Restoring Flow Regimes after Dam Construction and Operation: Evidence from Dynamic Systems Theory

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Abstract

Dams provide a variety of benefits to society, including hydropower generation, flood control, recreation, and water supply for municipal, industrial, and agricultural customers. However, constructing and operating dams for these purposes can negatively impact downstream ecosystems by altering natural flow regimes and interfering with the lifecycles of aquatic and riparian species. Increased concern from environmental interests has put pressure on dam operators to quantify the flow regime changes that have resulted from dam construction and to evaluate how future modifications to dam releases may impact river systems. In this study, we present a method for analyzing the impact of dam operations by reconstructing system trajectories from hydrologic flow time series for different periods of dam operation (pre-dam, post-dam, and post-modification). We apply these methods to flow data from eight rivers in the US to determine the dimensionality of each operating period and to analyze trends based on the primary purpose of dam operation. Hydropower dams operated without flow restrictions exhibit high dimensional, stochastic behavior. However, the system dimensionality is reduced to approximately three variables when ramping restrictions are implemented, or in cases where an afterbay is present to reregulate flows. This low dimensional behavior is more similar to natural flow regimes. For dams operated primarily for flood control or water supply, the flow regimes are typically low dimensional and more deterministic.

1. Introduction

Dams play an integral role in the management of water resources and provide multiple benefits to society by increasing water supply reliability, enhancing flood control, generating hydropower, and providing recreational opportunities (Graf 1999). However, dams can also have detrimental effects on riverine ecosystems. Construction of large dams and reservoirs reduces the longitudinal connectivity of river systems, preventing fish passage upstream and interrupting important migration patterns. Dam operations also cause significant changes in natural flow regimes by adjusting the timing and frequency of low flow and high flow events. These new flow patterns can disrupt the timing of fish spawning and migration, vegetative growth, and other lifecycle processes of aquatic and riparian species. Dam operations can also impact sediment and temperature regimes within a river system. Much of the sediment that would normally flow downstream and deposit in the floodplain is trapped behind the dam instead, causing major changes in the channel morphology and reducing the dynamic character of the instream habitat. In addition, low flows that occur when water is held back to fill reservoirs can lead to increased water temperatures and harm fish species, such as salmon, that rely on cooler water temperatures during their migration periods. Low flow periods can also disconnect the river from its floodplain, cutting off species from their former habitat. The net effect of all of these modifications is to weaken the native plant and animal populations and pave the way for the growth of invasive species that can take advantage of the modified flow regimes (Graf 1999; Richter and Thomas 2007; Nilsson and Berggren 2000).

As awareness of the degraded nature of rivers in the US grows, there is now more discussion of the benefits of modifying dam operations to mitigate the effects on fluvial systems. All hydroelectric projects that undergo relicensing through the Federal Energy Regulatory Commission (FERC) must now comply with National Environmental Policy Act requirements and incorporate flow recommendations from national and state fisheries agencies to minimize project impacts on aquatic species (DOE 2004). In addition, the US Army Corps of Engineers

(USACE), one of the largest reservoir operators in the country, has partnered with The Nature Conservancy (TNC) on an initiative known as the Sustainable Rivers Project. Through this initiative, USACE and TNC are studying ways to modify dam operations to mimic pre-dam flow regimes and improve the economic, social, and environmental sustainability of dams (TNC 2013). In recent years, there has also been increased support for removing dams to restore natural flow patterns and pre-development ecosystems. However, removal of large dams that are critical components of major water systems in the western US is unlikely in the foreseeable future. As a result, dam reoperation is an important component of multi-objective water resources management because it not only provides benefits for the river ecosystem, but also allows for the continued use of reservoirs to benefit society.

As a result of dam reoperation, hydropower generation capacity is often reduced, leading to a loss of low-cost, high-reliability power. Other energy sources, such as coal and natural gas, are required to replace the lost generation capacity. This is problematic for energy providers, who are now under more pressure to increase their clean energy production in order to reduce emissions and meet renewable portfolio standards (EPA 2015). Water supplies may also be reduced because of environmental flow requirements, forcing municipalities and irrigation districts to seek out more expensive sources in order to meet the demands of their customers. Thus, when faced with the need to develop new operating policies that consider downstream ecosystems, dam operators want to ensure that the new release schedules are actually achieving their stated goals.

Dynamic systems theory has been used in a variety of applications to characterize the multi-dimensional aspects of complex systems. Previous work related to rivers has focused on the fractal nature of the rivers themselves and how channel networks evolve over time (Tarboton et al. 1988; Rinaldo et al. 1993). More recently, fractal dimensions have been used to highlight the potential benefits of using chaos theory to serve as a bridge between deterministic and stochastic modeling of environmental systems, including river flows (Sivakumar 2012). However, to our knowledge, a system dynamics approach has not been applied to rigorously study watersheds and the effects of changes in dam operations on a river's flow regime. In this study, we use attractor reconstructions and their corresponding fractal dimensions to characterize flow regime changes on eight rivers. We then use these metrics to determine the dimensionality of distinct flow regimes and to evaluate whether certain types of dams have similar footprints based on the purpose of their operations. We also evaluate the effectiveness of operational changes meant to mirror natural flow regimes.

2. Methods

For this study, historical daily streamflow data was obtained from the USGS National Water Information System website for sites just downstream of dams along the eight rivers listed in Table 1 (USGS 2015). We performed our analysis in three parts, first creating an m-dimensional ($m>1$) reconstructed attractor from the flow time series, then determining the fractal dimension of the reconstructed attractor, and finally iterating in successively higher embedding dimensions until the fractal dimension leveled off. These steps were accomplished using a Matlab code modified from Henry et al. (2001). Our methodology is described in more detail below.

Table 1. Summary of Dam Sites

River	Dam	USGS Site ID	Drainage Area (sq mi)	Period of Record (Water Year)	Purpose
Colorado	Glen Canyon	09380000	111,800	1922-2014	hydropower flood control water supply
Columbia	Priest Rapids	12472800	96,000	1918-2014	hydropower
Kootenai	Libby	12305000	11,740	1928-2014	hydropower flood control
Merced	New Exchequer McSwain	11270900	1,061	1901-1914 1916-2014	hydropower water supply
Roanoke	Kerr	02080500	8,384	1912-2014	hydropower flood control
San Juan	Navajo	09365000	7,240	1931-2014	flood control
Skagit	Diablo Ross Gorge	12178000	1,175	1909-1914 1921-2014	hydropower
Willamette	Fall Creek	14151000	186	1936-2014	flood control

2.1. Attractor Reconstruction

According to dynamic systems theory, the evolution of a dynamic system, such as a river basin, can be displayed by its trajectory, or attractor, in the phase space that represents its variables. The dimensionality of the phase space (i.e., the number of relevant system variables) is typically unknown *a priori*. For a complicated system, its dimensionality can be very high, effectively precluding any deterministic analysis and modeling. However, if a dynamic system can be represented by a smaller number of variables (hence having a phase space with smaller dimensionality), it can potentially be analyzed mechanistically. More importantly, if the system undergoes structural modifications, such as dam construction on a river, the dimensionality of the reconstructed attractor can shed light on the effects of such changes.

As outlined by Takens (1981), the system trajectory can be reconstructed from a single observational series (e.g., daily flow data) using a delay embedding theorem, even without knowing the number of system variables. The reconstructed trajectory is invariant under continuous transformation of the system variables and is thus similar to the actual system trajectory (Takens 1981; Eckmann and Ruelle 1985). This reconstruction process can reveal the number of variables involved but cannot identify them. The essence of the process is to take observations from a single available time series with a delay τ and build a series of m-dimensional points, or vectors, that form the attractor. Thus, two parameters, the delay τ and the dimensionality m, must be recovered. An m-dimensional embedding X_i can then be constructed from a series of N discrete observations of x, as shown below.

$$X_i = \left(x_i, x_{i+\tau}, x_{i+2\tau}, \dots, x_{i+(m-1)\tau}\right) \qquad i = 1, 2, \dots, N-(m-1)\tau$$

An appropriate delay for the flow data can be determined using an autocorrelation function to ensure that x_i and $x_{i+\tau}$ are not highly correlated. Other methods, such as the mutual information method (Fraser and Swinney 1986), have also been proposed. For the flow data, the delay was set by selecting the value of τ at which the autocorrelation function (Eq. 1) first equaled zero, as suggested by Addison (1997).

$$R(\tau) = \frac{\sum_{i=1}^{N-\tau}(x_i')(x_{i+\tau}')}{\sum_{i=1}^{N-\tau}(x_i')^2} \qquad (1)$$

$$where\ x_i' = x_i - \overline{x_\imath}$$

2.2. Fractal Dimension Calculation

For each embedding dimension, the fractal dimension was determined by calculating the correlation dimension C_r of the attractor following the method of Grassberger and Procaccia (1983). C_r is determined using Eq. 2, where θ is the Heaviside function and r is a specified distance in the phase space. The summation term counts all point pairs, X_i and X_j, on the attractor trajectory that are separated by a distance less than r.

$$C_r = \frac{1}{N(N-1)}\sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N}\theta(r - |X_i - X_j|) \qquad (2)$$

The fractal dimension for the m-dimensional embedding is then calculated by finding the slope of the linear region of the log C_r versus log r plot, shown in Figure 1. This procedure is repeated for consecutively higher embedding dimensions. For dynamic systems of limited (small) dimensionality, the fractal dimension of the reconstructed attractor increases linearly with increasing dimension of the embedding phase space until it saturates (Eckmann and Ruelle 1985; Addison 1997). This saturation level is the “true” fractal dimension of the attractor, and the corresponding dimension of the embedding space is taken as the number of variables describing the system. Dynamic systems that have a high dimensionality, very often due to dominant stochastic elements, typically show a continued increase of the attractor fractal dimension with increasing dimension of the embedding space, without signs of saturation. The expected behavior for such a dynamic system is shown in Figure 2.

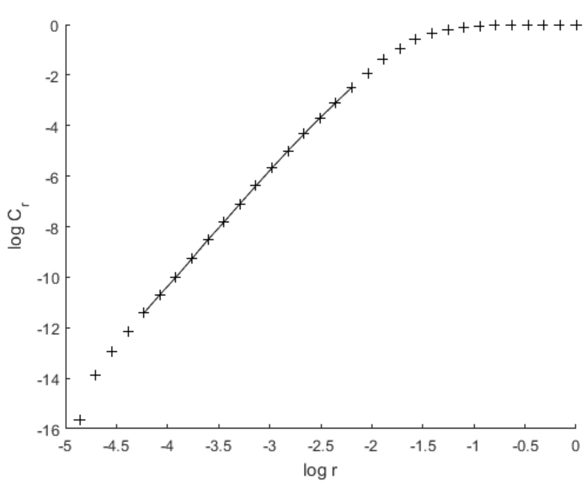

Figure 1. Example of correlation dimension method for finding fractal dimensions

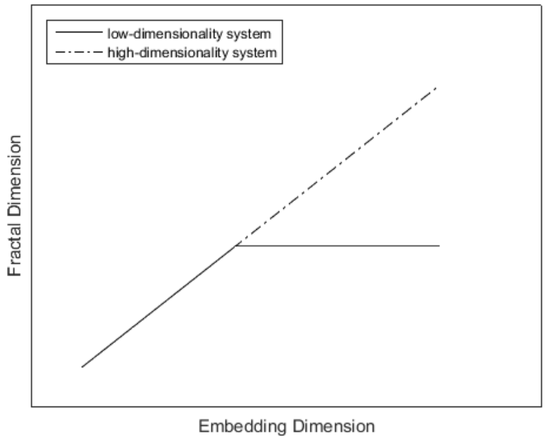

Figure 2. Expected behavior of low- and high-dimensionality systems

Three-dimensional attractor footprints were also plotted for each period of dam operation, using either the embedding dimension corresponding to the saturation level or, if the fractal dimension did not show signs of saturation, the highest embedding dimension. The fractal dimensions and attractor footprints for each operating regime (pre-dam, post-dam, and, if applicable, post-modification) were compared to analyze how each dam impacted the natural flow regime of the river system and to evaluate the dimensionality of each operating regime.

3. Study Areas

3.1. Colorado River

Glen Canyon Dam on the Colorado River in Arizona was completed in 1964 and provides flood control, hydropower generation, and water storage for agricultural, municipal, and industrial users. It is a 178-m (583-ft) concrete arch dam with eight hydropower generating units that provide a total capacity of 1.32 GW (USBR 2008). Figure 3 shows the time series of flow data for the Colorado River at Lees Ferry, AZ. From 1965 to 1992, releases from Glen Canyon Dam were based primarily on the combined power demands of approximately 100 entities serviced by the Western Area Power Administration in Arizona, Colorado, New Mexico, Nevada, Utah, and Wyoming (Harpman 1999). Changes in peaking power demands and the need to generate power during system emergencies resulted in large fluctuations in releases.

In 1992, the Grand Canyon Protection Act was passed, requiring modification to the operations at Glen Canyon Dam to reduce the impact on downstream ecosystems in Grand Canyon National Park. After consideration of various operating policies, the Modified Low Fluctuating Flow option was selected as the preferred alternative. This alternative sets minimum releases of 227 cubic meters per second (cms) (8,000 cubic feet per second [cfs]) from 7am to 7pm and 142 cms (5,000 cfs) during the rest of the day, with a maximum instantaneous release of 708 cms (25,000 cfs). It also restricts ramping rates, permitting a maximum increase of 113 cms/hr (4,000 cfs/hr) and a maximum decrease of 42.5 cms/hr (1,500 cfs/hr). The total allowable daily flow fluctuation in a given month ranges from 142-227 cms (5,000-8,000 cfs) per 24-hour period, depending on the monthly release volume. Overall, the policy aims to reduce daily and hourly flow fluctuations and provide more consistent flows for downstream wildlife. This alternative also includes beach- and habitat-building flows, which are infrequent, high-flow releases that exceed the maximum allowable release of 708 cms (25,000 cfs). These flows are intended to rebuild sandbars by introducing more sediment into the river and increasing sand deposition along the riverbanks, thus providing more riparian habitat and larger areas for camping (USBR 1995). High flow releases, which measured between 1,161 cms (41,000 cfs) and 1,274 cms (45,000 cfs), occurred in 1996, 2004, 2008, 2012, and 2013 and typically lasted between three and eight days (USBR 2014).

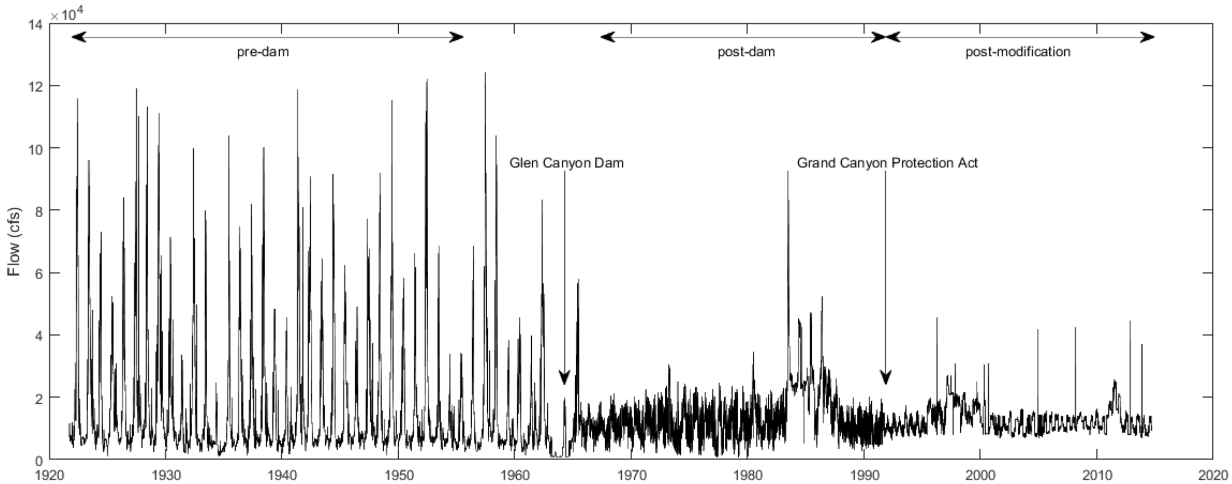

Figure 3. Historical daily stream flow record for USGS 09380000: Colorado River at Lees Ferry, AZ (USGS 2015)

3.2. Skagit River

The Skagit River Hydroelectric Project, operated by Seattle City Light, is located in Washington and consists of Gorge Dam, completed in 1924, Diablo Dam, completed in 1936, and Ross Dam, completed in 1952, with generating capacities of 93 MW, 156 MW, and 360 MW, respectively. The final component of the project, Gorge High Dam, was constructed in 1961 to replace the original Gorge Dam, adding an additional generator and 66.7 MW of generating capacity to the powerhouse (Seattle City Light 2002; Pitzer 1978). Figure 4 shows the time series of flow data for the Skagit River at Newhalem, WA. After construction of the dams, the project was operated to meet the power demands of Seattle, which led to high flow variability on a daily and hourly basis (Connor and Pflug 2004).

In 1981, flow releases from the dams were modified to prevent rapid dewatering and stranding of salmon and steelhead downstream of the project. Further flow restrictions took effect in 1991, when Seattle City Light signed the Skagit Fisheries Settlement Agreement as part of the FERC relicensing process for the project. This settlement established minimum flow requirements of 42.5-73.6 cms (1,500-2,600 cfs), restricted downramping to 85.0 cms/hr (3,000 cfs/hr) during the night, and eliminated daytime downramping (Conner and Pflug 2004). It also set monthly flow requirements based on the annual hydrology in the basin and provided even greater protection for salmon and steelhead populations (Seattle City Light 2002).

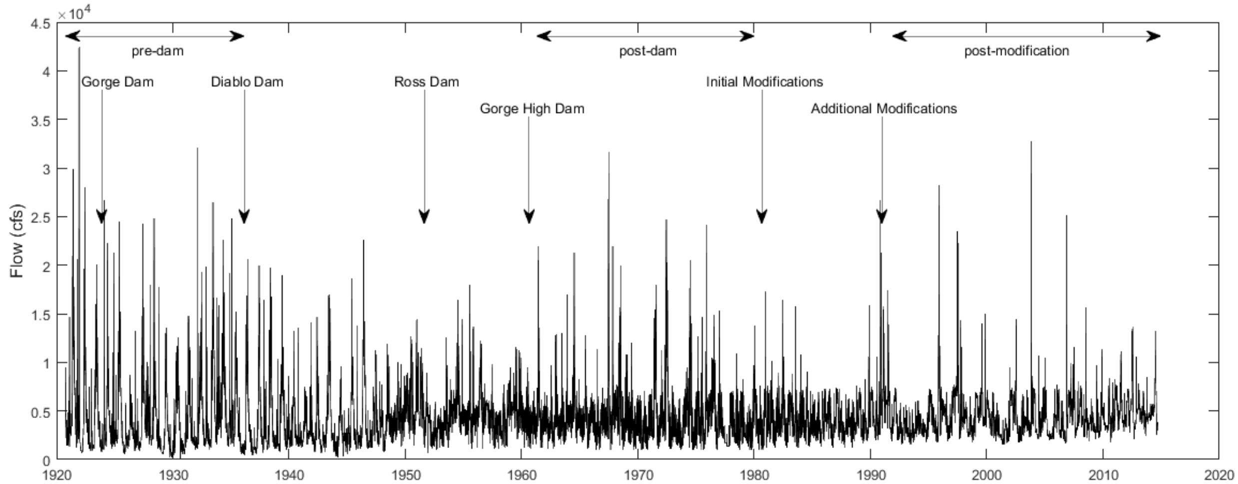

Figure 4. Historical daily stream flow record for USGS 12178000: Skagit River at Newhalem, WA (USGS 2015)

3.3. Kootenai River

Libby Dam on the Kootenai River in Montana was completed in 1973. The dam is operated by USACE for flood control and hydropower production and has a generating capacity of 600 MW (USACE 2006, 2015). Figure 5 shows the time series of flow data for the Kootenai River at Leonia, ID. Under the original hydropower operating plan, the minimum release from the dam was 56.6 cms (2,000 cfs), and water level fluctuations were limited to 0.30 m/hr (1 ft/hr), up to a maximum of 1.22 m/day (4 ft/day), from May through September and 0.61 m/hr (2 ft/hr), up to a maximum of 1.83 m/day (6 ft/day), from October through April (GAO 1979). After construction of the dam, several fish species along the Kootenai River and the Columbia River, further downstream, were listed under the Endangered Species Act. In 2000, the U.S. Fish and Wildlife Service and the National Marine Fisheries Service published a Biological Opinion, with the goal of reviving the dwindling fish populations. In response, USACE implemented an interim adjustment to dam releases. In 2003, a new operating procedure, known as variable discharge flood control (VARQ FC), was authorized to govern future releases. VARQ FC operations aim to increase flows during the spring and summer to support downstream fish populations, including white sturgeon, bull trout, salmon, and steelhead (USACE 2006).

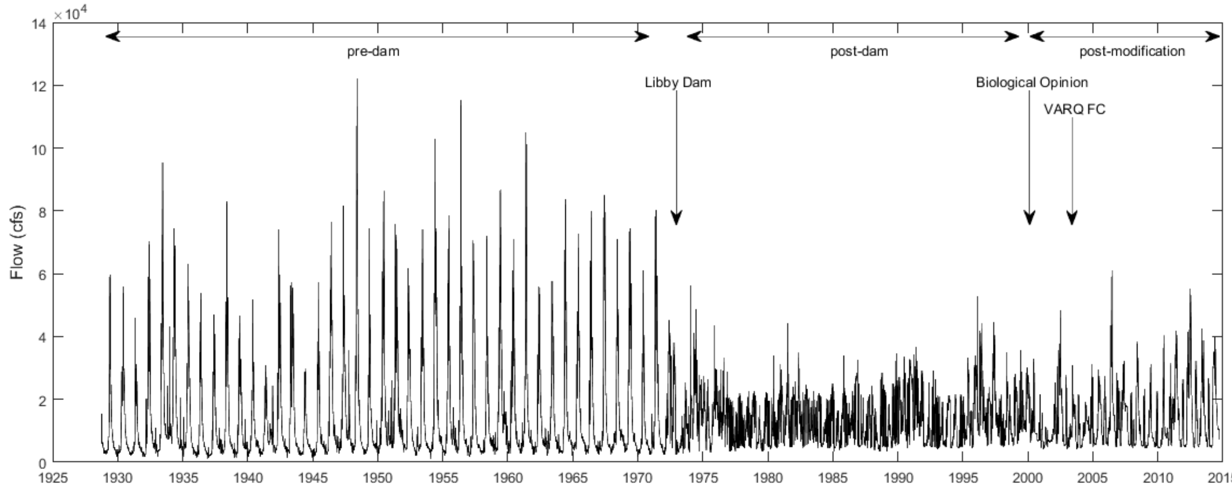

Figure 5. Historical daily stream flow record for USGS 12305000: Kootenai River at Leonia, ID (USGS 2015)

3.4. Roanoke River

Kerr Dam on the Roanoke River opened in 1953 and is operated primarily for flood control, hydropower generation, and recreation. USACE operates Kerr Dam in connection with Lake Gaston Dam (completed in 1963) and Roanoke Rapids Dam (completed in 1955), which are operated as run-of-the-river dams by Dominion Virginia Power and Dominion North Carolina Power (Pearsall et al. 2005). Figure 6 shows the time series of flow data for the Roanoke River at Roanoke Rapids, NC. Before 1989, Kerr Dam, which has a generating capacity of 200 MW, was operated to provide peaking power generation for the Southeastern Power Administration, resulting in large fluctuations in releases (Pearsall et al. 2005). Beginning in 1989, peaking releases were restricted to support downstream fish populations, including striped bass. From April 1 through June 15, minimum flow targets are set to provide adequate flows for spawning and ramping rates are restricted to 42.5 cms/hr (1,500 cfs/hr) (USACE 1995).

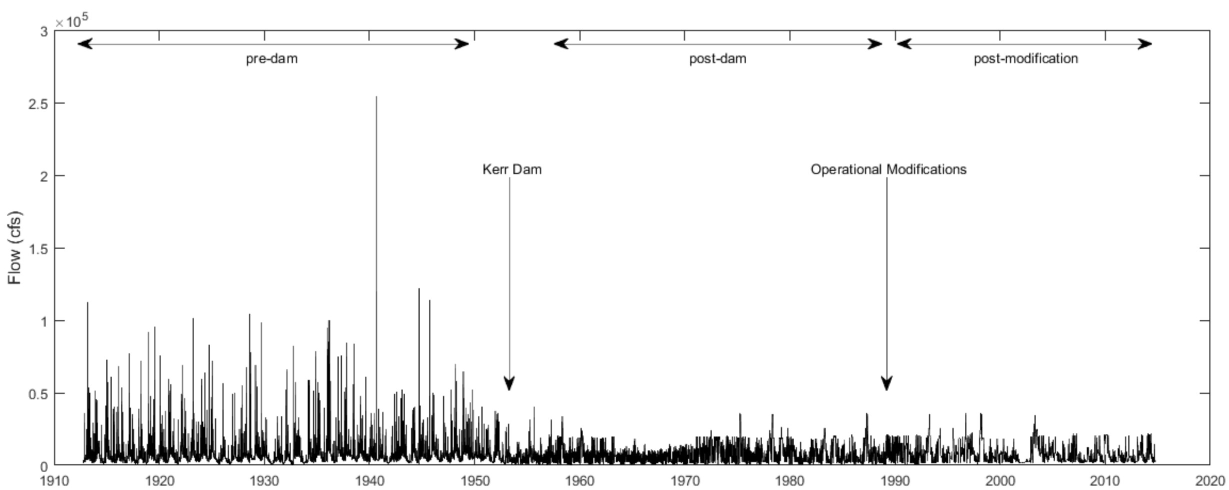

Figure 6. Historical daily stream flow record for USGS 02080500: Roanoke River at Roanoke Rapids, NC (USGS 2015)

3.5. Merced River

The Merced River is located on the western slope of the Sierra Nevada in California. Merced Irrigation District (MID) and the Pacific Gas and Electric Company (PG&E) operate a series of dams on the river, including New Exchequer Dam, McSwain Dam, and Merced Falls Dam. Figure 7 shows the time series of flow data for the Merced River below Merced Falls Dam near Snell, CA. New Exchequer Dam and McSwain Dam, with a combined generating capacity of 101 MW, were constructed in 1966 to replace Exchequer Dam, which had been in operation since 1926. Exchequer Dam had a small generating capacity of 31.3 kW but was primarily operated to meet the irrigation demands of MID (FERC 2015; MID 2015). The current dams are operated by MID to provide flood control, irrigation, recreation, and hydropower generation as part of the Merced River Hydroelectric Project No. 2179. The project provides flood control by capturing flows that exceed approximately 90.6 cms (3,200 cfs) during winter months and also enhances water supply by making controlled releases from March through October, which result in an increase in flows in the Merced River during the irrigation season as compared to the natural baseflows. Powerhouses at both dam sites are primarily operated to provide baseload power generation, although peaking power generation is produced at the New Exchequer powerhouse as well. McSwain Reservoir serves as an afterbay for New Exchequer Dam and is operated to minimize flow variability that results during times of peaking power generation. Merced Falls Dam, located downstream from McSwain Dam, is operated by PG&E as a run-of-the-river facility for hydropower generation as part of the Merced Falls Hydroelectric Project No. 2467.

As a result of the flow regime changes that have occurred since dam construction, the riverine habitat downstream of the project is degraded. Low flows and decreased variability, in combination with a reduction in sediment supply due to upstream impoundment, has turned the multi-channel, dynamic river into a single-channel river with nearly uniform substrate. This has negatively impacted native species, including salmon, along the Merced River by reducing viable habitat for spawning, rearing, and migration. Both the Merced River and Merced Falls hydroelectric projects are currently undergoing FERC relicensing, which will require MID and PG&E to consider mitigation strategies that will improve downstream conditions for wildlife (FERC 2015).

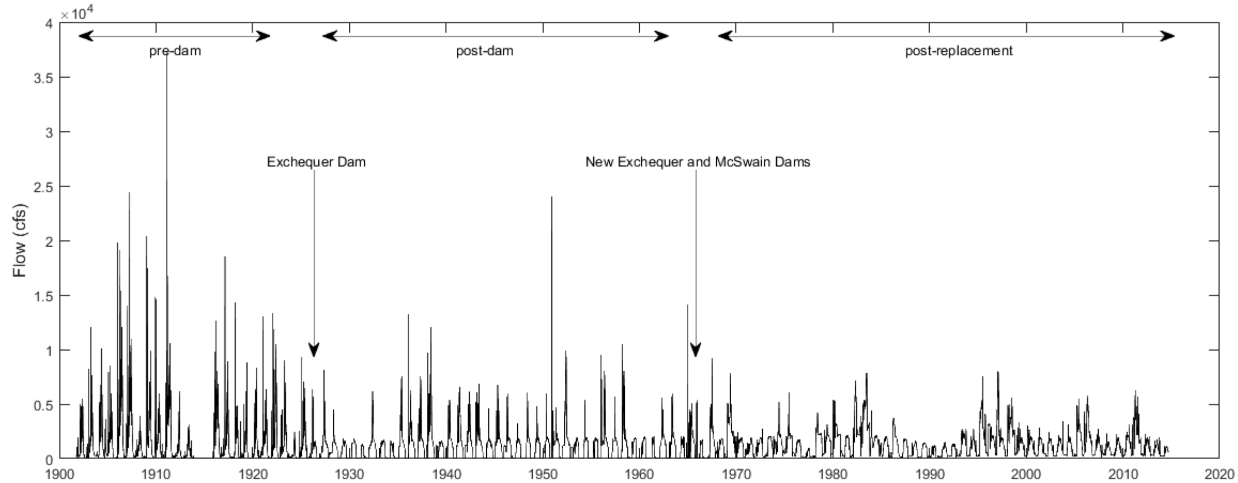

Figure 7. Historical daily stream flow record for USGS 11270900: Merced River below Merced Falls Dam near Snell, CA (USGS 2015)

3.6. Columbia River

Priest Rapids Dam on the Columbia River in Washington was completed in 1959 and has a total generating capacity of 855 MW. Figure 8 shows the time series of flow data for the Columbia River below Priest Rapids Dam, WA. The dam is operated to provide peaking power generation during the day and is then allowed to refill overnight. This leads to high variability in flows on a daily basis (FERC 2008). Since the construction of Priest Rapids Dam and other upstream impoundments, salmon populations have declined along the river, causing several species to be listed under the Endangered Species Act (FERC 2008; ODFW 2014). In 2008, a new FERC license was issued for the project, requiring minimum flow releases for Chinook salmon and other mitigation actions to protect salmon and steelhead (FERC 2008).

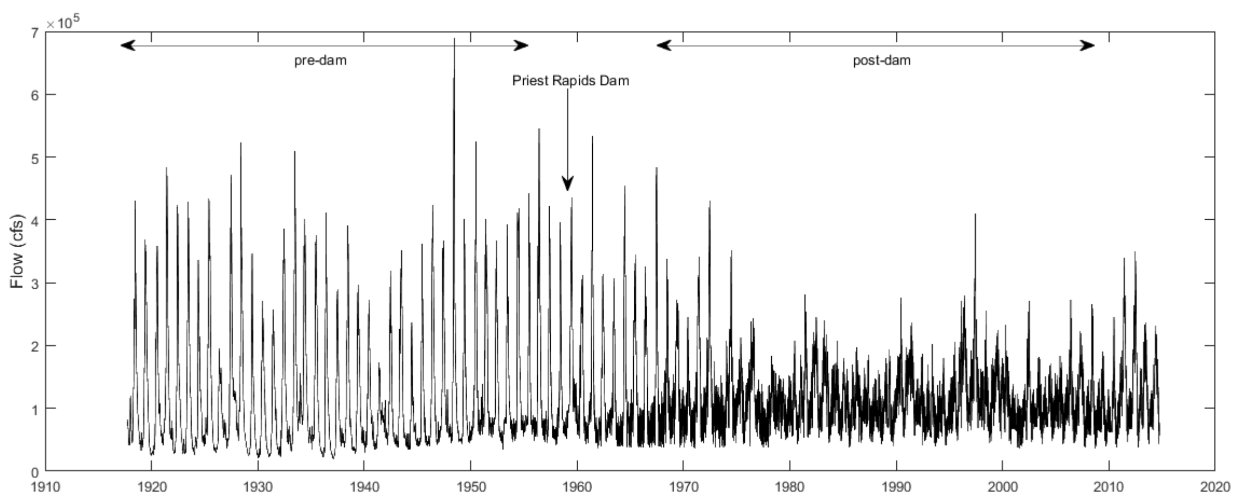

Figure 8. Historical daily stream flow record for USGS 12472800: Columbia River below Priest Rapids Dam, WA (USGS 2015)

3.7. Willamette River

Fall Creek Dam, just upstream of the confluence of Fall Creek and the Willamette River in Oregon, is part of USACE's Willamette Valley Project, which consists of 13 dams that provide hydropower generation, water supply, and flood control. Fall Creek Dam, completed in 1966, is operated for flood control during high-flow periods and water quality improvements during low-flow periods (USACE 2009). Figure 9 shows the time series of flow data for Fall Creek below Winberry Creek near Fall Creek, OR. USACE and TNC are currently working to develop new flow requirements for the Willamette Valley Project, including Fall Creek Dam, in order to improve conditions for native fish species along the river (TNC 2014).

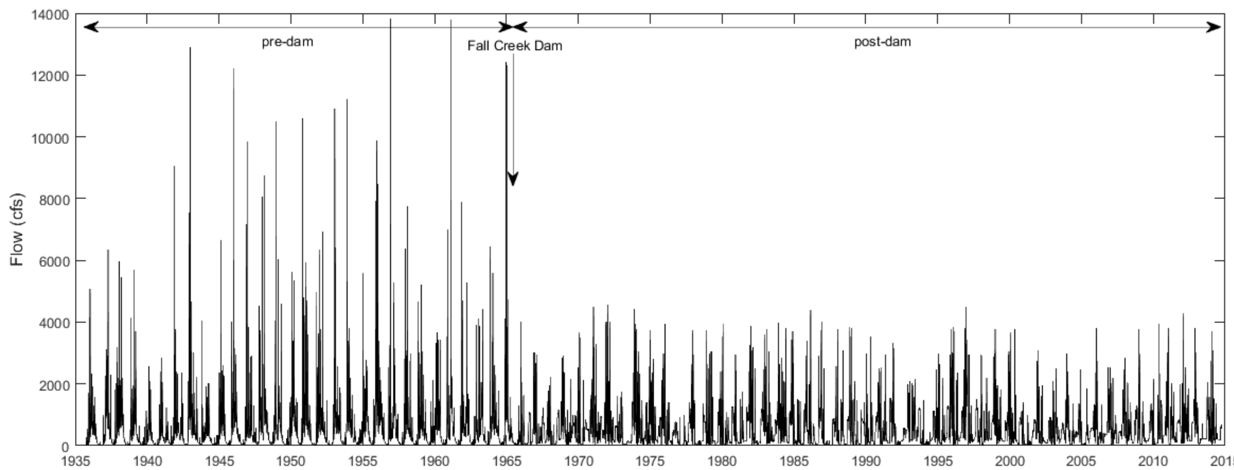

Figure 9. Historical daily stream flow record for USGS 14151000: Fall Creek below Winberry Creek near Fall Creek, OR (USGS 2015)

3.8. San Juan River

The San Juan River, a tributary of the Colorado River, is located in southwestern Colorado and discharges into Lake Powell. Navajo Dam, located approximately 350 river miles upstream from the confluence with the Colorado River, was completed in 1962 and is operated to provide water storage and irrigation supply. Figure 10 shows the time series of flow data for the San Juan River at Farmington, NM. A 23 MW powerhouse was added to the dam in 1983 to provide hydropower to Farmington, New Mexico (USBR 2016). In 1991, a Biological Opinion was issued for the Colorado pike minnow and razorback sucker downstream of Navajo Dam, requiring that dam operations be modified to mirror the natural flow regime. These modified releases began in 1993 and were intended to provide higher spring flows, similar to the flows that occurred due to snowmelt before the dam was constructed (Propst and Gido 2004).

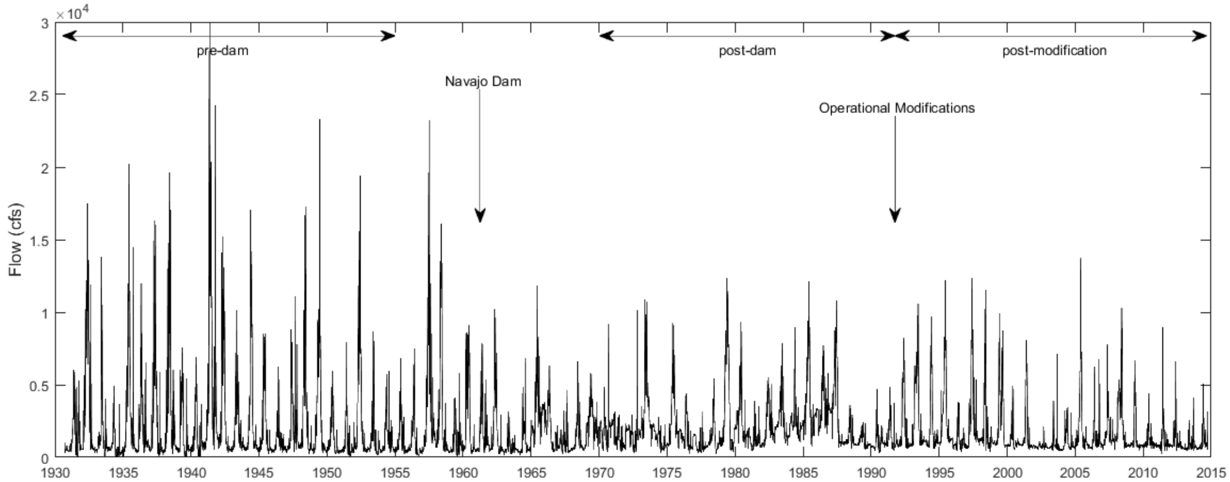

Figure 10. Historical daily stream flow record for USGS 09365000: San Juan River at Farmington, NM (USGS 2015)

4. Results and Discussion

4.1. Colorado River

Figure 11 shows the fractal dimension results for the Colorado River under natural conditions (Water Year [WY] 1922-1955), after construction of Glen Canyon Dam (WY 1967-1992), and after operational modifications implemented as a result of the Grand Canyon Protection Act (WY 1993-2014). The corresponding three-dimensional cross-sections of the attractors for each period of dam operation are shown in Figure 12.

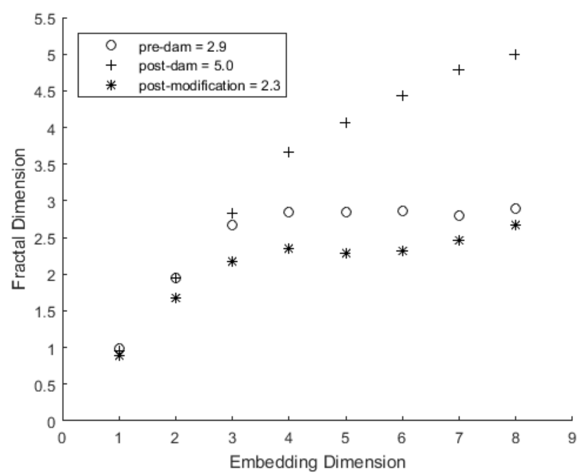

Figure 11. Fractal dimension versus embedding dimension for Colorado River

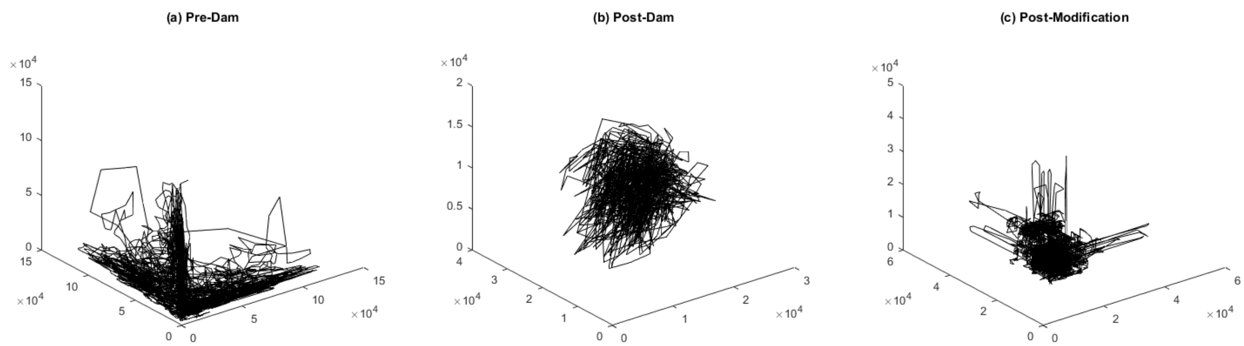

Figure 12. 3-dimensional attractors for Colorado River

The natural flow regime, which is low dimensional with a fractal dimension of 2.9, was regulated by seasonal precipitation patterns and year-to-year variability in runoff volumes. These hydrologic variations occurred over longer time periods than the hourly or daily flow fluctuations that were required for hydropower production and thus result in an attractor with a more predictable shape, with peaks stretching out along each axis but returning to the near-origin region. This suggests a structured system that mirrors the increases and decreases seen in a hydrograph after rainfall and runoff events. As a result, it may be possible to model the pre-dam period using a lower-complexity, deterministic model.

In contrast, after construction of the dam, the fractal dimension of the system increases to at least 5. This likely results from the variability in power demand across the service area of the Western Area Power Administration, which required frequent changes in release volumes in order to meet the electricity needs of the region. In addition, the graph of the fractal dimension versus the embedding dimension does not show a clear plateau consistent with inherent system dimensionality, but instead suggests a strong stochastic component during this period. The unpredictable, chaotic footprint seen during the post-dam period reflects the frequent flow variations that occurred for hydropower production. The lack of peaks in the trajectory is evidence of the restrictions on maximum flows that resulted from the operation of Glen Canyon Dam. Together, the high fractal dimension and clustered shape of the attractor suggest that a higher-complexity, stochastic modeling approach would be required to properly model the flow regime during periods of hydropower operation.

After operational modifications were put into place in 1992 to limit the impact of fluctuating electricity demands by restricting the short-term variability in flow releases, the system returns to a lower fractal dimension of approximately 2.3, although this value increases slightly for embedding dimensions greater than 6. In addition to restricting hourly flow variability, the new policy also damps out some of the naturally occurring, seasonal flow variation by cutting off peak flows during the wet season and maintaining minimum flows during the dry season. The attractor footprint maintains features of both the natural and hydropower regimes, with a main cluster of less-predictable structure as well as peaks forming along each axis. The peaks result from the high flow releases meant to move sediment and rebuild sandbars, while the clustered shape reflects the continued, although restricted, fluctuations that occur for hydropower production. Thus, while the attractor does recover some characteristics of the pre-dam attractor, it still has a clustered shape, indicating that a deterministic approach may not be appropriate for modeling this period.

The similarities between the fractal dimensions and attractor reconstructions for the pre-dam and post-modification periods suggest that the new operating policy implemented in 1992 to regulate releases from Glen Canyon Dam has been successful at recovering aspects of the natural flow regime, including higher flows and less flow variability, which are essential in the lifecycles of downstream fish species. This conclusion is supported by recent surveys of the Colorado River downstream of Glen Canyon Dam, which suggest that the modified operations have resulted in ecosystem improvements. Studies conducted after the 1996, 2004, and 2008 high flow experiments found that rehabilitation of sandbars occurred in most of Grand Canyon and in the lower part of Marble Canyon, through which the Colorado River flows before reaching Grand Canyon. These sandbars provide habitat for native species and campsites for rafters (USGS 2011). Populations of flannelmouth sucker, which prefer flowing streams (Mueller and Marsh 2002), appear to have stabilized since 1992 (USGS 2009). In addition, humpback chub, which depend on high spring flows for spawning (Mueller and Marsh 2002), increased in number from 2002 to 2008, despite a decreasing trend from 1989 to 2001 (Campbell et al. 2008).

4.2. Skagit River

Figure 13 shows the fractal dimensions for the pre-dam (WY 1921-1936), post-dam (WY 1962-1980), and post-modification periods (WY 1992-2014). In order to have more than ten years of flow data for the pre-dam period, the construction and initial operation of Gorge Dam, which had a total generating capacity of only 93 MW, was included in the pre-dam analysis. The post-dam period started after the completion of Diablo, Ross, and Gorge High dams, which substantially increased the total generating capacity to 676 MW. The three-dimensional cross-sections of the attractors for each period of dam operation are shown in Figure 14.

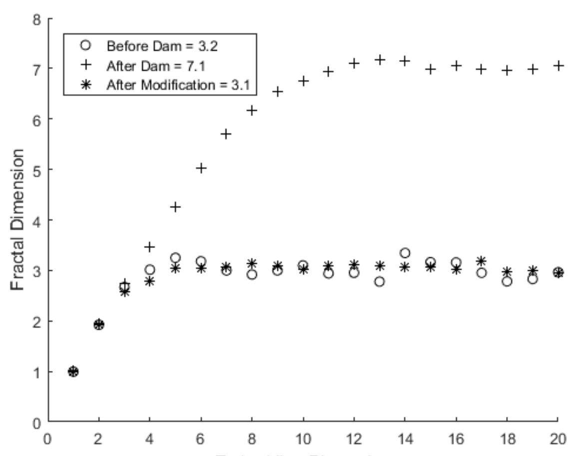

Figure 13. Fractal dimension versus embedding dimension for Skagit River

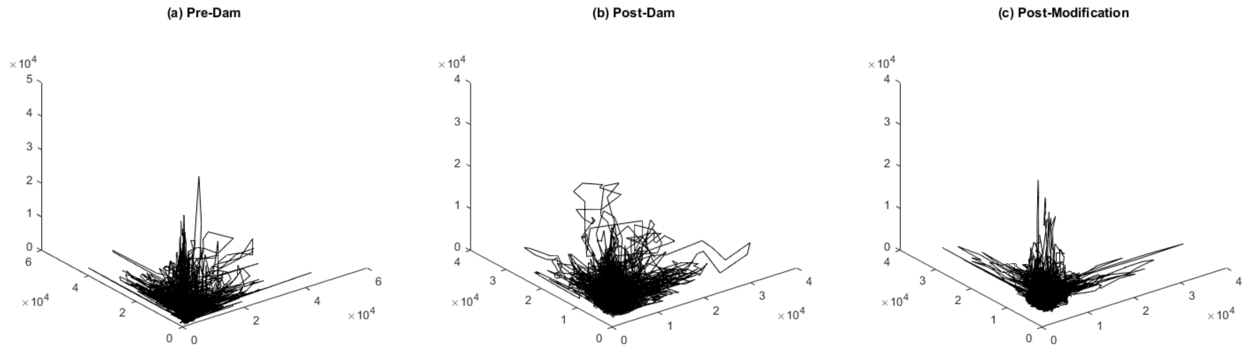

Figure 14. 3-dimensional attractors for Skagit River

The fractal dimension of the Skagit River system increases substantially after construction of Diablo, Ross, and Gorge High dams. During this period, the fractal dimension is 7.1, in contrast to the period before the dams were built, when the fractal dimension is only 3.2. The post-dam attracter retains some features of the pre-dam attractor, including the high-flow peaks. However, it has a slightly more clustered structure near the origin. After the new flow release restrictions were implemented, the fractal dimension decreases to 3.1, closer to the pre-dam condition. The corresponding attractor has more spikes along each of the three axes and appears to be less variable than the other two attractors, as exhibited by the cleaner structure.

Comparisons of pre- and post-1981 monitoring data collected along the Skagit River immediately downstream of the hydroelectric project indicate that the number of spawning pink, chum, and Chinook salmon increased significantly after flow modifications were put into place in 1981 (Connor and Pflug 2004). Connor and Pflug (2004) conclude that the reduction of downramping events, including daytime downramping, led to less stranding of fry, while increased minimum flows during incubation periods decreased the occurrence of redd dewatering. This is reflected in the fractal dimension results, which show lower dimensionality, and correspondingly lower flow variability, during the post-modification period.

4.3. Kootenai River

Figure 15 shows the fractal dimensions for the Kootenai River under natural conditions (WY 1929-1971), after construction of Libby Dam (WY 1974-1999), and after operational changes that resulted from the 2000 Biological Opinion (WY 2000-2014). The three-dimensional attractors for each period of dam operation are shown in Figure 16.

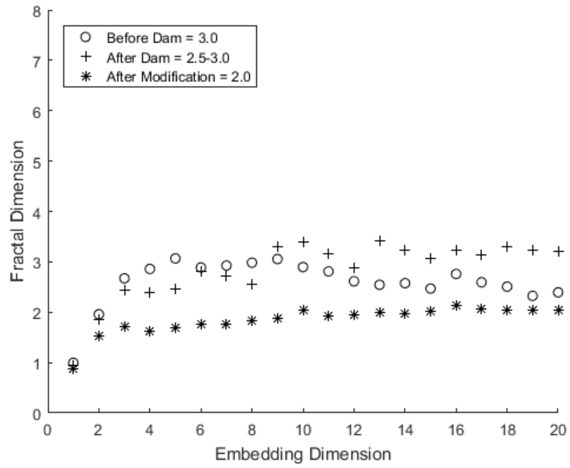

Figure 15. Fractal dimension versus embedding dimension for Kootenai River

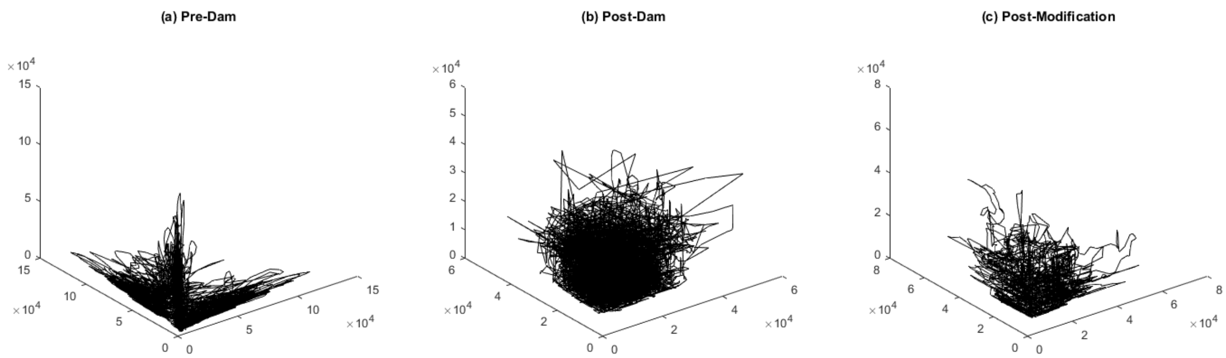

Figure 16. 3-dimensional attractors for Kootenai River

Before dam construction, the flow regime is characterized by a dimensionality of approximately 3. The corresponding attractor has points that extend out along each axis. After construction of Libby Dam, the fractal dimension of the system is between 2.5 and 3.0, a low dimensionality when compared to the post-dam periods for the Colorado and Skagit Rivers. This was likely due to the flow restrictions that were already in place at Libby Dam to limit hourly water level fluctuations for the benefit of downstream fish populations, thus making this operating regime more similar to the post-modification regimes implemented on the Colorado and Skagit rivers. The post-dam attractor is still indicative of hydropower operations though, with a clustered shape lacking high-flow peaks. Once operational modifications were put into place, the system dimensionality decreases slightly to approximately 2, and the attractor starts to develop some spikes similar to the pre-dam attractor, although it largely maintains the clustered shape characteristic of the post-dam period.

4.4. Roanoke River

Figure 17 shows the fractal dimension results for the Roanoke River under natural conditions (WY 1913-1949), after construction of Kerr Dam (WY 1957-1988), and after operational modifications implemented to improve recruitment of juvenile striped bass (WY 1990-2014). The corresponding three-dimensional cross-sections of the attractors are shown in Figure 18.

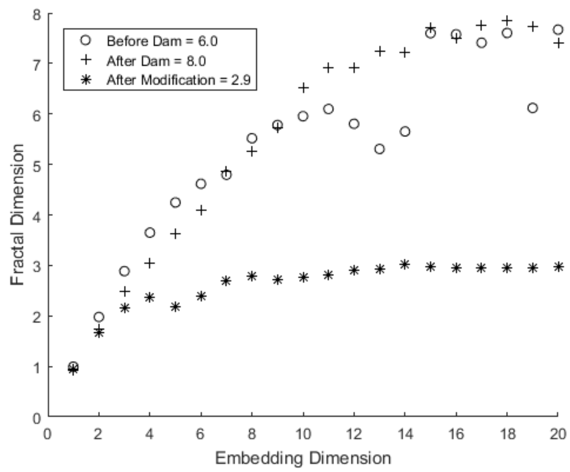

Figure 17. Fractal dimension versus embedding dimension for Roanoke River

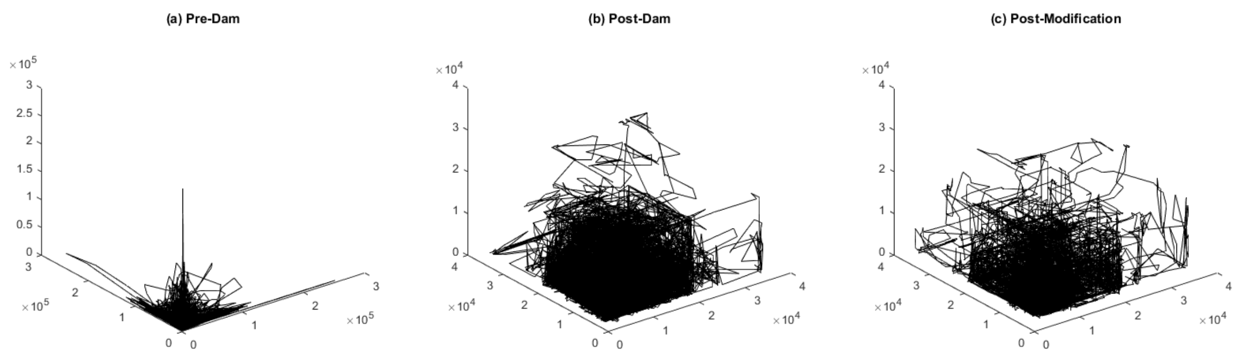

Figure 18. 3-dimensional attractors for Roanoke River

Before dam construction, the dimensionality appears to level off around 6, although the fractal dimension increases again for embedding dimensions above 11. When compared to other river systems that were analyzed, a fractal dimension of 6 is quite high for a natural system. This is likely due to differences in the hydrology of the Roanoke River, which experiences precipitation throughout the year, as compared to western rivers that experience more seasonal precipitation. The pre-dam attractor is characterized by peaks along each of the axes that return to the near-origin region, similar to the other rivers.

After construction of Kerr Dam, the system approaches a fractal dimension of approximately 8, slightly higher than the natural system due to the peaking power that was generated at the dam. The attractor appears more chaotic and is clustered around smaller flow values, reflecting the frequent changes in dam releases to meet peaking power demands and the restrictions on high flows for flood control purposes. After operational modifications were put into place in 1989, the dimensionality of the system decreases substantially to approximately 2.9, reflecting the restrictions placed on dam releases. However, the attractor is still clustered and lacks the peaks that were visible under natural conditions.

4.5. Merced River

Figure 19 shows the fractal dimension results for the Merced River under natural conditions (WY 1902-1922), after construction of Exchequer Dam (WY 1927-1963), and after construction of New Exchequer and McSwain dams (WY 1968-2014). Figure 20 shows the three-dimensional attractors for each period of operation.

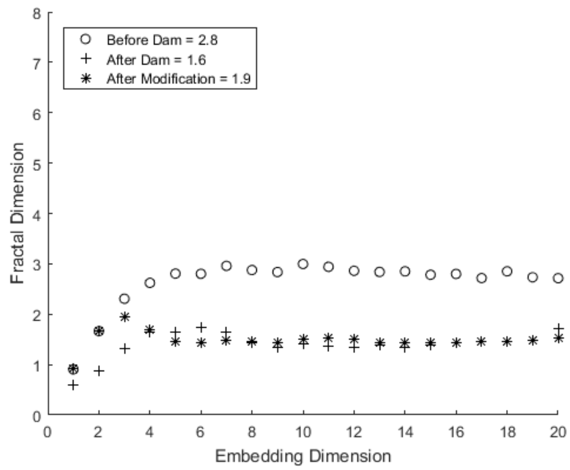

Figure 19. Fractal dimension versus embedding dimension for Merced River

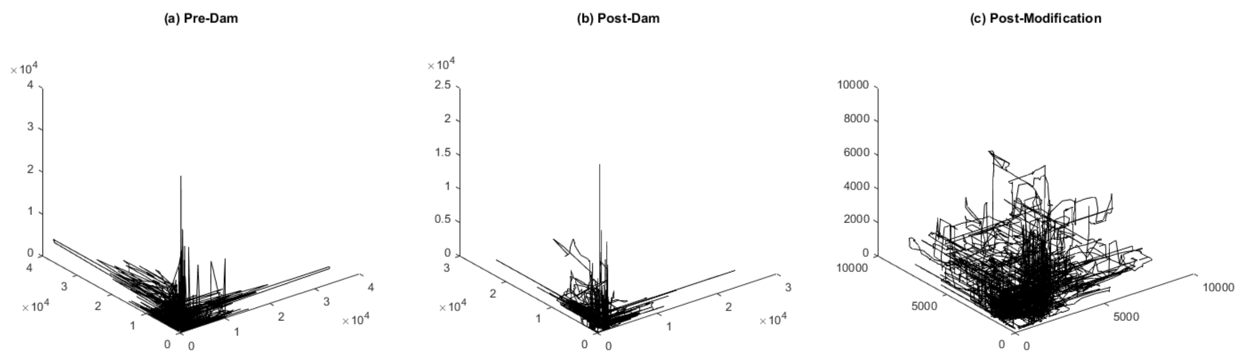

Figure 20. 3-dimensional attractors for Merced River

The fractal dimension decreases from 2.8 during the pre-dam period to 1.6 during the period after Exchequer Dam was constructed. Because Exchequer Dam was operated primarily for water supply purposes, it reduced the flow variability on the Merced River by cutting off flood peaks during wet periods and regulating flows to meet agricultural demands within the irrigation district during drier times. After construction of the Merced River Hydroelectric Project in 1966, the fractal dimension remains approximately the same as the previous period, at 1.9, despite the fact that hydropower generation began. The continued low dimensionality of the flow regime is a result of the operation of McSwain Dam, which reregulates the outflows from New Exchequer Dam and thus provides flow stabilization downstream of the project.

All three attractors are characterized by similar behavior, with spikes along each axis representing the rise and fall of high flow periods. After Exchequer Dam, the peak flows decrease from a maximum of 1,133 cms (40,000 cfs) to less than 850 cms (30,000 cfs). The maximum flows are even lower after construction of the Merced River Hydroelectric Project, after which flows never exceed 283 cms (10,000 cfs). Although the project is operated to provide hydropower generation, the attractors do not exhibit the same clustered shape as the attractors constructed for other hydropower sites. This is due to the very small generating capacity at

Exchequer Dam and the presence of McSwain Dam, which helps to regulate flows downstream of New Exchequer Dam.

4.6. Columbia River

Figure 21 shows the fractal dimension results for the Columbia River under natural conditions (WY 1918-1955) and after construction of Priest Rapids Dam (WY 1967-2008). The corresponding three-dimensional cross-sections of the attractors are shown in Figure 22. Because of the short length of the flow record after the new FERC license was issued in 2008, this period was not included in the analysis.

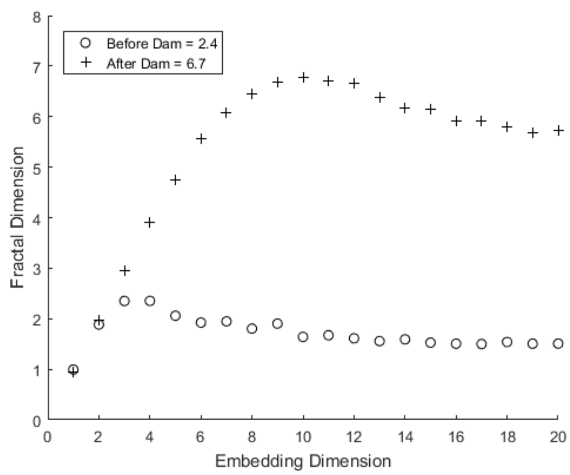

Figure 21. Fractal dimension versus embedding dimension for Columbia River

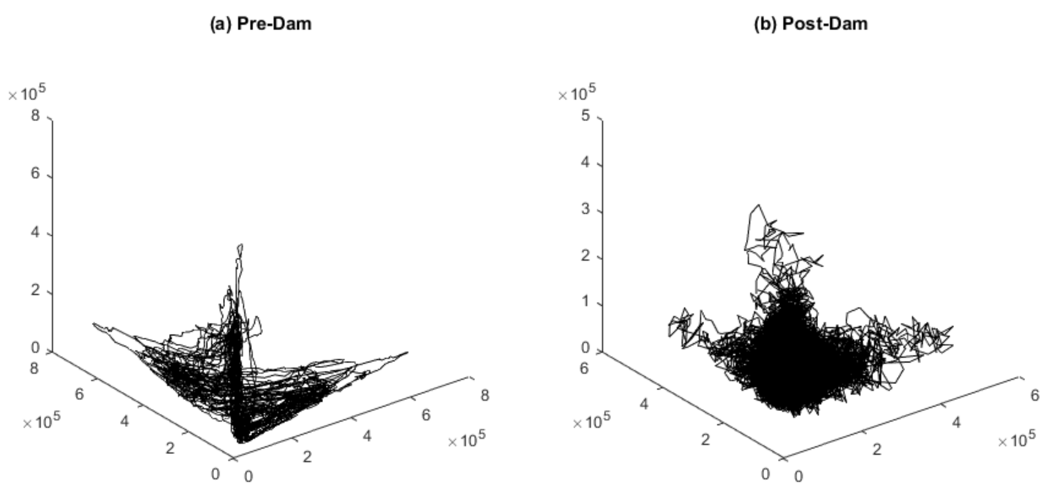

Figure 22. 3-dimensional attractors for Columbia River

The fractal dimensions and attractor reconstructions are similar to those seen for other hydropower sites with unrestricted peaking operations. Under the natural flow regime, the system is low dimensional, with a fractal dimension of 2.4, and the attractor is characterized by a predictable shape with three peaks along the axes. After dam construction, the fractal dimension increases to 6.7 due to the greater variability in flow releases for hydropower production. The attractor also becomes more clustered, and the magnitude of the peaks is reduced slightly. The increased variability is a likely contributor to the decrease in salmon counts downstream.

4.7. Willamette River

Figure 23 shows the fractal dimension results for the Willamette River under natural conditions (WY 1936-1965) and after construction of Fall Creek Dam (WY 1966-2014). The corresponding three-dimensional cross-sections of the attractors are shown in Figure 24. Under natural conditions, the fractal dimension for the Willamette River saturates at approximately 3.5. After the construction of the dam, the flow regime exhibits very similar behavior, although the fractal dimension decreases slightly for embedding dimensions above 6. The pre-dam and post-dam attractors also have similar structures, with peaks along each axis and a rather predictable shape. However, the post-dam attractor only reaches a maximum of approximately 113 cms (4,000 cfs), while the pre-dam attractor extends above 283 cms (10,000 cfs), reflecting the flow restrictions due to flood control operations.

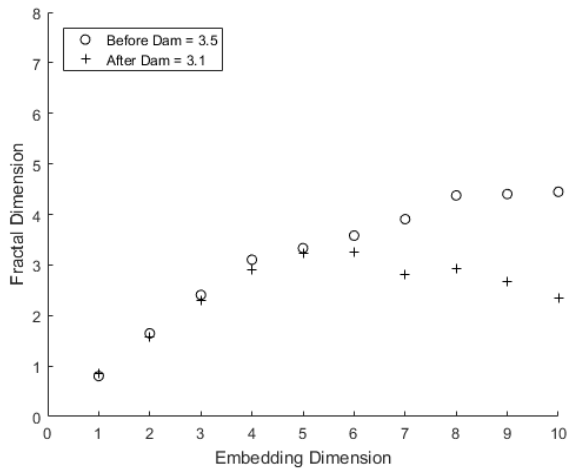

Figure 23. Fractal dimension versus embedding dimension for Willamette River

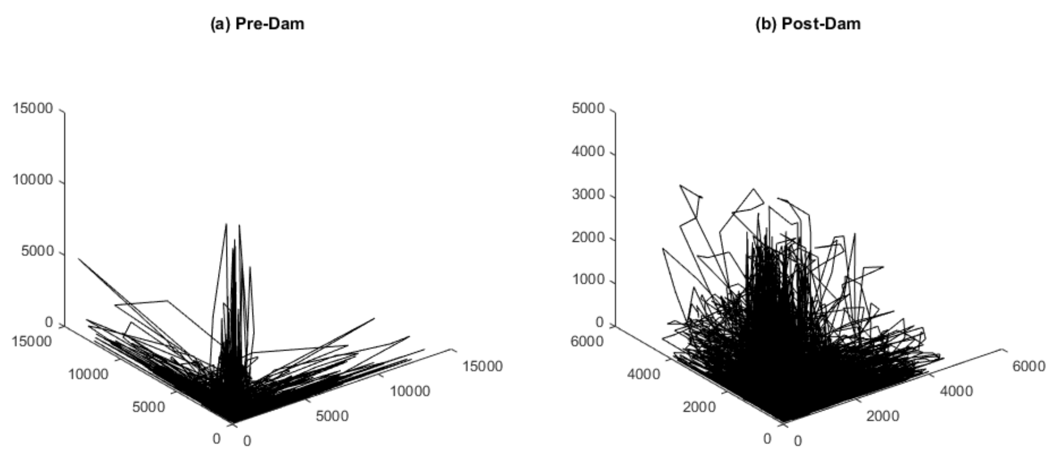

Figure 24. 3-dimensional attractors for Willamette River

4.8. San Juan River

Figure 25 shows the fractal dimension results for the San Juan River under natural conditions (WY 1931-1955), after construction of Navajo Dam (WY 1970-1992), and after operational modifications that resulted from the 1991 Biological Opinion (WY 1993-2014). The corresponding three-dimensional cross-sections of the attractors are shown in Figure 26. The pre-dam and post-modification periods exhibit very similar behavior, both saturating at a fractal dimension of 3. The corresponding attractors are also very similar, although the maximum flows during the post-modification period are only about half of those under natural conditions. The post-dam period has a slightly lower fractal dimension of 2. The post-dam attractor still maintains the peak flows along each axis, but also appears to have a clustered shape in the near-origin region, likely due to the hydropower production that began in 1983. An analysis of native fish species downstream of Navajo Dam indicated that speckled dace, fannelmouth sucker, and bluehead sucker populations all responded positively to the higher spring flows that were implemented in 1993 (Propst and Gido 2004).

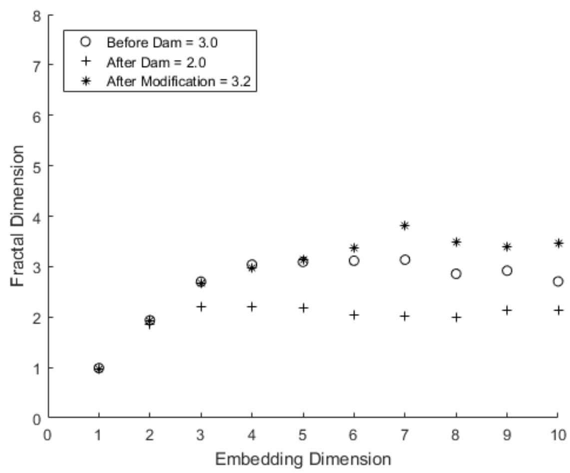

Figure 25. Fractal dimension versus embedding dimension for San Juan River

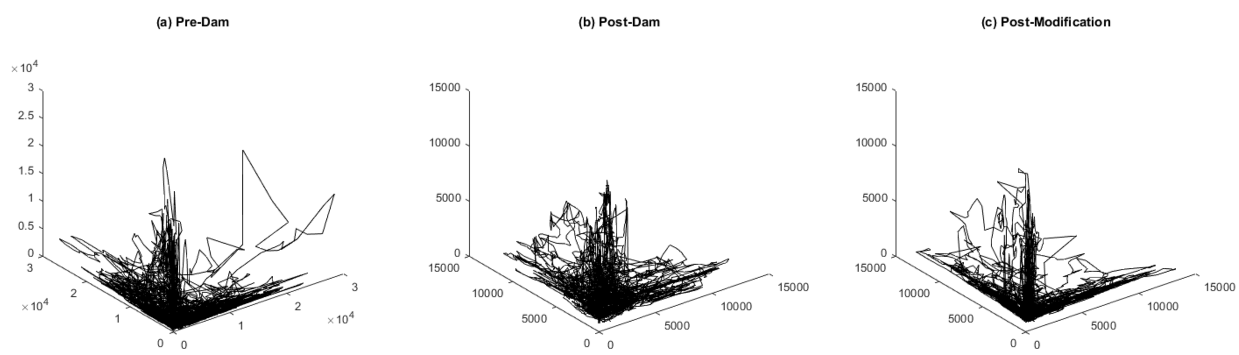

Figure 26. 3-dimensional attractors for San Juan River

5. Conclusions

5.1. Hydropower Dams

Unrestricted hydropower dam operations appear to produce the most stochastic flow regime behavior, as evidenced by the high fractal dimensions and chaotic attractors characterizing the original flow regimes downstream of Glen Canyon Dam, the Skagit River Hydroelectric Project, Kerr Dam, and Priest Rapids Dam. Because of the initial restrictions placed on water level fluctuations at Libby Dam, the flow regime on the Kootenai River never exhibited the same high dimensional behavior as the other rivers. Similarly, the Merced River maintained a low dimensionality throughout the historical flow record, likely due to the fact that Exchequer Dam was operated primarily for water supply and had a very small hydropower generation capacity compared to other dams. Even after hydropower generation increased with the construction of New Exchequer Dam, dam releases were reregulated by McSwain Dam, thus reducing flow variability.

The results also suggest that flow modifications to hydropower dams typically reduce the dimensionality of river systems. After new operating rules were implemented on the Colorado, Skagit, and Roanoke rivers, the flow regimes exhibited low dimensional behavior. In some cases, this may be beneficial because the new operating policies more closely match the dimensionality of the natural system. However, for rivers that exhibited high dimensionality under natural conditions, such as the Roanoke River, the new flow regime may not restore the essential features of the natural system.

In general, the operational modifications that we analyzed are more successful at reducing short-term flow variability than at recovering the high flows seen during the pre-dam periods. Although some policies do aim to provide higher flows during critical times in the lifecycles of fish species, these flows do not match the magnitude or frequency of the natural high flows. This is likely due to the fact that recreating high flow events can be challenging because of the potential for flooding and disruptions to recreational users downstream of the dams.

5.2. Flood Control and Water Supply Dams

Unlike hydropower dams, flood control dams tend to have a similar or, in some cases, even lower dimensionality than natural flow regimes and do not exhibit the same chaotic behavior as peaking power dams. Flood control dams are operated according to release schedules that increase or decrease flows based on snowmelt and rainfall forecasts, resulting in changes that are typically longer in duration than the hourly fluctuations that occur at hydropower dams. Similarly, water supply releases are scheduled ahead of time based on municipal or agricultural demands, which may vary by season but are fairly consistent from day to day.

5.3. Implications for Management

Overall, the information obtained from the fractal dimensions and attractor reconstructions is useful to dam operators and environmental groups, who are interested in quantifying the effects of the flow regime changes that have occurred. By determining the number of dimensions governing the flow regime, our approach provides a better understanding of the system's complexity. In cases where previous dam operations are not well documented, this type of analysis could be used to identify the general operating policies that were in place. In addition, this method allows river managers to evaluate the effectiveness of specific operating policies in recovering natural flow characteristics and mirroring the underlying dimensionality of the pre-dam flow regime.

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