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# The Integrated Basin-Scale Opportunity Assessment Initiative: Pilot Assessment for the Deschutes River Basin

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April 2014



**Pacific Northwest**  
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Pacific Northwest National Laboratory  
Richland, Washington 99352



## Summary

In 2010, the U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office provided funding to Pacific Northwest National Laboratory, Oak Ridge National Laboratory (ORNL), and Argonne National Laboratory to develop an approach for assessing a river basin as an integrated system within the context of existing uses and environmental conditions to identify opportunities for sustainable hydropower development and environmental improvements. The approach is intended to provide information that could be used to inform hydropower and environmental planning processes and potentially expedite licensing for new sustainable hydropower. Called the Integrated Basin-Scale Opportunity Assessment Initiative (BSOA Initiative), the project is one of seven action items of the March 24, 2010 Memorandum of Understanding (MOU) for Sustainable Hydropower between DOE, U.S. Department of Interior, and the U.S. Army Corps of Engineers.

Early efforts of the BSOA Initiative focused on forming a National Steering Committee, identifying potential basins for opportunity assessments, methodologies for stakeholder engagement, existing and needed analytical tools, barriers to the opportunity assessment process, and significant data gaps. One outcome of these efforts was construction of an online Opportunity Assessment Toolbox (<http://basin.pnnl.gov/Software/Index>) that contains various information, data, and analytical tools that exist for use among MOU agencies, non-federal partners, and stakeholders for assessing hydropower and environmental opportunities (described in the BSOA Initiative Fiscal Year 2011 Year-End Report).

This report describes the BSOA Initiative's pilot assessment of hydropower and environmental opportunities in the context of existing water uses in the Upper Deschutes River and Lower Crooked River subbasins in central Oregon. The goals of this pilot assessment was to develop and test a consistent approach and methodology for collaborative environmental and hydropower assessment, and to provide tools and information that could potentially aid evaluation of hydropower, environmental, and water use opportunities within the basin. Site visits and a Stakeholder workshop within the basin identified the need for collaborative decision-making tools that would allow a diverse group of stakeholders to explore and better understand the integration of hydropower opportunities, environmental opportunities, and water management in their basin.

In response to this need, the Basin-Scale Project Team chose a scenario-based modeling approach for assessing hydropower, environmental, and other water-use opportunities. The approach involved the development of a daily hydrologic model for the Upper Deschutes River and Lower Crooked River subbasins to simulate alternative water management scenarios designed to expose opportunities and tensions in the system. The model builds on previous work carried out by the Oregon Water Resources Department, the U.S. Geologic Survey, and the U.S. Bureau of Reclamation, and incorporates capabilities that were collaboratively envisioned by stakeholders at the beginning of the project. The Basin-Scale Project Team worked with water operators and modeling experts in the basin to calibrate and refine the model, which will be remain with the Bureau of Reclamation in the basin. A preliminary comparison of the model's baseline simulation to historic records indicates the need for an improved understanding of groundwater exchanges in the Upper and Middle Deschutes River; annual storage accruals at Crane Prairie, Prineville, and Ochoco reservoirs; and undocumented reservoir operations and water exchanges throughout the basin. However, these factors did not significantly hinder the ability to demonstrate the model's application to scenario-based modeling in the Deschutes Basin.

Project partners at ORNL identified potential hydropower opportunities from existing data sources and screened those opportunities for further evaluation. Twenty-nine potential sites (14 non-powered dams, 15 canal/conduit sites) were evaluated for their technical and economic feasibility using ORNL's Hydropower Energy and Economic Assessment tool. Results of the feasibility assessment indicated that eight of the sites (four non-powered dams, four canals/conduits) may be feasible and could add approximately 19 megawatts (MW) of hydroelectric capacity in the basin and generate over 78 gigawatt-hours (GWh) of energy per year. Most sites that were classified as feasible, as well as several that were classified as infeasible, were included in the hydrologic model developed by PNNL.

Two example scenarios were constructed to demonstrate the use of the hydrologic model to explore three management goals in the Deschutes Basin: 1) increasing hydropower assets by adding new generation at existing dams or diversions and in existing irrigation canals or conduits, 2) increasing instream flows to benefit fish and aquatic ecosystems, and 3) maintaining existing water uses (primarily irrigation). Actions to achieve these goals were simulated by incrementally increasing minimum flow requirements during the storage season and reducing water demands during the irrigation season, while simulating hydropower generation at non-powered dams and in irrigation canals. While this exercise was conducted primarily for demonstration purposes, results suggested that it may be beneficial to focus on water years in which management actions have the ability to move metrics above or below minimum criteria, because these years provide the best opportunity for identifying effective management actions.

As part of the effort to demonstrate scenario-based modeling, the project team also developed a web-based data-visualization interface for synthesizing modeling results. The interface allows users to view model results in raw form (daily flow) or in the form of value-based metrics that are based on specific information needs expressed by stakeholders (e.g., how often flow exceeds a conservation flow target at a certain location).

The approach presented here is intended to encourage consideration of methods that emphasize exploration of a range of potential management actions that may achieve a better balance among multiple, and often conflicting, management goals. It is important to consider the approach as an iterative and collaborative process focused on moving debates beyond agreement about an exact target that is acceptable to all parties to a discussion of how stakeholders can better understand how achieving their goals interacts with the goals by other stakeholder groups. By exploring the results of the model in this way, stakeholders are more likely to narrow the bounds of interest so that more in-depth analysis can be completed.

# Acknowledgments

The central idea of the Integrated Basin-Scale Opportunity Assessment Initiative is that by working together toward mutual goals we can accomplish more collectively than any one of us could working alone. This project represents one of many ongoing efforts to build respect, trust, and common purpose among stakeholders who have a stake in healthy rivers, clean energy, and adequate water supply now and into the future. It is both humbling and exciting to play a small part in this conversation and we acknowledge the hard work that has come before by agencies, industry, nongovernmental organizations, universities, national laboratories, and others to create the foundation and context for our current effort.

The Basin-Scale Project Team consisted of researchers from both Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL). PNNL acknowledges the expertise and hard work of ORNL researchers who contributed to this report as well as reports under separate cover (Zhang et al. 2013): Bo Saulsbury, Brennan Smith, Katherine Zhang, Amy Wolfe, and Kevin Stewart contributed information and expertise that informed stakeholder interaction, as well as hydropower inputs to the RiverWare model.

This project would not be possible without financial support from the U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office, as well as the vision, support, and participation by members of the hydropower industry, environmental community, agencies, irrigators, cities, and individuals willing to think creatively about new options and opportunities. We acknowledge the tremendous support and guidance from the following groups and individuals who have participated on Steering Committees and advisory groups for this project at the national scale as well as in the Deschutes Basin:

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- Mike Britton of the North Unit Irrigation District
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- 2011: Kearns and West (Anna West, Deb Nudelman, Megan Vinett, and Emily McGrath) carried out stakeholder interviews, facilitated the Deschutes Basin Workshop, and drafted the workshop report.
- 2013: Lara Fowler conducted pre-workshop interviews, facilitated the workshop, summarized outcomes, and carried out post-workshop interviews.



## Acronyms and Abbreviations

ANL	Argonne National Laboratory
BENO	Benham Falls, Oregon (gage site)
BSOA	Integrated Basin-Scale Opportunity Assessment (Initiative)
cfs	cubic foot/feet per second
COID	Central Oregon Irrigation District
Corps	U.S. Army Corps of Engineers
DEBO	below Bend, Oregon (gage site)
DOE	U.S. Department of Energy
DVWD	Deschutes Valley Water District
FERC	Federal Energy Regulatory Commission
GIS	geographic information system
GWh	gigawatt-hour(s)
HEEA	Hydropower Energy and Economic Assessment
Hwy	Highway
kW	kilowatt(s)
kWh	kilowatt-hour(s)
LCOE	levelized cost of energy
MAE	mean absolute error
MOU	Memorandum of Understanding
MW	megawatt(s)
MWh	megawatt hour(s)
NHAAP	National Hydropower Asset Assessment Program (DOE database)
NUID	North Unit Irrigation District
ODEQ	Oregon Department of Environmental Quality
ORNL	Oak Ridge National Laboratory
OWRD	Oregon Water Resources Department
PNNL	Pacific Northwest National Laboratory
PRB	Pelton-Round Butte (hydroelectric project)
RM	river mile
USBR	U.S. Bureau of Reclamation
WWPTO	Wind and Water Power Technologies Office (DOE)



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# 1.0 Introduction

The U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office (WWPTO) provided funding to Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and Argonne National Laboratory (ANL) (collectively referred to as the "Basin-Scale Project Team") to develop an approach to basin-scale hydropower assessment that emphasizes sustainable, low-impact or small hydropower and related renewable energies within the context of basin-wide environmental protection/restoration. Called the Integrated Basin-Scale Opportunity Assessment Initiative (BSOA Initiative), the assessment is one of seven action items identified in the March 24, 2010 Memorandum of Understanding (MOU) for Sustainable Hydropower between DOE, the U.S. Department of Interior (through the U.S. Bureau of Reclamation [USBR]), and the U.S. Department of the Army (through the U.S. Army Corps of Engineers [Corps]).

This report describes BSOA Initiative activities undertaken from October 2010 through October 2013, focusing on work to complete the BSOA Initiative's first pilot assessment in the Deschutes River Basin in central Oregon (2012–2013). This section provides background on the BSOA Initiative and activities leading up to selection of the Deschutes Basin pilot assessment.

## 1.1 Background

In 2010, the DOE WWPTO, in collaboration with the Corps, the USBR, the hydropower industry, and the environmental community, initiated scoping of the BSOA Initiative to identify and assess environmentally sustainable hydropower opportunities in river basins of the United States. Fundamentally, the BSOA Initiative asks the general question, "Within a given river basin, is it possible to increase hydropower generation and associated ancillary benefits, while at the same time improving environmental quality and protecting other important water uses?"

It is clearly recognized that environmental protection and development of renewable energy are linked and that hydropower will continue to provide significant generation of renewable electricity to the nation. There are opportunities for safe, sustainable development of new hydropower resources; powering of non-powered dams; and upgrading of many existing facilities to improve generation, grid services, and reduce environmental impacts (Hadjerious et al. 2012, 2013). However, these opportunities must be considered within the context of existing water uses and acknowledge adverse environmental effects associated with previous hydropower development.

The goal of the BSOA Initiative is to develop an approach that considers a basin as an integrated system within the context of existing uses and environmental conditions to identify opportunities for sustainable hydropower development and environmental improvements. In doing so, opportunity assessments would provide information that industry, stakeholders, environmental groups, the Federal Energy Regulatory Commission (FERC), affected Indian Tribes, and resource agencies could use to inform hydropower and environmental planning processes and potentially expedite licensing for new sustainable hydropower generation or ancillary services. Examination of river basins as integrated systems is possible through the use of advanced modeling and information-management tools, as well as through collaborative partnerships between industry, the environmental community, and agencies.

## **1.2 Development of the Deschutes Basin Pilot Assessment**

The Deschutes Basin pilot assessment, including formative efforts leading up to the assessment, took place between October 2010 and October 2013. Through 2010 and into 2011, efforts focused on the national level and included forming a National Steering Committee and identifying potential basins for opportunity assessments, preferred methodologies for stakeholder engagement, existing and needed analytical tools, barriers to the opportunity assessment process, and significant data gaps. These activities are described in greater detail in the BSOA Initiative Fiscal Year 2011 Year-End Report (Geerlofs et al. 2011).

While conducting these activities, the Basin-Scale Project Team, National Steering Committee, and other participants recognized the need for a pilot assessment to develop and apply an assessment approach in response to stakeholder needs within a specific basin. Together in 2010 and early 2011, they developed criteria for basin selection and evaluated a number of potential basins. An important part of this evaluation process involved developing an approach for evaluating stakeholder interest in participating in a pilot assessment. Upon completing these activities, the project team and National Steering Committee identified the Deschutes Basin as a preferred candidate for a pilot assessment, because it had strong stakeholder interest and sufficient geographic, jurisdictional, and operational complexity for testing assessment tools and methodologies. However, during this process it became apparent that an assessment focused narrowly upon hydropower and environmental opportunities would not be appropriate in the Deschutes Basin. Irrigation is tremendously important in the Deschutes Basin; in fact, nearly all the potential hydropower opportunities in the basin are associated with irrigation infrastructure, facilities, or practices. Therefore, it was decided the assessment should consider hydropower and environmental opportunities within the context of irrigation constraints and goals.

After selecting the Deschutes Basin for the BSOA Initiative's pilot assessment, efforts shifted toward developing tools necessary to assess hydropower and environmental opportunities at the basin scale. An online Opportunity Assessment Toolbox (<http://basin.pnnl.gov/Software/Index>) was completed in 2012 that compiles various information, data, and analytical tools that exist among MOU agencies, non-federal partners, and stakeholders. The Toolbox contains various information pertaining to environmental analyses, water resources analyses, systems modeling, geographic information system (GIS) expertise, new technology development, and data-management capabilities to support rapid, transparent, science-driven identification of hydropower and environmental opportunities. During this process, the project team began a high-level opportunity assessment in the basin through outreach to stakeholders and aggregation of existing data. From this high-level assessment, the team determined appropriate next steps and a detailed research agenda for identifying hydropower and environmental opportunities in the Deschutes Basin.

## **1.3 Report Contents and Organization**

The ensuing sections of this report describe the Deschutes Basin, results of the scoping assessments, and specific tasks that were performed to assess hydropower and environmental opportunities in the Upper Deschutes and Lower Crooked River subbasins. These tasks centered around development of a scenario-based modeling approach for assessing opportunities as described in Section 3.0. Section 4.0 summarizes an assessment of small hydropower economic and technical feasibility conducted by ORNL (described in detail by Zhang et al. [2013]). Section 5.0 describes a daily hydrologic model that was



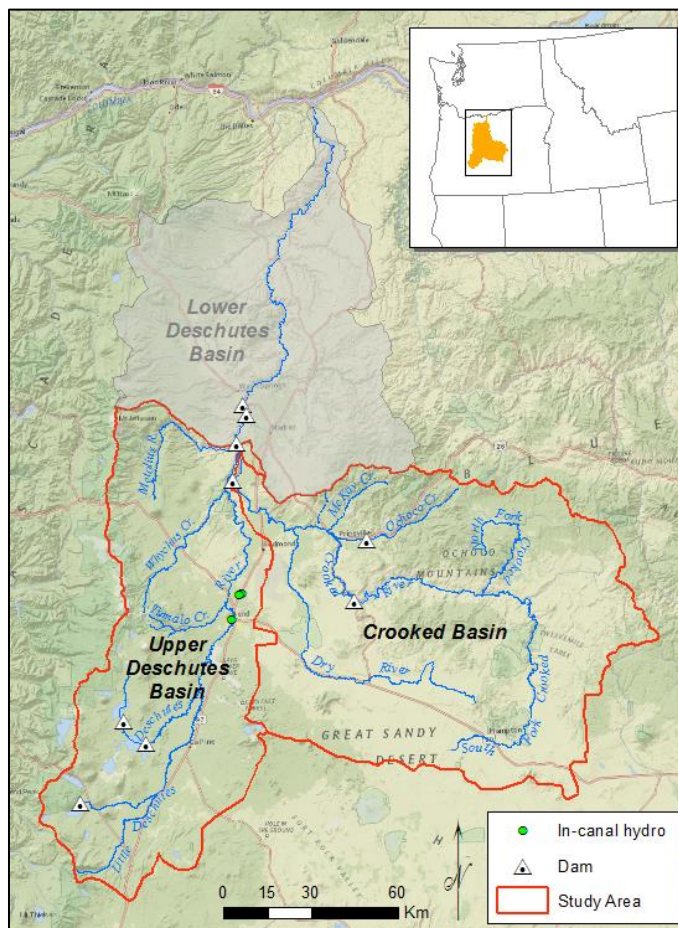
constructed to simulate how opportunities alter the system and identify where beneficial and adverse effects accrue from that alteration. Section 6.0 describes a web-based data-visualization interface that was created to facilitate interpretation of the model results. Key results and discussion of the Deschutes Basin pilot assessment are summarized in Section 7.0.



## 2.0 Description of the Deschutes Basin

Named “River of the Falls” (“Riviere des Chutes” in French), the Deschutes River originates in the Cascade Mountains of Central Oregon and runs 252 miles to join the Columbia River near The Dalles, Oregon. The Deschutes River Basin covers approximately 10,700 square miles and is the second largest river basin in Oregon (Aylward and Newton 2006). Major tributaries to the Deschutes River include the Little Deschutes River, Fall River, Spring River, Crooked River, Metolius River, Whychus Creek, and Tumalo Creek.

The Deschutes River Basin can be divided into three subbasins (Figure 2.1). This assessment focuses on two of these: the Upper Deschutes, which extends from the river’s headwaters downstream to Lake Billy Chinook reservoir formed by Pelton-Round Butte (PRB) Hydroelectric Project, and the Crooked River, which extends from the river’s headwaters to its mouth at the Deschutes River near Madras, Oregon. The PRB Hydroelectric Project is included as part of the assessment area because of its importance for energy and the environment throughout the Deschutes and Crooked river subbasins. This section describes key aspects of the Deschutes Basin that provide the necessary context for an opportunity assessment, including information about the hydrology, key environmental issues, existing hydropower infrastructure, and protected areas.



**Figure 2.1.** Map of the Deschutes Basin pilot assessment study area.

## 2.1 Hydrology

The upper and middle portions of the Deschutes River is primarily spring-fed systems due to permeable volcanic geology that allows rain and snowmelt to quickly infiltrate (Yake 2003). Consequently, the Deschutes River exhibits very stable natural flow regimes and infrequent flooding (Yake 2003). Many of the Crooked River's headwater tributaries are also spring-fed, although much of the system is fed by surface inputs.

The Deschutes River's naturally stable flow regime has been altered by the development of reservoirs and irrigation canals (Yake 2003; NPCC 2004). In the Upper Deschutes, Crane Prairie Dam and Wickiup Dam began regulating flows in 1922 and 1945, respectively. Water stored at the Crane Prairie and Wickiup reservoirs during the winter is used for irrigation downstream in the summer. Consequently, water storage creates very low flows in the Upper and Middle Deschutes during the winter (average winter flow varies from 20 to 500 cubic feet per second (cfs) in the Upper Deschutes and 450 to 1200 cfs in the Middle Deschutes), and water releases create very high flows in the Upper Deschutes during the summer irrigation season (average summer flow varies from 1,800 to 2,000 cfs, with an August average flow of 2,238 cfs) (Yake 2003; NPCC 2004; DRC 2011).

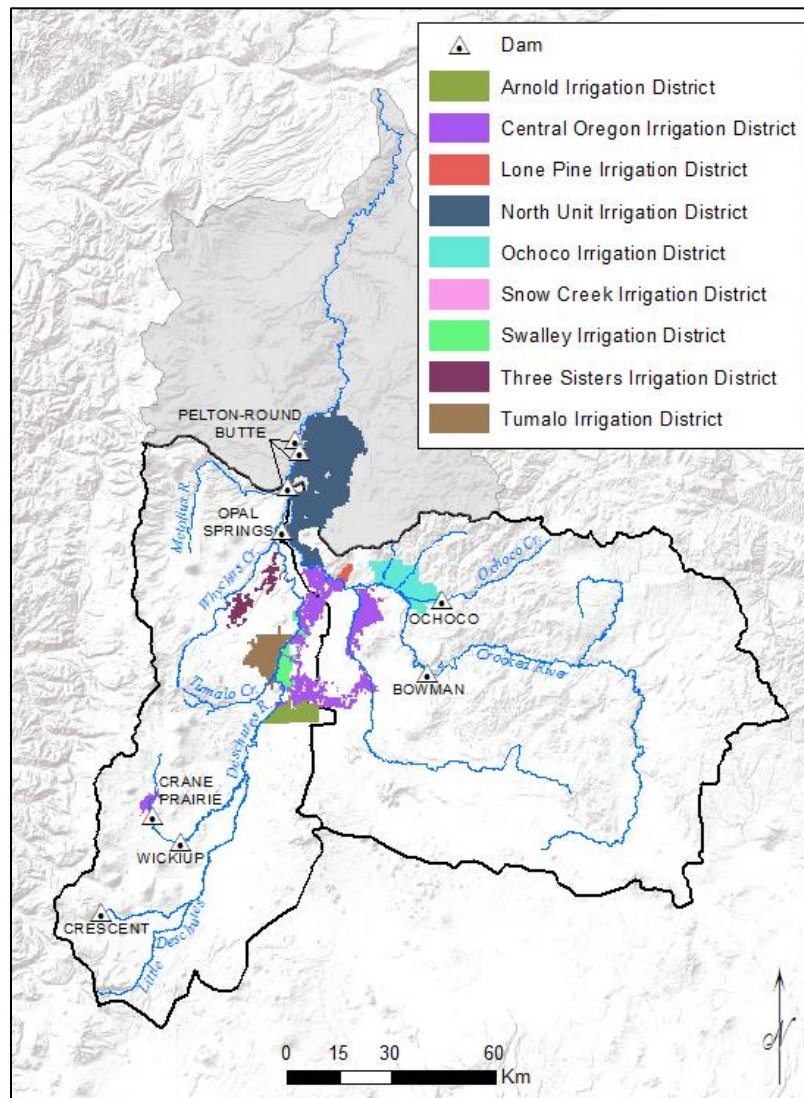
Much of the water in the Upper Deschutes is diverted at the six irrigation canals at Bend, resulting in low flows in the Middle Deschutes during the high withdrawal months of June through September (average summer flow varies from 30 to 75 cfs). As much as 50 percent of the water that is diverted from the Deschutes River in irrigation canals seeps into the ground before it reaches farms due to the porous nature of the soils and geology in the region (DRC 2011). As a result, the seven irrigation districts that serve the region (Figure 2.2) must divert approximately twice the amount of water needed to serve their patrons. However, more recently, conservation efforts by the districts and other basin stakeholders have improved this ratio and increased average summer flows in the Middle Deschutes by nearly 150 cfs.

The major tributaries to the Upper and Middle Deschutes are Tumalo Creek, Whychus Creek (formerly Squaw Creek), and the Metolius River. Stream flow in lower Tumalo Creek is substantially reduced by withdrawals for irrigation in the summer (NPCC 2004). Stream flow in Whychus Creek is notoriously "flashy," fluctuating from extremely high flows to low flows that at times go subsurface (NPCC 2004). Whychus Creek is also heavily used for irrigation and stream flows are over-allocated. However, the creek gains nearly 100 cfs from groundwater input near its confluence with the Deschutes River (NPCC 2004). The Metolius River runs near bankfull at all times because of stable input from groundwater springs.

Lake Billy Chinook, located at the lower extent of the Middle Deschutes, was created as part of the PRB Hydroelectric Project. Lake Billy Chinook impounds about 9 miles of the Deschutes River, 7 miles of the Crooked River, and 13 miles of the Metolius River (LIHI 2007; UNEP 2011; PGE 2009b).

The Crooked River flow regime has been significantly altered by the creation of dams and withdrawals for irrigation and municipal needs. Bowman Dam began regulating flows on the Crooked River in 1961. Ochoco Dam, located approximately 6 miles east of Prineville, Oregon, on Ochoco Creek, began regulating flows in 1921. Both dams are part of USBR's Crooked River Project, which was authorized by Congress in 1956 to provide irrigation water for approximately 20,000 acres as well as other beneficial uses (e.g., recreation). The Crooked River Project also includes a diversion canal and headworks on the Crooked River, Lytle Creek Diversion Dam and Wasteway, two major pumping

plants, nine small pumping plants, and Ochoco main and distribution canals (USBR 2011a). Much of the flow in the Crooked River is diverted during irrigation season, thereby resulting in very low summer flows (NFS 2010).



**Figure 2.2.** Map of irrigation districts in the Deschutes River Basin.

## 2.2 Key Environmental Issues

The Deschutes Basin ecosystem is highly valued for its environmental and recreational qualities. As a result, river protection, water conservation, and habitat restoration are key issues within the basin. Relicensing of the PRB Hydroelectric Project initiated extensive collaboration between the facility's owners (Portland General Electric [PGE] and the Confederated Tribes of Warm Springs) and more than 22 organizations to improve fish migration through the facility, as well as initiate habitat restoration for reintroduced steelhead in the upper basin (PGE 2009b). Groups such as the Deschutes River Conservancy, Trout Unlimited, The Nature Conservancy, irrigation districts, Deschutes Basin Board of Control, cities, the state of Oregon, and others have worked together to restore degraded habitat and

conserve flows within the river, while developing hydropower resources within irrigation canals and conduits. These opportunities for improving environmental conditions in tandem with hydropower development were important in this study. This section describes an initial assessment of environmental issues that form the basis for integrated hydropower and environmental opportunities. Environmental issues were assessed by reviewing existing water resource-management literature about the Deschutes Basin as well as interacting with stakeholders (workshops, working group meetings, and interviews). In general, the review focused primarily on issues resulting from alteration of hydrologic regimes because the bulk of environmental opportunities associated with hydropower development are tied to hydrologic restoration. Key environmental issues are described in focal areas within the Deschutes Basin, including the Upper and Middle Deschutes River, Tumalo and Whychus creeks, and the Lower Crooked River.

### **2.2.1 Upper Deschutes River**

Modifications to the hydrological regime in the Upper Deschutes River have contributed to degradation of aquatic habitats, riparian vegetation, and water quality (NPCC 2004). The hydrologic regime in Upper Deschutes River is affected most by the operations of Crane Prairie and Wickiup reservoirs. The management of these reservoirs for irrigation purposes results in low winter flows downstream when the reservoirs are being filled and high spring/summer flows when water is conveyed to downstream irrigation canals (Golden and Aylward 2006). Freezing and thawing of exposed river bed and banks during low winter flows loosen bank soils, making them prone to erosion during increased spring flows. Consequently, riparian vegetation has been degraded below Wickiup Dam by erosion and channel widening (NPCC 2004). Freezing of the stream channel during low winter flows also eliminates instream habitat for fish and aquatic invertebrates and may affect survival of eggs deposited in redds. Spawning gravels are also limited in the Upper Deschutes because of increased sediment loads, redistribution of gravel toward the channel margins during high spring flows, and lack of gravel recruitment from upstream sources (Yake 2003; NPCC 2004). Low summer flows also limit available habitat for trout and force them to concentrate in the few deeper pools, thereby increasing their vulnerability to predation, harvest, and competition (Yake 2003).

Water quality in the Upper Deschutes River is also affected by flow alterations. Seasonal temperature extremes (i.e., high summer temperatures and winter icing) can exceed temperature criterion for salmonid fish (NPCC 2004). High dissolved oxygen and turbidity levels are also frequently observed in the Upper Deschutes River during irrigation season releases (NPCC 2004).

### **2.2.2 Middle Deschutes River**

Flow alterations in the Upper Deschutes River and main tributaries to the Middle Deschutes (Tumalo and Whychus creeks) have contributed to degradation of water quality in the Middle Deschutes River (NPCC 2004). Flow can be limited throughout the year despite substantial input from groundwater sources due to water storage in the winter at Crane Prairie and Wickiup reservoirs and irrigation withdrawals during the summer at Bend and in Whychus and Tumalo creeks (NPCC 2004). Consequently, water temperature between Steelhead Falls and Big Falls often exceeds Oregon Department of Environmental Quality (ODEQ) temperature criteria for salmonid fish in the summer (NPCC 2004). This stretch often exceeds ODEQ criteria for pH as well (NPCC 2004).

Historically, the Middle Deschutes River supported anadromous salmon and steelhead populations up to Big Falls, which was a natural barrier to fish passage upriver (NPCC 2004). The dams of the PRB Hydroelectric Project (completed in 1964) were originally constructed with both upstream and downstream fish passage facilities to allow salmon and steelhead migration. However, unforeseen changes in the river currents and water temperature made it difficult for juvenile fish to find the downstream pipeline (PGE 2009b). The program that used the upstream fish ladders was later terminated and a fish hatchery was built below the dams to maintain the fish population in the Lower Deschutes (PGE 2009b). Efforts to restore downstream fish passage at Round Butte Dam were initiated in 2005 and the fish collection facility began operating in 2009 (PGE 2009b). In July 2012, the first return of adult sockeye occurred at PRB Hydroelectric Project and they were trapped and hauled upstream of the dams (PGE 2009b).

### **2.2.3 Tumalo Creek**

Environmental conditions in Tumalo Creek are generally good, although portions of the creek have been affected by wildfire and flow reductions caused by irrigation use. The Bridge Creek fire in 1979 has had long-term impacts on the upper portion of Tumalo Creek, including loss of riparian vegetation, which has contributed to increased bank erosion and recruitment of fine sediments. Subsequently, these impacts have negatively affected aquatic habitat for fish and aquatic invertebrates downstream (Yake 2003). After the fire, salvage operations removed much of the large woody debris from the affected stretch. Efforts to restore riparian vegetation and large woody debris were initiated in the early 1990s, but some of the inserted wood structures shifted during high flow events in 1995 and 1996 (Yake 2003).

Environmental conditions have also been affected in lower Tumalo Creek (below river mile [RM] 2.5) by reduced flows during the irrigation season. Flow reductions during the summer reduce habitat availability and quality for fish in this stretch. However, in recent years, approximately 5.8 cfs of flow has been restored by conservation efforts implemented by the Tumalo Irrigation District (NPCC 2004).

### **2.2.4 Whychus Creek**

Historically, Whychus Creek supported healthy populations of anadromous fish and higher-quality habitat conditions (NPCC 2004). Higher natural flows provided more off-channel and floodplain habitats as well as deeper pools for fish during summer months (NPCC 2004). These habitats and fish populations have been affected by human development and use, particularly in the lower portion of Whychus Creek below RM 25. Stream flow is significantly reduced below this point during summer months by a series of diversions that remove water for irrigation (NPCC 2004; Golden and Aylward 2006). Consequently, water temperatures in this reach often exceed ODEQ water-quality criteria for salmonid spawning during summer months. Fish movement may also be restricted in lower Whychus Creek during irrigation season due to intermittent flows (NPCC 2004). Fish habitat in lower Whychus Creek has also been affected by channel alterations and stream bank erosion (NPCC 2004). Riparian condition along Whychus Creek is generally good, although some areas show damage from timber harvest, grazing, channel alterations, development, and recreation use (NPCC 2004).

Until 2009, most diversions on Whychus Creek did not have state- or federally approved fish screens to prevent potential fish entrainment (UDWC 2011). Considerable effort has been made to reduce entrainment potential and as of 2011, approximately 79 percent of diversion from Whychus Creek has been screened (UDWC 2011).

### **2.2.5 Lower Crooked River**

Changes to the hydrologic regime of the Lower Crooked River have contributed to the degradation of water quality and aquatic habitat. Flows in this portion of the Crooked River are affected most by the operations of Prineville and Ochoco reservoirs, which are operated primarily for irrigation purposes (Golden and Aylward 2006). The management of this drainage for irrigation purposes results in low winter flow and high summer flow from the dams to the Highway (Hwy) 97 crossing when the reservoirs are being filled in the winter and when water is being conveyed to downstream irrigation diversions in the summer. Summer flow is reduced below the Hwy 97 crossing where 160 to 180 cfs are diverted for irrigation (NPCC 2004). Consequently, summer water temperatures in this reach generally exceed ODEQ criteria for salmonid rearing and spawning (NPCC 2004). Bacteria and pH levels also typically exceed water-quality criteria in this lower reach (NPCC 2004). Above this reach (Rice-Baldwin Dam to Bowman Dam) total dissolved gas levels generally exceed water-quality criteria during periods of reservoir spill and/or substantial discharge (NPCC 2004).

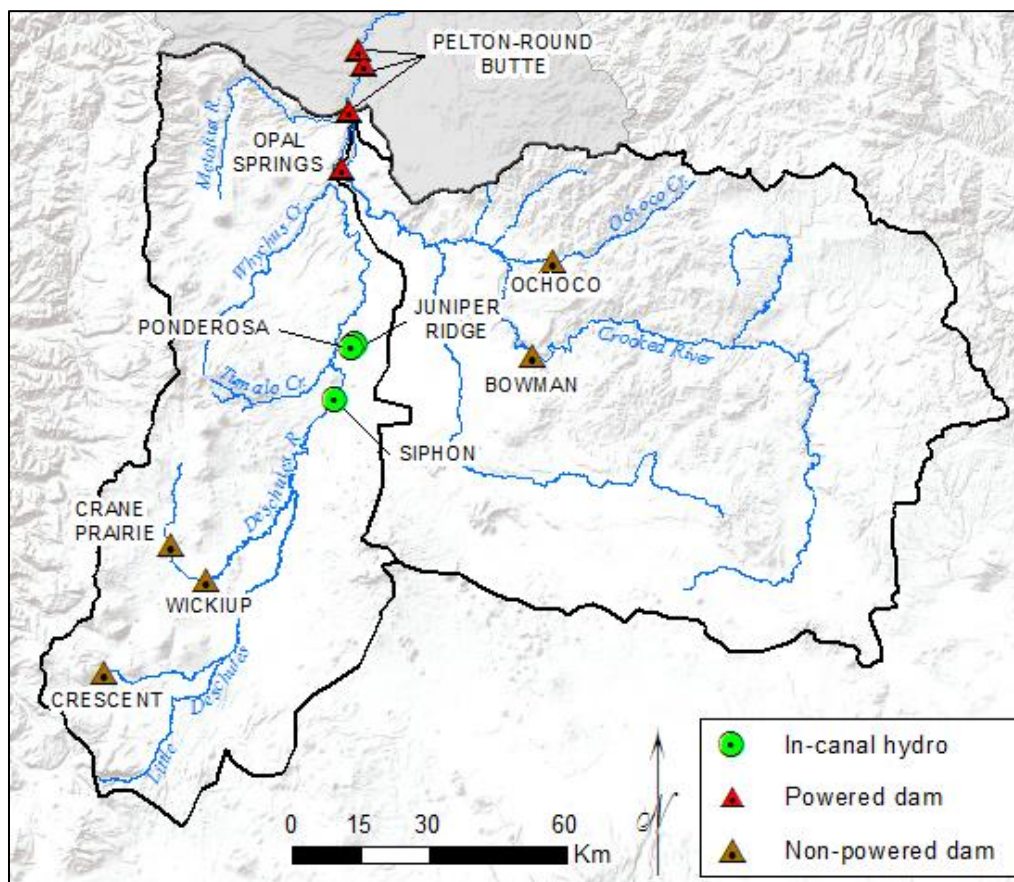
The hydrologic regimes of Ochoco and McKay creek systems have also been affected by irrigation uses and degradation of watershed conditions. Ochoco Creek experiences very low flow in the winter because the reservoir is being filled and summer flow in McKay Creek is generally low or intermittent in many reaches due to diversion and degradation of upland vegetation in the watershed (NPCC 2004). Summer water temperatures generally exceed ODEQ water-quality criteria for fish in both creeks (NPCC 2004). In addition, fish habitat has been degraded in both creeks by channel simplification, degradation of riparian vegetation, and sedimentation from bank erosion (NPCC 2004).

Before construction of dams and water diversions, the Crooked River supported anadromous fish including spring Chinook and summer steelhead in addition to resident populations of redband trout, bull trout, mountain whitefish, and non-game fish species (NPCC 2004). Although fish ladders were initially constructed at PRB Hydroelectric Project (completed in 1964), fish passage to the Crooked and Upper Deschutes river basins was eventually blocked because fish were not able to find the downstream passage structure. Recently, considerable efforts have been made to improve juvenile fish passage at the PRB Hydroelectric Project and reintroduce anadromous salmon and steelhead above the project (PGE 2009b). A new downstream passage facility was constructed and began operating at PRB Hydroelectric Project in 2009 to help restore anadromous runs above the dam complex (PGE 2009b). Because of the reintroduction, fish passage upstream of the PRB Hydroelectric Project, including the Opal Springs Hydroelectric Project on the Crooked River, needs to be improved. Plans are under way to build a fish ladder and improve downstream passage at Opal Springs (DVWD 2011), although significant challenges remain with improving flow, water temperature, and instream habitat in the Lower Crooked River to ensure long-term success of activities undertaken to restore native fish populations above Opal Springs. In addition, fish passage to the Upper Crooked River remains blocked by Bowman and Ochoco dams (NPCC 2004).



## 2.3 Existing Hydropower Infrastructure

According to DOE's National Hydropower Asset Assessment Program (NHAAP) database, there are 71 existing dams and large diversions in the Upper and Middle Deschutes River basin and Lower Crooked River basin. Of these 71 dams and diversions, currently only 7 generate hydroelectric power (Figure 2.3). Two other hydropower projects in the basin, Cline Falls and Bend Hydro (Mirror Pond), no longer generate electricity, but they are still operated for other purposes (primarily irrigation). The Bend Hydroelectric Project was completed in 1910 and is currently operated by PacifiCorp. The Cline Falls Project was originally completed in 1912, although generation was not added until 1942 when PacifiCorp entered into an agreement with Central Oregon Irrigation District (COID) to replace many of the facilities (PacifiCorp 2013). In 2011, FERC issued COID a preliminary permit (FERC No. 13858) to investigate the feasibility of upgrading and operating the Cline Falls Project. COID's proposed project would include one 750-kilowatt (kW) generator and have an annual average generation of approximately 2,000 megawatt-hours (MWh).



**Figure 2.3.** Map of existing hydroelectric facilities and non-powered dams of interest in the Deschutes Basin.

The seven hydroelectric facilities currently in operation represent a combined capacity of 382.3 MW. The largest of these facilities is the PRB Hydroelectric Project, which consists of three developments built between 1957 and 1964 that stretch a total of 20 miles on the Deschutes River (LIHI 2007; UNEP 2011; PGE 2009b). The complex has a combined capacity of 366.82 MW and is owned by PGE and the

Confederated Tribes of the Warm Springs Reservation. The uppermost development, Round Butte Dam (247.12 MW), was completed in 1964 and includes the 4,000-acre Lake Billy Chinook. The middle development, Pelton Dam (100.8 MW), was completed in 1958 and includes the 540-acre reservoir Lake Simtustus. The most downstream development, the Reregulating Development (18.9 MW), was also completed in 1958 and includes a 190-acre reservoir on the Deschutes River. The PRB Hydroelectric Project is operated as a peaking facility, typically generating between 6 a.m. and 11 p.m. daily. In 2007, the PRB Hydroelectric Project was certified as “Low Impact” by the Low Impact Hydropower Institute (LIHI 2007).

The Siphon Hydroelectric Project (FERC No. 7590), located on a COID diversion from the Deschutes River in the City of Bend, is the second largest hydroelectric facility in the basin. The plant has two units with a total capacity of 5.4 MW and began commercial service in 1989. The amount of water diverted for power generation at the Siphon Hydroelectric Project varies throughout the year depending on irrigation demands and minimum instream flow requirements between the diversion and the point of returning flow to the river. During the storage season, flow available for power generation ranges from none to the maximum capacity of the project. In 2010, the Siphon Hydroelectric Project was certified as “Low Impact” by the LIHI (2011).

The Juniper Ridge and Ponderosa hydroelectric projects are in-canal projects located north of the City of Bend, Oregon. Both projects were constructed in 2010 and classified by FERC as conduit exemptions from licensing. The Juniper Ridge Hydroelectric Project was constructed by COID in conjunction with a 2.5-mile canal-lining project and has an installed capacity of 5 MW. The Ponderosa Hydroelectric Project was constructed by Swalley Irrigation District in conjunction with a 5-mile irrigation canal-lining project and has an installed capacity of 0.75 MW. Both projects generate power during the irrigation season when water is being conveyed in the canals.

The seventh hydroelectric project in the basin is the Opal Springs Hydroelectric Project (FERC No. 5891), which was completed in 1985 by the Deschutes Valley Water District (DVWD). The project is the only hydroelectric project located on the Lower Crooked River and has an installed capacity of 4.3 MW. Recently, DVWD initiated consultation with FERC for a non-capacity amendment of its license to install upstream and downstream fish passage at the project to benefit Endangered Species Act-listed bull trout (63 FR 31647) and steelhead (64 FR 14517) and reconnect native populations of redband trout (DVWD 2011).

The Juniper Ridge and Ponderosa hydroelectric projects both represent unique partnerships between irrigation districts, the environmental community, the state of Oregon (through programs like the Allocation of Conserved Water Program and the now defunct Business Energy Tax Credit), and others to meet multiple goals, including water conservation, stream restoration, enhanced flows, hydroelectric generation, energy savings, and more efficient operation for irrigation districts. Oregon’s Conserved Water Program allows water-rights holders who conserve water to lease or sell a portion of that water (75 percent, with 25 percent going back instream), thereby creating a revenue stream to fund development projects like canal lining and piping (OWRD 2013).

The Deschutes River Conservancy worked closely with the Swalley and Central Oregon Irrigation districts through the Allocation of Conserved Water Program to facilitate conserved water piping projects, and put the saved water back into the Deschutes River. Piping projects created head and an opportunity for small hydropower at the end of the pipe. The Central Oregon and Swalley Irrigation districts used

funds from the sale of conserved water and assembled a financing package from loans, grants, and other means to fund piping and construction of hydroelectric facilities. Revenue from the sale of hydropower is now being used to pay back project debt over time.

Similar projects are under way in the Deschutes Basin—Three Sisters Irrigation District has worked closely with the Deschutes River Conservancy and other partners on a series of water-conservation and rights transfer projects to improve flows in Whychus Creek, put water into pressurized pipes (which saves energy from pumping), screen diversions, and eventually add small hydropower generation. When complete, project benefits will include all 60 miles of piped and pressurized irrigation district canals, thereby saving an estimated 9 million kilowatt-hours (kWh) per year from pumping and generating an additional 4 million kWh/year once hydroelectric capacity is installed. Whychus Creek will have more than 30 cfs of protected flow and farmers will have a more reliable supply of water, more confidence to invest in new agricultural activities, new revenue streams from hydro, and reduced electricity costs (Marc Thalacker, Three Sisters Irrigation District manager, personal communication).

When projects like this are successful, hydropower is one part of the equation, enabling improvements to irrigation infrastructure as well as conservation of water resources. There are, however, challenges associated with these projects, including high utility wheeling costs, uncertainty around fish passage requirements, long payback periods, challenging local siting and permitting issues, and the need for strong coalitions and unique funding arrangements. The American Recovery and Reinvestment Act funding—a one-time revenue stream—was important in all of these projects. In the future, reducing the costs of hydropower technologies, reducing wheeling costs or the need to wheel power (using it onsite, for example to offset pumping costs), and driving down siting and permitting costs, will likely be needed for successful project economics. Exploring new ways to fund projects through public-private partnerships and collocating generation with load could present new opportunities. Despite these challenges, projects like Ponderosa, Juniper Ridge, and Three Sisters stand as models for integration of environmental, energy, and irrigation goals made possible through the creativity and perseverance of project partners, and enabled through programs like the Allocation of Conserved Water Program.

## **2.4 Protected Areas**

Portions of the Upper and Middle Deschutes River and its tributaries have been designated as wild, scenic, or recreational under the Federal Wild and Scenic Rivers Act (16 U.S.C. 1271 et seq.). In the Upper Deschutes, these segments include a 40.5-mile recreational river from Wickiup Dam to the northern border of Sunriver, an 11.2-mile scenic river between the northern border of Sunriver and Lava Island, and a 3-mile recreational river from Lava Island to the Bend Urban Growth Boundary (Yake 2003). In the Middle Deschutes, the stretch from Odin Falls to Lake Billy Chinook is designated as a recreational river, a 6.6-mile segment of Whychus Creek from its source to the Three Sisters Wilderness Boundary is designated as a wild river, and an 8.8-mile segment of Whychus Creek from the Three Sisters Wilderness Boundary to the Whychus Creek Gauging Station is designated as a scenic river. The Metolius River is designated as a recreational river from Metolius Springs to Metolius River Bridge 99, and as a scenic river from Metolius River Bridge 99 to Lake Billy Chinook (NPCC 2004).

Some segments of the Upper and Middle Deschutes River have also been designated as scenic waterways under the State of Oregon's Scenic Waterway Act (ORS 390.805 to 390.925), which is intended to protect the free-flowing character of designated rivers for fish, wildlife, and recreation. The

segments of the Upper Deschutes that have been designated as scenic waterways are from Little Lava Lake downstream to Crane Prairie Reservoir, from the gauging station below Wickiup Dam to General Patch Bridge, and from Harper Bridge to the COID diversion in Bend (Yake 2003; NPCC 2004). Two segments of the Middle Deschutes have been designated as scenic waterways, including from Sawyer Park to Tumalo State Park and from Deschutes Market Road Bridge to Lake Billy Chinook. The Metolius River from its headwaters to Candle Creek is also designated a scenic waterway (Yake 2003; NPCC 2004).

The 17.8-mile segment of the Crooked River from Bowman Dam downstream to the Crooked River National Grasslands is designated as a Wild and Scenic River under the Federal Wild and Scenic Rivers Act (16 U.S.C. 1271 et seq.). Within the Wild and Scenic River segment, the 8-mile segment from Bowman Dam downstream to Dry Creek (the Chimney Rock Segment) is designated as a recreational river. In May 2011, legislation was introduced that would move the Wild and Scenic River boundary 0.25 miles downstream from Bowman Dam “to provide water certainty for the City of Prineville, Oregon, and for other purposes” (H.R. 2640 “Central Oregon Jobs and Water Security Act”).

## 3.0 Scenario-Based Modeling and Scoping

The goal of the BSOA Initiative is to identify opportunities for hydropower generation and environmental benefit, while avoiding impacts on other water uses. The latter aspect was particularly important to stakeholders in the Deschutes Basin, who expressed a need for tools that could be used to explore potential impacts of different water-management actions and facilitate collaborative decision-making among a diverse group of stakeholders. In response, the Basin-Scale Project Team developed a scenario-based modeling approach to examine tradeoffs among hydropower and environmental opportunities in the context of other water uses. The approach involved developing a daily water-balance model specific to the Deschutes and Crooked river basins that could be used to simulate alternative water-management scenarios. Scenarios were constructed through a scoping process aimed at identifying actions, measurements, and resource levels that expose opportunities and tensions in the system. A web-based data-visualization interface was also developed to facilitate understanding and communication of the model results. Here, we describe the results of the scoping process and details of the model scenarios.

### 3.1 Scoping Process

The Basin-Scale Project Team worked with stakeholders and modeling experts in the Deschutes Basin to conduct high-level scoping of potential hydropower and environmental opportunities in the basin that could be used to develop an initial set of water-management scenarios. Because water, hydropower, and environmental issues are often extremely complex, and because of the need to be sensitive to ongoing planning and policy processes in the basin, the team focused on developing relatively simple scenarios that examined the interaction between several key hydropower and environmental opportunities and would demonstrate the functionality of the hydrologic model and visualization interface. More important, however, was the need to demonstrate the power of collaborative scenario-based modeling, which is the ability to continue to refine scenarios and add additional data as needs arise and data become available. Scenario-based modeling requires collaboration between modelers and stakeholders to explore issues of interest in a transparent and coordinated way, so that model results are understood within the context of data limitations and uncertainty.

#### 3.1.1 High-Level Scoping of Hydropower Opportunities

Potential hydropower opportunities were screened using a combination of existing data sources, including DOE's NHAAP database, USBR's *Hydropower Resource Assessment at Existing Reclamation Facilities* (USBR 2011b), Energy Trust of Oregon's 2010 *Irrigation Water Providers of Oregon: Hydropower Potential and Energy Savings Evaluation* (Crew et al. 2010), Wickiup Hydro Group LLC's license application for the Wickiup Dam Hydroelectric Project (Symbiotics LLC 2011), and PGE's preliminary application document for the Crooked River Hydro Project at Bowman Dam (PGE 2009a). This information was supplemented with additional information from the USBR, hydropower license applicants, irrigation districts, and other available sources in the basin. A primary input into this process came from direct interaction with stakeholders in the Deschutes Basin, through formal workshops (August 2011 and February 2013), as well as numerous conference calls and smaller working sessions.

Two of the most likely opportunities for increasing hydropower in the Deschutes Basin that emerged from these sources were 1) adding new generation at existing non-powered dams and large diversions,

and 2) adding new generation in existing irrigation canals and conduits. The technical and economic feasibility of these opportunities in the Deschutes Basin was evaluated in greater detail using the HEEA tool being developed by ORNL (see Section 4.0).

### **3.1.2 High-Level Scoping of Environmental Opportunities**

Opportunities to improve river, riparian, and floodplain environmental conditions in the Deschutes Basin are inextricably linked to changes in management of the hydrologic regime. As summarized in Section 2.1, the hydrologic regime throughout the Deschutes Basin has been altered from natural conditions to meet the needs of agricultural irrigation supply, flood control, municipal supply, and other uses. Recognizing the need for changes in long-term management of water resources, a diverse coalition of partners from the Deschutes Basin initiated a series of planning studies to address the overall vision of balanced use of water resources among agriculture, urban, and ecosystem needs (Aylward and Newton 2006). Among the set of objectives developed by the coalition is the objective to “move stream flows toward a more natural hydrograph while securing and maintaining improved instream flows and water quality to support fish and wildlife” (Aylward and Newton 2006).

Modifications of the hydrologic regime toward a more natural hydrograph would increase the potential for improving river, riparian, and floodplain environmental conditions throughout the Deschutes Basin. It is widely accepted throughout the science, engineering, and management communities that some semblance of natural flow variability, magnitude, and timing is a desirable goal for sustaining riverine function and native biodiversity (Poff et al. 2003, 2010; Locke et al. 2008). Incremental changes toward a more natural hydrologic regime could result in associated improvements to other riverine ecosystem components such as water quality, biology, geomorphology, and connectivity throughout the Deschutes Basin.

The following sections describe how changes to the hydrologic regime relate to addressing important environmental issues in specific reaches of the Deschutes and Crooked rivers (Section 2.2). Other types of environmental opportunities are discussed as well.

#### **3.1.2.1 Upper Deschutes River**

Adjustments to the existing flow regime may benefit aquatic and riparian ecosystems in the Upper Deschutes. For example, increasing water releases at upstream reservoirs during winter may improve the quantity and quality of habitat for native trout and prevent channel freezing (NPCC 2004). Reducing peak flows at Wickiup Dam during irrigation season may also help reduce bank erosion and improve conditions for reestablishment of riparian vegetation downstream. Additional benefits to water quality, particularly temperature and dissolved oxygen level, may also be realized by modifying current flow regimes in the Upper Deschutes River (Golden and Aylward 2006).

#### **3.1.2.2 Middle Deschutes River**

Increasing stream flow in the Middle Deschutes River during summer months may provide opportunities for improving water temperature during the summer (NPCC 2004). Modifications to water use in the Whychus Creek drainage may provide additional opportunities for improving summer flow and temperature in the Middle Deschutes River (NPCC 2004).

### **3.1.2.3 Tumalo Creek**

Efforts to continue increasing instream flow in lower Tumalo Creek during the summer may improve habitat and water quality for fish (NPCC 2004). Continuation of efforts to restore riparian vegetation in upper portions of the creek affected by forest fire may improve bank stability, reduce erosion, and improve habitat quality for fish.

### **3.1.2.4 Whychus Creek**

Efforts to increase summer flow in the diversion-affected portion of Whychus Creek (below RM 23) would benefit aquatic communities in this section of river by improving water temperature, dissolved oxygen levels, and possibly increasing available habitat. These benefits are considered important for the long-term success of salmon and steelhead reintroductions above PRB Hydroelectric Project (NPCC 2004). Additional opportunities to improve riparian vegetation from the City of Sisters to 11 miles downstream may help to reduce sedimentation associated with stream bank erosion as well as provide benefits to fish habitat by improving channel cover and structural complexity.

### **3.1.2.5 Lower Crooked River**

Increasing summer flows in the Lower Crooked River below the Hwy 97 crossing may help to improve water temperature and water quality, and thereby benefit fish and other aquatic organisms. One possible opportunity for doing so may be to use some of unallocated water in Prineville Reservoir (OWSCI 2008). However, the use of this water for other purposes, including groundwater mitigation for the City of Prineville and other private entities (OWSCI 2008), is being discussed as well. Improving summer flows in the Lower Crooked River is also considered important for the long-term success of steelhead reintroductions to the Crooked River (NPCC 2004). Continuing efforts to provide fish passage at the Opal Springs Hydroelectric Project is also critical for reintroducing steelhead to the Crooked River.

## **3.2 Scenarios**

Based on information gathered during the scoping process, the Basin- Scale Project Team constructed three basic modeling scenarios to demonstrate how scenario-based modeling could be used to explore hydropower, environment, and other water-use opportunities in the Deschutes Basin. Although the context of the scenarios is based in part on management questions posed by stakeholders, the primary purpose of the scenarios is to demonstrate the functionality of the hydrologic model and data-visualization interface and to encourage further collaboration among stakeholders in the basin to develop scenarios that better address their needs.

In addition to increasing hydropower assets, the scenarios described herein focus on a key management goal in the basin to increase instream flows in the Deschutes and Crooked rivers through a combination of releasing water during the storage season and reducing water demands during the irrigation season. These actions were implemented in the model by incrementally changing minimum instream flows and reducing water demands for irrigators to assess the tensions and flexibility between different water uses. Separate scenarios (and model runs) were created for the Deschutes and Crooked river subbasins because these actions were implemented at different levels in each subbasin. A baseline scenario was also modeled to provide data for model calibration and to serve as a point of comparison for

the Deschutes and Crooked river scenarios. The following sections describe the three model scenarios in more detail.

### **3.2.1 Baseline Scenario**

The baseline scenario assumes current water-management practices are implemented in the Deschutes and Crooked river basins. This includes maintaining the current average minimum flow of 25 cfs below Wickiup Dam on the Deschutes River and 10 cfs below Bowman Dam on the Crooked River, as well as maintaining current water demands in both subbasins. Existing hydropower facilities (Siphon, Opal Springs, Juniper Ridge, Ponderosa) were also included in the baseline scenario.

### **3.2.2 Deschutes River Scenario**

The Deschutes River Scenario focuses on opportunities for enhancing instream flow and adding hydropower generation in the Upper and Middle Deschutes Basin. Under this model scenario, flow enhancement in the Upper Deschutes River was achieved by incrementally increasing minimum discharge from Wickiup Dam during the storage season (mid-October through mid-April) from the current average minimum flow of 25 cfs (baseline) to 350 cfs, and by incrementally reducing irrigation water demands in both subbasins by 0 (baseline), 5, and 10 percent. Minimum discharge below Bowman Dam on the Crooked River was maintained at the baseline level of 10 cfs.

Concomitant opportunities for adding hydropower generation were explored in the context of the aforementioned trial levels. Opportunities included adding generation at Wickiup, Crane Prairie, and Crescent dams, as well as at multiple locations on irrigation canals or conduits. The results of model runs performed under this scenario were also examined to determine where opportunities may exist to improve scheduling of PRB power generation to match daily peak power demand cycles in conjunction with timing upstream reservoir releases.

### **3.2.3 Crooked River Scenario**

The Crooked River Scenario examines opportunities for enhancing instream flow and adding hydropower generation in the Crooked River basin. Flow enhancement was simulated by incrementally reducing irrigation demands in both subbasins by 0, 5, and 10 percent, and increasing minimum discharge at Bowman Dam from 10 to 17 cfs using unallocated water in Prineville Reservoir. Minimum discharge below Wickiup Dam on the Deschutes River was maintained at the baseline level of 25 cfs.

While there is pending legislation to increase the minimum flow requirement below Bowman Dam from 10 to 17 cfs (H.R. 2640 “Central Oregon Jobs and Water Security Act”), there is no stipulation to use unallocated water in Prineville Reservoir. This was done in the model for demonstration purposes because of the ongoing uncertainty about how this requirement will be met. More detailed water-accounting rules can be added to the model in the future when this issue is resolved.

Concomitant opportunities for adding hydroelectric generation were explored in the context of the aforementioned scoping criteria. These opportunities included adding generation at Bowman Dam on the Crooked River, Ochoco Dam on Ochoco Creek, and at multiple locations on irrigation canals.



## **4.0 Small Hydropower Feasibility Assessment**

The technical and economic feasibility of potential hydropower opportunities identified during the high-level scoping process was evaluated in greater detail using the HEEA tool being developed by ORNL. The methods and results of this assessment are described in greater detail by Zhang et al. (2013), but are summarized here for background purposes.

### **4.1 Assessment Methodology and Tool**

The general approach of the feasibility assessment was to aggregate and rank feasible sites based on their estimated project cost, levelized cost of energy (LCOE), and economic returns in the context of site-specific conditions and the availability of green incentives. The assessment also investigated the sensitivity of each site's economic feasibility to different types of turbine equipment from domestic and international suppliers. Much of this information was compiled using the HEEA tool, which uses site-specific hydrological data and basic project information to 1) generate flow and power duration curves; 2) determine turbine design flow, net head, and technology type; 3) calculate monthly and annual power generation and determine design power capacity; 4) estimate project cost (both installation cost and LCOE); and 5) perform benefits and economic evaluations. The HEEA tool can be used to assess any run-of-river or run-of-reservoir small hydropower project (below 50 MW), including projects at new sites, non-powered dams operated as run-of-reservoir, and existing canals and conduits.

The HEEA tool was used to assess the technical and economic feasibility of 14 non-powered dams and 15 irrigation canal/conduit sites in the Deschutes Basin for which the necessary site information and flow data were available. Given the relatively small scales in terms of power and flow at the potential Deschutes Basin sites and the proximity of their locations, the HEEA tool used in this assessment assumed that 1) only one single unit would be installed at each potential site, and 2) the generating unit would be connected to the central grid system, and thus all available power would be absorbed by the power grid system. That is, the available power on the site is the power output of the turbine unit.



## 5.0 Deschutes System Hydrologic Model

Potential hydropower generation and environmental improvements are linked to the hydrology of the basin. It is essential for opportunity assessment scenarios to accurately account for changes in flow that result from natural factors and multiple uses. One method of doing so is to use a hydrologic model to explore how opportunity scenarios and existing water uses are affected by changes in hydrology over time.

During the early phases of the Deschutes Basin pilot assessment, the Basin-Scale Project Team worked with stakeholders and modeling experts in the basin to review existing hydrologic models and identify additional research needs. Based on this review, it was determined that existing model resources would provide a starting point for the assessment, but that additional capabilities were necessary to address specific hydropower and environmental scenarios. Therefore, the team chose to develop a daily mass-balance hydrologic model of the Upper Deschutes and Lower Crooked river basins to examine tradeoffs among hydropower, environmental, and other water uses under current (i.e., baseline) conditions and two alternative water-management scenarios (Section 3.2). This section describes existing hydrologic models for the Deschutes Basin and subsequent development of a daily hydrologic model that may be used to forecast the effects of alternative management scenarios.

### 5.1 Existing Hydrologic Models

In 2001, the USBR built a surface-water distribution model for the entire Deschutes Basin using MODSIM-DSS, a generalized river basin Decision Support System and network flow model. This model was later updated in 2012 in collaboration with Oregon Water Resources Department (OWRD) and PNNL. The model optimizes the allocation of water for both irrigation and instream flows on a monthly basis to simulate the effects of modifying flows in specific reaches to meet user demands throughout the entire basin (La Marche 2001). While these capabilities are vital for modeling water-use scenarios in the Deschutes Basin, the monthly temporal resolution of the MODSIM-DSS model is not ideal for the purposes of modeling hydropower and hydrologic-environmental processes that vary at finer time scales.

### 5.2 Deschutes RiverWare Model

RiverWare modeling software<sup>1</sup> was selected for implementing scenario-based modeling of baseline and alternative water-use scenarios in the Deschutes and Crooked river basins. RiverWare is a river-reservoir distribution model used to simulate river and reservoir operations for planning, biological assessment, and operational forecasts. RiverWare has the capability of distributing water based on operational constraints along with water rights to optimize for hydropower production or other desired water-management outcomes. This software was selected because of its capabilities for reservoir and dam operational decision-making, responsive hydrological forecasting, operational policy evaluation, river basin optimization, water accounting, water-rights administration, and long-term resource planning capabilities. RiverWare software is also capable of daily temporal resolution, which is beneficial for

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<sup>1</sup> RiverWare software is developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES), University of Colorado Boulder. For more information visit: <http://cadswes.colorado.edu/creative-works/riverware>.

assessing effects on hydropower. Here, we describe the development and validation of a daily RiverWare model for the Deschutes and Crooked river basins.

### 5.2.1 Model Development

RiverWare software was used to construct a mass-balance hydrologic model for the Upper Deschutes and Lower Crooked river subbasins. In a mass-balance modeling approach, water is accounted for and balanced as it enters and leaves each object in the system. For example, water that is diverted from the river into a canal would be balanced as a volume gain in the canal and a volume loss in the river.

The Deschutes Basin model was built to represent current water infrastructure in the basin such as dams, reservoirs, irrigation canals, municipalities, major tributaries, and pumping stations. Significant groundwater inputs were also included in the model. A total of 31 water-user accounts were included in the model, including Arnold, Central Oregon, North Unit, Ochoco, Three Sisters, Swalley, Lone Pine, and Tumalo irrigation districts. Two major pumping systems (Ochoco Relift and Barnes Butte Plant) were also included in the model.

The operation of these objects was regulated by two sets of parameters that control physical operations (e.g., storage release based on flood curves or maximum pool elevation, minimum reservoir outflow) and water-rights accounting. Physical operations were based on a set of prioritized policy statements set by multiple authorities in the basin, including the U.S. Fish and Wildlife Service, Oregon Department of Fish and Wildlife, OWRD, USBR Pacific Northwest Region, and Corps Portland District. Water rights were implemented as a network of water accounts based on existing paper water rights maintained by OWRD.<sup>2</sup> At each time step in the model, physical operations are reconciled with water accounting to determine water allocation for each object in the model. This process was validated with help from water operators in the basin to better represent actual operations (the Basin-Scale Project Team worked with Jonathan LaMarche and Kyle Gorman from OWRD and Jennifer Johnson from the USBR on model validation tasks).

Opportunities for increasing hydropower generation were simulated for locations that were evaluated for technical and economic feasibility using the HEEA tool. The HEEA tool was also used to select the turbine technology and establish minimum flow criteria and efficiency values (i.e., power curves) for each hydropower facility in the model. Hydropower generation occurred in the model whenever there was sufficient water available to meet the minimum flow requirement for a given facility. Conversely, water was also allowed to bypass facilities in the model when there was insufficient flow for generation or when there was surplus flow. Irrigation and municipal water use was simulated in the model for 31 water-user accounts. Demand levels for each user were based on historical use records obtained from OWRD. Because the model acknowledges water rights, future use scenarios could also be implemented in lieu of actual demands.

Inflow data in the model was based primarily on inflows from the existing MODSIM model for hydrologic years 1928 to 2008 because of limited availability of observed data. MODSIM monthly inflows were transformed to daily inflows using a stream flow disaggregation technique (Acharya and Ryu 2014) for ease of transitioning the RiverWare model to using daily inflow data in the future. Inflow

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<sup>2</sup> Oregon Water Resources Department, Water Right Information Search. Available online: <http://www.oregon.gov/owrd/pages/WR/wris.aspx>.

locations included five reservoirs (Crane Prairie, Crescent Lake, Wickiup, Prineville, Ochoco), four major tributaries (Little Deschutes River, Tumalo Creek, Whychus Creek, Metolius River), and summed surface-water inflows at two locations (Benham Falls on the Deschutes River and Opal Springs on the Crooked River). Significant gains or losses in flow due to groundwater flux were also included in the model. The relative locations and magnitudes of these gains/losses were derived from MODSIM.

### 5.2.2 Model Performance

To use the Deschutes RiverWare model as a tool to assess the impact of different water-management scenarios, the Basin- Scale Project Team compared model outputs to observed conditions and the existing MODSIM model for seven locations throughout the basin that represent the primary inflow locations in the RiverWare model (Table 5.1). The assessment was conducted using the best available descriptions of historical system operation rules together with historical storage and discharge records from 1980 to 2000. RiverWare was run at a monthly time scale to allow for side-by-side comparisons with MODSIM. Comparisons of simulated vs. observed reservoir storage, reservoir outflow, and stream discharge were made using statistical metrics of bias and mean absolute error (MAE). MAE was defined as the mean absolute difference between observed and simulated values over the simulation period, and provides a measure of overall model fit to observed values. Bias was defined as the difference between observed and simulated values summed over the simulation period, and provides a measure of whether modeled values trend higher or lower than observed values. To simplify understanding of these metrics, they are also reported as percentages of active reservoir storage and average annual discharge at each location.

**Table 5.1.** Summary of RiverWare and MODSIM model comparisons to observed data.

Location	RiverWare vs. Observed		MODSIM vs. Observed	
	Discharge	Storage	Discharge	Storage
Crane Prairie Reservoir	X	X	X	X
Crescent Lake	X	X	X	X
Wickiup Reservoir	X	X	X	X
BENO gage (Benham Falls)	X		X	
DEBO gage (below Bend, Oregon)	X		X	
Prineville Reservoir	X	X	X	X
Ochoco Dam	X	X	X	X



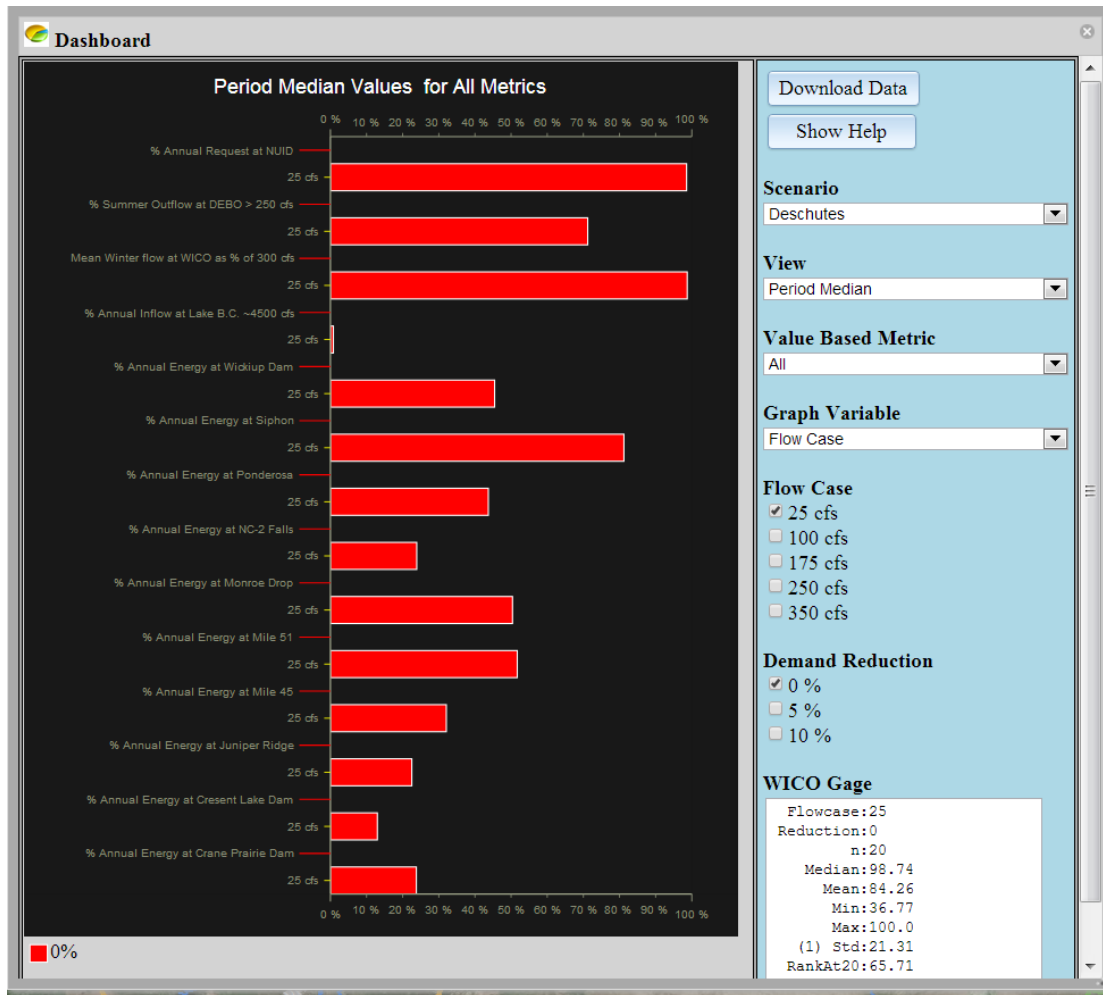
## 6.0 Data-Visualization Interface

A web-based data-visualization interface was developed to provide an intuitive means of assessing opportunities and tradeoffs among various hydropower development, water conservation, and other water-use strategies examined in the Deschutes Basin pilot assessment. The interface consists of four main components: 1) interactive map of the basin, 2) Opportunity Explorer tool, 3) Scenario Explorer tool, and 4) the Dashboard graphical interface.

The front page of the visualization system consists of an interactive map that allows users to explore information about the basin in relation to various geographic data such as aerial imagery, topography, hydrologic features, impoundments, water users, restoration activities, and land ownership. The map interface also contains a toolbar at the upper left that allows users to access the Scenario Explorer, Dashboard, and Opportunity Explorer. Users can turn map layers on or off and zoom in and out to create custom views that are specific to their interest.

The Opportunity Explorer tool allows users to view the locations and details of site-specific hydropower and environmental opportunities in the basin. When activated, the Opportunity Explorer displays the locations of opportunities in the map interface, which appear as clickable icons. Detailed information about each opportunity can be accessed by clicking on the icon, which displays a pop-up window with tabs containing information about the site description, opportunity details, and related photos if available. The Scenario Explorer tool provides users the ability to learn the context and details of modeling scenarios that have been applied in the basin. Together, the Scenario Explorer and Opportunity Explorer tools serve to lead users into exploration of the model results Dashboard.

The Dashboard is a graphical interface that allows users to view the results of modeling scenarios in a variety of ways to better understand where opportunities may exist (Figure 6.1). Data are presented in a hierarchical fashion in the Dashboard to allow the user to investigate model results at increasing levels of detail. Results may be viewed as raw time series of discharge or energy or as value-based metrics at one or more locations. The value-based metrics are pre-calculated metrics that are based on specific information needs expressed by stakeholders. For example, stakeholders may want to know how often flow exceeded a conservation flow target at a certain location in the model scenario. A useful way of conveying this information is to express the data as a percentage of some desired condition (e.g., instream flow, irrigation certainty, energy capacity). An added benefit of expressing value-based metrics as a percentage is that they can be compared on common axes or contrasted against each other, allowing users to evaluate model outcomes with respect to multiple interests.



**Figure 6.1.** Screen view of the Dashboard graphical interface.



## 7.0 Results and Discussion

This section summarizes results of the small hydropower feasibility assessment, performance of the RiverWare model, and its application to the opportunity scenarios described in Section 3.0. Using the data-visualization tool (Section 6.0), we discuss how hydropower and environmental opportunities interact with each other and their relationship to other uses of water in the basin, with a primary focus on irrigation supply. While the scenarios and results described here are basic, the intent is to demonstrate the utility of the approach. Further refinement of scenarios and additional model runs based on more detailed scenarios could aid in ongoing collaborative planning processes. The tools developed under this pilot assessment are intended to be flexible and available for future use as new management questions arise in the Deschutes Basin. The architecture of the visualization system and the assessment approach is intended to be easily exportable to other basins, meeting the national goals of the DOE-funded BSOA Initiative.

### 7.1 Small Hydropower Feasibility Assessment

The results of the small hydropower feasibility assessment are described in detail by Zhang et al. (2013) and summarized here for background purposes. The technical and economic feasibility of 14 non-powered dams and 15 irrigation canal/conduit sites in the Deschutes Basin was assessed using the HEEA tool. Results from the tool indicate the total potential generation capacity for these 29 sites would be approximately 27 MW. Based on the estimated life-cycle benefits and costs of each project, only four of the non-powered dam sites and four of the canal sites appear to be economically feasible. The eight potentially feasible projects could add about 19 MW of hydroelectric capacity to the Deschutes Basin and could generate more than 78 GWh of renewable energy each year (**Error! Reference source not found.** and In general, the discharge MAE was higher than that for the reservoir storage MAE. This is due in part to discharge error being amplified as a result of cumulative error in reservoir storage over time. However, several factors may confound this effect, including errors in inflow and groundwater exchange data used in the models, and misrepresentation of how reservoirs are operated in the models versus in actuality. Furthermore, it is difficult to differentiate which of these factors is most significant for any given location. For example, inflow into Ochoco Reservoir was based on estimated inflows from MODSIM due to the lack of observed inflow data and therefore may not be representative of actual conditions. However, this effect is difficult to separate from potential error related to operation of Ochoco Reservoir in the two models, which is evidenced by differences in how the RiverWare and MODSIM models estimated storage and discharge at this location. The RiverWare model generally overestimated storage and underestimated discharge at Ochoco Reservoir, whereas the MODSIM model generally produced the opposite pattern (see Appendix A).

). This could power about 6,000 households year-round and avoid greenhouse gas emissions of about 29,000 tons of CO<sub>2</sub> equivalent each year.

### 7.2 Model Performance

The relative performance of the Deschutes RiverWare model was assessed by comparing simulated discharge and storage to observed values for hydrologic years 1980 to 2000 at seven locations in the basin. Similar comparisons were made for the MODSIM model as well to provide additional context for

evaluating model performance. While this context is useful for evaluating RiverWare’s potential use in the basin, the primary purpose of this assessment was to determine the appropriateness of the model for comparing alternative management scenarios pertaining to the Deschutes Basin pilot assessment. This also represents the primary purpose of the model at this time. Suggested improvements to the model are provided at the end of this section and should be considered before applying the model for planning purposes.

Time-series plots and statistical measures of MAE and bias were used to evaluate model performance. To simplify understanding of these metrics, they are also reported as percentages of active reservoir storage and average annual discharge. The following discussion focuses primarily on MAE and time-series results because these provide a good basis for general comparison of the models and observed conditions. More detailed summaries of MAE and bias metrics are available in Appendix A. Comparison of MAE values indicates that both models yield similar estimates of reservoir storage (Figure 7.1). MAE values ranged from 7.0 to 13.0 percent and 7.1 to 14.9 percent of active reservoir storage in the RiverWare and MODSIM models, respectively. Both models also yielded similar estimates of reservoir/stream discharge, except at Wickiup and Ochoco dams and Benham Falls on the Deschutes River (BENO gage) (Figure 7.2). MAE values ranged from 25.3 to 80.7 percent and 15.6 to 118.0 percent of average annual discharge in the RiverWare in the MODSIM models, respectively.

**Table 7.1.** Assessment results for potential hydropower development at non-powered dams in the Deschutes Basin (adapted from Zhang et al. 2013).

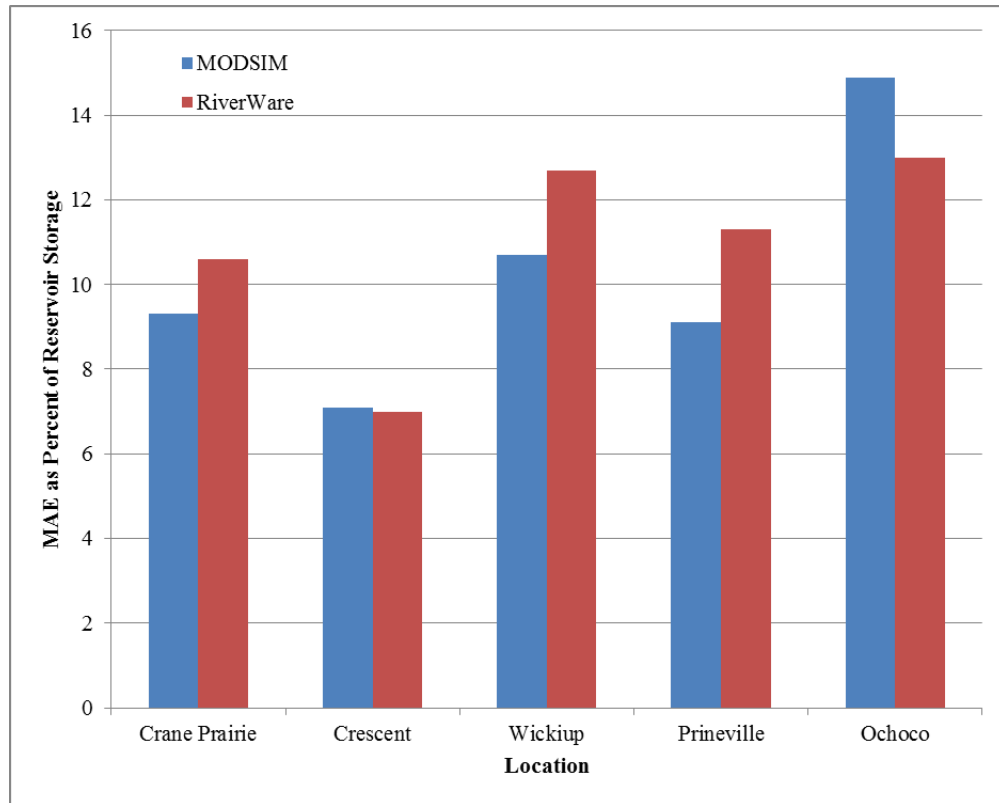
Site Name	Design Head (ft)	Design Flow (cfs)	Recommended Turbine Type	Design Capacity (kW)	Annual Energy Generation (MWh)	Economic Assessment Results
Wickiup Dam	67.0	1,400	Kaplan	7,118	29,010	Feasible
Bowman Dam	163.9	500	Francis	5,959	19,587	Feasible
North Canal Diversion Dam	33.0	461	Kaplan (Pit or Bulb)	1135	5,145	Feasible
Ochoco Dam	60.0	94.2	Francis	366	2,992	Feasible
Crane Prairie	18.0	262	Kaplan (Pit or Bulb)	337	2,037	Infeasible
Crescent Lake Dam	33.0	82	Kaplan (Pit or Bulb)	200	657	Infeasible
Fehrenback #2	14.0	41.6	Propeller	39	289	Infeasible
Merwin Reservoir #2	72.0	8.3	Cross-flow	39	179	Infeasible
Bonnie View Dam	36.0	12.7	Propeller	33	128	Infeasible
Gilchrist Log Pond	9.8	56.9	Propeller	31	160	Infeasible
Layton #2 Reservoir	18.0	23.6	Propeller	29	118	Infeasible
Bear Creek (Crook)	57.0	5.5	Cross-flow	20	94	Infeasible
Allen Creek	76.0	3.3	Cross-flow	16	75	Infeasible
Watson Reservoir	30.0	28.7	Propeller	15	59	Infeasible

In general, the discharge MAE was higher than that for the reservoir storage MAE. This is due in part to discharge error being amplified as a result of cumulative error in reservoir storage over time. However, several factors may confound this effect, including errors in inflow and groundwater exchange data used

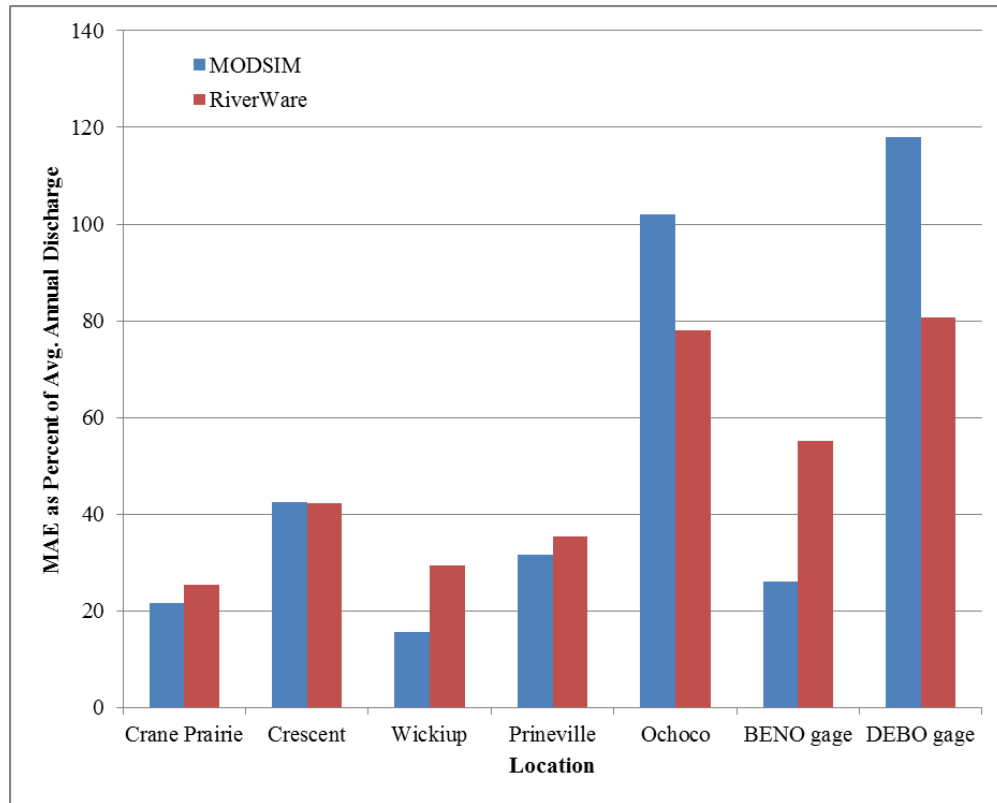
in the models, and misrepresentation of how reservoirs are operated in the models versus in actuality. Furthermore, it is difficult to differentiate which of these factors is most significant for any given location. For example, inflow into Ochoco Reservoir was based on estimated inflows from MODSIM due to the lack of observed inflow data and therefore may not be representative of actual conditions. However, this effect is difficult to separate from potential error related to operation of Ochoco Reservoir in the two models, which is evidenced by differences in how the RiverWare and MODSIM models estimated storage and discharge at this location. The RiverWare model generally overestimated storage and underestimated discharge at Ochoco Reservoir, whereas the MODSIM model generally produced the opposite pattern (see Appendix A).

**Table 7.2.** Assessment results for potential hydropower development at existing canals/conduits in the Deschutes Basin (adapted from Zhang et al. 2013).

Site Name	Design Head (ft)	Design Flow (cfs)	Recommended Turbine Type	Design Capacity (kW)	Annual Energy Generation (MWh)	Economic Assessment Results
Mile 45	104.0	354.0	Turbinator	2,700	12,556	Feasible
Haystack Canal	85.0	270.6	Conventional Kaplan	1,730	8,078	Feasible
58-11 Lateral	240.0	7.8	Pelton	137	560	Feasible
58-9 Lateral	150.2	6.8	Pelton	75	305	Feasible
NC-2 Fall	17.0	407.7	Propeller (Pit) or Natel	445	1,854	Infeasible
Brinson Boulevard	30.5	444.9	Propeller (Pit)	1,015	4,004	Infeasible
Young Avenue	16.0	311.9	Kaplan (Pit) or Natel	352	1,461	Infeasible
10-Barr Road	23.0	237.0	Kaplan (Pit)	399	1,672	Infeasible
Dodds Road	79.0	245.0	Francis	1396	6,690	Infeasible
Yew Avenue	42.0	164.0	Kaplan (S-type)	516	2,174	Infeasible
Smith Rock Drop	16.0	390.2	Propeller (Pit) or Natel	444	1,751	Infeasible
Ward Road	25.0	330.0	Propeller (Pit)	609	3,070	Infeasible
Shumway Road	79.0	150.0	Francis	850	4,071	Infeasible
Brasada Siphon	81.0	147.9	Francis	861	3,461	Infeasible
McKenzie Reservoir	96.0	30.0	Cross-flow	187	942	Infeasible



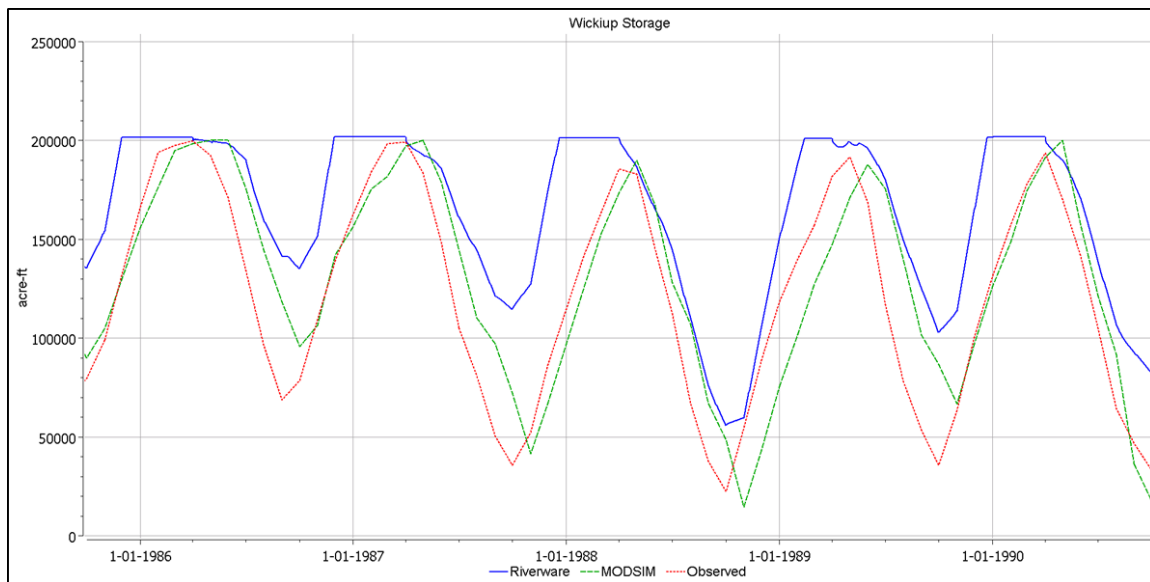
**Figure 7.1.** Mean absolute error (MAE) as a percent of reservoir storage.



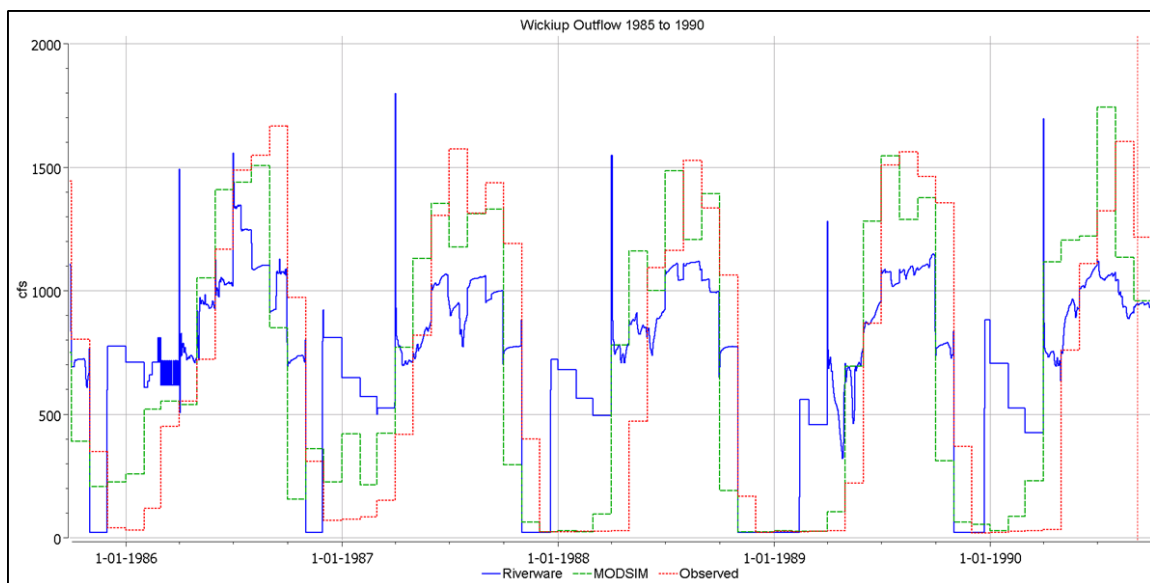
**Figure 7.2.** Mean absolute error (MAE) as a percent of average annual discharge.

Groundwater interactions may also be an important source of error in both models. The gages on the Deschutes River located at Benham Falls, Oregon (BENO) and below Bend, Oregon (DEBO) are useful for evaluating how groundwater losses/gains are represented in the models. The BENO gage, located downstream of the confluence of the Little Deschutes River, monitors flow from Wickiup and Crescent Lake reservoirs and may provide information about groundwater loss/gain after upstream releases. The DEBO gage monitors flow of the Deschutes River below the BENO gage and below Bend where there are several major irrigation diversions and significant groundwater exchange. In both models, the MAE increased considerably between the two gage locations, indicating there may be significant groundwater losses/gains that are not fully accounted for in the models.

Difficulty replicating reservoir operations was an evident source of deviation in the models, particularly at Ochoco and Wickiup reservoirs. Although there are established requirements and guidelines for water operators in the Deschutes Basin, many operational decisions are made based on the professional judgment of the operators and may not be documented. Consequently, these types of undocumented operations are not captured in the RiverWare model. This effect can be seen in time-series graphs of storage and discharge for Wickiup Dam. Reservoir storage typically peaked earlier in the RiverWare model than observed in actuality (Figure 7.3), resulting in larger releases during the storage season (Figure 7.4). This discrepancy can be attributed largely to greater carryover of storage than typically occurs because the RiverWare model does not account for unplanned releases during the irrigation season.



**Figure 7.3.** Observed and modeled storage at Wickiup Dam from 1985 to 1990.



**Figure 7.4.** Observed and modeled discharge at Wickiup Dam from 1985 to 1990.

In summary, the Deschutes RiverWare and MODSIM models yield similar estimates of reservoir storage. However, estimates of discharge varied more between models for certain locations in the basin. Multiple factors likely contribute to differences between models and locations, although key factors that were evident include uncertainty in the inflow and groundwater exchange data used to calibrate the models and difficulty replicating how reservoirs are operated. Due to limited availability of data derived from observations, it is difficult to differentiate which of these factors is most significant for any given location. Based on the results presented herein and more in-depth reviews completed by the Basin-Scale Project Team in consultation with experts in the Deschutes Basin, several key research needs have been identified for improving hydrologic modeling resources in the basin. These include a more robust calibration of groundwater exchanges in the Upper and Middle Deschutes River; additional calibration of

annual storage accruals at Crane Prairie, Prineville, and Ochoco reservoirs; and better understanding and documentation of reservoir operations and water exchanges throughout the basin.

As with any simulation model, improvements can and should be made when possible to improve model accuracy. However, these improvements should also be done within the context of the model's intended use. Future applications of the Deschutes RiverWare model may require more rigorous calibration and validation. For the purposes of this project, the model provides a suitable platform for demonstrating how scenario-based modeling can be used to explore alternative management opportunities. In addition, the model meets several other key objectives of the modeling portion of this project by providing the first daily hydrologic model of the Upper Deschutes River and Lower Crooked River system, integrating new and existing hydropower assessments in a system-scale modeling framework, and delivering hydrologic modeling and data analysis capabilities to the basin that were collaboratively envisioned by stakeholders.

## **7.3 Scenario-Based Modeling**

One of the primary objectives of the Deschutes Basin pilot assessment was to demonstrate how scenario-based modeling may be used to examine tradeoffs among hydropower and environmental opportunities in context of other water uses. The approach involved developing a daily water-balance model specific to the Upper Deschutes River and Crooked River subbasins that could be used to simulate alternative water-management scenarios. Scenarios were constructed through a scoping process aimed at identifying actions, measurements, and resource levels that expose opportunities and tensions in the system. A web-based data-visualization interface was also developed to facilitate understanding and communication of the model results.

In addition to increasing hydropower assets, the scenarios described herein focus on a key management goal in the basin to increase instream flows in the Deschutes and Crooked rivers through a combination of releasing stored water during the storage season and reducing water demands during the irrigation season. These actions were implemented in the model by incrementally changing minimum flow requirements and reducing water demands for irrigators. Separate scenarios (and model runs) were created for the Deschutes and Crooked river subbasins because these actions were implemented at different levels in each subbasin. Because there are many combinations of trial levels, it is important to sift through the results to narrow the focus to the combinations of trial levels that influence obtaining scenario goals. Here we provide an example approach to evaluating results of the Deschutes and Crooked river scenarios using the BSOA data-visualization interface. It is assumed the reader is generally familiar with these scenarios (Section 3.2), and therefore focuses on interacting with model results in the Dashboard interface.

### **7.3.1 Example Approach to Model Interpretation**

This example approach focuses on interpretation of model results for the Deschutes River Scenario (Section 3.2.2), because there was greater stakeholder input into the development of the scenario than for the Crooked River Scenario. However, a brief discussion of how the model results may be used to assess potential hydropower opportunities in both subbasins is included in this section.

The Deschutes River Scenario is driven by goals for increasing energy production, increasing environmental quality, and maintaining reliability for water users. Tradeoffs between these goals were explored in a series of simulations in the RiverWare hydrologic model by setting trial levels for storage season flows below Wickiup Dam (25, 100, 175, 250, and 350 cfs) and demand-reduction levels for water use (0, 5, and 10 percent). A simulation was run for each combination of trial level (16 total) for hydrologic years 1981 to 2000 (October 1, 1980 to September 30, 2000). The approach for evaluating scenario goals is likely to differ among stakeholder groups. The intent of this example approach is to identify the ranges of management actions that are influential and have the potential to meet some or all goals of the scenario. The approach follows three basic steps: 1) explore a time series of a value-based metric for trial-level combinations to identify sensitivities to water year differences; 2) summarize annual performance to identify tension among metrics as water availability varies among years; and 3) view monthly and daily values to understand how actions represented by the trial levels alter the timing of water availability, energy generation, and irrigation reliability.

The first step in this approach, exploring a value-based metric time series, is intended to identify sensitivities to water-year differences. Seven value-based metrics, five of which are relevant to the Deschutes scenario, are available to choose from in the visualization system's Dashboard (**Error! Reference source not found.**). The metrics are posed as relative measures of specific goals of the scenario, which have been informed by key stakeholders in the basin. For example, one metric is posed as the percent of the storage season (Oct 15–Apr 15) that flows meet or exceed 300 cfs below Wickiup Dam, which is a goal that has been discussed by stakeholders for improving conditions for aquatic communities in the winter. However, as with any goal, there is some uncertainty as to what is an acceptable or achievable level for that goal. For example, what percentage of the storage season flows that exceed 300 cfs below Wickiup Dam would be considered acceptable to stakeholders? One method to assess this issue is to arbitrarily choose target levels for metrics and determine how often criteria are met. This was done for several metrics in the Deschutes scenario to demonstrate how often goals were met over a 20-year period (**Error! Reference source not found.**). It is important to note the target levels presented here were arbitrarily selected and would likely vary depending on interests and available information.

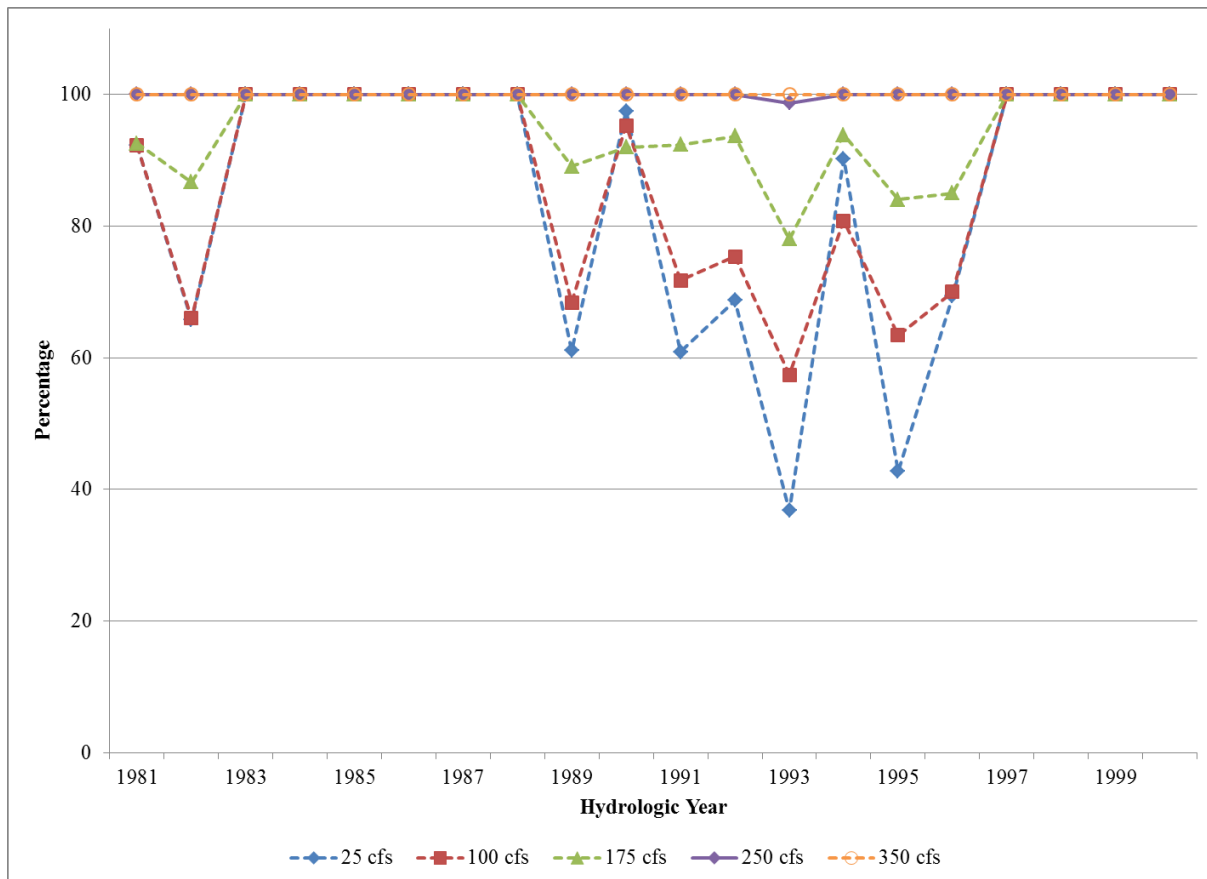
**Table 7.3.** Example value-based metrics used to explore scenario-based modeling results.

Category	Value-Based Metric Description	Target Level	Applicable Scenario
Hydropower	Percent of potential energy generated during water year	200% of baseline	Deschutes and Crooked
	Percent of water year where inflow to Lake Billy Chinook is 4400–4600 cfs	NA	Deschutes and Crooked
Environmental	Percent of storage season (Oct 15–Apr 15) that flow below Wickiup Dam $\geq$ 300 cfs	95%	Deschutes
	Percent of summer (Jun 1–Aug 31) that Deschutes River below Bend $\geq$ 250 cfs	65%	Deschutes
	Percent of summer (Jun 1–Aug 31) that Crooked River at Opal Springs $\geq$ 1430 cfs	NA	Crooked
Irrigation	Percent of NUID annual diversion request that was received	95%	Deschutes and Crooked
Recreation	Percent of water year that Prineville Reservoir storage $\geq$ 92,000 ac ft	NA	Crooked



NA = not applicable.

For the Deschutes scenario, we can examine how modifying minimum winter flows at Wickiup Dam affects downstream flow across years by plotting Wickiup metric values for all minimum winter flow trial levels (Figure 7.5). It becomes evident that trial levels for minimum winter flow have a strong influence on the metric value in some years but not in others. Similar plots are available for each metric and combination of demand-reduction levels, although an alternative method is needed to summarize results for multiple metrics and combinations of trial levels.

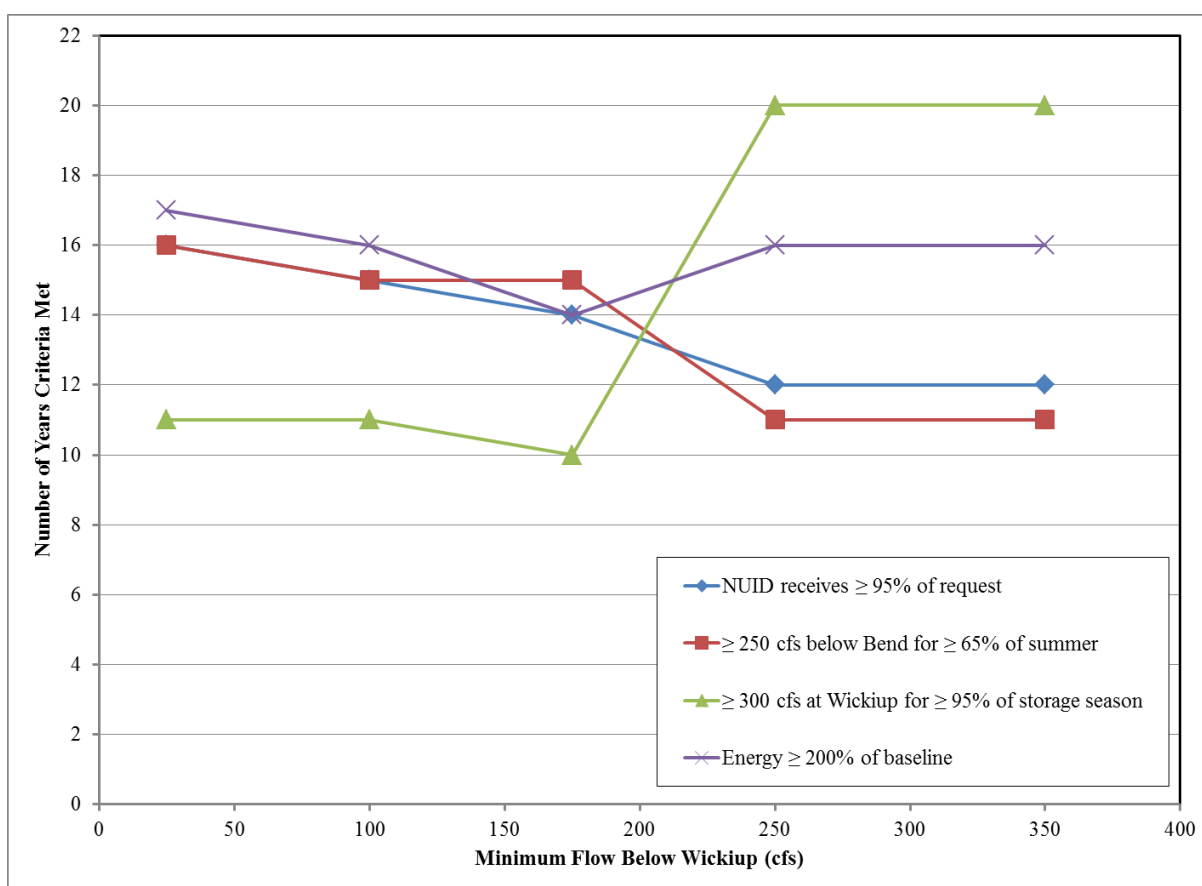


**Figure 7.5.** Percent of storage season flow is  $\geq 300$  cfs below Wickiup Dam based on minimum flow trial levels with no demand reduction.

In the second step of our example approach, we tabulate how many years meet criteria for each metric for every trial-level combination to help answer the question: “Which trial-level combinations result in meeting goals more often?” For this analysis, data were exported from the Dashboard for more detailed analysis using graphing software. The example tabulation shows that increasing minimum flow below Wickiup Dam during the storage season can influence how many years each metric is met, but some metrics are more sensitive to the trial level than others (Figure 7.5). As minimum flow is increased, the target level for exceeding 300 cfs below Wickiup Dam during the storage season is eventually met in all water years. In contrast, increasing minimum flow decreases the number of years the target level is met for the North Unit Irrigation District’s (NUID’s) annual diversion request and decreases the number of years that the target level is met for exceeding 250 cfs during the summer in the Deschutes River below

Bend, Oregon. The amount of additional energy generated also varies as minimum flows are increased, but there is less variation in the trend.

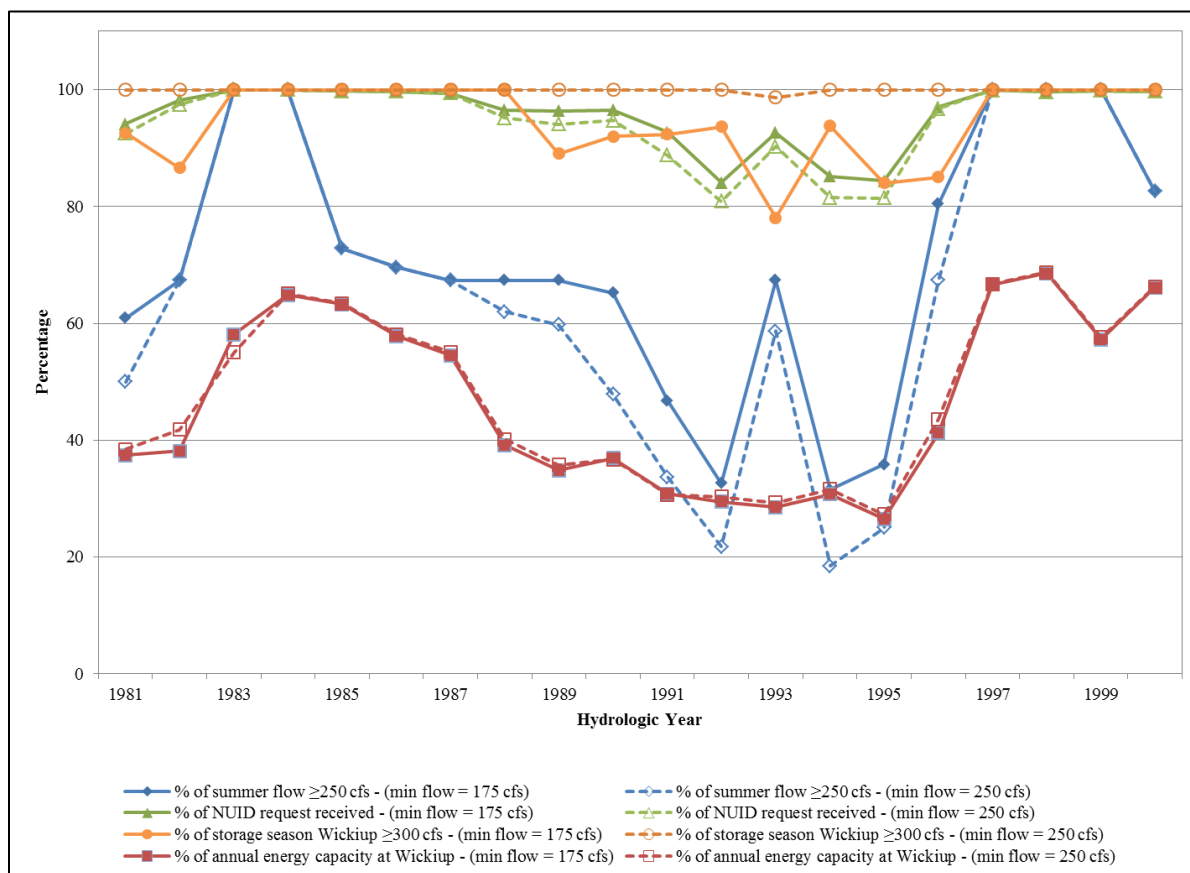
In Figure 7.6, the number of years that target levels for each metric were met changed most drastically when minimum flows were increased from 175 to 250 cfs. Plotting flow and water-use metrics for 175- and 250-cfs minimum flow levels across years reveals years that meet criteria for one trial level but not the others (Figure 7.7). In general, the metrics were more sensitive to changes in minimum flow in years of lower water availability (e.g., 1990–1995). Hydrologic year 1990 is intriguing because there is an evident tradeoff between meeting flow targets below Wickiup Dam during the storage season and below Bend during the summer. Conversely, increasing minimum flows from 175 to 250 cfs had little effect on the NUID and annual power generation at Wickiup Dam. Taking a closer look at the monthly values in 1990 for these four metrics may help understand how these changes in minimum flow are influencing the timing of water availability in the system.



**Figure 7.6.** Number of years that meet example target levels for Deschutes River Scenario value-based metrics based on minimum flow trial levels.

When data for 1990 are viewed at a monthly time scale (Figure 7.8) we can begin to better understand why certain metrics are more sensitive than others to changes in minimum flow below Wickiup Dam during the storage season. Increasing minimum flow during the storage season appears to reduce available water for instream flow during the summer months in years with lower water availability like 1990 (Figure 7.8). However, it is important to note that this relationship is also affected by water

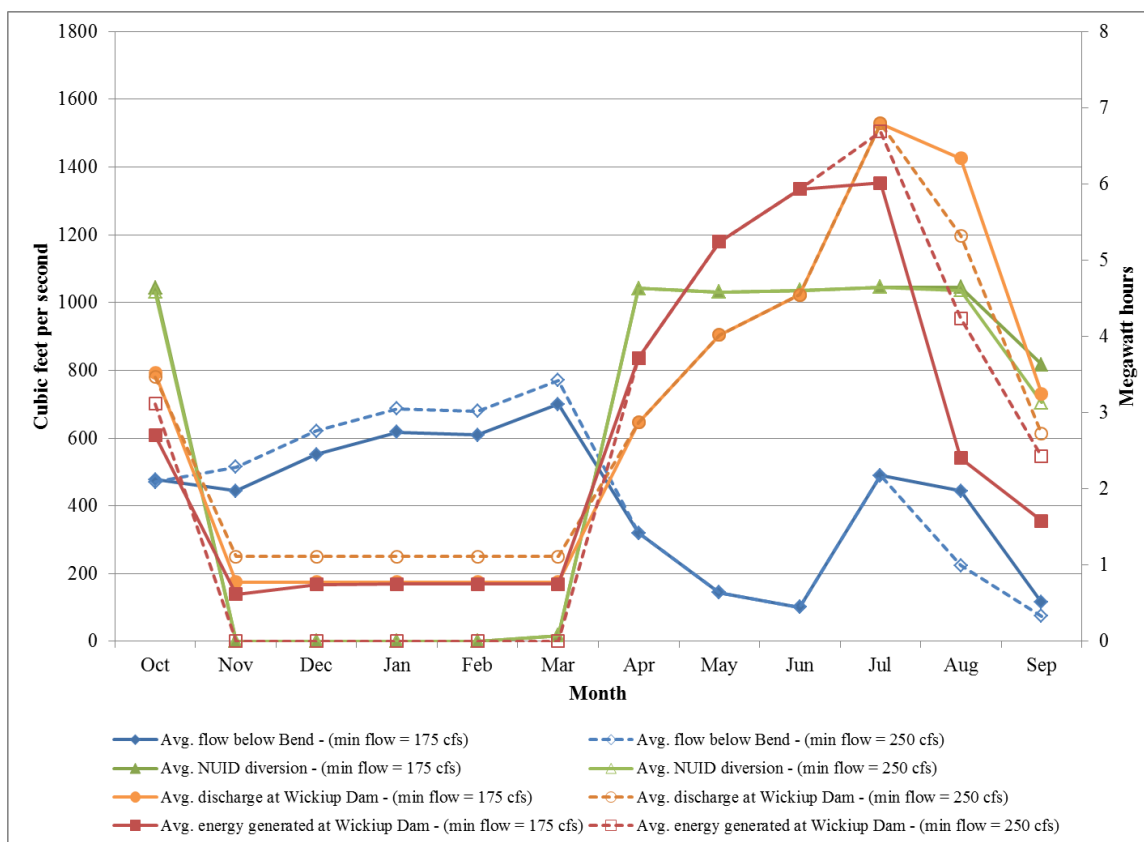
availability at the end of the previous hydrologic year and how reservoirs are operated in the RiverWare model. Previously, it was noted that increasing minimum flow had little effect on annual energy production at Wickiup Dam in 1990. However, when viewed at a monthly time scale there is an apparent tradeoff between the two minimum flow levels with respect to generation between storage months (November–March) and summer months (July–September).



**Figure 7.7.** Annual trends for value-based metrics describing summer flows below Bend, NUID annual diversions, storage season flows below Wickiup Dam, and power generation at Wickiup Dam.

Thus far, our example approach has focused on how increasing minimum flow requirements can help or hinder achieving the goals of the Deschutes River Scenario. In doing so, we determined that tradeoffs among scenario goals shifted the most in years of lower water availability and when minimum flows were increased from 175 to 250 cfs. Focusing on these years and trial levels provides a good starting point for examining how reductions in water demand may provide added benefit to balancing scenario goals. In the Deschutes River Scenario, actions to reduce water use were simulated by reducing water demand by 5 and 10 percent for all irrigation users in the model. Specific actions for demand reduction were not prescribed, because stakeholders are currently working through a number of strategies to achieve water-conservation goals in the basin. The effect of these reductions can be explored by plotting the number of years target levels for each metric are met. In our simulations, reducing water demand generally increased the number of years that metrics exceeded target levels, although it appeared no added benefit to NUID was gained by reducing demand from 5 to 10 percent (Figure 7.9). However, it is important to

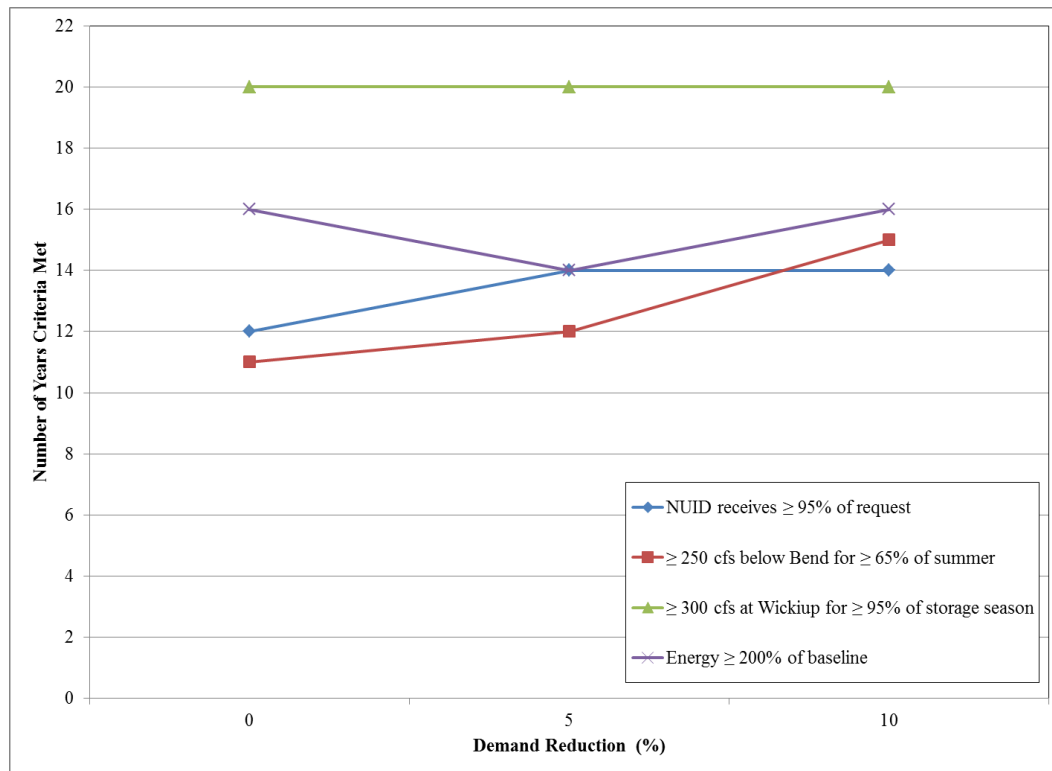
note that the outcome of this comparison is influenced by the target levels that are set for each metric. For example, the benefit of reducing demand would be greater if we had deemed 85 percent as the benchmark for NUID's annual allocation instead of 95 percent.



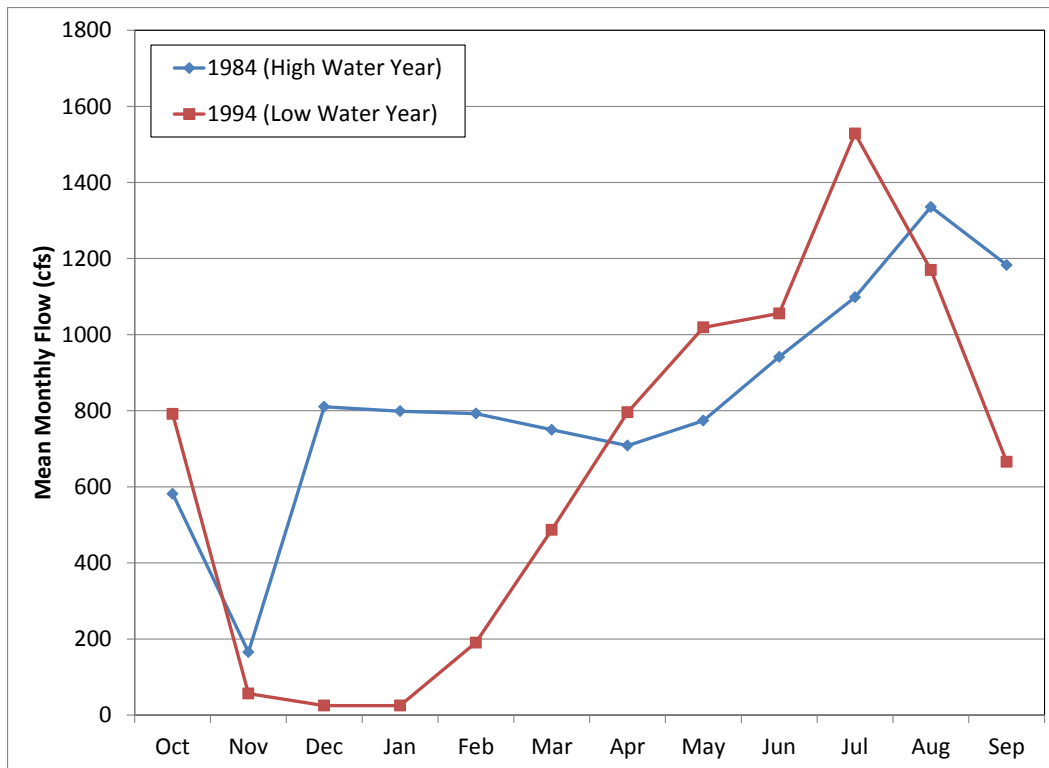
**Figure 7.8.** Monthly average flow below Bend and monthly average NUID diversion at the 175- and 250-cfs minimum flow trial levels.

In addition to investigating the effects on instream flow and water supply, the hydrologic model was used to examine concomitant opportunities for increasing hydropower in both the Deschutes River and Crooked River scenarios. Previously, we demonstrated how trial levels affected the percent of time (across years) that energy production exceeded 200 percent of baseline production (Figure 7.6 and Figure 7.9). However, stakeholders with hydropower interests may also be interested in how trial levels affect within-year timing of flows to determine when a potential site will be most productive. They may also want to examine the timing of flow in years with high and low water availability to assess the range of variability. To illustrate this example, we examined monthly discharge in 1984, a year with high water availability, and 1994, a year with low water availability, for two potential hydropower development opportunities in the Deschutes (powering Wickiup Dam) and Crooked rivers (powering Bowman Dam). At both dams, the primary differences in discharge occur after the reservoir approaches the desired storage level, but that level is reached at different times of year for these two dams (Figure 7.10 and Figure 7.11). The operation of the dams for storage has an obvious influence on the magnitude and timing of flow. In systems such as the Deschutes and Crooked river subbasins that are driven by water uses other than power production, the magnitude and timing of flow would be a strong determinant of the amount and timing of energy production. The range and variability of flow might also influence the type

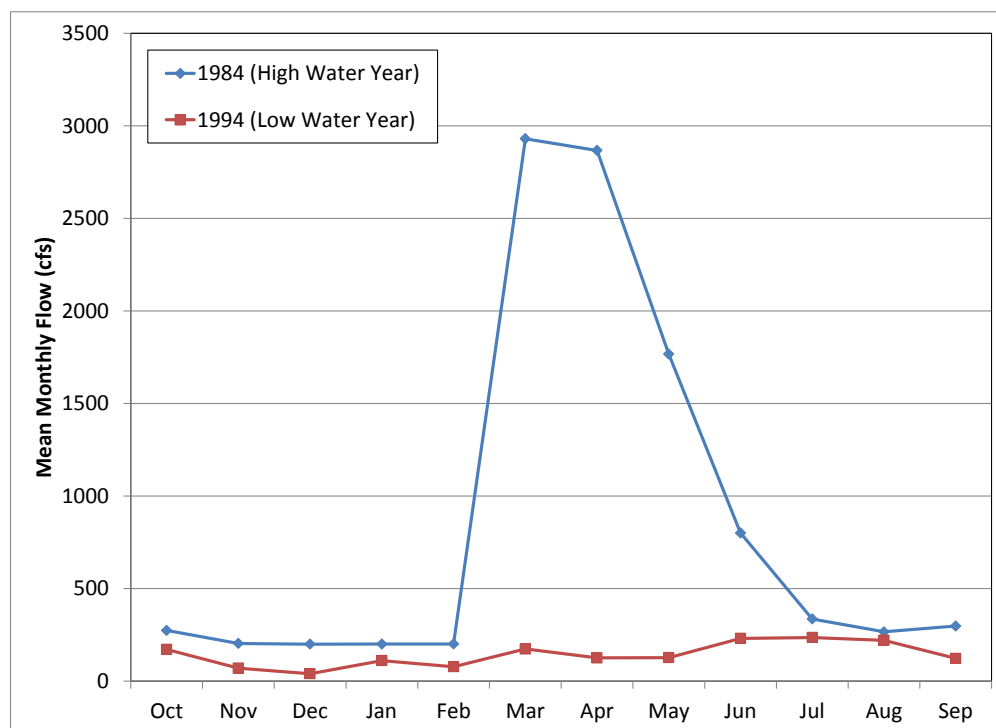
or size of hydropower generation equipment chosen for a dam. Exploring those possibilities in a scenario-based modeling framework could help direct where to conduct more detailed analysis to support actual development.



**Figure 7.9.** Number of years that target levels for value-based metrics were met based on simulated reductions in irrigation demand and a 250-cfs minimum flow below Wickiup Dam.



**Figure 7.10.** Monthly mean flows at Wickiup Dam during high and low water years.



**Figure 7.11.** Monthly mean flows at Bowman Dam during high and low water years.

In summary, the analytical approach presented here demonstrates one possible approach to evaluating the results of scenario-based hydrologic modeling. Although the approach is relatively simple, it demonstrates how influential management actions (as represented by the trial levels included) might be with respect to achieving multiple goals. An important finding from this exercise was that the range of trial levels for increasing minimum flow below Wickiup Dam during the storage season and reducing water demand had little influence on achieving target levels for our value-based metrics in the most favorable and least favorable water years. In the most favorable water years, target levels for the metrics were met at nearly every trial-level combination, including the baseline condition. Conversely, it was rare in the least favorable water years that target levels for the metrics were met by increasing minimum flow or reducing irrigation demand. Based on these findings, it may be beneficial to focus on water years in which management actions have the ability to move metrics above or below the minimum criteria, because these years provide the best opportunity for identifying effective management actions.

The approach presented here is intended to encourage consideration of methods that emphasize exploring a range of potential management actions that may achieve a better balance among multiple, and often conflicting, management goals. This includes, but is not limited to, continued refinement and validation of the hydrologic model, creating more comprehensive modeling scenarios and value-based metrics, and conducting more in-depth analyses to identify where benefits and tensions occur within the system. In doing so, it is important to remember that model scenarios and value-based metrics do not need to be perfect to be informative. By using them in an iterative and collaborative process, they may help move the debate beyond agreement of an exact target that is acceptable to all parties to a discussion of how stakeholders can better understand how achieving their goals interact with the achievement of the goals of other stakeholder groups. By exploring the results of the model in this way, stakeholders are more likely to narrow the bounds of interest so that more in-depth analysis can be completed.





## 8.0 Conclusions

This report summarizes the results of the BSOA Initiative's pilot assessment conducted in the Upper Deschutes River and Lower Crooked River subbasins. The focus of the study was to identify opportunities for sustainable hydropower development and environmental improvement in the context of existing water uses. The study builds on ongoing efforts within the subbasins to address hydropower, environmental, and water-use issues by providing a neutral forum in which opportunities can be discussed, data and information can be aggregated, and additional resources can be leveraged to build decision-support tools that can stimulate and inform dialogue among stakeholders. The study is not intended to provide specific recommendations for addressing these issues, but rather to provide new tools and approaches that can be used in a collaborative fashion to facilitate discussion. Important outcomes and conclusions of this study are described here.

Early efforts of the study were focused primarily on engaging stakeholders, identifying significant data gaps and needed analytical tools (described in the BSOA Initiative Fiscal Year 2011 Year-End Report [Geerlofs et al. 2011]). During this process, an online Opportunity Assessment Toolbox (<http://basin.pnnl.gov/Software/Index>) was created that contains various information, data, and analytical tools that exist for use among MOU agencies, non-federal partners, and stakeholders to assess hydropower and environmental opportunities. Types of information in the Toolbox include environmental analyses, water resources analyses, systems modeling, GIS expertise, new technology development, and data-management capabilities.

In addition to these tools, stakeholders expressed a need for modeling and analysis capabilities that would allow them to better understand tradeoffs among hydropower, environmental, and other water-use goals in their basin. The Basin-Scale Project Team provided a scenario-based modeling approach in response to this need that uses a daily hydrologic model of the Upper Deschutes and Lower Crooked subbasins to simulate alternative water-management scenarios. The hydrologic model was made available to USBR representatives in the basin at the conclusion of the project so that they may continue to refine and use it to answer questions important to basin stakeholders beyond the scope of this project. A preliminary evaluation of the model indicates its performance may be improved by a better understanding of 1) groundwater exchanges in the Upper and Middle Deschutes River; 2) annual storage accruals at Crane Prairie, Prineville, and Ochoco reservoirs; and 3) undocumented reservoir operations and water exchanges throughout the basin. For the purposes of this project, the model provided a suitable platform for demonstrating scenario-based modeling. It also provides new, system-scale hydrologic modeling capabilities to stakeholders in the basin, including daily temporal resolution, water-rights accounting, and simulation of hydropower generation.

Two example scenarios were created to demonstrate the use of scenario-based modeling. The scenarios focused on exploring tradeoffs among three management goals in the Deschutes Basin: 1) increasing hydropower assets by adding new generation at existing dams or diversions and in existing irrigation canals or conduits, 2) increasing instream flows to benefit fish and aquatic ecosystems, and 3) maintaining existing water uses (primarily irrigation). A web-based data-visualization interface was created to facilitate synthesizing model results within the context of these goals. A key function of the interface was the transformation of raw data from the model into the form of value-based metrics. These metrics were based on specific information needs expressed by stakeholders (e.g., how often flow exceeds a conservation flow target at a certain location).

Actions to achieve the goals outlined in the scenarios were simulated in the model by incrementally increasing minimum flow requirements during the storage season and reducing water demand. Through this process of evaluating trial levels, it was possible to illustrate how tradeoffs among multiple and often conflicting goals may be explored. An important finding of this process was that it may be beneficial to focus on water years in which management actions have the ability to move metrics above or below minimum criteria, because these years provide the best opportunity for identifying effective management actions.

The Basin-Scale Project Team also evaluated the technical and economic feasibility of 29 potential small hydropower sites in the basin (14 non-powered dams, 15 canal/conduit sites) using ORNL's HEEA tool. Results of the feasibility assessment indicated that eight of the sites (four non-powered dams, four canals/conduits) may be feasible and could add approximately 19 MW of hydroelectric capacity in the basin and generate more than 78 GWh of energy per year. Most sites that were classified as feasible, as well as several that were classified as infeasible, were included in the hydrologic model.

The Basin-Scale Project Team hopes that the hydrologic model will continue to be used for similar scenario modeling in the basin. The approach presented here is intended to encourage consideration of methods that emphasize exploring a range of potential management actions that may achieve a better balance among multiple, and often conflicting, management goals. It is also intended to encourage stakeholders to come together to create more comprehensive scenarios and value-based metrics, which can help achieve a common understanding of where benefits and tensions occur within the system.

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## **Appendix**

### **Supplemental Model Results**





**Table A.1.** Bias of reservoir storage estimates from Deschutes RiverWare and MODSIM hydrologic models.

Subbasin	Location	Active Storage (acre ft)	RiverWare vs. Observed		MODSIM vs. Observed	
			Bias (acre ft)	Bias (% of active storage)	Bias (acre ft)	Bias (% of active storage)
Upper Deschutes River	Crane Prairie Reservoir	55,300	2,485	4.5	506	0.9
	Crescent Lake	86,900	-3,159	-3.6	788	0.9
	Wickiup Reservoir	200,000	-22,823	-8.4	-2,613	-1.3
Crooked River	Prineville Reservoir	152,800	-157	-0.1	-6,299	-4.1
	Ochoco Reservoir	44,142	3,475	7.9	-2,931	-6.6

**Table A.2.** Mean absolute error (MAE) of reservoir storage estimates from Deschutes RiverWare and MODSIM hydrologic models.

Subbasin	Location	Active Storage (acre ft)	RiverWare vs. Observed		MODSIM vs. Observed	
			MAE (acre ft)	MAE (% of active storage)	MAE (acre ft)	MAE (% of active storage)
Upper Deschutes River	Crane Prairie Reservoir	55,300	5,885	10.6	5,155	9.3
	Crescent Lake	86,900	6,084	7.0	6,193	7.1
	Wickiup Reservoir	200,000	25,448	12.7	21,451	10.7
Crooked River	Prineville Reservoir	152,800	17,258	11.3	13,832	9.1
	Ochoco Reservoir	44,142	5,739	13.0	6,586	14.9

**Table A.3.** Bias of Discharge Estimates from Deschutes RiverWare and MODSIM Hydrologic Models.

Subbasin	Location	Average Annual Discharge (cfs)	RiverWare vs. Observed		MODSIM vs. Observed	
			Bias (cfs)	Bias (% of annual discharge)	Bias (cfs)	Bias (% of annual discharge)
Upper Deschutes River	Crane Prairie Reservoir	277.9	5.6	2.0	0.9	0.3
	Crescent Lake	52.2	0.9	1.8	1.2	2.4
	Wickiup Reservoir	715.1	34.7	4.9	-0.03	<0.01
	BENO Gage	383.9	19.5	5.1	-33.29	-8.7
	DEBO Gage	402.4	216.5	53.8	-407.7	-101.3
Crooked River	Prineville Reservoir	383.9	6.3	1.6	-13.8	-3.6
	Ochoco Reservoir	402.4	-10.0	-23.6	10.8	25.4

**Table A.4.** Mean absolute error (MAE) of discharge estimates from Deschutes RiverWare and MODSIM hydrologic models.

Subbasin	Location	Average Annual Discharge (cfs)	RiverWare vs. Observed		MODSIM vs. Observed	
			MAE (cfs)	MAE (% of annual discharge)	MAE (cfs)	MAE (% of annual discharge)
Upper Deschutes River	Crane Prairie Reservoir	277.9	70.2	25.3	60.3	21.7
	Crescent Lake	52.2	22.0	42.2	22.2	42.5
	Wickiup Reservoir	715.1	209.3	29.3	111.7	15.6
	BENO Gage	383.9	211.9	55.2	100.3	26.1
	DEBO Gage	402.4	324.8	80.7	474.9	118.0
Crooked River	Prineville Reservoir	383.9	136.0	35.4	121.5	31.6
	Ochoco Reservoir	402.4	33.2	78.1	43.3	101.9





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