Optimization of multiple hydroelectric power generation facilities on a single river system

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Problem Statement and Benefit Statement

Power plants are generally operated as standalone assets. With a given supply resource (i.e., fuel) and a given demand (i.e., electricity supply, usually contracted with Power Purchase Agreements), power plants are operated as single entities in which power output financial profits are optimized. For the vast majority of power plants (e.g., coal, natural gas, nuclear, and solar) each facility operates independently of each other, and thus this operating process works just fine. However, for hydroelectric power plants on the same river system, the supply resource (i.e., water flow) is not independent: the upstream hydroelectric facility will inevitably alter the supply resource for the downstream facility.

This concept brings about numerous questions. Does this present an opportunity to operate hydroelectric facilities in aggregate, rather than as independent systems? May facility owners be able to arbitrage pricing differences in successive facilities? In other words, for hydroelectricity, does the sum equal more than the parts?

The benefit of treating these facilities as a system can be significant. First, it would allow for the optimization of profits from hydroelectric facilities as a whole, which will allow for increased renewable energy generation within the United States in needed times and locations. Further, allowing for enhanced value through the ownership of these assets as a system may enable private ownership and development of hydroelectric facilities at higher levels. Rather than viewing these facilities at standalone projects, private owners may desire to hold portfolios of these assets, which will help to enable an inflow of private capital into the renewable energy industry. This will also allow federal and state entities (e.g., the Federal Bureau of Reclamation) to liquidate some of these assets, creating a potential for an increased budget for related projects.

Furthermore, once private developers and owners decide to acquire these assets, it is important to financially optimize these portfolios of assets. Financial optimization is an important component for the optimization of hydroelectric facilities and may bring more value than the simply operational optimization. This paper also explores the potential for Master Limited Partnerships (MLPs) as an option for optimizing this ownership structure. MLPs have never been utilized for renewable energy assets, although these assets are well-suited for this structure. Innovative financial structures may be able to leverage MLP or REIT status, although their feasibility is unclear.

Literature Review

Numerous research studies have explored the optimization of single hydroelectric facilities as a single entity. For instance, some research has focused on the optimization of hydroelectric energy through optimizing individual turbine operation and overall power facility on an hourly basis. These optimization strategies are linked together to exchange appropriate information to ensure consistency of operation of the hydroelectric facility.[1] Similarly, some research work has been done in optimizing the energy and profit of pump-assisted hydroelectric facilities. These can be complicated systems, due to the time-varying nature of power prices and varying water inflows. These studies have found that, on many occasions, the optimal operation for profit-seeking entities is often aligned with that of the optimal operation in maximizing the energy production of these facilities. [2]

Other research has well as hydroelectric facilities as part of a larger system of uses for the hydroelectric facility. For instance, numerous studies have researched the complicated relationships between water used for energy and water used for other functions. These may include flood control, recreation, water supply, navigation, dilution of pollutants, and irrigation, among other uses. Deciding between the varied uses of hydroelectric dams, and the profit

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[1] Georgakakos, Aris P., Huaming Yao, and Yongqing Yu. "Control Models for Hydroelectric Energy Optimization." *Water Resources Research* 33.10 (1997): 2367-379.

[2] Zhao, Guangzhi, and Matt Davison. "Optimal Control of Hydroelectricfacility Incorporating Pump Storage." *Renewable Energy* 34.4 (2009): 1064-077.

potential, as well as non-financial benefits (e.g., community uses), is a complicated measure that has been studied extensively. [3] There are numerous quantitative tools that have been used to help with the difficult decisions regarding various uses of these systems.[4]

However, limited research has been performed on systems in the middle: multiple hydroelectric facilities on single river systems that are co-dependent on the same resource (e.g., river system). Thus, there is an opportunity to conduct some very interesting research in order to determine whether it is feasible to optimize hydropower electricity output on single river systems by operating the facilities as an aggregate system rather than independent assets.

Idea for solution

As aforementioned, most power plants are generally operated as standalone assets. For power plants that use fossil fuels (e.g., coal and natural gas) and those that use renewable resources (e.g., wind and solar), each facility operates independently of each other. The fuel resource from one power plants does not impact the fuel resource for another plant. Of course, market dynamics will impact the amount of fuel that a particular plant can use (e.g., market shortages resulting in high commodity prices can result in significant impact for a particular plant), although one single plant should not impact the operations of another plant.

However, for hydroelectric power plants on the same river system, the supply resource (i.e., water flow) is highly dependent. In other words, the upstream hydroelectric facility will alter the supply resource for the downstream facility. Even though this is the case, research suggests that these power plants are still operated independently of each other. This is likely due to different ownership of the hydroelectric plants, and thus little incentive to alter the outflows of a particular facility. Nevertheless, there appears to be value left on the table because of this oversight.

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[3] Ferreira, L.R.M., R. Castro, and C. Lyra. "Assessing Decisions on Multiple Uses of Water and Hydroelectric Facilities." *International Transactions in Operational Research*3.3-4 (1996): 281-92.

[4] De Ladurantaye, Daniel, Michel Gendreau, and Jean-Yves Potvin. "Optimizing Profits from Hydroelectricity Production." *Computers & Operations Research* 36.2 (2009): 499-529.

The idea for this solution is to operate multiple hydroelectric facilities on the same river system as a portfolio of assets rather than each on a single asset basis. Because hydroelectric turbines have a specified range of allowable volumetric flows, altering the input resource for a particular dam so that it better fits the flow range of the turbines could result in significant improvement of energy generation and profit potential.

As shown in Appendix Figure 1, a hydroelectric facility can be represented by a flow duration curve. The plot shows the "percent exceedance" (i.e., the probability that the water flow will exceed that level in a given year) of various flow ranges, as shown on the y-axis. For a given hydroelectric facility, the turbines may have a specific flow range that is allowable, given the design of the turbine. In this example, the turbine range is 400 cubic feet per second to 800 cubic feet per second. Naturally, the flow amounts that fall outside of these ranges are essentially wasted water.

One might ask why the turbines are not simply sized to fit the flow range for a given location. However, it is a complicated endeavor and not all turbines will function properly at a given location. For instance, some turbines work better at certain head (height) than others. As shown in Appendix Figure 2, various turbine designs work better than others in different design parameters.

Given this, it would be beneficial for a hydroelectric facility to receive inflows that are more well-suited to its turbine design. Appendix Figure 3 shows a representative flow regime over time. The curve that is not covered by the highlighted box represented wasted inflows, due to flows outside of the turbine flow regime.

A flow curve shown in Appendix Figure 4 would be much better suited for this particular turbine design. The flows that previously were outside of the allowable range have been contracted (in the case of flows that were too high) or amplified (in the case of flows that were too low). In fact, this adjustment is possible through the use of an upstream hydroelectric facility (which includes a reservoir), which effectively serves as a damper to the downstream flows. In the following analysis, actual data has been analyzed to show how these flows could be adjusted to create more optimal water flows. In addition, the potential financial benefits have also been analyzed.

Analysis of Operational Optimization

The Yuba-Bear and Drum-Spaulding hydroelectric projects were analyzed as a case study for this research project. The Yuba-Bear hydroelectric project was a partnership between the Nevada Irrigation District and PG&E, which began in the mid-1950s. It consists of 12 dams with a combined gross storage capacity of about 207,865 acre-feet of water. Storage of water began in years ranging from 1859 – 1964 and the powerhouses have a capacity of nearly 75 MW. Similarly, the Drum-Spaulding hydroelectric project was developed by PG&E and is composed of 12 dams and powerhouses with a total of 16 generating units. The powerhouses have a capacity of nearly 190 MW and the average annual generation comes to 786 GWh. The Yuba-Bear and Drum-Spaulding hydroelectric projects are located west of Lake Tahoe. Appendix Figure 5 shows the schematic of Yuba-Bear and Drum-Spaulding hydroelectric projects.

For this analysis, the data was focused on Fordyce Lake, which consists of a large reservoir (named Fordyce Lake) of almost 50,000 acre-feet of storage capacity. There are flow gauges located above and below the dam at Fordyce Lake, which allows for the assessment of flow regimes with and without the "upstream" dam. By using these flow regimes, one can assess the relative differences in power generation and financial benefit given the different flow regimes.

A shown in Appendix Figure 6, the red line represents the flow patterns with the dam in place while the blue line represents flow patterns without the dam. As shown in the figure, the blue line appears to have more extreme flow events. For instance, the spikes in 1980, 1982, 1986, and other years are completely absent in the red line. Although there are some peaks for the red line, they appear to be of a lesser degree and not as prevalent. This is consistent with the idea of an upstream dam. Because it acts like a damper, absorbing high flow periods and supplementing low-flow periods, the peaking flows smooth out in the presence of this hydroelectric facility.

These flow patterns can also be seen clearly in the flow duration curve in Appendix Figure 7. As shown, the blue curve has a higher slope while the red curve is more stable. In other words, the relatively high flows (e.g., flows in the top decile) are at a higher level in the scenario with the nonexistent dam (blue line) while the relatively low flows (e.g., flows not in the top decile) are at a higher level in the scenario with the dam in place (red line). The red line, with the dam in place, has a lower range of flows because of the damping effect of the upstream dam. Thus, an upstream dam tends to “smooth out” the flow conditions of the hydroelectric facility.

Looking at the data more granularly, an upstream dam does appear to cause less extreme flow events. As shown in Appendix Figure 8, the blue line (non-existent dam) has nearly 6% of total flows over a large flow state of 600 cubic feet per second. However, the red line (the scenario with the dam in place) only has 2% of flows over a large flow state of 600 cubic feet per second.

Similarly, an upstream dam also appears to cause less low-flow events, as shown in Appendix Figure 9. In this instance, the blue line (non-existent dam) has only 30% of total flows over a low flow state of 100 cubic feet per second. On the other hand, the red line (the scenario with the dam in place) only has over 35% of flows over a low flow state of 100 cubic feet per second. Thus, the presence of an upstream dam can increase the percentage of flow states above a low flow amount by nearly 20%. Given a turbine flow parameters in this range, this could result in a significant increase in energy production.

Of course, the characteristics of the downstream hydroelectric facility greatly impact the effect of this change. It is possible to assume a standard hydroelectric facility of 148 foot head and 10 MW nameplate capacity to determine the impact. For instance, if the turbine flow range is between 200 CFS and 1,000 CFS then the net benefit in this scenario would be a gain of 90 MWh, as shown in Appendix Figure 10. However, if the turbine flow range changes only slightly to between 300 CFS and 1,200 CFS, then the net benefit in this scenario would be a loss of 540 MWh, as shown in Appendix Figure 11. Obviously, the net impact of the energy production is highly dependent on the flow characteristics of the downstream turbine. Even small changes in flow regimes can result in drastically different impacts for the net energy production for the downstream facility.

With this data, we can create a sensitivity table to assess the impact of potential energy production changes and its effect on the financial returns of the downstream hydroelectric facility. As shown in Appendix Figure 12, the net financial impact can range wildly. For some flow regimes (e.g., turbine flow range of 100 CFS – 1,600 CFS) the net result is zero. However, the net financial return can also be highly negative with decreases up to 50% (e.g., turbine flow range of 100 CFS – 1,600 CFS) or highly positive with increases up to 76% (e.g., turbine flow range of 350 CFS – 400 CFS).

In summary, optimization of hydroelectric facilities can be achieved through operational control due to the presence of an upstream dam. There can be significant gains from this production, although the exact amount can vary widely. For each potential scenario, research should be pursued to determine the specific impact on the downstream facility. Of course, not all of the flow regimes are appropriate in the above analysis, given the hydrologic constraints of the dam and the economic and energy needs of the surrounding areas. Nevertheless, it does show the potential for hydropower operational optimization.

Analysis of Financial Optimization

In addition to operational optimization, it is also important to assess whether there is an opportunity to financially optimize the ownership of hydroelectric facilities. Financial optimization is an important component for the optimization of hydroelectric facilities. Research suggests that Master Limited Partnerships (MLPs) are an option for optimizing this ownership structure. They have the tax advantages of an LLC (“pass-through” entity without double taxation) and the liquidity advantages of a C corporation (publicly traded). The MLP universe is large and growing, with over $200 BN in market capitalization and comprising over 90 entities. MLPs are compelling for both sponsors (with high valuations and tax benefits) and investors (via high-yields, tax benefits, and low correlation attract investors). MLPs have never been utilized for renewable energy assets, although these assets are well-suited for this structure. Innovative structures may be able to leverage MLP or REIT status, although feasibility is unclear.

Master Limited Partnerships are partnerships that can be publicly traded as corporations (as described in Internal Revenue Code Section 7704). There are stringent requirements for what can and cannot be treated as a Master Limited Partnership (MLP) 90% of entity's gross income must be "qualified income." "Qualified income" includes interest, dividends, real property, and "income and gains derived from the exploration, development, mining or production, processing, refining, transportation (including pipelines transporting gas, oil, or products thereof), or the marketing of any mineral or natural resource (including fertilizer, geothermal energy, and timber)"

As aforementioned, MLPs have the tax advantages of an LLC and the liquidity advantages of a C corporation. In regards to tax status, MLPs (like LLCs) have no corporate-level taxes and are a "pass-through" entity (no double taxation). This is in contrast to a C corporation, in which income taxed at corporate level which results in "double taxation" for shareholders (also taxed at personal level). In regards to liquidity, MLPs (like C corporations), can have an unlimited number of shareholders and can be publicly traded. This is in contrast to LLCs which generally cannot pursue initial public offering (IPO) to be publicly traded. Thus, MLP structures are really the best of both worlds in this respect.

Master Limited Partnerships are very attractive entities for their sponsors. First, they have a premium valuation, in that assets within the MLP structure typically trade at higher valuations in the market than those same assets within a C-corp structure. There is also a comparative advantage due to the tax benefits, as there is the potential to pay more for an acquisition than a corporation and realize the same cash flow. Similarly, an MLP has the potential to realize more cash flow from an acquisition given the same acquisition price. In addition, MLPs have greater capital access, making financing acquisitions and organic projects feasible.

MLPs are also very compelling for investors. They are stable and predictable, with stable cash flows that can be predicted with a high degree of accuracy (e.g., compared with the advertising revenue of Google in any given quarter). Investors have also come to view MLPs as providing an attractive yield, compared with other investments (e.g., bonds) with expected yields of 5% - 10% (with growth of 3% - 5%). In addition, MLPs offer a tax-efficient means of energy investing (i.e., tax shield for 80% - 90% of cash distributions, with tax-deferrals for remaining until asset sale). Finally, MLPs can provide significant portfolio diversification due to low correlation with most asset classes.

Congress has actually excluded inexhaustible energy sources, including hydroelectricity, as qualified income. In 1988, qualifying income was clarified to not include income from "fishing, farming (including the cultivation of fruits or nuts), or from hydroelectric, solar, wind, or nuclear power production." Other examples of inexhaustible resources that are not included are soil, sod, turf, water, air and minerals from sea water, although an exception was made for geothermal power in 1987. Under a 2008 law, Congress added industrial carbon dioxide, transportation biofuels, alcohol and certain other alternative fuels

There is a potential for lobbying efforts to include renewable energy to be included as qualifying income. For instance "Renewables for Publicly Traded Partnerships Group" lobbying entity was formed in July 2011. The American Wind Energy Association (AWEA) has also indicated that it would favor and pursue MLP status for wind.

There may be potential solutions around this problem. For instance there may be an opportunity to leverage the "real property" component of qualified income for hydroelectric power. In June 2007, a private letter ruling (PLR) was released by the Treasury (PLR 200725015) that confirmed the "real property" status of a broad range of energy assets. Real property status could be leveraged via a real estate investment trust (REIT) or master limited partnership (MLP). Various components of a hydroelectric system that are separate from the turbines in the power houses (e.g., reservoirs, dams, canals, watersheds, tunnels, pipes, flumes, aqueducts and associated land) could feasibly be applied to "real property." Obviously, further study is required to assess whether hydroelectricity assets could be applied to tax-favored corporate structures.

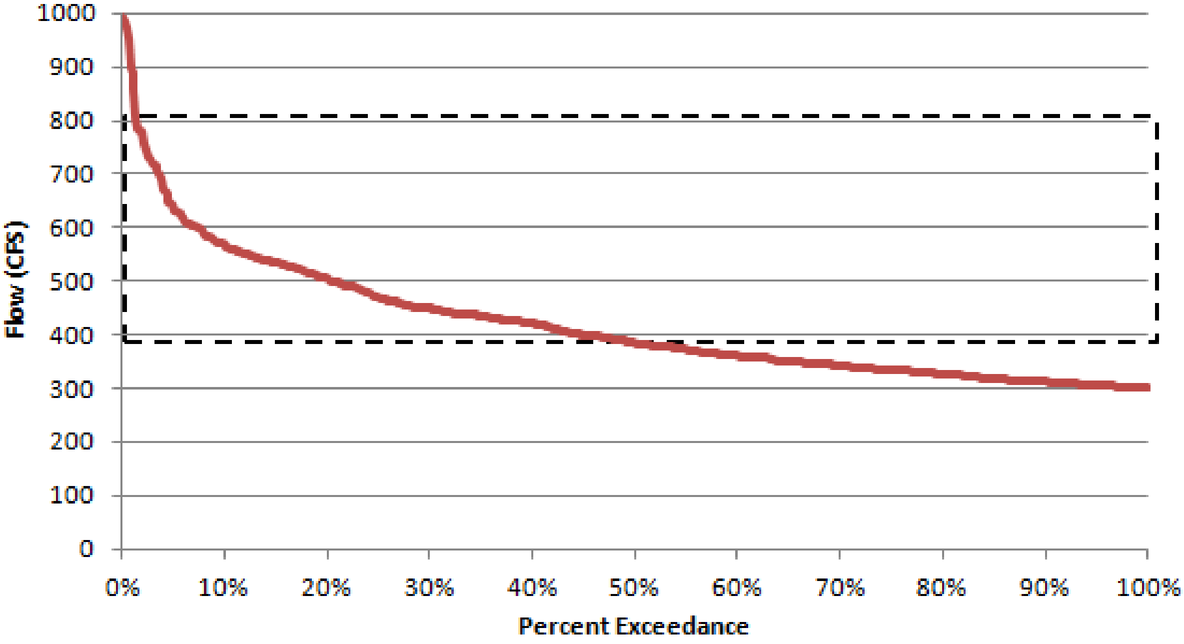
Conclusion

Unlike many other kinds of power plants, hydroelectric power plants on the same river system, have a supply resource (i.e., water flow) that is not independent: the upstream hydroelectric facility will inevitably alter the supply resource for the downstream facility. With some research, there appears to be an opportunity to operate hydroelectric facilities in aggregate, allowing for the arbitrage of pricing differences in successive facilities.

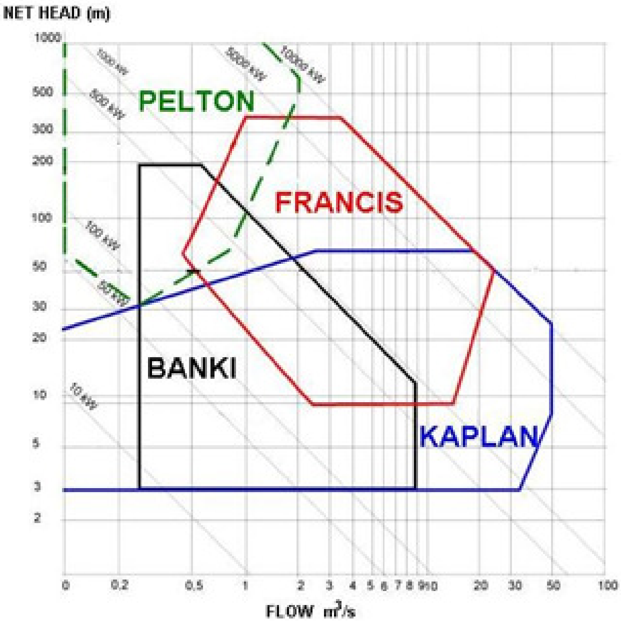
Treating these assets as a portfolio would allow for the optimization of profits from hydroelectric facilities as a whole. This may enable private ownership and development of hydroelectric facilities, which could help to boost the amount of private capital in the renewable energy industry.

Private owners may also financially optimize these portfolios of assets. Master Limited Partnerships (MLPs) are a potential avenue for optimizing this ownership structure. MLPs have never been utilized for renewable energy assets, although these assets are well-suited for this structure. Although further study is necessary, it does appear there is an opportunity to capitalize on this optimization potential.

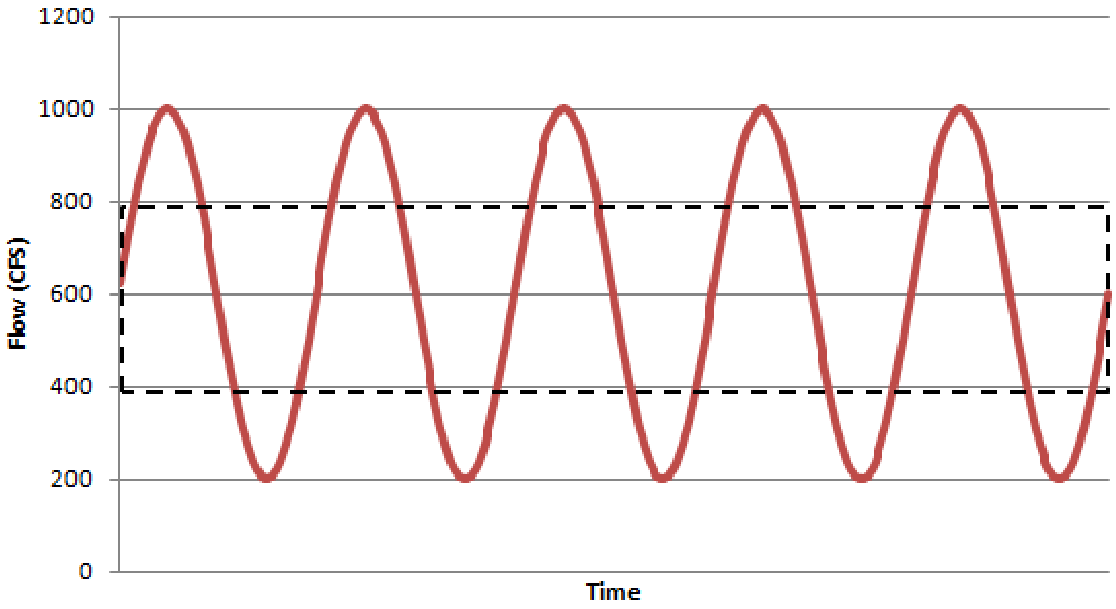
Appendix



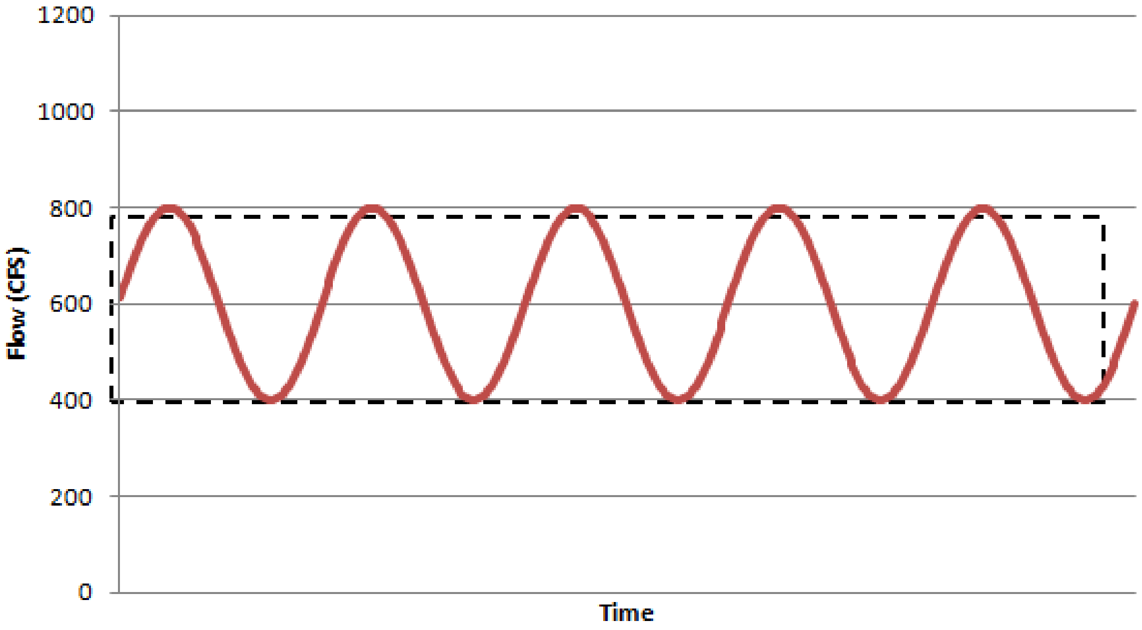
Appendix Figure 1: Representative flow duration curve



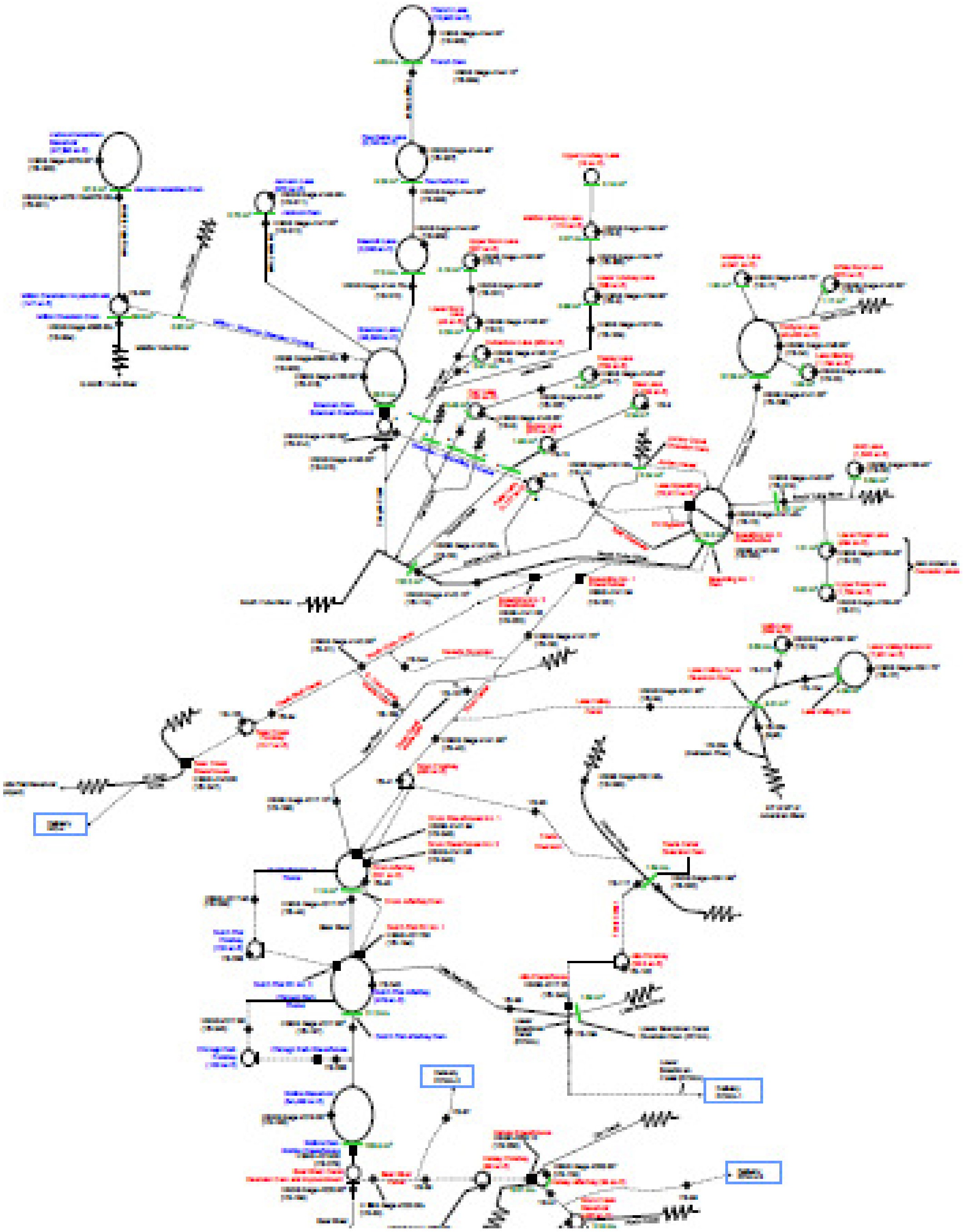
Appendix Figure 2: Hydroelectric turbine diagram



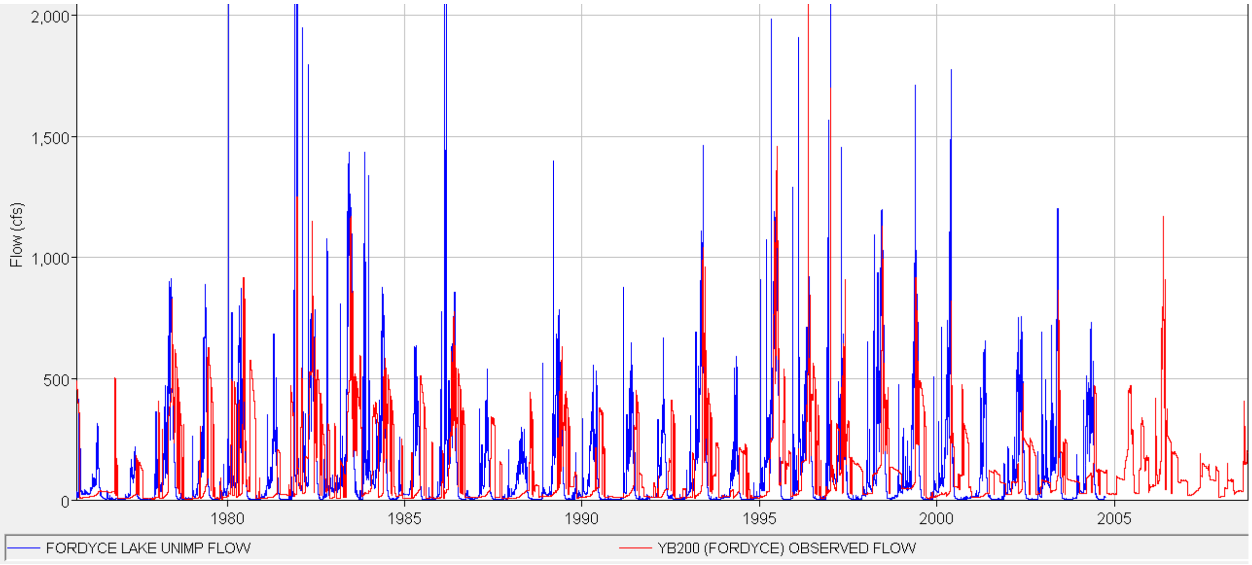
Appendix Figure 3: Representative flows over time



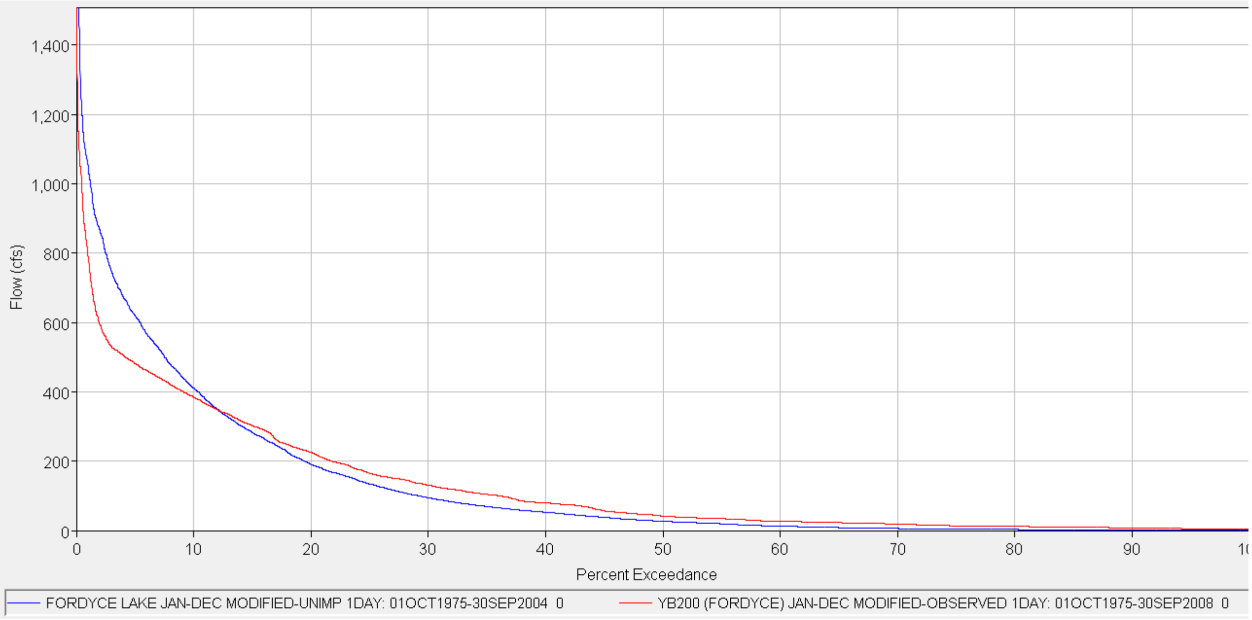
Appendix Figure 4: Representative flows over time



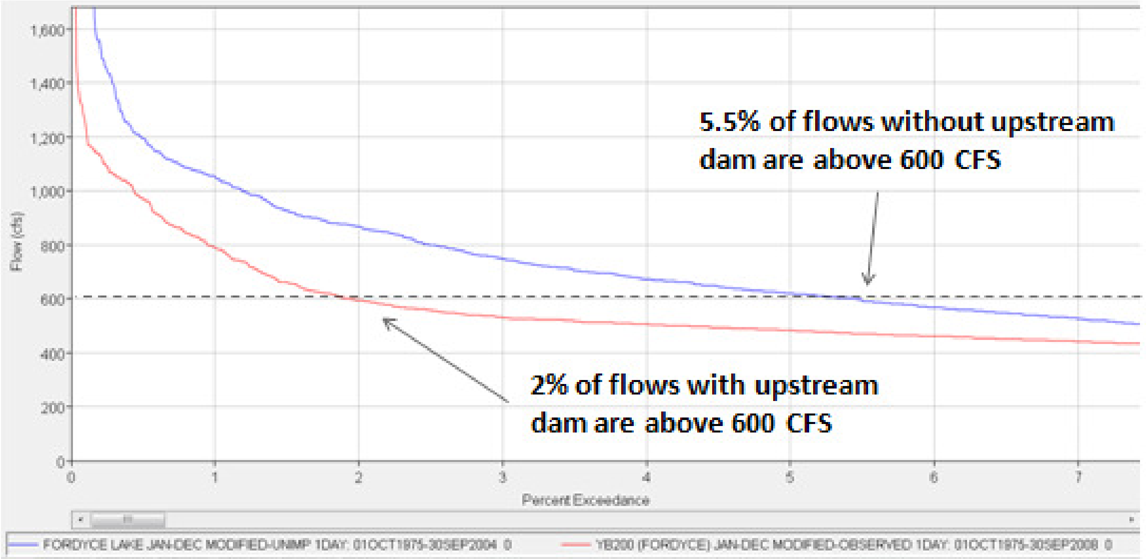
Appendix Figure 5: Schematic of Yuba-Bear and Drum-Spaulding hydroelectric projects



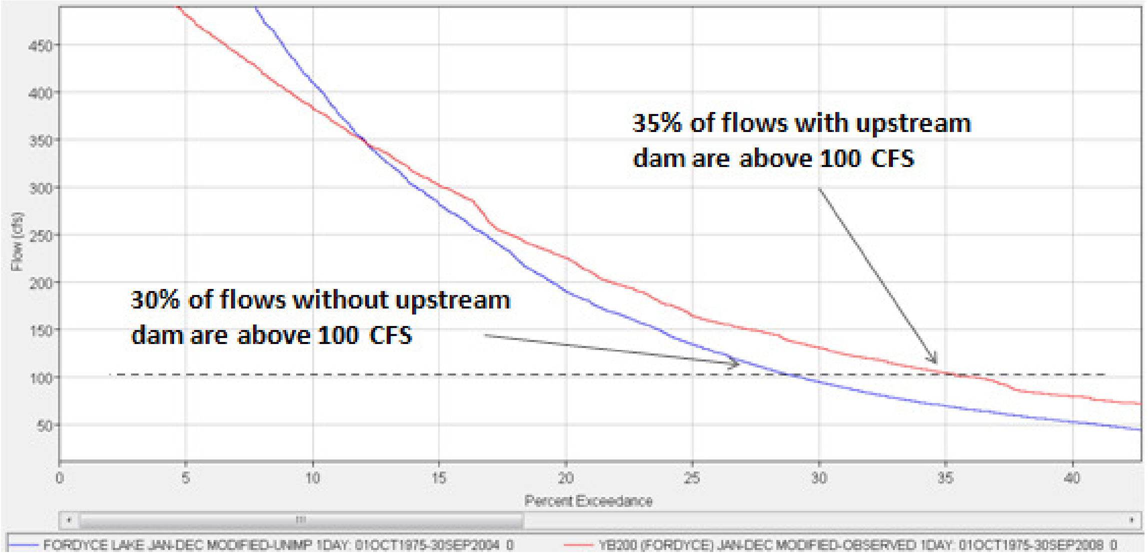
Appendix Figure 6: Flows at Fordyce Lake



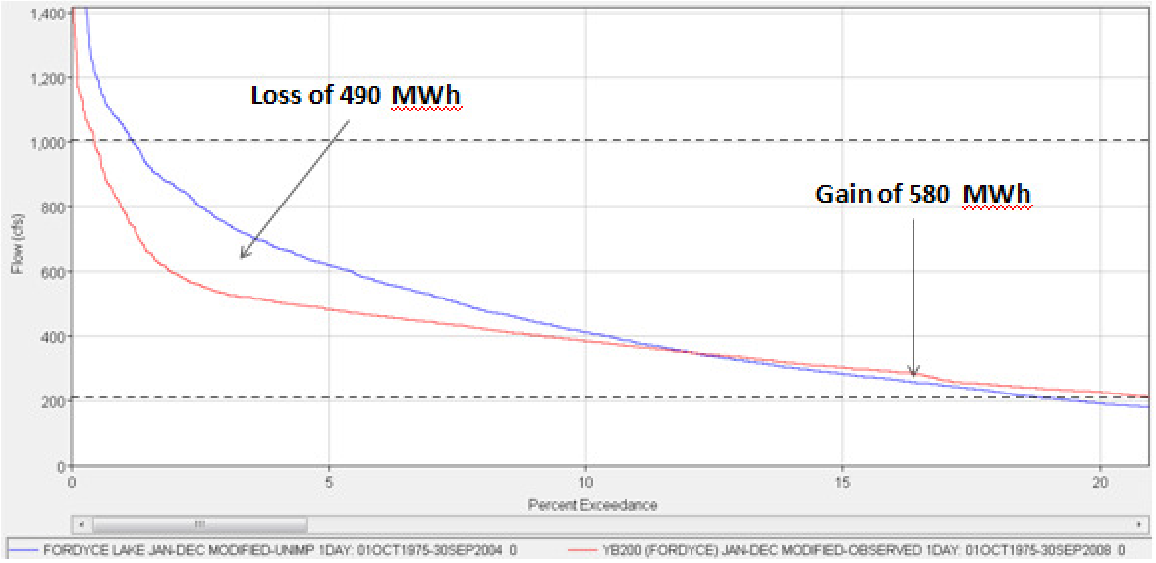
Appendix Figure 7: Flow duration curve for Fordyce Lake



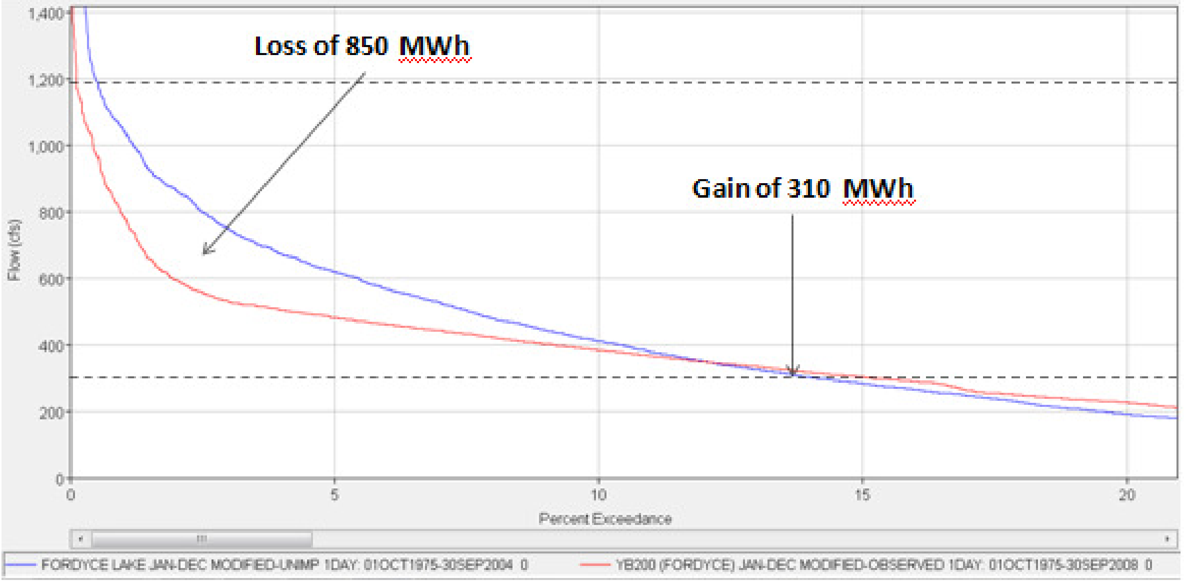
Appendix Figure 8: Flow duration curve for Fordyce Lake



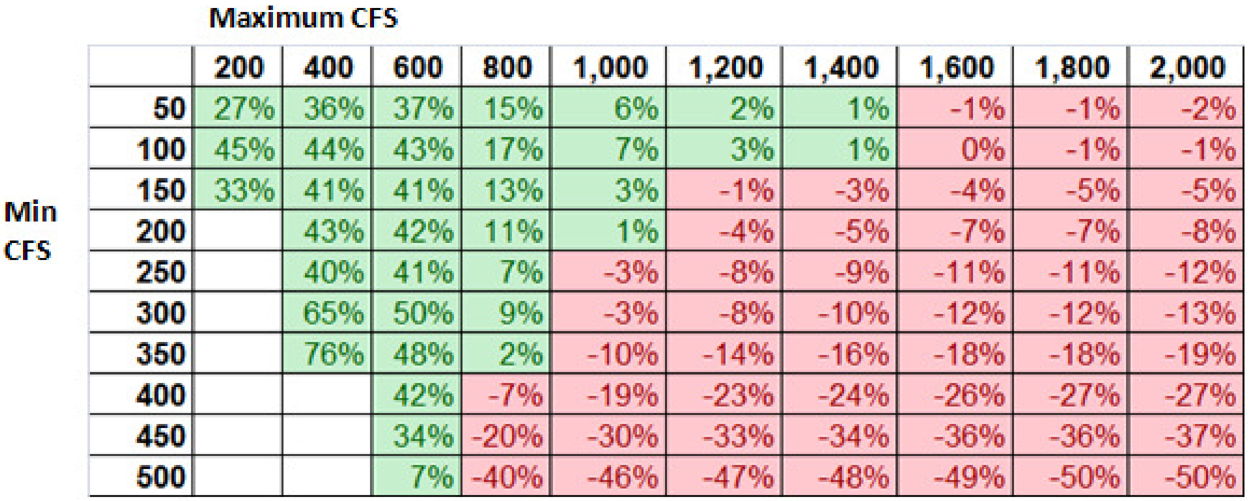
Appendix Figure 9: Flow duration curve for Fordyce Lake



Appendix Figure 10: Positive energy gain



Appendix Figure 11: Negative energy gain



Maximum CFS

Min CFS

	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
50	27%	36%	37%	15%	6%	2%	1%	-1%	-1%	-2%
100	45%	44%	43%	17%	7%	3%	1%	0%	-1%	-1%
150	33%	41%	41%	13%	3%	-1%	-3%	-4%	-5%	-5%
200		43%	42%	11%	1%	-4%	-5%	-7%	-7%	-8%
250		40%	41%	7%	-3%	-8%	-9%	-11%	-11%	-12%
300		65%	50%	9%	-3%	-8%	-10%	-12%	-12%	-13%
350		76%	48%	2%	-10%	-14%	-16%	-18%	-18%	-19%
400			42%	-7%	-19%	-23%	-24%	-26%	-27%	-27%
450			34%	-20%	-30%	-33%	-34%	-36%	-36%	-37%
500			7%	-40%	-46%	-47%	-48%	-49%	-50%	-50%

Appendix Figure 12: Sensitivity analysis