RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-2014-56

Research Priorities to Enhance Dam Infrastructure Sustainability

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Materials Engineering and Research Laboratory
Denver, Colorado

September 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Materials Engineering and Research Laboratory, 86-68180

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EXECUTIVE SUMMARY

Addressing the needs of aging infrastructure is critical to system reliability [1]. Research roadmapping enables us to determine where future research efforts should be focused in order to provide the greatest benefit. In this report, we explore the existing needs of aging infrastructure and identify key research needs, establishing a framework for research roadmapping (mapping). A peer-reviewed dam infrastructure research roadmap is included in attachment B, which provides a comprehensive description of the research need, including the adverse outcome, currently used mitigation practices, and the outstanding needs for tools, technology, etc. The intent of this information is to provide a thorough explanation of the research need to potential researchers in this area. The highest priority need statements are listed below:

- Seepage
    - Remote sensing or inspection method to detect seepage or material transport paths
    - Methods and materials to detect and fill or repair voids under spillway slabs
- Spillway
    - Improved understanding of concrete repair material properties and performance of the composite system as well as methods to prevent cracking of repair materials
    - Better tools to treat the underlying cause of concrete deterioration
- Mass concrete
    - More effective repair methods and materials to stop progression of concrete deterioration
    - Modeling tools to predict the rate of concrete deterioration
- Develop improved correlations between laboratory grout characterization tests and actual field performance

- Foundation
    - Evaluate and verify finite element modeling of existing concrete and embankment dams based on their historical loading
    - Methods or tools to characterize the effectiveness of in situ dam foundation repairs (stone columns, compaction grouting, and jet grouting)
    - Improved tools to better characterize foundation materials and properties
- Improved understanding of chemical interactions that adversely affect the performance of embankment dam filter material
- Structural steel
    - Much longer life coatings to protect metal components from corrosion
    - Improve tools to predict remaining coating life
- Gates
    - Improve gate reliability, including the need and frequency for gate exercising
    - Develop methods or tools to measure the health of a gate beginning with historical causes of nonperformance
- Physical testing to improve numerical models for spillway crest structure – soil interactions

INTRODUCTION

The Bureau of Reclamation's (Reclamation) Research and Development Office enacted several research roadmapping endeavors in order to strategically identify the organization's evolving scientific and engineering research needs. As an example, "Addressing Climate Change in Long-Term Water Resources Planning and Management, User Needs for Improving Tools and Information" addressed interagency impacts of climate change [2]. In addition, the "Desalination and Water Purification Technology Roadmap – A Report of the Executive Committee" identified opportunities for the growing water supply challenges [3]. Ecohydraulics mapping is ongoing.

The needs of Reclamation's aging infrastructure is addressed under the current research project. The "Bureau of Reclamation Asset Management Plan" reiterates that this is "central to the mission objectives of operation & maintenance (O&M) projects" [1]. Therefore, these three research questions (RQ) are of key interest:

RQ #1: What are the common reasons for reduced service life, extraordinary maintenance, or failure of Reclamation's infrastructure components?

RQ #2: What mitigation practices are currently used by Reclamation to address these failures or extend the working life of the infrastructure components?

RQ #3: What additional tools, measures, and technology, or improvements in existing technology, might allow us to extend the service life for all reserved and constructed Reclamation infrastructure components?

Table 1 provides Reclamation's mission-critical infrastructure (or assets) as described by Policy and Administration (P&A). Mission critical is defined as, "a facility or piece of equipment that if unavailable or inoperable, would substantially detract from the achievement of Reclamation's business objectives" [1]. The use of these component categories allows us to focus on each infrastructure type separately. Furthermore, the answers to RQ #1 are more apparent for their corresponding major components.

A parallel project, under which we are evaluating powerplant infrastructure, is ongoing under Project Manager Erin Foraker (Renewable Energy Research Coordinator, Reclamation). The focus of this project is on aging infrastructure from the perspective of its engineering disciplines. Therefore, the categories listed as "Other" in table 1 lie outside the scope of the existing framework; these categories may be approached by similar means at a later date.

Table 1.—Reclamation mission-critical assets

Category	Components
Dams	Dams, spillways, outlet works, gates (for dam operation)
Canals	Canals, laterals, reservoirs, gates, crane/lifts, trash rack structures, siphons, diversion dams, flow meters
Pipelines	Pipelines, surge tanks, associated components (with pipeline)
Powerplants	Gates, penstocks, turbines, excitation, generators, step-up transformers, auxiliaries, instrumentation and controls, unit breaker/switchgear, draft tubes
Pumping plants	Intake units, tanks, pump casings, motors, auxiliaries, instrumentation and control, discharge pipes
Other	Supervisory Control and Data acquisition (SCADA) systems, communication systems, associated land, etc.

RESEARCH METHOD

The "Research Roadmapping Method & Pilot Study" describes research method development [4]. The research roadmapping project proceeds in several phases. Table 2 provides the estimated timeline for the individual projects by fiscal year (FY) and quarter.

Table 2.—Roadmapping schedule

Category	FY13		FY14				FY15			
	3	4	1	2	3	4	1	2	3	4
Pipelines	Committee survey						Draft roadmap			
Pumping plants					Draft roadmap					
Canals				Draft roadmap						Combined research mapping
Dams				Draft roadmap						

Figure 1 summarizes the roadmapping method. SurveyMonkey® provided a means for obtaining data for the three RQs. Subject matter experts, including Technical Service Center (TSC) engineers, P&A program analysts, and field office—regional, area, and facility—personnel contributed to these datasets.

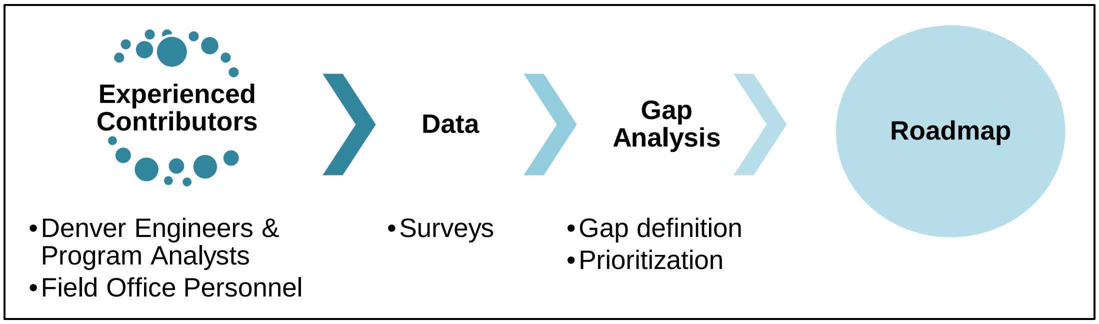

Figure 1.—Process for infrastructure sustainability roadmap.

The questionnaire data were collated, and similar responses were grouped together and coded. Some interpretation of responses was required. Each code is a summarized description of the statements made by respondents. These codes appear in the draft roadmap as "adverse outcomes" for RQ #1. In addition, these answers informed the development of the "causal analysis." Expert input from TSC engineers and P&A program analysts provided clarification and filled information gaps where appropriate. The final analysis of the roadmap included calculated statistics for "normalized frequency" and "average concern."

RQs #2 and #3 provided the "gap analysis" information. Again, TSC and P&A personnel critiqued the accuracy and completeness of the coded information.

Finally, the coded information for all three RQs aided in the development of the "research needs" for each adverse outcome. TSC and P&A personnel then scored the "gaps in existing tools" and "research needs." These two categories address the size of the gaps in existing tools and the value of anticipated research results, respectively.

This work resulted in four categories of quantitative information: frequency, concern, gaps in existing tools, and research needs. The respective rankings for these categories are 0–3, 0–3, 0–5, and 0–5. The four categories were summed, and the draft roadmap table was sorted from the highest to lowest score. The highest score represents the highest necessity for research.

TSC and P&A personnel evaluated the research needs for each adverse outcome and reduced the information to a short list of highest priority research needs.

RESULTS

Sixteen survey responses were included in the analysis. Denver personnel represented 44 percent of the survey respondents and included the following groups:

- Risk Advisory Team
- Asset Management
- Waterways and Concrete Dams
- Structural Analysis
- Materials Engineering and Research Laboratory

Dam Safety Office (DSO) and Embankment Dams and Geotechnical Engineering personnel participated in the survey analysis and roadmap development, but did not complete surveys.

The remaining 56 percent of the survey respondents represent field offices. The geospatial location of these personnel is critical to ensure that all of Reclamation's needs are included. For instance, climatic stresses (weather) varies greatly from region to region. Respondents hold offices in the following locations:

- Durango, Colorado
- Boise, Idaho
- Provo, Utah
- Grand Junction, Colorado
- Bend, Oregon

Attachment B provides the compiled survey results as the draft roadmap. This attachment includes the additional editing for accuracy and completeness provided by the TSC, DSO, and P&A personnel. Furthermore, it is prioritized based on the statistics for frequency (normalized:nrm) and concern (average:avg) as well as the rankings for sufficiency of current tools and research needs — provided by TSC and P&A personnel. The roadmap provides the average of these ranking results.

Table 3 provides the short list of highest priority research needs. The goal is for researchers in these respective areas to develop and implement solutions. A process for instituting the ensuing research projects is in progress.

Table 3.—Need statements for highest priority research needs

Spillway foundation and drains	A) Remote sensing or inspection method to detect seepage or material transport paths B) Methods and materials to detect and fill or repair voids under spillway slabs
Spillway (including gates and equipment)	A) Improved understanding of concrete repair material properties and performance of the composite system as well as methods to prevent cracking of repair materials B) Better tools to treat the underlying cause of concrete deterioration
Dam material	A) More effective repair methods and materials to stop progression of concrete deterioration B) Modeling tools to predict the rate of concrete deterioration
Dam foundation	Develop improved correlations between laboratory grout characterization tests and actual field performance
Dam foundation	A) Evaluate and verify finite element modeling of existing concrete and embankment dams based on their historical loading B) Methods or tools to characterize the effectiveness of in situ dam foundation repairs (stone columns, compaction grouting, and jet grouting) C) Improved tools to better characterize foundation materials and properties
Dam material	Improved understanding of chemical interactions that adversely affect the performance of embankment dam filter material
Outlet works	A) Much longer life coatings to protect metal components from corrosion B) Improve tools to predict remaining coating life
Spillway (including gates and equipment)	A) Improve gate reliability, including need and frequency for gate exercising B) Develop methods or tools to measure the health of a gate beginning with historical causes of nonperformance
Spillway (including gates and equipment)	Physical testing to improve numerical models for spillway crest structure – soil interactions

REFERENCES

[1] "Bureau of Reclamation Asset Management Plan," Bureau of Reclamation, Policy and Administration, Fiscal Year 2011, September 2012.

[2] Brekke, L.D., "Addressing Climate Change in Long-Term Water Resources Planning and Management, User Needs for Improving Tools and Information," Bureau of Reclamation, Science and Technology Program, Technical Report, January 2011.

[3] "Desalination and Water Purification Technology Roadmap – A Report of the Executive Committee," Bureau of Reclamation, Desalination & Water Purification Research & Development Program, Report #95, January 2003.

[4] Merten, B., "Research Roadmapping Method & Pilot Study," Bureau of Reclamation, Technical Memorandum No. MERL-2014-53, September 2014.

ATTACHMENT A

Dams Questionnaire

The Technical Service Center (TSC), in conjunction with the Research and Development Office, is preparing a research roadmap to identify ongoing research needs. This questionnaire allows us to take a closer look at Reclamation's infrastructure from its subset of "Dams" and related features. This information will be used to determine where future research efforts should focus, with a goal of providing the greatest benefit to the organization as a whole.

You were selected for this questionnaire based on your knowledge and experience. We appreciate your time and hope that you will complete it by May 31, 2014. It contains 6 topic areas (Dam Foundation, Dam Material, Spillway, Spillway Foundation/Drains, Outlet Works, Reservoir) with 5 questions each. The 2 additional questions determine contact information (in case an answer requires clarification) and feedback, for a total of 32 questions. The approximate time to complete is 1 hour. You do not have to fill-in all boxes if you feel no additional issues exist. You are free to navigate backward/foreword, edit responses, stop/re-start later, discuss answers with colleagues, etc. Your careful and well-constructed insight is appreciated.

Thank you in advance for your time. For questions or concerns, please contact me at 303-445-2399 or kvonfay@usbr.gov. For technical difficulties, contact Bobbi Jo Merten, 303-445-2380 or bmerten@usbr.gov.

Thanks

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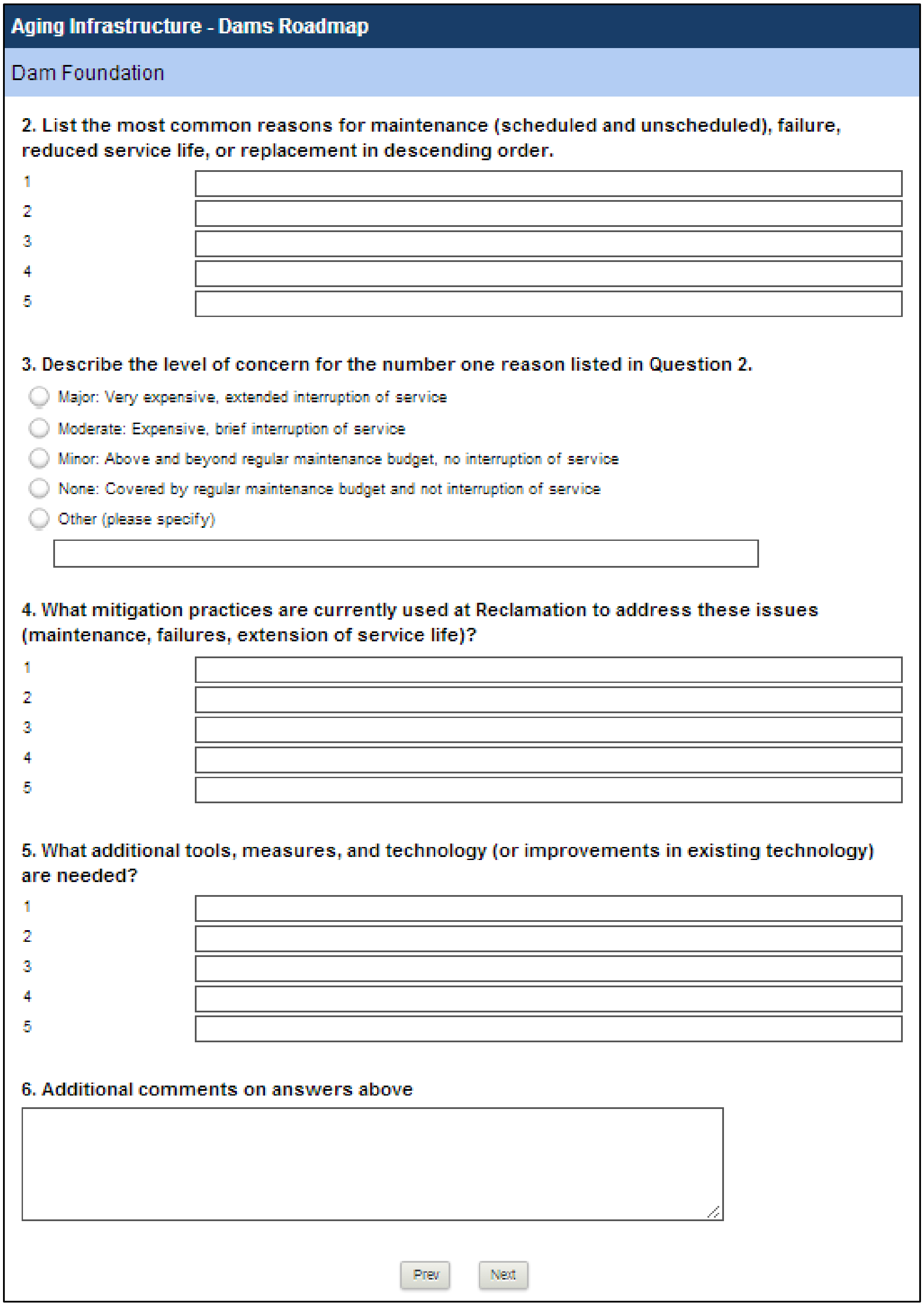
Bureau of Reclamation



Aging Infrastructure - Dams Roadmap

Dam Foundation

2. List the most common reasons for maintenance (scheduled and unscheduled), failure, reduced service life, or replacement in descending order.

1
2
3
4
5

3. Describe the level of concern for the number one reason listed in Question 2.

- Major: Very expensive, extended interruption of service
- Moderate: Expensive, brief interruption of service
- Minor: Above and beyond regular maintenance budget, no interruption of service
- None: Covered by regular maintenance budget and not interruption of service
- Other (please specify)

4. What mitigation practices are currently used at Reclamation to address these issues (maintenance, failures, extension of service life)?

1
2
3
4
5

5. What additional tools, measures, and technology (or improvements in existing technology) are needed?

1
2
3
4
5

6. Additional comments on answers above

Prev Next

Figure A1.—Dam questionnaire example, shown for "dam foundation."

ATTACHMENT B

Research Roadmap

Table B1.—Prioritized draft research roadmap for dam infrastructure

#	Causal analysis (dam infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
#	Structure	Adverse outcome	Process	Cause	Frq	Nrm 0-3	Conc. Data	Avg 0-3	Available tools	Gaps in existing tools	L - H 0-5	Results are high value	L - H 0-5	0-16
1	Spillway foundation and drains	Seepage beneath or along spillway, resulting in voids	Piping/internal erosion removes foundation material	Unsuitable foundation materials. No filter or poor filter. Poor filter compatibility. Drain movement or failures (heaving). Improper initial compaction.	15	2.50	1 Mod 3 Maj	2.75	Seepage monitoring/ instrumentation. Ground-penetrating radar. Partial or complete replacement of structures and foundation. Provide filters around drains.	Better methods of detecting and mapping voids below spillway slabs. Methods to detect seepage/material transport paths. Methods to address foundation voids without large-scale modifications to the spillway concrete (grouting?) Better design details for allowing future inspections of spillway underdrains. Improved filter design practices. Safety of Dams (SOD) modifications do not always address the outlet works.	4.00	A) Remote sensing or inspection method to detect seepage or material transport paths B) Methods and materials to detect and fill or repair voids under spillway slabs	4.00	**13.25**
2	Spillway (including gates and equipment)	Deterioration of spillway concrete	Concrete condition changes by cracking, spalling, etc.	Freeze thaw, wear and tear, environmental factors, abrasion erosion, alkali aggregate reaction, sulfate attack, chemical reactions, etc.	18	3.00	1 Oth 3 Mod 4 Maj	2.50	Routine patching, replacement of concrete. Better concrete patching program with saw cutting and reinforcement dowels. Grouting leaks.	Repair material innovations to reduce cracking and investigate why and what can be done. Better understanding of material compatibility issues. Longer lasting materials. Concrete repairs are not always very successful. Always room for better repair methods. Better ability to predict structural performance of spillways under extreme loads. Better ability to predict debris impacts on spillway structures.	3.67	A) Improved understanding of concrete repair material properties and performance of the composite system as well as methods to prevent cracking of repair materials B) Better tools to treat the underlying cause of concrete deterioration	4.00	**13.17**
3	Dam material	Deterioration of concrete (concrete dams)	Concrete condition changes by cracking, spalling, etc.	Freeze thaw, wear and tear, environmental factors, alkali aggregate reaction, sulfate attack, etc.	14	2.33	4 Maj	3.00	Coatings/sealers. Replacement/repair of deteriorated concrete.	Better understanding of material properties versus field performance. Improved nonlinear analytical methods to predict rate of future deterioration. Noninvasive/ nondestructive field testing methods. Better understanding of material compatibility issues.	3.67	A) More effective repair methods and materials to stop progression of concrete deterioration B) Modeling tools to predict the rate of concrete deterioration	4.00	**13.00**
4a	Dam foundation	Foundation material loss	Seepage/piping/ internal erosion	High exit gradients, highly erodible foundation materials, or flaws, such as voids or cracks, in the foundation.	10	1.67	4 Maj	3	Design modifications, seepage analysis, cut-off trench, grout curtains, cutoff walls (e.g., soil-cement, cement-bentonite, concrete panels), monitoring.	Better grouts. Better Inspection method – remote sensing. Better understanding of grout properties and actual field performance. Inability to identify concentrated seepage paths. Improved construction techniques for installing cutoff walls.	3.75	Develop improved correlations between laboratory grout characterization tests and actual field performance Remote sensing or inspection method to detect seepage or material transport paths	3.75	**12.17**
4b	Dam foundation	Dam structure becomes unstable or fails	Foundation block slide, liquefaction, or settlement	Dynamic or static load exceeds original design (seismic events, settlement, etc.)	10	1.67	3 Maj	3.00	Placement of materials to increase weight, anchoring of foundation blocks or drainage. In situ treatment such as dynamic compaction, stone columns, jet grouting, compaction grouting, remove, and replace, etc. Advanced finite element analysis.	Improved confidence in highly nonlinear numerical modeling for seismic loading in particular. Accelerometers to measure seismic impacts or effects. Visual inspections seem minimally useful for smaller events that may have unobservable impacts. Has the Bureau of Reclamation (Reclamation) done any review of the impacts and effects on dams in northern Japan or in Chile after the recent, large subduction zone events that occurred? Inability to completely characterize foundation materials and properties.	3.25	A) Evaluate and verify finite element modeling of existing concrete and embankment dams based on their historical loading B) Methods or tools to characterize the effectiveness of in situ dam foundation repairs (stone columns, compaction grouting, and jet grouting) C) Improved tools to better characterize foundation materials and properties Improved tools to better predict uplift pressure changes as a result of an earthquake (foundation rock blocks)	4.25	**12.17**

Table B1.—Prioritized draft research roadmap for dam infrastructure

#	Causal analysis (dam infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
5	Dam material	Embankment material loss due to internal erosion (embankment dams)	Internal erosion of embankment	Unsuitable materials or improper drainage or filters, seepage	8	1.33	4 Maj	3.00	Reservoir restriction. Monitoring. Replacement of materials, use of filter berms, drainage zones, weirs, piezometers, etc. Redesign/replacement of structure or major portion of structure.	Ability to identify concentrated seepage. Collaboration of best practices with other agencies such as the United States Army Corps of Engineers.	3.50	Improved understanding of chemical interactions that adversely affect the performance of embankment dam filter material Remote sensing or inspection method to detect seepage or material transport paths	3.75	**11.58**
6	Outlet works	Failure of the outlet works metal components	Corrosion of gates and metal components	Inadequate corrosion prevention, coating failure, maintenance inaccessibility	13	2.17	4 Mod 1 Maj	2.20	Replace gates or metal components. Clean and recoat. Add or modify cathodic protection.	Coatings that can be applied in humid, cold conditions. Monitoring of need and timing to do maintenance. Longevity of coatings.	2.67	A) Much longer life coatings to protect metal components from corrosion B) Improve tools to predict remaining coating life Development of coatings that can be applied in humid and cold conditions	3.67	**10.70**
7*	Spillway (including gates and equipment)	Failure of the spillway gate metal workings or structure	General corrosion of radial gates and associated metalwork	Inadequate corrosion prevention and reapplication of coatings protection. Cavitation.	11	1.83	1 Mod 1 Maj	2.50	Clean and recoat surfaces. Repair, strengthen, or replace gate metalwork. Add or modify cathodic protection.	Methods to identify need and timing of maintenance. Longer life coatings.	2.67	Longer life coating to protect metal components from corrosion. Improve tools to predict coating life.	3.67	**10.66**
8*	Spillway foundation and drains	Plugged, restricted, and failed drains	Buildup of debris, foundation material, or minerals in drains	Lack of cleaning and drain maintenance. Erosion or settlement of foundation material and structural movement. Poor joint connections (clay pipe).	12	2.00	2 Mod 2 Maj	2.50	Jetting, crawler cam inspections, periodic evaluation, and cleaning (can be problematic in older structures). Replace drains. Modifications to the spillway.	Easy to use field-level bore scopes or remotely operated vehicle (ROV)-type cameras. Better video capabilities within drains. Improved diligence with inspection and cleaning if possible. Remote sensing for inspection. Better design details for allowing future access/inspections of spillway underdrains. Better repair methods to seal damaged drains.	2.67	Methods and materials for accessing, evaluating, and repairing damaged drain	3.00	**10.17**
9*	Outlet works	Deterioration of concrete	Concrete condition changes by cracking, spalling, etc.	Freeze thaw, wear and tear, environmental factors, Alkali aggregate reaction, sulfate attack, etc.	5	0.83	2 Mod 1 Maj	2.33	Concrete repair/replacement. Coating/sealing concrete.	Longer lasting repair materials.	3.33	Improved understanding of structural concrete repair material properties and performance of the composite system as well as a means to prevent cracking. Better tools to treat the underlying cause of structural concrete deterioration.	3.67	**10.16**
10	Spillway (including gates and equipment)	Spillway gate equipment does not function properly	Long periods of gate motor inactivity	Lack of proper full travel exercising of gates in unbalanced or harsh operating conditions	7	1.17	1 Mod	2.00	Regular operational testing. Rope access to inspect gates for corrosion. Motor maintenance, lubrication, rope/chain replacements, gate painting.	Better enforcement of gate exercising full travel under load. Better design of radial gate arms. Risk analysis of gate operation to include proper power supply, loads and frictions, and operation with no power. Better tools for predicting gate reliability.	2.67	A) Improve gate reliability, including need and frequency for gate exercising B) Develop methods or tools to measure the health of a gate beginning with historical causes of nonperformance Better rope/chain materials	3.00	**8.84**
11*	Dam material	Dam structure becomes unstable or fails	Embankment liquefaction or settlement	Dynamic or static load exceeds original design (seismic events, settlement, etc.)	5	0.83	-	0.00	SOD modifications. Monitoring, replacement of structure. Finite element modeling (FEM) analysis of dam/foundation.	Dam deformation measurements. Lack of confidence in FEM modeling predictions due to difficulty in calibrating models.	3.00	Evaluate and verify finite element modeling of existing concrete and embankment dams based on their historical loading	3.50	**7.33**

Table B1.—Prioritized draft research roadmap for dam infrastructure

#	Causal analysis (dam infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
12*	Spillway (including gates and equipment)	Spillway gate leakage	Inadequate gate seal performance	Seal material is not suitable, or seal service life is surpassed	1	0.17	1 Mod	2.00	Seal replacement or do nothing	Longer lasting, more durable materials for gate seals	2.33	Better understanding of seal materials and performance and the impact of a leaking seal.	2.67	**7.17**
13	Spillway (including gates and equipment)	Spillway structure or equipment becomes unstable or fails	Seismic loads affect sidewall soil-structure or gates, joint offsets	Dynamic or static load exceeds original design (seismic events, etc.)	3	0.50	-	0.00	Tool to evaluate seismic loading on spillway structures. FEM analysis of soil-structure interaction.	Better of understanding and prediction of structure performance under extreme loading conditions. Research ongoing for soil-structure interaction – need testing to support nonlinear finite element results.	3.00	Physical testing to improve numerical models for spillway crest structure – soil interactions	3.33	**6.83**
14	Spillway (including gates and equipment)	Sediment and debris must be removed from stilling basins	Sedimentation, rocks, and cobbles collect in basin during stilling	Sediment, silt, and debris settle out of water in basin or are pulled into basin from downstream channel	3	0.50	-	0.00	Dewatering, mucking out with heavy equipment, underwater examinations. Hydraulic model study has evaluated effects of downstream eddies introducing material into stilling basins.	Evaluation of performance of spillway stilling basins to minimize impacts from sediment deposition.	2.67	More efficient sedimentation removal or reduced rate of sedimentation removal maintenance. Develop methods so that stilling basins will self-clean under certain flow conditions. Develop methods to prevent downstream material from being introduced into a stilling basin.	3.00	**6.17**
15	Dam foundation	Plugged drain	Foundation drain, relief well, or toe drain becomes plugged	Buildup of minerals (by environment or bacteria), toe drains may fail by overloading	6	1.00	1 None 2 Min	0.67	Rodding, high-pressure water cleaning, or chemical treatment of foundation drains. ROV inspection. Excavation and replacement of toe drain sections. Reclamation Manual: Drainage for Dams and Associated Structures.	More options for cleaning drains (such as chemicals or mechanical options). Better ability to predict long-term performance of drains and needed frequency of cleanings to maximize drain life.	1.75	Better installation procedures for two-stage filter old embankment toe drains. Technique to restore efficiency of relief wells in concrete foundation drains. Better tools to predict drain performance.	2.25	**5.67**
16	Dam material	Vegetation management or control required (embankment dams)	Trees/deep-rooted vegetation growth	Water provides source for large vegetation to thrive, vegetation on riprap is inaccessible	4	0.67	1 None 2 Min 1 Mod	1.00	Mechanical and chemical treatment. Burning when possible, though increasingly less of an option.	Communication of past/current herbicide research (products, methods, current regulations, etc.), which can be passed on to operating entities to improve vegetation control and removal.	1.75	Method to remove deep-rooted vegetation without interruption to service or expensive compaction.	2.00	**5.42**
17	Dam material	Spillway plugging and overtopping due to debris (embankment dams)	Debris plugs spillway	Floating debris piles or trash	2	0.33	-	0.00	Log booms. Routine maintenance to remove excessive debris.	Inability to accurately predict the potential for and the magnitude of spillway debris plugging. Ways to predict, reduce, or eliminate maintenance efforts related to debris removal.	2.67	Predictive tools for debris that could plug spillways based on storm events, basin conditions, spillway configuration, etc.	2.33	**5.33**
18	Outlet works	Gate leakage	Inadequate gate seal performance	Seal material is not suitable, or seal service life is surpassed	2	0.33	-	0.00	Seal replacement or do nothing.	Longer lasting, more durable materials for gate seals.	2.33	Better understanding of seal materials and performance and the impact of a leaking seal.	2.67	**5.33**
19	Dam material	Embankment material loss due to surface erosion (embankment dams)	Surface erosion of embankment	Wave action, storms	3	0.50	1 Maj	3.00	Use of concrete linings or elements, geosynthetics, etc. Redesign/replacement of portions of structure, add upstream or downstream buttress.	Deteriorated riprap is slowly becoming a major concern.	1.33	None apparent.	0.33	**5.17**

Table B1.—Prioritized draft research roadmap for dam infrastructure

#	Causal analysis (dam infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
20	Dam material	Burrows and holes in embankment (embankment dams)	Seepage/piping/ internal erosion	Inadequate control of burrowing animals and inadequate repair of damage to embankment	2	0.33	—	0.00	Various control methods. Fill burrows with cement slurry or excavate and replace with compacted material.	Improved control and repair methods.	2.25	Tools to control or prevent animal burrowing. Method to repair animal burrows without interruption of service.	2.50	**5.08**
21	Outlet works	Outlet works gate operators does not function properly	Long periods of gate motor inactivity	Lack of proper full travel exercising of gates in unbalanced or harsh operating conditions	7	1.17	3 Mod	2.00	Regular exercise of the gates. Monitoring/ instrumentation.	Improved maintenance practices of outlet works equipment. Increased monitoring and recordkeeping regarding gates and operating equipment. Where to find parts for equipment that is no longer made? Systems analysis of outlet works.	1.33	None apparent; can/should be addressed through facility operation and maintenance (O&M) practices.	0.33	**4.84**
22	Outlet works	Seepage into or out of conduits (piping)	Piping/erosion along the conduit	Poor historical design practices for seepage control/collection – no sand filter diaphragms, differential settlement	4	0.67	—	0.00	Monitoring of seepage into and along conduits. Originally designed cutoff collars.	Methods to detect voids below or outside conduits. Redundant design defensive measures for limiting seepage. Better understanding of material compatibility issues.	3.50	Methods to detect voids below or outside conduits. Methods and materials to repair voids below or outside conduits.	3.50	**7.67**
23	Reservoirs	Reservoir's capacity or geography changes, affecting operations	Rock falls, landslides, seiche waves, etc.	Dynamic or static load exceeds original design (seismic events, adjacent faults etc.)	8	1.33	1 Min 1 Mod 1 Maj	2.00	Landslide surveillance program. No mitigation being performed due to priority. Major seismic repairs (filters, berms).	Improved understanding of fault seismic potential. LIDAR inspection techniques. Photogrammetry.	2.25	Better tools for modeling seismic loading and effects. Developing tools to monitor/map land movement.	3.25	**8.83**
24	Reservoirs	Loss of reservoir capacity. Blockage of outlet works intakes.	Sediment buildup	Sediment, debris, silt in the water. Flush sediments.	2	0.33	2 Maj	3.00	Clean intakes. Repair damaged concrete or gates caused by debris. Reservoir surveys.	More critical look at the effects of reservoir sedimentation on reservoir life and reservoir capacity.	2.25	More efficient sedimentation removal. Reduced rate of sedimentation removal maintenance.	2.50	**8.08**
25	Reservoirs	Increased dam safety risk due to increased downstream populations	Developments (homes, etc.)	Issues of jurisdiction between various agencies on the lands around the reservoirs.	2	0.33	1 Mod	2.00	Land use planning. Consent to use/permitting.	Point and click database of permits.	1.75	Need better tools to raise awareness of dangers/issues in developing downstream from a dam and better ways to manage development.	2.75	**6.83**
26	Reservoirs	Dam movement causes lift lines/contraction joints to leak	Dam load removed and reloaded	Prolonged drought. Reservoirs draining (major construction purposes), etc., removed load from dam. Unbonded lift line joints.	1	0.17	1 Mod	2.00	Seal leaks. Good design details with appropriate waterstop materials. Good construction practice to ensure bond at life lines.	Better materials.	1.67	Identify/develop better materials and methods to seal leaks. Better tools to identify leaks or source of leaks.	2.67	**6.50**
27	Reservoirs	Overgrown vegetation	Vegetation grows in or along reservoir	Water provides source for large vegetation to thrive	1	0.17	2 Mod	2.00	Removal and control of undesirable vegetation as needed.	None apparent.	0.00	None apparent; can/ should be addressed through facility O&M practices.	0.00	**2.17**

*No new or high priority research needs identified.