation of the geomembranes took place during construction and during rehabilitation projects. The following sections summarize several landmark case histories documenting the use of geomembranes in dams.

The First

Geomembranes were first used in 1959 for a dam in Italy. Specifically, the geomembrane was installed during construction of the Contrada Sabetta dam. This geomembrane system continues to function as intended over 40 years after its installation. The structure involves a rockfill and rubble masonry dam. The cross-section of the dam is shown in Figure 1. The Sabetta dam is 32.5 meters high and has 1H:1V slopes on the upstream face. The geomembrane system was installed as a hydraulic barrier over reinforced concrete slabs placed on the upstream face. The system involved two sheets of polyisobutylene geomembrane, each with a thickness of 2 mm. Cardboard impregnated with bitumen and cast-in-place concrete slabs were placed over the geomembrane to protect the material from deterioration. Porous concrete was installed as a drainage system during construction of the dam. This pioneering project defined a new paradigm in the design of dams.

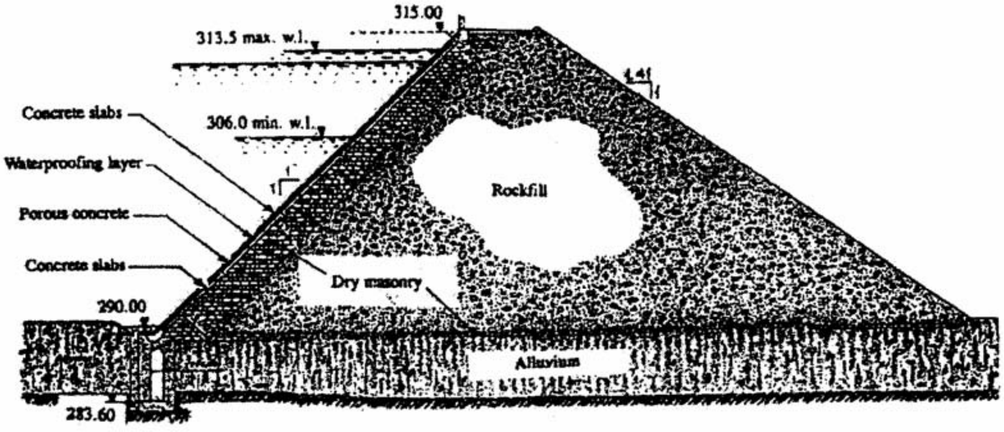

Figure 1: Cross-Section of Sabetta Dam in Italy (Sembenelli and Rodriguez 1996).

The Tallest

The tallest dam that involves a geomembrane liner system is the Kölnbrein dam in Austria. This concrete arch dam was built in 1977 to provide drinking water and hydroelectric power (Polaha 1999). Kölnbrein dam is 200 meters high and can store over 200 million m^3 of water. The dam was originally constructed without a geomembrane liner. However, not long after completion of construction, the dam experienced massive cracking due to seepage and uplift (Figure 2). In 1985, the dam was retrofitted with a CSPE (chlorosulphonated polyethylene) geomembrane placed on the upstream side. Installation of a geomembrane liner was only one of several actions undertaken to minimize the deterioration of the dam. The geosynthetic liner includes a partially covered-partially exposed 4-mm thick CSPE geomembrane and a geotextile used for drainage purposes. The geomembrane covers a comparatively small area but it provides some protection against seepage forces imposed on the dam.

Figure 2: Massive cracking and deterioration at Kölnbrein dam (Source: www.Simscience.org).

The Most Challenging Installation

The Lost Creek Dam is a concrete arch dam constructed in 1924 in northeastern California. The dam is part of a power generation project and it provides storage and diversion to an associated powerhouse. The area where the dam is located is prone to freeze-thaw cycles. During the winter, seepage water freezes and eventually induces numerous cracks in the concrete, leading to increased flow during the summer and further deterioration of the dam structure. The dam deterioration reached critical conditions in 1994, when rehabilitation was initiated. A PVC geomembrane system on the vertical upstream face was selected for protection of the dam from seepage. However, since the dam was used for power production, the reservoir could not be lowered below a certain level during rehabilitation (Onken et al. 1998). Consequently, waterproofing of the dam was conducted partially underwater. The underwater installation of the geomembrane was conducted by divers. This project represents the first underwater installation of a geomembrane system for a dam.

The Latest

Olivenhain dam (Figure 3) is the most recently completed dam involving use of a geomembrane as an impervious barrier. Located in San Diego, California, Olivenhain dam is the largest roller-compacted concrete dam in North America. The dam was constructed in 2003 for the purpose of emergency water storage for the city. The dam is 94.5 m high and can store over 30 million m^3 of water. A 2.5-mm PVC geomembrane was installed during construction, attached to the upstream face, and left exposed. Seismic design considerations played an important role in the selection of the barrier system used in this project. Specifically, the integrity of a flexible geomembrane barrier is not compromised for the design earthquake.

The Path Forward

A comprehensive survey of projects incorporating the use of geomembranes in dams is not presented herein as thorough reviews have been already compiled by Sembenelli and Rodriguez (1996), Scuero and Vaschetti (1996), and Scuero et al. (2003). However, some projects are summarized in this paper to illustrate the extent to which geosynthetic technology has been applied to dams. Overall, geomembranes can be used in a wide range of sizes and types of dams. They can be installed during construction or as part of dam rehabilitation programs. Finally, geomembranes have been placed over the upstream face of the dam as well as over the core of the dam.

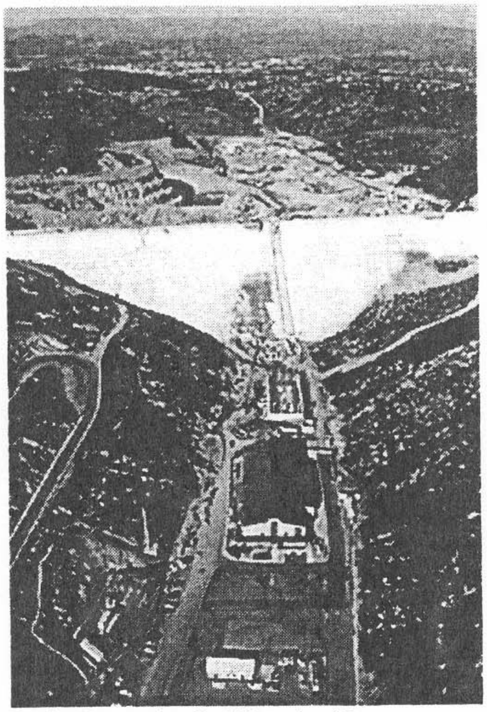

Figure 3: Olivenhain Dam in California (Source: www.nctimes.net).

As discussed by Scuero et al. (2003), PVC has been a common choice for geomembranes in dams. The material was often selected for both exposed and covered applications and for both large and small dams. However, the type of geomembrane that is more suitable for dam projects is a topic that deserves further evaluation. Equally relevant is the evaluation of composite liners (e.g. geosynthetic clay liners and geomembrane liners) in the design of liner systems for dams. Finally, the potential use of drainage systems associated with geomembrane liners offers design concepts not considered in the design of conventional dam structures.

Evaluation of the puncture resistance in geosynthetic liners is particularly critical for dam structures. Holes caused by mechanical damage, irregular surfaces and subgrades, vandalism, and wildlife decrease the effectiveness of the material. Geotextiles have been reported to provide adequate protection for the geomembrane (Comer and Dewey 1995). An aspect that may deserve further investigation, though, is the quantification of the leakage through geomembrane defects. Because of the comparatively high hydraulic loads in dam projects, current approaches for quantification of leakage through geomembrane defects may need experimental validation.

RESEARCH NEEDS

Hydraulic systems probably represent the segment of the geosynthetics market that has the largest opportunity for growth. This is particularly true in the U.S., where the use of geosynthetics in hydraulic structures is well below that in environmental and transportation structures. Consequently, identifying research needs for the use of geosynthetics in hydraulic structures is particularly relevant.

A survey on research needs regarding the use of geosynthetics in hydraulic structures was conducted in July 2003 during a short course at the University of Colorado at Boulder. Survey participants included a significant number of hydraulic engineers from federal agencies. Table 4 lists the research needs identified in this survey.

The common research needs identified for the different hydraulic structures included quantification of two critical issues: geosynthetic durability and leakage through liner systems. Additional research needs included assessing the share of the hydraulic applications in the geosynthetic market, evaluation of drainage, clogging, better guidance in the selection of materials and construction quality control and construction quality assurance (CQC/CQA) for various applications. Finally, evaluation of the impact of weather conditions (e.g. extreme temperature, altitude) was considered necessary. Table 4 also includes research needs that were felt to be specific to the different hydraulic structures, such as dams, canals, pond liners, pond covers, and tunnels and pipes.

The criticality of various research needs identified in Table 4 was evaluated during the same business meeting. Table 5 presents the assessment of the various research needs. The needs were classified as critical, major or minor. The five research areas identified as critical to the advancement of geosynthetics in hydraulic structures are durability, design details, quantification of leakage, CQC/CQA and better data for conducting benefit/cost analyses.

Table 4 – Identification of research needs

Application	Research Needs
Common Needs	Durability Quantification of leakage Interface shear strength % Geosynthetics market in hydraulic applications Drainage/clogging Various installation methods Selection of materials for various applications CQC/CQA for hydraulic applications Impact of weather conditions
Dams	Connections Sagging Potential use of composite liners Partial coverage Mechanical properties/design Use of sacrificial geosynthetic materials Quantification of half-life
Canals	Slope requirements Leveling of grade surface Seepage-induced stability Toe-cleaning
Pond Liners	Groundwater considerations Interface shear strength Generic material specifications Generic installation specifications Quantification of evaporation in open reservoirs Foundation structures within reservoir
Pond Covers	Cost Mechanical design Contamination Taste specification Wind uplift Temperature considerations
Tunnel and Pipes	Trench geometry Timing for deflection test Benefit/cost of pipe materials Bedding material/compaction considerations Damaging lining in tunnels Exposed geomembrane in tunnels Geotextile clogging Bridging voids under pipes Connection to concrete

Table 5 – Assessment of relevance of various research needs

	Assessment of Relevance		
Research Needs	**Critical**	**Major**	**Minor**
Durability	X		
Design details/connections/anchorage	X	X	
Clogging		X	
Dynamic/seismic		X	
Wind		X	
Leakage	X		
CQC/CQA	X		
Interface shear strength		X	
Benefit/Cost	X		
Design loads		X	
Variance and expected values		X	
Chemical compatibility			X
Installation underwater			X

FINAL REMARKS

An analysis is presented in this paper to provide insight into the cost-effectiveness of geomembrane systems used in hydraulic structures. This involved an assessment of construction costs and of the value of water that would be lost by seepage without a lining system. Use of geomembrane liners in canals can lead to a cost recovery of at least 4 times the construction costs. The benefits are quantified by the water conserved over the lifetime of the liner. Geosynthetics are primarily used in dams to increase their stability and prevent erosion and are not necessarily associated with cost recovery of water by a seepage reduction. However, use of geosynthetic liners provides an economic return in conserved water value should not be disregarded. Such economic considerations can make a geosynthetic system an attractive solution.

Dams are among the most critical hydraulic structures and stand to benefit the most from the use of geosynthetics. Deterioration and structural damage due to seepage are major concerns that can be addressed by geomembrane liners. Geosynthetic systems as hydraulic barriers in dams are effective solutions to the problem of degradation. Accordingly, geosynthetics have been used in a wide range of dam types and dam sizes. The first installation of a geomembrane in a dam occurred in Italy over 40 years ago. Since then, geosynthetics have been installed in dams worldwide, as part of new projects and of rehabilitation projects.

Most recently, the Olivenhain dam in San Diego was built with a geosynthetic system as an infiltration barrier.

Research on geosynthetics can certainly lead to an increased knowledge base, allowing more efficient and cost-effective designs. A recent survey of research needs indicated that the most critical research needs for geosynthetic technology in hydraulic structures are durability, quantification of leakage, design details, CQC/CQA, and better data for benefit/cost analyses. These needs can be considered as a starting point to identify further research to address major problems associated with expected lack of freshwater in the immediate future.

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HOT TOPICS IN GEOSYNTHETICS - IV
(Waste Properties; Geotextile Tubes; Challenges & Opportunities)

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