Alternatives for riverine backwater restoration by manipulation of severed meander bend

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Abstract

Current thinking in stream ecology emphasizes the dependence of large riverine ecosystems on the materials and habitats provided by floodplain backwaters. However, these types of habitat are becoming increasingly rare as development is transforming floodplain landscapes in fundamental ways. Despite the large sums of money spent on control and management of water pollution, environmental quality continues to decline due to diminished hydrological connectivity between rivers and floodplain backwaters even as water quality improves. Along rivers with wide valley bottoms, functional values associated with floodplain water bodies such as abandoned channels, sloughs, severed meander bendways and borrow pits have been reclaimed by re-opening relatively small connecting channels. Reconnection projects typically involve dredging connecting channels or installing weirs or other types of water control structures. Backwater inflow augmentation is sometimes necessary for reconnection due to changes in bed elevation that have isolated backwaters from the main channel. Flow augmentation may involve installing and operating pumps on a permanent or seasonal basis. Design approaches are illustrated using a case study from a 2.5-km long severed bendway adjacent to the Coldwater River, Mississippi. Costs for project construction, operation and maintenance and benefits to fish habitats are projected and compared.

Introduction

Prior to about 1900, much of the area presently under cultivation in the U.S. was characterized by low relief and gentle undulating topography such as ridge and swale patterns that produced high levels of physical and biological diversity. Vegetation cover was comprised of virgin bottomland hardwoods, cane breaks, and other wetland plants. Most importantly, hydrology of these regions was dominated by periodic flooding. Flood hydrographs tended to be of long duration and low amplitude. Stream channels were complex, with high sinuosity and multiple stage-dependent connections to floodplain backwaters: lakes, sloughs, wetlands, and depressions. Current thinking in stream ecology emphasizes the dependence of riverine ecosystems on the materials and habitats provided by floodplain backwaters (Buijse et al. 2002, Ward et al. 2001, Wiens 2002). This paper seeks to provide information supporting planning and design of a riverine backwater rehabilitation demonstration project.

Freshwater ecosystems in the U.S. are exceptionally diverse, even compared with the tropics (Master et al. 1998). In particular, streams in the southeastern United States are important ecological resources, but resident fauna are apparently experiencing accelerated extinction rates (Ricciardi and Rasmussen 1999, Warren et al. 2000). Many species are imperiled due to habitat and water quality degradation associated with erosion and sedimentation caused by channelization, watershed development, and other human activities (Karr et al. 2000, Warren et al. 2000). Floodplain development activities include tile drainage, precision land leveling, filling of wetlands, excavation of ditches, flood control and water table manipulation. Larger rivers have been dammed, channelized, stabilized and leveed, reducing aquatic area and the numbers of islands, back channels and other high-quality habitats (Gore and Shields 1995, Hohensinner et al. 2004). Only one large river in the contiguous 48 states of the U.S., the Yellowstone, has escaped major modifications Despite the large sums of money spent on control and management of water pollution, environmental quality continues to decline due to habitat degradation and diminished hydrological connectivity between rivers and floodplain backwaters (Aarts et al. 2004).

Restoration

Ecological restoration may be thought of as an attempt to return an ecosystem to its historic (pre-degradation) trajectory (Society 2002). Restoration workers attempt to establish this “trajectory” through a combination of information about the system’s previous state, studies on comparable intact ecosystems, information about regional environmental conditions, and analysis of other ecological, cultural and historical reference information (Society 2002). Ward et al. (2001) argue that large river restoration has been hampered by mistaken assumptions about the simplicity and stability of river corridors in their natural state. Natural rivers exhibit high levels of spatio-temporal heterogeneity due to the interplay of hydrologic, geologic, and topographic factors, particularly in the lateral dimension. These patterns are manifest in many ways: principally in the rise and fall (advance and retreat) of water, but also in complex patterns of velocity, water temperature (Uehlinger et al. 2003), turbidity, and movements of organisms. River corridors may be thought of as complex mosaics of various types of habitat patches, with permanent or temporary linkages through surface waters, subsurface waters, or the atmosphere (Weins 2002).

Since a hallmark of river corridor development is reduction of lateral linkages through many river restoration efforts have focused on managing floodplain water bodies and their connectivity with the main channel. Functional values associated with floodplain water bodies such as abandoned channels, sloughs, severed meander bendways and borrow pits have been reclaimed by re-opening relatively small connecting channels. Examples include:

- Between 1994 and 1999 eight isolated channels 10 to 150 m wide and 1 to 10 km long were reconnected to main channels of two European rivers. Connecting channels diverted only 0.3% to 5% of the main channel flow, and diverted flow durations ranged from 220 days per year to permanent, with reports of creation of a broad range of habitats suitable for a variety of aquatic and riparian species (Buijse et al. 2002).
- In 1989 the U. S. Corps of Engineers dredged a connecting channel between Monkey Chute, an 88-acre backwater lake, and the main channel of the Upper Mississippi River in Marion County, Missouri (Figure 1). Twelve years of monitoring revealed that the project had been successful in achieving stated objectives of flow introduction to the chute, improvement in fish populations, increase in recreational fishery, and revegetation of deposited dredged material. No maintenance was required during this period (Rock Island District 2001). The Corps also improved water level control structures for Lake Chautauqua on the Illinois River near Havana, Illinois. The lake had been managed as a National Wildlife Refuge since 1936, but wetland management capabilities and habitat quality had degraded. Water control structures for the southern pool were completed in 1999. Submersed aquatic vegetation and marsh plants colonized almost 1,400 acres after project completion. Positive responses by waterfowl and fish were also noted, with waterfowl numbers returning to levels not seen in several decades.

Figure 1. Monkey Chute. Connection to main channel of Mississippi River re-opened for habitat restoration in 1989.

These and other studies highlight the importance of hydrologic connection and the presence and magnitude of current in controlling the quality of backwater habitats (Valdez and Wick 1981, Grift et al. 2001).

Study site

A reach of the Coldwater River about 20 km downstream from Arkabutla Dam in northwestern Mississippi was selected for study due to the presence of more than 20 severed meander bends and other water bodies along the river (Figure 3). Elevated suspended sediment concentrations, habitat reduction associated with sedimentation, and water pollution associated with agriculture are primary resource problems in this locale (Mississippi Department of Environmental Quality 2003, Corps of Engineers undated). Despite these problems, reports indicate viable fish populations within the Coldwater River. Jackson et al. (1995) reported capture of 21, 22, 19, 17, and 13 species of fish using hoopnets in the Coldwater for the years 1990,

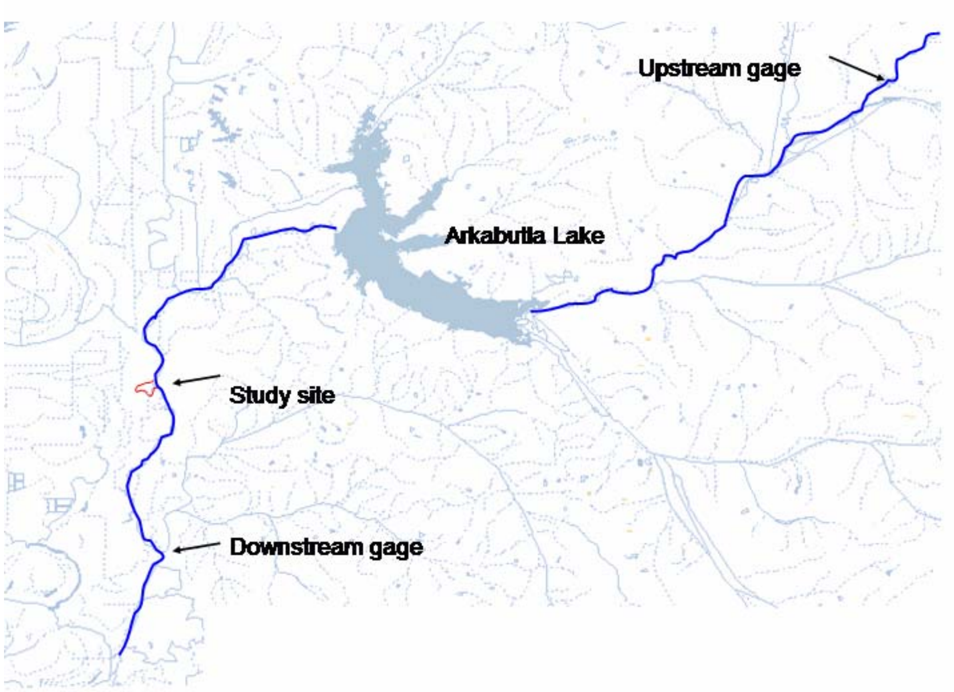

Figure 3. Coldwater River and Arkabutla Lake in northern Mississippi, showing location of study site and stream gages.

1991, 1992, 1993 and 1994, respectively. Catch per unit effort for the Coldwater River (all species and seasons) exceeded the four other Yazoo basin rivers sampled during the same time period.

After reconnaissance of the entire reach, a severed compound meander bend about 2.5 km long was selected for more detailed examination. The bend is inside the mainstem flood control levee, and is the result of a 0.4 km cutoff constructed in 1941-42 (Whitten and Patrick 1981). Lands both inside and outside the bend are in row-crop cultivation, but there is a buffer of natural vegetation several 5-100 m wide on both banks (Figure 2).

Figure 2. Severed meander bend selected for study.

Data

Available data to support planning and preliminary design included airborne LiDAR, conventional survey data, and bend bathymetery collected using an echosounder coupled with a global positioning system. Hydrologic records from gaging stations 14 km downstream from the study site and 60 km upstream from the Arkabutla Dam were also available. Records of water temperatures in the severed bend, the adjacent river main channel, and in the river upstream from the Lake were obtained using in-situ sensors. Water depth and current velocity were monitored at the bank toe and channel centerline within the bend using an incoherent acoustic-Doppler system. These data were used to assess the frequency and duration of hydrologic connection between the main channel and the bendway under current conditions. Deviations of water temperature from the regime in the channel upstream from the Lake were assessed for a short period of record.

Results

The bendway thalweg profile was superimposed on a stage duration curve based on 1960-2003 data (Figure 4). The stage duration curve was derived by adding a constant (1.7 m) to the curve for the downstream gage. In fact, analysis of a short period of concurrent stage records revealed that the relationship between stage at the bend site and the stage at the downstream gage is nonlinear, with considerable hysteresis, but more sophisticated adjustment of the downstream rating to fit our site was beyond the scope of this paper. Under current conditions, the study bendway is connected to the river mainstem at its downstream end whenever the river water surface elevation exceeds about 53 m MSL, and at the upstream end through a 0.5-m diameter culvert whenever river stages exceed 54.3 m MSL at that location. Examination of LiDAR topographic data verified that additional connecting channels do not exist at these stages. Stage-duration and event frequency values for key elevations are provided in Table 1. Connection with the river is limited due to the high elevation of the old bend channel relative to the river, evidently due to incision of the river channel and sedimentation in the bend channel. Connections most often occurred in December – April (82% of days with some type of connection), less so in May – August (13%) and rare in September – November (5%). Lotic conditions in the bend (connection at both ends) occur for about 8 days a year and last an average of 2 days. Connection from the downstream end of the bend, which presumably allows exchange of organisms and water but produced little current in the bend, occured for longer periods.

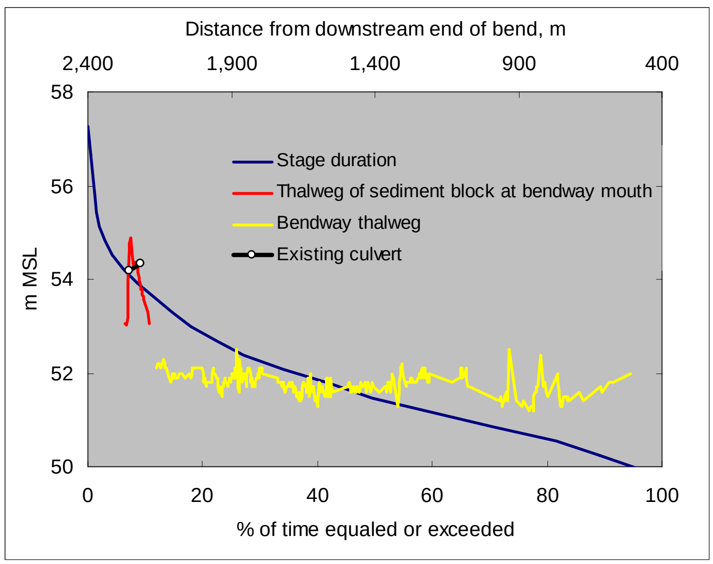

Figure 4. Stage duration curve and thalweg profile for study bend, Coldwater River, Mississippi.

Values shown in Table 1 were compared to conditions recorded in the meandering channel upstream from the reservoir (Figure 2) by computing the key elevations shown in Table 1 relative to flood stage. Results are shown in Table 2. Flooding is more frequent and of longer duration upstream of the reservoir. At the present, flow occurs through the bend an average of only 17 d/yr. If the hydrologic regime that is present upstream from the reservoir were imposed at the bend site, flow through conditions would exist an average of 44 d/yr. Analysis of seasonal records showed that connection events are more evenly distributed throughout the year, with 51% of days with connection falling December – April, 29% in May – August and 21% during September – November.

Table 1. Key study site elevations and relationship to river stage duration based on extrapolated once-daily stage readings, Coldwater River at Sarah, 1960-2004.

Location	Elevation (m MSL)	% exceedance	Number of events per year	Mean length of event (days)	Maximum length of event (days)
Crest of block at upstream bend entrance	54.8	3	5.3	1.8	16
Invert of culvert at upstream bend entrance	54.3	6	7.5	2.3	22
Controlling elevation at downstream bend entrance	53.3	12	3.7	4.7	52
Lowest point in bend thalweg*	51.3	51	1.7	11.1	90

Table 2. Key elevations and relationship to river stage duration based on extrapolated once-daily stage readings, Coldwater River at Lewisburg, 1960-2004.

Location at bend study site	Elevation relative to flood stage (m)	% exceedance	Number of events per year	Mean length of event (days)	Maximum length of event (days)
Crest of block at upstream bend entrance	-0.8	7	7.0	3.9	111
Invert of culvert at upstream bend entrance	-1.3	12	9.6	4.9	113
Controlling elevation at downstream bend entrance	-2.3	51	13.1	62.3	1683
Lowest point in bend thalweg*	-4.3	100	--	--	--

*Values in the last four columns of this row refer to events where the river is lower than the specified elevation. All other rows refer to events where the river equals or exceeds the specified elevation.

Short-term water stage, velocity, and temperature records (Figure 5 and Figure 6) were analyzed to identify patterns. Stage fluctuations of ~3 m in the Coldwater River produced smaller amplitude fluctuations within the bend, but little current velocity was detected. Evidently lotic conditions only occur in the bend when the upstream block (as shown in Figure 4) is overtopped. Water surface elevations in the river and in the bend were related in some sort of complex nonlinear fashion, at least in part due to the high flow resistance presented by existing connecting channels (Figure 7). Concurrent stage and water temperature records indicated that the river and the bend were distinct during autumn low flow conditions with warmer temperatures and strong diel fluctuations in the shallow, stagnant bend. The arrival of higher flows later in the year (along with cooler weather) produced a convergence of water temperatures.

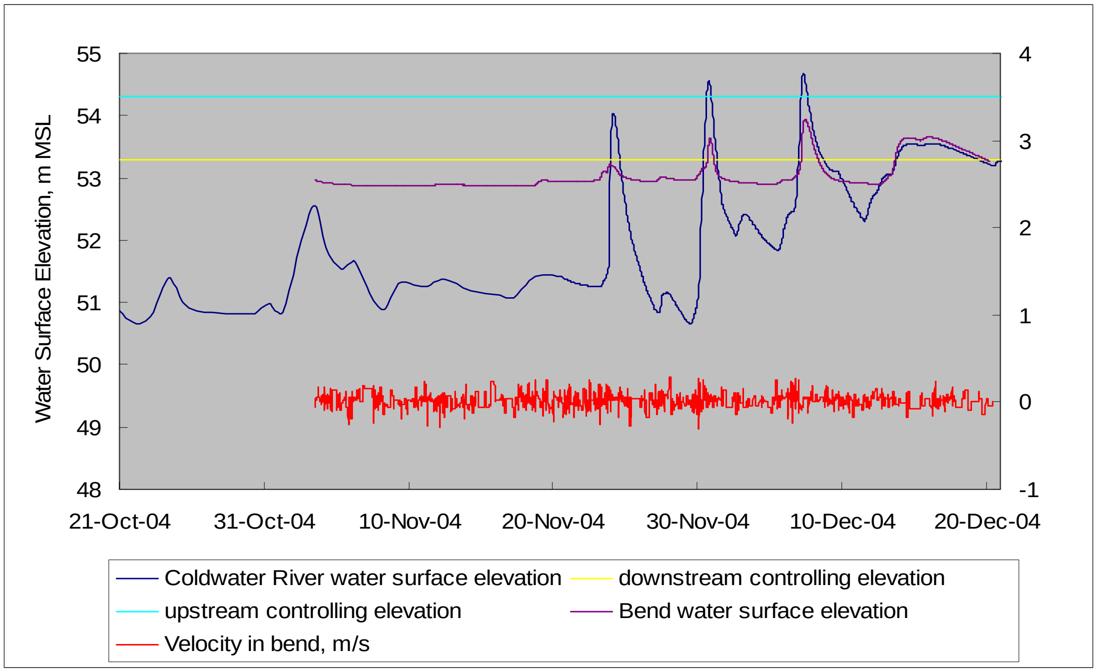

Figure 5. Water surface elevation and water velocity, Coldwater River and adjacent cutoff bend.

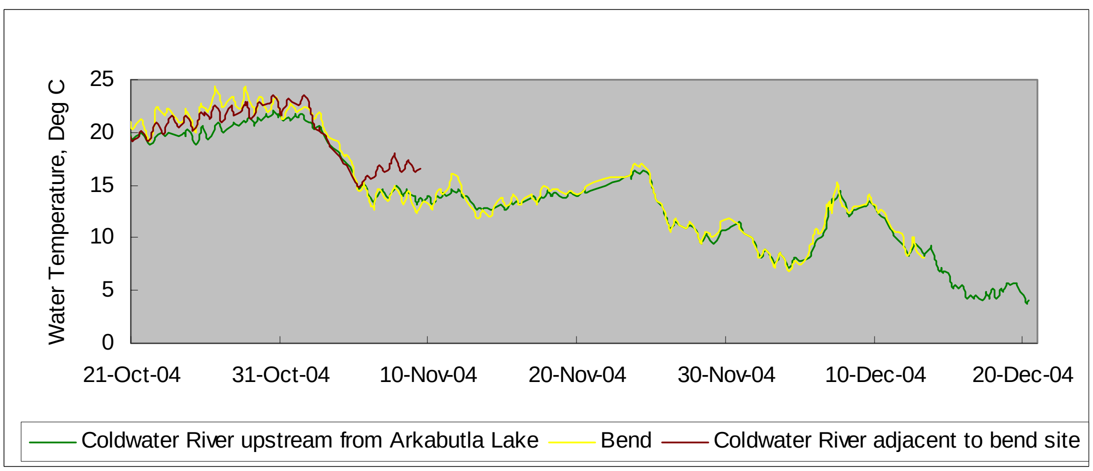

Figure 6. Water temperature for Coldwater River and cutoff bend.

Planning for restoration

Figure 7. Existing connecting channel at downstream end of bend. View shown is facing from the bend toward the Coldwater River.

Engineers charged with producing ecosystem restoration projects must adopt measurable goals and objectives as a basis for design. What conditions are desirable targets, and why? The site in question may be viewed as a remnant of an earlier riverine ecosystem with much higher levels of structural (physical) and biological diversity. Manipulation of the site might allow some of this diversity to be regained. In addition, using the aquatic systems within and adjacent to the bend to trap and, in some cases, process nonpoint source pollutants from the surrounding cultivated lands is worthy of consideration. Finally, the bendway might be used to convey water from the main channel closer to its point of application for irrigation. Work by ecologists working on European rivers that were braided prior to human development is helpful (e.g., Amoros 2001). In general, these systems produce the highest levels of biodiversity under conditions of intermediate hydrologic connectivity and disturbance (Ward and Tockner 2001). Specifically, the bend in question, when viewed as a component within the river landscape, should provide greatest ecological diversity (and perhaps the highest level of ecological services) if it is neither totally isolated from main channel flow nor experiencing flow-through connection continuously. However, such criteria still leave much room for design decisions, and thus error. How frequently should connections occur, and how long should they last? How much inter- and intra-annual variation in hydrologic connection is desirable? What are the relative merits of hydrologic connection at the downstream end only versus flow-through connection?

Four possible actions for bend management were identified:

1. Enlargement of the downstream connecting channel,
2. Placement of a water control structure (e.g., a weir or standpipe) at the downstream end of the bend, and
3. Enlargement/improvement of the culvert at the upstream end of the bend.
4. Periodic pumping of water from the main channel into the upstream end of the bend.

The relative merits of these four alternatives are compared in Table 3. However, actual projects might consist of one or more than one of these actions in combination. Actions other than pumping are likely to require regular maintenance for sediment removal (Buijse et al. 2002, Shields and Abt 1989). Flow augmentation through pumping is attractive for a demonstration project because it is fully reversible, likely to produce measurable changes in bend water quality and ecology over the short term, and has produced positive results in other systems.

We propose that flow augmentation through pumping divert ~5% of the mainstem flow at irregular intervals during the year in order to achieve the same frequency and duration (but not necessarily magnitude) of flow as a similarly situated backwater upstream from the reservoir. Comparison of daily stage records for our site and for the reference site upstream from the reservoir indicates that pumping will be required, on average, about 27 days per year (cumulative difference between existing and target conditions in Figure 8) to increase the current average frequency of connection. Ideally, pumping would be scheduled to improve fish access from the river to flooded terrestrial vegetation within the bendway for spawning (Lusk et al. 2003). An untreated bend nearby will be monitored for reference purposes (Henry et al. 2002).

Table 3. Comparison of bend restoration project components.

Project description	Connectivity	Flexibility	Cost components	Cost magnitude Initial/annual ($K)
Enlargement of downstream connecting channel	Improved	Water level in bend will be controlled by river stage	Earthwork, annual maintenance to remove vegetation and sediment	50/5
Weir at downstream end	Reduced	Water level within bend may be manipulated if weir includes operable drainage structure	Earthwork, stone, drainage structure, operation and maintenance	125/5
Replacement of water control structure at the upstream bend entrance	Improved	Water level and flow within bend will be controlled by river stage and operation of structure	Earthwork (will include deepening of upstream connecting channel), culvert, monthly sediment and debris removal during periods of high stage.	75/10
Pumping water from main channel into upper end of bend	Improved when downstream connection exists	Flow and stage within bend controlled by pumping during lower river stages	Lease and operation of pumps	5/15 Assumes pumping 1 m^3/s for 30d/yr.

Summary and conclusions

Future development of stream corridors must distance itself from the water resources engineering paradigm that has focused on structural means to achieve water supply, flood control, and stabilization. Instead, an ecological engineering paradigm (Mitsch and Jørgensen 2004) that manages ecosystems for the totality of services they provide is needed. Since cutoff bends and other types of hydrologically isolated water bodies are common along large, lowland rivers, these areas merit special attention in devising ecological engineering techniques. Cutoff bends may be managed using a combination of water control/flow diversion techniques. Key questions regarding the design of these measures have to do with the timing and duration of flow connection with the main channel. Existing information indicates that a level of connectivity intermediate to permanent flowing water and total isolation is desirable. Without additional information, a reference site may be used for hydrologic design criteria.

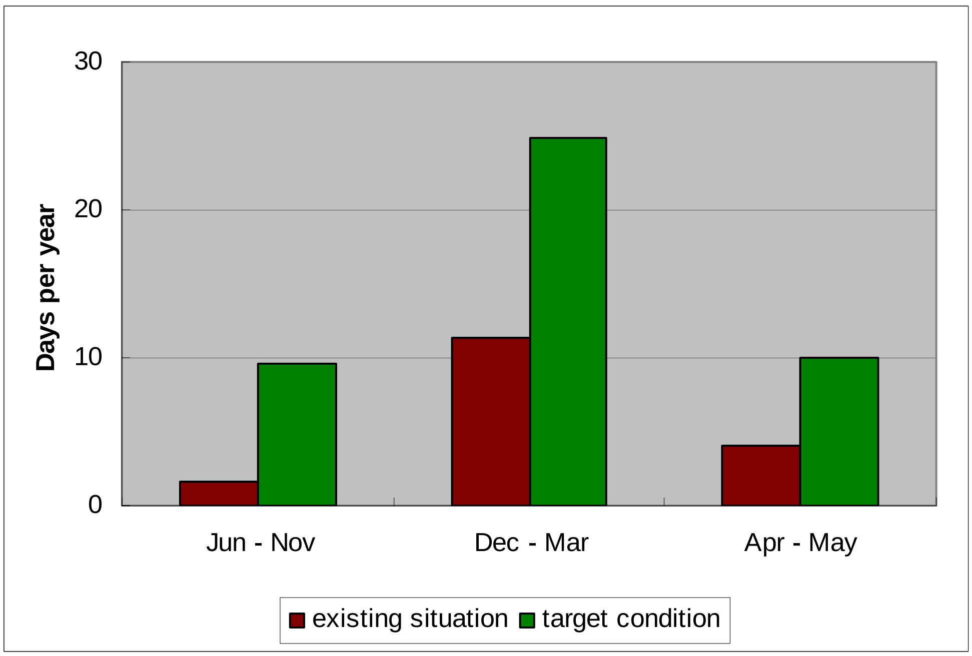

Figure 8. Average number of days per year that the bend experiences flow, by season, and target frequency based on gage records from site upstream from reservoir.

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