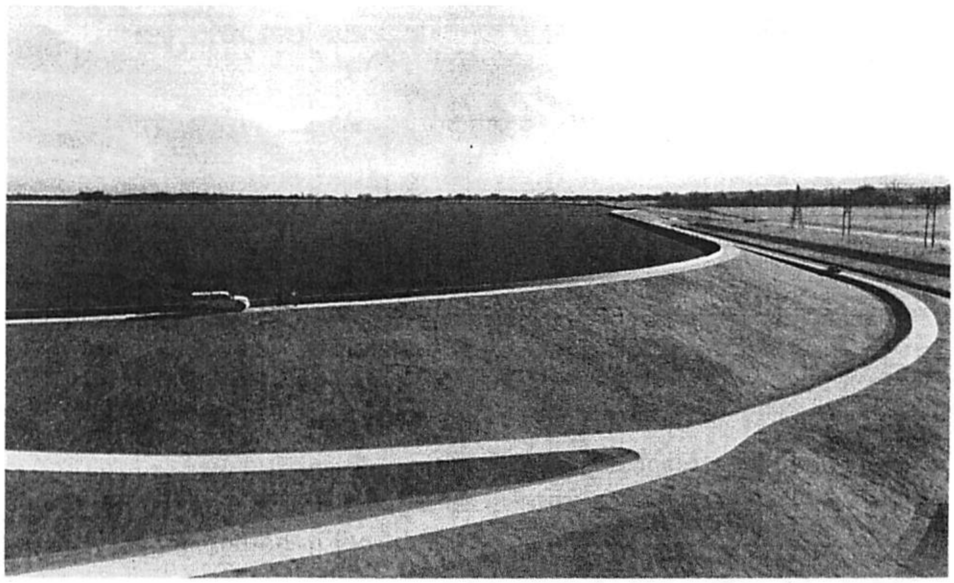
Innovative Solutions for Design and Construction of an Off-Channel Reservoir:

Arbuckle Reservoir Case Study



Prepared for:
Texas Water Development Board

Prepared by:
Lower Colorado River Authority
Contract Number 1400011761
May 2018

LCRA ENERGY • WATER • COMMUNITY SERVICES

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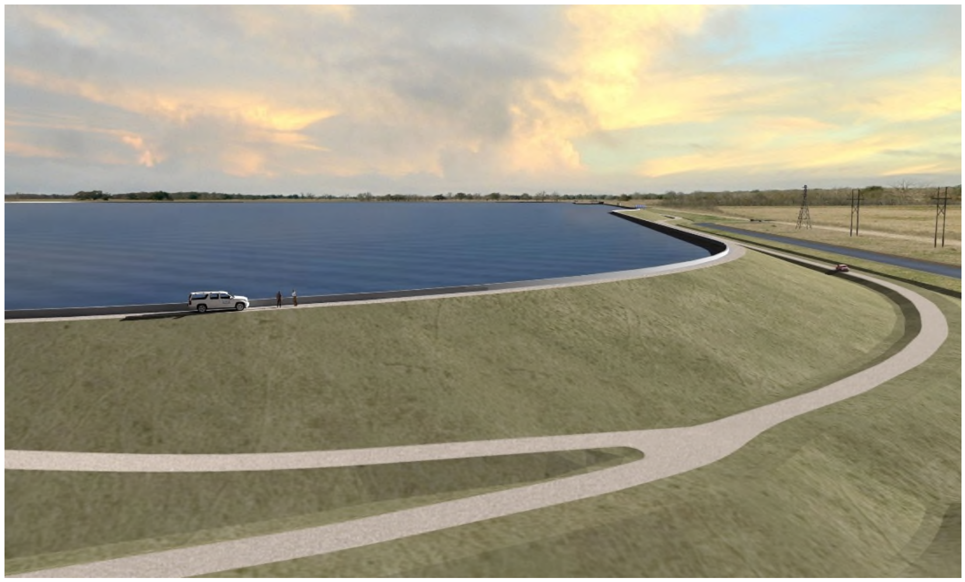

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Executive Summary

The Lower Colorado River Authority (LCRA) was awarded a Near-Term Water Supplies Demonstration Grant by the Texas Water Development Board (TWDB) in 2014 based on LCRA's submitted application. As part of the requirements to receive the grant, LCRA was required to complete four tasks for the TWDB.

- Task 1 – Prepare a report on the regulatory considerations to permit an off-channel reservoir (OCR).
- Task 2 – Construct the three innovative features of the project described in the grant application.
    - River return structure
    - Chimney drain
    - Wave wall
- Task 3 – Prepare a report on post-construction documentation, lessons learned and any related best practices.
- Task 4 – Work with TWDB to share information with respective agencies, public agencies and the general public, including participation in conferences, TWDB technical sessions and multi-media documentation of the construction process.

This report has been prepared to satisfy the grant requirements for Task 3. The Arbuckle Reservoir[1] provides several examples of innovative approaches for reservoir design and construction that may benefit other water supply developers in Texas. The purpose of this report is to document information that may be useful to others considering construction of an OCR. Figure ES-1 is an aerial view rendering of the Arbuckle Reservoir Project.

The scope of the report includes an overview of key design and construction considerations for off-channel reservoirs. Additional detail is provided for three innovative facility components of the Arbuckle Reservoir: (1) river return structure, (2) chimney drain and (3) wave wall.

[1] The Arbuckle Reservoir was previously called the Lane City Reservoir. In November 2017, the LCRA Board of Directors renamed the reservoir in honor of J. Scott Arbuckle, a former member of the LCRA Board.

Figure ES-1. Aerial View of Rendering of the Arbuckle Reservoir Project

The specific design approaches used for the Arbuckle Reservoir project will not apply to every OCR. Integrating site-specific construction considerations and a thorough understanding of safety, operational and regulatory requirements can result in cost-effective solutions. The Arbuckle Reservoir project used existing intake facilities and LCRA's site selection process to allow the use of a relatively simple water rights permitting process and nationwide permits to comply with Clean Water Act Section 404, resulting in a faster permitting process than is typical of complex projects like reservoirs.

Construction began in November 2015, and the project is expected to be in operation by the end of 2018. At the time of report preparation, most of the project components are complete, but construction of some components is still in progress and initial filling of the reservoir has not commenced.

Innovative components of the Arbuckle Reservoir project, including the layered chimney drain, the river return structure and the wave wall, helped efficiently meet engineering and operational requirements for the project and manage project costs.

The report is organized into the following six sections:

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Tables

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Acronyms and Abbreviations

AFD	Adjustable frequency drive
ASTM	ASTM International
CFD	Computational fluid dynamics
CFS	Cubic feet per second
CH2M	CH2M HILL Engineers Inc.
CLSM	Controlled low-strength material
CMAR	Construction manager at risk
CR	County road
EPA	U.S. Environmental Protection Agency
GC	General contractor
GMP	Guaranteed maximum price
GPS	Global positioning system
HPS	Horizontal pump station
LCD	Lane City Dam
LCRA	Lower Colorado River Authority
OCR	Off-channel reservoir
P&J	Phillips and Jordan Construction Inc.
QA	Quality assurance
QC	Quality control
RTU	Remote terminal unit
SBCOW	Soil-bentonite cut-off wall
SCADA	Supervisory control and data acquisition
TCEQ	Texas Commission on Environmental Quality
TRB	Technical Review Board
TWDB	Texas Water Development Board
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
VPS	Vertical pump station

1 Introduction

1.1 Purpose and Scope

This report has been prepared as part of a Near-Term Water Supplies Demonstration Grant awarded to the Lower Colorado River Authority (LCRA). As a demonstration project, the Arbuckle Reservoir provides several examples of innovative approaches for reservoir design and construction that may benefit other water supply developers in Texas. The purpose of this report is to document information that may be useful to others considering construction of an off-channel reservoir (OCR).

The scope of the report includes an overview of key design and construction considerations for off-channel reservoirs. Additional detail is provided for three innovative facility components of the Arbuckle Reservoir project: (1) river return structure, (2) chimney drain and (3) wave wall.

1.2 Arbuckle Reservoir Background

Over the 50-year period 2020 to 2070, the population of Region K, the water planning region that includes the lower Colorado River basin, is projected to increase by 87% to 3.2 million people. Consequently, the total water demand in the region in the same time period is projected to increase from 1.2 million acre-feet per year to approximately 1.5 million acre-feet per year (TWDB, 2017). To meet projected water demands within its region, the LCRA Board of Directors in February 2012 adopted a goal to add 100,000 acre-feet of firm water supply by 2017. A critical project for meeting that goal is an OCR in Wharton County — the Arbuckle Reservoir.

The reservoir will hold approximately 40,000 acre-feet of water and allow LCRA to capture and store significant amounts of water downstream of LCRA's two existing water supply reservoirs, lakes Buchanan and Travis, which are part of the Highland Lakes located upstream of the City of Austin. As previously modeled using a modified version of TCEQ's Water Availability Model, the added storage in the lower basin, combined with more efficient operation of LCRA's other water supplies, results in the addition of up to approximately 90,000 acre-feet per year to LCRA's available firm water supply, an increase of greater than 10 percent. Firm water is water that can be made available without shortage through a repeat of the Drought of Record. This increased firm supply derives from the capture of water in excess of daily demands and the reduced need to call on water from above the Highland Lakes watershed. With testing of the reservoir operations expected to be completed in early 2019, at that time the project will have increased supply within five years of the grant award contract.

The Arbuckle Reservoir project also will provide additional operational flexibility, decreasing the need to send stored water from Lakes Buchanan and Travis down the Colorado River to customers near the coast while improving water reliability and efficiency to meet agricultural and environmental demands (LCRA, 2018).

The project is located in Wharton County, Texas, near Lane City. LCRA purchased property adjacent to the existing Gulf Coast Irrigation Division Plant No. 2 along County Road 120 for the project. Figure 1-1 shows the project location, and Figure 1-2 shows the reservoir site and footprint.

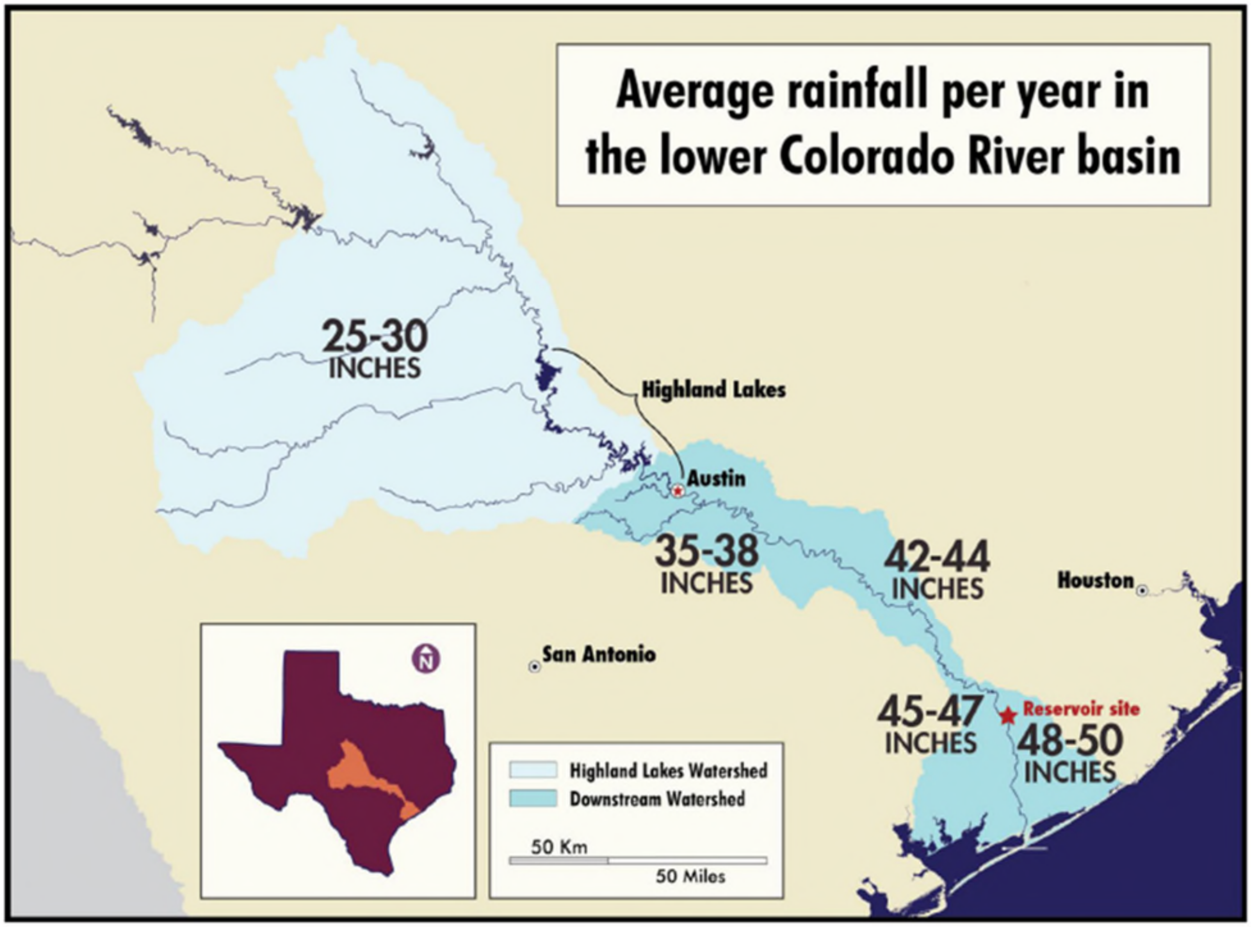

Figure 1-1. Arbuckle Reservoir Location Map

1.3 Construction Status and Chronology

The Arbuckle Reservoir project is currently under construction, and, as of May 2018, construction is approximately 80 percent complete. Reservoir filling and substantial completion is expected by the fourth quarter of 2018. Of the three innovative elements of the grant project, the chimney drain is 100 percent complete, the river return structure is approximately 60 percent complete, and the installation of wave wall panels is approximately 95 percent complete. A summary of milestone construction events is presented in Table 1-1.

Table 1-1: Summary of Milestone Construction Events

Date	Activity
February 2012	LCRA Board issues resolution to develop an additional 100,000 acre-feet of firm water supply for the lower Colorado River basin within five years; LCRA staff members begin pre-project planning and project definition to achieve this goal.
January 2013	LCRA Board authorizes Arbuckle Reservoir Project.
April 2013	Engineer (CH2M HILL Inc. [CH2M]) selected. Preliminary design begins.
May 2013	Technical Review Board (TRB) selected to provide LCRA independent review of design.
September 2013	Construction manager at risk (CMAR) contractor (Barnard Construction Co. Inc.) selected; CMAR begins performing preconstruction services, which include constructability reviews and preparation of construction cost estimates.
March 2014-May 2015	Detail design begins. Engineer prepares guaranteed maximum price (GMP) work packages for cost proposals by CMAR. (Five packages were planned.)
October 2014-April 2015	CMAR constructs test embankment.
	CMAR prepares updated construction cost estimates as GMP work packages are progressed.
April 2015	CMAR issues revised construction cost estimates for project.
May 2015	Revised cost estimates exceed project budget; LCRA decides to end cost negotiations and terminates CMAR contract.
July 2015	Engineer repackages GMP's packages into a single construction package.
	LCRA issues request for proposals from general contractors (GCs) for Arbuckle construction.
Nov 2015	Phillips and Jordan Inc. is selected as the GC; LCRA and Phillips and Jordan execute a fixed price, lump sum construction contract; Contractor begins mobilization.
Jan 2016	Construction begins.
September 2018	Initial filling of the reservoir and project commissioning anticipated to begin.
December 2018	Substantial completion (anticipated).
February 2019	Final completion (anticipated).

Figure 1-2. Aerial View of Rendering of the Arbuckle Reservoir Project

2 Life Cycle of an Off-Channel Reservoir

The primary purpose of this report is to describe the construction of the river return structure, chimney drain and wave wall of the Arbuckle Reservoir project. This report also describes how decisions made in the early phases of the project affected the construction of the three innovative components. This section presents a brief discussion of the Arbuckle Reservoir project phases and the effect on each component of construction.

2.1 Site Selection

Best Practice

Include a geotechnical engineer experienced in OCR design and construction to conduct a limited but targeted subsurface investigation to provide information to assess the need for a synthetic liner, the presence of sufficient and adequate material for embankment construction, and the need for groundwater dewatering during deep excavations.

Selecting a site for an OCR is a complex process unique to each project. The Arbuckle Reservoir project drew upon previous water supply planning studies, including the Region K Water Supply Plans, to identify general areas favorable for reservoir construction.

Water availability modeling studies demonstrated that OCRs located in the lower Colorado River basin are among the most cost-effective options for developing additional firm water supplies. An OCR located in the lower basin takes advantage of the wetter climate to capture and store runoff generated from rainfall downstream of the Highland Lakes and upper basin.

While these regional scale studies identified potential areas suitable for an OCR, the process for selecting a specific site also considered other factors, such as land costs, capital and operating costs, availability of water for storage, availability of land for acquisition, community acceptance, and the ability to permit the project within a reasonable period of time. All of these factors were considered in the evaluation of specific tracts of land for the OCR.

LCRA evaluated four specific sites within the lower basin and, based on the previously mentioned criteria, selected a site near Lane City, Texas, and contiguous with the LCRA irrigation system Pumping Plant No. 2. The 2,200-acre site was selected because of its favorable subsurface geology; sufficient clay material that eliminated the need for a costly synthetic liner; adequate native sand for construction of the blanket and chimney drains; the absence of pipelines to be relocated; a limited number of electric transmission lines to be relocated; and relatively few oil and gas wells to be plugged.

2.2 Permitting

Best Practice

Permitting is always a complicated task. Start early and prepare a detailed, written strategy for what is required and how it will be achieved.

LCRA prepared a report for the Texas Water Development Board Task 1 titled *Regulatory Considerations for Permitting an Off-Channel Reservoir* (LCRA, 2015b) that provides an overview of significant federal, state and local permits that may be necessary for similar projects and uses examples from the permitting of the Arbuckle Reservoir. Tables 2-1, 2-2 and 2-3 summarize permits (federal, state and local) potentially associated with an OCR and are provided herein.

Table 2-1: Summary of Major Federal Regulations/Permits

Permit, Approval, or Certification	Responsible Agency	Applicability Criteria	Required Actions
Clean Water Act (Section 404)/ Rivers and Harbors Act (Section 10) (33 United States Code (U.S.C.) 26 *et seq*. and 33 U.S.C. 403 *et seq*.; 33 CFR Part 328)	USACE	Activities (dredge and fill) in waters of the U.S.; construction in navigable waters.	Waters of the U.S. (including wetlands) delineation and jurisdictional determination, coordination with USACE, preparation of permit application. Section 404 permitting is contingent on Section 401 water quality certification by the TCEQ.
Endangered Species Act (16 U.S.C. § 1531 *et seq*.; 50 CFR Part 17)	USFWS	Construction in areas where threatened and endangered species or habitat could be impacted as a result of the construction and/or operation of the proposed facility.	Perform review and survey of threatened and endangered species on or in close proximity to the subject property.
Bald and Golden Eagle Protection Act (16 U.S.C. Section 668 *et seq*.; 50 CFR Part 17)	USFWS	Prohibits the take or commerce of any part of these species.	Perform review and survey of species on or in close proximity to the subject property.
Migratory Bird Treaty Act (16 U.S.C. Section 703-711 *et seq*.; 50 CFR Parts 20 and 21)	USFWS	Protects migrant bird species from take.	Perform review and survey of species on or in close proximity to the subject property.
Magnuson-Stevens Fishery Conservation and Management Act - Essential Fish Habitat Regulations (16 U.S.C. 1802(24) *et seq*.; 50 CFR Part 600)	National Marine Fisheries Service, Nation Oceanic and Atmospheric Administration	May apply if a habitat of concern is affected directly or indirectly.	An essential fish habitat conservation assessment and consultation could be required.
National Historic Preservation Act (Section 106) (16 U.S.C. 470 *et seq.; 36 CFR Part 800)*	State Historic Preservation Officer, Texas Historical Commission	Construction in an area where historic or archeological resources may be affected.	Perform review and survey of properties listed or eligible to be listed in the National Register of Historic Places.
National Flood Insurance Act and the Flood Disaster Protection Act (42 U.S.C. 40011 *et seq*.; 44 CFR Parts 59 - 80)	Federal Emergency Management Agency or qualified local authority (county or city)	Federal agencies must consider Executive Order 13690, which amends Executive Order 11988 to include Federal Flood Risk Management Standard.	Submit application to local floodplain administrator; may require modeling to demonstrate potential changes resulting from the project.
Invasive Species, Executive Order 13122 and associated acts, as amended: Nonindigenous Aquatic Nuisance Prevention and Control Act (16 U.S.C. 4701); Lacey Act (Sections 3371–3378); Federal Plant	All federal agencies; considered by the USACE in Section 404 permitting process	Construction or operation of project that could result in the spread of invasive species; applicable to water supply projects (particularly for projects transferring water among water bodies where zebra	Applicants may be required to develop control plans to prevent the spread of species during construction or operation.

Permit, Approval, or Certification	Responsible Agency	Applicability Criteria	Required Actions
Protection Act (7 U.S.C. 7701 *et seq.)*; and Federal Noxious Weed Act (7 U.S.C. 2801 *et seq*.)		mussels, hydrilla or similar species could spread).	

Note: In addition to the regulations cited in this table, numerous other executive orders, related regulations and agency policies may be applicable.

CFR = Code of Federal Regulations

TCEQ = Texas Commission on Environmental Quality (TCEQ)

U.S.C. = United States Code

USACE = U.S. Army Corps of Engineers
USFWS = U.S. Fish and Wildlife Service

Table 2-2: Summary of Major State of Texas Regulations/Permits
Regulatory Considerations for Permitting an Off-Channel Reservoir

Permit, Approval, or Certification	Responsible Agency	Applicability Criteria	Required Actions
Surface water rights (TEX. WATER CODE ch. 11; 30 TEX. ADMIN. CODE chs. 295, 297, & 298	TCEQ	Applies to authorization to divert, use and store surface water sources; bed and banks authorization may be needed; other conditions may apply.	Obtain appropriate amendment or new water right authorizing diversion, use and impoundment needed for the proposed reservoir.
Dam Safety (30 TEX. ADMIN. CODE ch. 299)	TCEQ	Private and publicly owned dams in Texas that meet one or more criteria: (1) 25 feet or more and store 15 acre-feet; (2) 6 feet or more and 50 acre-feet; (3) a high- or significant-hazard dam; or (4) provide pumped or terminal storage.	Conduct required analysis and submit to Dam Safety Program for review and approval.
Texas Antiquities Code (TEX. NAT. RES. CODE ch. 191)	Texas Historical Commission	Construction on land owned or controlled by a political subdivision of the state.	Conduct cultural resources evaluation.
Endangered and Threatened Species (TEX. PARKS & WILD. CODE chs. 67, 68 & 88)	Texas Parks and Wildlife Department	Construction in an area where threatened or endangered species or habitat could be impacted as a result of the construction and/or operation of the proposed facility.	Review of state threatened and endangered species list. Perform threatened and endangered species review and survey within the project area.
Marl, Sand, Gravel, Shell, or Mudshell Permit (TEX. PARKS & WILD. CODE ch. 86)	Texas Parks and Wildlife Department	Disturbance or take of materials within state-owned perennial streams or those more than 30 feet wide.	Obtain permit if needed.

Clean Water Act Construction Stormwater Permit (Section 402) (TEX. WATER CODE CH. 26; 30 TEX. ADMIN. CODE ch. 305)	TCEQ (U.S. EPA delegated this authority to the State)	Construction of any facility that disturbs 1 acre or more of land.	Prepare a Notice of Intent and Stormwater Pollution Prevention Plan for Construction. Submit Notice of Intent seven days prior to disturbance of earth start of construction
Authorization to construct in state right-of-way (TEX. TRANSP. CODE ch. 431)	TxDOT	Required if pipelines or project facilities are to be constructed under a roadway or in TxDOT right-of-way.	Develop and submit drawings of road crossing to TxDOT for review.
Oil & Gas Well Plugging (16 TEX. ADMIN. CODE § 3.14 (Rule 14))	Railroad Commission of Texas	May be required if oil and gas wells are located at the off-channel reservoir site.	Complete appropriate Railroad Commission form and plug wells according to technical specifications.
Permit, Approval, or Certification	**Responsible Agency**	**Applicability Criteria**	**Required Actions**
Invasive species (Harmful or potentially harmful fish, shellfish and aquatic plants, 31 TEX. ADMIN. CODE §§ 57.111- 57.137)	Texas Parks and Wildlife Department	It is an offense to release into the water of this state, import, sell, purchase, transport, propagate or possess any species defined as a harmful or potentially harmful.	A permit and control plan may be required.
Federal consistency review/certification (Texas Public Lands Management Act and Federal Coastal Zone Management Act; 31 TEX. ADMIN. CODE ch. 501)	GLO	Projects within the Coastal Management Zone (approximately 40 miles inland from coast in some or all of 17 counties).	Consultation and certification by GLO that the project is consistent with coastal management goals.
Miscellaneous Easement for right-of-way across state-owned land under the management authority of the GLO (TEX. NAT. RES. CODE § 51.291), or under the management authority of another state agency	GLO	Required for crossings of and construction of infrastructure within state-owned riverbeds/navigable streams.	Submittal of application and payment of fees.
Public Water Supply system approval for potable water supply (30 TEX. ADMIN. CODE ch. 290)	TCEQ	May be required if potable water supply is needed during construction or on a permanent basis for administrative or office buildings at the reservoir.	Submittal of plans prepared by a licensed engineer.

Note:
ch = Chapter
GLO = General Land Office
TEX ADMIN CODE = Texas Administrative Code
TxDOT = Texas Department of Transportation
TEX. NAT. RES. CODE = Texas Natural Resources Code

Table 2-3: Summary of Local and Regional Regulations/Permits
Regulatory Considerations for Permitting an Off-Channel Reservoir

Permit, Approval, or Certification	Responsible Agency	Applicability Criteria	Required Actions
Road crossings or relocations	County or city	Requirements vary by entity; many follow TxDOT design standards.	Generally, plans and profiles sheets of the crossing are reviewed; permits are sometimes required.
Building permits and associated inspections	County or city	Requirements vary by entity.	Requirements vary by entity.
On-site sewage disposal (septic tank)	County, city or other local delegated entity	May be required if an administrative building is constructed or potentially for temporary construction facilities if on-site sewage disposal is required.	Submit application, obtain permit and comply with construction and operating requirements.
Groundwater well drilling, production or closure permit	Groundwater conservation districts	May be required if groundwater will be used during construction, for drinking water at administrative facilities at the site or to close existing wells.	Submit application or other information and comply with construction and operating requirements in the district’s rules.
Development and/or water quality permits	Councils of governments, river authorities, regional water management districts or suppliers, cities	May be required on a case-by-case basis.	Requirements vary by entity.

2.3 Procurement

This section presents a brief overview of the major procurements for the project, and a summary of the use of the CMAR project delivery approach, the procurement process and the impact on construction when the delivery approach changed to a fixed price, lump sum contract.

2.3.1 Overview

Procurement, the selection of goods and suppliers, followed LCRA’s Supply Management policies. The methods and approach varied with the need and included using LCRA long-term contractors and responding to unique individual requests for proposals. A summary of the major procurements for the Arbuckle project is summarized in Table 2-4.

Table 2-4: Summary of Major Procurements for Design and Construction Activities

Phase/Service	Agreement/ Contract Type	Procurement Approach	Comments
Concept/ Preliminary Design	Professional Services	Request for qualifications interview; negotiated scope and fee.	Agreement April 2013.
Preconstruction Services	CMAR	Prequalification request for proposals interview; negotiated scope and fee for preconstruction services.	Contract September 2013; basis of construction fees set in proposal; work authorized based on negotiated GMP work packages.
GMP-1	Amendment to the CMAR contract	Negotiated scope and fee for the first GMP construction package.	GMP included constructing the test embankment; mobilizing to the site; building the construction laydown yard, fuel storage facility, maintenance shop building and office trailer facilities.
Final Design	Professional Services	Negotiated scope and fee.	Amendment March 2014.
Construction	General Contractor Construction Contract	Prequalification request for proposal interviews; best-and-final offer bid based on best value determination (not low bid).	Contract November 2015. Revised contract approach and re-bid when LCRA and CMAR could not come to terms on the largest construction work package.
QA Testing	Long-term Contractors	Negotiated scope and fee.	Authorized February 2016.
Services During Construction	Professional Services	Negotiated scope and fee.	Amendment August 2015.
Startup and Commissioning	Professional Services	Negotiated scope and fee.	Amendment February 2016.

Note:

QA = quality assurance

2.3.2 Construction Manager at Risk

LCRA evaluated various project delivery alternatives and initially determined the CMAR delivery approach was appropriate for the Arbuckle Reservoir project. The primary reasons included:

- **Schedule.** LCRA's goal was to have the project in service within five years. The CMAR approach reduces the overall project schedule because engineering design and construction can occur concurrently.

- **Constructability.** The CMAR approach brings the contractor into the design process at the start and allows the contractor's means and methods to be incorporated into the construction documents.

- **Improved cost estimates and construction schedules.** Developing construction cost estimates for a large earth-moving project is very dependent on assumed site conditions and productivity rates. A contractor experienced in large reservoir construction would have this information and be available to assist LCRA and the engineer to develop and update cost estimates as the design progresses.

- **Quantification of Risk**. Construction of large civil, earth-moving projects are inherently risky because of unknown subsurface conditions, weather and construction productivity. Construction work performed under GMP work packages provides additional certainty about the upper limits of construction costs.

LCRA also evaluated the use of a design-bid-build approach, but rejected it because of the time constraints presented by the five-year in-service goal for the project. Similarly, LCRA considered the use of a design-build or engineer-procure-construct approach, but rejected it primarily because of the absence of well-defined design and performance parameters for the reservoir, which would prevent accurate pricing.

LCRA used a two-step process to select the CMAR. Phase 1 was a pre-qualification phase, which included the following four criteria:

- Proven ability to self-perform construction of the reservoir portion of the project.
- Previous CMAR experience performing similar-sized projects.
- Related experience to the Arbuckle Reservoir project.
- Ability to meet bonding and insurance requirements.

Qualified contractors were notified and invited to submit detailed proposals. The Phase 2 proposals were evaluated based on references, key staff resumes, project approach and some cost categories. Cost categories included preconstruction services, general conditions, fee structure and markup percentages. The process also included site visits and interviews. The selection process required approximately 6 months to complete.

Best Practice
Include in the CMAR agreement a provision to off-ramp and terminate the contract.

In September 2015, the construction company Barnard Construction Inc. of Bozeman, Montana, was selected and authorized to perform preconstruction services (constructability reviews and cost estimating services). Subsequently, the first work package, GMP1 Site Mobilization and Test Embankment Construction, was negotiated and issued.

The CMAR contract included an “off-ramp” termination provision that allowed LCRA to terminate the contract if LCRA decides not to proceed with the construction of any stage of the project. LCRA invoked this article, and terminated the CMAR contract in May 2015. LCRA then began the process to select a GC to complete the project under a lump sum, fixed price agreement.

2.4 Engineering Design

CH2M joined the project team in April 2013 and continues to serve as the engineer of record for the project. The work scope includes the following:

- Preliminary design.
- Procurement assistance during selection of the CMAR.
- Detailed design.
- Preparation of construction drawings and specifications.
- Quality assurance during construction.
- Startup and commissioning services.
- Assistance to LCRA in preparation of various documents related to the acquisition of permits.
- Responding to comments and suggestion from the technical review board.

A brief discussion of these services is presented below.

2.4.1 Preliminary Design

Preliminary design included developing and evaluating the various design alternatives. The process involved multiple design workshops focused on making decisions for key components and issues. CH2M led the workshops attended by LCRA staff (engineering, project management, construction management and operations), the CMAR (Barnard) and members of the TRB. These workshops were important in evolving the design and moving the process forward efficiently by freezing key design decisions. During the workshops, contractor comments on construction means and methods were considered, which influenced some aspects of the engineering design and also provided guidance to LCRA on potential environmental impacts and permitting considerations. CH2M used advanced computer models to compare alternatives and refine designs in preparation for the final design. The resulting design maximized the use of existing conveyance facilities.

2.4.2 Final Design

The final design included not only preparation of the bid and construction documents, but also supporting design modeling efforts such as computational fluid dynamics modeling, physical modeling of key hydraulic structures, embankment stability modeling, floodplain modeling, etc.

The bid and construction documents were originally prepared for the CMAR approach and were developed around preparation of five GMP work packages. As noted in Table 2-4, when the contracting approach for construction transitioned from a CMAR to a best-value bid and lump sum contract, the GMP work packages were deconstructed and combined into a single set of bid and construction documents. These documents remain based upon the means and methods adopted from the CMAR.

Best Practice
The CMAR constructability reviews shaped the Arbuckle Reservoir project design to reflect their means and methods. A different constructor may have a different but equally effective approach. The engineer and constructor must remain open to different approaches that could modify the construction documents.

2.4.3 Technical Review Board

LCRA created a TRB of three recognized experts to advise LCRA on various topics related to the design and construction of the Arbuckle Reservoir project. The TRB reported directly to LCRA and participated in engineering design workshops and field inspection of construction activities. The TRB was composed of two geotechnical engineers with expertise in the design of soil embankments, and one hydrodynamics engineer with expertise in the design of large hydraulic systems. The following engineers are on the TRB:

Geotechnical
J. Michael Duncan, Ph.D., P.E. Professor Emeritus
Virginia Polytechnic Institute
Blacksburg, Virginia

Geotechnical
Stephen G. Wright, Ph.D., P.E. Professor Emeritus
University of Texas at Austin
Austin, Texas

Hydrodynamics
Henry T. Falvey, D. Ing
Henry Falvey & Associates
Conifer, Colorado

In addition to their role as technical reviewers, TRB members also participated in discussions with members of the TCEQ Dam Safety group.

2.5 Construction

Construction of the Arbuckle Reservoir project includes several distinct, but interrelated activities, most of which are the responsibility of the GC, Phillips and Jordan Inc. (P&J); however, some are performed or directed by LCRA and its contractors. The Arbuckle Reservoir project includes the following construction components.

- **Test Embankment –** A design phase construction activity to confirm critical engineering specifications, to evaluate construction equipment, and to refine means and methods for embankment construction.
- **Site Improvements –** A variety of construction work performed by LCRA to prepare the site for use by the GC.
- **Reservoir and Facility Construction –** Construction work performed by the GC, P&J.
- **Construction of the Grant Components –** Construction work also performed by the GC, P&J. Additional specifics about the construction of the three grant components, including construction duration, construction costs from the contractor schedule of values, and observed production rates during construction are included in this section of the report.

- **Owner Provided Services and Equipment –** Equipment and services provided by LCRA to the GC.
- **Quality Assurance and Quality Control Program –** The independent program performed by the GC and LCRA to monitor and ensure construction quality.

2.5.1 Test Embankment

The test embankment program was an early construction activity involving construction of two test embankments on the site to confirm embankment specifications and refine construction means and methods. The test embankments were constructed in March through April 2015 using specifications and drawings from the 60 percent complete engineering design. The work was performed by the CMAR as part of GMP-1.

The test embankments, TE-1 and TE-2, tested compaction densities, and the means and methods to build the embankment and the internal drain systems. The CMAR tested a variety of excavation and earth-moving equipment to calibrate production rates and haul distances necessary to develop the construction cost for the embankment. The test embankments were constructed to heights of 25 feet and 10 feet, respectively. Figure 2-1 shows a picture of TE-1.

Figure 2-1. Test Embankment TE-1

The results from the test embankment program provided a number of benefits to the constructor, engineer and LCRA. It demonstrated that specifying a 95 percent modified Proctor compaction density for embankment fill was not practical, confirmed that a 90 percent modified Proctor compaction specification was achievable and consistent with the desired embankment geometry, and identified specific pieces of equipment capable of performing the work. It also provided the contractor with

Best Practice
A test embankment program provides valuable engineering and construction information that will confirm design assumptions and improve the accuracy of cost estimates and schedules.

productivity rates for excavation and compaction, and familiarized the contractor with subsurface conditions, weather patterns and site drainage conditions.

The test embankment program also included an evaluation of the availability of sand for the chimney and blanket drains. It included characterizing on-site sand (native sand) and the availability of imported sand (sand products available from local sand and gravel operations). Local is generally defined as availability within a 50- to 75-mile haul radius from the site.

Minimizing the amount of imported sand is an important consideration in controlling construction costs. The total amount of sand required for the project (native and imported) totaled approximately 850,000 cubic yards, or 1.4 million tons. Approximately 60 percent, or 560,000 tons, would be imported sand. With a cost of $15 per ton, imported sand represents a significant cost to the project.

The sand evaluation significantly affected the designs of the chimney and blanket drain systems. Initially, the test embankment program started with a 3-foot-wide chimney drain composed of a single type of graded “asphalt sand,” ASTM D1073-11 Grade 3 (D1073). The chimney drain was to be constructed by excavating a 3-foot-wide trench in the compacted embankment and then filled and compacted with the D1073 sand. However, when the contractor approached local suppliers, they learned that local operations did not produce the specified D1073 sand, and local producers had no interest in producing the D1073 sand, but the local producers did make a “cement” sand, ASTM C33. The lack of a local supplier for the D1073 sand resulted in a redesign of the chimney and blanket drain systems.

The engineer and CMAR then evaluated the following two options:

1. A 3-foot-wide chimney drain filled with a blended sand material, a filter sand produced on-site as a combination of native and C33 sand

2. A 4-foot-wide “sandwich” chimney drain composed of a 2-foot vertical zone of native sand on the upstream side against the native clay and a 2-foot vertical zone of imported C33 sand downstream

The CMAR conducted a series of blending tests in which native and C33 sand were blended in various percentages to produce a product with the gradation and hydraulic properties of the D1073. A blended sand, composed of 60 percent imported sand and 40 percent native sand, proved to be a suitable substitute for the D1073; but, when the costs of the additional imported sand and the cost of the additional material handling were combined, the cost for the blending plan was higher than the 4-foot “sandwich” chimney drain and was eliminated from further consideration. The new chimney drain design would be the 4-foot sandwich option. The test embankment program refined the chimney drain design, but did not evaluate the means and methods to build it. Section 4 presents a discussion of how P&J subsequently developed its means and methods to build the chimney drain.

2.5.2 Site Improvements

Site Improvements is a category of construction work undertaken by LCRA to prepare the site for use by the engineer or GC. These efforts began in 2014 soon after the site was purchased and have continued through construction. While some of these activities occurred early in the project, several occurred during the construction period. Had the activities not been completed in a timely manner, the GC could have suffered a delay. Owners taking responsibility for these site improvement activities must carefully schedule and execute these activities. While these activities are very specific to the Arbuckle Reservoir project site, similar kinds of work should be anticipated for other reservoir projects. The following summary presents the significant site improvement activities conducted during the construction of the Arbuckle Reservoir project.

- **Relocation of existing AEP and CenterPoint 138-kilovolt transmission lines.** There are two major transmission lines at the Arbuckle Reservoir project site. LCRA's responsibility was to coordinate and contract with the transmission line owners for the relocation or realignment of these major structures. Critical to the start of construction was the relocation of the existing CenterPoint lines, which traversed through the middle of the reservoir footprint.

- **Demolition of existing on-site structures**. The site contained a number of old structures (houses and barns) that needed to be removed prior to the start of construction. Because of their age, many of these structures contained asbestos and lead-containing material. LCRA was responsible for the safe demolition and disposal of asbestos and lead material from the structures.

- **Construction of survey monuments for site survey control.** The Arbuckle site is large, and existing survey monuments were not within reasonable distance. LCRA surveyors established and constructed 12 permanent survey monuments in conformance with accuracy requirements provided by the engineer.

- **Preparation of site base map.** LCRA surveying and mapping staff developed the base maps for use by the engineer and contractor.

- **Plugging of existing oil and gas wells**. The Arbuckle Reservoir project site contained seven abandoned oil and gas wellbore casing that were located either within or close to the reservoir embankment. Several of the wells were within the contractor borrow areas and could be hit by excavation equipment. LCRA was responsible for locating the wells and confirming they were properly cemented. Wells casings located within the borrow area were lowered and re-cemented.

- **Plugging of existing water wells.** The Arbuckle Reservoir project site contained a number of abandoned water wells. LCRA was responsible for plugging all wells in accordance with state and local groundwater district regulations.

- **Installation on video surveillance camera network.** The Arbuckle site spans more than 2,200 acres and is approximately 3 miles long and 1.5 miles wide. Since construction activities were occurring in all areas of the site, inspection and monitoring over such a wide area was a challenge. Therefore, LCRA developed and constructed a three-camera, internet-enabled camera and digital video recording system that provided real-time observation at most areas of the site.

2.5.3 Reservoir and Facility Construction

This section presents an overview of construction activities for the Arbuckle Reservoir project, including a discussion of the work scope, the current status of construction and contract schedule requirements. It also describes construction status of the three innovative features and presents respective production statistics developed from construction.

P&J, based in Knoxville, Tennessee, is the GC for the Arbuckle Reservoir project. P&J provided construction management services for the entire project and self-performed construction of the OCR facility. Garney Construction, based in Kansas City, Missouri, subcontracted to P&J for mechanical, electrical and instrumentation work.

The work, as described in the CH2M plans and specifications, included construction of new facilities and renovation of existing ones. The work was organized geographically into the 10 facilities listed in Table 2-5. Grant-related items are included in Facility 04 River Outfall and Facility 07 Off-Channel Reservoir, which includes the chimney drain and wave wall components.

Table 2-5: Arbuckle Reservoir Project Facilities

Facility Number	Facility Name	Description *
01	Horizontal Pump Station	Renovation work to an existing 296-cfs pump station that diverts water from the Colorado River into the supply canal.
02	Vertical Pump Station	Renovation work to an existing 256-cfs pump station that diverts water from the Colorado River into the supply canal.
03	Canal	Renovation work in the existing irrigation canals. Work includes realignment of an existing irrigation canal, concrete lining at selected canal sections, construction of a new canal gate structure and replacement of the existing flume over Jarvis Creek.
04	River Outfall	One of the three facilities included in the TWDB grant. The river outfall is a new structure at the supply canal that returns up to 750 cfs of water stored in the reservoir to the Colorado River.
05	Relift Pump Station	A new multi-function 700-cfs pump station that can pump water from the supply canal into the OCR, and can pump water from OCR back into the supply canal.
06	OCR Inlet/Outlet	A new 120-inch-diameter steel pipe and outlet structure that conveys water in and out of the reservoir.

Facility Number	Facility Name	Description *
07	Off-Channel Reservoir	Facility includes construction of the chimney drain and wave wall, which are two of the three components included in the TWDB grant. A new 40,000-acre-feet ring dike, earthen embankment, water storage facility; work includes soil-cement armor of the interior, a soil-bentonite cutoff wall, emergency spillway, blanket drains, chimney drains and wave walls.
08	LCD	Repair and rehabilitation of LCRA's in-stream dam on the Colorado River that forms the pumping pool for the horizontal and vertical pump stations. (Note: This facility is an independent and complete project and not critical to the OCR.).
09	Pump Station Road	Construction of two new bridges, the Lane City Canal Bridge and the Jarvis Creek Bridge. These bridges provide all-weather access to the Arbuckle project facilities.
10	McGowan Road	Removal and restoration of an existing low water crossing in Jarvis Creek near the McGowan Road Bridge.

Notes:

* A detailed description of the work at these facilities is presented in Sections 3 and 4.

cfs = cubic feet per second

LCD = Lane City Dam

Construction of the Arbuckle Reservoir and LCD repairs were performed under a lump sum, fixed priced $174 million calendar-day contract. The contract allowed 1,020 calendar days from LCRA's Nov. 18, 2015, notice to proceed to substantial completion. The contract included provisions for liquidated damages for late completion and a bonus provision for early completion.

The contract included several provisions related to the availability of water. It required the contractor to schedule work such that it would not interfere with LCRA's irrigation operations during the period between March 15 and Oct. 15 of each year of construction. Additionally, the contract specified that a minimum of 250 cfs of river water be provided to the supply canal during the irrigation season, and it included a monetary penalty if these conditions were not met. The contract also included provisions in the event that water was not available for reservoir filling and testing.

2.5.4 Construction of Grant Components

This section presents selected construction specifics about the grant items. It includes the status of construction, construction duration, construction cost (based on the contractor's schedule of values) and a discussion of production rates, based on the work completed to date. Costs are for November 2015 and do not include any GC markups or costs for general conditions. See sections 3 and 4 for additional details on the construction of these components.

2.5.4.1 Chimney Drain (Included with Facility 07)

Construction Schedule

This is the construction schedule to install the chimney drain. It is closely aligned with construction of the embankment.

- Status: 100 percent complete.
- Start: June 2016.
- Completed: October 2017.
- Duration: 17 months. Actual days worked was 251 calendar days.

Construction Cost

- Not available.
- Chimney drain construction is included in the cost for embankment construction and is not broken out as a separate item.

Production Rates

- Total linear feet (lf): 890,000 lf.
- Chimney drains were installed in 18-inch lifts over the 5.2 miles of embankment length; the total presented is the sum of these lifts.
- Average production: 3,500 lf per day worked.
- Average production rate includes the two-month period of testing and refinement of the construction process.

Construction Comments

The construction of the two-zone 4-foot-wide chimney drain was a challenge. It required diligence on the part of the contractor and quality teams to ensure that the chimney was built uniformly over multiple lifts and able to maintain a clear interface between the native and imported sand layers. Because of a good collaborative effort between the contractor, owner and engineer, the equipment and processes evolved into a method that allowed the contractor to achieve good rates of production. This success was the result of the contractor's creativity and tenacity.

2.5.4.2 Wave Wall (Included with Facility 07)

Construction Schedule

This is the schedule to install the completed prefabricated wave wall section. See Fabrication Rates section for fabrication details.

- Status: 50 percent complete.
- Start: November 2017, started setting wave wall segments.

- Completed: May 2018, estimated.
- Duration: Seven months.

<u>Construction Cost</u>

$3,800,000. Based on contractor schedule of values; cost included fabrication, leveling pad, setting and anchoring.

<u>Production Rates</u>

- Total length: 27,456 feet.
- Length is the 5.2 miles of embankment length; some additional panels are required at the intersection where access ramps from the reservoir interior intersect with the embankment crest.
- Total panels: 8-foot-long pre-cast concrete panels.
- Average setting rate: 3,500 panels.
- Fifty panels per day worked, does not include fabrication of pane; includes a two-crane double-crew process.

<u>Fabrication Rates</u>

- Total Panels: 3,500.
- Number of Forms: Eight custom fabricated steel forms.
- Panels formed: Five panels per day. Forty panels per week. Panels were stored at fabricator's site then trucked over to the reservoir.
- Total Duration: 22 months represents the total time required to fabricate the wave wall panels.

<u>Construction Comments</u>

Maintaining a uniform alignment of the wave wall segments required construction of a grout-leveling pad prior to placement of each wave wall segment; installation rates improved considerably when a second crane was added to the production crew.

2.5.4.3 River Outfall (Facility 04)

<u>Construction Schedule</u>

This facility proved to be the most challenging to complete. The actual completion schedule varied significantly from the initial baseline schedule.

- Status: 60 percent complete.
- Start: January 2016.
- Completed: June 2018.
- Estimated. Baseline schedule estimated a February 2017 completion date.

- Duration: 30 months. Baseline schedule showed a 13-month construction period.

Construction Cost: $4,000,000

Based on contractor schedule of values; cost included canal outlet control structure, piping, and river stilling well and overflow slab.

Construction Comments

Construction of the river outfall and stilling basin was difficult because of the frequent over-topping of the temporary cofferdam in the Colorado River.

2.5.5 Owner Provided Materials and Services

LCRA provided the following materials and services for the project. All of these items required close coordination and communication with the GC:

- **Supervisory Control and Data Acquisition (SCADA) Programing.** LCRA staff provided SCADA system programming and integration. This responsibility included programming the contractor provided control equipment, integration into LCRA's communication and remote control systems, and compliance with LCRA's cybersecurity protocols. This responsibility also included working with the contractor to conduct performance testing and commissioning of the equipment and systems in the Arbuckle project.

- **Five Canal Check Structure Gates (and related control panel and systems).** These are the canal control gates forming the supply canal. The work included fabrication at an LCRA facility, installation of the gates and programming the SCADA controls.

- **Jarvis Creek Flume Flow Meter and Remote Terminal Unit (RTU).** LCRA provided and installed open channel ultrasonic flow meter and remote telemetry unit into the contractor-provided control panel.

- **OCR Bubbler Level Instrument and RTU.** LCRA provided and installed the reservoir level instrumentation and remote telemetry unit into the contractor provided control panel.

- **OCR Staff Gauges.** LCRA provided and installed reservoir staff gauges to measure water level in the reservoir.

- **Security Equipment.** LCRA provided and installed various security equipment, including cameras, mounting poles, gate controller, and gate and door hardware to meet LCRA physical security control requirements.

- **Relift Pump Station Meters:** LCRA provided five flow meters to measure pump discharges at each relift pump.

2.5.6 Quality Control and Quality Control Programs

The project quality program for the Arbuckle project includes the following components:

- **Quality Control (QC) –** The contractor's quality program helps confirm that construction is meeting the specifications of the contract documents.

- **Quality Assurance (QA) –**LCRA's and the engineer's program of construction oversight to confirm that the contractor's QC plans are being adhered to and the construction is meeting the requirements of the contract documents. LCRA and the engineer request that the GC develop corrective action plans for identified deficiencies. The plans are reviewed by LCRA and the engineer, and once approved, are implemented by the GC.

2.5.6.1 Quality Control Program

P&J maintains the QC program for all phases of construction for the Arbuckle Reservoir project. The QC program includes the plans, procedures and organization necessary to ensure construction is compliant with the contract requirements.

The requirements for the QC program are described in the contract documents and include compliance with ASTM D3740-12a, "Standard Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as used in Engineering Design and Construction"; and, ASTM E329-14a, "Standard Specification for Agencies Engaged in Construction Inspection, Testing or Special Inspection." The specifications require that the reporting structure for the project QC manager be independent of construction production. Additionally, the contractor used the following references to develop the QC program.

- U.S. Army Corps of Engineers, Contractor Quality Control. Unified Facilities Guide Specification (UFGS) 01 45 00.00 10. February 2010

- U.S. Army Corps of Engineers Engineer Pamphlet EP 715-1-2, A Guide to Effective Contractor Quality Control. February 1990

- U.S. Army Corps of Engineers Regulation ER 1180-1-6, Construction Quality Management. September 1995

The QC plan is organized into three phases: (1) Preparatory Phase and Readiness Evaluation; (2) Initial Phase Inspections; and (3) Follow-up Phase Inspections. It includes a corrective action component to identify, track and correct work if deficiencies or nonconforming conditions are identified. The corrective action program and nonconformance log is an important process that allows deficiencies to be tracked and corrected in a structured manner.

The QC program for the Arbuckle Reservoir project is extensive. It includes the setup and certification of an on-site laboratory, and staffing with qualified personnel to collect samples, conduct the laboratory test and report the data in a timely manner. The cost of the QC program is not reported as a separate item, but it is estimated to be in the range of 3 to 4 percent of the construction cost.

2.5.6.2 Quality Assurance Program

The LCRA's QA program facilitates the contractor's compliance with the QC plan and performance of any approved corrective actions.

The QA program also included a separate on-site laboratory. The laboratory was smaller in scale and capacity than the contractor's QC laboratory, with the capacity to perform split samples on approximately 10 percent of the contractor's samples. Periodically, these results were compared against QC results from the contractor and reviewed by CH2M and the TRB.

Fourteen staff members supported the QA effort. LCRA provided the project manager, construction manager and multiple staff members on-site during construction. LCRA staff members were supported by CH2M staff who performed construction observation and document controls.

2.6 Startup and Commissioning

Startup and commissioning of complex facilities is a challenging exercise involving considerable planning and coordination. For example, the Arbuckle Reservoir startup and commissioning had to consider not only operation of mechanical equipment and earthen facilities, but also the timing of irrigation season deliveries and availability of large quantities of water to test the integrated operation of the interdependent facilities.

Startup and commissioning is defined as the transitional phase between the end of construction and the start of commercial operations, referred to as "Substantial Completion." The processes and milestones during this period are defined in the Startup and Commissioning program. The program for the Arbuckle Reservoir project is structured around testing the individual facilities and followed by project commissioning, where all of the tested facilities are integrated and operated as a single project. The program is managed as part of the contractor's QC program. The startup and commissioning plan comprises a series of progressive facility testing and operational integration that includes the following steps:

- **Pre-functional Testing (Completion of Construction).** This is the GC's testing program that defines when the construction at an individual system or facility is complete and ready to run and start functional testing.

- **Functional Testing.** This is the testing of a facility or system to demonstrate that the manufacturer's installation, calibration and adjustment requirements, and any other specified requirements are met. The testing is done in the presence of the engineer and LCRA. When functional testing is completed and signed off, the facility is ready for performance testing.

- **Performance Testing**. This is the testing of a facility or system to demonstrate it can meet the performance criteria provided in the contract documents. Performance testing is performed after functional testing and in the presence of the engineer and LCRA. When performance testing is complete and signed off, the facility is ready for initial commissioning.

- **Initial Commissioning and Reservoir Filling.** When all functional and performance testing is complete, the reservoir is ready for filling and the project is ready for initial commissioning. Initial commissioning is the process that includes a complete review, demonstration and operational shakedown of all equipment and systems installed by the GC or its subcontractors.

- **Mechanical Completion.** After initial commissioning is complete, a comprehensive assessment of the status of construction is made. This assessment will confirm that all of the work, equipment, and/or systems:

1. Have been fully and properly installed in accordance with the contract documents and are operating at the levels specified in, and in accordance with, the requirements established by the contract documents.

2. Have been successfully tested and passed all performance tests required by the contract documents and have satisfied all related performance criteria set forth in the contract documents.

3. Are capable of being used for their intended function and are mechanically, electronically and structurally sound.

4. Are in compliance with all provisions of the contract documents regarding installation, testing, initial operation and adjustment of such system, components and equipment, including all mechanical completion requirements in the contract documents.

5. Are completed, including all initial commissioning and training for the project.

6. Are in compliance with all applicable codes.

- **Final Commissioning.** This includes the final review, demonstration and operational shakedown of all equipment and systems installed by the GC or its subcontractors for the Arbuckle Reservoir project, and the review of operation and maintenance of such systems with LCRA's personnel.

- **Substantial Completion.** Substantial completion is when all of the previous tests and commissioning have been completed and all construction work has been completed, except for minor items that will not unreasonably affect LCRA's ability to use the Arbuckle Reservoir project. Additionally, substantial completion is achieved when all required approvals and permits for use and completion of the Arbuckle Reservoir project have been issued by appropriate governmental authorities; any damage to roads or other aspects around the site have been returned to the same condition they were in prior to the start of construction; and when the contractor has completed all work required to enable LCRA to submit to USACE a true and accurate signed certification documenting completion of the activities authorized by USACE permits.

Not all facilities are included in the start-up and commission process. Of the 10 facilities comprising the Arbuckle Reservoir Project, the following seven facilities were included in the startup and commissioning process.

- Facility 01 – Horizontal Pump Station
- Facility 02 – Vertical Pump Station
- Facility 03 – Canal
- Facility 04 – River Outfall
- Facility 05 – Relift Pump Station
- Facility 06 – OCR Inlet/Outlet
- Facility 07 – Off-Channel Reservoir

At the time of this report, only Facility 02 – Vertical Pump Station has completed functional and performance testing.

2.7 Operations Staff Engagement

LCRA operations staff were engaged throughout all phases of the project in preparation for owning and operating the facilities. In particular, LCRA operations staff provided key operability feedback during the design phases on the multiple systems on the project. This feedback was a direct quality benefit to the resulting design and construction.

3 Anatomy of an Off-Channel Reservoir

ImagThe Arbuckle Reservoir is an off-channel reservoir (OCR) under construction in Wharton County adjacent to LCRA's existing Gulf Coast Irrigation Division Plant No. 2 pump stations. The reservoir will hold approximately 40,000 acre-feet of water and is designed to be drained and refilled multiple times over the course of a year, making it capable of adding up to 90,000 acre-feet per year of firm water to the region's supply. Figure 3-1 provides a schematic of the reservoir and associated facilities.

The existing conveyance system that serves the irrigation division comprises a horizontal river pump station and intakes, a vertical turbine pump station and intake, and the Lane City Canal that feeds the canal system on the east side of the river. The project uses the existing pump stations and existing water right on the river amended to include storage. When available per the terms of the water right, water will be pumped from the river into the Lane City Canal. From the canal, the water can either be directed farther down the canal system (via the Lane City Canal) to meet irrigation and/or industrial

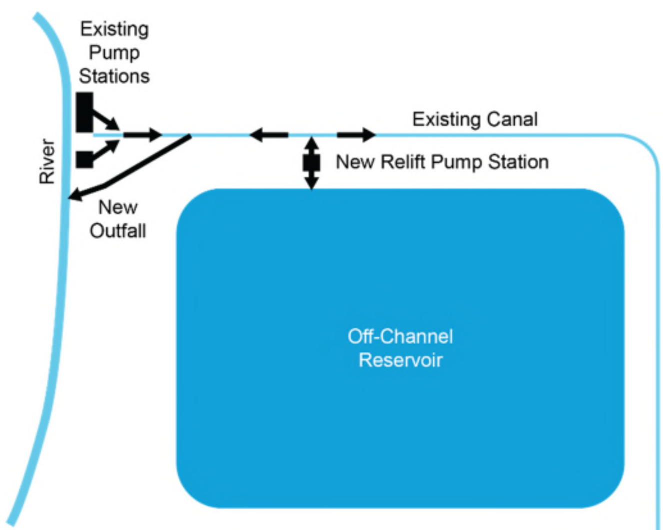

Figure 3-1. Schematic of Arbuckle Reservoir

demands, or diverted via a new relift pump station into the new OCR for storage and use at a later date.

LCRA intends to release water stored in the Arbuckle Reservoir back into the canal and then direct it either to the downstream canal system or back to the river through the new river outfall. The project requires upgrades to the existing pump stations, upgrades to the canal system, construction of the new river outfall, construction of the new relift pump station, construction of the new OCR, and supporting site access and security infrastructure.

The construction drawings are organized by facility as follows, and the subsections of Section 3 also are organized in this manner.

01 – Horizontal Pump Station

02 – Vertical Pump Station

03 – Canal

04 – River Outfall

05 – Relift Pump Station

06 – Off-Channel Reservoir Inlet/Outlet

07 – Off-Channel Reservoir

08 – Lane City Dam

09 – Pump Station Road

10 – McGowan Road

3.1 Horizontal Pump Station (Facility 01)

The Horizontal Pump Station (HPS) is the oldest portion of LCRA's existing Gulf Coast Irrigation Division Plant No. 2 (refer to Figure 3-2). It is located on the east bank of the Colorado River on the north side of the termination of Pump Station Road and was constructed in 1948. The HPS has an estimated total operating capacity of 296 cfs with three intake pipes (two 48-inches and one 36-inches in diameter) and three pumps discharging to the supply canal.

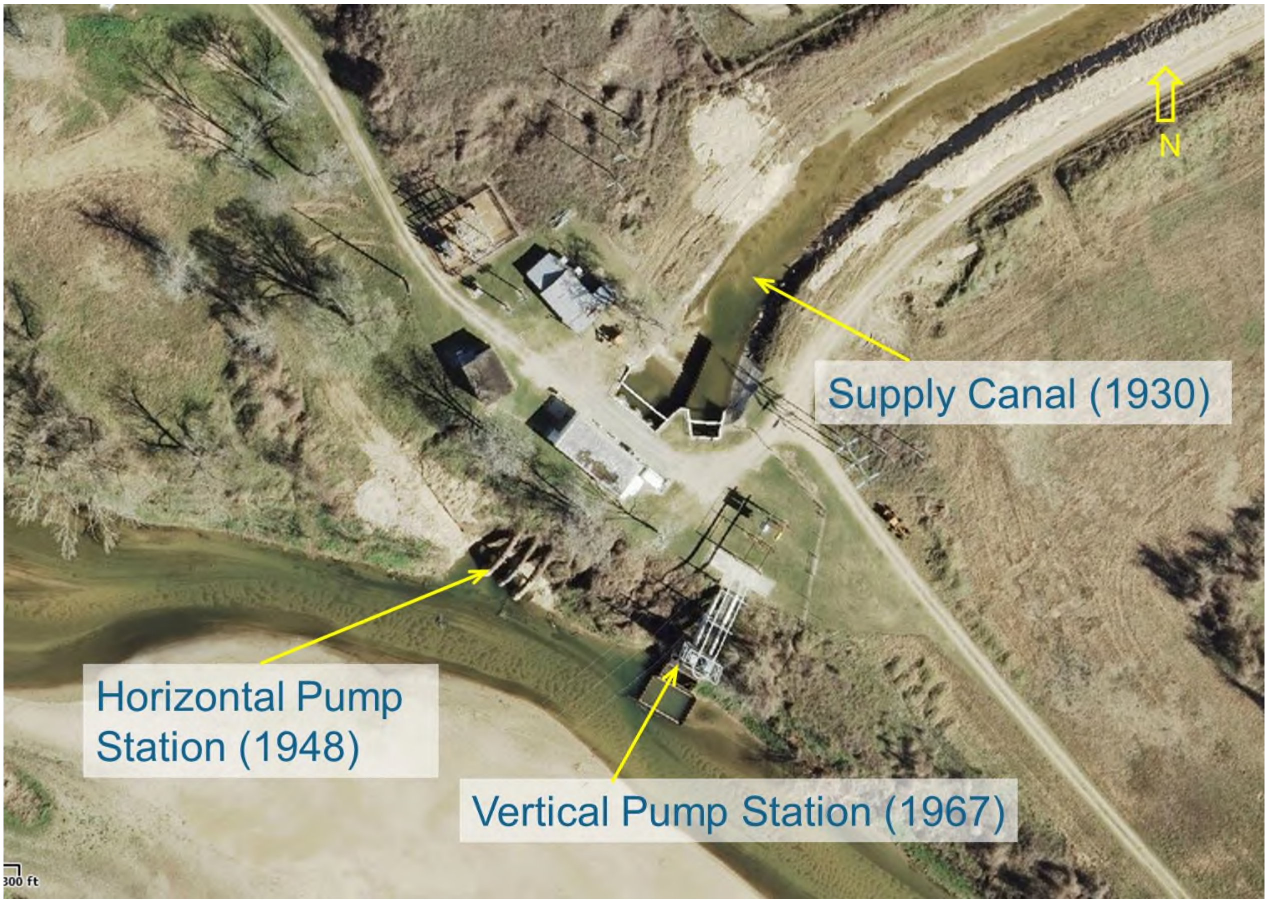

Figure 3-2. Gulf Coast Irrigation Division Plant No. 2 and Canal

The existence and location of Gulf Coast Irrigation Division Plant No. 2 was important in both the selection of the project site and the strategy for conveying water to and from the Arbuckle Reservoir. Evaluations in the conceptual design phase showed that using the existing pump stations (with some improvements) and the existing canal, and building a new Relift Pump Station between the reservoir and canal east of Jarvis Creek (see Figure 1-2), were more cost effective than building a new river intake, pump station and pipeline to the reservoir. The conveyance strategy also expedited permitting by limiting impacts to waters of the U.S.

The HPS rehabilitation included installation of an adjustable frequency drive (AFD) on the smaller pump, an extension to the pump building to house electrical equipment and bridge crane extension, a combination of replacement and lining of the intake suction pipes, replacement of discharge piping and flap gates, and addition of an automated vacuum priming system upgrade (Figure 3-3).

Because of the age and historical significance of the existing pump station buildings and the foundations of prior pump station buildings, changes to the building exteriors were minimized.

Figure 3-3. Pumps Inside HPS Building

3.2 Vertical Pump Station (Facility 02)

Best Practice
Overtoppings and flooding of the contractor's temporary cofferdam significantly extended the construction duration. To stay on schedule, contractor must provide adequate dewatering equipment for quick recovery of overtopping events.

The Vertical Pump Station (VPS) is the newer portion of the LCRA's existing Gulf Coast Irrigation Division Plant No. 2 (refer to Figure 3-4). It is located on the east bank of the Colorado River on the south side of the termination of Pump Station Road and was constructed in 1967. The VPS has an estimated total operating capacity of 256 cfs with two pumps and two 54-inch-diameter pipes discharging to the main or supply canal.

The rehabilitation to the VPS included installing new flap gates on the discharge lines to the canal; repainting the interior and exterior of the 54-inch-diameter discharge pipes; removing and repairing both vertical turbine pumps; including new motor controls and connection to supervisory control and data acquisition (SCADA); and replacing corroded portions of the vertical pump station wet well, trash rack and support structure.

[redacted]

Figure 3-4. Vertical Pump Station

Because of the amount of sediment in the wet well, the exact extent of the corrosion affecting the wet well, trash rack and support structure was unknown during design. In preparing to dewater the wet well so the sediment could be removed, LCRA supported the contractor by capturing and relocating aquatic life trapped in the wet well consistent with the relocation permit issued by the Texas Parks and Wildlife Department.

3.3 Canal (Facility 03)

The canal in its current configuration was completed in 1930; however, a canal at basically the same location was in place by the early 1900s. The unlined canal historically has carried water to agricultural and industrial customers east of the Colorado River in Wharton and Matagorda counties. As a component of the Arbuckle Reservoir Project, the portion of the canal from the river to the check structure just east of the Relift Pump Station is labeled the “Supply Canal,” and the portion of the canal east of the check structure is labeled the “Lane City Canal.”

The canal improvements were designed to address the change in operation due to the Arbuckle Reservoir Project. Historically, the canal has operated on a seasonal basis, between the months March and October. When complete, the pump stations and canal could be operated at various flow rates year-round, depending on water demands, water availability in the river and the water levels in the reservoir.

The canal improvements include lining in critical locations (see Figure 3-5), widening in others, a new canal flume, a check structure just downstream of the Relift Pump Station, and relocation of a portion of the canal to outside of the reservoir footprint on the northeast corner. Minor improvements also were made to various sections of the canal along the reservoir property.

Figure 3-5. Canal Lining Near Flume Over Jarvis Creek

3.4 River Outfall (Facility 04)

The River Outfall, or River Return System, is a new and innovative facility on the project site. The River Return System facilitates releases of water from the reservoir back to the Colorado River via the Supply Canal to meet various needs downstream. The River Return System includes a gate on the canal next to the pump stations, a pipe from the gate to the river that transitions from 108- to 84- to 60-inch-diameter, and an outfall structure with a stilling well in the river.

The innovative River Return System is described in further detail in Section 4.

3.5 Relift Pump Station (Facility 05)

The Relift Pump Station is the most critical conveyance facility of the project. It is responsible for safely transferring water from the canal to the reservoir, and from the reservoir back to the canal, at varying flow rates and head conditions. The Relift Pump Station is connected to the Off-Channel Reservoir Inlet/Outlet pipe, which reaches under the reservoir embankment to allow water to flow in and out of the reservoir.

Best Practice

Engage the design engineer, client's engineers and client. This approach resulted in some strategic relaxation of design flow requirements (under the most challenging head conditions) that allowed elimination of two pumps, several valves, and reduced length and diameter of pipes.

The Relift Pump Station is composed of a dual-purpose canal inlet/outlet structure; five vertical turbine pumps with AFDs and a combined 700-cfs pumping capacity; steel pipe ranging from 66 to 144 inches in diameter; a 40-foot-tall, 23-foot-inside-diameter stand pipe; 13 large valves; and an electrical controls building (see Figures 3-6, 3-7, and 3-8).

Because the water surface elevation in the canal is at roughly the midpoint of the maximum and minimum water surface elevation of the reservoir, the Relift Pump Station is designed to handle four distinct operating scenarios: (1) gravity flow from canal to reservoir, (2) pumped flow from canal to reservoir, (3) gravity flow from reservoir to canal, and (4) pumped flow from reservoir to canal. The wide variations in water surface elevations and flow rates in the canal and reservoir created complex design challenges to meet the flexible operating requirements. During design refinement, discussions between the design engineer, LCRA Engineering and LCRA Operations resulted in some strategic relaxation of design flow requirements (under the most challenging head conditions) that allowed elimination of two pumps and several valves, and reduced length and diameter of pipes.

Figure 3-6. Relift Pump Station Rendering

Figure 3-7. Relift Pump Station Pump Can Awaiting Installation

Figure 3-8. Relift Pump Station Construction

3.6 Off-Channel Reservoir Inlet/Outlet (Facility 06)

The Reservoir Inlet/Outlet pipe connects the Relift Pump Station to Off-Channel Reservoir, allowing water to travel from the canal to the reservoir and back to the canal. The Reservoir Inlet/Outlet is composed of a 120-inch reinforced concrete encased welded steel pipe, a depressed concrete box with grated top inlet/outlet structure, and soil cement erosion protection in the area near the inlet/outlet structure (see Figures 3-9 and 3-10).

Best Practice
Avoiding voids during backfilling around large pipes is very important. Consider adding language to the specification, including construction hold points to allow sufficient inspection.

Because the pipe travels under the embankment, good construction workmanship and following the design plans carefully is necessary to prevent water from undercutting the embankment by flowing along the outside of the encased pipe.

Figure 3-9. OCR Inlet/Outlet Construction

Figure 3-10. OCR Inlet/Outlet Pipe Sections Awaiting Installation

3.7 Off-Channel Reservoir (Facility 07)

The OCR stores river water for release to meet various water supply needs. The operating strategy for the reservoir involves frequent filling and significant releases throughout the year. The primary components of the off-channel reservoir are described in detail in this section (see Figure 3-11).

Figure 3-11. Off-Channel Reservoir Rendering

3.7.1 Embankment

The reservoir is formed by a roughly rectangular embankment over 5 miles long and almost 40 feet high that inundates approximately 1,100 acres. The embankment was built primarily from on-site earthen clay and sand materials; therefore, significant geotechnical exploration and testing was required to determine the suitability, availability and location of the soils on-site.

The main components of the embankment include the compacted fill embankment, the chimney drain, the blanket drain, the toe drain, the soil cement slope protection, the soil-bentonite cut-off wall, the wave wall and the spillway (Figure 3-12). The following subsections describe each of these components.

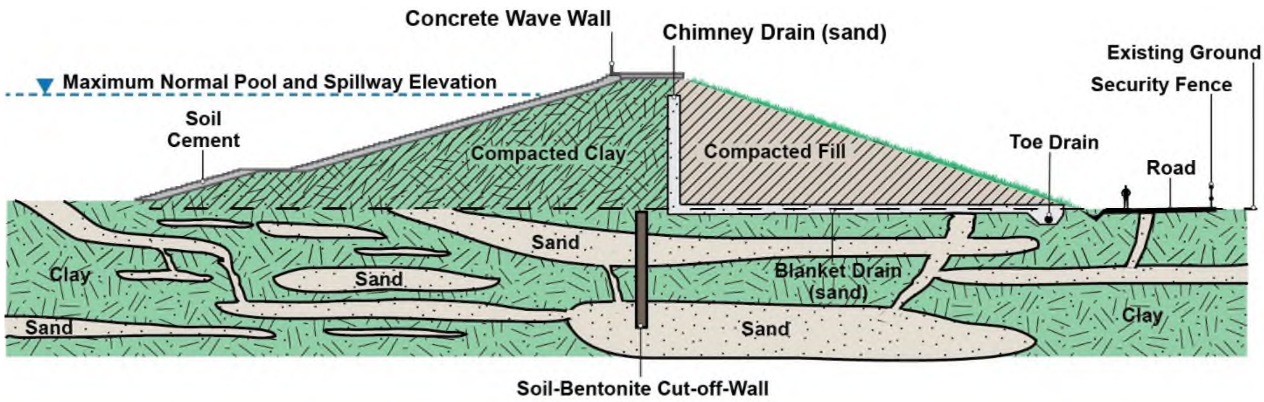

Figure 3-12. Off-Channel Reservoir Embankment and Subsurface Section Illustration

3.7.1.1 Compacted Fill Embankment

The compacted fill embankment is composed of two primary zones: compacted clay on the upstream side and compacted random fill (including clays, sands and silts) on the downstream side. The embankment is placed on a soil foundation that is stripped of organic materials, with soil removed to a specified depth and proof-rolled to confirm soundness.

Best Practice
The frequent filling and draining of the reservoir stresses the embankment, necessitating careful design and sound construction practices. This includes adequate slope armoring and erosion protection.

The upstream side of the embankment is placed in lifts and compacted to stringent specifications for density and moisture content. The upstream side must meet structural and stability requirements as well as provide a seepage barrier to the water held in the reservoir. The ability to frequently fill and drain the reservoir also affected the design and construction methods for the embankment. The interior (upstream side) of the embankment is protected from wave erosion by a layer of soil cement steps (refer to Section 3.7.1.5 for Soil Cement Slope Protection description).

The downstream side of the embankment is structural in nature and does not have seepage barrier requirements; therefore, the embankment materials in this area can include a mixture of clays, sands and silts that meet certain structural requirements. The downstream face of the embankment is protected from erosion with grass turf (see Figures 3-13 and 3-14).

Figure 3-13. Looking West from the Inlet/Outlet Excavation at the Northwest Corner of the Embankment at Full Height

Figure 3-14. Top of Northwest Embankment Corner, Looking South

3.7.2 Chimney Drain

The chimney drain is a vertical wall of sand that separates the upstream and downstream sides of the embankment. Its purpose is to capture seepage that manages to flow through the compacted clay upstream side of the embankment and carry the water safely down to the blanket drain and toe drain on the downstream side.

The Arbuckle Reservoir chimney drain configuration is an innovative component that is described in further detail in Section 4.

3.7.2.1 Blanket Drain

The blanket drain is a sand layer that lies under the downstream embankment and connects the chimney drain and toe drain. It therefore serves the function of carrying seepage captured by the chimney drain and seepage flowing under the embankment that the blanket drain captures before reaching the bottom of the downstream embankment.

Typically, a blanket drain is constructed of a single sand layer that meets specific gradation requirements to carry the estimated amount of seepage water to keep the dam safe and serves as a filter to prevent fine materials (clays and silts) from entering and clogging the sand blanket drain (see Figures 3-15 and 3-16).

Due to factors discussed in greater detail in Section 4, the blanket drain design (similar to the chimney drain) relies on a double sand layer approach, with native sand serving as a filter against the clay on the bottom and an imported ASTM C33 sand (often called concrete sand) layer above to meet the required flow capacity to carry the estimated seepage.

Best Practice
Characterize on-site sands early in the design phase to see if they are appropriate for use in the drains. Also, if imported sand is needed, check with local suppliers to make sure the specific gradation you need is available. Even commonly specified sand may not be available in sufficient quantities due to local geology or market demands in the area for other gradations.

Figure 3-15. Blanket Drain Installation, Northwest Corner of Embankment, Looking South

Figure 3-16. Blanket Drain Complete and Initial Soil Lifts Over Blanket Being Placed on South Embankment

3.7.2.2 Toe Drain

The toe drain gathers the seepage intercepted by the chimney and blanket drains, and safely diverts it to ditches downstream of the embankment. It is a trench at the downstream side of the blanket drain, filled with gravel and a perforated pipe (see Figure 3-17).

Figure 3-17. Toe Drain Installation

3.7.2.3 Soil Cement Slope Protection

Soil cement is created by mixing appropriate aggregate (typically on-site sand) with cement. When properly designed, mixed and placed, soil cement is effective protection for the upstream embankment slope subject to wave action's erosive forces. The most common configuration for placement is in overlapping steps about 18 inches thick and 8 feet wide.

Best Practice
Soil cement mix specifications are critical. Require a test section be constructed using the specified materials and equipment to ensure product quality.

The Arbuckle Reservoir has soil cement steps placed on its upstream face from the lower bench to the top of the embankment. The wave wall panels are anchored into the upper soil cement steps on the embankment (see Figures 3-18 and 3-19).

Figure 3-18. Soil Cement Steps and Wave Wall Placement on Embankment Top

Figure 3-19. Soil Cement Steps During Spillway Construction

3.7.2.4 Soil-Bentonite Cut-off Wall

The soil-bentonite cut-off wall (SBCOW) creates a barrier to seepage that could undercut the embankment. A trench is excavated under the embankment to designated depths depending on the specific location's underlying geology and is filled with a slurry mixture of water and bentonite (a special type of clay). Once the mixture is allowed to set, it creates a solid barrier to water (see Figure 3-20).

Best Practice
Designers are encouraged to use as many core-hole samples as possible to fully define the depth and limits of cut-off walls.

For the Arbuckle Reservoir, the depth of the SBCOW ranged from less than 30 feet on the east portion of the site to 85 feet on the west side of the site near Jarvis Creek. The necessary depth of the SBCOW is based on the location and depth of sand and clay layers under the embankment and associated modeling to estimate seepage flow rates.

Figure 3-20. Soil-Bentonite Cut-off Wall Installation

3.7.2.5 Wave Wall

The wave wall is a structural concrete wall installed in segments at the top of the embankment. It is part of the freeboard design for the embankment that limits overtopping rates during extreme wind events such as hurricanes. The wave wall absorbs the impact of the largest waves and redirects all or part of the water back into the reservoir depending on wave size.

The Lane City Reservoir wave wall is an innovative component that is described in further detail in Section 4.

3.7.2.6 Spillway

The spillway is located on the west side of the reservoir embankment just south of the existing bridge over Jarvis Creek at McGowan Road. It releases through a drainage feature into Jarvis Creek.

Because the Arbuckle Reservoir is an OCR, its tributary area during a storm event is the footprint of the reservoir (approximately 1,100 acres). This tributary area is very small compared with on-channel reservoirs, resulting in far fewer storm-related inputs for off-channel reservoirs. As a result, the passive spillways for off-channel reservoirs can be downsized and optimized to meet specific safety objectives, resulting in much smaller and more compact structures.

The spillway design concept started as a 200-foot-wide traditional spillway, but further evaluation and modeling resulted in a three-sided ogee weir jutting into the reservoir feeding a 20-foot-wide chute flowing down the downstream embankment to a stilling well in the drainage feature leading to Jarvis Creek (see Figures 3-21 and 3-22). The spillway capacity was designed to ensure that the Probable Maximum Precipitation event would not increase the water surface elevation above the base of the wave wall, that is, the top of the earthen embankment. This prevents standing water from ponding against the wave wall, which is designed to withstand wave impacts but is not watertight.

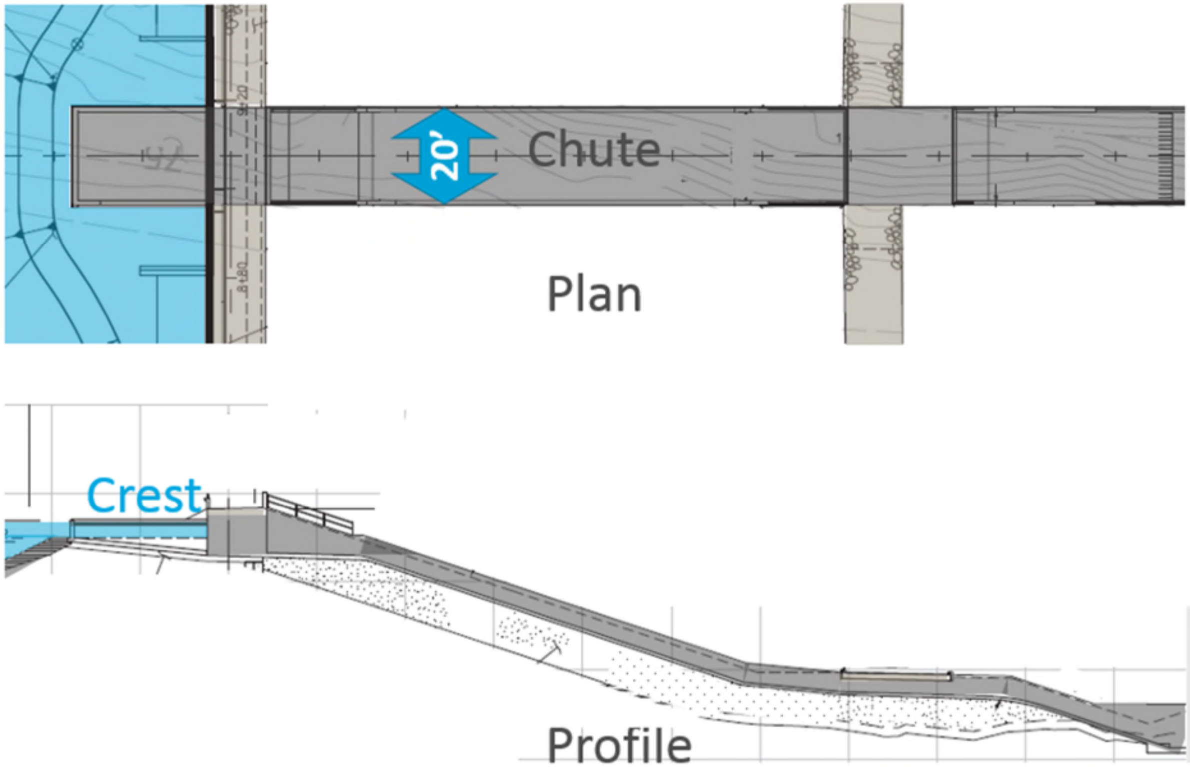

Figure 3-21. Plan and Profile Image of Spillway

Figure 3-22. Spillway Crest Construction Looking West from Inside Reservoir

3.8 Lane City Dam (Facility 08)

Lane City Dam (LCD) is a run-of-river diversion dam on the lower Colorado River near Lane City in Wharton County, Texas, at a location approximately 950 feet downstream of LCRA's existing Gulf Coast Irrigation Division Plant No. 2. The dam has not been classified by the State of Texas or listed in the National Inventory of Dams, but would likely be considered as a small, low-hazard dam.

LCD was constructed in 1984 to provide a pumping pool for the vertical and horizontal pump stations during periods of low river flows. The dam has a bascule gate that is raised from March 15 through Oct. 15 each year per the current water rights permit (see Figures 3-23 and 3-24).

LCRA is performing a maintenance project to repair and strengthen the dam, which has sustained damage during flood events and deteriorated as a result of normal wear and tear. The work for the LCD was a separate project, independent of the construction and operation of the OCR. Thus, it was authorized under a separate notice to proceed and a separate substantial completion date from the other facilities. The work was authorized under USACE nationwide permits.

Figure 3-23. Lane City Dam, Standing on Top of Left (East) River Bank Looking West

Figure 3-24. Lane City Dam, Right (West) River Bank Looking East

3.9 Pump Station Road (Facility 09)

Pump Station Road begins as CR 120 and runs from State Highway 60 in Lane City west to the river. The road will remain improved gravel and will include new bridges over the canal as it cuts under the road from the north as well as where the road crosses Jarvis Creek.

3.10 McGowan Road (Facility 10)

McGowan Road runs from the old CR 116 bridge over Jarvis Creek west to the Colorado River. No improvements have been made to the road; however, an existing low water crossing downstream of the existing bridge was removed and the stream bottom and banks in the area restored.

4 Innovative Components of LCRA Arbuckle Reservoir Case Study

Three innovative components of the project were noted in Section 3 for further detailed discussion in Section 4, as listed below.

- Chimney drain
- Wave wall
- River return structure

The chimney drain and the wave wall are components of the reservoir embankment (Facility 07). Both components help ensure the integrity of the embankment; the former captures seepage that might make its way through the embankment, and the latter controls the amount of wave overtopping of the embankment during extreme wind and wave conditions such as hurricanes. Figure 4-1 shows the location of the wave wall and the chimney drain near the top of the embankment.

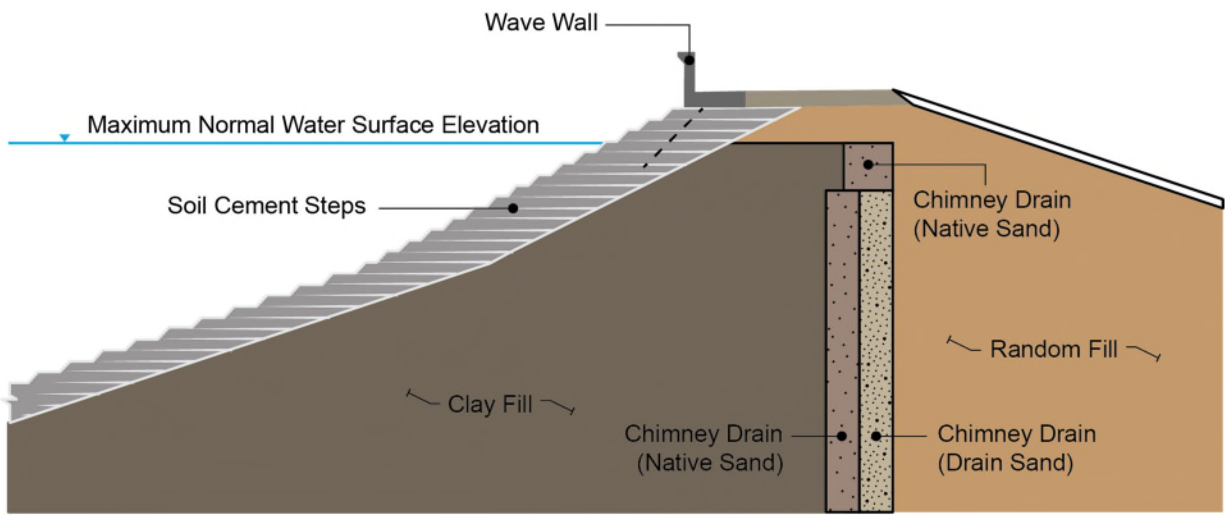

Figure 4-1. Embankment Top Showing Location of Wave Wall and Chimney Drain

The river outfall (Facility 04), also known as the river return structure, plays an important role in both normal and emergency operations. As discussed in Section 3, the OCR (Facility 07) can release water back to the canal (Facility 03) via the OCR Inlet/Outlet (Facility 06) and the relift pump station (Facility 05). Once in the canal, the water can be delivered down the Lane City Canal into the irrigation division or down the supply canal back to the river via the river outfall, or via both routes simultaneously. Figures in Section 4.3 show additional detail on the river outfall.

4.1 Chimney Drain

4.1.1 Facility Component Description

The chimney drain is an important component of a dam embankment. Its purpose is to intercept any seepage coming through the upstream side of the embankment. Chimney drains typically are constructed using layers of sand that form a vertical "chimney" from near the top of the embankment to the bottom where it connects to the blanket drain (refer to Figure 4-1 and Figure 3-12).

4.1.2 Design

Typical earthen embankment designs have a chimney drain up to 8 feet wide, providing significant width for construction equipment to install the layers of sand without contamination of fine-grained soils like clays. The chimney drain must be constructed with no intervening clay layers that could interfere with the lateral or vertical flow of seepage.

The need for a chimney drain to capture seepage through the embankment is determined by engineering analysis of seepage rates and the route that the seepage would take through or under the embankment. In some cases, the analysis may determine that a chimney drain is not needed depending on the embankment height (typically low embankments), cross section and seepage conditions. In cases where seepage control is needed, one alternative to a chimney drain is a liner over the upstream embankment or the entire interior of the reservoir, depending on the specific characteristics of the embankment and the subsurface conditions on the site. The design analysis for Arbuckle Reservoir showed that a chimney drain was significantly more cost-effective than a liner.

Design criteria for chimney drains focus on two primary requirements. The drain sand must act as a filter preventing fine material in the adjacent clay embankment from migrating into and clogging the drain sand, and it must provide adequate capacity to carry the calculated seepage flows in the chimney drain. The drain sand material also must provide a continuous vertical pathway for seepage flows from near the top of the embankment to the blanket drain under the downstream side of the embankment.

The original concept-phase chimney drain design was a traditional 8-foot width of imported sand meeting both the necessary filter and capacity requirements. During the value engineering process, the Construction Manager at Risk (CMAR) proposed a narrower chimney drain to save significant costs. The CMAR provided examples and documentation of how chimney drains as narrow as 2 feet wide had been successfully constructed. After evaluation by the engineer and approval by LCRA, a 3-foot-wide chimney drain was shown in the preliminary design.

Best Practice

When specifying common materials and gradations, evaluate the interest of local material suppliers in meeting the needs for the design.

The early preliminary design specified a common sand gradation, ASTM D1073 (D1073), typically used for asphalt fine aggregate. However, as the local aggregate vendors were contacted for pricing quotes, it became clear that the market for ASTM C33 (C33) sand (typically used as concrete fine aggregate in the area) was dominant to the extent that no vendors were willing to produce common D1073 sand.

The D1073 sand met both filter and capacity requirements for the chimney and blanket drains; unfortunately, the C33 sand did not meet the filter requirements to prevent fine clay particles from infiltrating the sand. Therefore, the final design utilizes a dual-layer chimney drain and blanket drain. Native sand from the site, which met the filter requirements, was placed against the clay upstream embankment to protect the adjacent C33 sand layer that provided the flow capacity for the potential seepage through and underneath the embankment. The total chimney drain width is 4 feet, comprising 2 feet of native, on-site sand and 2 feet of C33 imported sand.

4.1.3 Construction

As described in the previous section on the design of the chimney drain, the final design issued for construction was 4 feet wide, comprising 2 feet of native on-site sand on the upstream side and 2 feet of imported C33 sand on the downstream side to address both filtration and seepage capacity requirements. The narrow width and layered sand materials also created construction challenges. This section describes the evolution of the construction approach and customized equipment used to successfully construct the chimney drain. The contractor weighed both productivity and quality when finding the preferred installation approach.

4.1.3.1 Initial Placement Approach Using Modified Belly Dump Trailer

The contractor's initial installation approach used a modified belly dump trailer. A steel plate divider was welded into the trailer from front to rear to keep the two types of sand separate during placement (refer to Figure 4-2).

Figure 4-2. Modified Belly Dump Trailer with Steel Plate

This approach placed the sand material well in the trench. However, the large size and lack of maneuverability of the trailer created productivity issues. The trailer was difficult to maneuver because the wheel base was too narrow and the trench would collapse as it rolled forward, creating significant cleanup by hand to remove clay material.

4.1.3.2 Second Placement Approach Using Divider Box

The contractor's next approach continued with the trench first and fill approach, but with a new piece of filling equipment. A 12-foot-long divider box was constructed. The box was filled with the appropriate sand material on both sides of the divider by front end loaders, and then pulled along a trench by an excavator. Figure 4-3 shows this method.

Figure 4-3. Divider Box Pulled along Trench by Excavator

However, this method still could not provide the needed productivity. It also tended to tilt and not have a straight profile, creating quality problems that had to be repaired following initial installation.

4.1.3.3 Third Placement Approach Using Modified D6 Dozer

Because the quality and productivity of the second approach did not meet the contractor's requirements, a third concept was developed and refined using a D6 dozer. The dozer was equipped with a global positioning system (GPS) and had a rock spreader box and divider welded into the dozer. The height of the sides of the box was increased by welding additional steel plates on the sides (Figure 4-4).

Figure 4-4. GPS Equipped D6 Dozer and Modified Rock Spreader

The well graded import sand was observed to be discharging from its side of the box faster than the native sand on the other side. To help solve this problem, the contractor placed a Teflon coating on the inside of the native sand side of the box, which equalized the two discharge rates. Figure 4-4 shows the box placing the sand in the trench.

Additional refinements included replacing the splitter box's solid rubber tires with flotation tires from a John Deere tractor, as shown in Figure 4-5. These new tires did not cut into the subgrade, increasing the speed and quality of placement as well as allowing work in wet conditions. Also, the trench-first method was abandoned in favor of simply clearing off the top of the placement, placing up to 18 inches of the two sands, lightly compacting, and then placing embankment fill on each side of the chimney. Once the compacted embankment fill was level with the top of the chimney sand, the process was repeated.

Figure 4-5. Flotation Tires Added to Rock Spreader Box

These modifications increased productivity significantly. Before these changes, 800 feet of 18-inch-depth sand drain was placed in 10 hours; after the modifications, 5,000 feet of 18-inch-depth sand drain was placed in 10 hours. The additional productivity allowed the elimination of a night shift for the chimney drain installation.

Figure 4-6 shows the results of the chimney drain refinements. In the photo, the native sand is on the left where the hand-compactor is working over it, and the imported C33 sand is on the right.

Best Practice

The placement method that eliminated trenching ahead of sand placement, and instead placed the sand and built up the embankment on both sides of it, improved both quality and productivity.

Figure 4-6. Chimney Drain Sands Placement

4.1.3.4 Topping Out the Chimney Drain

The top of the chimney drain requires placement of a final 3-foot-by-3-foot cap of native sand. A long-reach placer sitting at the bottom of the embankment was used to install this cap, due to the narrow width of the embankment crest. Figure 4-7 shows the placer installing the chimney drain cap near the crest of the embankment.

Figure 4-7. Placement of Chimney Drain Cap

This construction approach evolved over about 5 months, roughly from March 2016 to August 2016.

4.2 Wave Wall

4.2.1 Facility Component Description

Best Practice
Installing the wave wall helped reduce the required embankment height, resulting in millions of dollars in construction savings.

One of the unique design features of the Arbuckle Reservoir is a vertical wall placed and anchored on the crest of the embankment facing the interior of the OCR. Freeboard, or height of the embankment above the maximum normal water surface elevation (the spillway crest), is designed to limit the potential for wave damage to the embankment from excessive wave overtopping of the dam during extreme storm events. The wave wall was included as part of the freeboard design because of its ability to efficiently deflect wind-generated waves.

Including the wave wall element as part of the freeboard helped reduce the required embankment height without a reduction in protection of the embankment from wave overtopping. Limiting the embankment height reduced the volume of earthen fill, sand for chimney and blanket drains, and soil cement erosion protection, resulting in significant construction savings. Figure 4-8 shows wave wall segments stored on the interior of the OCR before being placed on the crest of the embankment.

Best Practice
An OCR's tributary area is its footprint, so it is much less susceptible to flooding than an on-channel reservoir whose tributary area is dramatically larger.

Figure 4-8. Wave Wall Segments Stored and Awaiting Placement

4.2.2 Design

The location, operational approach and configuration of the embankment of the OCR created both challenges and opportunities when determining the appropriate freeboard. Freeboard for on-channel reservoirs is greatly influenced by rainfall in the tributary watershed, along with winds that may line up with the footprint of the reservoir that is much smaller than the contributing watershed. Conversely, an OCR's tributary area is simply its footprint, which is usually significantly smaller than an on-channel reservoir's tributary area.

Because the Arbuckle Reservoir is located near the Texas Gulf Coast, tropical storms including hurricanes must be considered in the design process. It is an OCR, so the reservoir is completely surrounded by its embankment, and wind effects must be considered from all directions. Also, from an operational standpoint, the reservoir is designed to be filled whenever water is available, and releases are likely to be made from the OCR first when customers in the lower basin request water delivery unless water is available in the river. Therefore, the OCR could remain relatively full under certain hydrologic conditions.

4.2.2.1 Freeboard Strategy

Because of the OCR's unique characteristics, the design of the freeboard was approached using two distinct design conditions. These conditions were developed in detail and then compared to decide which controlled the total freeboard necessary to keep the embankment safe.

Non-Tropical Wind and Rain Storms

This strategy uses precipitation and wind conditions that are extreme but non-tropical, and therefore cannot be reliably forecast well in advance the way that tropical events can. Heavy rainfall and high winds do occur in combination to generate these extreme event storms; however, it is not reasonable to combine both the worst-case rain and wind events. Therefore, the analysis uses realistic yet conservative combined values to create the critical design event. For these non-tropical events, the spillway is activated and considered in the calculation of the necessary freeboard.

Forecast Tropical Storms and Hurricanes

Tropical storms and hurricanes can be forecast days in advance. The predictable nature of these events, within reason, allows the water level in the OCR to be dropped at least 2 days prior to landfall in the vicinity of the reservoir. This proactive drawdown in advance of the event would be necessary if the OCR was full and within the cone of the potential storm path 48 hours prior to the projected landfall. The release of stored water back to the river would lower the water in the OCR by over 1 foot per day, resulting in a lower water surface elevation and increasing the effective height of the freeboard before the storm.

Best Practice

The limited drainage area of the OCR created the opportunity to lower the reservoir level in advance of tropical storms (which are easily tracked days in advance). The combination of the drawdown and the wave wall significantly reduced the needed freeboard and resulting embankment height.

Application of TCEQ Guidelines

The design team worked closely with TCEQ Dam Safety to ensure the wave wall design complies with applicable TCEQ guidelines on wave action overtopping and downstream slope protection.

4.2.2.2 Freeboard Design Approach

Determination of the required freeboard followed four primary steps:

1. Identify the range of loading conditions and combinations to consider. Loadings include:
    a. Initial reservoir water surface elevation

b. Operational adjustments to the reservoir water surface elevation (drawdown)
c. Antecedent inflows (flooding)
d. Concurrent design wind speeds

2. Determine reservoir parameters that affect wave generation:
    a. Design fetch length and angle
    b. Characteristic water depth
    c. Resulting wave type (deep water or shallow water)
3. Calculate wind setup and significant wave height.
4. Determine the minimum required freeboard for the given environmental conditions and estimated differential settlement of embankment.

Best Practice

Forces on the wave wall during hurricane events are enormous. The wave wall was designed structurally to withstand these forces and also required significant anchoring for each panel. It is important to note that the taller the wave wall, the higher the wave forces that it must withstand. A wave wall that is too tall could shear off the top of the embankment during an extreme wave event.

The wave wall and embankment height are designed to limit overtopping of waves to safe levels such that erosion of the embankment during extreme events will not pose a risk of failure to the reservoir. Overtopping calculations were made using the approach in the EurOtop manual, which features deterministic calculations of average overtopping rates supplemented with influence factors related to parapet walls from recent studies.

In this manner, the effect of various wave wall configurations on the overtopping rates were modeled. Based on the embankment crest configuration and the downstream slope protection of turf grass on clay soils, compared with multiple research studies that measured the erosive effects of overtopping rates on various soil and turf conditions, a target maximum overtopping rate of 10 liters per second per meter was used for all design storm conditions. In addition, the capacity of the spillway was refined to help keep flat water (as opposed to waves) below the base of the wave wall.

After numerous model simulations, the embankment top height and wave wall were optimized including the operational drawdown 48 hours in advance of a tropical hurricane scenario. The controlling factors for the wave wall were associated with the hurricane conditions and the cost tradeoff between higher embankment height or the height of the wave wall. Because the forces on the wave wall during the hurricane events are very large, the wave wall had to be designed structurally to withstand these forces and remain anchored on the top of the embankment. The resulting design featured:

- 3.5-foot-high wave wall with curved nose directing waves back into the OCR
- 8-foot-long pre-cast reinforced concrete wave wall panels
- Two 8-foot steel anchors grouted in place per panel

Figure 4-9 shows a simplified section of the wave wall and embankment top. Total freeboard above the maximum normal water surface elevation (e.g., the spillway crest elevation) is 5.5 feet. During operational drawdown, the effective freeboard increases to 7.5 feet.

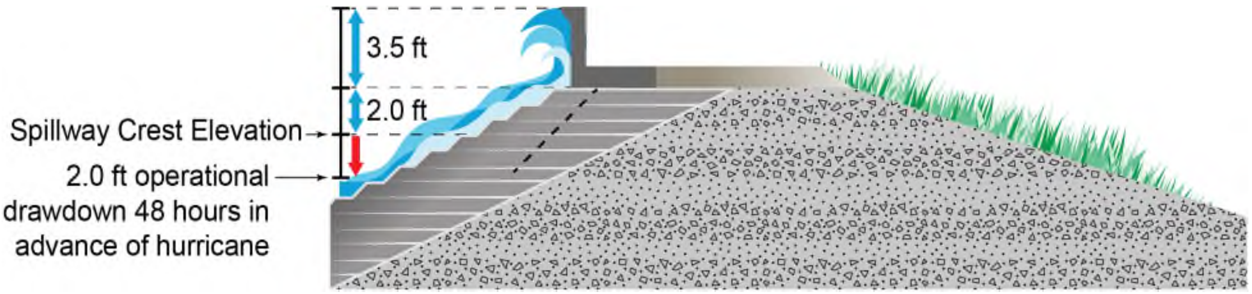

Figure 4-9. Wave Wall Simplified Diagram Showing Wave

The freeboard approach, including the wave wall, reduced the necessary height of the embankment by over 10 feet, resulting in significant savings. Alternatives to the reinforced concrete wave wall included significantly increasing the height of the embankment or using an alternative wave wall material such as steel. Both of these alternatives are much more expensive than the wave wall designed for the Arbuckle Reservoir project.

4.2.3 Construction

The contractor was consulted during the design process with respect to constructability and basic construction approaches. The most fundamental question was whether to cast the wave wall in-place on the crest of the embankment, or to prefabricate the concrete panels at a facility and then place and anchor the panels on the crest of the embankment. Based on contractor input, the design was completed as a prefabricated reinforced concrete panel. The length of each panel was set at 8 feet to facilitate transport and placement. The panel length also was short enough to make placement along the horizontal curves of the embankments easier.

4.2.3.1 Fabrication and Storage

The panels were fabricated in a Houston facility. Figure 4-10 shows one of the forms for the wave wall panels.

Figure 4-10. Wave Wall Panel Form

Over 3,400 panels were fabricated and delivered to the site on flatbed trucks to top the 5.2 miles of embankment. The panels were stored on the interior of the OCR where a turf farm formerly existed. Figure 4-11 shows an aerial view of a portion of the wave wall panels being stored in the OCR footprint.

Figure 4-11. Wave Wall Panels Stored On-site on OCR Interior

4.2.3.2 Placement and Anchoring

As shown on Figure 4-12, a crane was used to remove the wave wall panels from a flatbed truck and lift them up onto the embankment crest one at a time.

During placement, the wave wall panels are placed on the top soil cement step on the upstream face of the embankment (Figure 4-13). While a suitable material for erosion protection, soil cement is not smooth or level enough to set the panels tightly together. The contractor elected to grind a depression into the soil cement and place a layer of controlled low-strength material (CLSM), sometimes called flowable fill, into the depression to create a smooth surface.

Figure 4-12. Crane Lifts Wave Wall Panels to Embankment Crest

Figure 4-13. Wave Wall Panel Placed on CLSM Surface After Grout Applied

The panels are then anchored to the embankment crest by drilling two 8-foot-deep, angled holes into the soil cement steps (Figure 4-14).

Figure 4-14. Holes are Drilled into the Soil Cement Steps

Once complete, a steel rod with spacers is placed in each hole (Figure 4-15).

Figure 4-15. Steel Anchors are Placed in Each Drilled Hole

After placing the anchors, the holes are filled with grout (Figure 4-16).

Figure 4-16. Grout is Poured into the Holes with Anchors

This process is repeated for each of the more than 3,400 wave wall panels along the crest of the 5.2-mile-long embankment. Figure 4-17 shows a row of panels from the side after placement on the crest of the embankment.

Figure 4-17. Wave Wall Panels Placed on the Embankment Crest

4.3 River Return System

4.3.1 Facility Component Description

One important function of the Arbuckle Reservoir is the ability to store and release water throughout the year for use downstream. Using the existing improved Lane City Canal in conjunction with a new river return structure, LCRA was able to incorporate another cost-saving measure to return water to the river from storage. The use of the existing improved canal system to both deliver water to the reservoir and return water to the river saved construction costs.

The new river return structure was designed to minimize impacts to waters of the U.S., including the use of natural bank stabilization measures. Further, the capacity of the river return system and operating protocols will provide safe handling and discharge of water in high flood or wind events with a discharge capacity that can more than double the flow rate of typical operating procedures. Combined with the wave wall, this project component further reduced required freeboard height and the cost of embankment construction.

4.3.2 Design

During normal operations, releases from the OCR meet water delivery requests either down the canal system or downstream on the west side of the river. However, if the OCR water level is at full capacity during impending severe weather conditions, such as an approaching hurricane, the

OCR water level will be lowered to increase the effective freeboard. The canal return structure, canal, flume, canal gate structure and the river return structure were designed to safely convey up to 750 cfs of released water from the OCR to the river.

Figure 4-18 shows a plan view of the river return structure. The water flow into the structure is controlled by the canal intake structure at the head of the canal. The released water flows down the river return pipe, is discharged into the stilling well to dissipate the energy, and wells up into the river.

Figure 4-18. River Return Structure Plan View

Figure 4-19 shows the profile view of the river return structure. The design specifically limits the amount and depth of excavation to construct the structure. Early designs followed some standard approaches used in Federal Emergency Management Agency energy dissipation structures. However, the combination of the depth of excavation necessary in the river, the size and capacity of the structure compared with the capacity of more standard designs, and LCRA's concern that the standard designs were at greater risk of river sediment clogging the structure led to the development of the alternative design shown.

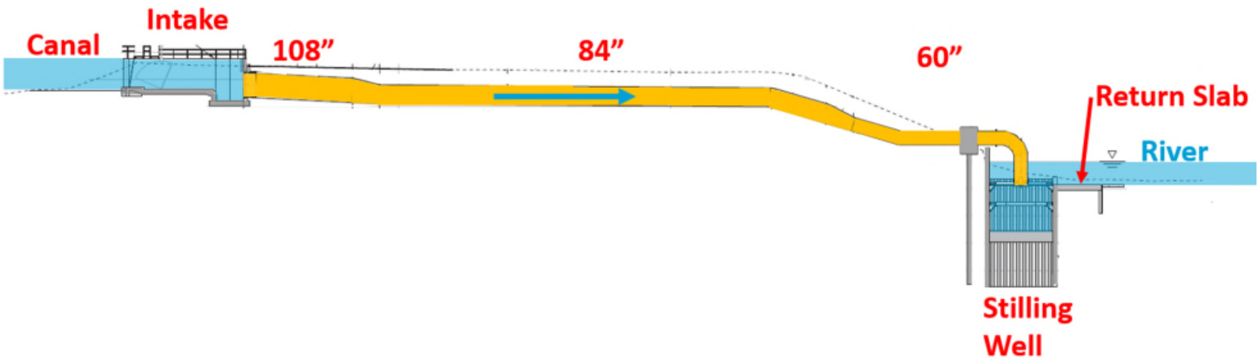

Figure 4-19. River Return Structure Profile

The nontraditional design required additional modeling to refine and complete the design. The design was facilitated using CFD modeling to evaluate the design's performance under various return flow and river flow scenarios. The CFD model was used to refine the design in preparation for physical modeling. A physical model was constructed at Utah State University, where the design was tested. The results of the physical testing helped further refine the design, resulting in the final design documents. Figure 4-20 compares the stilling well design plan, CFD model results and the physical model in operation.

Best Practice
The combination of the CFD modeling and physical modeling was an efficient and powerful way to improve performance and reduce construction costs significantly.

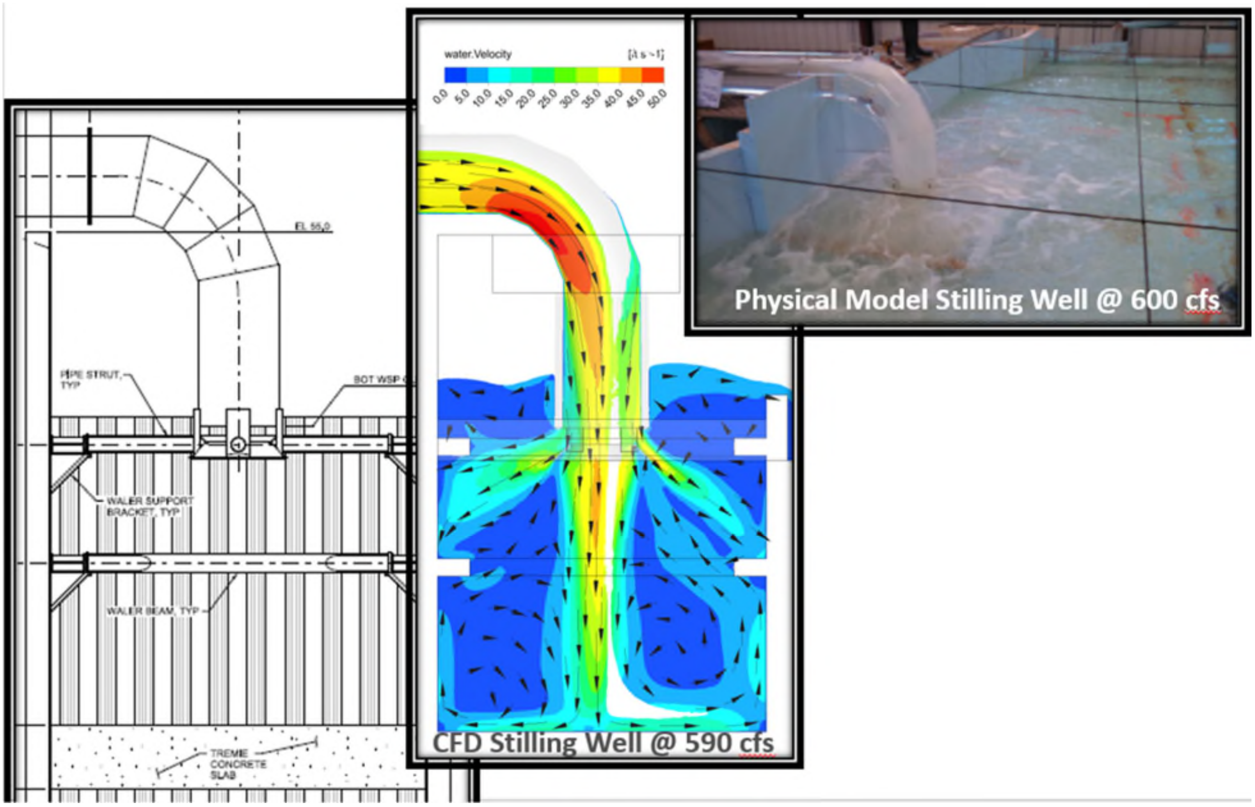

Figure 4-20. Stilling Well Profile, CFD Model Results and Physical Model

4.3.3 Construction

Although the river return structure begins near the head of the canal, the construction schedule was not significantly influenced by the irrigation season water deliveries. A temporary earthen berm was constructed in the canal, blocking the proposed entrance to the river return structure. This allowed work to begin and progress on the canal inlet structure, including the overshot gates that control flow to the river return structure.

The primary schedule challenge involved the work on the sheetpiles, stilling well and outfall slab in the river. The river overtopped the sheetpile cofferdam several times during the construction process. Each river high flow event that overtopped the cofferdam involved relocation of trapped aquatic life, removal of deposited sediment and related cleanup to begin construction again.

Best Practice
Construction in a river is always challenging. Prioritizing and accelerating construction when river levels are low and the weather is good helps avoid project delays.

Figure 4-21 is an aerial view of the river return structure construction at the river. Figure 4-22 shows the installation of the overshot gates on the canal inlet structure. Figure 4-23 is an image of the construction of the canal inlet structure and the first segment of pipe. Figure 4-24 features the cofferdam in the river and permanent sheetpile protecting the bank, the permanent sheetpile stilling well and the permanent sheetpile boundary for the outfall slab.

Figure 4-21. Aerial View of River Return Structure Construction at River

Figure 4-22. Installation of Overshot Gate in Canal Inlet Structure

Figure 4-23. Construction of Canal Inlet Structure and First Segment of River Return Pipe

Figure 4-24. Permanent Sheetpile Installation Inside the Cofferdam on the River

5 Summary

The specific design approaches used for the Arbuckle Reservoir project will not be applicable to every OCR. Integrating site-specific construction considerations and a thorough understanding of safety, operational and regulatory requirements can result in cost-effective solutions. The Arbuckle Reservoir project used existing intake facilities and LCRA's site selection process to allow the use of a relatively simple water rights permitting process and nationwide permits to comply with Clean Water Act Section 404, resulting in a faster permitting process than is typical of complex projects like reservoirs.

Innovative components of the Arbuckle Reservoir project, including the layered chimney drain, the river return structure and the wave wall, helped efficiently meet engineering and operational requirements for the project and manage project costs.

6 References

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7 TWDB Comments on Draft Report

Presented below is a summary of the TWDB comments and LCRA responses to the draft report "Innovative Solutions for Design and Construction of an Off Channel Reservoir" dated March 2018.

General Comments:

G.1 TWDB Comment: Conform the digital copy of the final report to the requirements and standards specified in statute Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites).

LCRA Response: The digital copy of the report was edited to conform to the TAC requirements**.**

G.2 TWDB Comment: Convert report graphics from black and white to color.

LCRA Response: All report graphics and photographs were converted to color.

Numbered Comments:

1. **TWDB Comment:** Section 4.1.1: Please consider including additional text regarding any consideration of options other than a chimney drain to intercept incoming seepage based on cost and effectiveness.

   LCRA Response: The section was modified to include a discussion of the use of a synthetic liner as an alternative to a chimney drain for seepage control.

2. **TWDB Comment:** Section 4.1.1: Please consider adding a closer view of cross section Figure 4-1 showing more detail of the chimney drain, wave wall, and return structure.

   LCRA Response: Figure 4-1 was modified to show additional details of the chimney drain, wave wall and return structure.

3. **TWDB Comment**: Section 4.2.1: Please consider including text regarding whether a material other than reinforced concrete could have been used for the wave wall to reduce costs while remaining effective.

   LCRA Response: The section was modified to include a discussion of alternatives to concrete wave walls.

4. **TWDB Comment**: Section 4.2.1: Please consider including text regarding whether longer wave wall panels could have been fabricated instead of the 3,400 panels that were fabricated to reduce cost while maintaining installation efficiency.

   LCRA Response: Section 4.2.1 was modified to include a discussion of modifying the length of the wave wall panel.

5. **TWDB Comment**: Section 1.2: Please consider updating Region K data to year 2017 rather than 2012.

   LCRA Response: Section 1.2 statistics were updated using 2017 Region K population and demand forecasts.

6. **TWDB Comment**: Section 1.2: Provide additional material in support of the contract deliverable "assess if the project increased the regional water supplies by 10 percent within 5 years." Though this relationship cannot be empirically demonstrated at this time, additional information explaining the modeling that predicted the increased yield would be beneficial.

   LCRA Response: Section 1.2 was modified to include additional modeling information to support the requirement that regional water supplies will be increase within the 5-year contract deliverable.