CRWR Online Report 06-04

Dam Re-operation: Influences on Natural and Productive River Processes (Glen Canyon and Green River Dams)

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May 2006

CENTER FOR RESEARCH IN WATER RESOURCES

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Section 1 - Overview

The objective of damming a river is to provide an increase in water-oriented benefits for the surrounding population through exercising a level of control over the river flow. Making an unpredictable river more predictable diminishes the negative impacts caused by variability in river flow and creates a constant and therefore more valuable water resource. But rivers are complex systems and although dams may offer benefits to the society that builds them, the manipulation of the river's flow regime can have serious and unanticipated consequences on the surrounding natural environment.

The International Commission on Large Dams estimates that approximately 45,000 large dams (higher than 15 m or between 5m and 15 m with 3 million m^3 of storage) have been built on nearly one half of the world's rivers. Each of these dams was constructed for the purpose of achieving specific benefits such as power generation, water storage, and flood control. Many large dams are operated under a management perspective which solely focuses on maximizing the specific benefits for which the dams were designed, with minimal consideration given to the dam's impact on the downstream natural river environment. A typical river system includes a variety of usage sectors which depend on a wide array of river supported resources for their persistence. The result of a limited management perspective is a regulated river system where the less tangible costs of water resource development such as species decline, water quality impacts and habitat degradation, are not included in planning future dam operation strategies.

Dam re-operation, the process of revising established dam operation practices to include environmental and other neglected but impacted areas into the management perspective, provides significant potential for improving dam degraded natural river environments while continuing to sustain the benefits which the dam was built to provide. Figure 1 displays a theoretical example of the economic justification for dam re-operation. By shifting the priority of dam operation to include the state of river supported natural systems, other river associated usage sectors such as recreational opportunities (boating, fishing, tourism) and cultural institutions (local/regional significance, traditional river subsistence practices) have potential for improvement in addition to the benefits and value associated with the restoration of the natural river systems themselves. If carried out effectively, re-operation should provide increased benefits in non-productive sectors while maintaining a comparable level of benefits for productive sectors, yielding an overall increase in operational benefits.

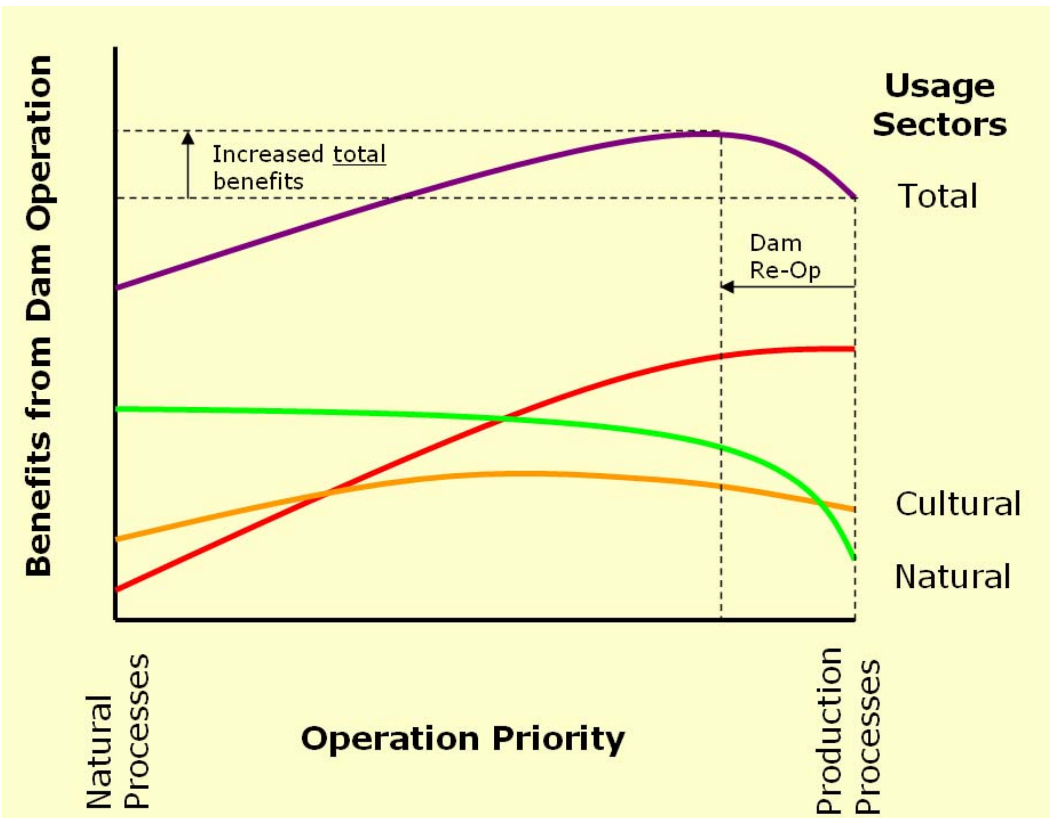

Figure 1 - Dam Re-operation Benefit Graph

There are a variety of measures that could be considered dam "re-operation". Examples include altering releases to maintain minimum environmental flows, installing structures to restore sediment transport and fish migration, releasing controlled floods to mimic pre-dam flow conditions, and upgrading components of the water supply and irrigation systems to achieve more efficient water use. Although the components of dam re-operation strategies differ between river systems, ultimately the re-operation process is an attempt to achieve an overall increase in the total amount of benefits being derived by dam operations or at the minimum, reduce the damages or costs resulting from established dam operation practices.

The Natural Heritage Institute, a non-profit organization established in 1989 for the purpose of solving environmental problems through bridging the gap between science and natural resource politics and management has initiated a "Global Survey of the Potential to Modify Major Dams to Restore Downstream Ecosystems and Human Livelihoods". One of their approaches is assembling a "Toolkit for Dam Re-operation"; a collection of global case studies examining current dam re-operation projects. The case studies will include an assessment of the impacts of previous dam operations and evaluate the potential for improvement under re-operated conditions. The purpose is to provide examples of successful re-operation projects to demonstrate re-operation as a feasible strategy for enhancing water resource management and stimulating governmental and assistance agency investment in re-operation projects.

This research project examined two case studies of dam re-operation for potential inclusion in the global case study collection; the Glen Canyon Dam on the Colorado River in Arizona and the Green River Dam on the Green River in Kentucky. This report contains a review of the two case studies, (sections 2 and 3) and a concluding section (section 4), proposing a general model for the restoration potential of dam re-operation projects.

Section 2 – Case Study of The Glen Canyon Dam

Background

Since its completion in 1963, the Glen Canyon Dam has had a significant effect on the downstream flow regime of the Colorado River as flood control and daily fluctuating releases from the dam have caused considerable ecological changes. Because the dam is located several kilometers upstream of the Grand Canyon, there is an enhanced interest in maintaining and restoring the downstream riverine ecosystems that depend on the Colorado River's flow conditions for their preservation.

Grand Canyon Environmental Studies, a Department of Interior program to study the downstream effects of the Glen Canyon Dam, was initiated in 1982 following concerns over the potential environmental impacts of a proposed hydropower production enhancement project at the dam. The findings of the GCES program were summarized in the Final Environmental Impact Statement published in 1995. The statement confirmed the dam's negative impacts on downstream ecosystems but acknowledged that there were too many uncertainties to propose specific restorative changes to dam operation procedures. Instead, in adherence with policies enacted under the Grand Canyon Protection Act of 1992, an adaptive management process was recommended. The Adaptive Management Program was adopted by the Bureau of Reclamation (owner/operator of the Glen Canyon Dam) in 1996.

Adaptive Management

Conceptually, adaptive management attempts to bridge the gap between traditional water resource management practices and ecosystem science; an area which proponents of adaptive management attest lacks sufficient consideration under conventional production focused management structures. At Glen Canyon Dam, the Adaptive Management Program is attempting to reduce the detrimental effects of dam operations on the downstream natural environment while sustaining productive functions such as water supply and power generation which the dam provides to the surrounding region.

Although the Adaptive Management Program at the Glen Canyon Dam is administered through the U.S. government, it attempts to incorporate a broader spectrum of interests through the Adaptive Management Work Group (AMWG). The AMWG is an advisory committee made up of stakeholder representatives from cooperating agencies, Colorado River basin states, environmental groups and recreation and power generation interests. The AMWG meets a minimum of two times per year to resolve key issues regarding current and future dam operation strategies and maintain a balanced consensus between the various interest groups. Ultimately, the Secretary of the Interior has the final authority over dam operation and management programs, however, the AMWG is the entity that issues the actual policies guiding management of the dam which the Secretary of Interior then approves. The information guiding the AMWG is provided through the collaboration of three subgroups which operate under the AMWG; the Technical Work Group (TWG) which is a separate advisory committee appointed by the AMWG that focuses on the technical issues of management of the dam, the USGS's Grand Canyon Monitoring and Research Center (GCMRC), which carries out the monitoring and research associated with the Adaptive Management Program and independent review panels which legitimize the research carried out by the research center. Acting together these subgroups ensure that the policies and decisions enacted by the AMWG are based on valid data and credible science.

The Adaptive Management Program at Glen Canyon Dam involves an ongoing iterative process of informed experimentation. Experimental operational strategies are carried out on a trial basis with the effectiveness of the strategies assessed through monitoring and research studies at the GCMRC. The results of the GCMRC's research serve as a basis for proposed revisions to existing operations which then starts the process over again.

There are typically a number of different sectors which are affected by the management and operation of a water resource project such as power production, water supply, species and habitat preservation and restoration, and recreational opportunities. Under the previous management structure, operations at the Glen Canyon Dam were focused on maximizing benefits from power generation and water supply and the decrease in benefits occurring in other sectors such as river rafting and native species preservation was not factored into the operation strategy. With adaptive management, the intention is to integrate the traditionally separate policy, science, and management perspectives and through experimentation, accumulation of knowledge and informed adjustment, achieve a more balanced and optimal distribution of the benefits and costs of water resource management amongst all involved sectors.

Natural versus Productive Resources

The Colorado River in the downstream portion of its basin provides a unique riverine environment in an arid region. Figure 2 includes a map of the study area. Grand Canyon National Park, one of the most significant natural landscapes in the world is located 24 km downstream of the Glen Canyon Dam In addition to human cultural and recreation oriented activities such as hiking, river rafting and camping, the river supports a variety of plant and animal species, some of which are on the federal list of endangered species. The ongoing relationship between river, landscape and ecosystems in the region plays a central role in the preservation of the unique and valuable natural environment downstream of the Glen Canyon Dam.

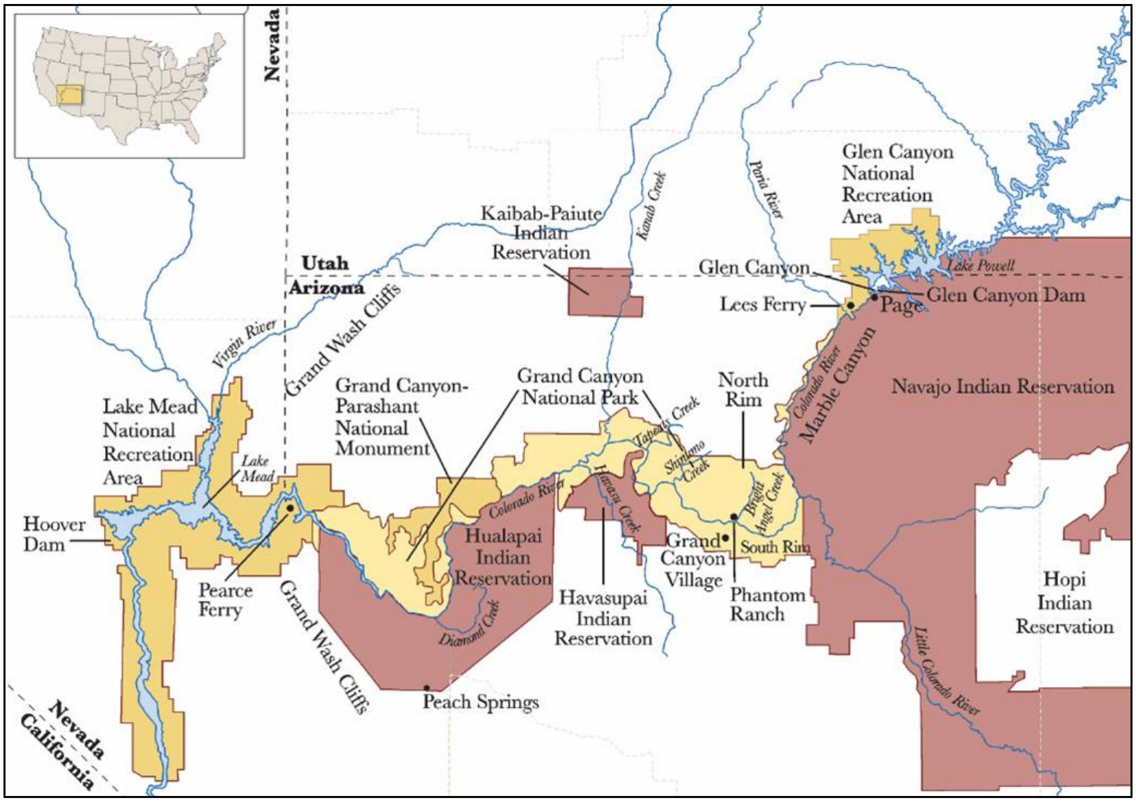

Figure 2 – Glen Canyon Dam Study Area (USGS)

The alteration in the Colorado River's natural flow regime below the dam has changed the how the river supports and influences the ecosystems and landscape surrounding it, but it has also provided significant benefits for the desert communities. A natural river is an unpredictable river and Glen Canyon Dam, one of the four major storage facilities in the Colorado River Storage Project, provides a much more consistent regional water supply than could ever be attainable on an unregulated river. Lake Powell, the reservoir formed by the Glen Canyon Dam holds over 33 million cubic meters of water which helps to supply the source of water for 25 million people in the Colorado River region (Gloss et al., 2005). Glen Canyon Dam is also used to generate electricity; between 1978 and 1999 the hydropower facility averaged 5.2 million megawatt hours of electricity generated per year which was sold and distributed to a roughly 200 wholesale customers which include a variety of utility companies and governmental and non-governmental organizations throughout Arizona, New Mexico, Colorado, Utah, Wyoming, and Nevada (Gloss et al., 2005).

Downstream Impacts

Prior to dam construction the Colorado River had a seasonally variable flow regime. The pre-dam flow regime was defined by high flood flows supplied by snowmelt in the Upper Colorado Basin during the spring and early summer with peaks typically reaching 3000 m^3/s and lower flows during the fall, and winter months with lows in the range of 28 to 85 m^3/s (Patten et al., 2001). Figure 3 displays the average annual flow regime for pre-dam and post-dam years at the USGS Lees Ferry Gage, just downstream of the Glen Canyon Dam. The construction of Glen Canyon Dam essentially eliminated the naturally occurring, seasonally fluctuating flow cycle and instead created a daily fluctuating flow cycle with releases based on power demands and water supply requirements. Releases from the dam are typically between 200 and 400 m^3/s and are varied throughout the day according to hours of peak power demand and over the longer term by the amount of water being stored in the Lake Powell Reservoir. This more consistent flow regime meant that portions of the Colorado River's floodplain which were routinely inundated during the yearly flooding were no longer directly connected to the river flow and portions of the river channel which were left dry during low flow conditions were now continually submerged.

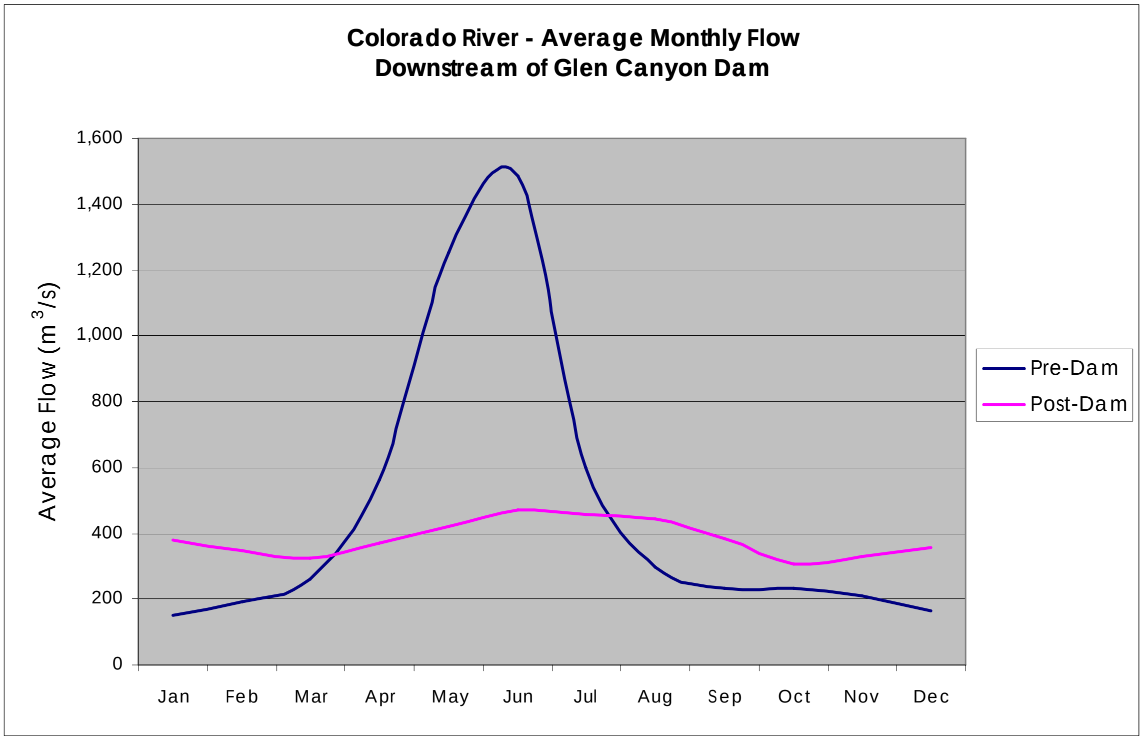

Figure 3 – Average Annual Flow Regime of the Colorado River
Data Source: USGS Gage 09380000

The Glen Canyon Dam not only changed the quantity of water flowing in the river but the quality of water was altered as well. With the dam holding back a large portion of the river's upstream flow volume, the relatively stagnant water in Lake Powell causes a settling of suspended sediments to the bottom of the reservoir. In addition, outflow from the dam is released through turbines positioned near the bottom of the reservoir. The roughly 100 meter depth of water in Lake Powell results in a temperature stratification in the reservoir with the cooler denser water sitting at the bottom. The combined result is the water released from the Glen Canyon Dam is colder and carries much less sediment than the water which flowed through the river prior to dam construction.

The change in water quantity and quality of the Colorado River is causing changes to the downstream river environment as it adjusts to the post-dam flow regime. Flooding conditions had routinely stripped vegetation from the channel banks, rebuilt sandbars and moved fallen boulders out of the river channel. With these high flows no longer occurring, native and exotic vegetation began encroaching onto beaches where it had never been before, segments of the river channel became partially obstructed due to sandy deposits collecting around the immobile boulders and with sandy deposits now occurring in the river channel, there has been a continual erosion of sandy beaches along the banks of the river (Collier et al., 1997). These changes in the river environment have caused shifts in species population as the cooler and clearer river flows have allowed the non-native trout population to flourish and bird and other wildlife populations have found additional habitat in the brush and trees along the river banks. Not all river species populations have increased though, as competition from trout and other non-native fish have caused further decreases in the endangered humpback chub populations (Gloss et al., 2005).

The human opinion of these changes has varied. Stakeholder groups' assessments of the changing river environment are typically dependant on how the changes have affected them specifically. River rafting companies are frustrated with the depletion of sandy beaches which has reduced the number of camping spots along the river making their services more difficult to provide. Fishing companies benefit from the increase in trout population which allows them serve a larger number of customers. Many scientists and naturalists are divided over the dam's effects, with some groups encouraged by the increases in riverine species populations and others discouraged by decreases in native populations as well as the suppression of pre-dam natural river conditions. There is also the perspective of potential users of the natural river environment, who may not be aware of their future association with the region, but whose future benefits from the river's natural processes are affected by what is occurring with the Colorado River today. The Glen Canyon Dam is providing essential services to the region's residential, commercial, and institutional communities, but these services are not coming without a cost to many of the groups which depend on the natural aspects of the river environment for their persistence and benefit.

Restoration Projects

The Adaptive Management Program attempts to achieve a greater balance between the productive and natural processes of the Colorado River by allowing natural resource restoration projects to occur in conjunction with the continuation of productive projects which the Glen Canyon Dam provides. In 1983 following an accelerated spring snowmelt which caused a rapid filling of Lake Powell, the Bureau of Reclamation was forced to open the Glen Canyon Dam's spillways and release flows of 2,750 m^3/s to prevent the Lake Powell reservoir from overfilling. Although the 2,750 m^3/s flow was still smaller than typical pre-dam peak flood flows, the magnitude of the 1983 flow was roughly ten times that of normal dam release rates. After the high flows subsided, one of the changes observed in the downstream river channel was an apparent increase in the size of sand bars along the river banks (Collier et al., 1997). One of the most obvious effects of the regulated flows of the Glen Canyon Dam had been the depletion of sand bars along the river banks. When the Adaptive Management Program was adopted, one of the initial restorative objectives was to attempt to reestablish the eroded sand bars downstream of the Glen Canyon Dam. Recognizing the importance of high flows for sediment transport and deposition, a controlled flood was proposed to rebuild sand bars and provide data needed to model water movement and sediment transport during flood flows (Anderson et al., 1996).

The first controlled flood was released in 1996. Peak flows of approximately 1274 m^3/s were maintained for seven days from March 27th to April 2nd. This flow level is the maximum the dam can release without using its spillways, but was smaller and occurred earlier than the majority of historical pre-dam floods (Patten et al., 2001). The initial results showed stretches of new beach at more than 50 points along the river down the Grand Canyon, promising a redistribution of sediment that would aid in the restoration of fish habitats and improve the quality of rafting and camping within the canyon. However, the experiment was not as successful as had been hoped. Scientists determined that the amount of sediment in the river was insufficient at the time of the flood to allow for durable sandbar formations. The Glen Canyon Dam creates a barrier to sediment transport from the river upstream of the dam which is the major of sediment supply for the Lower Colorado River. The deposits that occurred during the 1996 flood had largely disappeared within a year of the experiment (Schmidt et al., 2001).

Experimental water releases began again in 2004 with several adjustments. To reduce the erosive potential of the flood, the maximum release level was decreased to 1161 m^3/s and the duration of the flood was shortened to 60 hours. A prerequisite of the 2004 flood release was the inflow and partial retention of a minimum of 1,000,000 tonnes of sediment in the river channel from the Paria River, the Colorado's largest tributary upstream of the Grand Canyon (U.S. Department of Interior, 2004). This condition was set to ensure a sufficient supply of sediment for flood flows to rework through the river channel. The sediment conditions were met following the late summer rains in the Paria basin and the 2004 flood was released on November 21st. Just as with the 1996 flood, as waters receded initial observations indicated an increase in beach area, but detailed studies evaluating the overall effectiveness of the 2004 flood are still in progress.

The major shortcoming of the post-dam controlled floods is the limited sediment supply downstream of the Glen Canyon Dam. Figures 4 and 5 display a graphical comparison of the flow level and suspended sediment concentrations of the 1996 and two springtime pre-dam floods which occurred in 1956 and 1961. Although of a similar magnitude, the flood flows of the 1996 post-dam controlled flood was characterized by considerably lower suspended sediment concentrations than the pre-dam flood flows. The reduced suspended sediment concentration means a reduced amount of sand being deposited on the river's banks creating a limitation on the degree of beach restoration which can be accomplished through discrete high flow events.

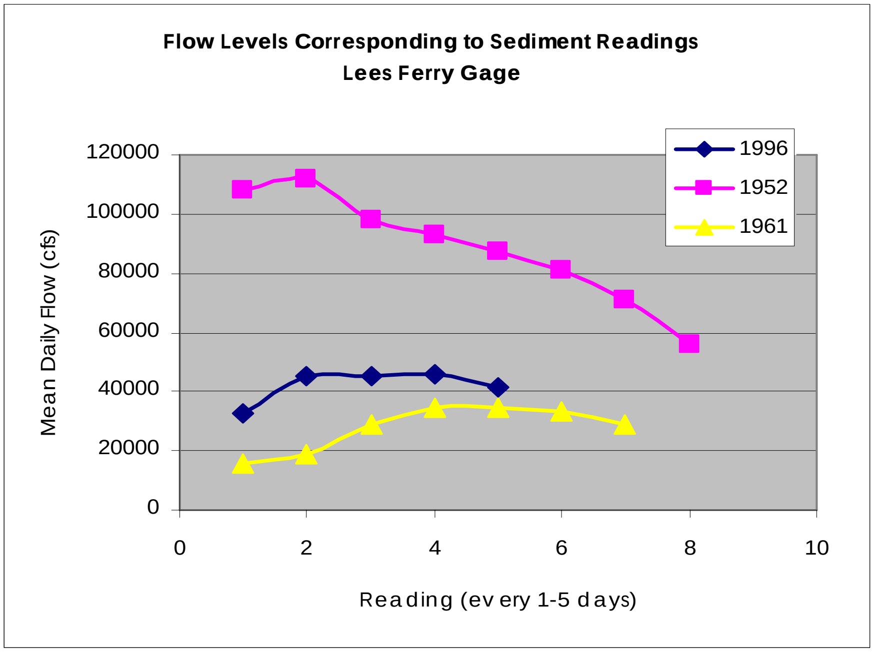

Figure 4 - Historical Flood Flow Levels
Data Source: USGS Gage 09380000

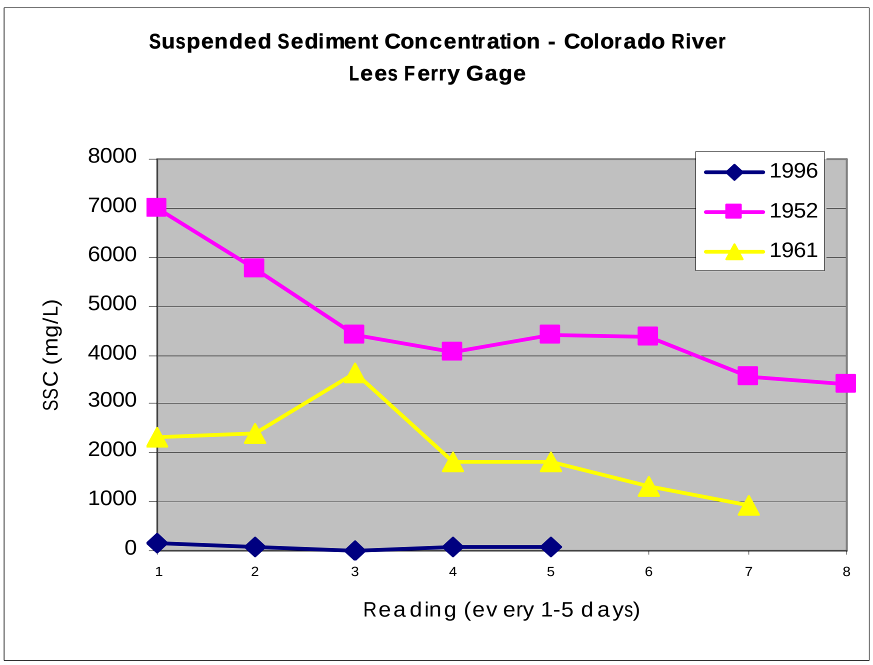

Figure 5 – Historical Flood Suspended Sediment Concentrations
Data Source: USGS Gage 09380000

The experimental floods are categorized by the Bureau of Reclamation as Beach/Habitat Building Flows, which are temporary experimental dam releases. Based on research carried out between 1995 and 2000, other temporary experimental flows have been tested since the year 2000. In the summer of 2000 a low summer steady flow regime was implemented which was characterized by two higher flow releases in the spring and fall and a constant 227 m^3/s release rate maintained from June to August. The main purpose of the low summer steady flow regime was to determine if low sustained flows would cause warming in the water of river channel's backwaters, similar to what would have occurred during a pre-dam flow regime, allowing greater stabilization of native fish and habitat.

In addition to experimenting with flow regimes to aid in native fish and habitat restoration, the Adaptive Management Program has also been exploring the possibility of installing a temperature control device which would allow warmer water to be released downstream of the dam. One of the major issues attributed to the decline in native fish numbers is the constant cooler temperature of water released from the Glen Canyon Dam. Prior to dam construction water temperatures in the Colorado River could vary from close to 0ºC during winter months up to 29ºC during summer months. Once the dam was constructed, the temperature of water released from the dam was fairly constant, usually somewhere between 7 ºC and 10 ºC. As the water flows downstream of the dam it slowly warms but only reaches about 16 ºC, which is still too cool for native warm water fish to reproduce in the river's main stem (Bureau of Reclamation Temperature Control Modification Summary). The temperature control device has been under consideration since 1994 and after several years of design iterations and comments, a smaller scale pilot device will most likely be installed on the dam in the near future to analyze potential effects on the downstream environment.

Normal Glen Canyon Dam operations fall under the modified low fluctuating flow (MLFF) operating regime. The range of flows allowed under MLFF is between 227 m^3/s and 708 m^3/s with the upramp and downramp of release rates limited to 113 $m^3/s/hr$ and 43 $m^3/s/hr$, respectively. The change in release rate is further constrained by a maximum allowable daily fluctuation in release rate of 227 m^3/s per day (Gloss et al., 2005). Under the MLFF the release rates are still aligned with electricity demands but the increased regulation of release volume and adjustment parameters is thought to provide more favorable conditions for the downstream natural environment than the previous less regulated operating regime.

Legal Framework

The MLFF operating regime was the preferred alternative out of several analyzed in the Final Environmental Impact Statement (EIS) published by Grand Canyon Environmental Studies (GCES) in 1995. The various restorative and operational procedures being implemented through the Adaptive Management Program at the Glen Canyon Dam are in accordance with the objectives and recommendations set forth in the EIS and the Grand Canyon Protection Act of 1992. The Grand Canyon Protection Act of 1992 specifies that the Glen Canyon Dam must be operated "..in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established, including, but not limited to natural and cultural resources and visitor use." Because of the complexity of the natural systems downstream of the dam and the lack of established studies characterizing the Colorado River's relationship with the natural systems, the GCES did not have the degree of certainty necessary to propose specific restorative measures in the EIS. Instead, the Adaptive Management Program was recommended.

The expectation is that initiating a program that combines the management of dam operations with research on the effect of dam operations will provide a more well-informed management perspective on the relationships between dam operations and their effects on the downstream environment. In addition, by establishing a management process which provides opportunities for adjustments, the improved management perspective can be used to achieve more effective downstream restoration. What was initially accomplished through the ratification of the Grand Canyon Protection Act and the EIS was the establishment of a preliminary operating regime (MLFF) being managed through a revised process (Adaptive Management) which allows for modifications in operations under consensus of the various stakeholder groups (AMWG) in progress towards enhancement of the downstream environment.

Although the EIS and Grand Canyon Protection Act are the main documents guiding the Adaptive Management Program, they are by no means the only documents influencing operations at the dam. Starting in 1922 with the Colorado River Compact, the utilization of water in the Colorado River has been increasingly regulated by a series of agreements, acts, and treaties. Some of the applicable documents are non-site specific, such as the National Environmental Policy Act and the Endangered Species Act. Although these types of laws can affect how the dam is operated; for instance altering flow in an attempt to protect the endangered humpback chub, they are not written with specific guidance on dam operations. Other regulating documents, like the Upper Colorado River Basin Compact of 1948 which apportioned yearly water volumes amongst the five upper basin states, are directly related to dam operations and specific provisions included in the various laws and agreements must be met through short and long term operations at Glen Canyon Dam. One of the consequences of the established laws and regulations is that modifications to release schedules and volumes are limited by their obligation to meet all associated legal requirements.

Power Generation and Revenue

A significant legal document pertaining to the development of the Colorado River's water resources was the Colorado River Storage Project (CRSP) Act of 1956. This act authorized the construction of the Glen Canyon Dam and provided a water resource development plan for the entire upper basin which included river regulation, power production, as well as several projects for irrigation and other uses (Bureau of Reclamation Law of River Summary). Power generated at the Glen Canyon dam is marketed by the Western Area Power Administration (Western). The CRSP established a power distribution hierarchy where electricity generated at Glen Canyon Dam is first provided to CRSP associated projects and then sold by Western to a preference allocation group made up of roughly 200 wholesale power customers who distribute power to approximately 1.7 million residential, commercial, industrial, and agricultural users. If power generation at the dam exceeds the needs of the preference group, then Western can sell it to other power suppliers, but if power generation is insufficient for the needs of the preference group, then Western must buy additional energy from the open market. Because Western is a federal utility, its rate structure is based on providing the lowest possible rates that still allow sufficient revenue to cover CRSP and other associated projects. In 1999 the Energy Information Administration estimated that Western's average revenue was 42% that of other utility companies operating in the West.

Western's electricity pricing and allocation structure create a somewhat inequitable distribution of benefits amongst the power community. The benefit of cheaper than market priced power is being provided to the preference allocation group who are not required to pass any share along to the buyers they sell to. The Glen Canyon Dam is a federal government owned and operated facility so if it is providing an excess of benefits to anyone it should be to the taxpayers who fund the government and the programs which manage the Glen Canyon Dam not to a select group of wholesale power companies.

Western's power generation revenues from Glen Canyon Dam as well as revenues generated from other facilities in the CRSP are credited to the Upper Colorado River Basin Fund (Basin Fund). These revenues are used for operation, maintenance, and upkeep of CRSP facilities and projects, with excess funds going to each of the Upper Colorado River Basin states. As the federally mandated framework for managing operations at the Glen Canyon Dam, the Adaptive Management Program, similar to other programs managing CRSP facilities, is financed through the Basin Fund. Under adaptive management, restorative measures at the Glen Canyon Dam such as controlled floods and sustained low flows are balanced with power generation and water storage and release requirements established by the CRSP. With different release volumes associated with meeting each objective, compromises in the timing and volume of dam releases are sometimes necessary in the achievement of various operational objectives. Because the amount of power generated at the dam is directly related to the amount of water released from the dam, the additional operational objectives implemented by the Adaptive Management Program have led to increased constraints on the dam's power generating capabilities. A reduction in power generation capability is typically quantified by estimating the reduction in potential power sales. In the case of operations at the Glen Canyon Dam, the reduction in potential hydropower revenue means there is less money going into the Basin Fund, which could potentially impact the Adaptive Management Program's funding if revenues are significantly affected.

Prior to the Adaptive Management Program, releases from the Glen Canyon Dam were oriented towards meeting power demands and CRSP requirements. This production focused release regime meant that there was little consideration given towards the environmental affects of upramping and downramping rates, sustained release volumes, and the seasonal timing of releases. One of the goals of instituting the MLFF was to further regulate dam releases in an attempt to reduce the degradation of the downstream environment caused by the daily fluctuation in flow rates associated with power production. While the MLFF does allow a degree of fluctuation, the reduction in allowable upramp and downramp rates delays the ability of power generation at the Glen Canyon Dam to adjust to meet changing power demands. According to a 1997 Bureau of Reclamation study using a modeled representative water release year and potential revenues based off power pricing at a major power interchange in Phoenix, AZ, the economic cost of using the MLFF operating regime compared to the historical operating regime was approximately $5 million, which translated to a reduction in total yearly hydropower revenue potential of 6.4 percent for the model year (Harpman, 1999). Other restoration oriented modifications in release schedule have similarly associated lost revenue potential. For instance, the cost attributed to the 1996 controlled flood release was roughly $1.8 million because the dam turbines were only able to convey a portion of the high flow released during the controlled flood, which meant the remaining flood flow volume could not be utilized for hydropower generation (Collier et al., 1997).

The Adaptive Management program has not been the only constraint on power generating capabilities at Glen Canyon Dam in the last decade. The onset of drought conditions beginning in 2000 caused the water surface elevation of Lake Powell to fall 41.6 m below full pool elevation by December of 2004. The decrease in Lake Powell's water surface elevation reduced the dam's power generating potential, which is dependant on the volume of water released through the turbines as well as the height of the water above the turbines (Collier et al., 1997). Although hydrologic conditions have improved in more recent years (the water surface elevation of Lake Powell rose 9.4 m during 2005), this incident illustrates the variation in power generation capability that can occur with or without the influence of adaptive management.

To offset the recent reductions in revenue, Western has proposed a rate increase over its current rate of $20.72/MWh to $25.77/MWh, a 24.4% increase. The rate proposal also included a provision for an additional cost recovery charge which can be initiated when revenue shortfalls are projected. This rate plan should further improve the financial future of the Basin Fund, while allowing Western to continue to provide one of the lowest cost sources of electricity in the West (Gloss et al., 2005). The price increase also helps to alleviate the misallocation of hydropower revenues, bringing the benefits back to the operation of the dam, and providing additional financial capability to support restoration programs which attempt to offset the downstream damages incurred by the operation of the Glen Canyon Dam.

One of the limitations of interpreting the cost of restorative releases and regimes as lost potential hydropower revenue is that it assumes that the sole purpose of water in the Colorado River is for generating electricity and water which is not used towards that purpose does not have value or benefit. This is exactly the sort of perception which the Adaptive Management Program was established to change. The water in the Colorado River is a multi-purpose resource and although the economic benefit associated with hydropower needs to be analyzed because it is what sustains the Glen Canyon Dam and the Adaptive Management Program, it cannot provide a complete picture of benefit producing water uses. During the 2004 flood, the Bureau of Reclamation released approximately 0.25 km^3 (202,700 ac-ft) of water from Lake Powell; a substantial volume, but only one third of the 0.75 km^3 (608.1 ac-ft) of water which is lost every year to evaporation and is one of the inherent but unaccounted costs of providing water storage and hydropower at the Glen Canyon Dam. As one of the most well known natural landscapes in the world, the Grand Canyon attracts roughly 5 million visitors per year. Operations at the Glen Canyon Dam have a responsibility towards sustaining the benefits of current and future Grand Canyon visitors and the community which serves them in addition to maintaining hydropower and water supply for surrounding residents.

Results and Future Projects

The Grand Canyon Protection Act requires the Adaptive Management Program to operate Glen Canyon Dam in a way that sustains and improves natural resources downstream of the dam. With certain aspects of the Colorado River's flow conditions impacted by the Glen Canyon Dam, such as upstream sediment contributions, there is limited potential for modifying current sediment supply conditions. Other river conditions downstream of the dam like flow volume, release staging, and water temperature have a much greater potential for adjustment towards more restorative capabilities, however any restorative adjustment must be balanced with the Glen Canyon Dam's existing responsibility of maintaining productive functions and established release requirements.

Sometimes restorative measures can be mutually beneficial to different usage sectors as it was with the Beach/Habitat Building Flows which created additional beach area which could be utilized for rafting stopovers and camping as well as providing additional habitat for the natural riparian species. With other operational adjustments at the dam, cost and benefit tradeoffs between different usage sectors are incurred. When the MLFF regime was implemented the more moderate upramping and downramping constraints reduced potential benefits that could have been derived from hydropower generation with the goal of increasing benefits to the downstream natural environment through a more ecosystem sensitive flow regime that would generate more positive environmental effects. In this case, the lost potential hydropower income is not the driving factor because a modification to the existing dam release regime was made mandatory through the establishment of legislation which required restoration to be part of the dam operation management framework. A more relevant factor is how effective the MLFF regime is at restoring the downstream natural environment and if the additional regulation is actually producing beneficial results downstream of the dam or if the MLFF just limits hydropower without having any positive environmental outcome. In a broad sense, adaptive management is an attempt to achieve an all around more optimal benefit structure within the various usage sectors affected by the Glen Canyon Dam. By continually experimenting with, analyzing, and adjusting operations at the dam, the Adaptive Management Program is attempting to build a base of knowledge so there is a continual improvement of future decisions and strategies.

The various release strategies tested during the 10 year span the Adaptive Management Program has been in place have all been carried out with specific restorative objectives in mind. Beach/Habitat Building Flows were released in an attempt to rebuild degraded beaches and sand bars. Low Summer Steady Flows were sustained to improve spawning conditions for native fish. The MLFF regime was established to provide more favorable conditions to downstream natural systems while still allowing dam operation to meet its production oriented obligations. So far the degree to which these release strategies have allowed the Adaptive Management Program to achieve their objectives has varied. The GCMRC assessed the predicted and actual responses of various usage and resource sectors to adaptive management. Although the complexity of the downstream environment makes definitive conclusions difficult, their assessment found that although some sectors such as sand bars and bird habitat saw minor improvements under adaptive management, many of the river's natural resources such as the native fish, fine sediment, and microvertebrates did not experience improvements and in actuality had little to no response to the modified flow regimes (Gloss et al., 2005). A similarly ambiguous result was found for whether the project increased or decreased total benefits for the stakeholder groups. Usage sectors such as river rafting and fishing saw increased benefits under the steadier, sustained flows of MLFF, but the portion of the benefit increase that can be directly attributed to adaptive management is uncertain. One of the most economically quantifiable effects of the Adaptive Management Program was the loss associated with limitation on hydropower generating capabilities from restoration oriented releases. The measurement of the success of the program will be based on whether the restoration and benefit inducing strategies implemented by the adaptive management process can actually yield tangible improvements for the downstream environment. The collective results from the various studies and analysis have not yet provided a definitive answer.

A distinct advantage of adaptive management over traditional management frameworks is that it allows a degree of flexibility in dam operation procedures. This flexibility provides an opportunity for running experimental flows to determine which flow conditions are the most beneficial and in the long term allows for continual improvement of dam operations. But the complexity of the downstream natural system necessitates extensive and detailed analysis of the experimental flows to determine their effect on the downstream environment and with the host of agencies, scientists, and stakeholders involved, progress can be slow. The major function of the Glen Canyon Dam is as a hydropower and water storage facility not an experimental facility. With the exception of Beach/Habitat Building Flows, the majority of restoration strategies at the Glen Canyon Dam involve slight modifications to existing flow conditions in an attempt to generate a favorable response from the downstream natural system. The response is not instantaneous but is more of a gradual change brought about from a sustained condition. The longer the condition is sustained, the greater the effect, so as the Adaptive Management Program continues with modified flows the more apparent their effect will be.

The GCMRC's 2006 annual work plan indicates a continued focus on the two major downstream deteriorations; the declining humpback chub population and continued beach erosion. Ongoing strategies such as the mechanical removal of nonnative fish and low fluctuating flows are being maintained in an attempt to bolster the humpback chub population in addition to new strategies such as the temperature control device and further flow experimentation to determine the effect of river flow on native and nonnative fish populations. The GCMRC still considers controlled high flow releases to be the key to rebuilding sandy beaches and banks, although no high flow release is scheduled in the next year because the analysis of the November 2004 high flow release is still incomplete. Instead the GCMRC is developing a fine sediment change monitoring system to better understand sediment movement and sand bar accretion and deterioration. The GCMRC will use the monitoring system as well as the results of the analysis of the 2004 high flow to further refine the timing and magnitude of future high flow releases.

Lessons Learned

Adaptive management is a continually evolving program. If there is not yet substantial evidence of an increase in downstream restorative benefits, there is at a minimum the capacity to achieve increased benefits through the Adaptive Management Program. An evaluation of the effectiveness of adaptive management must be done within the context of what the alternatives to the program could have accomplished. The Adaptive Management Program includes a representative group of stakeholders in the management process, the continual analysis of dam operations' influence on downstream resources and the opportunity to revise operations to achieve more effective results. It would be difficult to conceive of the Glen Canyon Dam's previous management structure which involved fewer stakeholders, minimal direct analysis of dam operation impacts, and no specific component for revising operations being able to achieve higher level of downstream benefits over the long term.

The implementation of the Adaptive Management Program is the Secretary of Interior and Bureau of Reclamation's attempt to comply with the Grand Canyon Protection Act of 1992 (Gloss et al., 2005). After several decades of observed deterioration of natural resources downstream of the Glen Canyon Dam, an evaluation of the issue through legislative and scientific analysis processes concluded a change in the established dam operations was necessary to prevent further degradation. The Grand Canyon Protection Act and EIS initiated the Adaptive Management Program not as a direct solution to the problem but as a means to find the solution to the problem. The Colorado River supports a diverse range of natural resources and productive processes which depend upon specific water quality and quantity conditions for their perpetuation and renewal. As a major facility controlling the downstream water quality and quantity, the Glen Canyon Dam has significant influence on the status of the Colorado River's natural resources and productive processes. With the Grand Canyon Protection Act, congress delineated the dam operation's scope of responsibility to include the maintaining and improving the status of downstream natural resources. The Adaptive Management Program allows the management of operations at the Glen Canyon Dam to incorporate this responsibility in tandem with generating the productive benefits such as hydropower and water supply which it was designed for. Utilizing water resources for productive processes and maintaining natural resources should not be conflicting or exclusive objectives. If carried out effectively the Adaptive Management Program has the potential to optimize natural and productive sector benefits and sustain production and natural preservation for the future.

Lessons that can be learned from this case study include:

- The impact of a dam's operating regime on various water resources usage sectors and the relationship between changes in dam operations and changes in usage sector benefits
- The power of governmental legislation to influence and regulate the management and operation of large scale water resource projects

- The importance of employing a management framework that has the capability to balance the needs of all affected sectors in the management large scale and long term projects
- The necessity to associate management of dam operations with potential benefits and costs related to all usage sectors, even sectors where benefits and costs are not directly measurable
- The opportunity for effectively integrating typically opposing dam operational strategies like power generation and environmental restoration under the guidance of a representative and balanced management work group

Section 3 – Case Study of The Green River Dam

Background

The Green River runs for roughly 300 miles through mostly agricultural and forested regions of Central Kentucky, draining a tributary area of approximately 24,000 km^2 and ultimately flowing into the Ohio River near Evansville, Indiana at the Kentucky, Indiana border. The river is known as one of the most species rich river systems in the United States and supports 151 species of fishes and 71 species of mussels, some of which are unique to the river system (Nature Conservancy, 2006). This diversity is further enhanced by the Mammoth Cave complex, a large limestone cave network containing approximately 200 species which live in the underground caverns and whose water source is supplied by the Green River. Figure 6 displays a map of the Upper Green River Basin.

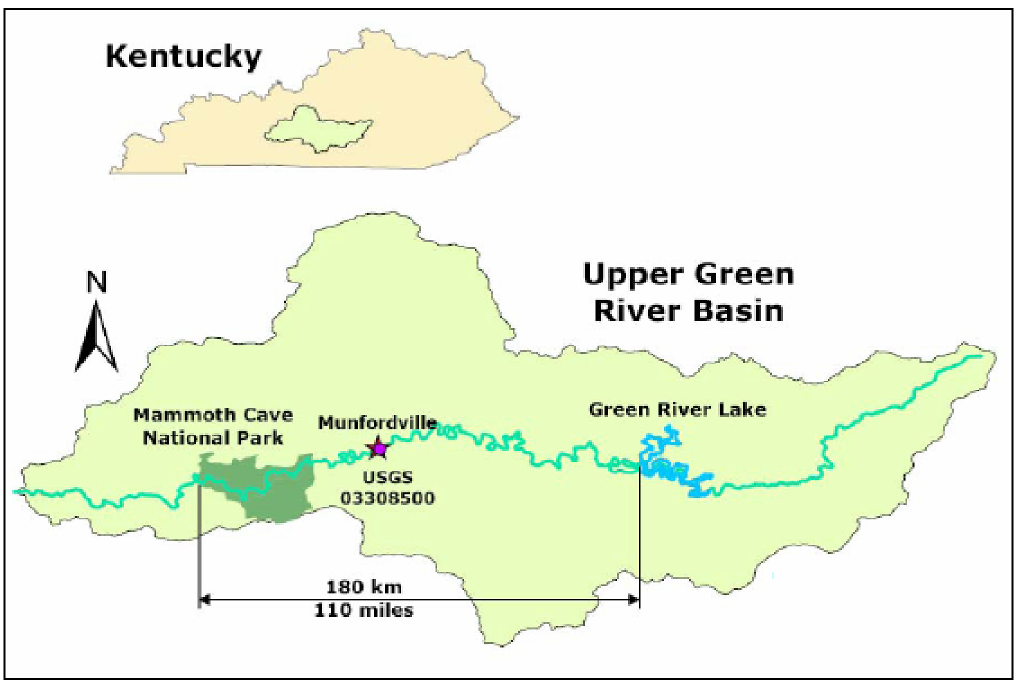

Figure 6 - Map of Upper Green River Basin

In 1906, continuing their project to provide further navigation upstream, the United States Army Corps of Engineers (USACE) built Lock and Dam 6 just downstream of Mammoth Cave, which reduced the natural free flowing habitat found in the cave environment by raising water levels in some portions of the Mammoth Cave Complex by as much as 4 meters (Postel and Richter, 2003). River flows upstream of Mammoth Cave were further affected by the construction of the Green River Dam, a USACE owned and operated structure located approximately 180 km (110 miles) upstream from and the cave features.

Construction of the Green River Dam was authorized under the Flood Control Act of 1938, but construction did not begin until April 1964 after a severe flood in 1962 caused extensive damages in the region. The Green River Dam was completed in June 1969 at cost of $33.4 million. During the course of its operation the USACE estimates the dam has prevented more than $109.2 million in flood damages and in 2004 the benefits derived from public recreation at Green River Lake were assessed by the USACE to be approximately $33 million. The primary function of the Green River Dam is for flood control, which serves the dual purpose of regulating flood waters on the local scale within the Green River Watershed and a more regional scale as a strategy to diminish tributary flood flows to the Ohio and ultimately the Mississippi Rivers. The other function the Green River Dam plays is forming a recreational resource of Green River Lake which is used for boating, fishing, and other lake related activities.

Historical Operation

The Green River Dam is a 43 meter (141 foot) tall earthen structure which restricts upstream flow of the Green River to form Green River Lake, a narrow and sinuous reservoir with roughly 33.2 million square meters (8210 acres) of surface area during summer months. Outflow from Green River Lake is through a 5 meter (16.4 foot) diameter concrete pipe located at the base of the dam structure and is controlled by the USACE. During summer months, the USACE maintains the Green River Lake's water surface at 675 feet, an elevation which was set through an agreement with shoreline recreation proprietors. In the fall, in preparation for probable high precipitation events and subsequent high tributary flow levels during winter months, the USACE lowers the lake level by roughly 3 meters (11 feet) to 664 feet to create additional storage volume for diminishing peak flood flows.

Effect on Natural Resources

During most of the year, to maintain a constant water surface elevation, releases from the Green River Dam are equivalent to upstream flows entering the reservoir, which essentially mimics the natural flow regime of the river. However, during the transition between summer and winter lake elevations, the USACE alters release rates to reach established seasonal water surface elevations in a relatively short time frame. In the fall the draw-down transition between the high summer water surface elevation and the lower winter water surface is accomplished over a ten week period usually during October and November.

The result of this release level was the river channel downstream of the Green River Dam experienced consistently higher October and November flow levels than were typical prior to dam construction. This pattern of high flow is illustrated in Figure 7. The average flow levels in October and November at the USGS at Munfordville, KY gage (USGS 03308500) are 36 m^3/s (1279 ft^3/s) and 68 m^3/s (2397 ft^3/s) following dam construction and 12 m^3/s (412 ft^3/s) 43 m^3/s (1502 ft^3/s) prior to dam construction. Higher flow levels during a season typically defined by lower flows is believed to flush small fish and mussel populations downstream, reducing an important food source for larger river species. In addition to higher flow levels, the depth of the dam's outlet pipe means the source of flow downstream of the dam is the deeper, cooler water from the reservoir. The combination of higher flows and lower water temperatures downstream of the dam are believed to interrupt the seasonal breeding cycle of some fish and mussel species by eliminating the flow conditions the species require for reproduction which further diminishes river species populations (DePhillip, 2003).

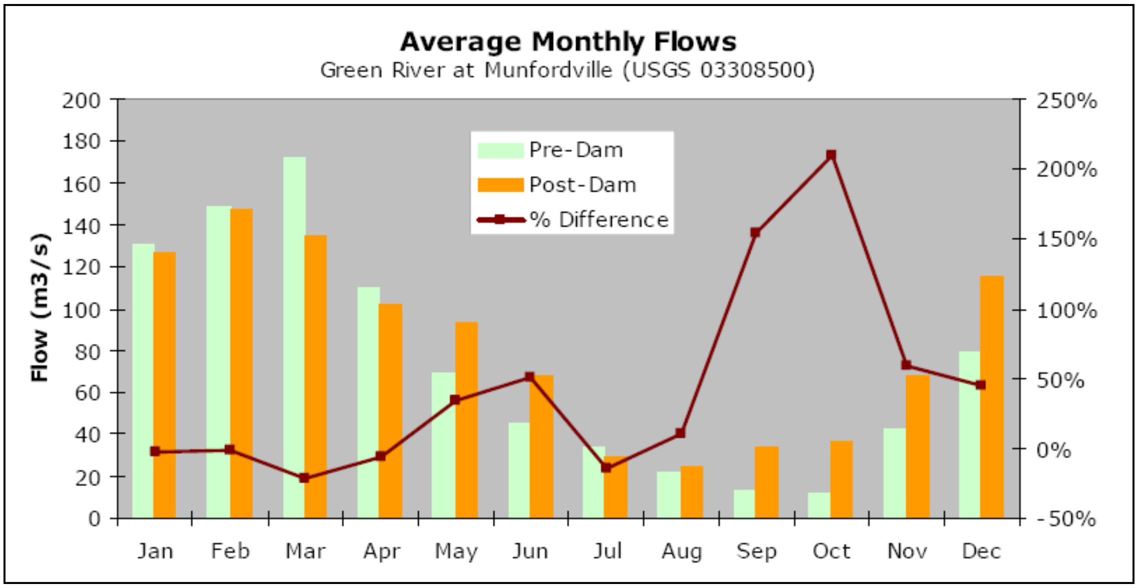

Figure 7 - Pre and Post-Dam Average Monthly Flows and % Difference Trend Data Source: USGS Gage 03308500

A similar process occurs in the spring, when the USACE raises the water surface elevation from its lower winter level to the higher recreation oriented summer elevation. The lake level increase was typically carried out over a four week time frame, with the USACE reducing the release volume to a minimal level until Green River Lake reached its summer water surface elevation. Although this action was a definite modification to the pre-dam springtime flow regime, scientific studies did not indicate the detrimental effects noted during the fall transition period possibly because it is not as much of a deviation from characteristic seasonal flows as during fall season draw-down flows (Postel and Richter, 2003).

Initiation of Restoration

In 2000, the USACE was preparing a proposal to remove Lock and Dam 6, the structure which had sustained higher water levels in Mammoth Cave and one they believed was responsible for much of the species loss occurring in the Green River. The structure had not been used for navigation since 1965, so besides the cost of removal, would not impair the use of the river. At the same time the Nature Conservancy, an international non-profit organization established in 1951 and focused on protecting natural community diversity through land conservation, was conducting their own analysis of the Green River system and concluded that although the removal of Lock and Dam 6 would improve conditions for the river and cave environment, a more significant environmental problem was being created by the operation of the Green River Dam. Specifically, the Nature Conservancy was concerned over the uncharacteristically high flows released in October and November when the USACE was drawing down the Green River Lake reservoir to its winter water surface elevation.

The Nature Conservancy's initial action was to set up a meeting with the USACE's Lousiville District office in June of 2000 to inform the USACE of the probable relationship between Green River Dam operations and downstream environmental impacts and determine if the USACE was receptive to modifying dam operations. The USACE operates the Green River Dam with the purpose of sustaining two objectives, flood control and providing recreational opportunities. The USACE's objectives are essentially based on the water surface elevation of Green River Lake; the high summer elevation provides a larger surface area with marina type facilities situated to operate at that water surface elevation and the low winter elevation provides a substantial storage volume for reducing flood severity. Whereas the Nature Conservancy's restorative objectives are based on modifying the Green River Dam's release rates to more closely mimic pre-dam flow volumes. Although the USACE's and the Nature Conservancy's objectives are related, they are not in opposition or competition with each other and the potential exists for them to be carried out simultaneously. The summer and winter water surface elevation's are not dependent on a specific release rate but rather the volume of water retained or released, so there is a degree of flexibility in the Green River Dam's release rate which is only limited by the USACE's responsibility to reach summer and winter lake levels in a sufficient time frame.

The USACE was receptive to the possibility of improving downstream flow conditions and started working with the Nature Conservancy to devise a revised operation regime that was more ecologically compatible. In years previous, through a series of revisions to Water Resources Development Act, Executive Order 13352, and other site specific governmental legislation, the USACE had been authorized to seek and develop partnerships for proposed and ongoing water resource management, development, and restoration projects. These regulatory permissions allow the USACE to collaborate with outside governmental and non-governmental organizations which have the potential to positively influence projects by enhancing the scope of project resources and directly including local stakeholder priorities into the process. In the case of the Green River, the USACE's partnership with the Nature Conservancy allowed them access to a source of technical expertise, stakeholder perspectives and certain cost sharing opportunities that would not have been available had they continued to manage the Green River system alone.

Previously, the Green River Dam had been operated by the USACE to transition between summer and winter lake levels as quickly as possible because their management plan placed priority on attaining the specified reservoir water surface elevation. By proposing a more environmentally beneficial operation strategy, the Nature Conservancy was expanding the USACE's management perspective to include additional components not considered under prior dam operation management. Including downstream ecosystem health into the operation of Green River Dam meant that the USACE would no longer establish the dam's release rates only as a means to maintain specified lake levels and control floods but would have the added responsibility, shared with the Nature Conservancy, of providing release rates that would sustain and potentially improve the health of the downstream natural river environment.

Components of Restoration

Discussions between the USACE and the Nature Conservancy yielded several opportunities for modifying dam operations. The persistence of downstream environmental issues had been associated with the release rates implemented during seasonal lake level transition periods. The major components of the proposed dam re-operation would be to reduce the scale of transition between summer and winter season reservoir water surface levels and expand the timing and duration of the transition period to produce more "seasonal" flows. The USACE and the Nature Conservancy initiated the following modifications to existing operations of the Green River Dam:

- Raise winter water surface elevation from 664′ to 668′ (summer elevation remains 675′)
- Shift summer to winter lake draw down from October to November (during onset of rainy season, after lake de-stratification)
- Extend winter to summer lake fill up period to from March through April to March through May.
- Modify release rates to coincide with storm events
- Increase maximum allowable release rate during non-crop season from 176 m^3/s (6200 ft^3/s) to 227 m^3/s (8000 ft^3/s)
- Increase maximum allowable release rate during crop season from 125 m^3/s (4400 ft^3/s) to 150 m^3/s (5300 ft^3/s)
- Increase maximum flood release rate during non-crop season from 9 m^3/s (300 ft^3/s) to 28 m^3/s (100 ft^3/s) after flood peak

Initial Results

The Green River Dam's revised release schedule incorporated a more environmentally beneficial flow regime into the ongoing flood control and recreation oriented dam operation program. Under historical operation, the USACE had a larger winter flood storage volume in Green River Lake but was limited in the release of stored water to flows that were less than characteristic pre-dam seasonal flows. By modifying release rate guidelines, a greater capacity for flood storage was created because following floods, occupied storage volume could be dissipated more quickly using higher release rates. This allowed the USACE to raise the winter water surface elevation by 1.2 m (4 ft) and still provide the same level of flood control as previous operation procedures.

Combined with the extension of the reservoir's filling and draining time frame, the higher winter lake level allowed the USACE to transition between lake levels more gradually, lessening the degree of control needed over transitional release rates, and allowing more natural downstream flows. With an increased range of release rates, the USACE can more closely mimic the typical flows of the pre-dam river by timing larger releases to coincide with actual precipitation driven high flow events which ultimately creates more favorable conditions for downstream ecosystems. The shifted reservoir draw down schedule also pushed the higher release rates to a time where much of the release would occur after lake de-stratification (the turnover and mixing of the lake's depth separated temperature regions) which meant that the temperature difference between released flows and natural tributary flows would be less.

The monitoring of downstream natural systems is a necessary component for most restoration projects. The analysis of data acquired from the monitoring process provides the measurements over which the project will be judged as a success of failure. Concurrent with the Green River Dam re-operation, scientists from the Nature Conservancy enacted a monitoring program to gauge the response the response of the Green River system to the revised management program. Some of the initial improvements noted by the Nature Conservancy are:

- Improved Green River Lake water quality (lower spring chlorophyll levels)
- Improved magnitude of fall downstream flows and water temperatures
- Improved reproduction of fall breeding aquatic species

Effect of Re-operation on Recreation and Flood Control

The re-operation of Green River Dam has been implemented with minimal increases in operation costs and no reduction in the recreation and flood control benefits provided under the previous operation program. The USACE has even cited certain recreational sectors experiencing improvements with increased fish and bird habitat providing a positive influence on fishing and hunting activities and the additional benefits associated with an extended recreation season. The re-operated release rates involve a more complex release schedule so the personnel time required to manage the program is greater than it was previously. The initial process of collaboration between the Nature Conservancy and the USACE was not without its inefficiencies either, as the two differently structured and intentioned organizations had to establish an efficient and defined working relationship before starting the actual restoration efforts. Neither of these issues provided a significant enough barrier or cost to diminish the positive impacts of the collaboration though. In fact, the USACE found the initial collaboration between the two organizations so successful that it has expanded its involvement with the Nature Conservancy to other projects around the country.

Looking Towards Future Management

At the end of 2000 the USACE signed a Memorandum of Understanding (MOU) with the Nature Conservancy to improve water management on various U.S. Rivers. A selection of specific objectives from the MOU include:

- Protect or restore freshwater and coastal habitats for native animals and plants and natural communities;
- Promote non-structural flood protection and other measures to maintain natural ecosystem functions at sustainable levels;
- Encourage water management measures that benefit native animals and plants and natural communities while meeting human needs:

The MOU objectives listed above are in close alignment with the specific objectives of the Green River project. The partnership defined in the MOU has been advanced and defined even further through the Sustainable Rivers Project, an agreement signed by the Nature Conservancy and the USACE in 2002. The Sustainable Rivers Project involves a similar process of review and alteration of USACE dam operations to what was carried out at the Green River Dam and currently includes thirteen candidate sites on nine rivers around the U.S. The influence of this collaborative project can be traced further through the USACE organization as well. In the USACE Civil Works Program Strategic Plan for fiscal years 2003-2008, the USACE cites their partnership with the Nature Conservancy as the basis for one of the plan's initiatives to "seek partnerships to promote integrated environmental management."

The influence of the Green River Dam re-operation project has helped the Nature Conservancy bolster and synergize additional conservation and restoration efforts on the Green River to create what they are calling the Green River Bioreserve. The Biorserve area includes roughly 1,350 square miles and extends along roughly 180 km (110 miles) of the Green River from the Green River Dam to just below Mammoth Cave National Park. The Nature Conservancy has procured involvement from the U.S. Department of Agriculture, the U.S. Environmental Protection Agency, and several academic institutions and community groups. Project initiatives outside of re-operation strategies include reducing riparian sedimentation and agricultural runoff, addressing environmentally incompatible rural development, and a conservation buyer program which identifies biologically significant lands at risk for development and assists participating buyers to purchase land and locate permanent conservation easements on the property. River networks are complex, interrelated systems where impacts occurring in one portion of a rivers watershed can propagate through numerous locations throughout the river system. By establishing a more watershed and process comprehensive conservation and restoration program, the Nature Conservancy is attempting to provide measures which protect the entire natural system, a strategy that should be more effective than typical site specific protection which is open to exterior environmental impacts.

Lessons Learned

Prior to the Nature Conservancy's involvement, the USACE had a range of flexibility in their operation of the Green River Dam, but had no specific reason to alter established operations until collaboration with the Nature Conservancy provided justification to do so. Once given the opportunity to collaborate the USACE was a willing participant in expanding their management responsibilities at the Green River Dam and in projects beyond to include environmental restoration and protection as a part of their management purpose. The partnership between the Nature Conservancy and the USACE has provided both organizations with management, restoration, and protection capabilities in excess of what would have been possible under independent projects. The overall result of the Green River Dam re-operation project is water resource management that continues to provide the societal benefits which it was designed for in addition to increasing environmental benefits derived under the revised management program. Lessons that can be learned from this case study include:

- The benefit of more "naturally" oriented flows on the downstream natural environment
- The potential for improvement through collaboration between owner/operators and stakeholder representative organizations
- The ability of specific operation strategies to accomplish more than one objective simultaneously
- The need to continually assess the effectiveness of dam and water resource management programs to ensure operation is at optimal conditions
- The scale of impact small re-operation and restoration projects can have on the larger field of water resources systems planning management

Section 4 – Model for Re-operation Restoration Potential

The Glen Canyon Dam and Green River Dam case studies provide specific examples of the complex relationships between natural, productive, managerial, legal, cultural, and political systems that surround large dam projects. Although the management of a dam can be a complicated endeavor; at its most basic level of function a dam simply regulates the quantity of water flowing downstream. Whether the objective is to limit the amount of flow for flood control, maintain a consistent level of flow for downstream water supply, or correlate the flow to power generation demands, depends on the physical characteristics of the river system and the needs of the community which surrounds it.

Building a dam establishes an instream storage facility which severs the connection between the flow upstream and the flow downstream of the dam. A discontinuity in the flow conditions along the course of the waterway alters physical characteristics of the water which are shaped by the magnitude of flow in the river. Suspended sediment concentration, temperature, nutrient levels, chemical composition, and dissolved oxygen concentration are some examples of water quality attributes which are altered by regulating water quantity. Pre-established water quality and water quality conditions enable the development and maintenance of the downstream natural river environment. What this suggests is that restoring the natural environment downstream of a large dam project is to a degree, dependent on re-establishing some of the water quantity and quality characteristics that supported the natural systems prior to dam construction. In general then, the potential for downstream natural system restoration is defined by the degree to which critical downstream pre-dam water quantity and water quality conditions can created. This scenario is represented by the water quantity and water quality models presented in Figures 8 and 9.

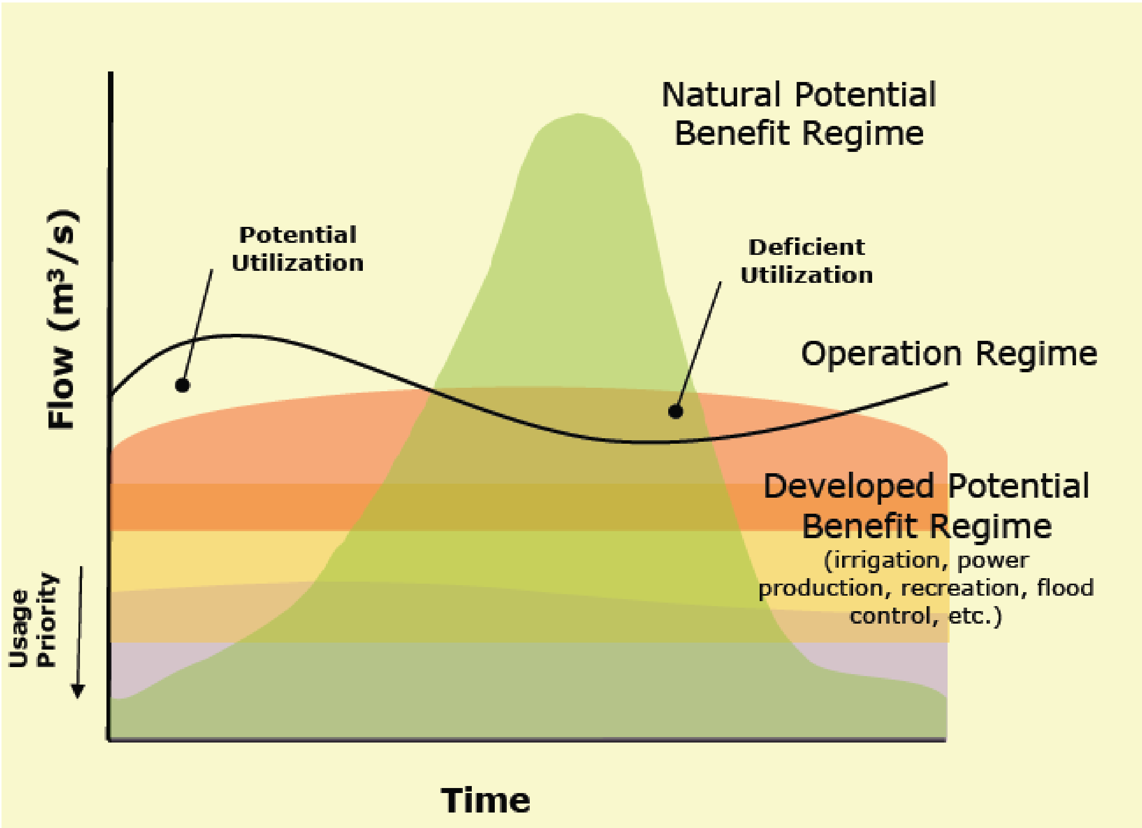

Figure 8 - Water Quantity Model

Figure 8 shows a theoretical model of the potential benefit sectors associated with the quantity of flow released from a dam. Some of the benefits associated with the volume of water released from the dam overlap, such as how water released for hydropower generation has the potential to be used for irrigation in addition to providing a flow level which sustains the downstream natural environment. The natural potential benefit regime assumes that the downstream natural system has a specific flow regime to which it responds positively. Likewise, the developed potential benefit regime has specific levels of flow associated with it that allow the most productive generation of benefits. In reality though, there is the actual amount of water being released by the dam; represented by the operation regime and defined by hydrologic conditions and release requirements. The degree of downstream restoration attainable is limited by the similarity between the natural and developed benefit regime and the potential utilization volume available to provide or withhold from the downstream natural systems. A highly developed river system such as the Colorado River, where water volumes are already over-allocated to downstream usage sectors will have less restoration potential than a river system such as the Green River, where there exists a greater flexibility in the release schedule because of more limited and less constricted utilization.

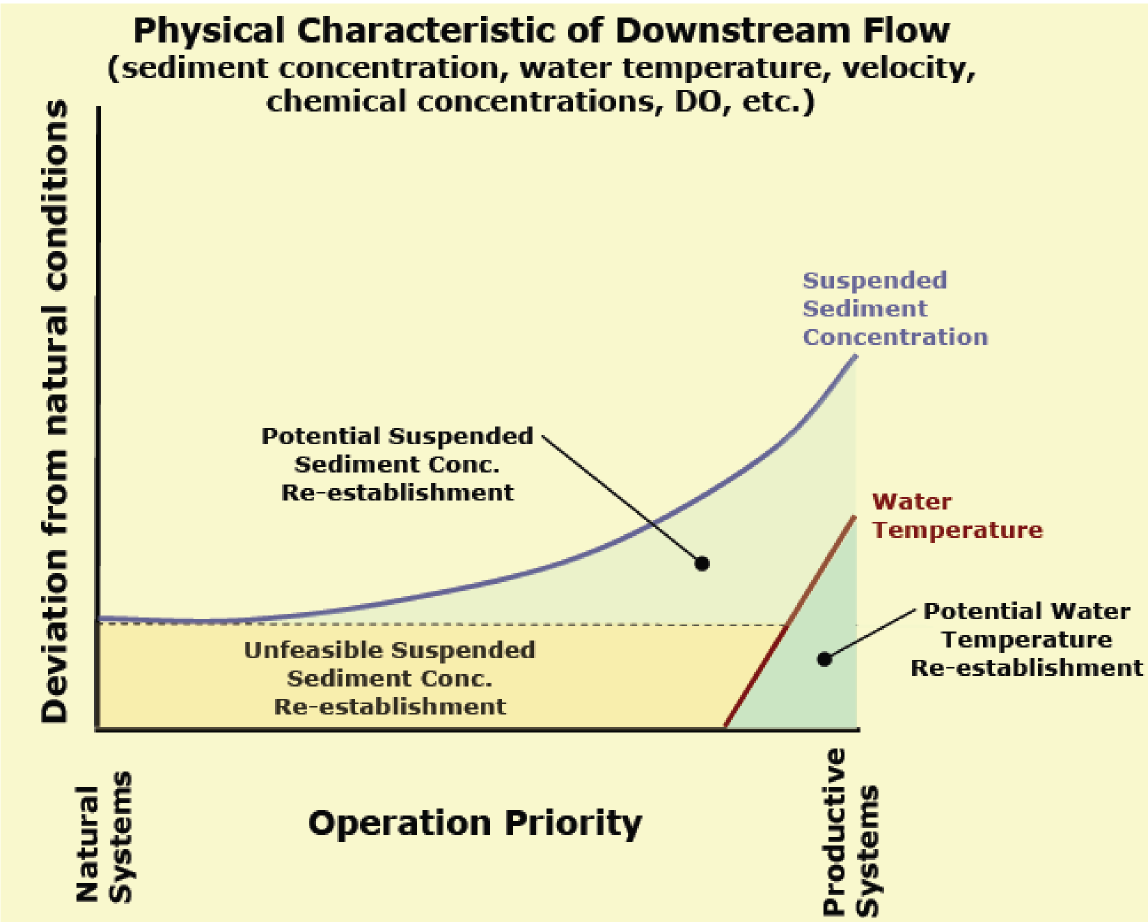

Figure 9 - Water Quality Model

The potential for water quality restoration is similarly defined. Figure 9 displays a theoretical model of the water quality characteristics downstream of a dam. Although certainly variable prior to dam construction, the water quality model assumes that as dam operation becomes more focused providing releases for productive systems, the water quality characteristics that were defined by the natural flow regime deviate further from their pre-dam range. By revising dam operations to include specific flows significant to downstream natural systems, certain water quality characteristics can be restored. However, the upstream and downstream decoupling caused by the dam structure and its scale of impact on the downstream flow can limit the restoration to a certain level no matter how closely the releases mimic natural flow conditions. This issue is demonstrated at the Glen Canyon Dam by the limitation of sediment supply created by storage in Lake Powell which prevents downstream releases from attaining suspended sediment concentrations measured prior to dam construction. In the case of water temperature though, the installation of a temperature control device, could allow the water released from Glen Canyon Dam to more closely replicate pre-dam water temperature conditions.

Re-operation is not specifically characterized by the re-establishment of downstream flow conditions. In reality, the re-operation process is a balancing act, attempting to achieve an optimization of downstream systems to obtain the maximum amount of benefits through equitable distribution. Whether re-operation is initiated through an explicit modification of dam operations or an ongoing series of experimental and analytical procedures depends on the complexity and diversity of the affected natural and societal systems. In either case, although quantifying the actual benefits and improvements achieved under re-operation is complicated, it would be difficult to conceive of a dam management system which only considers a portion of the communities affected by the operation of the dam being able to sustain a greater effectiveness than a re-operated approach which attempts to provide a more comprehensive and realistic view of the possibilities and limitations and benefits and costs of dam operations.

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