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An Assessment of Hydropower Potential at National Conduits

Shih-Chieh Kao
Lindsay George
Carly Hansen
Scott T. DeNeale
Kurt Johnson
Alden K. Sampson
et al.

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OAK RIDGE National Laboratory

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Front Cover Image:

Top-right photograph is of a dual turbine design commissioned in 2012 in a water treatment plant. Photo courtesy of Frank Zammataro, Rentricity, Inc.

Bottom-right photograph is of a 150 kW Francis turbine unit from the Watson Hydro Power Demonstration Facility, located at the Watson Reservoir, southeast of Sisters, Oregon. Photograph courtesy of Scott DeNeale; dated August 22, 2019.

Left photograph is of an irrigation canal by Unknown Author (licensed under CC BY-SA-NC).

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Environmental Sciences Division

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Shih-Chieh Kao
Lindsay George
Carly Hansen
Scott T. DeNeale
Kurt Johnson
Alden K. Sampson
Marshall Moutenot
Kevin Altamirano
Kathryn Garcia
Jim Downing
Mary Beth Day
Kelsey Rugani

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
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ABBREVIATIONS

AWIA	America's Water Infrastructure Act of 2018
DOE	US Department of Energy
EIA	US Energy Information Administration
EHA	Existing Hydropower Asset
EPA	US Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FPA	Federal Power Act
HREA	Hydropower Regulatory Efficiency Act of 2013
LOPP	lease of power privilege
NAIP	National Agricultural Imaging Program
NDA	nondisclosure agreement
NED	US Geological Survey National Elevation Dataset
NHDPlus	National Hydrography Dataset Plus
NPD	non-powered dam
NPDES	EPA National Pollutant Discharge Elimination System
ORNL	Oak Ridge National Laboratory
POTW	publicly owned treatment work
PRV	pressure-reducing valve
PWS	public water system
QA/QC	quality assurance and quality control
Reclamation	US Bureau of Reclamation
SDWIS	Safe Drinking Water Information System
TIGER	Topologically Integrated Geographic Encoding and Referencing
USGS	US Geological Survey

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Oak Ridge National Laboratory

- Michael Johnson
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EXECUTIVE SUMMARY

In support of the mission of the US Department of Energy Water Power Technologies Office to promote domestic next-generation hydropower growth, this study provides a first-of-its-kind assessment of the hydropower development potential on existing water conduits nationwide.

Context

For the purposes of this study, a conduit is defined as "any tunnel, canal, pipeline, aqueduct, flume, ditch, or similar manmade water conveyance that is operated for the distribution of water for agricultural, municipal, or industrial consumption and not primarily for the generation of electricity."[1] Such conduits include irrigation canals and ditches, pipes in municipal water and wastewater systems, and cooling water discharge pipes at thermoelectric power station stations. Conduit hydropower projects generally have less than 10 MW capacity, falling into the small-scale (100 kW–10 MW capacity) and micro-scale (<100 kW capacity) hydropower categories.

The current total conduit hydropower capacity in the Unites States is around 530 MW. Several characteristics of conduit hydropower make it a promising candidate for substantial expansion. They include the following:

- Conduit hydropower projects typically have few environmental impacts because the channels involved are not natural streams and projects do not involve new dams or impoundments. The projects also do not result in increase of greenhouse gas emission.
- Recognizing the potential benefits of conduit hydropower and its low impact, Congress has created a simplified, 45 day federal regulatory approval process for such projects through the Hydropower Regulatory Efficiency Act of 2013 and its amendments in America's Water Infrastructure Act of 2018.
- In most states, conduit hydropower projects are eligible for net metering, which can make project economics more favorable by increasing the effective value of the electricity generated by installations at facilities that have significant on-site power demand, such as water supply and wastewater treatment plants and industrial sites.

Approach

This study evaluates the potential for conduit hydropower development in the municipal, agricultural, and industrial sectors across the United States. The research team developed systematic methods to evaluate conduit hydropower capacity potential (MW) and energy generation potential (GWh/year) at four categories of conduits across the United States. They include the following:

- Water supply pipelines for municipal and industrial uses
- Wastewater discharge conduits from municipal and industrial systems
- Agricultural water conduits including irrigation canals and ditches in the 17 western states that rely heavily on irrigation
- Thermoelectric power plant cooling water discharge conduits

For each type of conduit, the team developed and implemented a method to estimate hydraulic head and annual water flows—and the hydropower potential—based on analyses of satellite imagery, topography,

[1] Code of Federal Regulations (CFR) Title 18, Chapter 1.B.4.D § 4.30 (b) (2)

and existing data sets on water systems and power plants. These methods support a consistent, replicable estimate of conduit hydropower potential across 3 sectors and all 50 states, aggregated at the county and state levels. The assessment was conducted at the reconnaissance level, considering resources that could be available for development at the state and national levels using present-day assumptions about conduit hydropower technology.

Key Findings

Key takeaways of this study include the following:

- The study estimates **a total of 1.41 GW of new conduit hydropower potential** across the United States (Figure ES.1), with the largest portion of conduit hydropower potential found in the agricultural sector (662 MW), followed by industrial (378 MW) and municipal (374 MW) sectors.
- In general, **the largest resource potential exists in the western states**, with **the highest total power potential in California (243 MW), followed by Colorado (204 MW), Washington (119 MW), Nebraska (99 MW), and Oregon (77 MW)** (Figure ES.2). These potential estimates jointly reflect the amount of water supply and suitable topography to provide sufficient net hydraulic head for hydropower generation.
- Compared with the **530 MW of existing conduit hydropower projects in the United States, the 1.41 GW undeveloped potential presents a great opportunity** to develop clean and renewable hydroelectric energy across the nation.

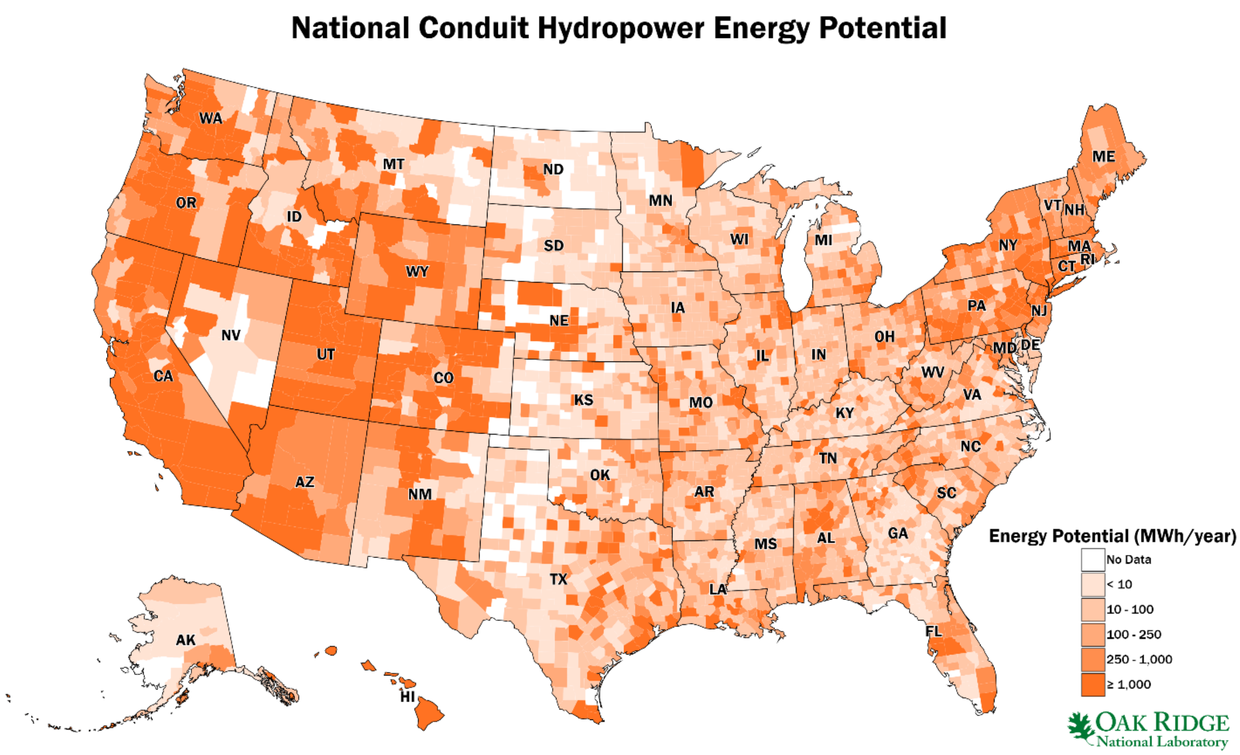


Figure ES.1. Map of overall conduit hydropower capacity potential by county.

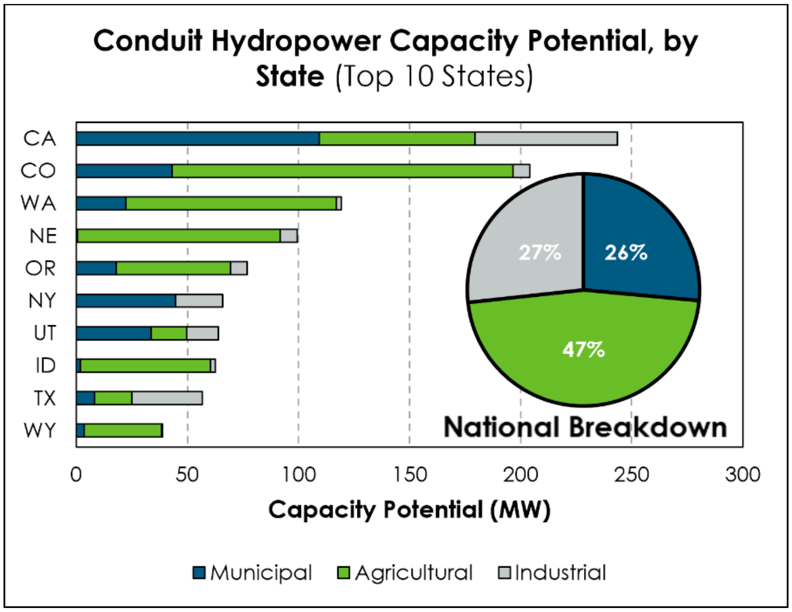


Figure ES.2. Top 10 states with the highest conduit hydropower capacity potential.

Conduit hydropower potential in the agricultural sector was greatest in states with a combination of a large amount of irrigated acreage and hilly or mountainous terrain. Colorado had the highest conduit potential (154 MW), followed by Washington, Nebraska, California, Idaho, and Oregon.

In the municipal sector, conduit potential scaled generally with population—which is roughly proportional to flows in municipal water and wastewater systems—and terrain. The study found California to have more than twice the conduit development potential (109 MW) than the second-ranked state, New York, followed by Colorado, Utah, Washington, Oregon, and Pennsylvania.

Municipal water supply systems accounted for 90% of the total potential, compared with 10% for wastewater systems, mainly because of the greater water pressure in closed pipelines in water supply systems (Figure ES.3). However, in nine states, primarily in the Midwest, potential from wastewater systems may exceed that of water supply systems.

Industrial conduit hydropower potential was greatest in California, followed by Texas, Missouri, New York, and Maryland. Of the three sectors evaluated, the industrial sector had the greatest uncertainty because most of the measured conduit potential (60%) was associated with cooling water discharges from thermoelectric power plants (Figure ES.3). Multiple potential economic and regulatory obstacles to conduit hydropower development exist at such sites, and, to the authors' knowledge, there are currently no cooling water associated conduit projects in the United States (though successful projects have been built in Europe).

Collectively, these potential conduit hydroelectric projects could deliver a range of benefits. They could provide stable energy output in distributed microgrids and help offset local energy demands for water system operators in local communities, for which energy costs are typically a substantial portion of operational costs. Tapping conduit hydropower potential in water distribution systems can be a sustainable long-term water and energy supply solution, and pending upgrades and overhauls of aging water infrastructure offer many opportunities.

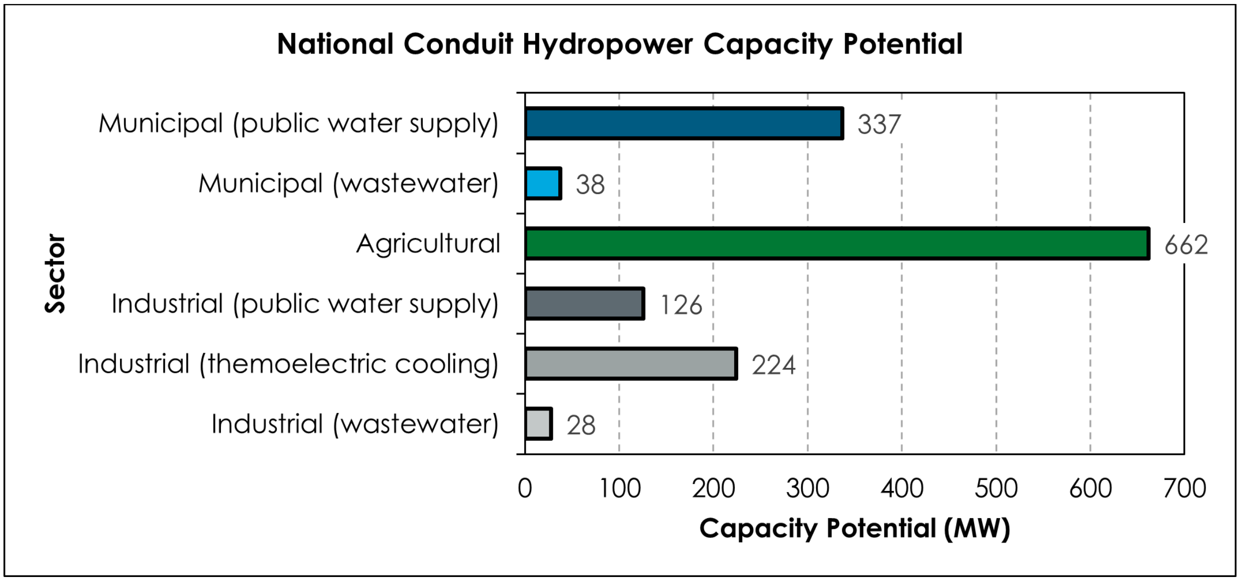


Figure ES.3. National conduit hydropower capacity potential by sector.

Limitations

Given the high priority of estimating state and national total resource potentials, *the assessment does not provide site-specific generation and cost estimates that are sufficiently accurate to support project-specific feasibility assessment or to justify investments*. In addition, the analysis is conservative, with several known categories of conduit hydropower resources not included because of data limitations or other challenges. The uncounted resources include the following:

- Self-supplied municipal and industrial water systems
- Energy recovery opportunities from hydraulic head generated by pumping (as opposed to gravitational head)
- Agricultural conduit potential outside the 17 western states that rely heavily on irrigation
- Water intakes and treatment plants known to be missing from the data sets used in the analysis
- Opportunities for applications in water-intensive industry systems (e.g., food and beverage processing, mining, and oil and gas processing)
- Opportunities for hydrokinetic hydropower development in large agricultural conduits

Next Steps

This study points to several potential next steps to further the development of conduit hydropower.

- **Enhance resource characterization:** Future work should refine the understanding of conduit hydropower resources, such as by working directly with water utilities and irrigation districts to characterize sites and contexts that are most suitable for potential development. Further study could also expand the scope of analysis to include the assessment of the conduit resource potential for next-generation hydropower technologies such as hydrokinetic turbines.

- **Understand the development challenges and required incentives:** Although the Hydropower Regulatory Efficiency Act of 2013 and America's Water Infrastructure Act of 2018 streamlined the regulatory approval process for conduit hydropower, the sector continues to face development challenges, including—as noted by technical reviewers of the report—uncertain project economics and a lack of consistent and equitable incentives. A comprehensive techno-economic assessment would improve understanding of cost-recovery mechanisms and how conduit hydropower projects may take advantage of incentives such as the Energy Power Act of 2005 Section 242 incentive program. Such an assessment could also help to clarify key market hurdles and inform the design of future incentive programs.
- **Explore novel water distribution concepts and technologies:** The integration of conduit hydropower into irrigation and municipal water supply systems can recover energy from pressurized pipelines and increased overall energy efficiency. Further research is needed to support the development of turbine technologies for these applications and the design and optimization of integrated systems.
- **Increase public awareness and engagement:** In all three sectors evaluated in this report, a known barrier to conduit hydropower development is limited awareness of the feasibility and benefits of conduit hydropower technology and its potential contributions to meeting sustainability goals. The perception that the technology is high-risk and operationally demanding is a particular obstacle. Thus, there is a need for targeted outreach to utilities, asset owners, developers, technology providers, and community representatives.

1. INTRODUCTION

1.1 BACKGROUND

Among various undeveloped hydropower resources classified by the US Department of Energy (DOE), the hydroelectricity potential from conduits has been estimated as being relatively small but as having the highest development feasibility (Hydropower Vision report; DOE 2016). According to the Code of Federal Regulations (CFR) Title 18, Chapter 1.B.4.D § 4.30 (b) (2), conduit means "any tunnel, canal, pipeline, aqueduct, flume, ditch, or similar manmade water conveyance that is operated for the distribution of water for agricultural, municipal, or industrial consumption and not primarily for the generation of electricity." This type of small hydropower development does not require the construction of new dams or impoundments, involves minimal environmental concerns, is eligible for net-metering in most states, yields high value for the energy generated, entails reduced development timelines, and may qualify for an expedited 45-day regulatory approval process through the qualifying conduit approval process created by the Hydropower Regulatory Efficiency Act of 2013 (HREA) and its amendments in America's Water Infrastructure Act of 2018 (AWIA). In addition to the HREA and AWIA, the US Bureau of Reclamation (Reclamation) Small Conduit Hydropower Development and Rural Jobs Act of 2013 (PL 113-24) also streamlined Reclamation lease of power privilege (LOPP) authorizations for small conduit hydropower development on Reclamation Projects.

Based on the features of conduits, conduit hydropower development can be classified into three main sectors (Johnson et al., 2018):

- ***Municipal*** conduit hydropower mainly refers to generating facilities located at pressurized pipelines used for drinking water supply in public water systems (PWSs) (Morgan et al. 2018). This type of small hydropower project is installed in parallel to existing flow control or pressure-reducing valves (PRVs) with hydropower generators that use excess pressure (regularly reduced by PRVs) for hydropower generation and energy recovery. Municipal conduit hydropower also includes publicly owned treatment works (POTWs) that utilize the outflows and gravitational elevation difference between the discharge point and receiving waters for hydropower generation.
- ***Agricultural*** conduit hydropower mainly refers to generating facilities at drop locations (i.e., locations with a sudden channel bottom elevation change) within open water ditches and canals that are primarily used for irrigation. This type of small hydropower project typically uses the gravitational hydraulic heads at existing drop sites for hydropower generation. A relatively smaller portion of agricultural conduit hydropower is located at pressurized pipelines within irrigation systems. Although agricultural conduit hydropower has seasonal variation, given the larger flow (compared with PWSs), the hydropower capacity of canal conduit projects is usually larger than that of PWS projects.
- ***Industrial*** conduit hydropower refers to generating facilities that utilize industrial pipelines or canals. Although the industrial sector (including industrial, mining, aquaculture, and thermoelectric) has the largest water withdrawal volume, the conduit hydropower opportunities associated with industrial conduits are the least understood. Based on a review of Federal Energy Regulatory Commission (FERC) qualifying conduit application data,[2] there is little industrial sector development of conduit hydropower—despite the fact that industrial developments are likely to be particularly efficient and cost-effective since they are typically eligible for on-site net-metering.

Despite the high development feasibility, the amount of total conduit hydropower resource potentials and their spatial distribution across the United States are not clearly known. This knowledge gap is mainly

[2] https://www.ferc.gov/media/status-intent-construct-qualifying-conduit-hydro-facilities

due to disparate data sources that do not contain common or complete information and restrictions on information owing to security concerns. This lack of understanding hinders the active development of the conduit hydropower market. To guide future research and investment strategies, a more comprehensive national conduit resource assessment is needed, and this study seeks to fill the gap.

1.2 CURRENT STATE OF CONDUIT HYDROPOWER DEVELOPMENT

Many small conduit projects (<40 MW) qualify for exemption from the licensing requirements of Part I of the Federal Power Act (FPA) and can follow a simpler FERC exemption application process compared with the full license process, known as a Conduit Exemption. This FERC regulatory process was further reduced by the HREA of 2013 and its amendments in AWIA. Qualifying conduit facilities are considered outside of FERC jurisdiction and can secure a non-jurisdictional determination from FERC per the HREA within 45 days provided that they

- are less than 40 MW,
- use a nonfederally owned conduit,
- serve a primary purpose other than hydropower generation, and
- are not currently licensed or exempted.

Between the passage of the HREA in August 2013 and October 2021, 128 projects nationwide with a combined total of more than 40 MW in capacity received HREA "qualifying conduit" determination from FERC.[3] They are mostly clustered in the western United States and are split roughly evenly between municipal and agricultural projects (Figure 1). These projects are as large as the 4.8 MW U Canal Hydro #2 Project by the North Side Canal Company Ltd. in Jerome, Idaho (FERC Docket CD14-1) and as small as the 300 W Weir Road PRV Vault Project in Beaverton, Oregon (FERC Docket CD19-9).

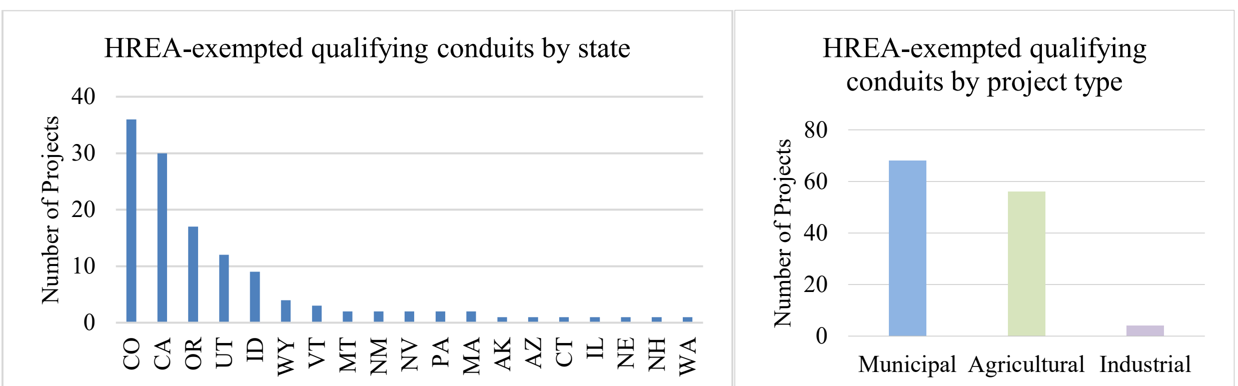


Figure 1. HREA-exempted qualifying conduits by state and project type (as of October 2021).

As of October 2021, 358 conduit projects have received FERC exemption through the FPA or HREA. Out of these 358 projects, 140 are located on agricultural conduits (40%), 203 on municipal conduits (56%), and 15 on industrial conduits (4%). A further summary is shown in Figure 2. An additional six conduits on the Reclamation agricultural conduits totaling 18.4 MW were permitted through the

[3] As a reference, 58 projects received FERC FPA conduit exemptions during 2004–2013, and 15 projects received FERC FPA conduit exemptions during 1994–2003. In total, 90% of projects submitted to FERC were considered qualifying conduit facilities.

Reclamation LOPP process.[4] Overall, the vast majority of US conduit hydropower projects and capacity are located on municipal or irrigation conduits. Very few conduit hydropower projects are in the industrial sector, despite almost half of water withdrawals being made for industrial purposes (Section 2.1).

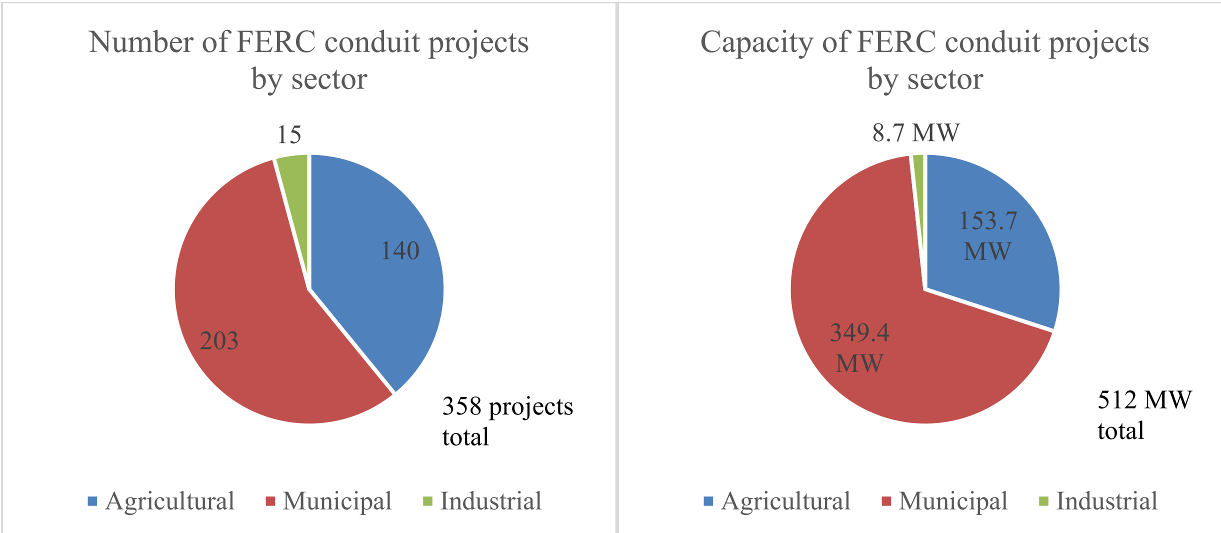


Figure 2. Number and capacity of FERC-approved conduit projects by sector (as of October 2021).

However, the rate of conduit hydropower development has been slower than might be expected, in which limited public awareness of conduit hydropower potential is one main reason. Given that PRVs are commonly used in many pipeline networks, and irrigation canal drops are also common in irrigation systems, many municipal, agricultural, and industrial water users should have sites suitable for conduit hydropower development. Apart from the challenges identified by Grimm (2021), one barrier can be the limited awareness among water utilities across multiple sectors. Hydropower development, particularly the regulatory process, is still viewed by some as high-risk and time-consuming, so water utilities and industrial users may not be motivated or incentivized to explore it. To help spur awareness of this clean and low-impact hydropower resource, this study provides an estimate of the total conduit hydropower potentials across the United States. Together with the non-powered dam (NPD) (Hadjerioua et al. 2012) and new stream-reach development (Kao et al. 2014) resource assessments, this national conduit development resource assessment contributes to a more complete US hydropower resource characterization.

1.3 PRIOR CONDUIT HYDROPOWER RESOURCE ASSESSMENT EFFORTS

As noted in the Hydropower Vision report (DOE 2016), no nationwide resource assessment has focused on potential hydroelectricity capacity and energy available through powering existing conduits. Based on existing studies and data, DOE (2016) roughly estimated that there could be around 1–2 GW total conduit hydropower potential across the country. However, an in-depth national conduit resource assessment had not yet been conducted. Although several states have conducted their own conduit resource assessments, those studies were based on different approaches and assumptions and examined only a subset of conduits.

[4] https://www.usbr.gov/power/LOPP/LOPP_Development_2_2020.pdf. Reclamation conduits authorized for federal hydropower development are permitted through Reclamation's LOPP process, while all other Reclamation conduits (those not authorized for federal hydropower development) are licensed through FERC.

A report prepared for the California Energy Commission (Kane et al. 2006) suggested that approximately 255 MW of Renewables Portfolio Standard–eligible small hydropower projects in California (i.e., also likely HREA-qualifiable) could be developed in constructed conduits. This resource estimate was based on survey data from 43 large- and medium-sized water purveyors (water agencies and irrigation districts) that collectively accounted for about 65% of the total annual water entitlements in California. In 2020, the California Energy Commission (Badruzzaman et al. 2020) revisited this assessment with a new methodological approach, and the California potential was estimated to be 414 MW. The method included supplementing information from the 2006 study with select on-site surveys and questionnaires, combined with water delivery data from several sources, as well as using Monte Carlo simulation to address the uncertainty and estimate the potential across all water delivery agencies in California.

To develop an understanding of the conditions, barriers, and opportunities related to the small hydropower market in Oregon, Summit Blue Consulting (2009) surveyed a sample of water rights holders with estimated annual water allocations greater than 10,000 acre-ft within the Portland General Electric and PacifiCorp service territories. Although challenges related to small hydropower development were comprehensively discussed, the study did not offer a state-level estimate of the potential small hydropower resources.

Allen and Fay (2013) and Allen et al. (2013) evaluated the in-conduit energy generation potential for PWS and POTW facilities in Massachusetts using survey data and publicly available information. Under low- and high-head assumptions (required because of a lack of site-specific data), they suggested that there could be around 4,300–39,500 MWh/year of hydroelectric energy in PWS systems and 600–3,000 MWh/year in POTW systems in Massachusetts.

The Colorado Energy Office (2016) conducted a conduit hydropower resource assessment focusing on existing PRVs within water utility delivery systems. Based on available information collected through its online PRV geodatabase, and using other assumptions, the Colorado Energy Office estimated that there is 20–25 MW of hydropower potential by placing conduit hydropower turbines in parallel with existing PRVs statewide. The Colorado Department of Agriculture (2013) completed an agricultural hydropower assessment that estimated 30 MW of untapped potential using on-farm pressurized irrigation.

Grimm (2021) evaluated the conduit hydropower potential in drinking water systems that serve Syracuse, Albany, and Niagara Falls in New York based on demonstrating the greatest financial feasibility and environmental justice applicability in the state. In addition to energy modeling and financial analysis, interviews with water department officials were also conducted to understand the challenges associated with conduit hydropower development. The findings suggested that conduit hydropower assessment should be more readily promoted through state and federal policy as well as further studied through interdisciplinary research, particularly in the context of environmental justice to improve equitable access to clean water and renewable energy.

Focusing on agricultural conduits, Reclamation conducted a hydropower resource assessment for Reclamation-owned canals and showed approximately 268 MW and 1.2 million MWh of potential resources (Reclamation 2012). Some additional agricultural conduit sites were also evaluated in a prior resource assessment study (Reclamation 2011). To locate and identify conduit hydropower sites on Reclamation-owned canals, Reclamation staff researched project drawings and aerial imagery, gathered expertise from local area officials, and in some cases physically visited the canals. To identify the available flows at each site, Reclamation and irrigation district personnel identified the best available seasonal, monthly, or daily flow information to support the assessment.

Overall, multiple challenges associated with performing conduit hydropower resource assessments have been reported in previous studies. They include the following:

- **Data availability**: As indicated in multiple previous studies, data availability is one of the primary challenges and uncertainties for conduit resource assessment. Whereas the US Army Corps of Engineers National Inventory of Dams serves as a good foundation for an NPD hydropower resource assessment, there is no national or regional conduit database to provide necessary baseline information for hydropower resource evaluation. This data issue is further complicated by the different conduit settings in each sector.
    - **Municipal**: For PWSs, the locations, pressure differences, treatment capacities (e.g., gallons per day), age, and integrity of existing pipelines are the most desired information. Alternatively, the total elevation differences, types of material, and pipeline diameters could be used to estimate the possible head loss and the total available head of a closed conduit. However, although each water utility is fully aware of the status of its own water treatment system and the locations of existing PRVs, such information has not been comprehensively collected into a regional or even national database. Furthermore, given infrastructure safety concerns, most PWS information is confidential and exempt from the Freedom of Information Act of 1967. Such PWS-related data can only be accessed by a government (or a quasi-government) entity. For POTWs, although there are fewer infrastructure safety concerns, most of the data required for conduit hydropower resource assessment are also lacking. Some high-level simplifications are needed (e.g., prescribed head as suggested by Allen et al. [2013]) to estimate conduit hydropower potentials in POTWs.
    - **Agricultural**: Fewer infrastructure concerns are associated with agricultural conduits, but canal drop sites are usually known only to the irrigation districts and have not been comprehensively documented across the United States. Furthermore, although public geospatial data sets such as the National Hydrography Dataset Plus (NHDPlus) contain nearly 174,000 mi of artificial pathways and 177,000 mi of canal ditches, the data sets are not always up to date; and some pathways and ditches reportedly are not contained in the data set. Getting an estimate of canal flow is even more challenging since most canals are not gauged. Canal flow also cannot be simulated through conventional rainfall-runoff models. A systematic approach to identifying possible canal resources is desired.
    - **Industrial**: Although the industrial sector (particularly thermoelectric; Maupin et al. 2014) has the greatest total water use, the understanding of conduit hydropower potential in the industrial sector is lacking. The total water use and discharge may be approximated from some federal or state databases, but reasonably assuming or approximating possible hydraulic head opportunities for the purpose of conduit hydropower resource evaluation has not been feasible. Furthermore, types of conduits are expected to vary across industries (e.g., thermoelectric vs. mining), adding further complexity to data collection.
- **Limitation of surveys**: Targeted surveys remain one viable approach when data are extremely limited (Kane et al. 2006; Colorado Energy Office 2016), but such an approach is time- and resource-consuming. In addition, although higher survey participation is desirable, that was not usually the outcome, which could be attributed to a variety of reasons. For example, the Colorado Energy Office (2016) encouraged water utilities to participate in the development of a statewide database of PRVs. Although this initiative was well regarded and received positive responses from participating utilities, only a fraction of water systems provided their system information. Unless a large, representative sample is collected during the process, a survey-based approach will inevitably involve significant uncertainty.
- **Inconsistent methodology**: The current small hydropower resource assessments conducted in each state have been based on different data types and methodologies. They all have been developed based on the unique legal and market features in each state, so incorporating the findings into a common regional or national platform is challenging. For the purpose of interregional resource comparison, a spatially consistent resource evaluation method is needed.

1.4 SCOPE AND OBJECTIVE OF THIS STUDY

To help DOE and the broader hydropower and water supply industries quantify the total hydropower potential from conduits nationwide, a reconnaissance-level hydropower resource assessment was used in this study. Recognizing the current gaps and challenges in different water sectors, sector-specific approaches that are best suited for the current state of data availability were developed for three main conduit hydropower sectors (municipal, agricultural, and industrial). The assessment method was designed at the reconnaissance level (RETScreen International 2005), considering technical resources that could be available for development (NRC 2013) at the state and national scales using modern assumptions about conduit hydropower technology. Given the high priority of estimating state/national total resource potentials, the assessment does not provide site-specific generation and cost estimates that are sufficiently accurate to support project-specific feasibility assessment or to justify investments. Instead, the assessment uses a spatially consistent approach to systematically analyze the conduit potentials across different states to allow further interregional resource comparison and enable a national assessment.

The assessment leveraged the best available data acquired through federal and state drinking water and wastewater regulatory agencies, as well as novel remote sensing and feature detection techniques for systematic identification of national canal drop sites. The estimated conduit hydropower resource potentials are reported at both state and county levels without revealing sensitive or proprietary information at any site. In addition to helping the broader hydropower and water supply industries quantify the magnitude of potential HREA-eligible conduit hydropower resources, the capacity and energy estimates can be used in national energy deployment models to improve the projections of future hydropower growth. Based on the research, initial market assessments and engagement can assess the potential and begin to build market interest in the subsectors. Overall, this study presents one of the first national efforts toward a comprehensive understanding of conduit hydropower potentials across different sectors and geographical regions.

2. ASSESSMENT APPROACH

The following sections provide an overview of total US water withdrawal (Section 2.1). Considering system nature and data availability, different assessment methods were designed for four main water systems (i.e., public water supply, irrigation canals, thermoelectric cooling, and wastewater) in Sections 2.2–2.5. The summary of overall assumptions is further discussed in Section 2.6.

2.1 OVERVIEW OF US WATER WITHDRAWAL

The amount of total water withdrawal can help provide an understanding of the potential hydropower opportunities in national conduits. The US Geological Survey (USGS) estimates water use in the United States every 5 years. The annual fresh/saline groundwater and surface water withdrawals by sector from the most recent 2011–2015 estimates (Dieter et al. 2018) are summarized in Table 1. Overall, thermoelectric accounts for the largest water withdrawals (41%), followed by irrigation (37%) and then public supply (12%). Although the amount of conduit hydropower capacity and energy also depends on the available hydraulic head, this flow-based water withdrawal analysis can help identify major water users for a more complete national conduit hydropower picture.

Table 1. Estimated annual water withdrawals by sector (in million gallons per day; Dieter et al. 2018)

USGS 2011–2015 estimates	Groundwater		Surface water		Total	Percentage	Conduit hydropower sector
	Fresh	*Saline*	*Fresh*	*Saline*			
Public supply	15,200	—	23,800	—	—	—	
Domestic	—	—	—	—	23,300	7%	Municipal
Industrial/commercial	—	—	—	—	9,460	3%	Industrial
Estimated losses	—	—	—	—	6,240	2%	—
Domestic (self-supplied)	3,210	—	49	—	3,260	1%	—
Irrigation	57,200	—	60,900	—	118,000	37%	Agricultural
Livestock	1,240	—	760	—	2,000	1%	Agricultural
Aquaculture	1,600	0	5,950	0	7,550	2%	Industrial
Industrial (self-supplied)	2,670	43	11,300	743	14,800	5%	—
Mining	1,010	1,860	877	256	4,000	1%	Industrial
Thermoelectric	425	172	94,700	37,600	133,000	41%	Industrial
Total	**82,555**	**2,075**	**198,336**	**38,599**	**312,810**	**100%**	

For municipal conduits, water can come from the domestic public supply (7%, from PWSs) or domestic self-supply (1%). Based on the available data, an approach was designed to estimate the total conduit hydropower potential in PWSs (described in Section 2.2), considering the amount of water withdrawals for domestic public supply reported by Dieter et al. (2018). Although domestic self-supply also withdrew a large amount of water, given the lack of information, the conduit hydropower potential cannot be estimated in self-supply water systems.

For agricultural conduits, water is withdrawn/used for irrigation (37%) and livestock (1%). More specifically, this type of conduit hydropower potential is typically at existing canal drop locations. Motivated by Reclamation (2012), an approach was designed to first systematically identify national canal drop locations through remote sensing and feature detection techniques, and then estimate conduit hydropower potential at each drop location based on assumed canal geometries (Section 2.3).

The rest of water withdrawals are broadly considered "industrial" in this study, which includes public water supply for industrial[5]/commercial users from PWSs (3%), industrial self-supply (5%), mining (1%), and thermoelectric (41%). For public water supply to industrial/commercial users (3%), the same approach was used as indicated for PWS supplying the municipal sector (described in Section 2.2) but considered the amount of water withdrawals for industrial/commercial users. Although conduit hydropower potential from water withdrawals for industrial self-supply (5%), aquaculture (2%), and mining (1%) may exist, given the lack of information, it could not be evaluated in this study. However, the potential from wastewater discharge was included (described in Section 2.5). For thermoelectric usage (41%), the theoretical conduit hydropower potential was estimated from discharge from top withdrawers that cover more than 95% of total cooling water withdrawals (Section 3). Although the authors are not aware of any such existing hydropower conduit projects in the United States, successful cases in Europe motivated the authors to evaluate the potential in the United States. However, whether these US thermoelectric power plants may consider additional conduit hydropower in their facilities is unknown, given the cost/benefit factors, retirement of coal facilities, future upgrades to recirculatory cooling systems, and other regulatory challenges. Also, although the potential conduit hydropower resources in the thermoelectric power plants may seem large (because of the large water withdrawals), they are much smaller in magnitude (~1%) compared with the capacity of thermoelectric power plants. Nevertheless, to gain a full understanding of national hydropower potential, these plants were still evaluated in this study.

Additionally, conduit hydropower potential of municipal and industrial wastewater discharge was also estimated based on available data. Similar to PWSs, a portion of the wastewater potential is included in the municipal sector, and the rest is included in the industrial sector. There could be further issues such as how climate change may affect regional water supply and future flow availability, but they were not evaluated in this study. The details, limitations, and uncertainties of the methods used for these four systems (i.e., public water supply, irrigation canals, thermoelectric cooling, and wastewater) are further described in Section 2.5.

2.2 PUBLIC WATER SYSTEM

The methods used to estimate conduit hydropower potential in PWSs were developed by Kao and Johnson (2018) in a pilot study for Colorado and Oregon, and also used by Grimm (2021) for three cities in New York. With additional national PWS data acquired from the Environmental Protection Agency (EPA) and other sources, the assessment was expanded to the national scale. For data set and methodology consistency, the resource estimates for Colorado and Oregon derived in this study supersede the original estimates reported by Kao and Johnson (2018).

2.2.1 Data Sources

To quantify the conduit hydropower potential associated with each PWS, detailed conduit characteristics—including PRV location, conduit length, slope, diameter, material, pressure, and discharge—are desired. Although such information is known to each PWS owner and utility, no comprehensive data set is available at state and national scales to support overall resource evaluation. To estimate the conduit hydropower potential nationally associated with PWSs, alternative data sets and necessary simplifications are needed. After consulting with several state drinking water agencies, USGS, and EPA regarding the availability and limitations of PWS-related data, multiple national and state data sets were selected in this study (summarized in Table 2 and visualized in Figure 3 using publicly available

[5] Industrial water use is described by USGS as providing "water for such purposes as fabricating, processing, washing, diluting, cooling or transporting a product; incorporating water into a product or sanitation needs within the manufacturing facility. Some industries that use large amounts of water produce commodities such as food, paper, chemicals, refined petroleum or primary metals."

information). Although most of these data sets are publicly available, one critical type of information, PWS water intake location, is protected in most states. A nondisclosure agreement (NDA) is generally required to access such information. These protected data are also prohibited from being shared or disseminated beyond the party that executed the NDA.

Table 2. Summary of data used in the PWS analysis

Data type	Data source	Reference/website
PWS information	EPA Safe Drinking Water Information System	https://www.epa.gov/enviro/sdwis-overview
Water intake and treatment plant locations	EPA	Protected information acquired through a nondisclosure agreement
City boundary	US Census Bureau Topologically Integrated Geographic Encoding and Referencing Dataset	https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html
Digital elevation	USGS National Elevation Dataset	https://apps.nationalmap.gov/datasets
Historical water use	USGS National Water-Use Science Project	https://pubs.er.usgs.gov/publication/cir1441
Existing hydropower asset	ORNL HydroSource Existing Hydropower Asset Dataset	https://hydrosource.ornl.gov/dataset/existing-hydropower-assets-eha-2020

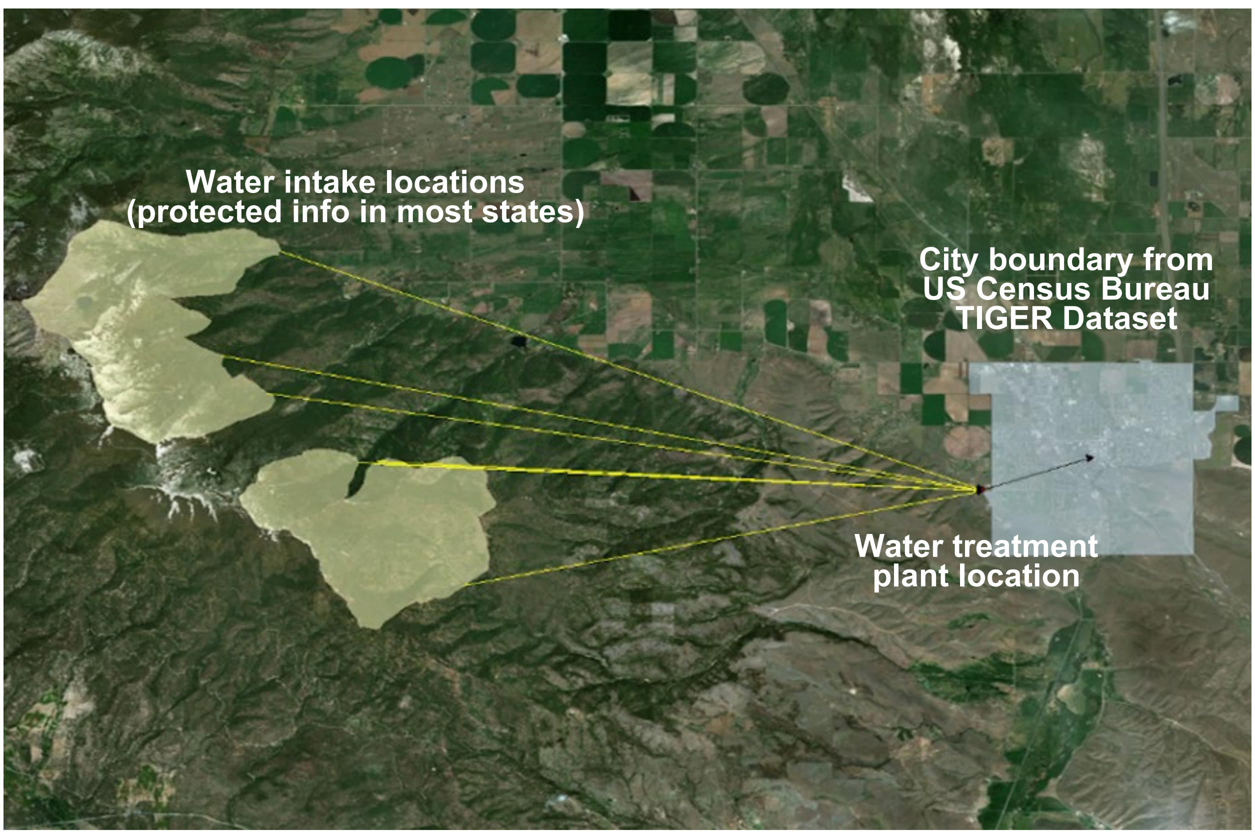


Figure 3. An example of multiple data sets collected in this study. TIGER: Topologically Integrated Geographic Encoding and Referencing.

- **PWS information**: Baseline US PWS information can be obtained from the EPA Safe Drinking Water Information System (SDWIS). SDWIS tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments. Under the Safe Drinking Water Act, each state supervises its PWSs to ensure that each system meets state and EPA standards for safe drinking water. Information such as the PWS characteristics (e.g., system name, identification number, city/county served, number of people served, system type), violations, and enforcement records are reported regularly to EPA. For this assessment, the PWS service population is the main information obtained from SDWIS.
- **Water intake and treatment plant locations**: The water intake and treatment plant locations provide key information for estimating conduit hydropower potential in PWSs. However, given the infrastructure safety concerns, such in-depth PWS information can usually be shared only with another agency for governmental use only. For the purpose of this assessment, a nondisclosure agreement was established between EPA and Oak Ridge National Laboratory (ORNL) to exchange and protect such data. Although the location of water intakes and treatment plants cannot be disclosed, the derived and spatially aggregated conduit hydropower estimates can be reported.
- **City boundary**: Because there is no comprehensive, state/national geospatial data set of PWS service areas, the US Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) city/place geospatial data set was used as a proxy in this study. The TIGER shapefiles and related database files are extracted from selected geographic and cartographic information from the US Census Bureau's Master Address File and TIGER (MAF/TIGER) Database. The TIGER shapefiles include both incorporated places (legal entities) and census-designated places (statistical entities). An incorporated place is typically a city, town, village, or borough, but it can have other legal descriptions. Census-designated places are delineated for the decennial census as the statistical counterparts of incorporated places. The boundaries for census-designated places often are defined in partnership with state, local, and/or tribal officials and usually coincide with visible features or the boundary of an adjacent incorporated place or another legal entity. Although the TIGER boundary data set is different from the actual PWS service area, it should capture the majority of the population within a community, which can help clarify the main destination of the PWS. In this assessment, city boundaries were overlapped with digital elevations to estimate the average elevation of a city. An example is shown in Figure 3.
- **Digital elevation**: To determine the elevation at water intakes, water treatment plants, and destination cities, the 1/3 arc-s (~10 m) horizontal resolution USGS National Elevation Dataset (NED; Gesch et al. 2002) was used in this study. NED is the primary elevation data product of the USGS that is derived from diverse data sources and processed to a common coordinate system and unit of vertical measure. All elevation values are in meters and, over the conterminous United States, are referenced to the North American Vertical Datum of 1988. The overall root mean square error of the absolute vertical accuracy of NED is reported to be within approximately 2.44 m (Maune 2007). NED was also used in other national hydropower resource assessments (e.g., Kao et al. 2014).
- **Historical water use**: To estimate conduit hydropower potential, the water treatment plant capacity (i.e., gallons per day) is another necessary piece of information. Although there is no obvious sensitivity or concern regarding the treatment plant capacity information, such data have not been collected regularly and comprehensively by EPA (or perhaps by many states). To estimate the historical water use of each PWS, the per capita water use from the 2011–2015 USGS assessment (Dieter et al. 2018) was examined as an alternative. First, the per capita water use of domestic and industrial/commercial supply at each county was calculated. Based on the county that a PWS mainly serves, the per capita water use was then multiplied by PWS service population to approximate the water treatment plant capacity. This estimate could be different from the actual water treatment plant capacity, but it is the best available approximation for all systems given the data limitations.

- **Existing hydropower assets**: Existing hydropower development information was obtained from the ORNL HydroSource Existing Hydropower Asset (EHA; Johnson et al. 2020) data set. HydroSource is an integrated hydropower information platform maintained by ORNL for the DOE Water Power Technologies Office. Hydropower plant characteristics such as location, capacity, number of turbines, turbine types, modes of operation, permit number, plant owner/operator, and historical generation are regularly incorporated from multiple agencies, including the US Energy Information Administration (EIA), FERC, US Army Corps of Engineers, Reclamation, and the Tennessee Valley Authority. The characteristics of some exempted conduit projects were reviewed to inform the design of the proposed resource assessment model.

2.2.2 PWS Conduit Hydropower Model

To estimate the total hydropower potential in a region, three key pieces of information are required: (a) available sites, (b) distribution of net hydraulic head, and (c) distribution of turbine flow. With data limitations in mind, the biggest challenge is to estimate these three required parameters based on best available data. Some necessary assumptions were made, and when applicable, the effects of these assumptions were further evaluated in a model sensitivity analysis.

2.2.2.1 Power and Energy Estimates

Consistent with previous hydropower resource assessments (Kao et al. 2014; Reclamation 2011; DOI 2007), the following equations were used to estimate the potential hydroelectric power P (W) and energy E (W * h) that may be produced with net hydraulic head H_{net} (ft) and turbine flow Q_{tur} (ft^3/s) at each site:

$$P = c * \gamma * \eta * H_{net} * Q_{tur} \ , \tag{1}$$

$$E = P * T \ . \tag{2}$$

In Eqs. (1) and (2), η is the generating efficiency, γ = 9,800 N/m^3 is the specific weight of water, c = (0.3048)^4 m/ft is the unit conversion factor, and T is the total amount of time (h) for which a conduit hydropower plant is operated (annually or seasonally). For hydropower resource assessments, turbines and systems are usually designed for the optimal operating point; therefore, η = 0.85 can be reasonably assumed (e.g., USACE 1983). However, given that the size of a conduit project is generally smaller than other conventional hydro projects, this 0.85 efficiency may not be easily achieved. This assumption of efficiency should be further examined in future assessments by identifying a most representative value from commonly used conduit hydropower turbines.

Another important variable that is needed to evaluate the potential of conduit hydropower is capacity factor C_f. Capacity factor is the proportion of hours per year that a turbine-generator is operated compared with the total number of hours in 1 year. It can be defined as

$$C_f = \frac{E}{P*365*24} = \frac{T}{365*24} \ . \tag{3}$$

In general, the value of C_f varies depending on the nature and economics of the project (e.g., peaking vs. conduit). Based on Kao and Johnson (2018) and Johnson et al. (2020), C_f = 68% was used to estimate the conduit hydropower potential in national PWSs.

2.2.2.2 Net Hydraulic Head Estimates

For open water conduits, the H_{net} is usually estimated by the elevation difference between upstream and downstream locations (i.e., $H_{diff} = Z_{up} - Z_{down}$). However, if the flow is transported through a long, pressurized conduit, an adjustment of head loss h_L is needed:

$$H_{net} = H_{diff} - h_L \, . \quad (4)$$

The total h_L can be further divided into two components: (1) major (frictional) head loss h_f caused by viscous effects in the pipes, and (2) minor head loss occurring in various pipe components. For a straight pipe with conduit length L (ft), the Darcy-Weisbach equation (Morris and Wiggert 1972) is generally used to estimate h_f:

$$h_f = f * \frac{L}{D} * \frac{V^2}{2g} \, , \quad (5)$$

where f is the friction factor, D is the conduit diameter (ft), V is the average velocity (ft/s) within the conduit, and g = 32.2 ft/s^2 is the gravitational constant. The friction factor can be determined from the Moody diagram (Morris and Wiggert 1972) or solved by the following Colebrook formula:

$$\frac{1}{\sqrt{f}} = -2 * log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) , \quad (6)$$

$$Re = \frac{\rho V D}{\mu} \, , \quad (7)$$

where ε is the roughness height (ft) determined by the conduit material, Re is the Reynolds number, ρ = 1.94 slug/ft^3 is the water density, and μ = 2.34 × 10^{-5} lb·s/ft^2 is the dynamic viscosity.

Without the full details for existing conduits (i.e., size, material, spatial distribution), these equations cannot be solved. To overcome this data limitation, the following simplifications were made for conduit hydropower resource evaluation:

- **Gravitational head only (i.e., no pumping)**: This assessment focused only on the gravitational head potential by analyzing the elevation difference and head loss from the PWS source to destination without evaluating the additional head potential generated by pumping. This simplification is needed mainly because of data limitations. Nevertheless, some existing conduit hydropower developments utilize the excess head generated from pumping for energy recovery. Examples include the 32.7 MW Mojave Siphon project within the California Aqueduct (P-14580), as well as other inter-basin water transfer projects. Therefore, there could actually be additional conduit hydropower potential for a PWS with very little or even negative gravitational head compared with that reported in this study.
- **Two-part analysis**: Based on the available geographical location data collected from multiple sources, a two-part analysis is suggested. It includes the following:
  - **Part 1—raw water**: The first part of the analysis focuses on the net hydraulic head from water intake to water treatment plant. The authors calculated the direct distance from intake to treatment plant as L, found the elevations of these locations in NED, and used the information in Eqs. (1) – (7) to calculate H_{net}.
  - **Part 2—finished water**: The second part of the analysis focuses on the net hydraulic head from the water treatment plant to the main service city/county. The direct distance from the water treatment plant to the city center was calculated as L, the polygon of the city was overlapped with

NED to calculate the average elevation of the city, and the information in Eqs. (1)–(7) was used to calculate H_{net}.

- **Conduit material**: The conduit material was assumed to be commonly used commercial steel with roughness ε = 0.00015 ft. The effects of this assumption were further evaluated in a model sensitivity analysis in Section 3.5.
- **Conduit velocity**: After some previous HREA applications with available average conduit flows and velocity information (e.g., 1.6–2.5 ft/s in CD13-6 Bear Creek Hydroelectric Project) were reviewed, the mean annual conduit flow velocity V = 2 ft/s was selected. With the assumed conduit velocity and PWS flow information (derived from USGS water use information discussed in the following section), the corresponding conduit cross-section area, diameter, and friction factor were calculated, as well as frictional head loss from Eqs. (1)–(7).
- **Total head loss**: Without the actual distribution of all conduits, the actual conduit length and all possible minor losses are unknown. To avoid significantly underestimating the total head loss, the following equation was used to approximate head loss:

$$h_L = 2 * h_f \ . \tag{8}$$

  In other words, another straight-line frictional loss is used to account for all possible minor losses, as well as the true non-straight length of the conduit. With this approach, one main factor controlling head loss will be L in Eq. (5). If the distance between the intake and the treatment plant is very small, the head loss term will be close to zero; and hence, the net hydraulic head will be the simple elevation difference between upstream and downstream locations (i.e., $H_{net} = H_{diff}$). The effect of head loss will become more significant with increasing L. The effects of this assumption were further evaluated in a model sensitivity analysis in Section 3.5.

2.2.2.3 Flow Estimates

As stated, in the absence of national water treatment plant capacity data, the USGS water use estimates (Dieter et al. 2018) and PWS service population were used to derive an approximation. First, the units from Dieter et al. (2018) were converted from gallons per day to cubic feet per second. The estimated water treatment plant capacity Q_{PWS} (ft^3/s) can be expressed as

$$Q_{PWS} = Q_{DO} + Q_{IC} = S * (q_{DO} + q_{IC}) \ , \tag{9}$$

where S is the total service population from SDWIS, Q_{DO} (ft^3/s) is the deliveries for domestic water supply, Q_{IC} (ft^3/s) is the deliveries for industrial/commercial water supply, and q_{DO} (ft^3/s/person) and q_{IC} (ft^3/s/person) are the per capita domestic and industrial/commercial water use, respectively. Since Dieter et al. (2018) provided q_{DO} for each county, q_{DO} was determined from the same county where each PWS is located. q_{IC} was further estimated at each county by

$$q_{IC} = \frac{(Q_{county\_withdrawl} - Q_{county\_DO\_supply} - 0.16 * Q_{county\_withdrawl})}{S} \ , \tag{10}$$

where $Q_{county\_withdrawl}$ is the total water withdrawals for public supply, and $Q_{county\_DO\_supply}$ is the total domestic delivery from public supply at each county from Dieter et al. (2018). The $0.16 * Q_{county\_withdrawl}$ term in Eq. (10) assumed that an average 16% of total withdrawal is lost during treatment and delivery (EPA 2013). Therefore, the numerator in Eq. (10) represents the total public supply for industrial/commercial users at each county. Overall, Q_{PWS} represents the mean annual total water treatment plant capacity. Seasonal, monthly, weekly, and/or diurnal variability can be expected.

The next factors are how much of the flow can be used for conduit hydropower generation, as well as how to determine Q_{tur} from Q_{PWS}. Given that the intention is to understand the maximum potential of a PWS, all PWS flow was assumed to be able to pass through the conduit hydropower turbine. Considering that PWS conduit hydropower projects are developed by placing conduit hydropower turbines in parallel with an existing PRV, without constructing further bypassing structures, this assumption is reasonable. With this assumption, the relationship between Q_{tur} and Q_{PWS} becomes

$$Q_{tur} = \frac{Q_{PWS}}{n * C_f}, \tag{11}$$

where n represents the number of total intakes (with available information from the state/EPA) of a PWS, or the number of targeted service areas (from the TIGER data set). After the capacity and energy are calculated by Eqs. (1) and (2), P and E are further multiplied by ratio $\frac{Q_{DO}}{Q_{PWS}}$ to calculate conduit hydropower potentials in the municipal sector, and by ratio $\frac{Q_{IC}}{Q_{PWS}}$ in the industrial sector.

In addition, water treatment plants are typically designed not only to satisfy the current public water demand but also to have reserve capacity and capacity to address growth in demand. The existence of this additional capacity that will likely be utilized in the future presents an opportunity for conduit generation growth. Although the data to quantify such growth are not available, this additional opportunity is recognized.

2.2.2.4 Assessment Procedure

The overall assessment procedure is illustrated in Figure 4. This assessment was conducted for all PWSs with available data (in particular, intake and water treatment locations). Additional quality assurance and quality control (QA/QC) checks were also conducted to remove PWSs with obviously erroneous intake locations (e.g., the intake to treatment plant connection spanning across a long distance and across other PWSs). All results are summarized and discussed in Section 3.

2.3 IRRIGATION CANAL SYSTEM

Motivated by Reclamation (2012), the authors designed an approach to (a) systematically identify national canal drop sites (that were not included by Reclamation [2011, 2012]) through remote sensing imagery and feature detection techniques, and to (b) estimate conduit hydropower potential at each canal drop location based on assumed canal geometry. The approach was applied in all 17 western states in Reclamation's area of operation (Arizona, California, Colorado, Idaho, Kansas, Montana, North Dakota, Nebraska, New Mexico, Nevada, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming) that heavily rely on irrigation. Although similar sites likely also exist in other states, they were not estimated in this study given the project scope and resource limitations. The uncounted potential is further discussed in Section 4.2.

2.3.1 Data Sources

A broad suite of remotely sensed imagery and georeferenced hydrographic data was used to identify potential conduit hydropower locations in irrigation canal systems and their characteristics. Although detailed canal characteristics (e.g., canal geometry, gauged records of flow rates in canals) should be known to each irrigation district, the information has not been comprehensively documented at the regional and national scales. Therefore, alternative data sources (summarized in Table 3) with national coverage were identified to enable systematic identification and evaluation of conduit hydropower across the western states.

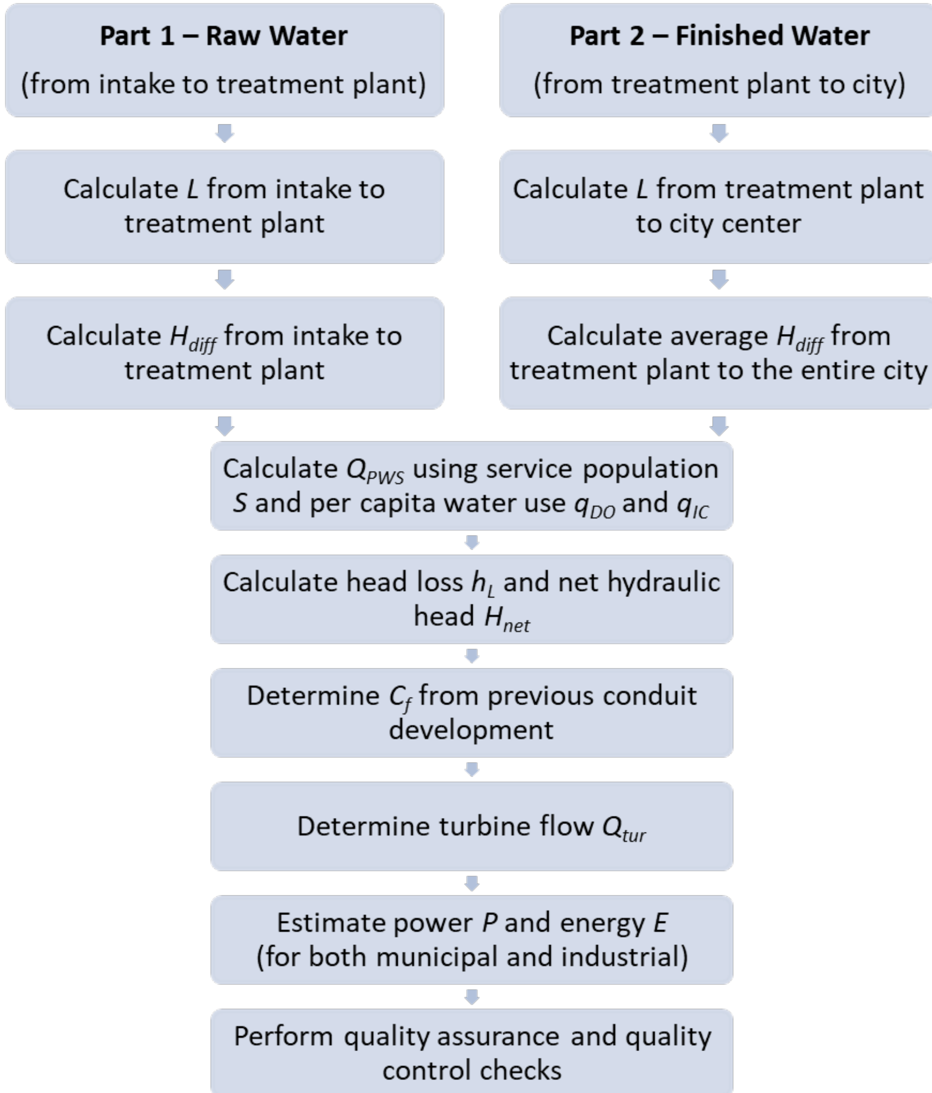


Figure 4. PWS assessment procedure

- **Known canal drop locations**: Locations of known canal drops in agricultural irrigation systems were required for training and validating a drop-detection model. The research team utilized canal drop sites identified by Reclamation (2012) in Reclamation-owned canals, and other known sites.
- **Aerial and satellite imagery**: Remotely sensed imagery data support detection of canal drop features and enable estimates of canal characteristics. Tiles of imagery were obtained from the National Agricultural Imaging Program (NAIP), which provides nearly comprehensive coverage for the continental United States every 2–3 years at less than 1 m spatial resolution. This NAIP imagery provides a digital record of surface reflectance in the red, green, blue, and sometimes near-infrared wavelength ranges (also called *bands* or *channels*). Imagery from the Sentinel-2 satellite was also obtained, providing time-series (with a 14-day revisit time) of surface reflectance data. Sentinel-2 contains a multi-spectral imaging platform with 13 bands spanning the visible to short-wave infrared range. Spatial resolution of the bands varies; bands used in this analysis include the green and near-infrared bands, which both have 10 m resolution.

- **Digital elevation**: In addition to NED being used in the PWS assessment (Section 2.2), high-resolution elevation data were obtained from Terrain-RGB layers from Mapbox. These data provide high-resolution (0.1 m increment in the vertical direction) elevation information across the globe.

Table 3. Summary of data used in the agricultural analysis

Data type	Data source	Reference/website
Known canal drop location	Reclamation 2011 and 2012 Canal Resource Assessment Other sites known by the research team	Reclamation (2011, 2012)
Aerial and satellite imagery	NAIP Sentinel-2	https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/ https://sentinel.esa.int/web/sentinel/missions/sentinel-2
Digital elevation	USGS National Elevation Dataset (NED) Mapbox Terrain-RGB	https://apps.nationalmap.gov/datasets https://docs.mapbox.com/help/getting-started/mapbox-data/#mapbox-terrain-rgb
Flow line	USGS NHDPlus High Resolution	https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution
Existing hydropower asset	ORNL HydroSource EHA Dataset	https://hydrosource.ornl.gov/dataset/existing-hydropower-assets-eha-2020
County boundary	TIGER Dataset	https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

- **Flow lines**: The detection of drops along canals requires knowledge of where canals are located. Candidate flow lines to search for drops were obtained from the USGS NHDPlus High Resolution. Only those identified as artificial waterways were considered possible canals.
- **Existing hydropower assets**: During the QA/QC process, the identified canal drop sites were compared with the EHA (Johnson et al. 2020) data set used in the PWS assessment (Section 2.2). If a canal drop location has received either a FERC exemption (through the FPA or HREA) or a Reclamation LOPP, it is considered a known site and was excluded from further analysis.

2.3.2 Drop Detection

An existing commercial drop-detection model developed by Upstream Tech was used to identify national canal drop locations. This machine learning–driven drop-detection model was developed based on a pre-trained general object detection algorithm (i.e., not focused specifically on canal drops) using the TensorFlow Object Detection API framework. The algorithm is a convolutional neural network that consists of connections between inputs, outputs, and a series of weights assigned to each neural connection. The inputs to the drop-detection model are aerial imagery, and the outputs are bounding boxes around the detected drop locations. The most recent NAIP imagery acquired in 2018 provided relatively up-to-date representations of existing agricultural irrigation infrastructures. Imagery tiles were limited to those within 100 m from flow lines identified by the NHDPlus database as artificial waterways to avoid unnecessary search outside of existing canals.

In a typical neural network model, the network is made of relationships between inputs, a series of layers with nodes (also called neurons), and outputs (predicted values). The neurons accept inputs from the previous layer and apply weights, calculate a bias, and then pass an output to the next layer until the model has transformed raw inputs into a desired output. The number of layers and ways neurons are connected is determined by the designer of the network, and the weights and biases are determined by training data (i.e., pixels with corresponding expected values). Convolutional neural network models are particularly useful in imagery and object detection applications because they assume that information contained in one pixel can inform weights and connections between nodes that connect to nearby pixels.

Training data for the drop-detection model consisted of pairing NAIP imagery with drop locations from Reclamation (2012) and other known sites. As known drop locations were input into the model during the training phase, values for the weights were fine-tuned to evaluate the likelihood that a particular location contains a drop and to approximate a bounding box around the drop. During a proof-of-concept analysis for canal drop sites in Colorado, at least 85% of drops in the training set correctly identified. Only drops >0.6 m (approximately 2 ft) were considered as outputs of the model. Finally, a post-processing step was applied to the predicted bounding boxes. For cases in which flow lines spanned multiple tiles, which resulted in detection of adjacent drops, a geospatial union operator was applied to connect drops into a single drop feature. Point locations for the drops were approximated from the centroids of these polygons. The identified locations were further examined during a QA/QC process to ensure that the drops were reasonably identified (see Section 2.3.3.4). This included cross referencing spatial distribution of drop sites with known agricultural regions in the west to ensure no regions were being systematically omitted by the model.

Although this approach may help detect the typical canal drop sites that are fully visible in remotely sensed imagery, it cannot identify "hybrid" canal sites that combine canal drops and underground conduits for water transport. To identify these hybrid sites, further collaboration with canal owners or irrigation districts would be required. The uncounted potential is further discussed in Section 4.2. This approach may also identify drop sites located in the inter-basin water transfer aqueducts. Strictly speaking, these aqueducts were used for general water supply, not just for irrigation. However, they are also considered as part of the agricultural conduit hydropower potential since their potential is not accounted for in other parts of this assessment.

2.3.3 Canal Drop Hydropower Model

The hydropower potential in an agricultural canal drop location is also controlled by both head and flow, but it has some fundamental differences from the hydropower potential in a PWS (Section 2.2). The different approaches and assumptions are described in this section. Similarly, the effects of these assumptions were further evaluated in a model sensitivity analysis.

2.3.3.1 Power and Energy Estimates

The potential conduit capacity and energy at individual canal drop locations were estimated following the same Eqs. (1) and (2) used in the PWS assessment (Section 2.2). A notable departure in assumptions from other conduit cases (municipal and industrial) is the lower assumed efficiency for canal projects owing to the typically lower heads. The low-head sites in Reclamation (2012) were hence reviewed, and a 0.72 efficiency η value was selected to calculate capacity and energy at identified canal drop locations. Another main difference of the canal projects is the seasonal variability of flow, which affects the calculation of C_f (Eq. 3). Instead of a prescribed C_f, remote sensing images were used to estimate the duration of canal operation (i.e., the fraction of a year when water flows in the canal). The method is described in Section 2.3.3.3.

2.3.3.2 Net Hydraulic Head Estimates

To estimate the hydraulic head at the drop locations, changes in elevation were estimated from the Terrain-RGB data. The drop height was calculated by subtracting the minimum elevation from the maximum elevation within each drop's bounding box around the detected drop locations. Additional losses in hydraulic head were considered negligible compared with uncertainties in elevation estimations. The estimated head H_{net} was further examined during the QA/QC process. In a few cases, head was recalculated with NED manually.

2.3.3.3 Flow Estimates

Although measured flow was used by Reclamation (2012) to estimate canal conduit hydropower potentials, it cannot be comprehensively collected in this study given the broad geographical scope and limited resources. As an alternative, canal flow capacity was estimated as a proxy based on simplified canal geometry. Several characteristics are fundamental to estimate flow capacity in a canal, including the overall geometric shape (top width W, bottom width B, depth d, and side slope z_0) and slope of the canal (S_0). Following the Reclamation Canal Design Standard (Aisenbrey et al. 1978), a simplified canal shape was used to estimate flow capacity, assuming $B = 2 * d$ and $z_0 = 1.5$. Water depth $h = 0.7 * d$ was assumed for the calculation of flow. An illustration of the geometry is shown in Figure 5. These assumptions were further examined in the model sensitivity analysis.

Among these parameters, the top canal width W (ft) is estimated through NAIP imageries. An algorithm is applied to identify pixels with a high confidence of water present in the canal. Several indices using bands (also called *channels*) of multi-spectral remote sensing data are commonly employed to identify water from other surfaces (e.g., land, ice/snow), including the Normalized Difference Water Index (NDWI; McFeeters 1996). The NDWI was determined using NAIP imagery and was applied as a mask so that only the pixels above the NDWI threshold were retained. For canal width estimation, a threshold of 0.4 was found empirically to separate water and land most reliably in the NAIP-based NDWI and was used in this step. The NHDPlus flow line was assumed to run generally parallel through the center of the canal, so width could be estimated by measuring the width of the non-masked water pixels perpendicular to the flow line. The calculation of NDWI used is as follows:

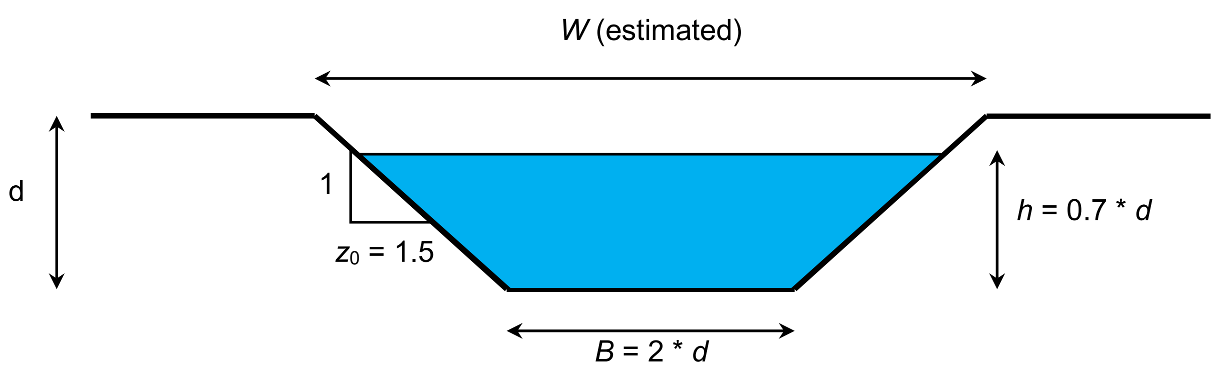


Figure 5. Simplified canal geometry.

$$NDWI = \frac{Green - NearInfrared}{Green + NearInfrared}, \quad (12)$$

where *Green* is the reflectance (percentage of incident radiant flux that is reflected and detected by the remote sensing instrument) in the green band of remotely sensed imagery, and *NearInfrared* is the reflectance in the near-infrared band. The NDWI effectively separates pixels with water from those surrounding the canal. After W was estimated, it was used to calculate other canal geometric characteristics and also the wetted perimeter P (ft), area A (ft^2), and hydraulic radius $R = A / P$ (ft).

In addition to canal width, the canal slope of each identified location was estimated (during the manual QA/QC process). At each canal drop location, a segment of canal was digitized using the geographical information system software, and the digitalized segment was overlapped with NED to estimate elevation change, segment length, and average slope S_0. With these inputs, Manning's equation was used to estimate flow velocity V (ft/s) and discharge Q (ft^3/s):

$$V = \frac{1.49}{n} R^{2/3} {S_0}^{1/2} , \tag{13}$$

$$Q = V * A , \tag{14}$$

where n is Manning's roughness coefficient, which is governed by the material of the canal. In this study, $n = 0.014$ was selected as typical for unfinished concrete canals. To avoid unreasonably large flow estimates (that can be caused by inaccurate slope estimates and other theoretical limitations), a maximum velocity $V = 6.56$ ft/s (2 m/s) was set up. During the manual QA/QC process, neighboring drop locations located in the same canal were identified. To maintain the consistency of flow within each group, the median flow of each drop group was calculated as Q_{tur} in Eq. (1) for all drops in the group. An example of these grouped canal locations is shown in Figure 6. Many of these assumptions were further evaluated in the model sensitivity analysis to understand their effects on the overall findings.

In addition to the flow rate, the duration of flow (length of time when water flows in the canal) is also needed. Similar to the calculation of NDWI for detecting canal width, a time series of NDWI was estimated using Sentinel-2 data from 2018 to 2020. Sentinel-2 images are collected every 14 days with a 10 m spatial resolution. The time series is necessary to capture the number of months when water flows in the canal. The width of canals is generally larger than 10 m, so the resolution is adequate for detecting at least one water pixel if water is flowing at that time. A water mask was applied to the bounding boxes of canal drop locations; pixels were identified as water or non-water based on a threshold of -0.2 Sentinel-2 NDWI. A lower, more sensitive Sentinel-2 NDWI threshold was used for months of flow estimation because of sensor sensitivity differences between NAIP and Sentinel-2 and to detect water in canals that only partially covered a single 10 m Sentinel-2 pixel. This threshold was validated against available canal flow data across multiple regions of the study area. For a given month, if the average NDWI values within the bounding box were above the threshold, then water was assumed to flow in the canal. After the average number of months was estimated, it was further converted to hours and used in Eqs. (2) and (3) to calculate E and C_f at each canal drop location. For grouped neighboring canal drops, the median approach used for the magnitude of flow was also applied for the duration of flow.

Figure 6. An example of neighboring canal drop locations (yellow dots).

2.3.3.4 Assessment Procedure

The overall assessment procedure is illustrated in Figure 7. This assessment was conducted in all 17 western states in Reclamation's area of operation (Arizona, California, Colorado, Idaho, Kansas, Montana, North Dakota, Nebraska, New Mexico, Nevada, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming). Additional QA/QC checks were conducted to review all identified canal drop sites. The QA/QC steps include the following:

- **Check if an identified site is located within an irrigation canal**: In some cases, a site within a natural stream may be erroneously identified, and the hydropower potential should have been captured in other hydropower resource assessments such as NPD (Hadjerioua et al. 2012) and new stream-reach development (Kao et al. 2014). These sites were removed from further evaluation.
- **Correct unreasonably large width and head**: All sites with large width (greater than 50 ft [15.2 m]) and head (20 ft [6.1 m]) estimates were further reviewed. For instance, the original width estimates of some sites were over 100 ft, which is very unlikely for irrigation canals. Although this procedure cannot ensure perfectly accurate width and head at all sites, it can avoid large overestimation of conduit hydropower potential in the final estimate.

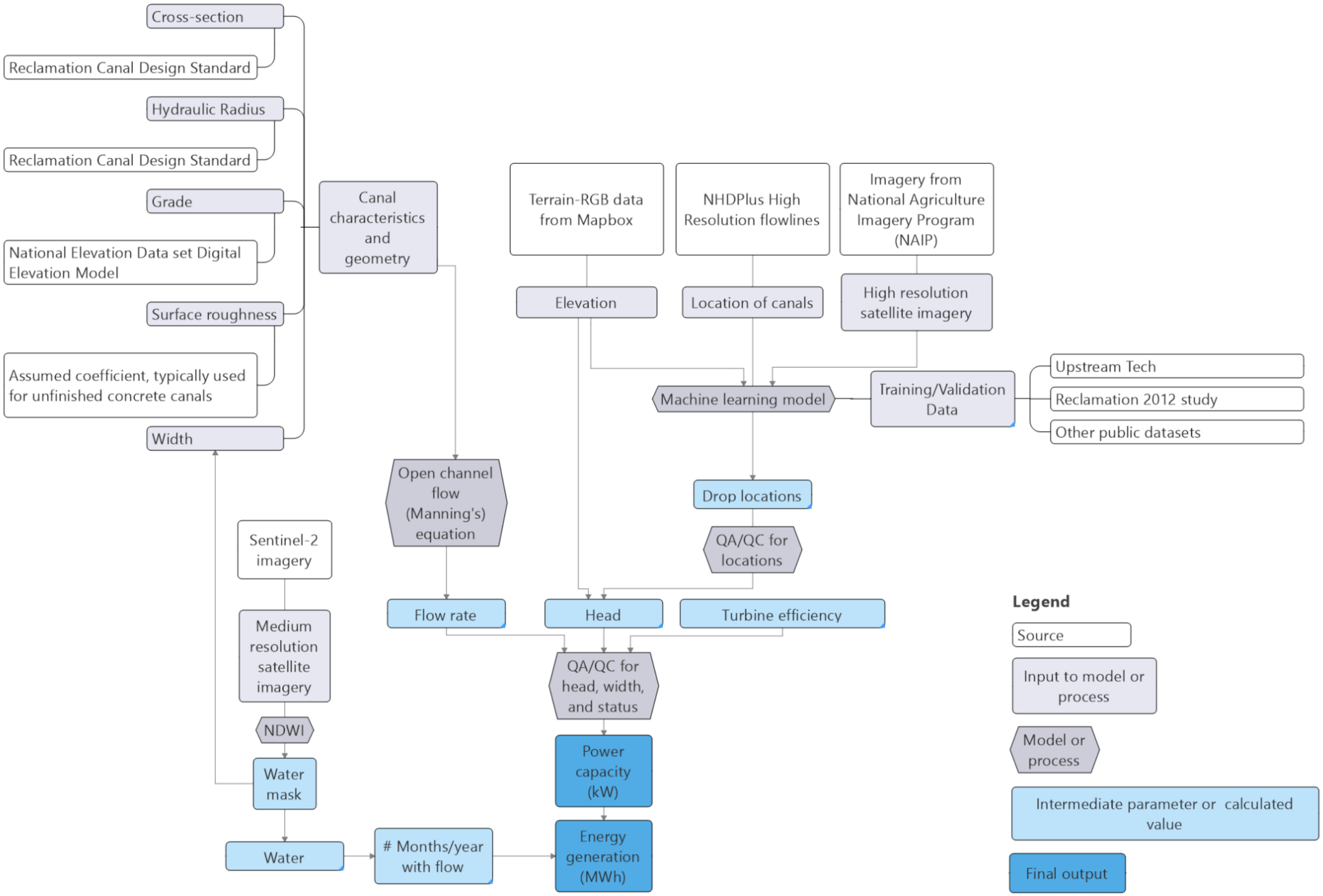


Figure 7. Diagram of irrigation canal assessment procedures.

- **Remove locations that have received FERC exemptions, Reclamation LOPP permits**: All sites were overlapped with the EHA data set (Johnson et al. 2020) to remove sites that have received FERC exemptions or Reclamation LOPP permits.
- **Treatment of sites reported by Reclamation (2011, 2012)**: Since Reclamation sites have been used to train the canal drop-detection model, they were considered as the known ground truth and were not reevaluated in this study. However, because many Reclamation (2011, 2012) sites have not been developed, they are still an important part of the undeveloped national conduit hydropower resource potential. Therefore, the undeveloped conduit sites from Reclamation (2011, 2012) were included in the final regional and national totals, in addition to the new potential identified in this study. All results are summarized and discussed in Section 3.

While the method can be used to estimate the potential capacity and generation at each canal drop, there could be other site-specific limitations that cannot be captured in this study. For instance, the tailwater height may change depending on the downstream flow conditions and may affect the available net head. These site-specific limitations should be clearly understood before proposing new projects at these locations.

In addition, given the crucial role of these canals to supply water for irrigation, the construction of any new conduit hydropower project should not affect the original mission of these canals. In theory, a temporary diversion could be constructed, but that is impractical at the scale of most of these schemes. The installation must also be designed such that if the equipment breaks or otherwise needs to be shut down, the delivery of irrigation water is unaffected. The developers need to work closely with canal owners/users to identify suitable timeline and alternatives to make the development practical and feasible

2.4 THERMOELECTRIC COOLING SYSTEM

Water withdrawals associated with the generation of thermoelectric power account for the greatest percentage of US water withdrawals in any sector. The primary demand for water within a thermoelectric power plant is for condensing steam. Thermoelectric power generation typically converts the energy in a fuel source (fossil, nuclear, or biomass) to a steam and then uses the steam to power a turbine generator. After the steam is exhausted from the turbine, it is condensed and recycled for use in steam production again. Because the condensate must be cooled as much as possible to reduce back pressure on the turbine, recycling the steam is a critical process in the efficiency of the plant.

Opportunities for conduit hydropower may exist at drop locations in the discharge canals in thermoelectric facilities. In general, cooling water is pumped from the water source into the plant intake and discharged by gravity. Therefore, if there is a large elevation difference between a discharge outlet and the receiving waterway, conduit hydropower potential may exist in the discharge canals. The authors are not aware of any existing projects in the United States, but there are two examples in Europe—the Skawina Thermoelectric Project in Poland (1.5 MW) and the Sangüesa Biomass Cooling Tower in Spain (75 kW). To estimate the comparable opportunities in the United States, an approach was designed to evaluate thermoelectric plants with the highest cooling water withdrawals. The focus was limited to the discharge canals, although in some cases, there may also be large elevation drop and potential in the intake canals if cooling water is supplied by gravity.

2.4.1 Data Sources

The data sets used to support the estimate of conduit hydropower potential in US thermoelectric power systems are summarized in Table 4. They include the following:

- **Thermoelectric plant information**: Information about US thermoelectric power plants was obtained from the EIA Form 860 data set. EIA collects, analyzes, and disseminates independent and impartial energy information across all generation technologies. The unique power plant code, plant generating capacity, generator technology, and location (in latitude and longitude) were included in the study data set. Other characteristics of the power plants are included in the data but were not pertinent to the study, such as power plant owner and address.
- **Water discharge amount and location**: The EIA thermoelectric cooling water data make up a separate database that reports water withdrawal and water consumption volumes in million gallons per day per unit annually. Based on the EIA info, the total amount of withdrawals in 2018 across all 847 thermoelectric power plants was 147,500 MGD, largely consistent with the 2015 USGS estimate of 133,000 MGD. The database also provides names of cooling water source and discharge water bodies. NHDPlus (as described in Section 2.3) was used to identify the named discharge water bodies.
- **Elevations and aerial photographs**: The power plant and discharge waterbody elevations were manually determined using Google Earth aerial photographs and elevations. Google Earth elevation data come from a variety of sources depending on the regional availability. In areas where lidar data are not available, Google Earth relies on Shuttle Radar Topography Mission data to fill in the gaps. Absolute elevations were not crucial for this study, only the relative elevation difference between nearby locations. Although these elevation data are different from NED used in PWS (Section 2.2) and irrigation canal (Section 2.3) assessments, they yield reasonable head estimates for the purposes of this analysis.

Table 4. Summary of data used in the thermoelectric analysis

Data type	Data source	Reference/website
Thermoelectric plant information	EIA Form 860 Dataset	https://www.eia.gov/electricity/data/eia860/
Annual water withdrawals and consumption	EIA thermoelectric cooling water data	https://www.eia.gov/electricity/data/water/
Discharge water body	USGS NHDPlus	https://nhdplus.com/NHDPlus/
Digital elevation and aerial photographs	Google Earth Pro	https://www.google.com/earth/versions/#earth-pro
County boundary	TIGER Dataset	https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

2.4.2 Thermoelectric Conduit Hydropower Model

Given the lack of site-specific thermoelectric power plant information, a simplified model was used to estimate the overall conduit hydropower potentials focusing on cooling water discharge back to the river system. The two key metrics, head and flow, were estimated using the data described. The assessment was conducted for 186 thermoelectric power plants that make up 95% of the total cooling water withdrawals in the United States.

2.4.2.1 Power and Energy Assumptions

Similar to the PWS assessment, Eqs. (1)–(3) described in Section 2.2.2.1 were used to estimate power and energy. Following the same assumptions used for the PWS assessment (Section 2.2), an η of 85% and C_f of 68% were used. The flow was assumed to be available yearlong without large temporal variation.

Although there can be large spatial variability and different site-specific constraints across these thermoelectric power plants, given the very limited data, these assumptions could not be further refined for the purpose of a national-scale assessment. The main purpose of this study was to estimate the total conduit resources, not the actual feasibility at a specific site. Some of these assumptions were further evaluated in the model sensitivity analysis.

2.4.2.2 Net Hydraulic Head Estimates

The net hydraulic head at each power plant was estimated in a manual process. The aerial photographs and elevation data were used to determine the elevation difference H_{diff} (ft) between the power plant location and the discharge water body. An example is shown in Figure 8. In particular, the location of the discharge outlet was identified. However, without further information, the total head loss h_L (ft) at each site could not feasibly be estimated. Therefore, the authors assumed a uniform 10 ft head loss at each site for the purpose of this analysis (i.e., $H_{net} = H_{diff} - 10$). The 10 ft of head loss was selected to estimate the loss through the physical plant. This value was determined by examining the elevations of representative facilities and estimating the elevation difference between the plant and the discharge immediately exiting the facility. Furthermore, a minimum 10 ft net head requirement was imposed, and conduit hydropower potential was only analyzed for sites with more than 10 ft of net head. Despite the simplicity of this approach, the manual process (i.e., to select representative power plant and discharge locations) was time-consuming. Therefore, this analysis was limited to a subset of thermoelectric plants with top cooling water withdrawals.

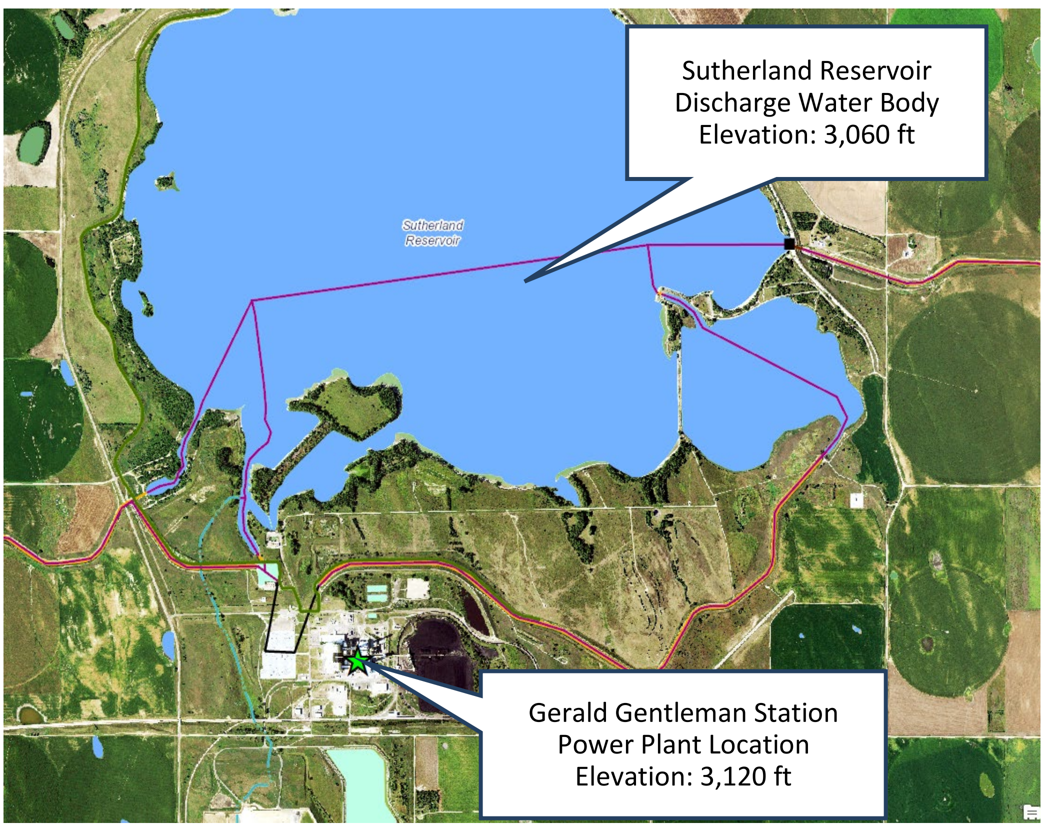


Figure 8. Example of elevations collected for thermoelectric power plants.

2.4.2.3 Flow Estimates

The EIA thermoelectric cooling water data report the annual volume of water withdrawals and water consumption for each unit of the power plants in a spreadsheet. The total annual volume for each power plant was calculated as the sum of all units. The discharge volume was calculated as the difference between the water withdrawals and the water consumption. The turbine flow was then estimated by Eq. (11). Overall, 186 power plants that made up 95% of the total water withdrawals were considered in this assessment.

2.4.2.4 Assessment Procedure

The overall assessment procedure is illustrated in Figure 9. Additional QA/QC checks were also conducted to remove power plants with obviously erroneous location information. All results are summarized and discussed in Section 3.

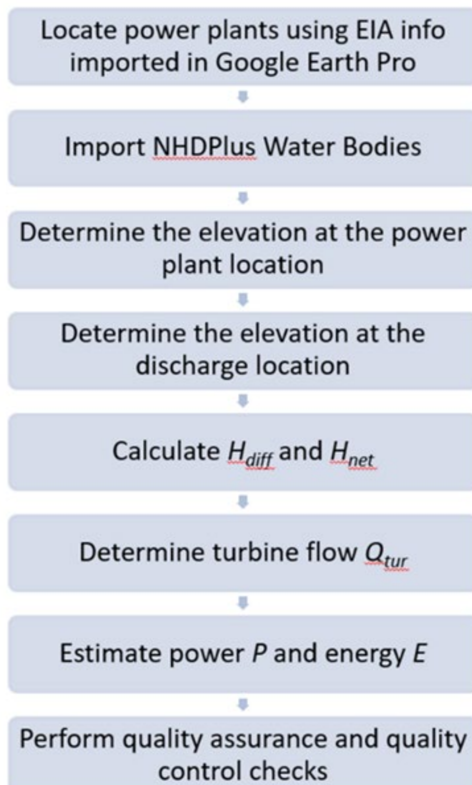


Figure 9. Summary of thermoelectric cooling water assessment procedure.

2.5 WASTEWATER SYSTEM

Municipal and industrial wastewater facilities may consider conduit hydropower generation using the treated or discharged water before returning into a natural waterway. Despite the different water sources (i.e., municipal vs. industrial), the types of discharge conveyances and opportunities for conduit hydropower are similar. The opportunity will only exist where the receiving waterway is at a lower elevation than the discharge point. Two examples of US conduit hydropower on municipal wastewater treatment facilities are Deer Island in Massachusetts (2 MW) and Point Loma in California (1.35 MW); both discharge to the ocean. International examples include facilities in Toronto, Canada (750 kW), Sydney, Australia (4.5 MW), and Yorkshire, United Kingdom (180 kW). These facilities all take advantage of larger than typical drops to the discharge waterways.

2.5.1 Data Sources

The data sets used to support the estimate of conduit hydropower potential in the US wastewater discharges are summarized in Table 5. They include the following:

Wastewater Facility Information

The EPA National Pollutant Discharge Elimination System (NPDES) data set is the main data set used to estimate the conduit hydropower potential for wastewater discharge nationally. The NPDES permit program was created in 1972 by the Clean Water Act. The program regulates point sources that discharge to waters of the United States, including any municipal or industrial/commercial water discharged from a facility or site after treatment, if required. Some existing hydropower plants also have NPDES permits for non-generation related cooling and process water discharges. The NPDES permit program is authorized by EPA to perform many permitting, administrative, and enforcement aspects of the program.

Facilities are permitted through either an individual permit or a general permit that covers multiple dischargers with similar operations and types of discharges. Individual permits are issued directly to an individual discharger. In contrast, a general permit is issued to no one in particular; multiple dischargers obtain coverage under that general permit after it is issued, consistent with the permit eligibility and authorization provisions.

The NPDES ECHO (Enforcement and Compliance History Online) database provided the facility latitude and longitude, standard industrial classification code, annual flow estimates, and other information about each facility. Three flows are reported—the total facility design flow, actual average facility flow, and total facility flow. Data reported in 2019 were used in this study.

NPDES Flow Estimates

Conduit hydropower potential was only considered for individual NPDES permits that reported annual discharge volumes (discussed further in Section 2.5.2.3). Discharges from irrigation return and thermoelectric power plants were removed from this analysis to avoid double counting (as estimated in Sections 2.3 and 3). Sewage treatment facilities, or POTWs, were analyzed similarly to industrial facilities. The estimated conduit hydropower potentials were allocated to municipal or industrial sectors.

NPDES Head Estimates

The NPDES program collects specific information for the facility outfalls, including location.[6] Submitting outfall information was optional until the electronic reporting rule went into effect in 2017. The initial available data were published in mid-2020 but were limited to a few thousand sites and will be incomplete until all facility permits are renewed (on a 5-year cycle) and the database is updated. This database could provide site-specific information regarding head by comparing the outfall elevation with the receiving waterway elevation. However, because these data are unavailable on a national level, generalized assumptions were made regarding the available head. The more detailed NPDES data have potential for future site-specific applications.

[6] https://echo.epa.gov/tools/data-downloads/icis-npdes-discharge-points-download-summary

Table 5. Summary of data used in the wastewater analysis

Data type	Data source	Reference/website
Wastewater facility information	NPDES Dataset	https://echo.epa.gov/trends/loading-tool/get-data/custom-search/
County boundary	TIGER Dataset	https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

2.5.2 Wastewater Conduit Hydropower Model

Although NPDES ECHO provided much useful information about US wastewater discharges, it does not provide all desired information for the estimation of conduit hydropower potential (in particular, hydraulic head). With the data limitations in mind, a simplified model was used to estimate the conduit hydropower potential, focusing on the discharge of wastewater. The assessment was conducted for almost 32,000 discharge facilities with available information.

2.5.2.1 Power and Energy Assumptions

Similar to the PWS and thermoelectric assessments, Eqs. (1)–(3) described in Section 2.2.2.1 were used to estimate power and energy. Following the same assumptions used for the PWS assessment (Section 2.2), an overall efficiency η = 0.85 and a C_f = 0.68 were used. The flow was assumed to be available yearlong without large temporal variation. Once again, although there can be large spatial variability and different site-specific constraints across national wastewater discharges, given the very limited data, these assumptions could not be further refined for the purpose of a national-scale assessment. Again, the main purpose of this study was to estimate the total conduit resources, not the actual feasibility at a specific site. Some of these assumptions were further evaluated in the model sensitivity analysis.

2.5.2.2 Net Hydraulic Head Estimates

Few assessments of wastewater hydropower potential have been completed in the United States (e.g., Torrey 2011; Allen et al. 2013) and the United Kingdom (Power et al. 2014). These studies provide a set of constructed and potential sites, which are compiled in Figure 10. Several of the constructed examples fall outside of the axes. The range of head and flow is much greater in the examples from the United Kingdom since these sites spanned several countries, whereas the New York examples are all within one state. Considering these results, the Massachusetts (Allen et al. 2013) assumptions, and knowledge of wastewater facility design, the available head was assumed to range between 2 and 10 ft. This conservative assumption was applied across all facilities using an average of 6 ft. Outliers will exist, such as several that have already been developed and fall outside of the axis limits of Figure 10. However, without the support of further site-specific data, this assumption was kept for the purpose of a national-scale resource assessment.

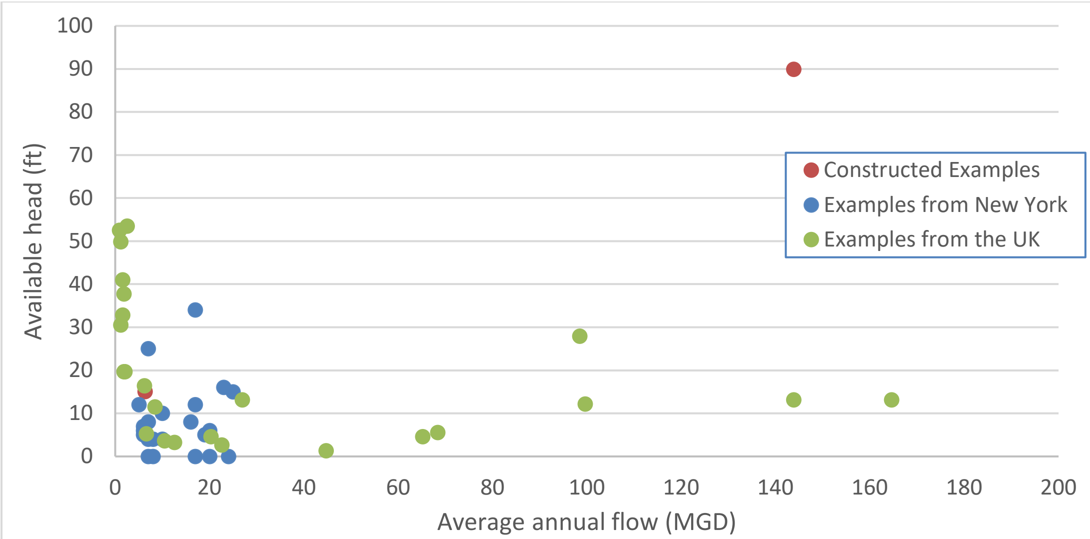


Figure 10. Sampling of potential wastewater site head and flow conditions.

2.5.2.3 Flow Estimates

Permittees report flow to the NPDES program in three possible ways. Total facility design flow (MGD) and actual average facility flow (MGD) are the flows reported on a permit application and do not change year to year. The total facility flow (million gallons per year) is the effluent flow calculated based on monitoring data. Not all facilities report all flows. The minimum of the flows reported was used as the average annual flow rate available for hydropower. The minimum was also chosen to avoid misreported data. A quality control check of the largest flows revealed that some facilities reported flow in the incorrect units (e.g., in gallons per day). By searching for the facility ID in the Pollutant Loading Tool,[7] the correct flow could be confirmed. The turbine flow was later estimated by Eq. (11).

The sewage treatment facilities' annual flow totaled more than 45,000 MGD, while the USGS estimated 42,260 MGD of public supply withdrawals. The remaining industrial discharge totaled just over 27,000 MGD, while the USGS estimated approximately 26,350 MGD of industrial withdrawals. Given the overall consistency between NPDES and USGS data, the authors consider that the NPDES data set provides a reasonable estimation of flow.

2.5.2.4 Assessment Procedure

The overall assessment procedure is illustrated in Figure 11. The authors conducted this assessment for almost 32,000 sites with available information. The authors also conducted further QA/QC checks to remove sites with obviously erroneous location information. All results are summarized and discussed in Section 3.

[7] https://echo.epa.gov/trends/loading-tool/water-pollution-search

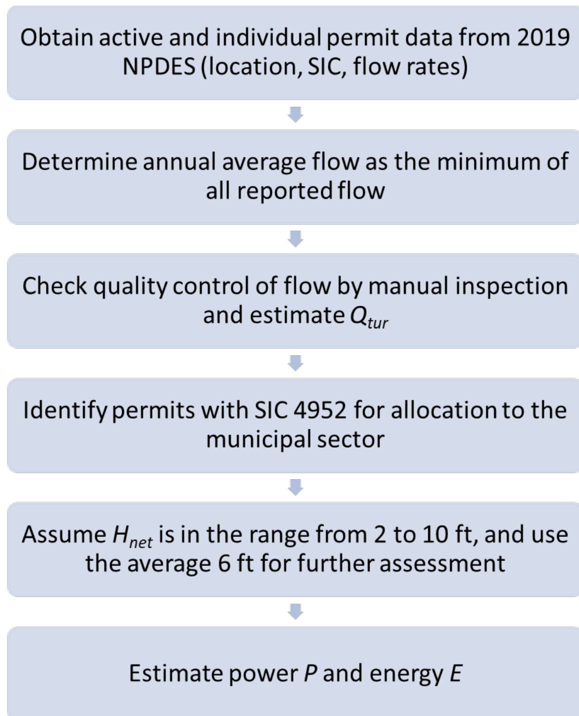


Figure 11. Summary of wastewater assessment procedure.

2.6 SUMMARY OF ASSUMPTIONS AND SIMPLIFICATIONS

Given the data limitations (from either availability or sensitivity perspectives), as well as the main objective of this study (i.e., to inform state/national total conduit hydropower resource estimates), multiple assumptions and simplifications were made in this study. These assumptions are summarized in Table 6.

Table 6. Summary of main assumptions and simplifications of this study

Main assumption/ limitation	Description
	For all systems
Reconnaissance-level assessment	Given the goal to estimate state/national total resource potentials, the proposed method was designed at the reconnaissance level, considering the total technical resources that could be available for development at the state and national scales. Therefore, while the findings may inform as to regions with relatively higher potential, project-specific feasibility assessment is still required to identify actual conduit hydropower sites for development.
Gravitational head only (i.e., no pumping)	Given the data limitations, this assessment focuses only on identifying gravitational head potential without considering the additional excess head generated during pumping. This is a necessary simplification, but it also may lead to underestimation of the full conduit hydropower potential.
Generating efficiency	Following the prior resource assessments, a consistent η = 0.85 was used for all municipal and industrial conduits; η was reduced to 0.72 for all agricultural conduits.
Capacity factor	Based on Kao and Johnson (2018) and Johnson et al. (2020), C_f = 68% was selected in this assessment for all municipal and industrial conduits. For agricultural conduits, C_f was calculated by the number of months water is presented in canals detected by Sentinel-2.
	For public water supply system
Conduit material	The conduit material was assumed to be the commonly used commercial steel with roughness of ε = 0.00015 ft. The sensitivity analysis (Section 3.5) suggested a low sensitivity for this assumption.
Conduit velocity	After reviewing some previous HREA applications with available average conduit flow and velocity information, the authors selected a mean annual conduit flow velocity V = 2 ft/s. With the assumed conduit velocity and PWS flow information, the corresponding conduit cross-section area, diameter, friction factor, and frictional head loss were further calculated.
Total head loss	Without the actual distribution of all conduits, the actual conduit length as well as all possible minor losses are not known. To avoid significantly underestimating the total head loss, two times the frictional head loss (calculated from a straight distance) was used to account for all possible minor losses, as well as the non-straight length of the conduit.
PWS treatment capacity	Given the lack of data for actual water treatment plant capacity at the national scale, the PWS service population (from SDWIS) and county-based publicly supplied per capita water use information (from USGS) were used to approximate the mean annual water treatment capacity of a PWS.
Flow availability	To understand the full PWS conduit hydropower potential, all PWS flow was assumed to be used for generation without possible flow bypass. This is a similar assumption to those used in prior national hydropower resource assessments (e.g., NPD and new stream-reach development). There could be further issues such as how climate change may affect regional water supply and future flow availability, but they were not evaluated in this study.

Table 6. Summary of main assumptions and simplifications of this study (continued)

Main assumption/ limitation	Description
	For irrigation canal system
Remote sensing and feature detection	The proposed remote sensing imagery and feature detection techniques were assumed to help identify most of the canal drop sites in the western states. Although model validation suggested good performance of the canal detection model, further evaluation with local stakeholders is desired. Also, this approach cannot detect the hybrid canal sites that combine both canal drops and underground conduits for water transport.
Canal geometry	Following the Reclamation Canal Design Standard (Aisenbrey et al. 1978), a simplified trapezoidal canal shape was used to estimate flow capacity that assumed the bottom B = 2 * canal depth and side slope z_0 = 1.5. These parameters were further examined in the model sensitivity analysis.
Canal material	The canal material was assumed to be to be unfinished concrete with Manning's roughness of n = 0.014, which is common for irrigational canals used for conduit hydropower generation. These parameters were further examined in the model sensitivity analysis.
Conduit velocity	To avoid unreasonably large flow estimates (that can be caused by inaccurate slope estimates and other theoretical limitations), a maximum velocity V = 6.56 ft/s (2 m/s) was set up.
Canal drop group	During the manual QA/QC process, neighboring drop locations located in the same canal were identified. To maintain the consistency of flow within each group, the median flow of each drop group was calculated as Q_{tur} in Eq. (1).
Flow availability	Time series of NDWI constructed by Sentinel-2 data from 2018 to 2019 were used to estimate the number of months water is presented at canals. There could be further issues such as how climate change may affect regional water supply and future flow availability, but they were not evaluated in this study.
	For thermoelectric cooling system
Conduit opportunities	Opportunities of conduit hydropower may exist at drop locations in the discharge canals within the thermoelectric facilities. Although the authors are not aware of any existing hydropower conduit projects in the United States, there have been successful cases in Europe, which motivated the authors to evaluate the potentials in the United States.
Hydraulic head	The net hydraulic head at each power plant was estimated through a manual process by identifying the elevation differences between at the power plant location and the discharge water body. However, without further information, there is no feasible way to estimate the total head loss at each site. Therefore, a uniform 10 ft head loss at each site was assumed for the purpose of this analysis. A minimum 10 ft head requirement was also set up, and conduit hydropower potential was only analyzed for sites with more than 10 ft head. These parameters were further examined in the model sensitivity analysis.
Flow availability	The discharge volume was calculated as the difference between the water withdrawals and the water consumption reported by EIA. Overall, 186 power plants that made up 95% of the total water withdrawals were considered in this assessment. The average discharge flow rate of these 186 power plants exceeded 240 ft^3/s. The flow was also assumed to be available yearlong without large temporal variation. There could be further issues such as how climate change may affect regional water supply and future flow availability, but they were not evaluated in this study.

Table 6. Summary of main assumptions and simplifications of this study (continued)

Main assumption/ limitation	Description
	For wastewater system
Conduit opportunities	Opportunities of conduit hydropower may exist because of the elevation difference between the facility and the receiving waterway.
Net hydraulic head	Considering data limitations, prior studies, the Massachusetts (Allen et al. 2013) assumptions, and knowledge of wastewater facility design, the available head was assumed to range between 2 and 10 ft. This conservative assumption was applied across all facilities using an average of 6 ft.
Flow availability	The minimum of three flows reported to NPDES (i.e., total facility design flow, actual average facility flow, and monitored effluent flow) was used as the average annual flow rate available for conduit hydropower generation. The flow was assumed to be available yearlong without large temporal variation. There could be further issues such as how climate change may affect regional water supply and future flow availability, but they were not evaluated in this study.

3. RESULTS

The following sections provide sector, national, and sensitivity results based on the approach described in Section 2. Results are further aggregated to state and county levels for discussion.

3.1 MUNICIPAL SECTOR

Municipal conduit hydropower potential is available from public water supply for domestic usage and discharge from domestic wastewater. The state-level capacity and energy generation potential are provided in Table 7, Table 8, and Figure 12. State- and county-level maps of municipal conduit hydropower capacity potential are provided in Figure 13 and Figure 14, respectively.

Table 7. Summary of municipal conduit hydropower capacity potential by state (MW)

State	Public water supply	Wastewater	Total	State	Public water supply	Wastewater	Total
AL	1.33	0.48	1.81	**MT**	1.18	0.08	1.27
AK	0.55	0.06	0.61	**NE**	0.24	0.18	0.43
AZ	9.76	0.34	10.10	**NV**	0.62	0.26	0.88
AR	1.51	0.35	1.86	**NH**	0.26	0.08	0.34
CA	106.98	2.35	109.33	**NJ**	4.05	1.03	5.08
CO	42.57	0.38	42.95	**NM**	1.69	0.09	1.77
CT	2.12	0.39	2.51	**NY**	42.09	2.51	44.60
DE	0.34	0.09	0.44	**NC**	2.12	0.70	2.82
DC	—	0.30	0.30	**ND**	0.03	0.02	0.05
FL	1.13	0.72	1.86	**OH**	1.65	1.92	3.58
GA	1.60	0.75	2.35	**OK**	0.75	0.29	1.04
HI	4.46	0.09	4.55	**OR**	17.60	0.29	17.89
ID	1.81	0.13	1.95	**PA**	9.29	1.66	10.95
IL	0.75	2.47	3.22	**RI**	0.62	0.14	0.76
IN	0.46	0.86	1.32	**SC**	1.37	0.40	1.77
IA	0.23	0.63	0.86	**SD**	0.12	0.03	0.15
KS	0.32	0.27	0.59	**TN**	1.35	0.67	2.02
KY	0.55	0.39	0.95	**TX**	6.02	2.36	8.38
LA	0.31	1.37	1.67	**UT**	33.57	0.13	33.70
ME	0.44	0.09	0.53	**VT**	0.32	0.06	0.37
MD	0.95	0.47	1.42	**VA**	2.69	0.83	3.52
MA	2.18	1.12	3.31	**WA**	22.10	0.16	22.26
MI	0.34	2.37	2.71	**WV**	1.01	0.45	1.46
MN	0.22	0.46	0.68	**WI**	0.15	0.57	0.72
MS	0.39	0.26	0.65	**WY**	3.43	0.07	3.49
MO	1.23	5.40	6.62	**Total**	**336.85**	**37.60**	**374.46**

Table 8. Summary of municipal conduit hydropower energy generation potential by state (GWh/year)

State	Public water supply	Wastewater	Total	State	Public water supply	Wastewater	Total
AL	7.90	2.88	10.79	**MT**	7.03	0.50	7.54
AK	3.30	0.36	3.66	**NE**	1.45	1.09	2.54
AZ	58.13	2.01	60.14	**NV**	3.68	1.56	5.23
AR	9.01	2.09	11.10	**NH**	1.57	0.47	2.03
CA	637.27	14.00	651.27	**NJ**	24.12	6.16	30.27
CO	253.58	2.28	255.86	**NM**	10.05	0.52	10.57
CT	12.61	2.32	14.93	**NY**	250.70	14.98	265.68
DE	2.05	0.55	2.60	**NC**	12.63	4.17	16.79
DC	—	1.78	1.78	**ND**	0.18	0.13	0.31
FL	6.76	4.31	11.06	**OH**	9.85	11.46	21.30
GA	9.53	4.47	14.00	**OK**	4.50	1.70	6.20
HI	26.55	0.56	27.11	**OR**	104.83	1.71	106.55
ID	10.79	0.80	11.59	**PA**	55.36	9.86	65.23
IL	4.49	14.69	19.18	**RI**	3.69	0.82	4.51
IN	2.76	5.13	7.89	**SC**	8.17	2.40	10.57
IA	1.36	3.75	5.11	**SD**	0.71	0.17	0.88
KS	1.88	1.62	3.50	**TN**	8.03	4.01	12.04
KY	3.30	2.34	5.65	**TX**	35.83	14.07	49.90
LA	1.82	8.13	9.95	**UT**	199.97	0.77	200.73
ME	2.61	0.55	3.16	**VT**	1.89	0.34	2.23
MD	5.68	2.77	8.45	**VA**	16.02	4.96	20.98
MA	13.01	6.69	19.70	**WA**	131.67	0.96	132.63
MI	2.01	14.14	16.16	**WV**	5.99	2.70	8.70
MN	1.31	2.76	4.07	**WI**	0.88	3.40	4.28
MS	2.33	1.55	3.88	**WY**	20.41	0.39	20.80
MO	7.30	32.16	39.46	**Total**	**2,006.55**	**224.00**	**2,230.56**

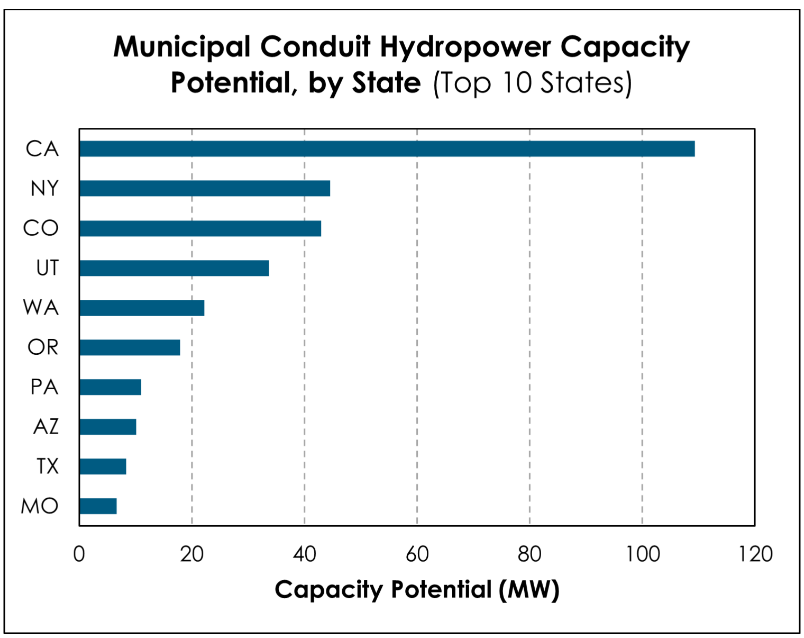


Figure 12. Top 10 states with the highest municipal conduit hydropower capacity potential.

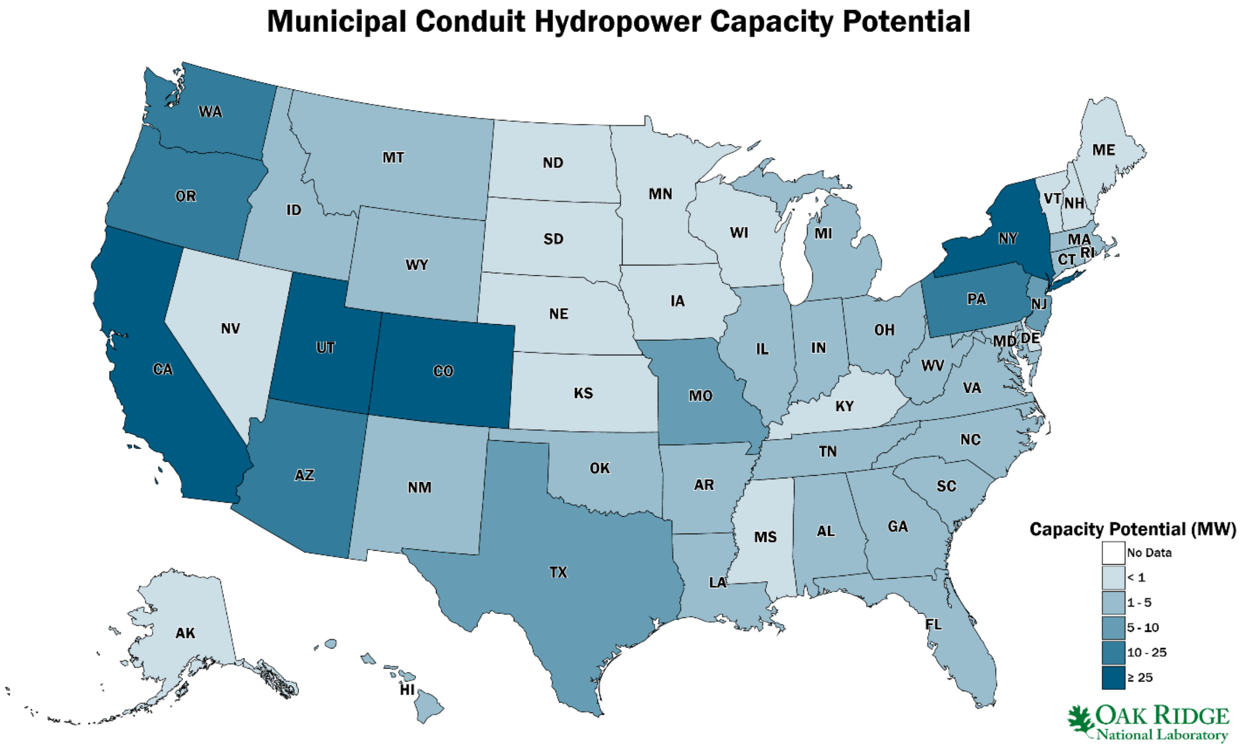


Figure 13. Map of municipal conduit hydropower capacity potential by state.

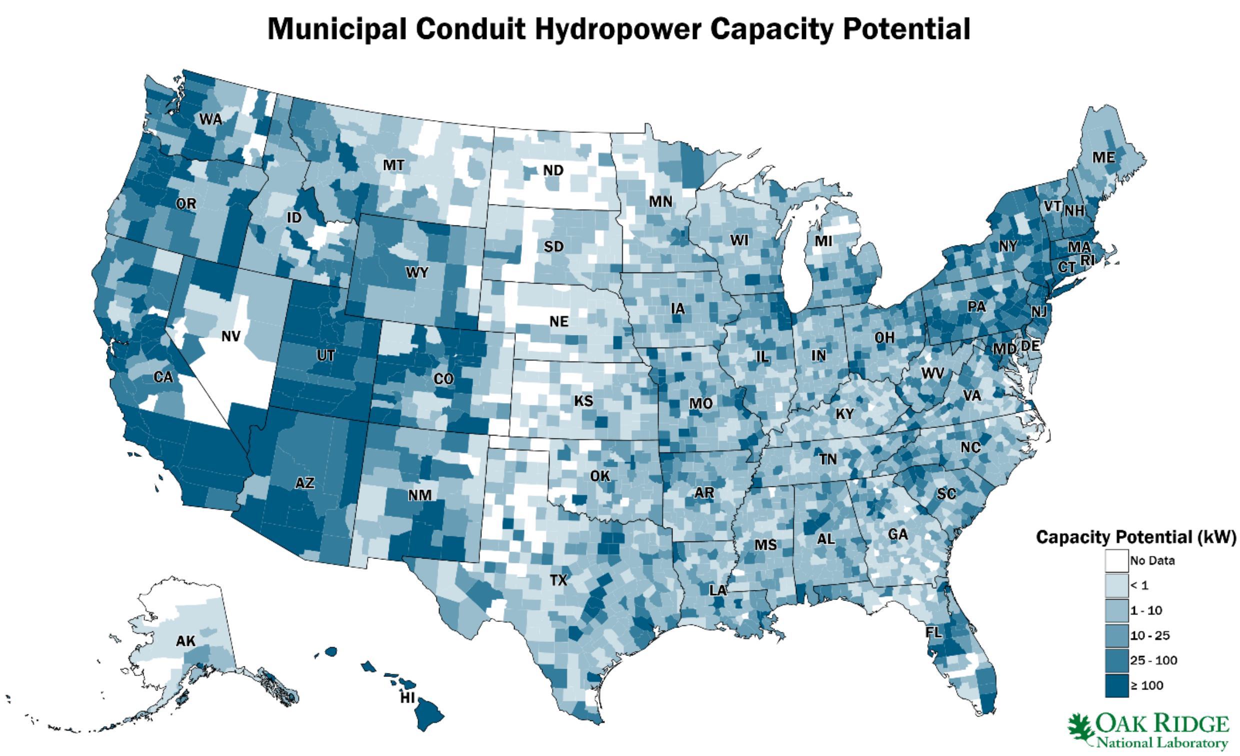


Figure 14. Map of municipal conduit hydropower capacity potential by county.

The total municipal conduit hydropower capacity potential is nearly 374 MW, with 337 MW from public water supply and 37 MW from wastewater. California has more than twice as much resource potential as the state with the next highest potential (New York). In general, states with higher populations and greater elevation differences (i.e., more mountainous terrain) appear to have correspondingly higher capacity potential; this trend is generally visible in the maps in Figure 13 and Figure 14. In terms of subsector potential, public water supply represents a significant majority (90%) of overall municipal capacity potential in the United States, whereas wastewater systems represent a smaller fraction (10%). This difference is mainly due to the different hydraulic head assumptions in public water and wastewater systems (i.e., closed versus open pipelines). Although wastewater represents a smaller overall fraction of national total potential, it can vary sizably across individual states; for example, Illinois, Michigan, and Missouri have a relatively smaller portion of conduit hydropower in water supply.

3.2 AGRICULTURAL SECTOR

Agricultural conduit hydropower resource estimates are available from undeveloped sites reported by Reclamation (2011, 2012), and additional sites and estimates reported by this study (ORNL [2022]). The state-level capacity and energy generation potential are provided in Table 9, Table 10, and Figure 15. State- and county-level maps of agricultural conduit hydropower capacity potential are provided in Figure 16 and Figure 17, respectively. The assessment was only conducted in 17 western states in Reclamation's area of operation. Agricultural conduit hydropower potential may exist in other states but was not evaluated in this study.

Table 9. Summary of agricultural conduit hydropower capacity potential by state (MW)

State	ORNL (2022)	Reclamation (2011 & 2012)	Total	State	ORNL (2022)	Reclamation (2011 & 2012)	Total
AZ	4.30	4.30	8.59	**ND**	0.01	—	0.01
CA	68.43	1.57	70.00	**OK**	0.41	0.02	0.43
CO	118.43	35.16	153.59	**OR**	32.60	18.94	51.54
ID	55.64	2.77	58.41	**SD**	16.85	0.13	16.98
KS	6.07	—	6.07	**TX**	16.51	—	16.51
MT	13.51	18.61	32.13	**UT**	10.73	5.24	15.96
NE	85.74	5.50	91.25	**WA**	93.75	1.05	94.80
NV	0.37	1.53	1.90	**WY**	9.13	25.70	34.83
NM	7.49	1.56	9.05	**Total**	**539.95**	**122.08**	**662.03**

Table 10. Summary of agricultural conduit hydropower energy generation potential by state (GWh/year)

State	ORNL (2022)	Reclamation (2011 & 2012)	Total	State	ORNL (2022)	Reclamation (2011 & 2012)	Total
AZ	35.58	23.14	58.71	**ND**	0.02	—	0.02
CA	546.79	4.80	551.59	**OK**	1.88	0.11	1.99
CO	851.43	141.28	992.71	**OR**	258.41	70.74	329.16
ID	427.49	11.45	438.94	**SD**	126.88	0.57	127.45
KS	40.60	—	40.60	**TX**	123.35	—	123.35
MT	103.29	59.12	162.41	**UT**	82.76	16.48	99.24
NE	636.35	13.79	650.15	**WA**	658.84	2.89	661.73
NV	3.04	8.67	11.71	**WY**	66.24	92.32	158.56
NM	59.84	4.01	63.85	**Total**	**4,022.79**	**449.37**	**4,472.17**

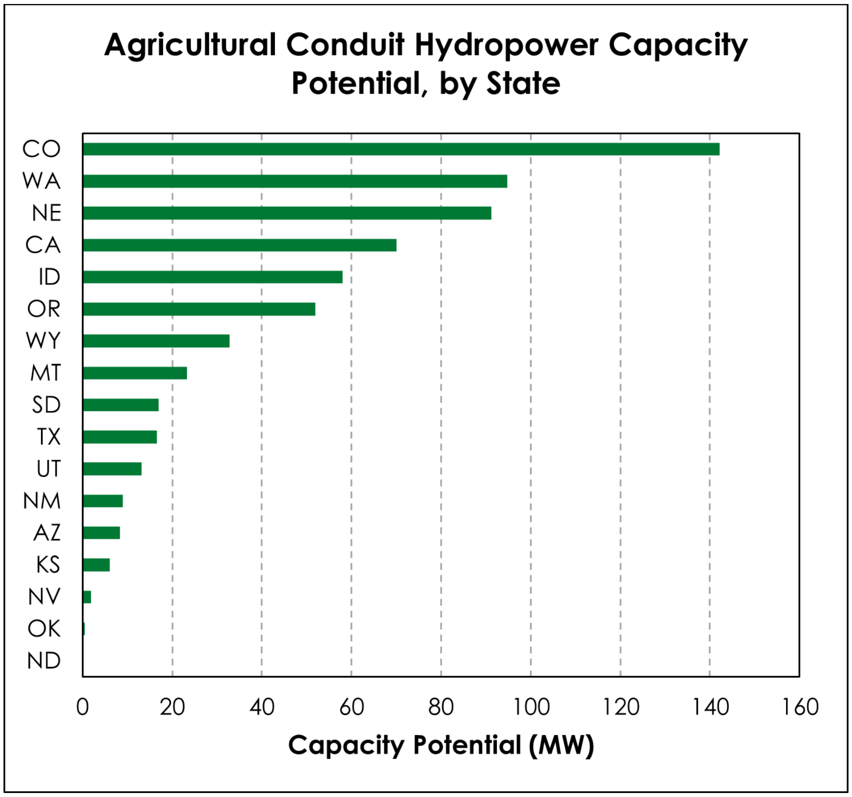
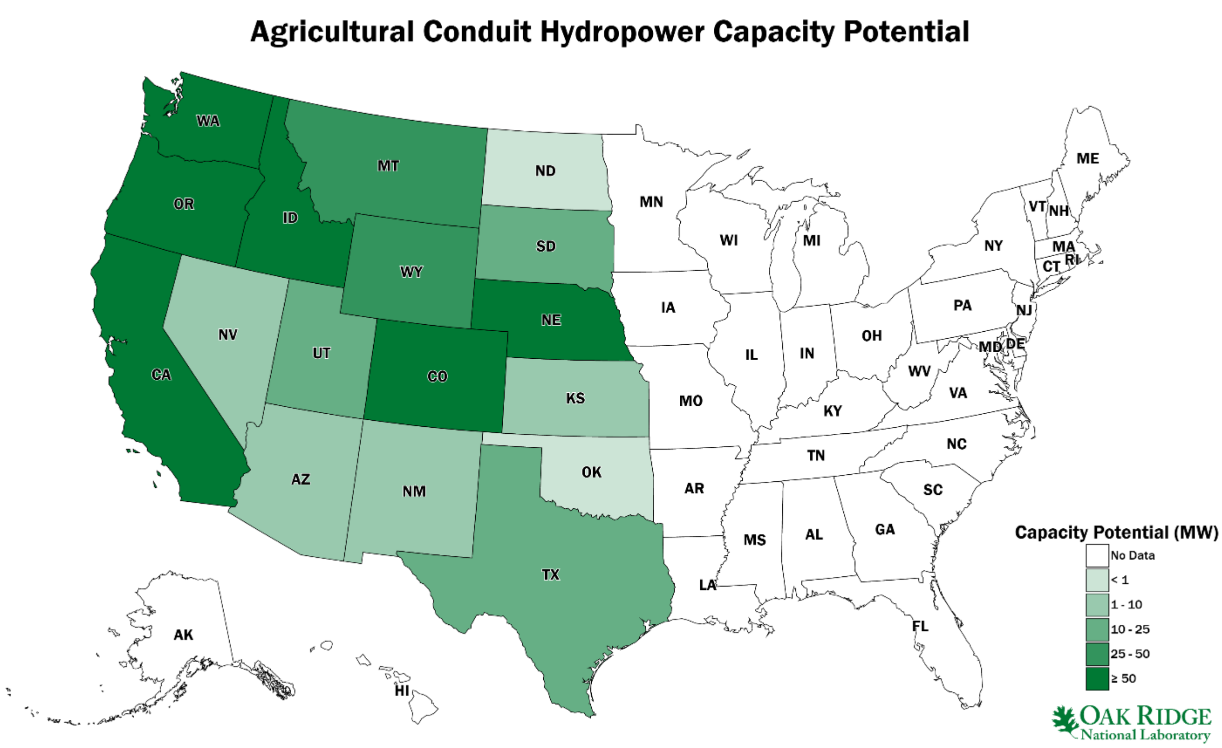
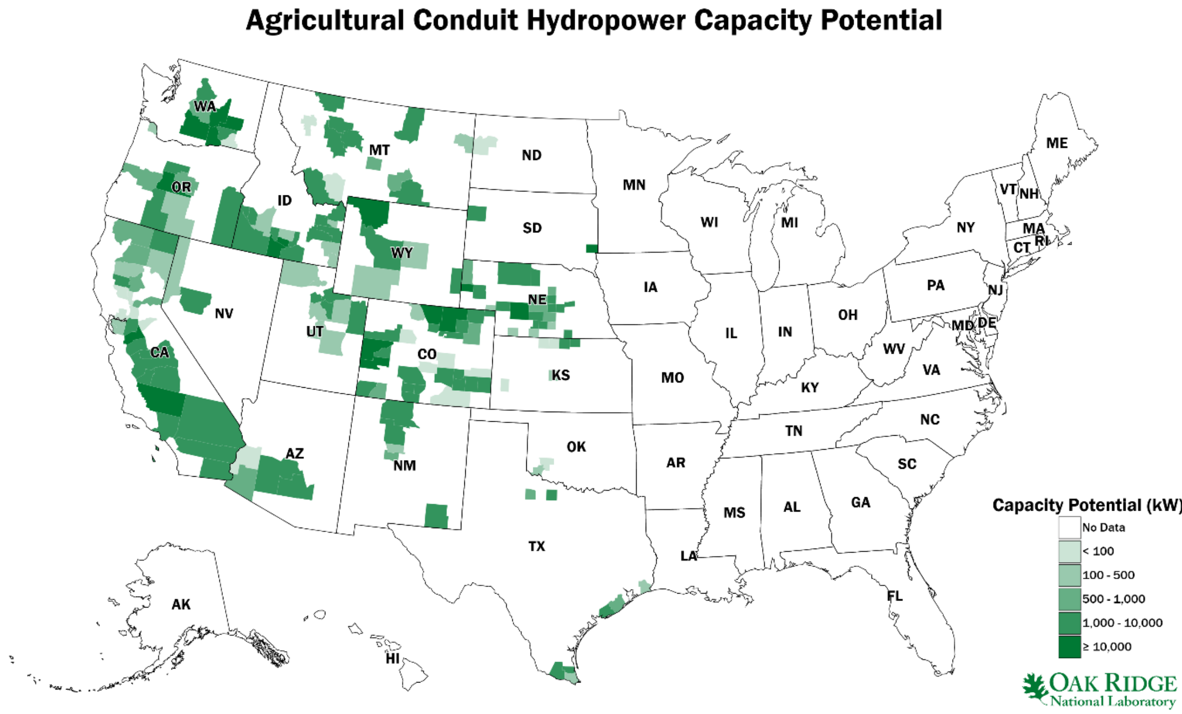


Figure 15. Agricultural conduit hydropower capacity potential by state.



Assessment only conducted in 17 western states. Potential may exist in other states but was not evaluated.

Figure 16. Map of agricultural conduit hydropower capacity potential by state.



Assessment only conducted in 17 western states. Potential may exist in other states but was not evaluated.

Figure 17. Map of agricultural conduit hydropower capacity potential by county.

The national agricultural conduit hydropower capacity potential is nearly 662 MW. Roughly 122 MW of capacity potential identified by Reclamation (2011, 2012) has not been developed, and an additional 540 MW outside of Reclamation's canals is identified in this study. More than 70% of the conduit hydropower potential is in Colorado, Washington, and Nebraska, California, and Idaho.

3.3 INDUSTRIAL SECTOR

Industrial conduit hydropower potential exists from public water supply for industrial/commercial usage, discharge from thermoelectric cooling, and discharge from industrial wastewater. The state-level capacity and energy generation potential are provided in Table 11, Table 12, and Figure 18. State- and county-level maps of industrial conduit hydropower capacity potential are provided in Figure 19 and Figure 20, respectively.

Table 11. Summary of industrial conduit hydropower capacity potential by state (MW)

State	Public water supply	Thermoelectric cooling	Wastewater	Total	State	Public water supply	Thermoelectric cooling	Wastewater	Total
AL	1.50	9.36	1.77	12.63	**MT**	0.53	—	0.06	0.59
AK	0.43	—	0.06	0.49	**NE**	0.06	7.59	0.09	7.74
AZ	0.31	—	0.11	0.42	**NV**	0.37	—	0.20	0.57
AR	0.73	1.90	0.36	2.99	**NH**	0.18	—	0.06	0.23
CA	32.51	31.27	0.33	64.12	**NJ**	3.24	—	0.26	3.50
CO	7.39	—	0.16	7.55	**NM**	0.70	—	0.03	0.73
CT	2.49	4.04	0.04	6.57	**NY**	16.55	3.77	0.93	21.25
DE	0.09	2.39	0.56	3.04	**NC**	1.29	1.49	0.20	2.97
DC	—	—	0.00	0.00	**ND**	0.17	2.71	0.48	3.36
FL	0.48	1.89	0.61	2.98	**OH**	1.38	10.36	0.73	12.47
GA	1.25	—	0.50	1.75	**OK**	1.06	—	0.18	1.24
HI	1.41	1.76	0.15	3.32	**OR**	7.30	—	0.17	7.47
ID	0.73	—	1.38	2.11	**PA**	12.12	0.88	0.72	13.72
IL	0.25	16.11	0.60	16.96	**RI**	0.64	—	0.03	0.67
IN	0.19	7.76	1.15	9.10	**SC**	0.33	1.45	0.17	1.95
IA	0.19	0.74	0.08	1.00	**SD**	0.07	—	0.03	0.10
KS	0.25	—	0.02	0.26	**TN**	1.00	15.47	1.00	17.47
KY	0.35	2.30	0.27	2.93	**TX**	2.91	27.16	1.68	31.75
LA	0.17	—	2.22	2.39	**UT**	14.35	—	0.01	14.36
ME	0.41	—	3.21	3.62	**VT**	0.30	—	0.03	0.33
MD	0.07	19.22	0.31	19.60	**VA**	1.34	13.11	0.47	14.91
MA	4.08	—	0.26	4.34	**WA**	1.89	—	0.31	2.20
MI	0.14	9.82	1.97	11.93	**WV**	1.10	—	0.89	2.00
MN	0.13	3.80	0.37	4.30	**WI**	0.07	6.61	0.33	7.02
MS	0.15	0.86	0.19	1.19	**WY**	0.37	—	0.19	0.56
MO	0.66	20.68	1.87	23.21	**Total**	**125.69**	**224.49**	**27.81**	**377.98**

Table 12. Summary of industrial conduit hydropower energy generation potential by state (GWh/year)

State	Public water supply	Thermoelectric cooling	Wastewater	Total	State	Public water supply	Thermoelectric cooling	Wastewater	Total
AL	8.94	55.76	10.54	75.25	**MT**	3.15	—	0.35	3.50
AK	2.59	—	0.36	2.95	**NE**	0.36	45.21	0.56	46.13
AZ	1.85	—	0.64	2.49	**NV**	2.22	—	1.16	3.39
AR	4.32	11.34	2.13	17.80	**NH**	1.05	—	0.34	1.39
CA	193.68	186.26	1.99	381.93	**NJ**	19.31	—	1.55	20.86
CO	44.04	—	0.96	44.99	**NM**	4.16	—	0.18	4.34
CT	14.81	24.08	0.25	39.15	**NY**	98.57	22.48	5.51	126.56
DE	0.56	14.23	3.34	18.14	**NC**	7.67	8.88	1.16	17.72
DC	—	—	0.01	0.01	**ND**	0.99	16.12	2.89	19.99
FL	2.84	11.25	3.65	17.74	**OH**	8.20	61.69	4.37	74.26
GA	7.47	—	2.98	10.45	**OK**	6.32	—	1.08	7.40
HI	8.40	10.47	0.92	19.79	**OR**	43.50	—	1.02	44.52
ID	4.34	—	8.21	12.55	**PA**	72.20	5.21	4.29	81.70
IL	1.50	95.96	3.54	101.00	**RI**	3.79	—	0.20	3.99
IN	1.13	46.24	6.86	54.23	**SC**	1.95	8.64	1.04	11.64
IA	1.12	4.38	0.47	5.97	**SD**	0.42	—	0.18	0.60
KS	1.46	—	0.10	1.56	**TN**	5.98	92.13	5.98	104.09
KY	2.11	13.73	1.61	17.45	**TX**	17.30	161.79	10.01	189.11
LA	1.02	—	13.20	14.22	**UT**	85.47	—	0.08	85.54
ME	2.45	—	19.11	21.56	**VT**	1.80	—	0.16	1.96
MD	0.42	114.50	1.85	116.77	**VA**	7.99	78.07	2.78	88.83
MA	24.33	—	1.55	25.88	**WA**	11.25	—	1.84	13.09
MI	0.83	58.50	11.74	71.07	**WV**	6.58	—	5.32	11.89
MN	0.76	22.64	2.21	25.61	**WI**	0.44	39.39	1.97	41.80
MS	0.87	5.10	1.13	7.10	**WY**	2.22	—	1.14	3.36
MO	3.93	123.17	11.14	138.24	**Total**	**748.68**	**1,337.23**	**165.66**	**2,251.57**

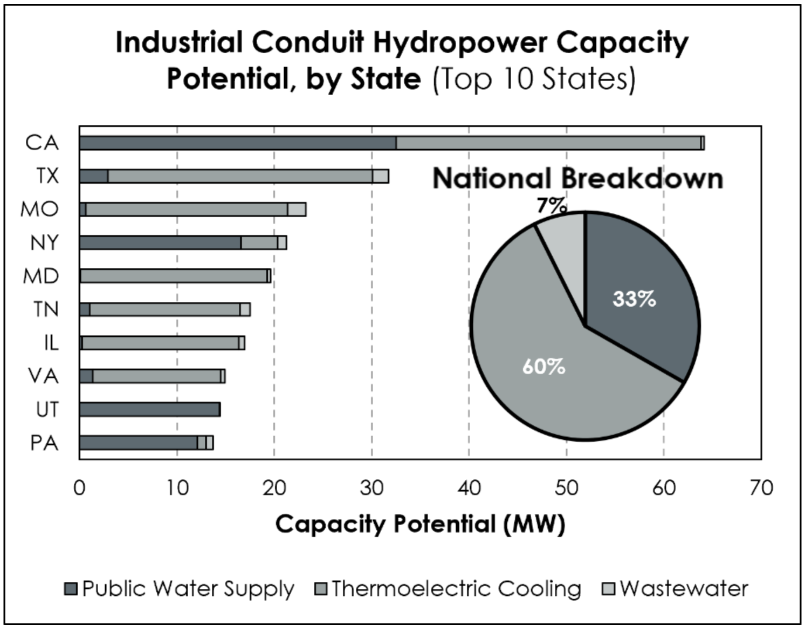


Figure 18. Top 10 states with the highest industrial conduit hydropower capacity potential.

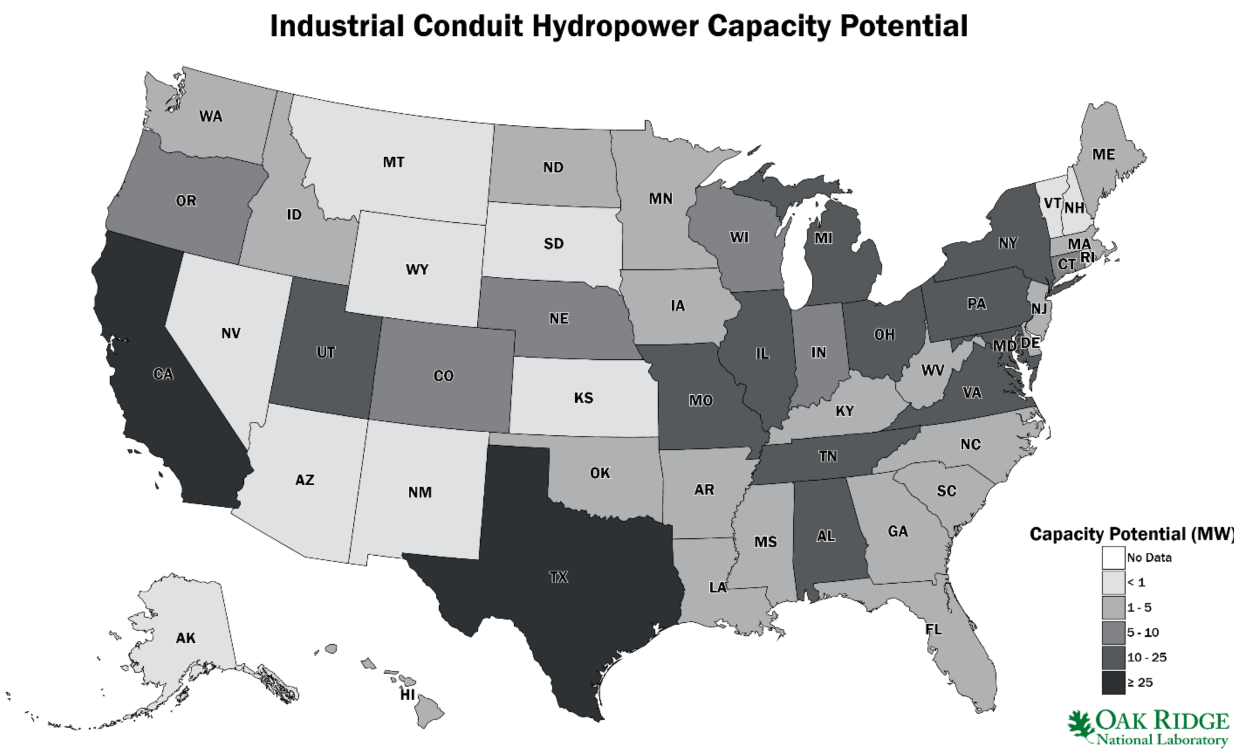


Figure 19. Map of industrial conduit hydropower capacity potential by state.

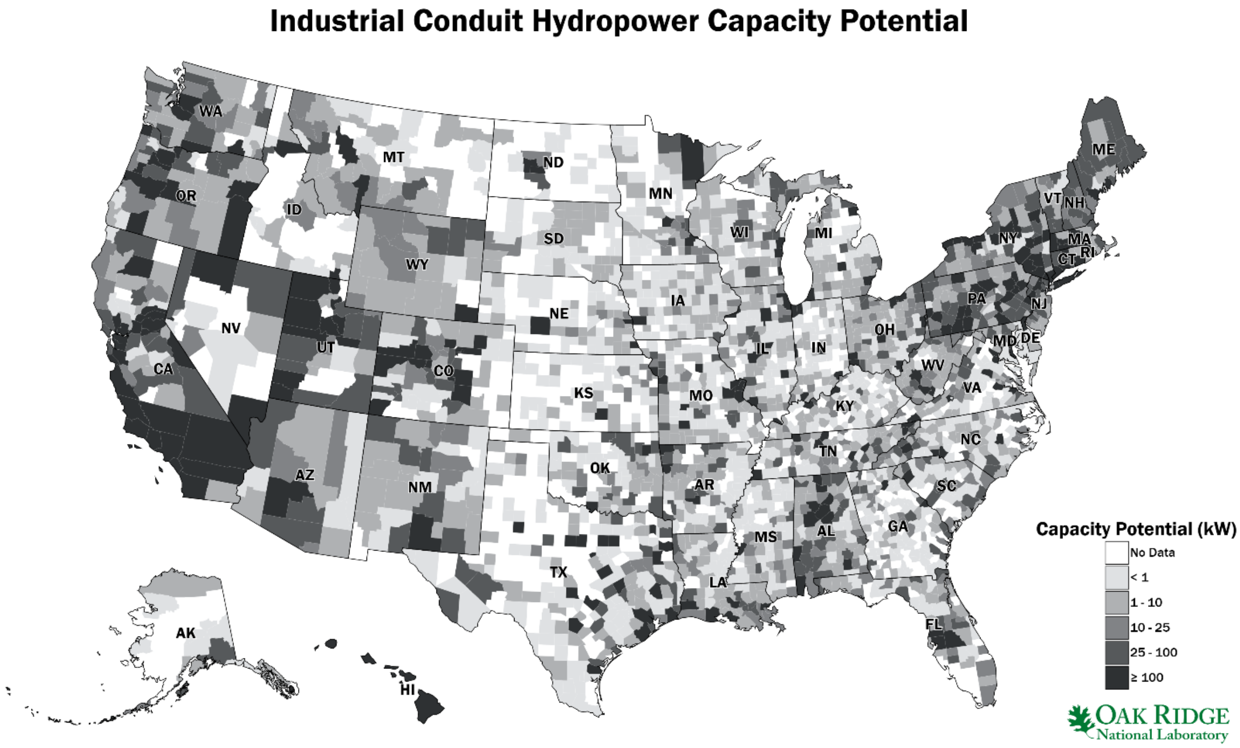


Figure 20. Map of industrial conduit hydropower capacity potential by county.

The national total industrial conduit hydropower capacity potential is nearly 378 MW, with 33% from public water supply systems, 60% from thermoelectric cooling systems, and 7% from wastewater systems. California has more than twice as much total capacity potential as the state with the next highest potential (Texas). The industrial sector potentials from public water supply systems and wastewater systems are somewhat similar to their counterparts in the municipal sector. Again, given data limitations, some clear potential such as the water withdrawal from self-supplied industrial users cannot be accounted for. The uncounted potential is comprehensively discussed in Section 4.2.

Although the majority of industrial conduit hydropower potential is from thermoelectric cooling systems, the results should be carefully interpreted. As discussed in Section 2, the authors are not aware of any such existing hydropower conduit projects in the United States, but there have been successful examples in Europe, which motivated the authors to evaluate the potential in the United States. However, considering the challenges associated with cost/benefit factors, retirement of coal facilities, future upgrades to recirculatory cooling systems, and other regulatory limitations, it is unclear how much of this potential is actually feasible for development. Considering that these add-on conduit hydropower opportunities are much smaller in magnitude (~1%) than the capacity of thermoelectric power plants, one may even suggest that more power and energy can be achieved through efficiency improvement and capacity expansion. Therefore, the findings are reported for completeness from a water use perspective, but the major challenges associated with its development are to be further explored in future studies.

3.4 NATIONAL OVERVIEW

National-level conduit hydropower resources are the aggregation of municipal, agricultural, and industrial sector potential. The sector breakdown of capacity and energy generation potential is shown in Figure 21 and Figure 22, and the state-level capacity and energy generation potential are provided in Table 13, Table 14, and Figure 23. State-level and county-level maps of the results for power potential are provided in Figure 24 and Figure 25, respectively.

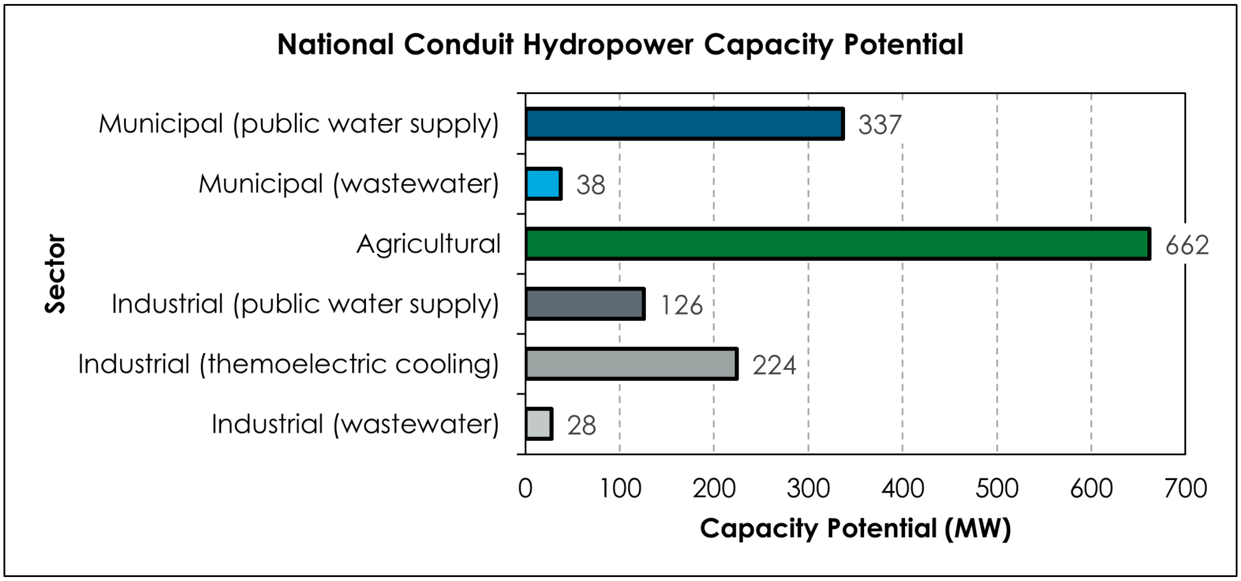


Figure 21. National conduit hydropower capacity potential by sector.

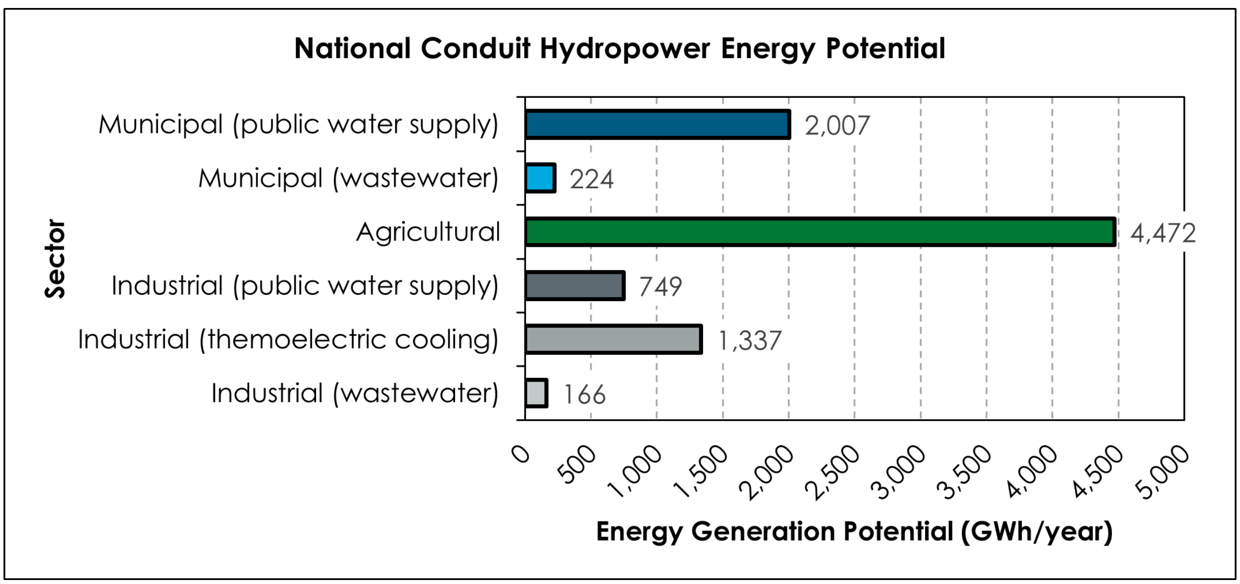


Figure 22. National conduit hydropower energy generation potential by sector.

Table 13. Summary of national conduit hydropower capacity potential by state (MW)

State	Municipal	Agricultural	Industrial	Total	State	Municipal	Agricultural	Industrial	Total
AL	1.81	—	12.63	14.44	**MT**	1.27	32.13	0.59	33.98
AK	0.61	—	0.49	1.11	**NE**	0.43	91.25	7.74	99.42
AZ	10.10	8.59	0.42	19.11	**NV**	0.88	1.90	0.57	3.35
AR	1.86	—	2.99	4.85	**NH**	0.34	—	0.23	0.57
CA	109.33	70.00	64.12	243.45	**NJ**	5.08	—	3.50	8.58
CO	42.95	153.59	7.55	204.09	**NM**	1.77	9.05	0.73	11.55
CT	2.51	—	6.57	9.08	**NY**	44.60	—	21.25	65.85
DE	0.44	—	3.04	3.48	**NC**	2.82	—	2.97	5.79
DC	0.30	—	—	0.30	**ND**	0.05	0.01	3.36	3.41
FL	1.86	—	2.98	4.83	**OH**	3.58	—	12.47	16.04
GA	2.35	—	1.75	4.11	**OK**	1.04	0.43	1.24	2.71
HI	4.55	—	3.32	7.87	**OR**	17.89	51.54	7.47	76.90
ID	1.95	58.41	2.11	62.46	**PA**	10.95	—	13.72	24.67
IL	3.22	—	16.96	20.18	**RI**	0.76	—	0.67	1.43
IN	1.32	—	9.10	10.43	**SC**	1.77	—	1.95	3.73
IA	0.86	—	1.00	1.86	**SD**	0.15	16.98	0.10	17.23
KS	0.59	6.07	0.26	6.92	**TN**	2.02	—	17.47	19.50
KY	0.95	—	2.93	3.88	**TX**	8.38	16.51	31.75	56.63
LA	1.67	—	2.39	4.06	**UT**	33.70	15.96	14.36	64.02
ME	0.53	—	3.62	4.15	**VT**	0.37	—	0.33	0.70
MD	1.42	—	19.60	21.02	**VA**	3.52	—	14.91	18.43
MA	3.31	—	4.34	7.65	**WA**	22.26	94.80	2.20	119.26
MI	2.71	—	11.93	14.64	**WV**	1.46	—	2.00	3.46
MN	0.68	—	4.30	4.98	**WI**	0.72	—	7.02	7.74
MS	0.65	—	1.19	1.84	**WY**	3.49	34.83	0.56	38.89
MO	6.62	—	23.21	29.83	**Total**	**374.46**	**662.03**	**377.98**	**1,414.47**

Table 14. Summary of national conduit hydropower energy generation potential by state (GWh/year)

State	Municipal	Agricultural	Industrial	Total	State	Municipal	Agricultural	Industrial	Total
AL	10.79	—	75.25	86.04	**MT**	7.54	162.41	3.50	173.44
AK	3.66	—	2.95	6.61	**NE**	2.54	650.15	46.13	698.82
AZ	60.14	58.71	2.49	121.35	**NV**	5.23	11.71	3.39	20.33
AR	11.10	—	17.80	28.90	**NH**	2.03	—	1.39	3.42
CA	651.27	551.59	381.93	1584.79	**NJ**	30.27	—	20.86	51.13
CO	255.86	992.71	44.99	1293.56	**NM**	10.57	63.85	4.34	78.76
CT	14.93	—	39.15	54.09	**NY**	265.68	—	126.56	392.24
DE	2.60	—	18.14	20.73	**NC**	16.79	—	17.72	34.51
DC	1.78	—	0.01	1.80	**ND**	0.31	0.02	19.99	20.32
FL	11.06	—	17.74	28.80	**OH**	21.30	—	74.26	95.56
GA	14.00	—	10.45	24.45	**OK**	6.20	1.99	7.40	15.59
HI	27.11	—	19.79	46.90	**OR**	106.55	329.16	44.52	480.22
ID	11.59	438.94	12.55	463.08	**PA**	65.23	—	81.70	146.93
IL	19.18	—	101.00	120.18	**RI**	4.51	—	3.99	8.50
IN	7.89	—	54.23	62.12	**SC**	10.57	—	11.64	22.21
IA	5.11	—	5.97	11.08	**SD**	0.88	127.45	0.60	128.93
KS	3.50	40.60	1.56	45.66	**TN**	12.04	—	104.09	116.14
KY	5.65	—	17.45	23.09	**TX**	49.90	123.35	189.11	362.36
LA	9.95	—	14.22	24.17	**UT**	200.73	99.24	85.54	385.51
ME	3.16	—	21.56	24.73	**VT**	2.23	—	1.96	4.19
MD	8.45	—	116.77	125.22	**VA**	20.98	—	88.83	109.81
MA	19.70	—	25.88	45.58	**WA**	132.63	661.73	13.09	807.44
MI	16.16	—	71.07	87.23	**WV**	8.70	—	11.89	20.59
MN	4.07	—	25.61	29.67	**WI**	4.28	—	41.80	46.08
MS	3.88	—	7.10	10.97	**WY**	20.80	158.56	3.36	182.72
MO	39.46	—	138.24	177.70	**Total**	**2,230.56**	**4,472.17**	**2,251.57**	**8,954.30**

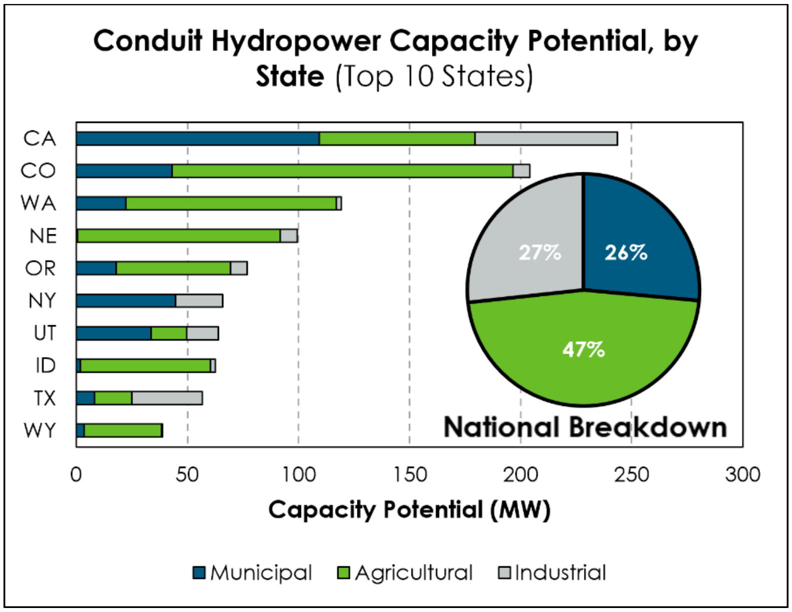


Figure 23. Top 10 states with the highest conduit hydropower capacity potential.

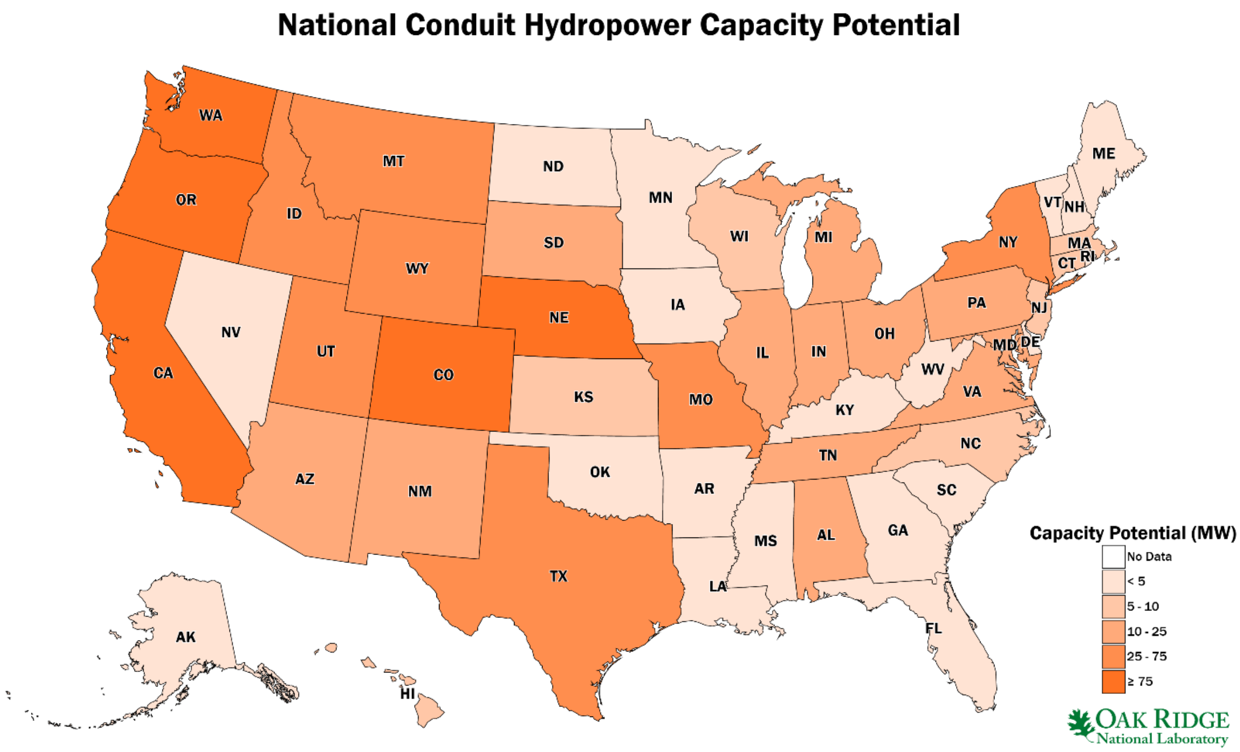


Figure 24. Map of overall conduit hydropower capacity potential by state.

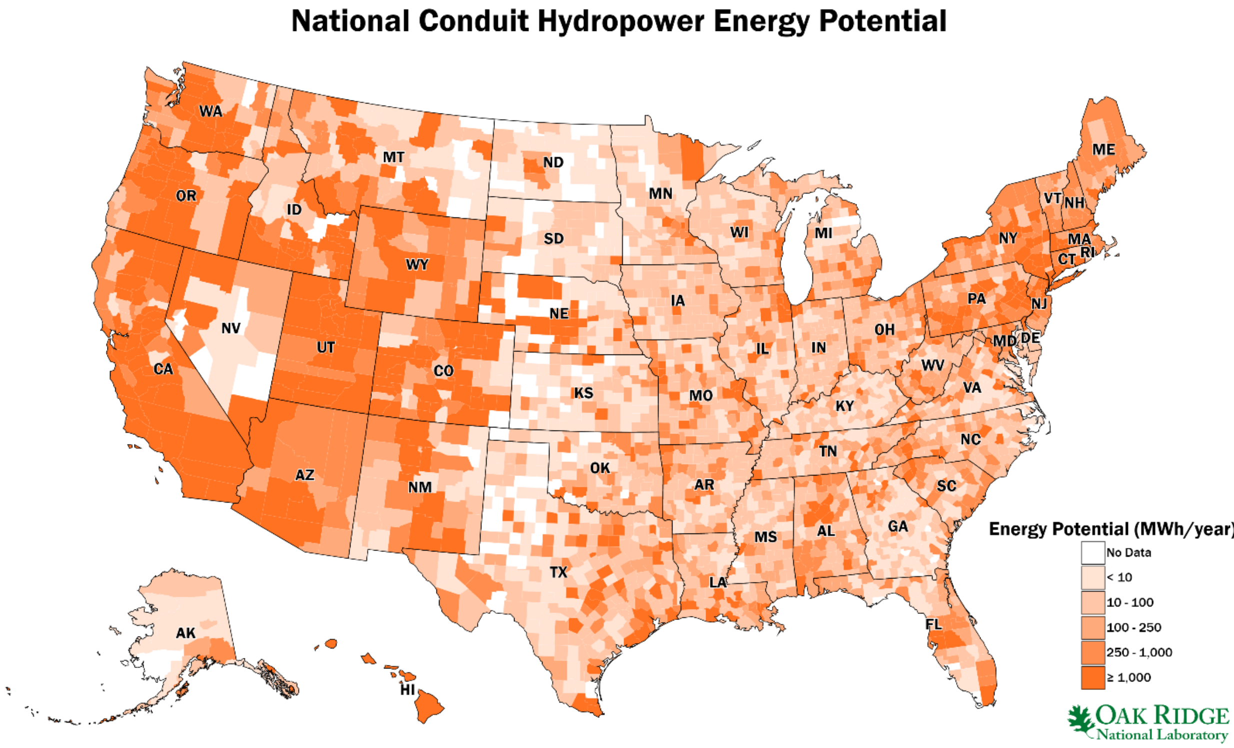


Figure 25. Map of overall conduit hydropower capacity potential by county.

Overall, 1.41 GW of capacity potential is estimated across the United States, with the largest portion of conduit hydropower potential found in the agricultural sector (662 MW), followed by the industrial (378 MW) and municipal (374 MW) sectors. In general, the largest resource potential exists in the western states, with the highest total capacity potential in California (243 MW), followed by Colorado (204 MW), Washington (119 MW), Nebraska (99 MW), and Oregon (77W).

Among these different conduit hydropower opportunities, larger projects (i.e., in terms of capacity per site) are generally expected in agricultural irrigation canals because of the relatively larger flow in these canals, as evidenced by several existing agricultural conduit projects in the United States. However, the flow within these canals is likely to be seasonal (in accordance with the irrigation schedule) and will not be able to support hydropower generation yearlong. The relatively lower head is also a common challenge for hydropower development, which has further cost/benefit implications (O'Connor et al., 2015).

In contrast, the projects in public water supply systems are generally located in pressurized pipelines with higher head and generating efficiency. However, given the smaller flow (when compared with the irrigation canals), the capacity per site is generally smaller. With this difference in mind, although the total conduit capacity potential in the public water supply systems is smaller, there should be many more conduit hydropower sites for a variety of different communities. Furthermore, the municipal conduit hydropower projects are likely to be important contributors to local microgrids and can be useful for communities in rural areas to be more self-sufficient and less dependent on the central main grid. This important feature can be a focus area for future study and development to enhance energy equality and justice.

3.5 SENSITIVITY ANALYSIS

To understand the sensitivity of some assumptions made during the assessment (that are quantifiable), model sensitivity analyses were conducted for the four models discussed in Sections 2.2 to 2.5. The results are summarized in Table 15 for public water supply systems, in Table 16 for irrigation canal systems, in Table 17 for thermoelectric cooling systems, and in Table 18 for wastewater systems.

For the public water supply system model (Table 15), the default scenario S0 assumed a conduit roughness ε = 0.00015 ft (commercial steel), a pipeline velocity V = 2 ft/s, and a total head loss h_L as two times the frictional head loss h_f. Those assumptions indicated a 462.5 MW conduit hydropower capacity and 2,755 GWh annual energy production for water delivered to both the municipal and industrial sectors. In scenario S1, the sensitivity of ε was tested by using ε = 0 ft in S1a (e.g., high-density polyethylene pipe) and ε = 0.0003 ft in S1b. The results showed that the effect is very limited (less than 1% change). Therefore, the specific material assumed in the assessment had little effect on sensitivity. A larger sensitivity was found in the assumption of velocity. In scenario S2, V = 1 ft/s was used in S2a, and V = 3 ft/s in S2b. Those assumptions resulted in a 9.7% to −13% change of capacity and energy. Given that velocity is a square term in the equation for head loss (Eq. [5]), this larger sensitivity can be expected. In scenario S3, the total head loss h_L assumption (Eq. [8]) was examined. A factor of 1.5 was tested in S3a, and 2.5 in S3b, and it resulted in a 2.5 to −2.2% change of capacity and energy. Overall, the highest sensitivity was found for the assumption of velocity, followed by head loss and then roughness. In practice, the choices of conduit, size, velocity, and other conduit features are all site-specific decisions that can hardly be generalized. The sensitivity analysis here mainly demonstrates how the choices of model parameters may affect the estimate of national conduit hydropower resources.

Table 15. Summary of model sensitivity: public water supply systems (municipal and industrial)

Scenario	Roughness ε (ft)	Velocity V (ft/s)	Total head loss h_L (ft)	Capacity (MW)		Energy (GWh/year)	
S0 (default)	0.00015	2	2 * h_f	462.5	—	2,755	—
S1a	0	—	—	464.9	(0.5%)	2,769	(0.5%)
S1b	0.0003	—	—	460.6	(−0.4%)	2,743	(−0.4%)
S2a	—	1	—	507.2	(9.7%)	3,021	(9.7%)
S2b	—	3	—	402.7	(−13%)	2,399	(−13%)
S3a	—	—	1.5 * h_f	474.1	(2.5%)	2,824	(2.5%)
S3b	—	—	2.5 * h_f	452.2	(−2.2%)	2,694	(−2.2%)

For the irrigation canal system model (Table 16), the default scenario S0 assumed a canal roughness n = 0.014 (unfinished concrete), a side slope z_0 = 1.5, a bottom width B of two times the canal depth d, and a maximum canal velocity V = 6.7 ft/s (2 m/s). Those assumptions indicated a 540 MW conduit hydropower capacity and 4,023 GWh annual energy production for all canal drop sites. In scenario S1, the sensitivity of Manning's n was tested by using n = 0.012 in S1a (finished concrete) and n = 0.022 in S1b (earth channel). Those assumptions resulted in a 4% to −13% change of capacity and energy. In scenarios S2 and S3, two parameters were tested to control the assumed canal geometry. In scenario S2, side slope z_0 = 1 was used in S2a, and z_0 = 2 in S2b. Those assumptions resulted in a 44% to −26% change of capacity and energy. In scenario S3, bottom width B = 1.5 * d was used in S3a, and 2.5 * d in S3b. Those assumptions resulted in a 4% to −5% change of capacity and energy. Between these two parameters, side slope has a much higher sensitivity than bottom width. Collectively, the analysis indicated a high sensitivity associated with the assumed canal geometry, which affects the cross-section area, velocity, discharge, and eventually capacity and energy. In scenario S4, the maximum V = 4.9 ft/s

(1.5 m/s) was used in S4a, and V = 8.2 ft/s (2.5 m/s) in S4b. Those assumptions resulted in a −20% to 18% change of capacity and energy. Overall, these analyses highlight the importance of flow estimates in calculating the agricultural conduit hydropower potentials. Whereas Reclamation (2012) used historical flow observations to estimate conduit hydropower potentials, such types of data could not be comprehensively collected in this study. However, although remotely sensed imagery can help identify national canal drop sites, the current techniques have not matured enough to estimate the flow rates directly. All-in-all, the assumptions here should be sufficient to estimate the total regional and national potentials, but they will not be accurate enough to support site-level investment decisions. Collaboration with irrigation districts in obtaining the most accurate canal features will be a crucial step to ensure the successful development of agricultural conduit hydropower projects.

Table 16. Summary of model sensitivity: irrigation canal system

Scenario	Manning's *n*	Side slope z_0	Bottom width *B*	Max. *V* (ft/s)	Capacity (MW)		Energy (GWh/year)	
S0 (default)	0.014	1.5	2 * *d*	6.7	540.0	—	4,023	—
S1a	0.012	—	—	—	562.3	(4.1%)	4,185	(4.0%)
S1b	0.022	—	—	—	469.5	(−13%)	3,506	(−13%)
S2a	—	1	—	—	777.6	(44%)	5,787	(44%)
S2b	—	2	—	—	401.7	(−26%)	2,996	(−26%)
S3a	—	—	1.5 * *d*	—	561.9	(4.1%)	4,185	(4.0%)
S3b	—	—	2.5 * *d*	—	514.5	(−4.7%)	3,834	(−4.7%)
S4a	—	—	—	4.9	430.7	(−20%)	3,204	(−20%)
S4b	—	—	—	8.2	633.6	(17%)	4,727	(18%)

For the thermoelectric cooling water system model (Table 17), the default scenario S0 assumed a uniform head loss of 10 ft, and a minimum 10 ft net head requirement. Those assumptions indicated a 224.5 MW conduit hydropower capacity and 1,337 GWh annual energy production for cooling water discharge from thermoelectric power plants. In scenario S1, the sensitivity of head loss with 5 ft head loss was tested in S1a, and 15 ft head loss in S1b. Those assumptions resulted in a 37% to −29% change of capacity and energy. In scenario S2, the sensitivity of minimum net head requirement was further tested with 5 ft in S2a and 15 ft in S2b. Those assumptions resulted in a 9% to −12% change of capacity and energy.

Table 17. Summary of model sensitivity: thermoelectric cooling water systems

Scenario	Head loss (ft)	Min. net head (ft)	Capacity (MW)		Energy (GWh/year)	
S0 (default)	10	10	224.5	—	1,337	—
S1a	5	—	308.4	(37%)	1,837	(37%)
S1b	15	—	159.3	(−29%)	949	(−29%)
S2a	—	5	244.1	(9%)	1,454	(9%)
S2b	—	15	196.6	(−12%)	1,171	(−12%)

For the wastewater system model (Table 18), the default scenario S0 assumed an average head of 6 ft. This assumption indicated a 65.4 MW conduit hydropower capacity and 390 GWh annual energy production for wastewater discharge from both municipal and industrial facilities. In scenario S1, the sensitivity of head was studied with 2 ft in S1a and 10 ft in S1b. Those assumptions resulted in a −67% to 67% change of capacity and energy.

Table 18. Summary of model sensitivity: wastewater systems (municipal and industrial)

Scenario	Assumed head (ft)	Capacity (MW)		Energy (GWh/year)	
S0 (default)	6	65.4	—	390	—
S1a	2	21.8	(−67%)	130	(−67%)
S1b	10	109.0	(67%)	649	(67%)

When more accurate data become available in the future, these initial estimates could be revisited to obtain more accurate understandings. Cooling water and wastewater models are simpler and involve more assumptions. These simplifications are necessary because of data limitations since many of the data needed for a conduit hydropower resource assessment have not been accurately documented at the regional and national scales. Furthermore, some other conduit hydropower potential cannot even be estimated. Those uncounted resources are qualitatively discussed in Section 4.2.

4. DISCUSSION AND CONCLUSIONS

4.1 MAIN FINDINGS

The hydropower potential from constructed water conduits (e.g., pipelines, aqueducts, irrigation ditches, water conveyance canals) across the municipal, agricultural, and industrial sectors has been estimated as being relatively small but having high development feasibility. However, the total conduit hydropower potential across states and/or regions has not been comprehensively quantified, mainly because of data limitations. Recognizing the knowledge gaps and challenges in each conduit hydropower sector, sector-specific approaches that are best suited for the current state of data availability and understanding are required. To quantify the total hydropower potential from conduits nationally, a reconnaissance-level hydropower resource assessment was conducted in this study, covering three main conduit sectors (municipal, agricultural, and industrial). The assessment leveraged the best available data acquired through federal and state drinking water regulatory agencies, as well as novel remote sensing and feature detection techniques for systematic identification of national canal drop sites. The analysis introduced herein represents the first step in understanding national conduit hydropower potential.

Overall, 1.41 GW of capacity is estimated across the United States, with the largest portion of conduit hydropower potential found in the agricultural sector (662 MW), followed by the industrial (378 MW) and municipal (374 MW) sectors. In general, the largest resource potential exists in the western states, with the highest total capacity potential in California (243 MW), followed by Colorado (204 MW), Washington (119 MW), Nebraska (99 MW), and Oregon (77 MW). This potential jointly reflects the amount of water supply as well as suitable topography to provide sufficient net hydraulic head for hydropower generation. Compared with the 530 MW existing conduit hydropower projects in the United States, the undeveloped potential presents a great opportunity to develop clean and renewable hydroelectric energy across the nation. Furthermore, given data limitations, additional conduit hydropower opportunities may exist but could not be quantitively evaluated in this study. The uncounted-potential is qualitatively discussed in the following section.

Conduit hydropower is one highly feasible new hydropower development for the near future given its numerous benefits—such as the lack of need for new construction of dams or impoundments, minimum environmental concerns, reduced development timelines, eligibility for net-metering in most states, and qualification for an expedited 45-day regulatory approval process through the HREA of 2013 and its amendments in AWIA. Although the 1.41 GW conduit hydropower resource potential may seem smaller than other hydropower resource opportunities such as NPD development, collectively, these types of hydroelectric projects may provide stable energy output in distributed microgrids and help offset local energy demands for water system operators in local communities, for whom energy costs are typically a substantial portion of operational costs. Additionally, since much of the existing water infrastructure is aging and in need of upgrades, tapping conduit hydropower from water distribution systems can be a sustainable long-term water and energy supply solution. This study encourages water resources managers to consider leveraging this type of opportunity through an integrated energy/water system development approach.

4.2 UNCOUNTED POTENTIAL

The authors attempted to incorporate a variety of data and approaches to estimate the national conduit hydropower potentials, but the significant data gaps still represent a major hurdle to capturing the full resource potential. Sources of uncounted potential include the following:

- **Water withdrawal from self-supplied domestic and industrial users**: The amount of water withdrawn for self-supplied users accounts for 6% of the total US water withdrawal, compared with the 12% total water withdrawal for public water supply. Although the wastewater discharge should have been captured by NPDES and covered in the wastewater conduit hydropower estimates, the opportunities on the supply side are unknown. In other words, resource potential from self-supplied water withdrawal is likely significant, but data are not available to support the assessment.

- **Missing/incorrect coordinates for water intake and treatment plants**: SDWIS and NPDES data provide very useful information to help analyze the conduit hydropower potential, but many of the geographical coordinates of water intakes and treatment plants are either missing or incorrect. This issue is further complicated by infrastructure safety concerns, which prevent disclosing this type of sensitive information for further data review and update. These limitations likely lead to significant underestimation in some states in which the number of available geographical coordinates is noticeably lower than that of neighboring states.
- **Energy recovery opportunities caused by pumping**: Given the data limitations, this assessment focuses only on identifying gravitational head potential without considering the additional excess head generated during pumping. Although this simplification is necessary, it leads to underestimation of the full conduit hydropower potential. Several existing US conduit hydropower projects have been developed for energy recovery (e.g., energy recovery projects by Pendleton, Oregon; FERC P-14407 and P-14440), so this type of project is not uncommon.
- **Additional agricultural conduit hydropower sites**: Given the project scope and resource limitations, an existing canal drop detection tool can only be used to identify canal drop sites in the 17 western states that rely heavily on irrigation. Similar sites likely also exist in other states but were not estimated in this study. Additionally, the feature detection technique has its own limitations and therefore may still miss other suitable irrigation canal drop sites in the 17 western states. Also, although this approach may help detect the typical canal drop sites that are fully visible in remotely sensed imagery, it cannot identify hybrid canal sites that combine both canal drops and underground conduits for water transport.
- **Additional hydrokinetic hydropower potential in canals**: For agricultural conduits, the authors only examined hydropower opportunities associated with existing drops. However, there could be additional hydrokinetic hydropower opportunities at larger canals that may generate hydroelectric energy without using drops. Such a novel opportunity was not evaluated in this resource assessment but may be worth exploring in future studies.
- **Additional industrial conduit hydropower opportunities**: As stated, the potential opportunity in industrial sector is the least understood. Flow control and PRVs are commonly deployed in food, beverage processing, mining and oil and gas processing, in which enormous amounts of water are used. In addition, modern data centers have also become another major user of cooling water. A novel concept could be developed to pursue industry-specific conduit hydropower solutions for energy recovery in the system. However, industrial stakeholders will need more incentives to explore these new opportunities since they generally require shorter economic payback cycles than the municipal sector.

Given these uncounted opportunities, there could be more conduit hydropower potential than the 1.41 GW estimated in this study. Therefore, unlike the other previous NPD and new stream-reach development hydropower resource assessments that reported the theoretical upper potential, this assessment represents the best estimate based on the available data. Future research should continue to collect and expand the required data sets to support the breadth and depth of the resource assessment.

4.3 AVAILABILITY OF RESULTS

To inform future policy discussion and resource planning, the findings of this study are summarized at the state and county levels for public dissemination. However, given that some of the input data include sensitive infrastructure information acquired through an NDA, the underlying system- and site-level data are limited for publicly distribution. The sub-county data will be used by DOE and other agencies to support development of further research investment strategies and policy for the acceleration of national conduit hydropower development. All publicly available data will be disseminated through the ORNL HydroSource data portal.

4.4 FUTURE RESEARCH AND DEVELOPMENT NEEDS

Based on the findings from this study, some next steps to support the further development of national conduit hydropower projects are discussed in this final section. They include the following:

- **Enhance conduit hydropower resource characterization:** Given the need to estimate the national total conduit hydropower potentials, several approaches were designed to estimate the regionally aggregated total resources. These proposed approaches are sufficient for the stated purposes, but they may not identify accurate site-specific opportunities that are more suitable to support further feasibility assessments and investment decisions. Future work should continue enhancing the accuracy and usefulness of conduit hydropower resource characterization. For instance, direct collaboration with water and irrigation districts can be an effective way to understand the most likely opportunities within each district, as well as the regional challenges and considerations. Further efforts may also be considered to better understand some more novel technologies, such as hydrokinetic hydropower that may be developed at larger agricultural/industrial conduits without using drops. A review of next-generation conduit hydropower technologies would be beneficial to better identify and characterize those nonconventional resources.
- **Understand the development challenges and required incentives:** Despite the regulatory opportunities provided by the HREA, many development challenges still exist, such as cost, lack of support, lack of incentives, and lack of awareness, which prevent the effective deployment of conduit hydropower across the United States. According to the stakeholder feedback collected during the peer review process, the lack of consistent and equitable incentives compared with other renewable resource technologies is a major impediment for the growth of conduit hydropower. Better understanding the cost/benefit aspect of conduit hydropower development through a comprehensive techno-economic assessment will help guide future work, particularly in regard to an improved understanding of mechanisms for cost recovery, and how the new development may utilize some existing incentives such as the Energy Power Act of 2005 Section 242 Incentive Program managed by DOE.[8] The assessment may help identify the main market hurdles and inform suitable incentives to support broader development of national conduit hydropower.
- **Explore novel water distribution concepts and technologies:** Considering the complications and needs of aging infrastructure, conduit hydropower development can be utilized in a more integrated manner (i.e., not as a simple turbine placement effort). For instance, during irrigation modernization, a combination of pumping, pressurized pipelines, and conduit hydropower can be incorporated to minimize water loss, minimize energy input, and maximize benefits. Many drinking water delivery and distribution systems can also utilize a similar integrated systems approach, including conduit hydropower as a sustainable long-term water and energy supply solution. The development of turbine technologies that are specific to the technical advancement of conduit hydropower can be another area of research. Broader opportunities associated with energy development and management in water and wastewater utilities were comprehensively discussed in the research roadmap by Badruzzaman et al. (2015).

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[8] https://www.energy.gov/eere/water/section-242-hydroelectric-production-incentive-program

- **Increase public awareness and engagement**: Apart from the challenges identified by Grimm (2021), one barrier to broader conduit hydropower development is the limited awareness among water entities across multiple sectors. Hydropower development, particularly the regulatory process, is still viewed by some as high-risk and time-consuming, so water utilities and industrial users may not be motivated or incentivized to explore it. In addition, such benefits of conduit hydropower are also not clearly understood by many other key stakeholder groups, such as private developers and local communities. To help promote awareness of this clean and low-impact hydropower resource, targeted stakeholder engagement efforts that include utilities, asset owners, developers, technology providers, and community representatives where these projects are located will be useful and beneficial. The use of conduit hydropower in the adoption of environmental, social and governance factors in sustainable business practices can also encourage conduit hydropower development in industry.

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APPENDIX A. SUMMARY OF RESPONSE TO KEY REVIEW COMMENTS

To ensure the accuracy and quality of this study, an extensive external peer review was conducted in May 2022. More than 30 external reviewers were invited to provide comments and feedback on this study. The main review comments, as well as the detailed responses from the research team, are provided here. Statements in italics are the reviewer comments; they are followed by the authors' responses.

Reviewer 1

1.1 This report adds good information and rounds out the information found in the other national hydropower assessments. The authors did a nice job of laying out the potential and estimating potential across the different conduit types, and especially by including the sensitivity analysis and uncounted potential.

- Thank you for the positive feedback and encouragement.

1.2 There is no mention of the new bipartisan infrastructure bill as relates to both hydropower and water infrastructure improvements, although the report mentions aging water supply infrastructure in need of upgrades.

- Thank you. We have included the 242 incentive program information in Section 4.4.

1.3 There is no mention of climate change effects on future availability of irrigation water in particular. In the west, supply has been curtailed due to extended drought which reduces the estimates of available flow.

- Thank you for raising this issue. We have clarified in multiple places in Section 2 that the issue of climate change is not included in this analysis. Although climate change will affect water availability across different regions, the flow within these conduits is mainly controlled by demand and less by natural variability. The potential impacts of climate change on water availability for regional conduit supply and hydropower generation would be worthy of further investigation.

1.4 For the wastewater treatment section: Note that many existing hydropower plants have NPDES permits for significant amounts of non-generation related cooling and process water. Given an onsite dam and typical cooling water withdrawal from the impoundment, sufficient head may exist to potentially support a conduit turbine on the inlet or outlet end that is not captured in this report but could at least be mentioned as uncounted potential.

- Thank you. We have included this info in Section 2.5.

1.5 Potential audiences could include irrigation districts, state-level associations of districts, water supply associations (just google them: e.g., American Waterworks Assoc., National Association of Clean Water Agencies, Atlantic States Rural Water & Wastewater Association, Association of Metropolitan Water Agencies, National Rural Water Association) and other owners of the actual existing conduit systems.

- Thank you for the recommendation. We will include these associations in our further stakeholder engagement efforts.

Reviewer 2

2.1 Good report overall. Just wondering if the authors have had a chance to discuss potential current projects with existing in-conduit hydro turbine manufacturers. I believe Soar, Voith and Harris

Engineering sell some models. There was also a vendor demo'ing there product at one of the NHA conferences in either 2020 or 2021.

- We invited turbine manufacturers in the external review process. Ten of the external reviewers are in-conduit hydro turbine manufacturers.

Reviewer 3

3.1 Agreed that in-pipe energy extraction only makes sense where you already have a PRV. Fundamental to avoid mis-interpreting this study, at least w/r/t in-pipe, is the reader's understanding that unless excess pressure is present, power extraction often makes no sense, except possibly in the case of gravity-based pipe flows. You generally don't run the hydropower equipment during any times which the PRV would not already be open. As such, the plant capacity factor of many in-pipe installations isn't very high. I'm sure there is a better way to write about this, but I feel it's a pretty important point.

- Thank you for the insightful comment. It is consistent with our understanding of the conduit hydropower opportunities. These concepts have been mentioned in multiple places of this report.

3.2 Consider whether Industrial should even be included in this report. Essentially nothing is known about it.

- For the completeness of a national resource assessment, we suggest that industrial should still be included. The assessment conducted in this report is mainly to estimate the overall potential. These limited understandings have been discussed in multiple places of this report.

3.3 Imprecise (unit for DEM resolution); arc-seconds of latitude are constant, but not of longitude. ~10m is only at the Equator.

- We agree with this comment. However, this approximation has been used by USGS and most of the studies. We are retaining our current usage for consistency.

3.4 Figure 7 should probably mention/account for tailwater effect; i.e. net head can vary significantly as a function of flow, especially in things like sequential irrigation drops.

- Thank you. We have added the discussion related to tailwater in Section 2.3.3.4.

3.5 I would add a new paragraph 2.3.3.5 and call it something like "Special Considerations for Irrigation Conduits". Then, discuss the unique requirements for irrigation schemes: our company has found, in pitching hydro plants to irrigation cooperatives, that two of the key challenges are (i) non-invasiveness and (ii) systems that "fail open." As to (i) their job is to supply water on demand and without interruption. If power can be generated, that's great, but it must not entail any blockage or dewatering during construction. In theory, a diversion could be constructed, but at the scale of most of these schemes that is impractical. As to (ii), the installation must be designed such that if the equipment breaks or otherwise needs to be shut down, the delivery of irrigation water is unaffected. Unless both of these conditions can be met, in our experience building hydropower stations at irrigation conduits is a non-starter.

- Thank you. We have added these challenges at the end of Section 2.3.3.4.

Reviewer 4

4.1 Well written interesting report. I suggest adding a comment about the lack of incentives in the beginning of the report as well as at the end.

- Thank you. We have highlighted this need in the revised Executive Summary.

4.2 Is the 40 MW limit still true given the PURPA changes--I'm suggesting checking as I'm not 100% sure.

- 40 MW is the limit for FERC-qualifying conduit facilities; this is not the same as PURPA-qualifying small power production facilities, which are limited to less than 80 MW.

Reviewer 5

5.1 Recommend incorporating a paragraph describing the relationship between technical capacity potential and economically feasible capacity potential. The 1.39 GW of capacity potential noted in the Report does not consider site specific conditions and/or constraints – that may undermine the economic feasibility of a given site. It's important for the audience to understand that technical capacity potential does not necessarily translate to economically feasible capacity potential.

- Thank you, and we agree with this comment. We have highlighted this limitation in various parts of the report about this limitation, including in the Executive Summary. We also highlighted the importance working with stakeholders to identify sites that are suitable for development.

5.2 Pleased to see the Report referencing/utilizing Reclamation's 2012 Resource Assessment. I'd note that whereas Reclamation's 2011 Resource Assessment (referenced on p. 11) focuses on non-powered dam sites, it also analyzes select conduit sites. I do not believe conduit sites analyzed in the 2011 Resource Assessment are referenced in the Report – advise incorporating if not already done so.

- Thank you very much for notifying us of this issue. The conduit sites evaluated in Reclamation (2011) are now included in the revised manuscript. The total resource has been raised from 1.39 GW to 1.41 GW because of this change.

5.3 In addition to the HREA and AWIA – the Bureau of Reclamation Small Conduit Hydropower Development and Rural Jobs Act of 2013 (PL 113-24) streamlined Reclamation Lease of Power Privilege (LOPP) authorizations for small conduit hydropower developed on Reclamation Projects. Recommend noting PL 113-24 along with HREA and AWIA – here and elsewhere in the Report (HREA and AWIA are referenced several times, e.g., p. 1, lines 107-109). The National Renewable Energy Laboratory (NREL) analyzed PL 113-24 impacts here: https://www.osti.gov/biblio/1439274-bureau-reclamation-hydropower-lease-power-privilege-case-studies-considerations.

- Thank you. We have included PL 113-24 in the Introduction.

5.4 You may consider a follow-up paragraph detailing the distinction between a FERC and Reclamation LOPP authorization.

- We have added a footnote explaining the difference between LOPP and FERC licensed projects.

5.5 "What is the driver behind (albeit minor) discrepancies between Report Table 9 Reclamation (2012) state data and state data shown in the Reclamation 2012 Resource Assessment, Table 2 (see: https://www.usbr.gov/power/CanalReport/FinalReportMarch2012.pdf, p. 13)? E.g., Reclamation 2012 Resource Assessment Table shows 5.061 MW of capacity in Arizona, the Report Table 9 shows 3.980 MW of capacity in Arizona.

- Thank you. Three Reclamation (2012) sites are very close to the borderline of two states and were assigned to a different state during our geospatial processing. This issue has been fixed in the revised report.

*5.6 As the Report only considers agricultural conduit hydropower capacity potential in the 17 western states - the statement, "The *national* agricultural conduit hydropower capacity potential is nearly 637 MW." is not accurate, correct?*

- Correct. Although the 17 western states should likely capture the most potential, this will not be verified unless we extend the analysis to other states. We have discussed this limitation in Section 4.2.

Reviewer 6

6.1 This is a 50+ page report with significant technical information throughout. For non-technical readers the upfront summary is as far as they will read and will be the only opportunity to communicate to them the results, key facts, and other important messages of the study. I recommend greatly expanding the amount of information included here. Otherwise, they have to seek information throughout the document and go to p.50 to the discussions and conclusions section. Also would add the word "Executive" in front of "Summary".

- Thank you for the suggestion. We have revised the Executive Summary following this suggestion.

6.2 Can additional points of reference be used to provide the impact of 1.39 GW? For example, how much power is this in terms of powering x number of homes? Or the city the size of X? (If not for inclusion in this report, it would be nice to have these kinds of examples included in talking point information when it is released.)

- We have expanded the Executive Summary to highlight the potential impacts.

6.3 Also, there was no characterization of the GHG emissions reduction benefit of this much generation. Could that be included in the report or as a talking point when released?

- We have stated that, “The projects also do not result in increase of greenhouse gas emission” in the revised Executive Summary.

6.4 As part of the key takeaways section, or as a section of the executive summary on its own, there should be a "next steps" or "further research needs" discussion. This is included at the end of the document, but most readers are not going to flip back to page 51 to find them.

- Thank you for the suggestion. We have revised the Executive Summary following this suggestion.

6.5 Why make the comment that the 1.39 GW "may seem small?" This seems to downplay the impact. In the context of meeting US/DOE climate goals, every MW counts. This statement was used elsewhere in the report and would recommend changing it. Also, the average size of retiring coal plants appears to be about 154 MW. This conduit potential then could be characterized as replacing almost 10 coal plants. In that context, I don't think it sounds "small.".

- Thank you. It has been modified in the revised report.

6.6 I note that these are distributed energy resources, but yet I don't recall that term being used descriptively at all in the report.

- Thank you. It has been modified in the revised report.

Reviewer 7

7.1 After reading whole report, it may be helpful to copy Figures 21, 22 and 23 up into the STUDY SCOPE AND SUMMARY section starting on page ix… the 1.39 GW punchline is there, but I think adding those figures up to this could result in a nice Executive Summary 2-pager.

- Thank you for the suggestion. We have revised the Executive Summary following this suggestion.

7.2 Agree that for purposes of the study reasonable to assume all water available, but may want a footnote to effect that may not always be the case if some nominal amount need for cooling water or some other purpose specific to the generating equipment.

- Thank you for the suggestion. While we agree with this comment, we do not want to overcomplicate the description here. The actual flow availability will certainly be site-specific and can be quite different from the gross assumption.

7.3 May want a footnote to effect that potential developers may want to confirm this (a permit does not always necessarily mean it got developed)…also, could there be a list or table of such sites that were so deemed and excluded (as an appendix).

- Thank you. We have revised the original description to avoid confusion. These permitted but undeveloped sites are tracked by the ORNL Hydropower Market Report Team. The latest development pipeline data can be accessed at https://hydrosource.ornl.gov/dataset/us-hydropower-development-pipeline-data-2022.

Reviewer 8

8.1 The research and report is a good start, however, it lacks anecdotal insight that might have been achieved by including input from entities deploying these technologies in solid pipe infrastructure. Perhaps in future studies.

- Thank you for the insightful comment. We have included public engagement as one important next step in Section 4.4.

8.2 The adoption of Sustainable (ESG) business practices can be mentioned in conclusions as a driver for more focus on conduit hydropower by industrials.

- Thank you for the insightful comment. We have included this point in Section 4.4.

8.3 Requiring energy recovery audits on new pipeline infrastructure projects financed by federal government can be recommended as a policy consideration to support better data gathering and assessment.

- While we agree that this may be a possible approach, it is outside our ability to make such kinds of recommendations in this resource assessment. This can be a possible topic in future policy-focused studies.

8.4 It should be noted that a growing trend is to transition open channel irrigation system to closed solid pipe infrastructure eliminate evaporation and drought and flood control. As this transition occurs, the infrastructure can be designed to become energy recovery ready.

- Thank you for the insightful comment. We discussed this concept in Section 4.4 as one potential next step.

8.5 Flow control and PRVs are deployed in food, beverage processing, mining and O&G processing and enormous amounts of water is used during 24/7/365 cycles. Industrials need more ESG incentives to increase adoption since they generally require shorter economic payback cycles than municipal entities. The study does not appear to address the growning need of colling water in data centers. "The total annual operational water footprint of US data centers in 2018 is estimated at 5.13 × 108 m3," the paper states, with the industry relying on water from 90 percent of US watersheds. 5.13 billion cubic meters equates to 5.13 trillion liters (1.128 trillion imperial gallons, 1.36 trillion US gallons) of water.

- Thank you for the insightful comment. We have added these as uncounted potential in Section 4.2.

8.6 Limitations in data should include the effects of back-pressure on wastewater operations which potentially change operational procedures at plants where hydropower is deployed.

- Since we only consider conduit hydropower potential using the treated or discharged water before returning into a natural waterway, the back-pressure during wastewater operations may not be a concern here.

8.7 Cooling systems are engineered to take full advantage of inlet head/flow hydraulics delivering and distributing water from chillers. Best opportunity is at outflow infrastructure and releases.

- Thank you for the insightful comment. It is consistent with our proposed method in this study.

Reviewer 9

9.1 This report is done very well in a systematic approach. Although many necessary assumptions and simplifications were made, it still provides a good baseline, reconnaissance-level understanding of the potential.

- Thank you for the positive feedback and encouragement.

9.2 I'm interested in what potentials exist for other U.S. territories (Puerto Rico, Guam, etc.). Due to the remote nature, reliance on fossil fuels, and susceptibility to atmospheric hazards/disasters this could be a really important piece of the puzzle for them.

- We agree with the needs to better understand the conduit hydropower potentials in other US territories. The data availability may be the main limiting factor but may be overcome through the direct collaboration with local authorities. We may explore this in potential future studies.

9.3 Are fossil, nuclear, biomass plants the types of thermoelectric plants that were analyzed here? Or are there others? Maybe explicitly state what types of plants were included in this study.

- We are analyzing thermoelectric power plants reported by the EIA Form 860 data set (discussed in Section 2.4.1).

9.4 On all maps, consider placing a graticule or labels on perimeters of the maps to provide location information for the reader to reference where appropriate.

- Maps in the report are provided to present examples; the location of the examples should not be relevant.

9.5 Consider using average flows instead of the minimum. If the minimum was chosen to avoid misreported data, fix the units of the misreported data and then use the average. This would seem more appropriate than simply using the minimum.

- We are using the minimum of total facility design flow, actual average facility flow, and total facility flow to avoid potential overestimation. In this context, we suggest that the minimum among these three types of flow should be the most trustworthy one.

9.6 Why doesn't DC have a PWS listed?

- Based on the data and method, we did not identify positive capacity and generation potential for PWSs in Washington DC.

Reviewer 10

10.1 In the Next Steps section (Increased Public Awareness): One of the reasons of low private investment in hydropower projects is a lack of understanding in private developers on the benefits of the projects. I think one of the next steps should be engaging with the key stakeholders involved in the conduit hydropower development projects. It is mentioned in the public awareness subsection but I was wondering whether it would be a separate subsection. Some examples are key stakeholders are: developers, technology providers, community representatives where these projects are hosted, environmental groups, etc.

- Thank you. We have expanded the final item to incorporate this suggestion.

Reviewer 11

11.1 Has the potential for climate changes which result in different precipitation patterns and amounts been incorporated in the analysis?

- Thank you for raising this issue. We have clarified in multiple places in Section 2 that the issue of climate change is not included in this analysis. Although climate change will affect water availability across different regions, the flow within these conduits is mainly controlled by demand and less by natural variability. The potential impacts of climate change on water availability for regional conduit supply and hydropower generation would be worthy of further investigation.

11.2 Has an estimate of the energy revenues available for infrastructure rehabilitation or improvement been made to indicate what proportion of the cost of these improvements could be recovered?

- It is not within the scope of this study. We do however acknowledge the need of further assessment in Section 4.4.

11.3 It would be helpful to know what percent of the small conduit expedited process applications were ultimately determined to be "qualifying conduits" and approved using the expedited process. This may give developers insight into their likelihood of expedited approval. It may be additionally helpful to provide this percentage for each of the 3 sectors.

- A footnote was added stating that 90% of projects submitted were found to be qualifying conduit facilities.

11.4 Footnote 1 should indicate that the definition of, eligibility for, and process for obtaining FERC conduits exemptions were different during the time periods that are presented.

- Clarification has been added to distinguish between exemptions and qualified conduit facilities.

11.5 Were relatively few industrial conduit applications made due to lack of information or some other reason?

- We expect to further discuss this question through the extended stakeholder engagement meetings after the publication of this report.

11.6 The Water Research Foundation prepared a nationwide road map for energy development at existing water infrastructure facilities in 2014, Report No. 4356. The report included 32 potential energy development projects which had a high likelihood of implementation.

- Thank you. The suggested literature has been included in the revised report.

11.7 Table 2: What is the accuracy of the Digital elevation dataset? The level of uncertainty could affect the economic feasibility of each site.

- We have cited the Maune (2007) study, which suggested that the overall root mean square error of the absolute vertical accuracy of NED is approximately 2.44 m. Overall, the accuracy of digital elevation dataset is considered to be much smaller than other factors, such as the location of water intakes/drinking water plants.

11.8 Was any amount of correlation or agreement evaluated between the TIGER data and the PWS service area data to determine how well they agreed or what the accuracy was for capturing all of the subject population?

- We did not conduct such an evaluation since it requires more detailed PWS data that are not nationally or regionally available. TIGER data appear to be the best available data to support our intended analysis.

11.9 10-meter vertical resolution does not appear to be fine enough to assess small conduit hydropower potential. There are operating, conventional hydropower projects with less than 10m of head. Given that small conduit hydropower projects have a huge challenge to be feasible, a much finer level of accuracy of the total head would be needed. I would expect that actual elevation data is available for constructed infrastructure, which, when used with the 10-meter resolution for those points where actual data is not available, would provide more accurate results of the energy potential.

- 10 m is the horizontal resolution. We have clarified it in the revised report.

11.10 Was a single, national per capita water use value used for all assessments or were regional per capita values produced? Regional per capita values would be more accurate, just as regional energy consumption values are.

- We have revised the original description to avoid confusion. We do have separate per capita data for domestic and industrial/commercial use at each county. They are both used to estimate PWS conduit hydropower potential.

11.11 The significant assumptions should be presented and described, as well as how they were used in the model.

- The assumptions are discussed in Section 2.6. Further sensitivity analyses are provided in Section 3.5.

11.12 If most of the head was achieved in a relatively short horizontal distance of the conduit, that could indicate a more attractive and economically feasible site than of the total head is achieved over the entire conduit length. Although indicated in this section, this scenario does not appear to be considered in the sensitivity analysis, other than as a function of calculating head loss.

- This understanding may not be fully accurate. In a pressurized conduit, although the pressure drop occurs at the location of a PRV/turbine, one will need the entire closed pipe to build up the pressure head. It is unclear what sensitivity analysis can be done here.

11.13 Water treatment plants are designed not only to satisfy the current public water demand but also to have reserve capacity and capacity to address growth in demand. In the discussion of flow estimates, the existence of this additional capacity which will likely be utilized in the future, presents an opportunity for energy generation growth in the future as well. While this report does not have the data to quantify such growth, presenting this potential may increase the attractiveness of developing PWS energy resources.

- Thank you for the insightful comment. We have included this insight in the revised report.

11.14 Aren't these 2 equations (9 and 11) circular? Doesn't QDO = Q county_DO_supply? If Q county_withdrawal is known, can this be used as a proxy for water treatment plant capacity (adjusted for losses)? If this suggestion is accepted, Figure 4 will need to be revised to reflect this change.

- No, these are not circular. Q_county_DO_supply is the county-based total from the USGS 2011–2015 estimates (Dieter et al. 2018), while Q_DO is the flow of the PWS that we need. A PWS may not serve the entire county.

11.15 Given the significant assumptions in developing Q pws, is there value in estimating the conduit hydropower potential by sector (municipal vs. industrial)? Further, depending on where the maximum net head is in the entire conduit, siting the hydropower facility may be upstream of all water users. I suggest deleting these lines.

- We suggest that there are good values to report potentials for the industrial sector. As shown by our findings, there should be sizeable amount of conduit hydropower potential from industrial conduits. However, the development of conduit hydropower is extremely limited. We hope that the specific number can promote industrial stakeholders to evaluate the conduit hydropower opportunities in their systems.

11.16 This paragraph implies to me that multiple drop sites which were identified on a flow line where aggregated into a single drop for the purposes of this analysis. If this is an accurate interpretation of the information presented, then this artificially inflated the energy potential. Developing a hydropower generation facility at a single location with an economically-feasible net head is different and likely less expensive than developing hydropower at multiple, adjacent sites with smaller heads but the same total head.

- The purpose of this processing step is to avoid identifying duplicated drops. The process will not simply combine multiple drops together. Also, all identified locations were further examined during a QA/QC process to ensure that the drops were reasonably identified.

11.17 Were the Reclamation data on actual canal slopes compared to the calculated slopes to determine if the calculated slopes are reasonable?

- Reclamation data do not provide canal slope information.

11.18 Was the energy potential calculated in this report from each of the undeveloped Reclamation sites that were retained in this analysis compared to the energy potential as determined in the Reclamation 2012 report for accuracy?

- Since Reclamation (2012) sites have been used to train the canal drop-detection model, they were considered as the known ground truth and were not reevaluated in this study.

11.19 It is not clear from the text how source data were used to calculate the net head for each thermoelectric facility. Were plant cooling water discharge points visible on aerial imagery? What is the resolution or accuracy of the vertical data?

- We tried to manually identify the discharge canal and determine elevation change from Google Earth. Although Google Earth provided a different digital elevation dataset, these DEM data sets overall provide comparable estimates should be adequate for the purpose of this study.

11.20 Summing the total cooling water flows from each thermoelectric facility will underestimate the economic value of the energy estimates if the multiple cooling water pipes do not converge prior to the point where they discharge water back to the lake. Multiple hydro turbines would be required, with the associated cost increases to achieve the total estimated energy production.

- We agree with this insightful comment, but we do not have sufficient data to refine the level of assessment. The current assessment is only meant to provide a high-level estimate of the total potential.

11.21 Assuming that a constant flow was available all year would overestimate the energy potential of the site, particularly for those facilities that include stormwater in their discharge outfalls or that have irregular wastewater discharges. Given the limits of the data used, a pro-rata factor should be applied.

- We agree with this insightful comment, but we do not have sufficient data to refine the level of assessment. The current assessment is only meant to provide a high-level estimate of the total potential.

11.22 The 68% capacity factor seems arbitrary. Using a comparison between actual flows and the facility design flow should provide a justifiable range of capacity factors.

- The 68% capacity factor was in agreement with the values used for the PWS assessment. The determination of actual capacity factor requires site-specific data that cannot be collected within the scope of this study.

11.23 Six feet of head is not economic to develop hydropower. At that point, the analysis should be discontinued as little or none would be developed in reality. To provide an estimate and not consider the economic feasibility presents an illusion of potential capacity.

- While we agree that the 6 ft value is small and not economic, the real challenge here is that the head information cannot be estimated based on the current datasets. Therefore, the 6 ft assumption represents a conservative estimate for the purpose of total potential calculation. As suggested by Figure 10, higher head may likely exist in many sites for potential future development.

11.24 If a subset of the NPDES permittees could be evaluated and determined if higher than 6 feet of head existed, further analyses should be done with that subset only to estimate energy potential.

- We agree with this suggestion. Further efforts should be considered to improve the accuracy of the resource data.

11.25 Most NPDES discharge facilities do not want to have discharge water back up into their facility. Without a reservoir installed between the facility and the potential hydroturbine, it should be anticipated that many facilities would decline to pursue hydropower development on their wastewater discharges.

- Our method considers conduit hydropower generation using the treated water before returning into a natural waterway. The opportunity will only exist where the receiving waterway is at a lower elevation than the discharge point. The method does not expect that the discharge water will back up into the facility.

11.26 Table 7: It would be helpful to include the number of locations in each state to provide an indicator of average development size.

- Since the proposed method is designed to calculate the total potential in the system, it cannot tell the number of sites and the average size per site.

11.27 It may be helpful to also present the national data by state from largest potential to smallest potential.

- Thank you for the suggestion. We have provided the top 10 states in Figure 23. All county and state summary data will be publicly available to support further evaluation.

11.28 It may be more indicative to only present counties with potential above 25kw. Less than that is very unlikely to be developed.

- While we agree that sites in counties with lower potential are unlikely to be developed, we do not assign a minimum threshold in this study since our goal is to estimate the total potential. Data users will be able to set up desired thresholds themselves when reviewing the findings of this study.

11.29 The estimated potential should be further filtered for only sites that have an estimated capacity of more than 25 kw (a case could be made to use 100 kw as well) as these small potential sites have practically no chance to be developed.

- While we agree that sites with lower potential are unlikely to be developed, we do not assign a minimum threshold in this study since our goal is to estimate the total potential. In addition, much of the site-level information cannot be shared because of NDA restrictions.

Reviewer 12

12.1 ALL CONDUITS: By assuming only conventional hydropower technologies and efficiencies this is a technical resource assessment. Would it have been beneficial to estimate the theoretical assessment first? See IEC TC 114 TS for definitions. Please state explicitly the type of resource assessments conducted *(technical) and cite IEC TS 62600-1 for definition of theoretical, technical and practical resource. It would be good to include a paragraph to distinguish these 3 types of resource.*

- Thank you for the suggestion. We have described the scope of this reconnaissance-level hydropower resource assessment in Section 1.4. The scope and terminologies are consistent with our previous resource assessments, such as NPD and NSD.

12.2 IRRIGATION, INDUSTRY CANALS: For better alignment with WPTO resource assessment approach for marine energy, would prefer sequential assessment of resource like river resource, starting with theoretical, then technical, and eventually practical resource, See IEC TC 114 62600-1 for definitions of theoretical, technical and practical resource. The theoretical resource assessment would use a similar methodology as US river resource assessment, which was the theoretical hydrokinetic resource for segments other than those with drops. Therefore, there is a much larger theoretical and technical resource than is estimated here. There should at least be a justification statement why this theoretical and technical hydrokinetic resource was not included.

- Thank you for the suggestion. We have described the scope of this reconnaissance-level hydropower resource assessment in Section 1.4. The scope and terminologies are consistent with our previous resource assessments, such as NPD and NSD. We also acknowledge in Section 4.2 that the hydrokinetic hydropower potential in canals is not counted in this study.

12.3 IRRIGATION, INDUSTRY CANALS: Consider next step to assess national theoretical and technical hydrokinetic resource using similar methods as US river resource assessment. Note that the National Academy endorsed the methods for the river hydrokinetic theoretical resource, but not for the technical resource assessment.

- Thank you. We have acknowledged in Section 4.4 the needs to examine hydrokinetic potential in future research.

12.4 IRRIGATION CANALS: The resource assessment for canals only includes hydraulic drops.

- Thank you. We have acknowledged in Section 4.2 that the hydrokinetic hydropower potential in canals is not counted in this study.

12.5 The methods, equations are sound. The assumptions seem reasonable, and I believe were validated. Consider conducting a simple first order uncertainty propagation analysis to estimate the uncertainty of P in Equation 1, with propagation of any systematic or random error in independent parameters, flow rate, head, efficiency, and capacity factor. This way you can bound the national assessment based on the assumptions and uncertainties quantifying these independent parameters.

- Thank you for the recommendation. To understand the propagation of uncertainty, further information about the correlations/dependencies among the main factors will be required, which is not available based on our current data. This can be a focus of future research.

12.6 This report would ideally include a review of the hydropower technologies, conventional and hydrokinetic, that could generate power from these conduits, including their operating ranges, efficiencies, etc. Following this review, there should be a justification why only conventional hydropower technologies were considered.

- Thank you. We have acknowledged in Section 4.4 the needs to examine hydrokinetic potential in future research. We designed the current study to focus on conventional technologies since they have been widely accepted and demonstrated in existing applications.

Reviewer 13

13.1 "The authors should explicitly state that these estimates provide an upper-bound estimate for the canal resource using both 'conventional hydropower technology and using hydrokinetic technologies.

I know that this suggestion is in direct contradiction to feedback you have received from others who suggest you ""state that this resource assessment does not say anything about the hydrokinetic resource"". However, I simple energy-balance analysis can show that it is not possible to get more energy out of these systems than is contained in the potential energy (volume flux times head).

Stating this in your report would do a great service to the marine hydrokinetic industry because it would give a definitive picture of what the U.S. canal hydrokinetic market is. If you'd like to have a follow up conversation, I'd be happy to discuss the topic further.

I am especially interested in this because I frequently get asked in my work, ""what is the US canal potential for marine energy technologies"". I'll be pointing people to your report as the answer to this question, and so it would be good if the report were explicit about this. At the very least, please do not add a statement such as ""this does not provide an assessment of the hydrokinetic resource"", because that would just create more confusion."?

- Thank you for the recommendation. To balance the conflicting comments among reviewers, we have added some additional comments in Sections 4.2 and 4.4 to state that some additional hydrokinetic hydropower potential may exist in canals, and further efforts may be beneficial to help understand these more novel technologies. We designed the current study to focus on conventional technologies since they have been widely accepted and demonstrated in existing applications.