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An Assessment of Energy Potential at Public Drinking Water Systems: Initial Report on Methodology

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Environmental Sciences Division

AN ASSESSMENT OF ENERGY POTENTIAL AT PUBLIC DRINKING WATER SYSTEMS: INITIAL REPORT ON METHODOLOGY

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

CDA	Colorado Department of Agriculture
CDP	census-designated place
CDPHE	Colorado Department of Public Health and Environment
Census	US Census Bureau
CEO	Colorado Energy Office
DEQ	Oregon Department of Environmental Quality
DOE	Department of Energy
DOI	Department of Interior
EHA	Existing Hydropower Asset
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FRS	Facility Registry Service
HDPE	high-density polyethylene
HREA	Hydropower Regulatory Efficiency Act
MAF	Master Address File
MTDB	Master Address File and Topologically Integrated Geographic Encoding and Referencing Database
NAVD88	North American Vertical Datum of 1988
NDA	nondisclosure agreement
NED	National Elevation Dataset
NHAAP	National Hydropower Asset Assessment Program
NHD+	National Hydrography Dataset Plus
NPD	non-powered dam
NRC	National Research Council
NSD	new stream-reach development
ORNL	Oak Ridge National Laboratory
POTW	publicly owned (wastewater) treatment work
PRV	pressure-reducing valve
PWS	public water system
QA/QC	quality assurance and quality control
Reclamation	Bureau of Reclamation
RPS	Renewables Portfolio Standard

SDWA	Safe Drinking Water Act
SDWIS	Safe Drinking Water Information System
SWRCB	California State Water Resources Control Board
TIGER	Topologically Integrated Geographic Encoding and Referencing Dataset
USACE	US Army Corps of Engineers
USGS	US Geological Survey

LIST OF VARIABLES

C_f	Capacity factor
D	Conduit diameter (ft)
E	Hydroelectric energy (watt * hour)
f	Friction factor
g	Gravitational constant
GW	Gigawatt (10^9 watt)
kW	Kilowatt (10^3 watt)
kWh	Kilowatt–hour (10^3 watt * hour)
H_{diff}	The elevation difference (ft) between upstream and downstream locations
H_{net}	Net hydraulic head (ft)
h_L	Total head loss (ft)
h_f	Frictional head loss (ft)
L	Conduit length (ft)
MW	Megawatt (10^6 watt)
MWh	Megawatt–hour (10^6 watt * hour)
P	Hydroelectric power (watt)
Re	Reynolds number
S	Total service population
Q_{PWS}	Water treatment plant capacity (ft^3/s)
q_{PWS}	Domestic, publicly supplied per capita water use (ft^3/s/person)
Q_{tur}	Turbine flow (ft^3/s)
T	Total annual hydropower plant operation time (hours)
V	Average conduit velocity (ft/s)
Z_{down}	The elevation (ft) at the downstream location
Z_{up}	The elevation (ft) at the upstream location
ε	Roughness height (ft)
η	Generating efficiency
ρ	Water density ($slug/ft^3$)
γ	Specific weight of water (N/m^3)
μ	Dynamic viscosity (lb s/ft^2)

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ABSTRACT

The hydroelectricity potential from man-made water conduits (e.g., pipelines, aqueducts, irrigation ditches and water conveyance canals) across municipal, agricultural, and industrial sectors has been estimated as being relatively small but having high development feasibility. Given the various benefits of conduit hydropower—e.g., no need for new construction of dams or impoundments, minimal environmental concerns, reduced development risks, eligibility for net-metering in most states, and probable qualification for the expedited 60 day regulatory approval process through the Hydropower Regulatory Efficiency Act of 2013—conduit hydropower development may be the most economically feasible type of new hydropower development for the near future. While individually these projects may seem small, collectively, they may provide stable energy output and help offset local energy demands for water system operators.

However, mainly because of data limitations, the total conduit hydropower potential across states and/or regions has not been comprehensively quantified. 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 support the Department of Energy and the broader hydropower community in estimating the national conduit hydropower potential for further policy and program planning, focusing on municipal conduit hydropower as the starting point, a geospatial conduit resource assessment method designed for national public water systems (PWSs) is introduced in this study. Multiple public and non-public data sets, including PWS information, water intake locations, water treatment plant locations, city boundaries, digital elevations, historic water use, and existing conduit hydropower development, were collected for the states of Oregon and Colorado for the proof-of-concept assessment. The analysis introduced herein represents the first step in getting a systematic understanding of national conduit hydropower potential across various states/regions and eventually across multiple sectors (i.e., municipal, agricultural, and industrial). PWS projects examined in this study will be developed mainly through installation of hydropower generation in parallel to existing pressure-reducing valves to recover the otherwise wasted energy.

Following the proposed methodology and assumptions, conduit hydropower potentials using surface water with a positive gravitational net head were identified in 89 PWSs in Oregon and 63 PWSs in Colorado. In terms of the total population, these PWSs serve 1.92 million of 4.14 million people in Oregon, and 2.86 of 5.61 million people in Colorado. *A total 12,380 kW of potential conduit hydropower capacity was estimated in Oregon and 33,990 kW in Colorado. Their corresponding annual hydroelectricity energy supply is estimated to be 65,068 MWh/year in Oregon and 202,475 MWh/year in Colorado.* In Oregon, the most conduit hydropower potential was identified in the western parts of the state. In Colorado, the highest conduit hydropower potential was identified in the western and central parts of the state. These potentials jointly reflect the amount of water supply (highly related to population) as well as suitable topography to provide sufficient net hydraulic head for hydropower generation. Additional conduit hydropower opportunities for use of the excess hydraulic head from pumping may exist but are not evaluated in this study due to data limitations. We expect to gradually expand the assessment to other states or regions to enable a comprehensive understanding of the national PWS conduit hydropower potential and the inter-regional differences.

1. INTRODUCTION

1.1 BACKGROUND

Among various undeveloped hydropower resources classified by the US Department of Energy (DOE), the hydroelectricity potential from man-made water conduits (e.g., pipelines, aqueducts, irrigation ditches and water conveyance canals) has been estimated as being relatively small but as having the highest development feasibility (DOE, 2016). This type of small hydropower development does not require the construction of new dams or impoundments; involves minimum environmental concerns; entails reduced development risks; is eligible for net-metering in most states, yields high value for the energy generated; and is likely to qualify for an expedited 60-day regulatory approval process through the qualifying conduit approval process created by the Hydropower Regulatory Efficiency Act (HREA) of 2013. Based on the features of conduits, conduit hydropower development can be further 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). This type of small hydropower project is installed in parallel to existing pressure-reducing valves (PRVs) with hydropower generators that use excess pressure (originally reduced by PRVs) for hydropower generation and energy recovery. Municipal conduit hydropower also covers publicly owned wastewater treatment works (POTW) conduits that are mostly gravitationally fed.

- **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 much larger flow (compared with PWS), the hydropower capacity of canal conduit projects is usually larger than that of PWS projects.

- **Industrial** conduit hydropower refers to generating facilities located at industrial pipelines. Although the industrial sector (including industrial, mining, aquaculture and thermoelectric) has the largest water withdrawals, 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, thus far there is little industrial sector development of conduit hydropower—notwithstanding the fact that industrial developments are likely to be particularly efficient and cost-effective insofar as they are typically eligible for onsite net-metering.

Nevertheless, despite the high development feasibility, the amount of total conduit hydropower resources and their spatial distribution across the country are not clearly known. The lack of understanding hinders the active development of the conduit hydropower market. To support policy planning and to guide future research and investment decisions, a comprehensive national conduit resource assessment is needed to quantify the magnitude of potential conduit hydropower resources.

1.2 CURRENT STATE OF CONDUIT HYDROPOWER DEVELOPMENT

Many small conduit projects (<40 MW) already qualify for exemption from the licensing requirements of Part I of the Federal Power Act and can follow a simpler (compared with the full license) FERC exemption application process. This FERC regulatory process was further reduced by the HREA of 2013.

Qualifying conduit projects can secure FERC approval per HREA within 60 days provided that they (1) are less than 5 MW, (2) use a non–federally owned conduit, (3) serve a primary purpose other than hydropower generation, and (4) are not currently licensed or exempted. Between the passage of HREA in August 2013 and June of 2018, 97 projects nationwide with a total of almost 33 MW in capacity received "qualifying conduit" determination from FERC. They are mostly clustered in Western 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 Idaho (FERC Docket CD14-1) and as small as the 1.7 kW Adak Water System in the city of Adak, Alaska (FERC Docket CD15-25).

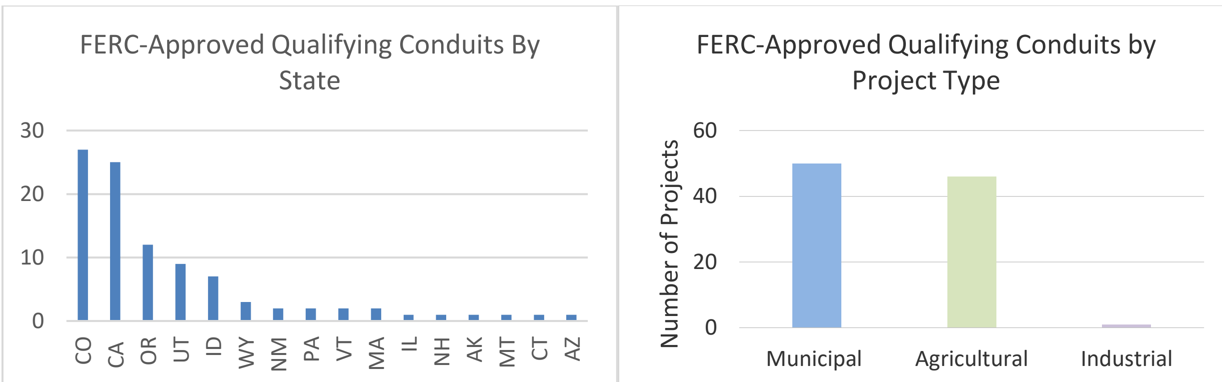

Figure 1. FERC-approved qualifying conduits by state and project type (as of June 2018).

This rate of project development is slower than originally expected. Given that PRVs are commonly used in almost every PWS (as well as in industrial pipelines), a number of municipal and industrial water users should have sites suitable for HREA development. One barrier can be the limited awareness among water utilities of 2013 federal reforms. 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 have sufficient motivation and incentive to explore it. A federally supported, nationwide conduit resource assessment could be a good motivator. The prior non-powered dam (NPD; Hadjerioua et al., 2012) and new stream-reach development (NSD; Kao et al., 2014) resource assessments have promoted wide public awareness of potential undeveloped hydropower resources. An analogous study focusing on the national conduit resource is likely to have a similar effect, helping to spur awareness and project development.

1.3 PRIOR CONDUIT HYDROPOWER RESOURCE ASSESSMENT EFFORTS AND CURRENT GAPS

As noted in the Hydropower Vision report (DOE, 2016), there has been no nationwide resource assessment focusing on potential hydroelectricity capacity and energy available through powering existing conduits. 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. A report prepared for the California Energy Commission (Kane et al., 2006) suggested that there were approximately 255 MW of Renewables Portfolio Standard (RPS)–eligible small hydropower projects in California (i.e., also likely HREA-feasible) that could be developed in man-made conduits. This resource estimate was based on survey data from 43 large and medium-size water purveyors (water agencies and irrigation districts) that collectively accounted for about 65% of the total annual water entitlements 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. While challenges related to small hydro development were comprehensively discussed, the study did not offer a state-level estimate of the potential small hydropower resources. For Massachusetts, Allen and Fay (2013) and Allen et al. (2013) evaluated the in-conduit energy potentials for PWS and POTW facilities using both survey data and publicly available information. Under low- and high-head assumptions (required owing to 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 600–3000 MWh/year in POTW systems in Massachusetts. The Colorado Energy Office (CEO, 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, CEO estimated that there is 20–25 MW of hydropower potential in replacing PRVs statewide. The Colorado Department of Agriculture (CDA, 2013) completed an agricultural hydropower assessment that estimated 30 MW of untapped potential using pressurized irrigation. In addition, the Bureau of Reclamation (Reclamation, 2012) conducted a hydropower resource assessment focusing on Reclamation-owned canals and showed approximately 268 MW and 1.2 million MWh/year of potential resources. Overall, based on the existing studies and data (presented above and Sale et al., 2014), DOE (2016) made a ballpark estimate that there could be around 2 GW of total conduit hydropower potential across the country. However, an in-depth national conduit resource assessment has not yet been conducted.

Overall, multiple challenges associated with conduit hydropower resource assessment 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 (USACE) National Inventory of Dams serves as a good foundation for an NPD hydropower resource assessment, there has not been a national or regional conduit database to provide necessary baseline information for hydropower resource evaluation. This data issue is further complicated by the different conduit setting in each sector.

    - **Municipal**: For municipal conduits, the locations, pressure differences, and pipeline capacities (e.g., gallons/day) 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. To overcome this data barrier, federal government (e.g., DOE) support and coordination is needed.

    - **Agricultural**: Although there are fewer infrastructure concerns associated with agricultural conduits, canal drop sites are usually known only to the irrigation districts and have not been comprehensively documented across the country. Furthermore, although public geospatial data sets such as the National Hydrography Dataset Plus (NHD+) contain nearly 174,000 miles of artificial pathways and 177,000 miles of canal ditches, the data sets are not always up to date; and there are pathways and ditches that 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 largest total water utilization, the understanding of conduit hydropower potential in the industrial sector is minimal. While the total water utilization and discharge may be approximated from some federal or state databases, there has been no good way to reasonably assume or approximate possible hydraulic head opportunities for the purpose of conduit hydropower resource evaluation. Furthermore, types of conduits are expected to vary across industries (e.g., thermoelectric versus mining), adding further complexity to data collection.

- **Limitation of survey**: While targeted surveys remain the most viable approach when data are extremely limited (Kane et al., 2006; CEO, 2016), such an approach is time and resource consuming and always suffers from lower response rates than are desirable. For example, CEO (2016) encouraged water utilities to participate in the development of a statewide database of PRVs. Although this initiative was well-perceived 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 larger uncertainty.

- **Inconsistent methodology**: The current small hydropower resource assessments conducted in each state have been based on different data types and methodologies. While they all have been developed based on the unique legal and market features in each state, it is challenging to incorporate the findings into a common regional or national platform. For the purpose of inter-regional resource comparison, a spatially consistent resource evaluation method is needed.

Recognizing the current gaps and challenges in each sector, sector-specific approaches that are best suited for the current state of data availability and understanding for each sector are required. The methodology developed in this study presents one first step toward the quantification of conduit hydropower potential within the municipal sector. We expect that this proposed methodology may contribute to and eventually help lead to the first quantitative estimate of total US conduit hydropower potential.

1.4 SCOPE AND OBJECTIVE OF THIS STUDY

To support DOE and the broader hydropower industry in quantifying the total hydropower potential from conduits, this study introduces a generalized conduit hydropower resource assessment method focusing on public drinking water systems within the municipal sector. The assessment method is 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 present-day assumptions about conduit hydropower technology. Given the higher priority of estimating state/national total resource potentials, the assessment method will not emphasize deriving site-specific generation and cost estimates that are sufficiently accurate for direct use to support project-specific feasibility assessment or to justify investments. Instead, the assessment will use a spatially consistent approach to systematically analyze the conduit potentials across different states to allow further inter-regional resource comparison and enable a national assessment in a spatially consistent manner.

The assessment leverages the best available data acquired through federal and state drinking water regulatory agencies. Two states with readily available drinking water system information, Oregon and Colorado, are included in this pilot study. At each state, the potential conduit hydropower resources associated with each PWS (with available information) are estimated without revealing sensitive PWS information at any site. The initial findings and experience gained through this pilot study are summarized in this report to support a future DOE national conduit hydropower resource assessment across multiple sectors. In addition to helping the hydropower industry quantify the magnitude of potential HREA-eligible conduit hydropower resources, the capacity and energy estimates can be used by national energy deployment models such as the National Renewable Energy Laboratory Regional Energy Deployment System and the Energy Information Administration (EIA) National Energy Modeling System to improve projections of future hydropower growth.

2. PROPOSED METHODOLOGY

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. Nevertheless, although such information is known to each PWS owner and utility, there is no comprehensive data set available at state and national scales to support overall resource evaluation. To estimate the conduit hydropower potential associated with national PWSs, alternative data sets and necessary simplifications are needed. After consulting with state drinking water agencies, the US Geological Survey (USGS), and the Environmental Protection Agency (EPA) regarding the availability and limitations of PWS-related data, multiple national/state data sets were selected in this study (summarized in Table 1). While most of these data sets are publicly available, one most critical type of information, PWS water intake location, is protected information in most states. A nondisclosure agreement (NDA) is required to access such information.

- **Public Water System Information**

  The 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 (SDWA) and its 1986 and 1996 amendments. Under SDWA, 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 that was obtained from SDWIS.

- **Water Intake Location**

  The water intake location is one key piece of information for the estimation of conduit hydropower potential in PWS. However, given 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 initial assessment, an NDA has been established between the Colorado Department of Public Health and Environment (CDPHE) and Oak Ridge National Laboratory (ORNL) to exchange and protect such data. Similar data usage agreements with the California State Water Resources Control Board (SWRCB) and EPA have been put in place in preparation for the expanded national assessment in the future. Oregon is among the states with publicly available drinking water source area information. Using the polygons of surface water drinking water source areas released by the Oregon Department of Environmental Quality (DEQ), we identified the PWS water intake locations from further geospatial analysis. An example is shown in Figure 2.

- **Water Treatment Plant Location**

  Public water treatment plant locations are looked up from the EPA Facility Registry Service (FRS) Facility Interests Dataset. The EPA FRS identifies and geospatially locates facilities, sites, or places subject to environmental regulations or of environmental interest. The FRS Facility Interests Dataset provides integrated location and facility identification information for all facilities that are available in the FRS individual feature layers. It comprises the FRS major program databases including SDWIS, National Pollutant Discharge Elimination System, Integrated Compliance Information System, and others. An example of water treatment plant locations is shown in Figure 2.

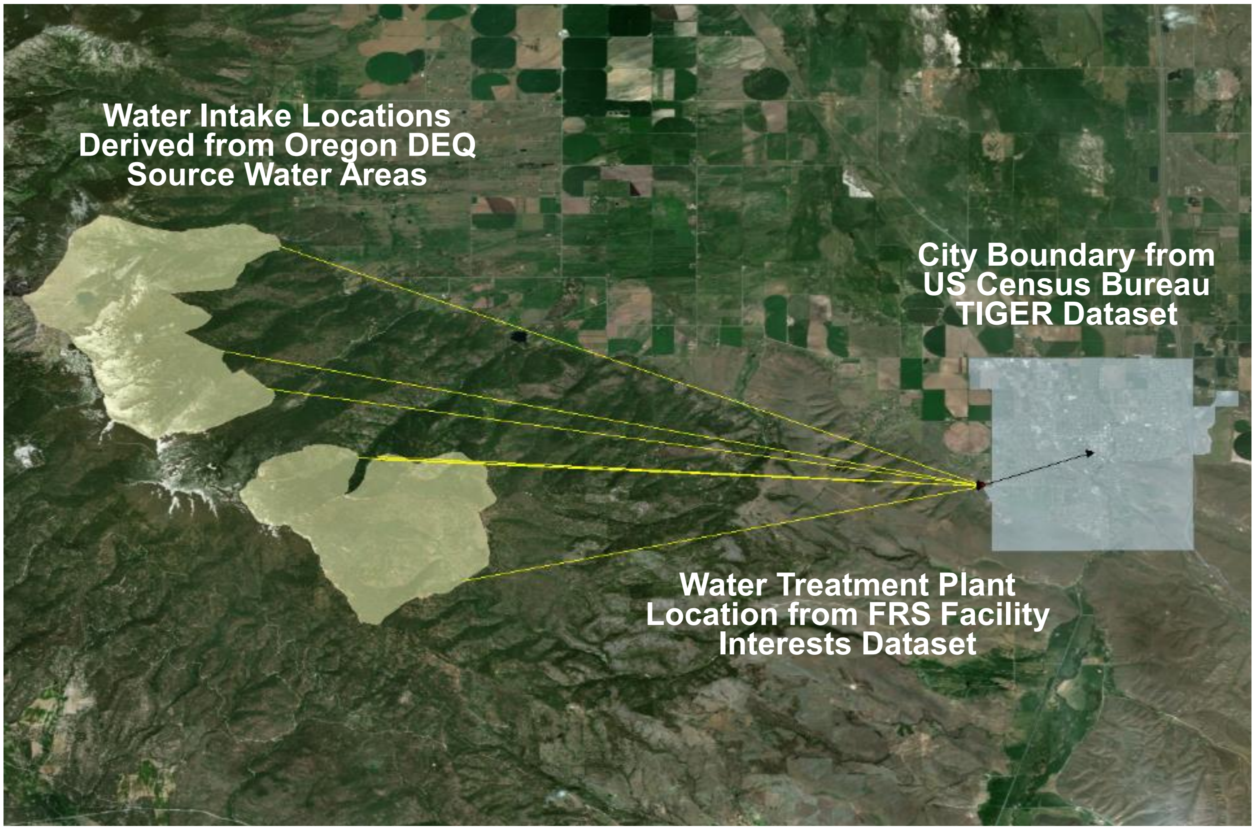

Figure 2. An example of multiple data sets collected in this study.

- **City Boundary**

  Since there is no comprehensive, state/national geospatial data set of PWS service areas, we used the US Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) city/place geospatial data set as a proxy in this study. The TIGER shapefiles and related database files are an extract of selected geographic and cartographic information from the US Census Bureau's Master Address File and Topologically Integrated Geographic Encoding and Referencing (MAF/TIGER) Database (MTDB). The TIGER shapefiles include both incorporated places (legal entities) and census-designated places (CDPs; statistical entities). An incorporated place usually is a city, town, village, or borough, but can have other legal descriptions. CDPs are delineated for the decennial census as the statistical counterparts of incorporated places. The boundaries for CDPs 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 us understand the main destination of the PWS. In this assessment, we overlapped city boundaries with digital elevations to estimate the average elevation of a city. An example is shown in Figure 2.

- **Digital Elevation**

  To look up the elevation at water intakes, water treatment plants, and the destination cities, we used the 1/3 arc-second (~10 m) resolution USGS National Elevation Dataset (NED; Gesch et al., 2002) in this study. The 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 (NAVD88). The overall root mean square error of the absolute vertical accuracy of NED is reported to be around 2.44 meters (Maune, 2007). The NED data set was also used in other national hydropower resource assessments (e.g., Kao et al., 2014).

- **Historic Water Use**

  To estimate conduit hydropower potential, the water treatment plant capacity (i.e., gallons/day) is another necessary piece of information. Nevertheless, 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 historic water use of each PWS, we used the domestic, publicly supplied per capita use from the 2010 USGS water use assessment (Maupin et al., 2014) as an alternative. The series of 5 year USGS assessments reported average daily withdrawals (in gallons per day) by source (groundwater and surface water) and quality (fresh and saline) for each county and state. Withdrawals are classified by category of use: public supply, domestic (including self-supplied domestic and deliveries from public supply), irrigation, livestock, aquaculture, industrial, mining, and thermoelectric power. Based on the county that a PWS mainly serves, we looked up the per capita water supply information from the USGS water use assessment and multiplied it by the PWS service population to approximate the water treatment plant capacity. During future national assessments and discussions with each state, if it is determined that more detailed water treatment plant information (e.g., monthly or seasonal) can be made available, the per capita–based water use approximation can be replaced to increase the accuracy of the assessment.

Table 1. Summary of data sources

Data type	Data source	Reference / website
Public water system information	• EPA Safe Drinking Water Information System (SDWIS)	• https://www.epa.gov/enviro/sdwis-overview
Water intake location	• Colorado Department of Public Health and Environment (CDPHE) • Oregon Department of Environmental Quality (DEQ)	• Protected information in most states
Water treatment plant location	• EPA Facility Registry Service (FRS) Facility Interests Dataset	• https://www.epa.gov/enviro/geospatial-data-download-service
City boundary	• US Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) Dataset	• https://www.census.gov/geo/maps-data/data/tiger.html
Digital elevation	• USGS National Elevation Dataset (NED)	• https://nationalmap.gov/elevation.html
Historic water use	• USGS National Water-Use Science Project	• https://pubs.usgs.gov/circ/1405/
Existing hydropower asset	• ORNL NHAAP Existing Hydropower Asset (EHA) Dataset	• https://nhaap.ornl.gov/existing_hydropower_assets

- **Existing Hydropower Assets**

  Existing hydropower development information was obtained from the ORNL National Hydropower Asset Assessment Program (NHAAP) Existing Hydropower Asset (EHA; Samu et al., 2018) data set. NHAAP is an integrated hydropower information platform maintained by ORNL for the DOE Water Power Technologies Office. Hydropower plant characteristics such as capacity, number of turbines, turbine types, modes of operation, permit number, plant owner/operator, and historic generation are regularly incorporated from multiple agencies, including EIA, FERC, USACE, Reclamation, and the Tennessee Valley Authority. We studied the characteristics of PWS conduit hydropower projects permitted in each state either before or after the enactment of HREA to understand the features of developed conduit projects and to summarize some project characteristics (e.g., historic generation and capacity factor) to use in our proposed resource assessment model.

2.2 PWS CONDUIT HYDROPOWER RESOURCE ASSESSMENT MODEL

To estimate the total hydropower potential in a region, three key pieces of information will be required: (1) available sites, (2) distribution of net hydraulic head H_{net} (ft), and (3) distribution of turbine flow Q_{tur} (ft^3/s). With the data limitations in mind, our biggest challenge will be to estimate these three required parameters based on the best-available data. The detailed methods and procedures are discussed in this section.

2.2.1 Power and Energy Estimates

Consistent with previous hydropower resource assessments (Kao et al., 2014; Reclamation, 2011; DOI, 2007), the following equations are used to estimate the potential hydroelectric power P (watt) and energy E (watt * hour) 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 = 9800 N/m^3 is the specific weight of water, c = $(0.3048)^4$ is the unit conversion factor, and T is the total amount of time (hours) for which a conduit hydropower plant is operated (annually or seasonally). For the purpose of hydropower resource assessment, the future hydropower turbine is usually considered to be designed around the optimal operating point; therefore, η can be reasonably assumed to be a constant 0.85 (e.g., USACE, 1983). However, given that the sizes of conduit projects are generally smaller, this 0.85 efficiency may not be easily achieved. This assumption of efficiency will be further examined in future assessment by identifying a most representative value from commonly-used conduit hydropower turbines.

Another important variable that can help to characterize a hydropower plant is capacity factor (C_f). It can be defined as

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

In general, the value of capacity factor C_f varies depending on the nature and economics of the project (e.g., peaking vs. conduit). For instance, many irrigation systems only operate seasonally (from April to October), so their C_f can be 50 to 60% at best. To be consistent with previously proposed conduit projects, we summarized the historic generation and capacity factors from NHAAP EHA to inform the assumptions of our methods.

2.2.2 Net Hydraulic Head Estimates

For open water conduits, the net hydraulic head H_{net} is usually estimated by the elevation differences 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:

$$H_{net} = H_{diff} - h_L \ . \tag{4}$$

The total head loss h_L can be further divided into two components: (1) major (frictional) head loss h_f due to 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:

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

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 looked up from the Moody diagram (Morris and Wiggert, 1972) or solved by the following Colebrook formula:

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

$$Re = \frac{\rho V D}{\mu} \ , \tag{7}$$

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 $\times 10^{-5}$ lb·s/ft^2 is the dynamic viscosity.

Clearly, without the full details for existing conduits (i.e., size, material, spatial distribution), the above equations cannot be solved. To overcome this data limitation, we made the following simplifications and assumptions for the purpose of conduit hydropower resource evaluation:

- **Gravitational head only (i.e., no pumping)**: This assessment focused only on the gravitational head potential, i.e., analyzing the elevation difference and head loss from PWS source to destination, without evaluating the additional head potential generated by pumping. This simplification is needed mainly because of data limitations. Nevertheless, it should be noted that some existing conduit hydropower developments utilize the excess head generated from pumping for energy recovery. Examples include the 32.7MW Mojave Siphon project within the California Aqueduct (P-14580), as well as other inter-basin water transit projects. Therefore, in reality, there could be further conduit hydropower potential for a PWS even with very little or negative gravitational head, as reported in this study.

- **2-part analysis**: Based on the available geographical location data collected from multiple sources, a 2-part analysis is suggested. It includes the following:

    - **Part 1—untreated water**: The first part of the analysis focuses on the net hydraulic head from water intake (data from state drinking water agencies) to water treatment plant (data from EPA FRS). We calculated the direct distance from intake to treatment plant as L, looked up the elevations of these locations from NED, and used the information in Eqs. (1) – (7) to calculate H_{net}.

    - **Part 2—treated water**: The second part of the analysis focuses on the net hydraulic head from the water treatment plant to the main service city/county (data from TIGER). We calculated the direct distance from water treatment plant to city center as L, overlapped the polygon of the city with NED to calculate the average elevation of the city, and used the information in Eqs. (1) – (7) to calculate H_{net}.

- **Conduit material**: We assumed the conduit material to be commonly used commercial steel with roughness ε = 0.00015 ft.

- **Conduit velocity**: After reviewing 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), we selected the mean annual conduit flow velocity V = 2 ft/s in this study. With the assumed conduit velocity and PWS flow information (derived from USGS water use information discussed in the following section), we were able to calculate the corresponding conduit cross-section area, diameter, and friction factor, as well as frictional head loss from Eqs. (1) – (7).

- **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, we propose to use the following equation to approximate head loss:

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

  In other words, we are using another straight-line frictional loss 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 intake and treatment plant is very small, the head loss term will be close to zero; and hence the net hydraulic head will decay to 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. During the future expanded national assessment, we will communicate with stakeholders across different states/regions, gather their feedback on these assumptions, and revise this assumption based on more detailed local information on conduits.

2.2.3 Flow Estimates

As stated in Section 2.1, given the lack of actual data for water treatment plant capacity Q_{PWS} (ft^3/s), we used Eq. (9) to approximate Q_{PWS}:

$$Q_{PWS} = S * q_{PWS} \ , \tag{9}$$

where S is the total service population from SDWIS and q_{PWS} (ft^3/s/person) is the county-based domestic, publicly supplied per capita water use information from the USGS water use assessment (with unit conversion from gallon/day to ft^3/s). We selected q_{PWS} from the same county in which each PWS was located. Here, Q_{PWS} represents the mean annual total water treatment plant capacity. Seasonal, monthly, weekly, and/or diurnal variability can be expected.

The next questions 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 our intention is to understand the maximum potential of a PWS, we assume that all PWS flow can be passed 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 can be considered reasonable. With this assumption, the relationship between Q_{tur} and Q_{PWS} becomes

$$Q_{tur} = \frac{Q_{PWS}}{n * C_f} \ , \tag{10}$$

where n represents the number of total intakes (with available information from state/EPA) of a PWS, or the number of targeted service areas (from the TIGER data set). To be consistent with previously proposed conduit projects in the same state or region, we looked up C_f from existing PWS conduit hydropower projects from NHAAP EHA. The results are shown and further discussed in Section 3.1.

2.2.4 Assessment Procedure

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

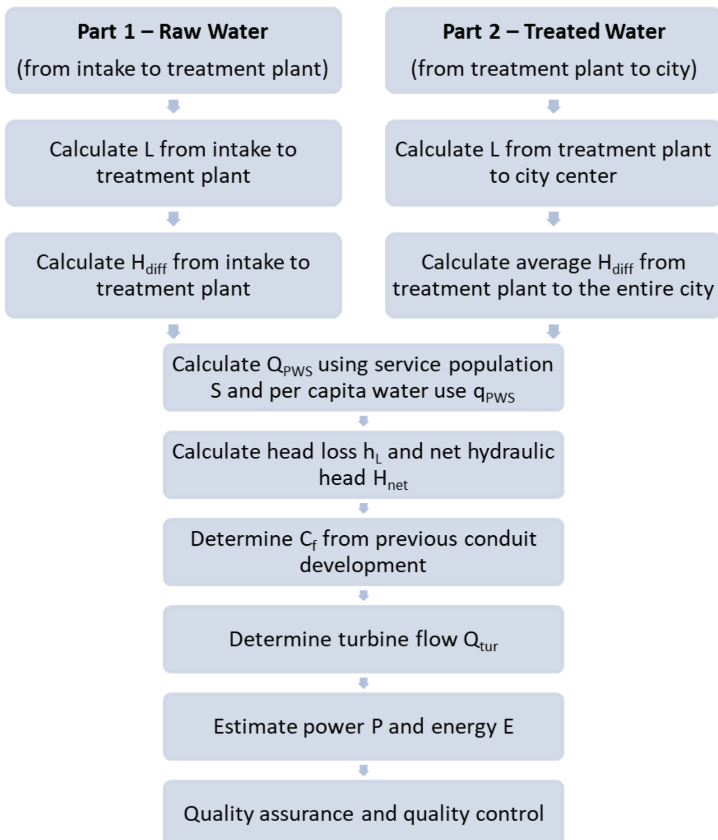

Figure 3. Summary of assessment procedure.

3. PILOT STUDY

3.1 STUDY AREA

To test and demonstrate the applicability of the proposed methodology, we conducted a pilot study for the states of Oregon and Colorado. The main consideration in selecting these two states is data availability (in particular, water intake locations). As discussed in Section 2.1, Oregon is among the states with publicly available drinking water source area information. For each water intake location, DEQ delineated the watershed boundary above the water intake into geospatial polygons. We overlapped the DEQ source area polygons with NED and identified locations with the lowest elevations to be water intakes in this assessment. For the state of Colorado, we were able to establish an NDA between CDPHE and ORNL within the pilot study timeframe to secure the protected water intake information. While we originally planned to include California in this pilot study, the NDA negotiation took longer than expected and hence did not leave sufficient time for assessment. Nevertheless, it is worth noting that similar data agreements with the California SWRCB and directly with EPA are now in place. These established NDAs will help to expedite the national assessment in the future.

For Oregon and Colorado, we started by reviewing PWS conduit hydropower projects that were permitted either after or before the enactment of HREA (Table 2 and Table 3). The information summarized in Table 2 and Table 3 is mostly pre-development final license information collected from the FERC eLibrary. If a project has been built and is reporting to EIA, the information from EIA Forms 860 and 923 is then used (see Samu et al., 2018 for further information). Overall, 4 Oregon (118 kW, 615 MWh/year, average C_f = 60%) and 16 Colorado PWS projects (1005 kW, 5975 MWh/year, average C_f = 68%) acquired HREA exemptions from FERC. Given the nature of HREA, these HREA conduit projects are generally smaller than the earlier conduit projects exempted through the conventional FERC process (6 projects in Oregon with 839 kW, 3719 MWh/year, average C_f = 51% and 19 projects in Colorado with 34565 kW, 96183 MWh/year, average C_f = 32%). Another main difference between the projects before or after HREA is the sizes of utilities and projects. In both states, the conduit projects permitted before HREA are mostly larger projects developed by large water utilities (e.g., City and County of Denver, City of Boulder, Portland Water Bureau), whereas medium- to small-size utilities seem to pursue smaller projects through HREA.

Based on the results from Table 2, we selected C_f = 60% for Oregon and C_f = 68% for Colorado in the following assessment. Note that given the design of the proposed methodology, the maximum total energy potential will be fixed no matter which C_f is used. A smaller C_f will lead to a large total capacity value (and vice versa).

Table 2. Permitted PWS conduit hydropower projects through HREA in Oregon and Colorado

State	FERC docket #	Project name	Exemptee	Capacity (kW)[a]	Estimated annual net generation (MWh/yr)[a]	Estimated capacity factor (%)
Oregon	CD17-16	Wallowa Lake County Service District Hydro Station	Wallowa Resources Community Solutions Inc.	20	149	85
Oregon	CD14-19	Rock Creek Water Treatment Plant Hydropower Project	City of Corvallis	28	219	89
Oregon	CD13-6	Bear Creek Watershed Hydroelectric Project	City of Astoria	60	175	33

Oregon	CD13-5	Corbett Hydroelectric Project	Corbett Water District	10	72	82
		Total		**118**	**615**	**60**
Colorado	CD17-15	NTM Water Treatment Plant Hydro Project	North Table Mountain Water and Sanitation Dist.	150	250	19.0
Colorado	CD17-11	Gypsum Hydroelectric	Town of Gypsum	85	650	87
Colorado	CD17-8	Nettle Creek WTP	Town of Carbondale	28	190	78
Colorado	CD17-5	Alma WTP Hydro Project	Town of Alma	25	200	91
Colorado	CD17-4	SCWTP Hydro Project	City of Louisville	34	196	66
Colorado	CD17-3	Louisville Recreation	City of Louisville	13	78	69
Colorado	CD17-2	Louisville HBWTP	City of Louisville	33	196	68
Colorado	CD16-11	SCMWD Treatment Plant	St. Charles Mesa Water	40	40	11
Colorado	CD15-34	Manitou Springs WTP	City of Manitou Springs	40	250	71
Colorado	CD15-31	Grand Lake WTP	Town of Grand Lake	20	150	86
Colorado	CD15-27	Double Cabins PRV	Mountain Village	5	10	23
Colorado	CD15-26	San Joaquin PRV	Mountain Village	15	15	11
Colorado	CD15-18	Soldier Canyon	Soldier Canyon Filter Plant	100	875	99
Colorado	CD14-20	Fort Collins Micro Hydro	City of Fort Collins	75	550	84
Colorado	CD14-5	Pandora Water System	Town of Telluride	320	2135	76
Colorado	CD14-2	Orchard City WTP	Orchard City	22	190	99
		Total		**1005**	**5975**	**68**

[a] Capacity and estimated net generation values are summarized from FERC elibrary material. WTP = water treatment plant, SCTWP = Sid Copeland WTP; HBWTP = Howard Berry WTP

Table 3. Exempted conduit hydropower projects (before HREA) in Oregon and Colorado

State	**FERC docket #**	**Project name**	**Exemptee**	**Capacity (kW)[a]**	**Net annual generation (MWh/yr)[a]**	**Capacity factor (%)**
Oregon	P-14498	Conduit 3	Portland Water Bureau	200	1200	69
Oregon	P-14440	Energy Recovery Phase II	City of Pendleton	239	1012	48
Oregon	P-14407	Energy Recovery Phase I	City of Pendleton	161	697	49
Oregon	P-14371	Will Crandall Reservoir & Pump Station	City of Hillsboro	94	60	7
Oregon	P-13732	Vernon Station	Portland Water Bureau	25	206	94
Oregon	P-7058	Wolf Creek	Tualatin Valley Water District	120	545	52
		Total		**839**	**3719**	**51**
Colorado	P-14326	Basalt Hydroelectric Project	Town of Basalt	40	300	86
Colorado	P-13357	Project 7	Project 7 Water Authority	152	600	45
Colorado	P-13322	Cortez Micro Hydro	City of Cortez	240	1400	67
Colorado	P-12841	Plateau Creek	Ute Water Conservancy	610	2400	45
Colorado	P-12624	Cascade Generating Project	Colorado Springs Utilities	900	5114	65
Colorado	P-11531	Silver Lake Hydro	City of Boulder	2750	10951	45
Colorado	P-10973	Hillcrest	City & County of Denver	2000	4611	26
Colorado	P-10947	Longmont	City of Longmont	600	4340	83
Colorado	P-9922	Lakewood Hydro	City of Boulder	1500	8699	66
Colorado	P-9903	Orodell Powerhouse	City of Boulder	255	1160	52
Colorado	P-9545	Hotchkiss Powerhouse	Town of Hotchkiss	60	--	--
Colorado	P-9087	Sunshine Powerhouse	City of Boulder	800	3100	44

Colorado	P-8962	Kohler Powerhouse	City of Boulder	150	770	59
Colorado	P-7564	Maxwell Powerhouse	City of Boulder	68	520	87
Colorado	P-6282	Betasso Hydro Plant	City of Boulder	3100	8340	31
Colorado	P-5771	Foothills Hydro Plant	City & County of Denver	3100	4734	17
Colorado	P-3496	North Fork Hydro Plant	City & County of Denver	5500	6832	14
Colorado	P-1005	Boulder Canyon Hydro	City of Boulder	5000	15569	37
Colorado	P-768	Ruxton Park–Manitou Springs	City of Colorado Springs	7200	16345	26
		Total		**34565**	**96183**	**32**

[a] Capacity and net generation values are summarized from FERC elibrary material and EIA Forms 860 and 923 data sets. Net generation obtained from FERC elibrary is estimated value, while net generation from EIA is historic observation. See Samu et al. (2018) for further information.

3.2 FINDINGS

Following the proposed methodology and assumptions, we analyzed conduit hydropower potential for all PWSs using surface water with available information. Overall, we identified conduit hydropower potential from 89 PWSs in Oregon (i.e., with positive gravitational net head $H_{net} > 0$). These PWSs service a total of 1.92 million people (out of the total 4.14 million Oregon population; Census, 2018). In Colorado, we identified conduit hydropower potential from 63 PWSs in Colorado. These PWSs service a total of 2.86 million people (out of the total 5.61 million Colorado population; Census, 2018). As noted in Section 2, since we can analyze only the gravitational net head given the data limitation, there could be some additional conduit hydropower potential due to the excess net head generated during pumping that may be used for energy recovery.

3.2.1 Flow

A summary of the estimated treatment capacity of these analyzed PWSs is shown in Figure 4. The distribution of treatment capacity is highly skewed and concentrated on a few major PWS. The USGS domestic per capita public water supply varies largely across these PWS, from 54 to 222 gallons/day/person in Oregon and from 33 to 245 gallons/day/person in Colorado. Note that these average PWS treatment capacities were estimated from the service population and per capita data, not the actual treatment capacity information (which is unavailable at the national scale). Using more accurate and refined (e.g., seasonal or monthly) water treatment capacity information will help improve the accuracy of the assessment.

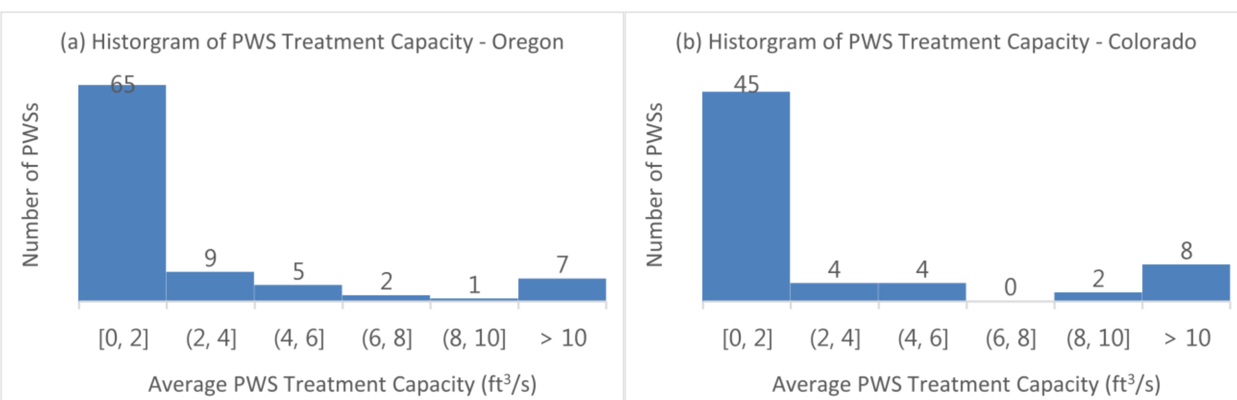

Figure 4. Histogram of PWS treatment capacity of (a) Oregon, and (b) Colorado.

3.2.2 Net Hydraulic Head

The estimated net hydraulic heads H_{net} of each PWS (with available information) in Oregon and Colorado are summarized in Figure 5 and Figure 6. The first part of H_{net} analyzed the net hydraulic head from location of intake to location of water treatment plant, and the second part of H_{net} analyzed the average net hydraulic head from location of water treatment plant to the entire city.

Overall, the topographic differences between Oregon and Colorado can be clearly seen. The average parts 1 and 2 H_{net} are 172 and 149 ft in Oregon (Figure 5) and 448 and 364 ft in Colorado (Figure 6). The higher hydraulic head in Colorado is consistent with the fact that more conduit hydropower projects were pursued in Colorado (than Oregon). The higher H_{net} would suggest the likely existence of PRVs that are needed to ensure a workable pressure within the entire water transit system.

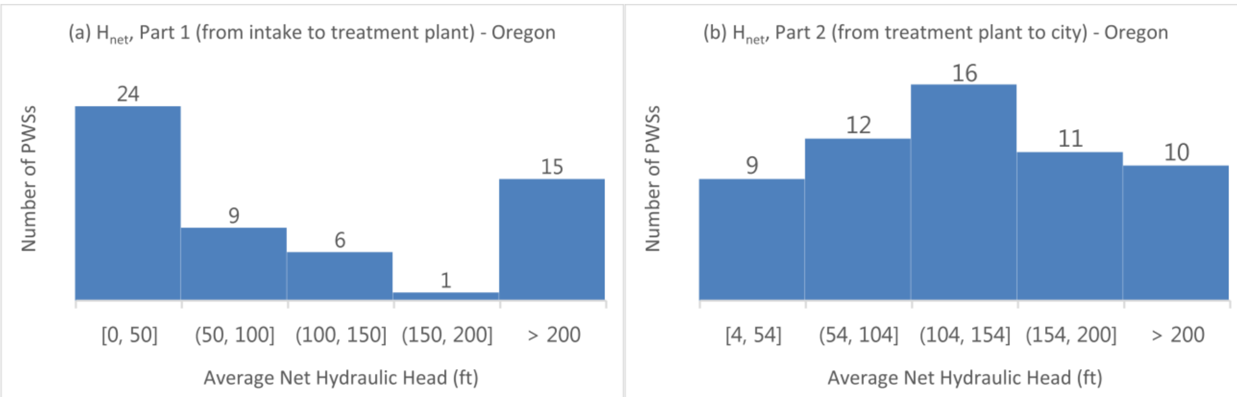

Figure 5. Histogram of (a) part 1 and (b) part 2 net hydraulic head of Oregon PWSs.

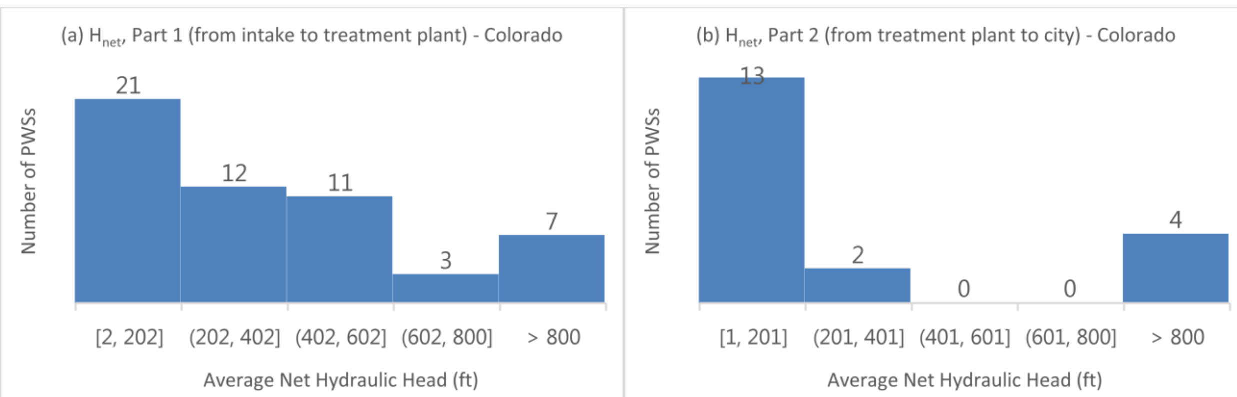

Figure 6. Histogram of (a) part 1 and (b) part 2 net hydraulic head of Colorado PWSs.

Note also that this part of the analysis involves the largest uncertainty within this assessment. Although our data sources provided the best available water intake and treatment plant locational information (among all other sources), nonetheless, the locational information is not available for all PWSs. In addition, it was noticed that some of the locational information might be inaccurate (e.g., water intake is several counties away from the corresponding treatment plant) and had to be excluded during the QA/QC process. However, given the sensitive nature of water intake information (i.e., per the terms of the NDA), it is challenging for us to conduct extensive cross-validation or solicit support from entities. With the continual improvement of the national PWS locational information, we expect that the accuracy of H_{net} can be enhanced in the future.

3.2.3 Power and Energy

Using both flow and head information, we estimated the potential conduit capacity P (kW) and energy E (MWh) for all PWSs (with available information) in Oregon and Colorado. The summary histograms are shown in Figure 7 and Figure 8. *Overall, the total potential conduit capacity (including parts1 and 2) is 12,380 kW in Oregon and 33,990 kW in Colorado. The total potential annual hydroelectricity energy is 65,068 MWh/year in Oregon and 202,475 MWh/year in Colorado.*

The distribution was again highly skewed (mainly because of the larger water treatment capacity in some utilities). Despite the fact that the total potential is concentrated in some larger water utilities (as expected), it is encouraging to see that conduit hydropower potential also exists in many mid-size to small utilities. Given the reduced and expedited regulatory process through HREA (as the resulting reduced development cost), these mid-size to small utilities can now also enjoy the potential benefits from conduit hydropower development.

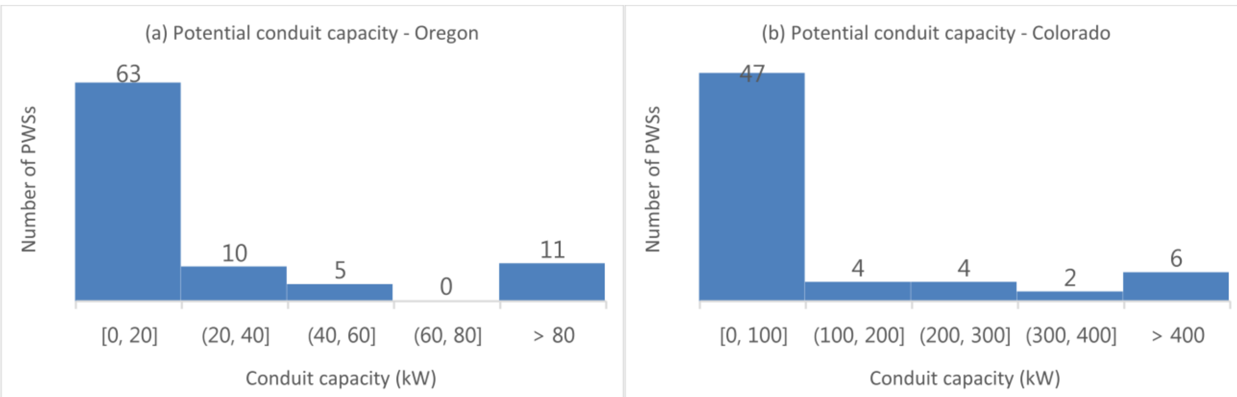

Figure 7. Histogram of potential conduit capacity of (a) Oregon and (b) Colorado.

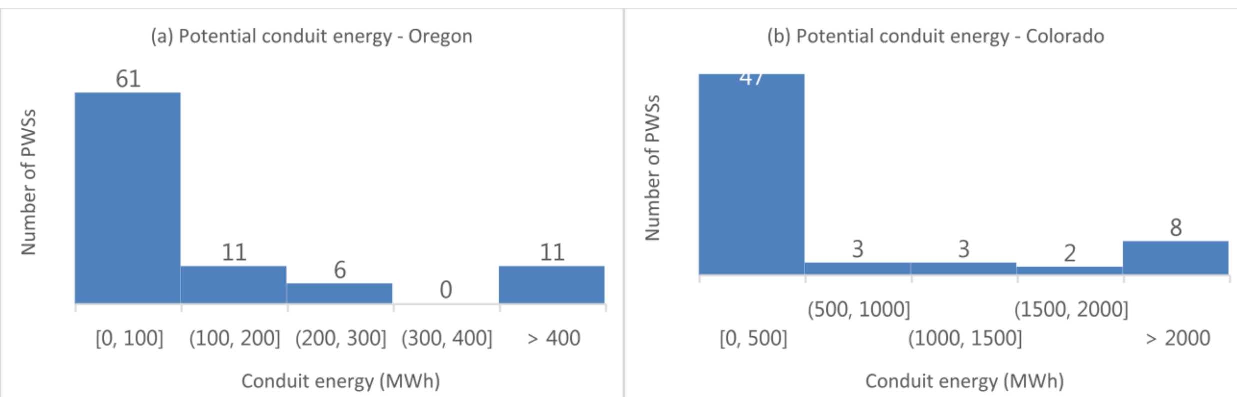

Figure 8. Histogram of potential conduit energy of (a) Oregon and (b) Colorado.

In Oregon, most potentials were identified in the western parts of the state (mostly following the distribution of population). In Colorado, the top conduit hydropower potentials were identified in the western and central parts of the state, in which the topography has a more significant influence.

3.3 MODEL SENSITIVITY

To understand the sensitivity of some assumptions made during the assessment (that we can quantify), we conducted a further model sensitivity analysis, which is discussed in this section. Specifically, we focused on the assumptions for conduit material/roughness, conduit velocity, and total head loss calculation. The results are reported in Table 4.

Our default scenario S1 assumed a conduit roughness ε = 0.00015 ft (commercial steel) and velocity V = 2 ft/s. Those assumptions led to the finding of 12,380 kW conduit hydropower capacity in Oregon and 33,991 kW capacity in Colorado. In scenario S2, we tested the sensitivity of ε by using ε = 0 ft in S2a (e.g., high-density polyethylene [HDPE] pipe) and ε = 0.0003 ft in S2b. The results showed that the effect is in fact 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 S3, we used V = 1 ft/s in S3a and V = 3 ft/s in S3b. Those assumptions resulted in a 5.6 to –10.5% change of capacity in Oregon and a 3.7 to –7.4% change of capacity in Colorado. Given that velocity is a square term in the equation for head loss (Eq. [5]), this larger sensitivity can be expected. In scenario S4, we examined the total head loss h_L assumption, which is approximated by 2 times the frictional head loss h_f in the default S1 scenario (Eq. [8]). A factor of 1.5 was tested in S4a and 2.5 in S4b, and it resulted in a 1.7 to –1.6% change of capacity in Oregon and a 1.1 to –1.1% change of capacity in Colorado. Overall, the highest sensitivity was found for the assumption of velocity, followed by velocity 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 assumptions and simplifications made herein are necessary to help form a regionally consistent assessment framework that can later allow comparison of the potential conduit hydropower resources across different states and regions.

Table 4. Summary of model sensitivity

Scenario	Roughness ε (ft)	Velocity V (ft/s)	Total head loss h_L (ft)	Oregon		Colorado	
				Capacity (kW)		Capacity (kW)	
S1 (default)	0.00015	2	2 * h_f	12380		33991	
S2a	0	2	2 * h_f	12422	(0.3%)	34072	(0.2%)
S2b	0.0003	2	2 * h_f	12343	(–0.3%)	33920	(–0.2%)
S3a	0.00015	1	2 * h_f	13075	(5.6%)	35252	(3.7%)
S3b	0.00015	3	2 * h_f	11078	(–10.5%)	31481	(–7.4%)
S4a	0.00015	2	1.5 * h_f	12588	(1.7%)	34375	(1.1%)
S4b	0.00015	2	2.5 * h_f	12176	(–1.6%)	33610	(–1.1%)

4. SUMMARY AND NEXT STEPS

4.1 SUMMARY

The hydroelectricity potential from man-made water conduits (e.g., pipelines, aqueducts, irrigation ditches, and water conveyance canals) across municipal, agricultural, and industrial sectors has been estimated as being relatively small but having high development feasibility. However, mainly because of data limitations, the total conduit hydropower potential across states and/or regions has not been comprehensively quantified. 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 support DOE and the broader hydropower community in estimating the national conduit hydropower potential for further policy planning, focusing on municipal conduit hydropower as the starting point, a geospatial conduit resource assessment method designed for national PWSs is introduced in this study. Multiple public and non-public data sets—including PWS information, water intake location, water treatment plant location, city boundary, digital elevation, historic water use, and existing conduit hydropower development—were collected for the states of Oregon and Colorado for the proof-of-concept assessment. The analysis introduced herein represents the first step in obtaining a systematic understanding of national conduit hydropower potential across various states/regions and eventually across multiple sectors (i.e., municipal, agricultural, and industrial).

Following the proposed methodology and assumptions, conduit hydropower potentials (with positive gravitational net head $H_{net} > 0$) were identified in 89 PWSs in Oregon and 63 PWSs in Colorado. In terms of the total population, these PWSs serve 1.92 million out of 4.14 million people in Oregon and 2.86 out of 5.61 million people in Colorado (Census, 2018). *A total of 12,380 kW of potential conduit hydropower capacity was estimated in Oregon and 33,990 kW in Colorado. The corresponding annual hydroelectricity energy potentials are estimated to be 65,068 MWh/year in Oregon and 202,475 MWh/year in Colorado.* In Oregon, the highest conduit hydropower potentials were identified in the western parts of the state. In Colorado, the highest conduit hydropower potentials were identified in the western and central parts of the state. These potentials jointly reflect the amount of water supply (highly related to population) as well as suitable topography to provide sufficient net hydraulic head for hydropower generation. Additional conduit hydropower opportunities that use the excess hydraulic head during pumping may exist but were not evaluated in this study because of data limitations.

Given the multiple benefits of conduit hydropower—such as the lack of need for new construction of dams or impoundments, minimum environmental concerns, reduced development risks, eligibility for net-metering in most states, and likely qualification for an expedited 60-day regulatory approval process through the HREA of 2013—conduit hydropower may be the most economically feasible type of new hydropower development for the near future. PWS projects examined in this study will mostly be developed through installing hydropower in parallel to existing PRVs to recover the otherwise wasted energy. While individually these projects may seem small, collectively, they may provide stable energy output and help offset local energy demands for water system operators, for whom energy costs are typically a substantial portion of operational costs.

4.2 ASSUMPTIONS AND LIMITATIONS

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), this study makes multiple assumptions and simplifications. These assumptions are summarized in Table 5.

Table 5. Summary of main assumptions and limitations of this study

Main assumption/ limitation	Description
Reconnaissance-level assessment	Given the higher priority of estimating 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 gravitational head potential without considering the additional excess head generated during pumping. While this is a necessary simplification, it also may lead to underestimation of the full conduit hydropower potential (e.g., opportunities located at the inter-basin water transit conduits)
Surface water only	In the current assessment, we focus only on surface water–source PWSs, since they have a higher magnitude of flow and are the main control to the total conduit hydropower resource estimate. However, although it is relatively smaller, conduit hydropower potential exists at PWSs that use groundwater as the main source. Some HREA exemptions were in fact issued to groundwater-based PWS
Conduit material	We assumed the conduit material to be the commonly used commercial steel with roughness of $\varepsilon = 0.00015$ ft. The sensitivity analysis (Section 3.3) suggested a lower sensitivity for this assumption.
Conduit velocity	After reviewing some previous HREA applications with available average conduit flow and velocity information, we selected a mean annual conduit flow velocity $V = 2$ ft/s in this study. 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, we propose to use two times the frictional head loss (calculated from a straight distance) 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, we used the PWS service population (from SDWIS) and county-based domestic, publicly supplied per capita water use information (from USGS) to approximate the mean annual water treatment capacity of a PWS
Flow availability	To understand the full PWS conduit hydropower potential, we assumed that all PWS flow can 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 NSD).
Capacity factor	Based on the proposed HREA project characteristics, we selected C_f = 60% in Oregon and C_f = 68% for Colorado in the assessment
Generating efficiency	Following NPD and NSD studies, a consistent $\eta = 0.85$ is used. However, we recognize that this may not be the most representative value for some commonly used conduit hydropower turbines. This assumption will be further reviewed and modified in the future assessment.

4.3 AVAILABILITY OF THE RESULTS

Given that parts of the input data are sensitive infrastructure information that were acquired through an NDA, the supporting PWS-level information cannot be publicly distributed. It will be used by DOE and other agencies to support development of further policy and investment strategies for the acceleration of national conduit hydropower development. The underlying data sets will continue to expand to support national-scale assessment, with an assumption that data, once released, will be summarized at the county level for public dissemination.

4.4 NEXT STEPS

Recognizing the different conduit settings in each sector (e.g., type, material, pressurized or open water, annual or seasonal operation, data availability), we think a sector-specific assessment approach will be needed to comprehensively evaluate the total conduit hydropower resources across the country. The methodology introduced in this study represents a very first step in quantifying the conduit hydropower potentials associated with PWS in the municipal sector. Given that most of the required input data are available at the national scale, the assessment can be gradually expanded to other states or regions to enable a comprehensive understanding of the national PWS conduit hydropower potential and the inter-regional differences.

Further efforts are needed to design the best assessment strategy for quantifying the conduit hydropower resources in other sectors (i.e., agricultural and industrial), as well as to evaluate other missing opportunities in the municipal sector (e.g., POTWs). During the discussion and interaction with other state drinking water agencies and PWS owners, we also hope to gather their feedback and use the more accurate PWS conduit information to enhance the accuracy of this assessment. These issues are to be explored in the future assessment.

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