Highlights

We evaluate the impact of current water allocation on the natural flow regime of the Yakima River using IHA/RVA. We analyze the sustainability of the current water allocation scheme based on a range of sustainability criteria, from weak to strong to environmentally sustainable. We find that the Yakima River flow regime is highly altered with ecodeficit far in excess of ecosurplus. We conclude that this allocation scheme is weakly sustainable, if at all. Water markets alone will not solve the Yakima's water allocation problems.

An analysis of the allocation of Yakima River water in terms of sustainability and economic efficiency

Brett Hillman[1], Ellen M. Douglas[1]*, David Terkla[2]

[1]Environmental, Earth and Ocean Sciences Department, University of Massachusetts Boston, 100 Morrissey Blvd, Boston, MA 02125; phone: 617-287-7437; email: ellen.douglas@umb.edu

[2]Department of Economics, University of Massachusetts Boston, 100 Morrissey Blvd, Boston, MA 02125; phone: 617-287-6506; email: david.terkla@umb.edu

*corresponding author

Abstract

Decades of agricultural growth has led to the over appropriation of Yakima water and the ecological integrity of the basin has been compromised. We evaluate the impact of current water allocation on the natural flow regime of the Yakima River using the Indicators of Hydrologic Alteration/Range of Variability Analysis and by quantifying indicators of ecosurplus and ecodeficit. We analyze the sustainability of the current water allocation scheme based on a range of sustainability criteria, from weak to strong to environmentally sustainable. Economic efficiency is assessed by describing the current allocation framework and suggesting ways to make it more efficient. Our IHA/RVA analysis suggests that the allocation of water in the Yakima River has resulted in a highly altered flow regime. Ecodeficit is far in excess of ecosurplus. We conclude that this allocation scheme is weakly sustainable, if sustainable at all, in its current framework. The allocation of water is also not economically efficient and we suggest that a reallocation of water rights may be necessary in order to achieve this objective. The creation of water markets to stimulate voluntary water rights transactions is the best way to approach economic efficiency. The first step would be to extend beneficial use requirements to include instream flows, which would essentially allow individuals to convert offstream rights into instream rights. The Washington trust water rights program was implemented as a means of creating a water market, which has contributed to the protection of instream flows, however more needs to be done to create an ideal water rights market so that rights migrate to higher valued uses, many of which are met instream. However, water markets will likely not solve the Yakima's water allocation problems alone; some degree of regulation may still be necessary.

1. Introduction

Water is very scarce in parts of the American West (Reisner, 1993; Glennon, 2009), and hence irrigated agriculture is the backbone of many local western economies. Early water law was based on the prior appropriation doctrine, under which the first individual to put water to “beneficial use” was entitled to the continuing use of that water in the future (Washington 2006). Beneficial use generally consisted of offstream water use (water withdrawn from the river channel and used elsewhere), and any drop of water left in the riverbed was considered wasteful by many. River water was allocated with little consideration for long-term sustainability and almost no regard for the value (either environmental or economic) of instream uses, which include water required by aquatic and riparian ecosystems, as well as recreational and aesthetic uses.

Sustainability is a term that is often used but poorly defined. The most basic definition of sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). Although intuitive in concept, conflicts can arise when attempts are made to quantify the ‘needs’ of current or future generations.

Economists recognize two general types of sustainability: weak and strong. Proponents for **weak** sustainability believe that total capital stock should be conserved across generations. It makes no difference how that capital stock is disaggregated among natural and manufactured capital. In this neoclassical view, natural capital – trees, minerals, water – is seen only as a factor of production. Although future generations are deprived of natural resources, they can be compensated if today’s generation invests the rent realized from exploiting scarce resources (Hartwick 1977). In this way, capital stock is sustained over time, so future generations are no worse off and the weak sustainability criterion is satisfied.

Those who favor an approach governed by the **strong** sustainability principle argue that manufactured capital cannot be substituted for natural capital. Advocates of strong sustainability recognize three other functions performed by natural capital in addition to supplying resources for production (Ekins et. al. 2003): 1) assimilating wastes; 2) sustaining ecosystem health and function; and 3) providing non-use values. These services cannot be performed by manufactured capital, and, therefore, proponents of strong sustainability argue that natural capital must be conserved if future generations are to be at least as well off as the current generation.

The major shortcoming with this view is that it assumes perfect substitutability among forms of natural capital (Dietz and Neumayer 2007). However, different types of natural capital perform different functions. Sea lampreys, for example, are not adequate substitutes for the lake trout they displace in the Great Lakes. Tietenberg (2006) defines an even stricter type of sustainability, which he coins **environmental** sustainability. In both weak and strong sustainability, the value of the stock of capital is to be conserved. Under environmental sustainability, the flows of each resource considered must be maintained in order to uphold the critical functions they perform. It is the physical flows of individual resources that are maintained, not simply the value of these resources. Thus, ecological functions are preserved, not just their economic value.

Ciriacy-Wantrup (1952) defines the critical zone of the population of a renewable resource as a range of resource flow rates below which a decrease in this flow rate cannot be reversed economically under foreseeable conditions. He identifies any ecological function as critical if it has one of the following characteristics: 1) it is not substitutable by another function; 2) the loss of the function is irreversible, or 3) the loss of the function would entail large costs to society. Resources described as having a critical zone include soil, water, plants, and animals. After the critical zone is breached as a result of overexploitation, the depletion is irreversible. At this point it becomes uneconomical to stop harvesting and start conserving because stocks will never rebound.

Ciriacy-Wantrup advocates the establishment of a ‘safe minimum standard,’ which is the smallest quantity of a stock that can be maintained above the critical zone. Bishop (1993) then goes on to convert this idea of a safe minimum standard into a sustainability standard. This is accomplished by recognizing that irreversibility will ultimately hinder the welfare of future generations. This step is important in that it bridges the gap between nature and humans by acknowledging that breaching the safe minimum standard today leaves the future worse off, and is thus by definition, unsustainable. Rather than viewing sustainability based on discrete and exclusive definitions, we propose that sustainability can be understood as a spectrum, ranging from entirely unsustainable (resource exploitation with no regard for the future) to completely sustainable (no alteration to the current resource stocks).

Decades ago, Ciriacy-Wantrup (1952) defined water as having a critical zone. Despite this, water has been undervalued and the critical functions it performs have often been ignored. While it is easy to see how human society benefits from offstream water uses for agricultural, industrial, and domestic purposes, humans also depend on the ecosystem processes that are sustained through healthy instream flows. Biological communities living near rivers or around floodplains have adapted to the natural flow regime (Acreman et. al., 2000), and modifying streamflow alters these communities. Damming and diverting a river in the Pacific Northwest, for example, can seriously diminishing upstream salmon populations. This can incur economic and cultural losses to recreational and commercial fisheries, plus losses to those who depend on fishing for sustenance. Lockie et. al. (2009), found that flow alteration of Australia's Fitzroy River forced all resource users to face higher costs and greater uncertainty.

While the loss of water from a river through consumptive offstream use may not be irreversible (since water is a renewable resource), the loss of the ecosystem functions derived from water may well be. Navarro et. al. (2007) found that regulation of the natural streamflow regime is the main factor leading to the extinction of several local populations of *chondrostoma arrigonis*, a freshwater fish species endemic to the Jùcar River Basin in Spain. Many other aquatic species are either imperiled or locally extinct in the basin as well. Even if natural water quality and/or quantity are restored, some natural processes are unable to rebound, perhaps because invasive species have significantly altered the ecosystem. For instance, Brasher et. al (2006) reported that altered, urbanized stream reaches were dominated by introduced fish and crustacean species, while more natural stream reaches contained about half the number of these generalist, more tolerant introduced species.

Perhaps the most compelling argument for a sustainable approach to water allocation is that, unlike other important natural resources, such as fossil fuels, minerals, and crops, there is no substitute for water in the natural world (Postel et. al. 1996). Hence if one agrees that freshwater is a form of critical natural capital, then the logical and necessary next step is to manage water carefully and sustainably. This includes maintaining instream flows.

Streamflow is considered to be a master variable that limits the composition of aquatic plant and animal species (USGS 2006). The degree of sustainability of a river system is a function of many other factors besides water withdrawals, including pollution, species harvesting, and land use. In this paper we focus only on the sustainable management of surface water withdrawals. Over abstraction of river water can, and often does, result in the alteration and degradation of crucial ecosystem functions (see Pearce [2007] for examples from around the globe). Water use characterized by such over abstraction is unsustainable because future generations are forced to bear the costs associated with the environmental degradation.

If the critical zone is breached, ecosystems are either destroyed, replaced or reach a new equilibrium point which cannot be reversed. This has happened in the Colorado River delta, for example, where upstream dams and water abstractions have nearly eliminated flows to the delta and have irreversibly changed the ecology of the region (Pearce 2007). The main challenge, then, for water resource managers and policy makers is to quantify how much water is required to avoid irreversible environmental degradation and the consequent loss of ecosystem services and still satisfy the demands of a growing human population.

1.1 Assessing the impacts of water allocation on river flow

The dynamics of river flow and the effects on ecosystems are extremely complex. River ecosystems depend on the natural variability of flow regimes, and alterations of these flow regimes – such as damming and withdrawing large quantities of water for offstream uses – degrades the river environment and can lead to the loss of benefits provided by a natural river system, such as healthy fisheries, purification of water, and esthetic values (Matthews and Richter, 2007). Dams tend to dampen extreme high- and low-flow events, and while droughts and floods are a nuisance to humans, these occasional extreme events are often necessary for the ecological vitality of ecosystems.

Life-history theory predicts that the magnitude, frequency, and predictability of streamflow affect how species evolve. For example, invasive species are more likely to outcompete native species if they are better adapted to the modified flow regime (Naiman et. al, 2008). The natural flow regime can be characterized by five parameters – magnitude, duration, frequency, timing, and rate of change (Poff et al., 1997). To evaluate the impacts of human activities on the natural flow regime, Richter et. al. (1997) presented a method called the Range of Variability Approach (RVA), which compares 33 indicators of hydrologic alteration (IHA) before and after flow modification. These 33 parameters were selected based on ecological relevance and for their ability to reflect human modifications of the natural flow regime. The suite of statistics represents both intra- and inter-annual variability of streamflow. (Apse et. al., 2008) and can be analyzed either parametrically or non-parametrically. Shiau and Wu (2004) and Shieh et al (2007) offer examples of applications of the RVA method.

Economic Efficiency

When dealing with a scarce resource, it is important to decide on an optimal allocation, and, according to classical economics theory, this occurs when the net benefits (benefits minus costs) to society are maximized. These include monetary as well as non-monetary (i.e., environmental, social, aesthetic) benefits and both use and non-use values. Economic efficiency is reached when the marginal net benefits are equal across all users of a given resource.

1.3 Efficient use of water

Because water is a scarce resource, there exist trade-offs between human and environmental requirements as well as among disparate human uses. Water must be allocated to the highest valued uses in order to be economically efficient; however, we realize this approach may not yield the most socially acceptable solution. In the American West, approximately 90% of developed water is used by the agricultural sector for irrigated farmland (Trimble 2007). In much of the 20th century, government subsidies were used to entice farmers to cultivate the West and spur economic growth. The financial cost of water to farmers was kept artificially low, hence much of the agricultural water use in Western states has less economic value than if it were reallocated to higher valued uses, such as residential, recreational, or environmental uses (Brewer et. al 2008). In fact, Watts et al. (2001) showed that values associated with instream flow are greater than the value attributed to irrigation of low-value crops.

Reaching a sustainable and economically efficient allocation

An ideal resource allocation would be both efficient and sustainable; however an efficient allocation does not necessarily imply a sustainable one, and vice versa. When an allocation is neither, it is sometimes possible to improve sustainability and efficiency at the same time, perhaps even through the same measures. In over-appropriated streams, the marginal net benefits to society of leaving more water in a given stream are greater than the benefits realized from water abstraction. When this is the case, restoring instream flow, which is beneficial to sustaining aquatic ecosystems, is also more efficient.

Consider a stream which is so over-appropriated that flow is below the safe minimum standard, meaning that fish and aquatic species, as well as important ecological functions, are severely degraded. If water continues to be allocated in this manner, species extinctions and other irreversible losses may result. This allocation of water is unsustainable. Over-allocation can arise when instream flows are undervalued, as is often the case because many benefits associated with instream flow are not fully captured in markets. Offstream uses, such as irrigation and industrial uses, have clear and quantifiable contributions to economic production and water pricing structures which make them easily captured in markets. Non-market instream uses such as angling, kayaking, or the aesthetic value, biological diversity and the bequest value associated with preserving ecosystems for future generations, are attributed zero net benefits in markets. Estimating environmental flow requirements is, therefore, a crucial step in promoting both sustainability and economic efficiency. The purpose of this study is to evaluate the impacts of the current water allocation structure on the natural flow regime and suggest ways that water pricing/water markets can be used to make water allocation from the Yakima river more efficient and sustainable.

2. Case Study: The Yakima River

2.1 The Yakima River Basin

The Yakima River (Figure 1) originates from Keechelus Lake on the Eastern slope of the Cascade Mountains in central Washington State. The river flows more or less southeasterly for 220 mi (350 km) until its confluence with the Columbia River. The watershed encapsulates 6,155 mi^2 (approximately 15,940 km^2). Precipitation in the Yakima River basin varies greatly, both spatially and temporally. In the mountains, winter snowfall is the main contributor to the 120 in (3050 mm) of precipitation received annually. In the drier portions of the basin, average annual rainfall is only 7 in (180 mm). The majority of precipitation occurs during the winter and spring months in both the wetter and dryer parts of the watershed.

Approximately 1000 mi^2 (2600 km^2) of the Yakima basin is irrigated (USBR 2002) and over 97% of water withdrawals from the Yakima River go to irrigated agriculture (Kent 2004), which is the backbone of local economies. Intensive irrigation has transformed the arid Yakima basin into one of the most productive agricultural regions in the United States (USDA 2007). In Yakima, Benton, and Kittitas counties, which roughly approximate the watershed boundary, the market value of agricultural production in 2007 was $1.8 billion USD (USDA 2007).

Today, the United States Bureau of Reclamation (USBR) Yakima Project is composed of six major dams and storage reservoirs, 5 diversion dams, canals, laterals, pumping plants, drains, 2 power plants, and a series of transmission lines. The Project is responsible for irrigating approximately 730 mi^2 (1900 km^2) of land, which accounts for about 73% of the total irrigated area within the basin. Another 70 mi^2 (180 km^2) are also served by the USBR, as well as 76 mi^2 (200 km^2) that are privately irrigated. The bulk of this water comes from the Yakima and its tributaries, although almost 200 mi^2 (520 km^2) are also equipped for irrigation from groundwater (Vaccaro and Sumioka, 2006).

Allocating Yakima water in a manner that is desirable to all stakeholders is a very difficult task, and it will likely be compounded by forecasted effects due to climate change. Temperatures in the Yakima River basin are likely to be measurably warmer in only a few decades, altering streamflow patterns (Mastin 2008). It is likely that snow will melt earlier, decreasing streamflow in the late spring and summer when irrigation water demand is at its peak. The USBR is looking into the possibility of constructing more dams to catch this increased early spring snowmelt in order to have it available during the irrigation season. Therefore, improving the allocation of Yakima water becomes even more urgent when the potential effects of climate change are considered.

2.2 Laws governing water allocation in the Yakima River Basin

Yakima River water is governed by the old Western water law known as the prior appropriation doctrine, which is often described as “first in time, first in right.” Under this doctrine, the individual that first makes “beneficial use” of water has the right to future use of that water. This is in contrast to the riparian doctrine of the Eastern portion of the country, under which only individuals owning land adjacent to water sources had the right to reasonable use of that water. In 1917, the Washington Water Code was passed, which declared prior appropriation as the exclusive method for determining water rights and created a centralized water rights administration system (Washington 1998).

There are two main principles of the prior appropriation doctrine that affect how water is used. First, water rights holders are required to make beneficial use of their water or lose their water right. Beneficial use is defined as the application of water for any “non-wasteful” purpose. It was believed that any offstream use, even extremely low-valued uses, increased the net benefits. Second was the “use it or lose it” principle: if water is not used by a water rights holder for a specified number of years, the water right is forfeited. Concerns about over-allocation arose as early as the 1940s, and the 1945 Consent Decree established two types of water rights: non-proratable (senior) and proratable (junior). Senior water rights holders are those that filed water rights claims first, and their water claims are guaranteed. Junior water rights holders are supplied with what remains of the total water supply after senior water rights holders have been served. Water shortages are shared equally by proratable water users (USBR 2002). In addition, the Yakama Nation has been awarded a “time immemorial” water right for the minimum instream flow necessary to sustain anadromous fish life. This flow is determined by prevailing annual conditions and is established by a number of organizations in tandem (USBR 2002).

In addition, Congress has set “target flows” for the Yakima at two points along the watercourse, just downstream of the Sunnyside and Prosser dams (TCWRA 2001). Target flows are determined according to table 3-25 of the Tri-County Water Resources Agency Watershed Assessment (TCWRA 2001), and are shown in Table 1. The column at the far right of Table 1 displays the target flows once the Yakima River Basin Water Enhancement Program (YRBWEP) is fully implemented. The YRBWEP began in 1995 and consists of various projects designed to progress water management by improving existing water storage, water delivery, and irrigation infrastructure, as well as by enhancing wetlands and improving habitat. These target flows were determined by the Yakima Project’s Field Office Manager, with recommendations from the Yakima River Basin System Operations Advisory Committee (SOAC) and irrigation managers, among others (USBR 2002).

3. Analysis of Yakima River flows

The Yakima River and its tributaries were originally developed with the goal of maximizing the productivity of irrigated farmland, and there was no consideration for the environmental functions of water associated with instream flow. The next two sections provide a look at the degree of sustainability and economic efficiency currently achieved.

3.1. Sustainability analysis

This section addresses the concept of sustainability by qualitatively considering the condition of river ecosystems and looking at how these issues are addressed by managers. A Range of Variability Analysis (RVA; Richter et. al. 1997) will be presented to quantitatively display the degree of alteration resulting from human activities. Finally, the all-important linkages from hydrologic and ecologic data to sustainability will be discussed.

3.1.1. The current conditions

Before settlement in the watershed, the Yakima River provided spawning habitat for five species of salmon as well as steelhead and bull trout. Salmon and steelhead runs in the nineteenth century have been estimated at 790,000 returning adults annually. Between 1981 and 1990, that number was down to 8,000. Native summer chinook, coho, and sockeye salmon have been extirpated from the basin, while both steelhead and bull trout are listed as threatened under the Endangered Species Act (Kent 2004). While dams obstructing migration routes and overharvesting are key reasons for this decline, the alteration of natural streamflow plays a major role as well. The majority of dams on the Yakima and its tributaries were constructed in the early 20th century, prior to 1940.

Water abstractions have increased incrementally over time as more farmers moved into the basin. The combined effects of these human influences can be seen in Figure 2, which compares average daily flows in the Yakima River flow observed at the Kiona stream gage, just upstream of the confluence with the Columbia River (location shown in Figure 1) aggregated over three time periods: 1940-1959, 1960-1979 and 1980-

2008. Also included in Figure 2 are the earliest recorded average daily flows (aggregated over 8 years; 1906, 1908 through 1914; data for 1907 were missing).

Over the period of record, the shape of the annual hydrograph has been substantially altered, with an approximate halving of both the magnitude and duration of peak flow season (approximately days 150 to 250 or March through May) and an overall reduction in the annual variability of flows. Table 2 compares flow statistics computed on model simulated flows (representing unaltered flows, to be described later) and observed flows at the Kiona gage. In general, both the magnitude (mean) and variability (standard deviation) of the simulated (unaltered) flows are higher than those computed on observed (altered) flows. In fact, all statistics computed for observed flows were about 60% of those statistics computed on the simulated (unaltered) conditions, with the exception of the first quartile (Q1 or 25th percentile), for which altered flows were only 90% of unaltered. This again suggests that higher flows have been impacted more than lower flows, not unexpected from flow regulation due to dams. However, model error has no doubt contributed somewhat to these results and will be discussed later.

Species extinction is, of course, irreversible, and will clearly limit the welfare of future generations that depend on these species. While fish species are the imperiled animal species that receive most of the attention, there are a number of other species and ecosystem processes that are affected by the human altered flow regime. For example, the regulated flow regime has reduced the recruitment, altered sex ratios, and produced skewed population age and gender structures of black cottonwoods (*Populus trichocarpa*), the dominant riparian tree species along the Yakima (Braatne et. al. 2007). The cottonwood decline has changed the composition of the plant community and has allowed for the intrusion of invasive weeds.

In 1998, the Washington Legislature passed the Watershed Planning Act. This act allowed for the voluntary creation of watershed groups, made up of representatives from county, city, tribal and state governments, as well as local stakeholders. The task of these planning groups is to create a watershed-wide management plan, which will then be adopted by local governments. The majority of watrersheds are represented by planning groups, including the three subwatersheds (Upper Yakima, Lower Yakima, Naches) comprising the Yakima, which are managed together (Blomstrom et. al. 2005).

Planning groups have the option to set instream flow rules which the Washington State Department of Ecology (WaDOE) must adopt and enforce. Many of the planning groups have set or are in the process of setting instream flow rules. They have used a variety of methods for determining environmental flow requirements, including the Instream Flow Incremental Method (IFIM) and the toe-width methods (Blomstrom et. al. 2005). Detailed descriptions of these methodologies can be found on the WaDOE website (http://www.ecy.wa.gov/programs/wr/instreamflows/Images/pdfs/if-msum.pdf).

The Yakima planning group, which has adopted the Yakima Basin Watershed Management Plan (YBWMP), has not set instream flow rules and has no plans to do so in the future (Blomstrom et.al. 2005). Instead, instream flow rules are determined by the Yakama Nation’s requirement for instream flow (as mandated by their tribal rights). However, this right, which was originally a fixed volume of water, has been diminished, and now the Yakama Nation is allotted the “absolute minimum amount of water necessary to maintain anadromous fish life in the Yakima river” according to annual prevailing conditions (Superior Court of the State of Washington 1997). Instream flow requirements for the Yakama Nation are determined annually by the Yakima Project Field Office Manager and the SOAC. These requirements are based solely on the estimated water supply (see table 1), and therefore do not address all components of the natural flow regime.

3.1.2 Range of Variability Analysis (RVA)

For this analysis, we used the Indicators of Hydrologic Alteration software (IHA; available at http://www.nature.org/initiatives/freshwater/conservationtools/art17004.htm). One of the capabilities of this program is performing RVA. The target ranges can be specified by the user, and Richter et. al (1998), recommended three ranges using quartiles: the lower target range is less than first quartile; the middle target range is between 25th and 75th quartile and upper target range is greater than 75th quartile. Using Richter et. al.'s (1998) recommendations for defining the target ranges, half of the data points fall within the middle target range, while a quarter fall in both the low and the high target ranges. If a flow is relatively unaltered, the number of data points falling within each of these three ranges should be about the same under the altered flow regime as under the natural flow regime. The deviation of the altered flow regime can be quantified by the degree of hydrologic alteration (*D*, Richter et. al., 1998):

$$D = \frac{N_o - N_e}{N_e} \qquad (1)$$

N_o is the *observed* number of years in the altered flow regime for which the IHA parameter in question falls within the RVA target ranges while N_e is the *expected* number of years that an unaltered flow would fall within the same target range. *D* ranges from -1 to infinity. If there is no flow alteration, then *D* would theoretically equal zero. A positive value of *D* indicates that the number of values in a particular target range is greater than expected under unaltered conditions, while a negative *D* indicates fewer than expected values in that target range. As a general rule, Richter et. al. (1998) suggests the following thresholds for hydrologic alteration: $|D|<0.33$ signifies slightly altered, $0.34<|D|<0.66$ signifies moderately altered, and $|D|>0.67$ signifies highly altered.

The RVA is best performed on a flow record that contains time periods of both unaltered and altered flows, and Richter (1997) recommends at least 20 years of unaltered flow. Target range thresholds should be developed from the unaltered flow record and then the results of the altered flow record compared with the specified ranges. However, for the Yakima River, the observed flow record represents only altered flow data. The unaltered flow record had to be simulated using a hydrologic model. Therefore, the natural flow record was simulated and the altered flow was observed and both regimes covered the same time period. While not ideal, there are some benefits to using this approach. First, many rivers have been slowly and continuously altered over time, and it is often difficult to delineate distinct pre- and post-alteration time periods. Second, the use of a simulated record allows for the analysis of flows over the same time period and hence, reduces the influence of climatic variability and extreme events that may occur during one time period and not the other.

The simulated streamflow for this analysis was provided by John Vaccaro (Vaccaro, J., US Geological Survey, written communication, 2009). Vaccaro used the Modular Modeling System (MMS; Leavesley et al., 1996) to estimate natural streamflow at the Kiona gaging station for water years 1950 through 1998. MMS is an integrated modeling system that simulates a number of hydrologic, energy, and biogeochemical processes. Mastin and Vaccaro (2002) offer detail on the MMS model and calibration for the Yakima River and noted that problems with simulating the timing and volume of rain-on-snow events resulted in higher simulated flows in October through December and lower flows in May and June. However, they concluded that the timing of the snowmelt peak in the downstream reach was reasonably simulated. The Kiona gaging station is located at the most downstream reach of the river, so it is reasonable to assume the MMS output at the Kiona gage provides a good representation of climate driven flows for the entire basin that have not been influenced by impoundments or water withdrawals.

Figure 3 compares the average daily flows of both time series used in this analysis and again illustrates the “flattening” of the hydrograph due to both flow impoundment and water withdrawals. The average daily flow from the earliest observations at the Kiona station (WY 1906, 1908 through 1914, dotted grey line), was included to visually assess how well the model represents the natural hydrograph. The peak flows that occur between days 50 and 70 (late November to early December) and between days 170 and 270 (March through June) appear to be well represented, although the spring flows are overestimated by the model. As noted by Mastin and Vaccaro (2002), the model overestimates fall flows (days 1 through 50). The model also appears to underestimate the spring flow recession, hence overestimating late spring and summer flows (days 270 through 365). Overall, the variabililty of the simulated hydrograph appears to be lower than that of the natural hydrograph, however, this is not unexpected due to the difference in averaging timeframes. Hence the RVA results are likely to be somewhat conservative, with RVA results for high flows slightly inflated and for low flows slightly suppressed.

In 2003, an RVA was performed on the Yakima River by Mark Bowen of USBR using MMS output to represent unaltered streamflow (Bowen, M., USBR, personal communication, 2009). Six points were selected along the watercourse, with the furthest downstream located at the Parker gaging station (see Figure 1). Bowen found that the most altered gaging station (in terms of the number of IHA parameters showing high degrees of alteration) was the Parker station. For this study, we performed an RVA on observed and simulated flows further downstream at the Kiona gaging station (see Figure 1). At this location, 92% of the watershed is drained and flows at this location integrate flow alteration throughout the majority of the basin. We performed our RVA using non-parametric statistics, and the three target ranges for each of the 32 indicators of hydrologic alteration were defined by the first and third quartiles of the unaltered (simulated) daily streamflow.

The results of our RVA analysis are presented graphically in Figures 4a through 4c. We use the October average monthly streamflow to illustrate how the RVA statistics are calculated. Monthly average streamflow is computed for both the unaltered (simulated) and altered (observed) conditions from the 49 years of daily flow records. For October, the 25th percentile (771 cubic feet per second; cfs) and 75th percentile (2019 cfs) from the unaltered (simulated) October mean monthly flows define the upper middle and lower target ranges. If the observed flow had not been altered, one would expect twelve or thirteen October flows less than 771 cfs, twenty-five between 771 and 2,019 cfs, thirteen or twelve or thirteen flow greater than 2,019 cfs. The IHA for observed flows, however, indicated no mean monthly October flows in the low range, eleven in the middle range and thirty-eight in the high range. The degree of hydrologic alteration (*D*) can then be determined for each of the three target ranges using eqn 1.

Using the classification suggested by Richter et. al. (1998), the middle range mean monthly October flows are moderately altered ($|D| \leq 0.67$) and the high and low range flows are highly altered ($|D| > 0.67$).

Figure 4a indicates a high degree of positive alteration in the low range monthly flows from March through July and a large negative alteration in the high range monthly flow for March through August. In other words, in the spring, low flows have become higher and high flows have become lower. There has also been a high degree of positive alteration in the high range monthly flows in September and October, which could be attributable to the model as could the higher low flows in May and June. Figure 4b illustrates a high degree of positive alteration in the high range of minimum flows across 1-day through 30-day durations and in the low range of maximum flows across all durations, again illustrating a reduction in flow variability. The baseflow index is also highly positively altered, suggesting that human water uses have impacted the groundwater fluxes as well. Figure 4c shows that the number of low pulses in the high range and the number of high pulses in the low range, as well as the length of these pulse have been highly altered, indicating an increase in the persistence (serial correlation) structure of the flow data, a typical alteration due to flow regulation. A pulse is defined as the length of time consecutive flows remain above or below a pre-defined threshold. In all, of the 32 indicators of hydrologic alteration computed for this analysis, only eight fell within the unaltered range: mean monthly flows November through Februrary, 90-day minimum flow (for middle range flows), date of maximum (for middle range flows), and fall rate (for middle and low range flows). Less flow alteration was generally identified in the middle range of the flow data suggesting that human water uses in the Yakima have impacted flows at the extremes more than flows closer to the mean.

We compared the results above with an RVA performed on the eight years of flows at the beginning of the record (WYs 1906, 1908-14) and eight years at the end of the record (WYs 1991-1998) in order to assess the effect of using simulated flows to represent the natural flow regime. Despite the difference in record lengths, we found the results were quite similar, especially for parameters group 1 (monthly average flows, Figure 4a) and parameter group 2 (minimum and maximum flows averaged over different durations and the BFI, Figure 4b). This gave us confidence in the RVA performed on the simulated versus observed flows. Overall, the IHA analysis has confirmed our assessment that the flow regime of the Yakima River has been highly altered by human water uses within the river basin.

The next step is to link these results to the degree of sustainability achieved by the current flow regime. Again, it should be noted that sustainability is best viewed as a spectrum, and determining whether or not a flow regime is sustainable will be subjective until an agreed upon definition of sustainability exists. However, if it is agreed that the current regime falls somewhere between unsustainable (characterized by extinctions and other irreversible losses) and completely environmentally sustainable (no alteration whatsoever) then there is certainly margin for enhancing sustainability.

3.1.3 Linking RVA to ecological impacts.

RVA is strictly a statistical analysis of hydrologic data. Moving from degrees of hydrological alteration to sustainable environmental flows is a supremely difficult task. Two linkages must be made: first, the link from hydrology to ecology, and secondly, the link from ecology to sustainability. The degree of hydrologic alteration describes how a stream's altered flow varies from its natural flow, but it does not show how the biota are affected. Relationships between natural flow variability and ecological responses are not well understood (Naiman et. al., 2008). A common assumption is that natural flows are best for aquatic ecosystems, and that any human-induced change is negative. This point of view further assumes that species have adapted perfectly to the natural flow regime, although a lot more research is required before this assumption can be proven (Jager and Smith, 2008).

There have been many studies linking hydrologic alterations to ecological responses in streams around the world. Welcomme (1989) determined, for example, that a shortened pulse duration (an extended period of high or low flows) can contribute to weak growth in African fish species. The increased frequency of summers with low flows could also affect fishes; Harvey et. al. (2006) showed that growth rates in rainbow trout (*Oncorhynchus mykiss*) in a small stream in northwest California were 8.5 times lower when streamflow was reduced during a 6 six week period during the summer. The spring, summer, and fall flow alterations, the dampened flow extremes, and the higher frequency of years with a high base flow are all indicators that Yakima flow is far less variable under the regulated flow regime. Reduced variability in streamflow can lead to varied ecological responses. Auble et. al. (2005), for example, found that decreased flow variability affected riparian plant communities along the Fremont River in Utah by decreasing the width of wetland and transitional plant zones.

Our RVA of the Yakima indicates that high flow events (7-, 30-, and 90-day maximum flows) are far less extreme under the altered flow regime. These naturally occurring high flow events are important for the exchange of nutrients between the river and the floodplain. As mentioned earlier, black cottonwoods are in decline along the riverbanks, and these trees depend on the occasional flood for nutrients, to disperse seeds, and for the creation of barren areas that become nursery sites for seedlings (Braatne et. al. 2007). Altered high flow events also impact the salmon and trout species within the Yakima River, which require high flows in the springtime to keep their redds (spawning nests) inundated and away from predators.

Although the RVA does not provide environmental flow recommendations, it does provide a statistical comparison between the natural and modified flow regimes. If one can assume that a more natural flow regime corresponds to a more sustainably managed river system, then it can be concluded that RVA is capable of at least qualitatively depicting the degree of sustainability. For the Yakima River, the results of the RVA combined with observed impacts on riverine ecosystems suggests that the current water allocation scheme falls at the lower end of the sustainability spectrum .

One of the shortcomings of the RVA approach is the number of indicators that need to be interpreted and the lack of information regarding the possible redundancy contained in the IHA (Gao et. al. 2009; Olden and Poff,). Vogel et al. (2007) introduced the metrics of ecodeficit and ecosurplus, which are based on a flow duration curve (FDC). An FDC provides an estimate of the percentage of time (a.k.a. percentile) a given flow value was equaled or exceeded over a specified time period (Vogel and Fennessey, 1998). High magnitude flows (i.e., floods) occur infrequently and hence correspond to low percentiles; low magnitude flows (low flows) are exceeded regularly and hence correspond to high percentiles.

Figure 5 presents period of record FDCs for the two flow series (daily simulated and daily observed) over the same time period (water years 1950 through 1998; note that y-axis is logarithmic) and supports the assertions about flow alterations previously discussed. Unaltered (simulated; dashed line) flows with percentiles less than 0.8 are higher than altered (observed; solid line) flows. Conversely, the unaltered flows with the highest percentiles (greater than 0.8) are lower than altered flows. A full 80 percent of the time, the observed flow record is lower than the natural (simulated) flow record.

The area between the two FDCs defines the “ecodeficit” which represents the net volume of water now unavailable to meet aquatic ecosystem requirements (and other instream flow uses) due to human influences (Vogel et al., 2007). Only 20 percent of the time, during the lowest flows, are observed flows greater than natural (simulated) flows. This coincides with a small area defined as “ecosurplus”, which represents additional water available to aquatic ecosystems. The volume of water represented by the ecosurplus is approximately four percent of the ecodeficit, indicating a dramatic reduction in flow volume over the period of record due to human water use.

Gao et. al. (2009) extended this concept and present three generalized indexes that explain most of the variability within the IHA: total annual ecodeficit, summer ecosurplus, and winter ecosurplus. For the Yakima River analysis, the ecodeficit was computed as 0.37. The winter and summer ecosurpluses were computed as 0.01 and 0.05, respectively. Although, Gao et al. (2009) caution that their results were specific to their individual study, these three indexes support our interpretation of a highly altered flow regime.

3.2. Efficiency analysis

There are a number of ways to increase the productivity of water, including technological innovation (more efficient methods of irrigation, for instance), conservation, and recycling. There has been some effort in using these measures as a means to decrease the amount of water diverted offstream. However, they do not address the issue of allocative efficiency of water resources. A reallocation is required when the net benefits of water use are not maximized. The best way to reallocate water rights without ruffling the feathers of rights holders is with voluntary transactions through competitive water markets (Howe et. al. 1986;Syme et. al. 1999; Kaiser and Phillips, 1998; Bauer, 2003).

3.2.1. Water marketing in the Yakima basin

The trust water program was implemented with the objective of increasing instream flows by opening up markets for water rights. As of 1997, no water rights had been transferred from offstream to instream uses (Gillilan and Brown 1997). The State launched the Washington Water Acquisition Program in 2003 in an effort to enhance and improve the program. The 2003 program provides a framework that brings together alternatives designed to increase instream flows and make water rights transactions proceed more smoothly (Lovrich et. al. 2004). The program was launched partly to increase streamflows in sixteen basins in Washington that had been deemed “fish critical” (three of the sixteen are the upper Yakima, the lower Yakima, and the Naches).

The success of these programs in the Yakima basin is extensively evaluated by Lovrich et al. (2004) who conclude that the programs have not reached their full potential. The main reason for this is farmer’s distrust towards WaDOE and suspicion that leased water rights will never be returned. From 2001 through 2003, WaDOE completed four water rights transactions (one purchase in 2002 for 363 acre-feet of water and four one-year leases in 2001 totaling 1080 acre-feet) in the upper Yakima portion of the basin (which was Lovrich et. al. [2004]'s study area). Meanwhile, the Washington Water Trust (WWT), a non-profit environmental organization operating exclusively on the Teanaway River, a small tributary, completed twelve water rights leases and received a one-year donation in 2003, putting 1276 acre-feet of water back into the Teanaway over the course of the year.

As discussed earlier, a competitive market for water rights is prone to market failure. A governing body is likely required to mediate transactions and disallow any that may lead to undesirable consequences. Failure to account for changes in consumptive use is one source of potential market failure, because return flow will be less if a new water user uses water more consumptively. Any transaction that increases the consumptive use of diverted water limits return flows and decreases the downstream water supply. WaDOE comprehensively reviews all potential water transactions, estimates how much consumptive use will change, considers potential return flows, and will not approve any water rights transfer that will be detrimental to downstream flows. In this fashion the issue of increased consumptive use resulting from a water rights trade is accounted for. Upstream transfers, which can decrease the water supply in the stream reach between the buyer and seller, are reviewed and dealt with in a similar manner by WaDOE.

There are other transaction costs that hinder exchanges in water markets, including inefficient mechanisms for connecting buyers and sellers, lack of confidence in the process for enforcing water rights, difficulties in monitoring water use in order to effectuate transfers, and difficulties in collecting and analyzing the data required to be sure the water being transferred is measured correctly and the impact of the transfer is well understood (McCann and Easter, 2004; McCann, et.al., 2005).

The idea for a centralized place for the exchange of water to better connect buyers and sellers does exist, as the seeds for the Yakima Water Exchange (YWE) were planted in 2003. “The YWE’s principal mission would be to facilitate the exchange of water and water rights in the Yakima basin from willing sellers or lessors to those who wish to acquire water and water rights for both in and out of stream uses on a temporary or permanent basis” (YBWE 2003). The main responsibility of the YWE would be to streamline the trust water program and make the market more efficient. Possible services provided by the YWE include pre-application technical review for water transfer proposals, documentation of water transfer proposals, orderly and consistent technical review of proposals, provision of information of water banking and service providers, listing of buyers and sellers of water rights, market analysis and outreach to potential buyers and sellers, provision of pricing and ownership information, providing water transfer research and analysis, and/or measuring and monitoring (Barwin, B., WaDOE, written communication, 2009).

The YWE recognizes that WaDOE and USBR are active in acquiring water rights for the purpose of enhancing instream flows; however, it is not the main purpose of these agencies and their budgets are insufficient to provide the water exchange services listed above while also putting forth efforts to acquire water rights. A water exchange will also aid WaDOE in reviewing potential transfers, thus enhancing protection from market failures. Moreover, it is nearly impossible for these agencies to enforce their instream water rights, given their limited resources. An efficient YWE will encourage more private ownership of water property rights for instream flow, and private owners are likely to spend more effort monitoring their water rights and reporting any violations to WaDOE.

Proponents of the YWE believe that there are willing buyers and sellers of water rights, but they are unable to locate each other. This is a source of inefficiency that the YWE can correct. Moreover, it is believed that many of these potential buyers are interested in improving instream flows. Thus, the YWE can help create a more efficient and sustainable market for water rights in the Yakima basin at the same time.

A full-functioning YWE will be able to address most of the deterrents that might hold back a perfectly competitive water market (including externalities and issues of non-exclusiveness). However, in order make perfect information available to all market participants, environmental flow requirements must be determined. If the YWE took on the role of communicating these in the marketplace (after they have been determined by scientists), the economic efficiency of the water market would be greatly improved.

4. Conclusions and Recommendations

Decades of agricultural growth has led to the over appropriation of Yakima water (Kent 2004), and the ecological integrity of the basin has been compromised as evidenced earlier in the discussion of imperiled species and ecosystem processes. More recently it has been recognized that the old way of allocating water needs to be adjusted in order to foster economic efficiency and sustainability (Kent 2004). Despite this recognition, there has been little if any effort in establishing environmental flow requirements in the Yakima; instead, the Yakama Nation’s time immemorial, senior (albeit diminished) water right, along with vague target flows required by Congress, are the only means by which instream flows are currently protected. An RVA demonstrated that the current flow regime is highly altered relative to the natural (albeit simulated) flow regime.

The allocation of water is also not economically efficient and a reallocation of water rights may be necessary. The creation of water markets to stimulate voluntary water rights transactions is the best way to approach this sensitive issue. There have been efforts to create a market for water rights in the Yakima, and these efforts have produced favorable results. The first step was to extend beneficial use requirements to include instream flow, which essentially allowed individuals to convert offstream rights into instream rights. Secondly, the Washington trust water rights program was implemented as a means of creating a water market. These measures have contributed to the protection of instream flows, however more needs to be done to create an ideal water rights market with low transactions costs so that rights migrate to higher valued uses, many of which are met instream.

Until a better market for water rights is created, it will be necessary to govern water use based, at least in part, on some sort of environmental flow methodology, even though these instream rights will be junior in priority. Existing efforts to determine environmental flow requirements (EFR) and implement them in the management plan are minimal. The “target flows” required by Congress fail to take into account all five components of a natural flow regime. In an efficient market, all participants have access to perfect information so that they can make informed decisions. Once hydrologically and biologically meaningful EFR are established and communicated to the public, market participants will have a measure of the amount of water that needs to be allocated to sustain ecological integrity. If environmental flow requirements are determined for several points along the watercourse, those with an interest in environmental flows can determine exactly where flow should be restored or conserved. Armed with this information, those with an interest in instream flows can better decide on how to allocate funds for the purchase or lease of water rights.

Right now it is necessary to restrict junior water rights to meet environmental flow requirements. If a perfectly competitive market is created, an incentive-based management system will replace the command-and-control approach in which instream flow rules are set and cannot be violated without penalty. Ideally, those with an interest in instream flows will purchase water rights until environmental requirements are met. If this point is reached, a sustainable and efficient allocation can be reached with a diminished need for regulation. There are drawbacks, however. It isn't possible to exclude people from benefitting from increased streamflow. Therefore, market demand is likely to be understated due to these “free riders”. For this reason and for others (e.g. upstream transfer externalities) water markets will not single-handedly solve the Yakima's water allocation problems; some degree of regulation is still necessary.

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Figure captions

Figure 1: The Yakima River Basin with counties and USGS streamgage locati

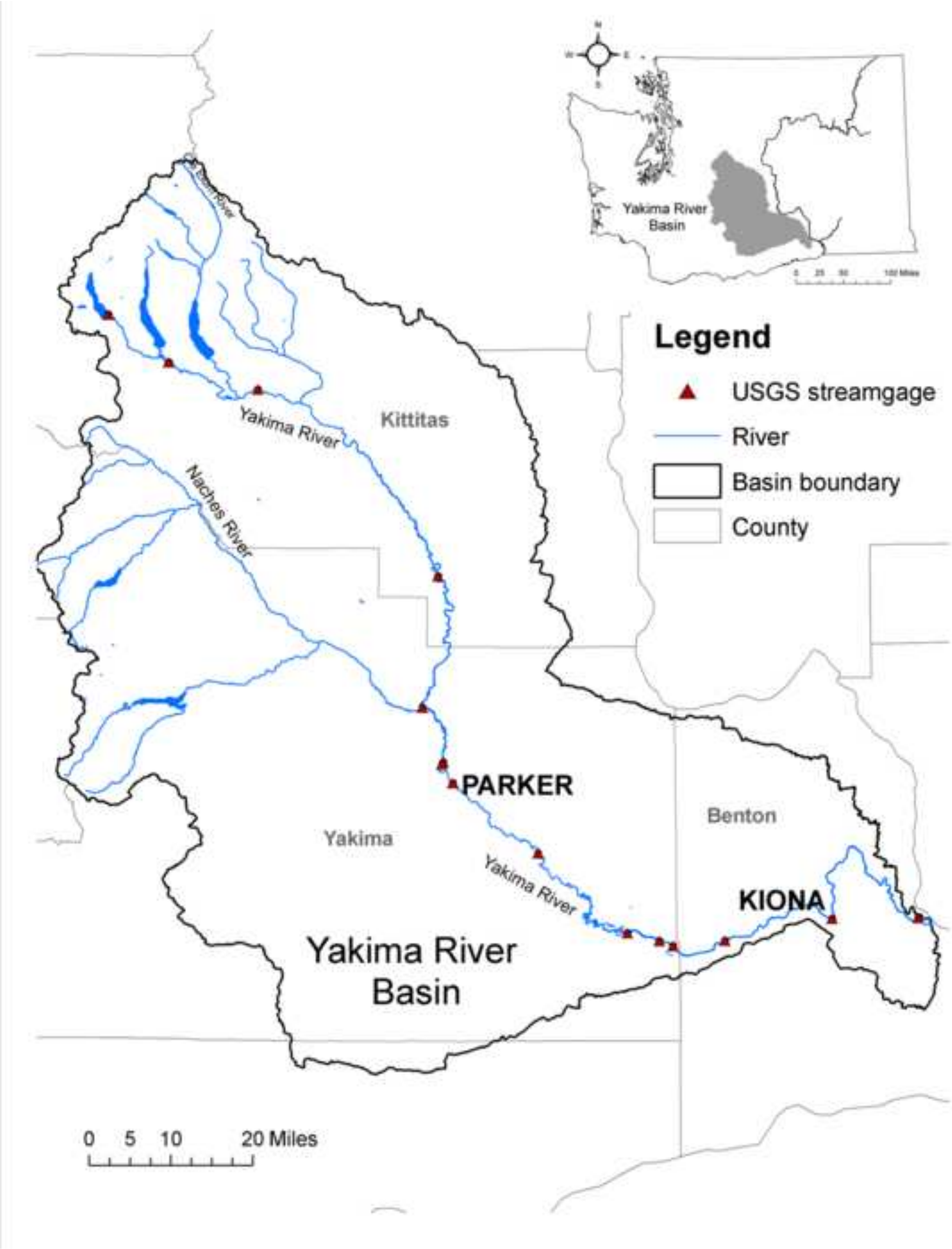
Figure 2: Comparison of average daily flow in the Yakima River measured at the Kiona station, averaged over 20 year increments. Note that the 1906-1914 time period represents the earliest flow records and includes only seven years (WY 1906, 1908 through 1914). The flow record in WY 1907 and WYs 1915 through 1939 are missing.

Figure 3: Comparison of model simulated (dashed line) and observed (solid line) average daily flow for water years 1949 through 1998. Water day is the number of days since the beginning of the water year, with Day 1 = October 1 and Day 365 = September 30 of the following calendar year. Leap year flow observations (February 29) were deleted prior to averaging.

Figure 4: Plots of RVA results for natural (simulated) versus observed (altered) time series from WY 1949 through 1998: a) parameter group 1; b) parameter group 2; and c) parameter groups 3 through 5. Filled symbols highlight highly altered values.

Figure 5: Daily flow duration curves (FDC) at Kiona, WA gage location. Solid line is unaltered (MMS simulated) flows and dashed line is altered (observed) flows for water years 1948 through 1998. Ecodeficit and ecosurplus as defined by Homa et al. (2005) are highlighted.

Figure 1 (hi res)



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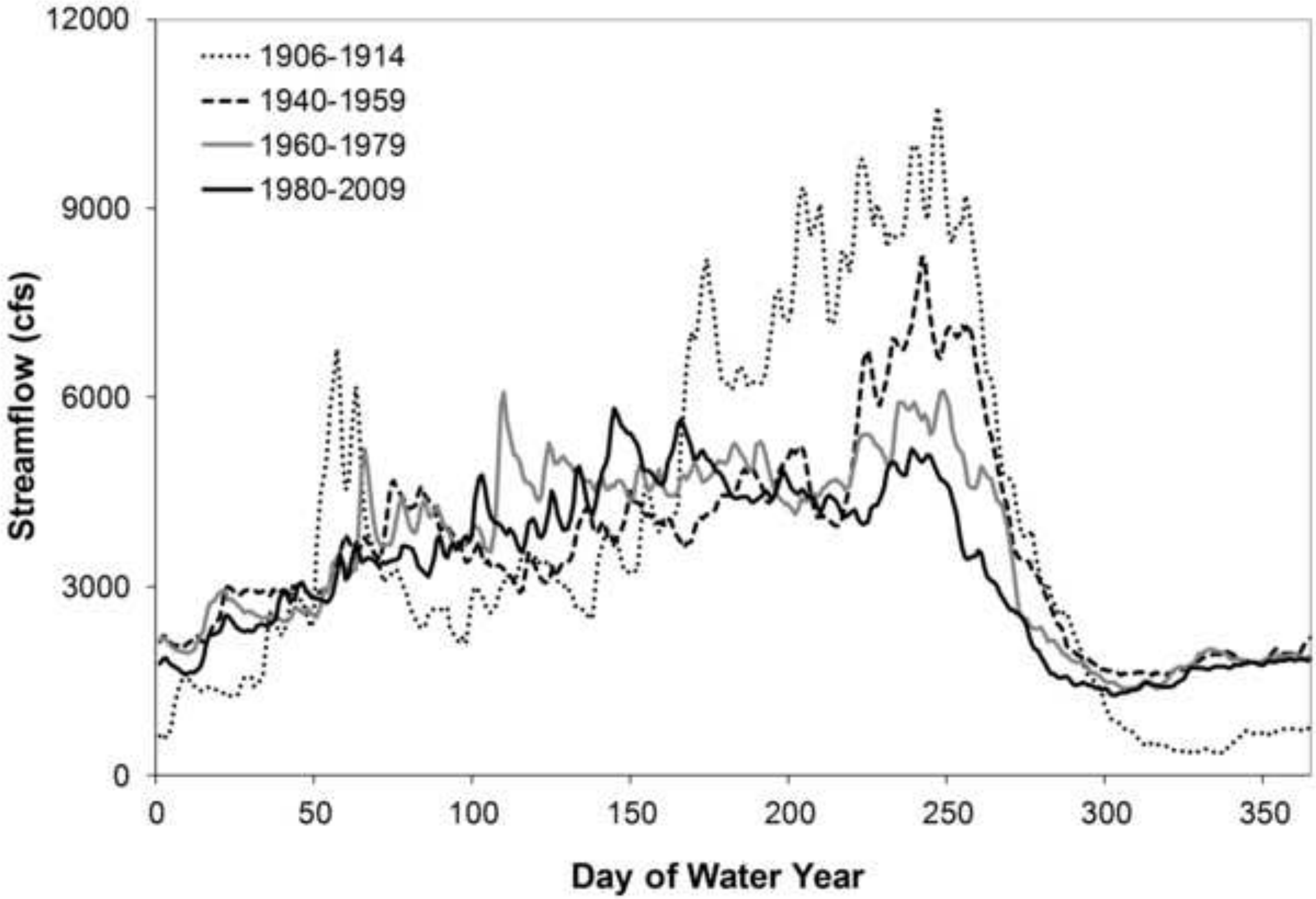

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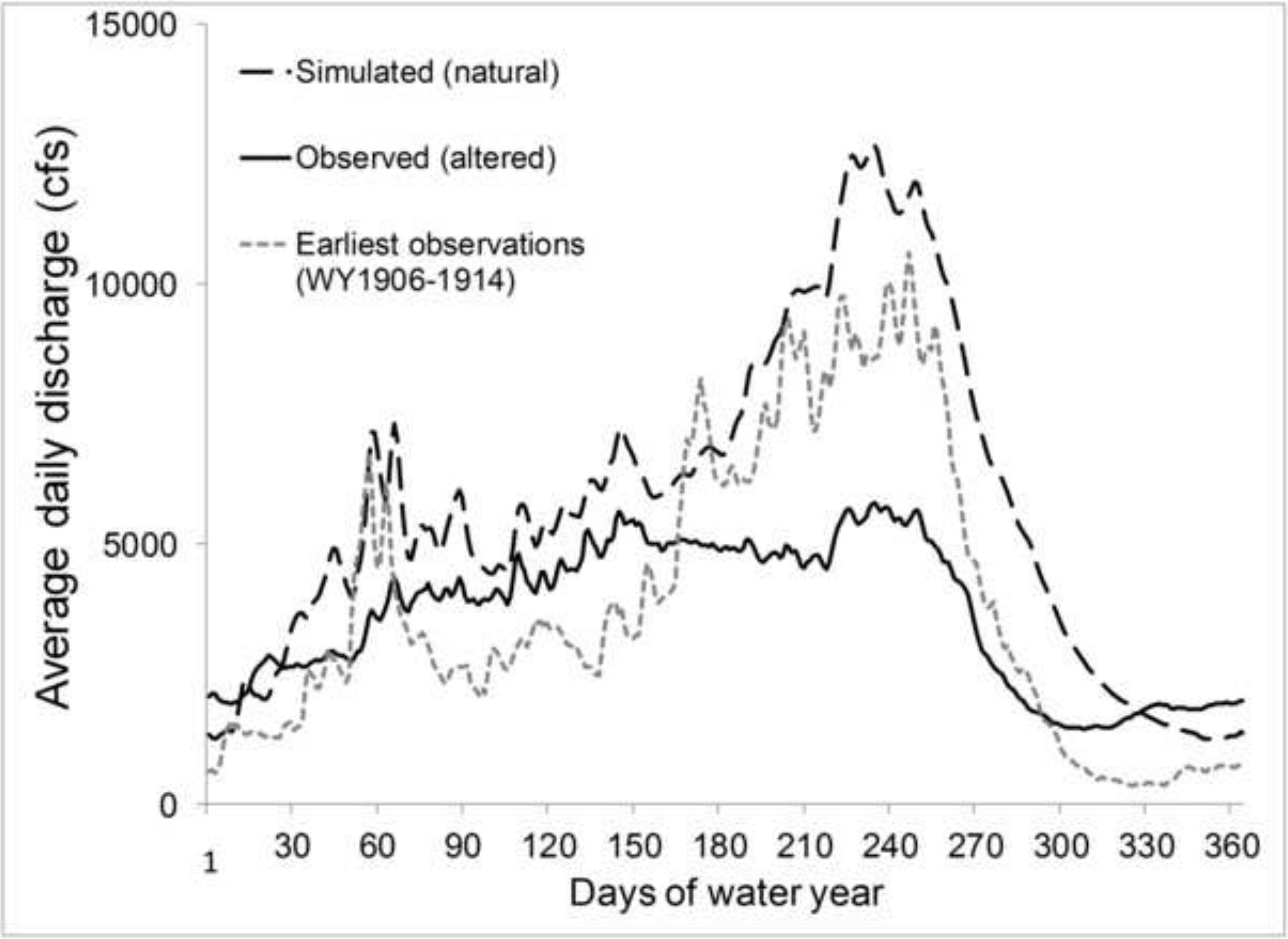

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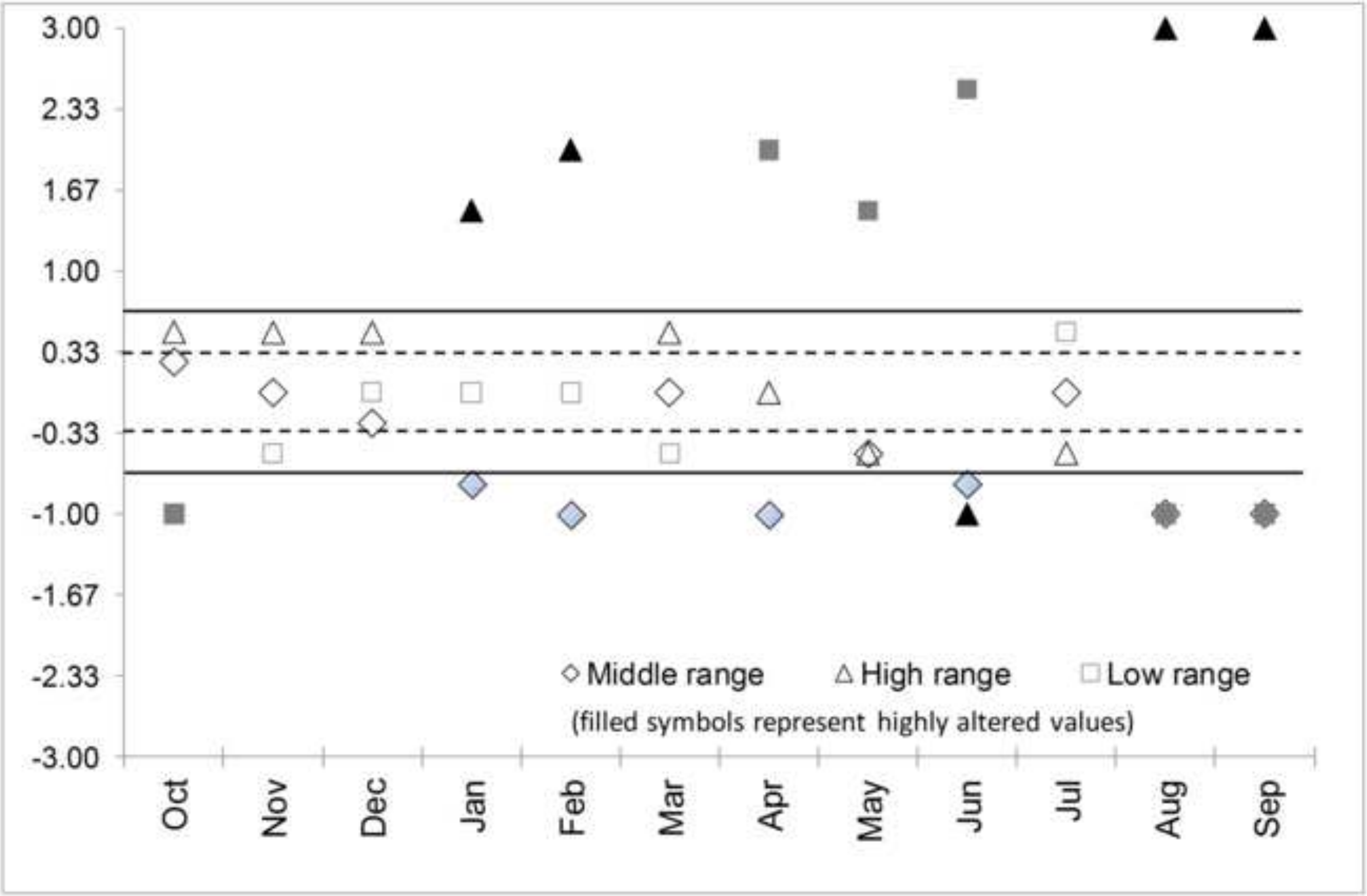

Figure 4b (hi res)

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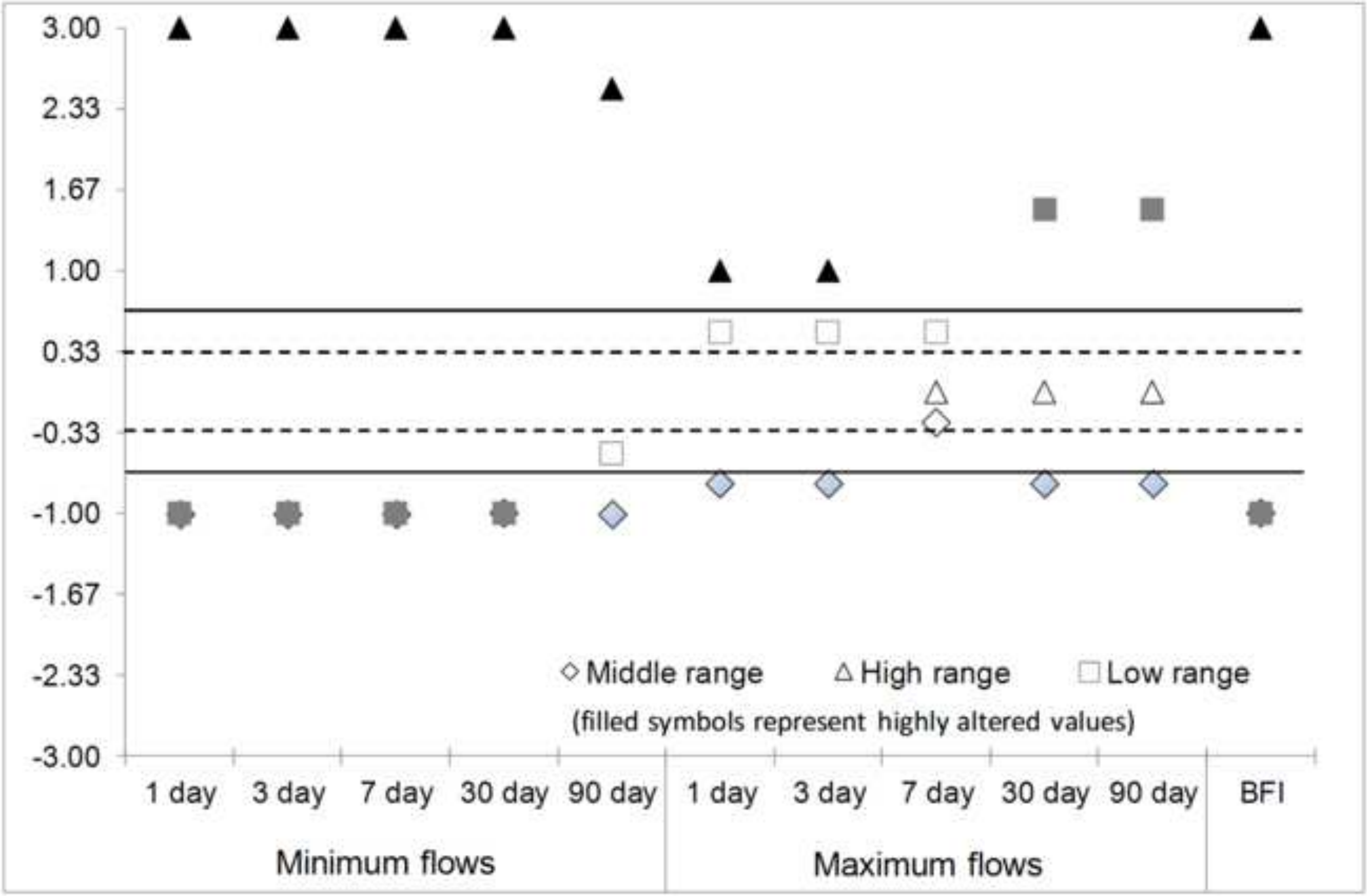

Figure 4c (hi res)

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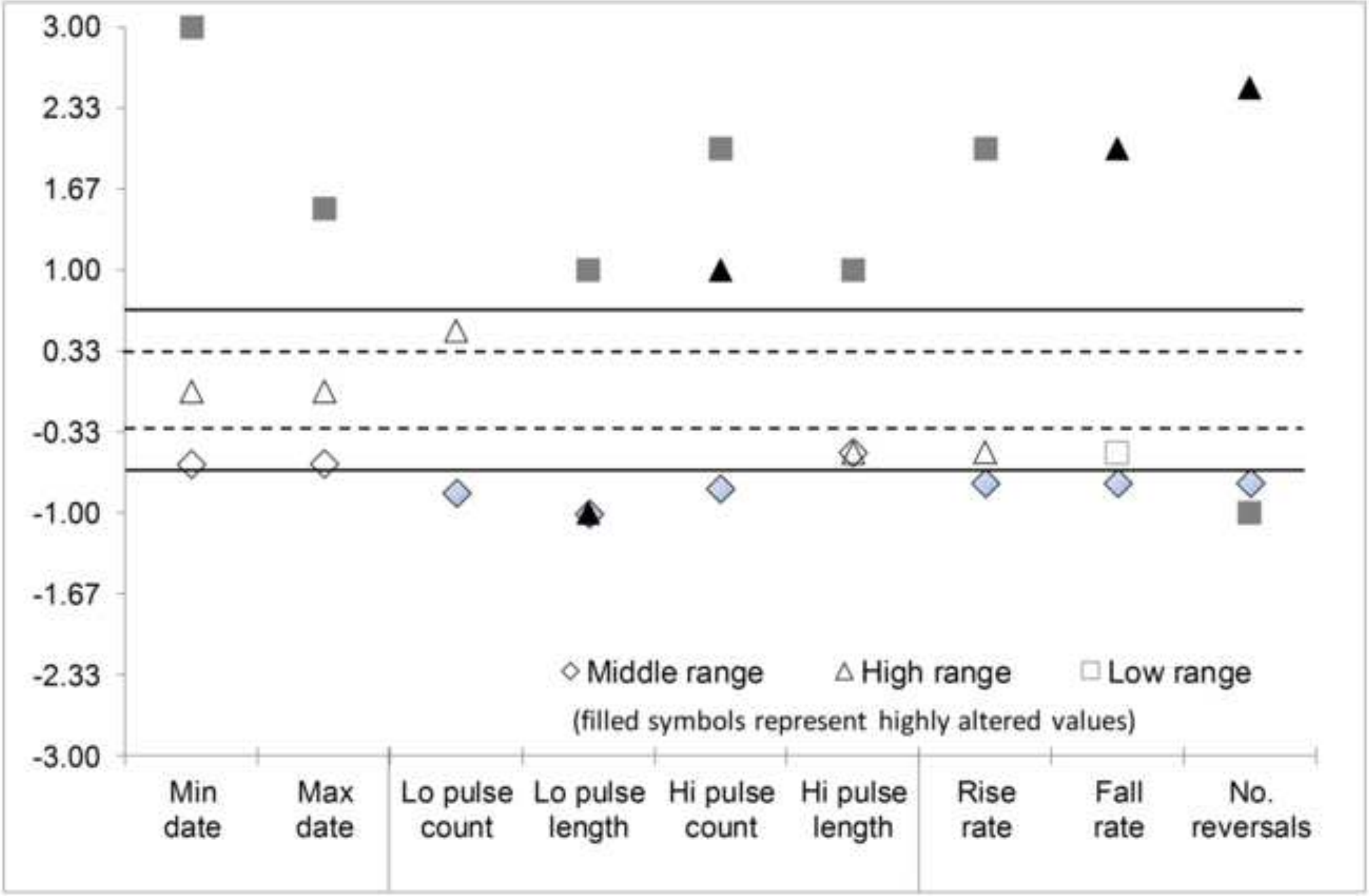

Figure 5 (hi res)
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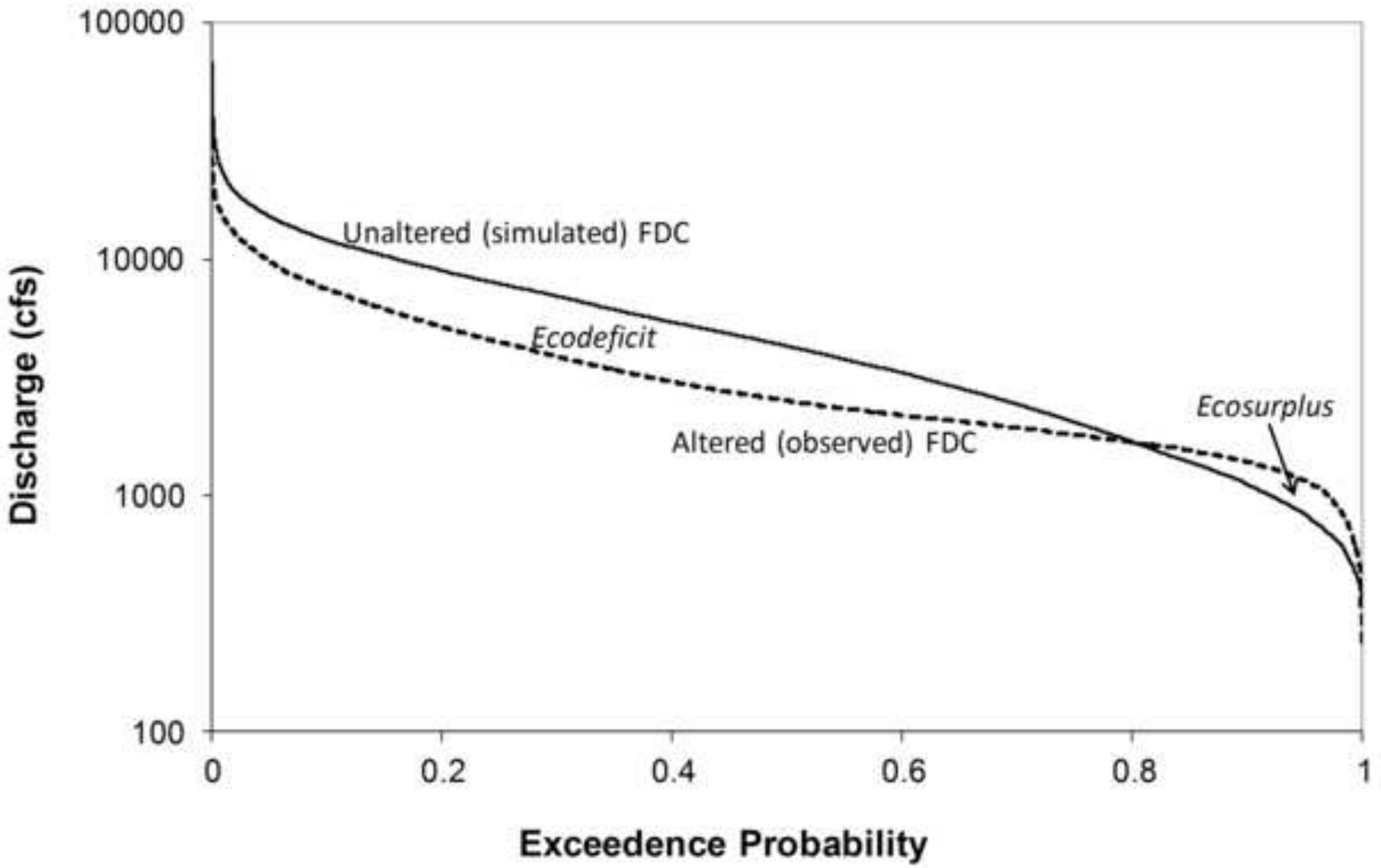

Tables 1 and 2

Table 1: Target flows set by Congress for the Yakima river (source: TCWRA 2001)

Target Instream Flows at Sunnyside and Prosser Diversion Dams					
Water supply estimates in billions ft^3				Target Flow (cfs) through October downstream of Sunnyside and Prosser Diverion Dams	
April through September	May through September	June through September	July through September	Without Basin conservation	With Basin Conservation
139	126	105	83	600	900
126	115	96	74	500	800
115	105	87	65	400	700
<115	<105	<87	<65	300	300[a]
[a]Only increased with reduced diversions below Sunnyside.					

Table 2: Comparison of flow statistics between simulated (unaltered) and observed (altered) flows at the Kiona, WA gage location.

Statistic	**Unaltered (simulated) flow (cfs)**	**Altered (observed) flows (cfs)**	**Ratio**
Mean	5702	3645	0.64
Std Dev	5068	3000	0.59
Median	4279	2520	0.59
Q1	2041	1800	0.88
Q3	7869	4460	0.57
Maximum	67759	45900	0.68
Minimum	352	225	0.64