Contributing Paper

Managing for Unforeseen Consequences of Large Dam Operations

Peter Goodwin; Michael Falte
University of Idaho, USA
A.D.K. Betts
University of California, USA

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World Commission on Dams
5th Floor, Hycastle House
58 Loop Street
PO Box 16002
Vlaeberg, Cape Town
8018, SOUTH AFRICA
Telephone: +27 21 426 4000
Fax: +27 21 426 0036
Email: info@dams.org
http://www.dams.org

Summary

Large dams have provided extensive benefits during the past 60 years: for example, fueling the powerful economy in the Western United States through cheap power, irrigation and municipal water supplies. There has also been a dark side of these massive civil works projects that were not fully comprehended during the early project planning process. This is not surprising since ecosystem response and physical processes at the basin scale are immensely complex and could not have been fully anticipated with the state of science in the 1930s and 40s. The implementation and management of large dams is still a relatively new science, compared to the time frame necessary to detect and understand some negative impacts occurring at the watershed scale. This paper attempts to summarize the unforeseen or unanticipated environmental consequences of these projects, as well as potential ramifications to the overall performance of the project. One of the important management concerns is to ensure that there is a viable decommissioning strategy for the dam at the end of its design life, and including this cost in the life cycle cost-benefit analysis.

The value of a central knowledge base, checklist of potential environmental effects, and potential consequences of altering operational rules is presented. The role of new technologies to develop real time flood forecasting systems and monitoring programs to ensure the project performs according to the design expectations is outlined. These new technologies can facilitate an adaptive management strategy capable of anticipating any unexpected outcomes and adjusting the operation rules of the reservoir to minimize any adverse impacts.

1. Introduction

The desire and ability to impound water by different civilizations dates back many millennia. Some of the early cities in Mesopotamia, Pakistan and China were termed 'hydraulic civilizations' and were probably formed specifically to organize the large labor necessary to construct canals and flood embankments (Wittfogel, 1957;Pearce, 1992). One of the first known dams was near Memphis City in the Nile Valley. This structure was 15m high and 450m long, with a composite structure comprising a rock fill core and clay blanket on the upstream side. Frequently these dams were constructed in difficult conditions by skilled artisans, whose work is still visible many centuries later. For example the complex system of weirs, dams, reservoirs and channels constructed in about 3000 BC in the town of Jawa in what is now Jordan (McCully, 1996).

These early structures allowed civilizations to flourish, allowing powerful communities to emerge that were prosperous, well-nourished and provided an infrastructure and order to the community life. Many of these structures undoubtedly influenced local ecosystems and agricultural practices, but the scale of the projects were relatively small and ecological impacts to entire river basins were probably relatively insignificant. The last 70 years have seen a remarkable change in dam technology, with the advent of large dams. Few feats of engineering have exerted such a profound influence on the landscape, the ecosystem and the quality of life for people living in catchments of these large dams. These dams were designed and technology developed in an era that is perhaps typified by the mission of the Institution of Civil Engineers, one of the most respected and august bodies of professional engineers in the world:

A Society for the general advancement of Mechanical Science and more particularly for promoting the acquisition of that species of knowledge which constitutes the profession of a Civil Engineer, being the art of directing the great sources of power in Nature for the use and convenience of Man.

At this time the emphasis was on the exploitation of resources for the economic development of regions and the age of the large dam began with the construction of Hoover Dam in 1931. This structure contains over 60 million tonnes of concrete, and outweighed the sum of the previous 50 concrete dams constructed by the US Bureau of Reclamation. At a height of 221 meters, it was 87 meters higher than any other dam in the world at the time. By 1990, the number of large dams (with a height from foundation to crest that exceeds 15m) around the world had increased to more than 40,000 (McCully, 1996; ICOLD, 1988). Similarly, the number of major dams – having a height greater than 150m, or volume greater than 15 million cubic meters, or reservoir storage greater than 25 cubic kilometers, or generation capacity exceeding 1,000 megawatts has grown to more than 300.

These dams have provided many benefits such as a cheap source of power, irrigation water, flood hazard reduction, navigation, all of which provided economic benefits. Despite all these benefits, large dam technology has come under increasing scrutiny during the past decade. The primary questions that have arisen are:

- Are the benefits predicted during the original design really achieved?
- Is the dam and reservoir system managed in the way that the original designers intended?
- Are there consequences resulting in the dam implementation and operation that were not foreseen by the original designers?
- Are damages to the ecosystem, particularly related to specific species being pushed toward extinction, really worth the benefits?
- Are the forced changes to the way of life of indigenous people worth the benefits?
- Are the lessons learned from earlier large dam design being systematically included in the design of new projects?
- Are the lessons learned in North America, Europe, Japan and Australasia being considered and incorporated into the designs and operational rules of new projects in developing countries – particularly related to long-term environmental consequences.

The latter four issues are compounded by the paradigm shift in public perception and values associated with environmental issues. These changing values are gradually being reflected in governmental agencies in many countries. This is also reflected in the substantial private donations from foundations, charities and public interest groups in North America, Australasia, Japan and Europe to provide support to local communities and to protect key ecological areas in developing countries. The intent of this funding is to try and avoid some of the mistakes or unforeseen consequences made in the design of large dams observed in the developed countries. Few new large dams are likely to be constructed in the "developed" countries and emphasis is being placed on quantifying effects of existing dams, and operating the dams in a way to minimize potential adverse impacts (Collier et al, 1996). In the "developing" countries, where abundant locations for potential large dams still exist, the emphasis is on understanding the river system and attempting to design the projects to avoid many of the negative consequences experienced in earlier projects.

2. Unforeseen Environmental Issues

The benefits of large dams in the early stages were relatively easy to quantify. Hydropower, irrigation and flood storage were approached as primarily a mass balance analysis related to timing and delivery of water. The downside of these projects, when acknowledged, was approached from the perspective that any problem had an engineering 'fix'. Of course, hindsight is 20/20 and it is easy to critique this naïve approach of the original designs or approaches to resolve complex environmental issues. Research during the past two decades is just beginning to reveal the true complexities and linkages of watershed ecosystems.

2.1 Downstream Effects

The downstream effects of dams on sediment transport and geomorphic changes have been recognized and anticipated for several decades (for example, Simons and Senturk, 1977). Typical responses include the reduction in channel bed slope downstream of the dam and degradation of the river channel. These tendencies can influence downstream infrastructure such as bridges, leaving diversion intakes at wrong elevations or loss of filtering capability on water supply systems such as sub-surface Raney collectors. An example of major infrastructure impacts include the replacement of the Esna Barrage and new navigation locks at Naga Hammadi barrage as the result of a reduction in channel elevations and water levels on the River Nile as a result of the High Aswan Dam (Gasser, 1996). More subtle channel changes are the subject of another WCD White Paper and can result in processes such as the coarsening of the bed substrate (which may result in the loss of fish spawning habitat, or the loss of rearing or refuge areas. Reduction in the peak flows and alteration of the flood hydrograph may stabilize bedforms due to insufficient peak flows to disturb the bed or established vegetation. In heavily developed areas, operational rules may require that the reservoir releases be held at bankfull flow for long periods of time, compared with a natural runoff event. An example is the Russian River in Northern California where the river is run at bankfull discharge for many weeks, instead of the normal few days in an unregulated system (Florsheim and Goodwin, 1995). The extended period of bank inundation results in the loss of soil strength in the banks and accelerated bank erosion.

Downstream impacts can be generated by structural failure of gates of parts of structures. These structures are designed to withstand extreme events, but the scale of the projects are beyond the standard design manuals available in hydraulic engineering. The scour and repair problems created at Tarbela and other dams during the operation of spillways have illustrated the importance of scale and the importance of learning from similar projects (Lowe et al., 1979; Tesaker, 1992). Secondly, there will always be a flood larger than the design flood that can occur within the river system, even though statistically the chances are very small. These failures are not pose a threat to life, but can create extensive property and ecological damage (Lemperiere, 1993).

Less obvious effects include the development of mature vegetation throughout the channel that lacks diversity in age and species (Florsheim et al., 1993; Wirth, 1997; Schmidt et al., 1998;USBR, 1994). This uniform habitat may be detrimental to the overall ecosystem because different species may use plants at different stages of growth. When the vegetation is finally scoured in a major event, the extensive loss may leave a scarred system more susceptible to the invasion of non-indigenous plant species.

Other effects occur on such a large scale that it is difficult to comprehend and differentiate from other watershed processes. White (1988) and Pearce (1994) provide comprehensive overviews of downstream consequences of the High Aswan dam. Another large-scale example is the Parana Basin (Bonnetto et al., 1989), where 23 large HEP projects are either planned or have been constructed. Some of the basin scale impacts are:

1. The retention of suspended solids in the reservoirs have reduced the levels of phosphorous in downstream reaches. This process has been compounded by the increase in nitrogen levels

due to more intensive agricultural practices, and this has resulted in an increase in algal blooms at certain times of the year.

2. Perhaps the most significant ecological change has resulted from the alteration to the hydroperiod on downstream floodplains. Alevines and small migratory fish have historically used the extensive floodplains of the Parana River as rearing habitat. In addition, the lower reaches of the ecosystem had been reliant on the delivery of organic material and plankton from floodplain areas. The reduced inundation and the separation of floodplains from the river is creating major adjustments to the ecosystem.

The spillway and gate structures on a dam can introduce water quality problems associated with total dissolved gases. The aeration of flows as it passes over control structures has been studied extensively, but most analyses terminated in the plunge pool. The increase in TDG to up to 120% of saturation can stress biota and in extreme cases can be lethal to fish (refer to Weitkamp and Katz (1980) for an early review of the problem. More recent studies have shown that these elevated levels of TDG is not confined to the local reach downstream, but significant levels can be detected hundreds of kilometers downstream, before natural de-aeration processes allow normal levels to be achieved again. This topic is the subject of extensive current studies in the Northwest region of the US (US Army Corps of Engineers, 1996,1997).

Many downstream water quality issues arising from the dam such as alterations to the temperature regime and increases in the fine organic material have been anticipated during project design. However, as these problems had been rarely encountered on projects creating such extensive disturbance, the scale and severity of the problem was frequently underestimated (d’Angeljan, 1994). Some problems are specifically linked to local conditions. One of the most dramatic examples is the mercury problem associated with the James Bay hydroelectric project. The problem was anticipated, but the impact to local communities was not predicted during the design process. The soils of the Canadian Shield contain mercury that is normally in an insoluble and harmless form. Following inundation by the James Bay I project, the saturated conditions induced the growth of bacteria that converted the mercury to soluble methyl mercury (Rougerie, 1990). Once mobilized, the pollutant could be assimulated into the food chain and passed to fish, fish-eating animals (beavers and other marine mammals) and humans. The level of mercury in pike exceeded 2ppm. The consequences of this form of mercury include birth defects, and all fishing was banned in order to protect the community. Fishing is an important element of the traditional culture of the Cree, the indigenous tribe (Pearce, 1992). Other examples of mercury problems associated with reservoirs have been documented in Finland and tropical regions such as Thailand (Rosenburg et al., 1995). The elevated levels of mercury in reservoir systems due to the inundation may persist for decades.

2.2 Upstream Effects

Sedimentation issues are not confined solely to the reservoir and downstream reaches. The backwater reach upstream of the reservoir can extend many miles upstream. The depositional environment immediately following implementation is confined to the delta region at the head of the reservoir. As this delta builds up, additional sediment is deposited in the upstream reach of river. The aggradation reach in turn raises the local water surface elevations, creating additional backwater and deposition even further upstream. This feedback mechanism allows the depositional environment to propagate much further upstream than the initial hydraulic backwater curve might suggest. Analyses of the Sardar Sarovar dam have indicated that the upstream river reach will experience aggradation of the river bed to a depth of 3.5 metres. This corresponds to an additional 20 villages being inundated in the 100-year flood, compared with the situation immediately following the filling of the reservoir (Bettess, 1993).

Another upstream effect of dams is the potential influence on natural barriers within a basin. For example, this may promote the spread of some fish species beyond their pre-project domains. For example, when the Itaipu reservoir inundated Guayara Falls, a natural barrier which had prevented fish from the Superior Parana spreading through the lower watershed was eliminated (Bonetto et al., 1989). Conversely, in other parts of the world, dams are being used to protect native headwater species from harmful exotics. In Colorado, dams are used to prevent native greenback cutthroat trout from mixing with the bigger more aggressive introduced brook trout (Pringle, 1997). However, reservoirs can pose risks to headwater streams if facultative river species move up through a watershed displacing local populations.

Another key issue related to large dams is rooted in Conservation Biology theory. If the hydrologic and ecologic system is stressed too far by the implementation of large dams, the ecosystem may not be able to recover from major natural perturbations to the system such as droughts, tributary ‘blow-outs’, or sub-basins whose ecological linkages are reduced due to a slope failure or other natural process. If there are insufficient stronghold watersheds remaining in the system, then these types of natural disturbance could be catastrophic to specific species. [Rieman et al., 2000; Gup, 1994]

2.3 Basin-Wide Effects

Alteration to the nutrient balance is not solely restricted to downstream reaches. Recent research (Cederholm et al., 1999 and Bilby et al., 1996) has demonstrated the role of pacific salmon and other anadromous salmonids in transporting marine nutrients across ecosystem boundaries. Migratory fish and their carcasses can be important elements of the nutrient cycling in an ecosystem and sustaining the production of fish, avian and terrestrial species within watersheds. As researchers begin to unravel the complexities of the ecology of streams with migratory fish, it is clear that the linkages between the fish and the terrestrial ecosytem is significant. Reimchen (1994) estimated that 63% of an entire salmon run was transferred to the riparian zone in a stream in Gwaii Haanas, British Columbia. This allows for random distribution of salmon biomass through direct deposition or through fecal matter of animals that have consumed fish or carcasses (Cederholm et al., 1999). This can have a fertilizing influence on the riparian vegetation, for example Bilby et al. (1996) found that 18% of nitrogen in foliage in a riparian corridor was marine derived. Although more research is needed on this issue, Willson and Halupka (1995) projected that the loss of an entire anadromous salmon population could alter the spatial distribution, the nutritional status and reproductive success of wildlife in the basin. There are also other subtle processes important to retaining these marine nutrients in the system. These include the need for organic debris recruitment in tributaries. This organic debris provides habitat and geomorphic function, but also help retain carcasses in eddies and by snaring so that it is available for biological activity (Bisson et al., 1987).

Migratory fish are also influenced by other processes. The altered hydrology of the river system can create shifts in the timing of the migration. For example, juveniles used to swim downstream on the spring flood in the Columbia Basin, but now the migration along the Snake River is delayed until after the peak flows requiring a greater effort by the fish to reach the ocean. Similarly, the return of the mature salmon to spawn now usually occurs in September rather than the historic period of late June. Increased temperatures in rivers due to reservoirs may also create difficulty, either by creating temperature barriers or by increasing the metabolic rate of the fish. Adult salmon spend an extended period of their life cycle in the ocean and on returning to freshwater they will not feed again (Kline et al., 1993). An increase in the metabolic rate of the fish may cause it to run out of energy before returning to the spawning areas in headwaters. Thus the elimination of migration paths for anadromous fish may not be detrimental to the species alone, but can play a much broader role in the health of the basin ecosystem.

A different unforeseen large scale problem is the release of green house gases (Fearnside, 1995). This has been observed in upland forest and peatland habitats (Rosenburg et al., 1995). Generally peatlands are sinks for CO_2 and slight sources for CH_4 , whilst upland forests are slight sinks for CH_4 but not sources or sinks for CO_2 . This undisturbed system results in approximately a zero net release of gases to the atmosphere. Following inundation by dams, the microbial decomposition of peat and vegetation can alter this balance and provide a net flux to the atmosphere. In fact, the release of these greenhouse gases may be comparable to power plants run on fossil fuel and the emissions can persist for decades.

Seismic activity can also raise serious concerns at the watershed scale. These concerns may occur in areas that were thought to be seismically inactive or with a low seismic risk. Subsequent data, or the occurrence of a significant earthquake in the region, then upgrades the risk to the reservoir. Examples include the suspension of the Auburn dam during construction in Northern California. A second seismic issue that it is now recognized that it is possible for large dams to induce earthquakes and reservoir management is now linked to seismic activity at over 70 sites (Gupta, 1992; McCully, 1996). Examples include Srinagarind Dam (Klaipongpan et al., 1991), Khao Laem Reservoir (Hetrakul et al., 1991) both in Thailand. The largest reservoir induced earthquake is a 6.3 at Koyna dam in India (Gupta, 1992), but numerous other events greater than 4.0 have been recorded in Africa, Europe, Australia, USA, Japan, China and Brazil.

2.4 Coastal Zone Effects

The influence of diminished freshwater outflow to bays, estuaries and coastal wetlands has become generally accepted during the past decade (Rozengurt and Haydock, 1993). One well-documented example of additional stresses created by dams pushing an ecosystem toward collapse has been documented in San Francisco Bay. Prior to 1850, approximately 34 km^3 was discharged on average into San Francisco from the San Joaquin and Sacramento River systems. Today, there exists more than 20 km^3 of water storage capacity in the Central Valley. Approximately 40% of the flows in the these Central Valley rivers are removed for local consumption and 24% is pumped from the San Francisco Bay Delta and exported to Southern California and the Central Valley. Less than 40% of the river flows are now discharged to the Bay (Nichols et al., 1986.) The effects of altering the natural drainage have been dramatic. Some of the more significant impacts include the loss of salmonid spawning habitat or migratory corridors- Shasta Dam alone eliminated 50% of spawning habitat in the Sacramento river system. The reduction and altered distribution of freshwater has resulted in salinity intrusion and altered location of the null zone, or region of accumulation of nutrients where river flows meet the tidal flows of the Bay. Williams (1989) showed that in dry years the river flows are significantly less than the flows that would occur in an unimpaired (or reservoir free condition). In the extreme drought of 1977, releases dropped to $100m^3/s$, from the customary dry season discharges of $400m^3/s$. This reduction in freshwater inflow contributed to a drop in phytoplankton biomass to less than 20% of normal, and zooplankton was also significantly reduced. These conditions resulted in striped bass, one of the key indicator species of the health of the ecosystem, being reduced to the lowest recorded levels (Nichols et al., 1986). The effect on the ocean was not quantified in these studies, but it might be expected to be significant. The Three Gorges Dam on the Yangtze River in China is expected to reduce the productivity of the East China Sea, one of the largest fishing grounds in the world. It has been estimated that if the Yangtze River outflow is cut back by 10%, the cross-shelf water exchange will be reduced by 9% with a similar reduction in the onshore nutrient supply. Primary production and fish catch in the East China Sea is expected to diminish by a similar proportion (Chen, 2000). Concern has also been raised about wide-scale erosion of the shoreline due to the reduction of sediment from the Yangtze as a result of this project (Barber and Ryder, 1993). Accelerated coastal erosion has been detected as a result of regulated flows and dams reducing sediment discharge to the littoral cells. For example, local coastal regions along the Egyptian Mediterranean coast have experienced erosion rates that were three times greater than the period prior to the Aswan High Dam (Smith and Abdel-Kader, 1988).

This list of unforeseen problems, assembled from a very incomplete survey of literature, would suggest the value of developing a comprehensive checklist of experiences encountered in the large projects around the world, as well as a standard post implementation monitoring protocol.

Further, the upstream effects and basin-wide effects of dams and reservoirs are in general more difficult to simulate or predict, but should be considered in addition to the more widely recognized downstream impacts.

3. Sensitivity of Benefits Analysis

Traditionally, reservoirs have been designed for optimizing the cost-benefit ratio of the project and various methodologies appeared extensively in the literature through the 1970s and 80s (for example, Loucks et al., 1981). This approach represents a logical and defensible approach to the engineering and economic aspects of the project. These computations were undertaken from the best available flow records, sedimentation predictions, reduction in flood damages, power generation, irrigation deliveries and municipal usage.

However, out of necessity many projects were design with incomplete or short record data. Very few of these analyses consider a sensitivity analyses that was then verified periodically following implementation. For example, in developing representative flow sequences to evaluate benefits an assumption of stationarity in the statistical characteristics is usually assumed. The validity of stochastic models and other key economic elements of the analysis are rarely verified and the operational rules revisited to ensure the best balance of benefits are achieved.

Even projects which have considered the sensitivity of the benefit-cost ratio, could not have anticipated the extreme changes in flows or operational inflexibility generated by changing laws or observed ecological damages. For example, the Clean Water Act and Endangered Species Acts in the US, have created a paradigm shift in the way utilities and agencies manage reservoirs that could not have been anticipated by the original designers. Many of these issues are subjective and ‘fuzzy’ – incapable or being quantified neatly through the traditional cost-benefit analyses. Yet these issues can force dramatic changes in reservoir operation and associated benefits. The FERC re-licensing program has forced some innovative approaches. For example, the powerful whitewater recreational lobby on the Snake River is demanding recovery of sand-bars –or at least preservation of existing sites - suitable for camping during rafting trips. Other issues include fish passage, where the cumulative effects of multiple dams are forcing many salmonid species toward extinction. Obviously other causes such as predators, ocean conditions and harvest also contribute to the demise of these species, but dams are thought to probably be the main contributor. It is also an issue that is possible to control.

The prospect of dam failure is also rarely factored into cost-benefit analysis. The probability of failure is very small, but finite. The potential loss of life and economic implications are massive – thus introducing a potentially significant unknown into the benefit-cost analysis. Statistics published in 1980 (Jansen, 1980) estimated that about 200 significant reservoirs had failed in the 20th Century with the loss of about 8000 lives. With the rapid increase in the number of large dams, failure of just one major structure could eclipse the estimated loss of life experienced to date. This risk of loss of life was one of the primary reasons for the founding of ICOLD (International Commission on Large Dams) in 1929 at the World Power Conference in Berlin. The safety factor is of particular importance in seismic areas or areas of potential seismicity. The Tehri Dam in Utter Pradesh, India was constructed to withstand tremors of 7.5, far in excess of any anticipated seismic activity. On March 28, 1999, the region experienced an earthquake of magnitude 6.8, renewing concerns about the risk to downstream residents and may force modification to the reservoir operation in the future (Power in Asia, 1999 and New Scientist, 1991)

Some large projects are reliant on cumulative benefits from several separate dams to fully realize the anticipated benefits. For example, the Sardar Sarovar project is anticipated to have a sedimentation half-life (or expected time for half of the live storage in the reservoir to be lost) to be in excess of 100 years. However, this assumption assumes that the Narmada Sagar project is completed. Without this upstream dam, the half life would be reduced to about 60 years (Bettess, 1993). As another example, the 1986 flood on the American River (section 5.3) almost created catastrophic flooding of Sacramento, California. The preferred solution developed by the federal agencies responsible for the reservoir operation, was to propose the construction of a major new flood control dam at Auburn (US Army Corps of Engineers, 1991,1992). This recommendation and the lack of detailed analysis of alternatives sparked a major controversy between city, state and federal government agencies as well as public interest and environmental groups. During this heated debate, flood risks remain unchanged and development continues within the downstream floodplains.

4. Changing Societal Values During the Design Life

A large dam is a massive structure that is not solely a fixture in the landscape, but is also capable of dramatically altering the landscape during its design life (McCully, 1996, Gup, 1994). The physical and ecological changes are described earlier. However, given the long design life of these structures it is probable that the political and societal values may change. As an example, many of the first large dams in the Western US were developed to break the society out of an economic depression. The creation of jobs, cheap power and delivery of irrigation water fueled the economic recovery. During the past three decades, societal values have shifted toward environmental preservation and enhancement which is reflected in legislation such as the Clean Water Act and Endangered Species Act (ESA). Many countries do not have such strong legislation to balance extractable resources, environmental values and quality of life for people living in the impacted regions.

These changing societal values, have resulted in an interest in minimizing some of the most detrimental effects outlined in Section 2. Many piece-meal fixes, have resulted in abject failure and there is an increasing recognition that the key to minimizing these impacts is the restoration of physical processes (Ligon et al., 1995; USBR, 1994; Wirth, 1996; Schmidt et al., 1996).

The importance of monitoring after the implementation of the dam has been stressed by Collier et al. (1996).

Future management of dams and rivers must take into account the dynamic nature of a regulated river. Adaptive management attempts to track these changes through time. As dam *operations are modified, the downstream effects are tracked and integrated back into the dam's management plan. This adaptive management can of course be extended to upstream and regional effects.*

5. Management Issues

5.1 Accountability

A major issue surrounding large dam projects is the question of management accountability and whether the routine operation is linked back to the original project objectives, mitigation requirements and project performance. Multi-purpose reservoirs are frequently managed by multiple agencies, each with a different bias. This can result in communication difficulties, or the inability to optimize the benefits of the reservoir. Further, downstream impaired areas may be out of the jurisdiction of the dam managing agency, for example in a different province or country. Allocating responsibility for regional impacts then becomes challenging particularly when assessing cumulative impacts of several projects in the system, or when trying to develop an holistic view of managing a river system.

Another variation on the difficulties in managing the reservoir is that the responsible entity may represent only narrow interests. For example, powerful urban water users, industry and agriculture may exert disproportionate influence compared with flood management or the benefit to the small farmer.

However, this is a difficulty, where recent advances in technology can play a significant role in improving management.

Real Time forecasting

Sophisticated forecasting tools such as NEXRAD, snow pack telemetry and satellite imagery can be used to gage the flood risk and provide flood warning and additional lead time to reservoir operators. This real time forecasting can also be applied to dam failure warning systems (Martinsen, 1995).

What If scenarios:

Integration of aerial or satellite imagery, geographical information systems and hydrodynamic/water quality models allow complex issues to be evaluated and different interested parties to pose "what-if" scenarios.

WWW

Access to the worldwide web allows NGOs, agencies and landowners access to meteorological, hydrological data, predictions and feedback on current conditions, forecasts and summaries of past management decisions. This technology of course assumes that there is the ability to represent all interests fairly in the decision-making structure and all interested parties have ready access to the technology. However, the rapid development of the internet, facilitates dissemination and communication on complex natural resource projects.

5.2 Flexibility in Operational Rules

Operation rules for dams are frequently based on only short data records, which were the best available prior to construction. Stochastic analysis will allow the generation of flow sequences with the same statistical properties as the observed record, but this approach cannot anticipate extreme events that are out of the expected range of those records. An example of this problem is Lake Chad in Nigeria. Since the 1960s, the surface area of the lake has shrunk from 25,000 km^2 to less than 3,000 km^2 due to reduced rainfall and river inflow (Hutchinson et al., 1992). Projects to construct pumping stations on the banks of the lake for irrigation projects are now sited several kilometers from the lake.

Climate models and inferred long-term records from surrogate techniques such as tree ring analysis can provide more accurate flow sequences, but there will often be the need to allow some flexibility in the operational rules to account for changing hydrology or the natural meteorological cycles. As an example, the Sanmenxia dam has faced dramatic sedimentation problems necessitating the need to adapt the reservoir management (Soong and Zhao, 1994). From 1960-64, the approach was to impound all floods (and sediments borne by the high flows). Following the loss of the majority of live storage in the reservoir, the reservoir was operated to detain flood flows and sluice sediments during these high flow events. Since 1973, clear water is released during non-flood periods, detain peak floods, but operate the dam as ‘run-of-the-river’ at small and intermediate floods so that sediments are flushed through the reservoir. This adaptation could only be achieved by a massive reduction in power generation of the system, which again stresses the need for post-implementation performance analysis and a thorough sensitivity analysis in the planning phases of a project.

A similar approach has bee adopted on the North Fork Feather River in Northern California. Live storage had been reduced dramatically during the past 40 years, but the two main reservoirs (Rock Creek and Cresta) are fed by a much larger storage reservoir upstream (Lake Almanor), lessening the need for live storage at the site of the power intakes. Adapted operation rules, now allow sediment to be passed through the dam (Sediment Pass-Through alternative), maintaining the reservoir bed elevation to a sustainable configuration, whilst keeping the power intakes clear of sediment (Harrison, 1992). An additional benefit included the ability to pass spawning-size gravel to the sediment starved reaches downstream of the reservoirs. The revised operational rules will be closely monitored for any downstream impacts such as bank erosion, degradation of existing habitat, or encroachment of sediments toward the power intakes and refinements made as needed.

Barriers to developing revised operational rules through adaptive management or reservoir re-operation studies are frequently encountered in multi-objective reservoirs. Institutional difficulties may be encountered due to the missions of different agencies, contractural limitations established in the planning phase of the project when little was known about the true performance of the project and legal issues such as water rights or the liability associated with flooding.

However, flexibility in operational rules should be exercised with care, particularly when managing for specific or indicator species. Often indicator species or species of concern are the focus of mitigation activities, but it is important to recognize that the full range of species should be considered. One of the primary mitigation strategies in the Columbia Basin during the past 20 years has been barging or trucking juveniles around dams and the construction of screens to divert fish away from turbines. These solutions were designed for Chinook Salmon and steelhead. This form of transportation affects the homing ability of sockeye salmon more severely than other salmonids and lamprey suffer much higher mortality at the dams. The results are that only 3 listed Snake River sockeye have returned in the past five years and Lamprey numbers have declined by almost 95% during the past 30 years (Fryer and Hatch, 1999).

5.3 Failure to Follow Operational Rules

In most multi-objective reservoirs there is an inherent conflict between flood management and power generation, irrigation and water supply. Documentation of management of reservoirs under flood flow conditions is rarely published, but the temptation to encroach on flood storage space is great since the cost of flood management have no tangible cash or economic benefit. As an example, consider the 1986 flood through the Folsom Dam on the American River above Sacramento in California, which has been debated by Local, State, Federal agencies as well as public interest groups. The operational rules of the 1.0 million acre-feet multi-purpose reservoir were developed to maintain the flows in the downstream channel to "non-damaging levels". Reservoir management is a very complex issue, and the rule curves are established so that operators have a series of instructions based on current storage and inflow. The rules are based on numerous simulations of historical floods and synthetic hydrographs. The basis of the rules are to maximize benefits, but this sets an inherent conflict between the objectives. This was recognized by the US Corps of Engineers in the Regulation Manual (1959):

> The temptation to infringe on flood control space is sometimes strong, because usually losses to other functions are obvious, and losses to flood control (although usually much greater) may not occur or indeed probably will not occur in any particular case. Consequently, a very rigid attitude against infringement on flood control space must be maintained at all times.

In 1986, memories of the drought of record through the 70s was still vivid in the state’s mind, and the first part of the 1985-86 winter was dry, raising concerns about the ability to meet irrigation water deliveries. A comparison of the theoretical rule curve and the actual operation of the reservoir in February 1986 has been described by Williams (1993). This event was complicated by the failure of the Auburn cofferdam upstream, but this analysis indicated that (a) the design flood reservation was not available at the start of the flood, (b) the increase in reservoir releases was delayed by several hours, (c) surcharge storage was used and (d) reservoir releases exceeded the downstream designated floodway capacity. A major flood of the City of Sacramento was narrowly avoided in what was estimated (Williams, 199?) to be the 50-70 years event (compared to the 100+ year design event). Thus, relatively minor deviations in the operational rules, almost resulted in a catastrophic flood event. This example serves to illustrate the problems of reservoir operation and the potential value of being able to predict the severity of storms with a 48 hour lead-time and to be able to simulate the anticipated river flows.

5.4 Managing for Social and Cultural Issues.

The social and cultural impacts of large dams and their impact to the physical landscape can be severe. Detailed description is beyond the scope of this paper, and several detailed treatises exist in the literature. Examples include Goldsmith and Hildyard (1984), Barber and Ryder (1993), Hubbel (1994), Ledec et al. (1997). However, operating and designing dam projects to minimize impacts to local communities is a management concern of paramount importance.

6 Feasibility of Decommissioning Methodology

During the past decade there has been a surge in interest in removing dams (for example, American Rivers, 1999; American Society of Civil Engineers, 1997; Ross, 1993;Breining, 1994; Shuman, 1995; USBR, 1995; Snow, 1999, Bowler, 1999; and Wade, 1999.) The e-periodical, *http://www.riverrevival.org* provides monthly information updates on projects studying or implementing decommissioning. The reasons for considering dam removal include:

- Aesthetic enhancement
- An alternative is available that can meet the same objectives that the dam provided
- Cost savings – it is no longer cost effective to maintain the dam
- Fish and wildlife habitat improvement
- Removal of public safety hazard
- Creation of recreational amenities
- Improvement of water quality

To date it has been estimated that 465 dams in the US have been removed and 26 case studies are described in a recent report (American Rivers et al., December 1999). Worldwide, there appears to be no central repository of data, and no comprehensive information about the reasons and experiences for implementing these drastic measures. NGO organizations have recently developed an electronic newsletter through the internet that attempts to disseminate information on some of the more prominent case studies currently under investigation [http://www.riverrevival.org]. The interest in decommissioning is likely to increase since dams, like any other civil engineering structure, are designed to have a finite life from both the economic return and material durability perspective. However, very little thought was given in the design process to how these massive structures might be refurbished or removed at the end of their life cycle. Other structures can be disassembled to make way for new infrastructure, but dams are unique because of their profound impact on the landscape, physical processes and ecosystem. It is certainly feasible to remove the structure, but what should become of the vertical step in the longitudinal profile of the river bed? Even if this issue can be addressed from an engineering perspective at the dam site, the prospect of dredging and disposing of sufficient material to recreate a stable river channel that will not dump massive volumes of fine (and possibly contaminated) sediment is a daunting prospect. A template for the various issues and steps that should be considered in dam decommissioning is outlined in a recent ASCE publication (1997).

Most large dams in the world have not yet reached the end of their design life, and the issue of decommissioning is only now being perceived as a major issue. Most dams removed to date have been relatively small scale (American Rivers et al., 1999), although larger systems such as the breaching of the lower four dams on the Snake River in the northwest of the US is being considered as a viable alternative to restore salmon runs. What is evident from studies contemplating dam removal or even operating existing dams as a run-of-the-river for parts of the year, is that the potential impacts and costs are very substantial.

These costs have not been considered as part of the life cycle costs, or overall benefit-cost ratios when deciding on the feasibility of implementing these projects.

7 Future Recommendations

The key to improved management of regulated rivers is in the collection of data and the interpretation and conversion of this data to knowledge.

The interpretation of scientific understanding, however limited or conditional, must be translated by the scientists into concrete recommendations designed for the manager. We must make small changes initially. But it should be understood very clearly by the people who are supporting the investigation that more changes will be needed. The need for long-term measurements is the unassailable conclusion of studies made to date. The data collection program should be designed with great care, it should consider a wide variety of data needs, and each part should be installed and operated as soon as practicable even though not all parts. . . . . begin at one time (Leopold, 1990)

Despite the acknowledged severe potential impacts of large dams, there appears to be no systematic standard methodology for monitoring the downstream, reservoir or upstream ecological responses to dams (Ligon et al., 1995). Further, there appears to be no systematic monitoring and reporting of the benefits or impacts accrued by the large dam. This monitoring could justify the original investment, develop knowledge that could be used in other projects and adapt operational rules to minimize adverse impacts.

This systematic assessment of project performance would include:

- Mandatory monitoring for performance assessment
- Processing of basic data to knowledge, or development of information that allows management actions to be taken.
- Validation of design assumptions
- Achievement of benefits forecast during design
- Assessment of predicted impacts during implementation
- Assessment of predicted post-implementation impacts
- Documentation of any unforeseen consequences
- Flexibility in operation rules to account for changing physical or socio-economic conditions
- Application of adaptive management – direct feedback from monitoring to operation on a real-time basis.
- Accountability for dam operation and maintenance
- Mandatory decommissioning methodology developed prior to implementation
- Application of technology to minimize public safety risks (Kuo and Yen, 1999; Marengo, 1996), monitor the benefits and impacts of the project, and facilitate adaptive management to optimize the longterm comprehensive performance of the project.

Components of a program for monitoring physical processes in an adaptive management plan.

1. Characterize the channel and watershed for geomorphic and physical characteristics.
2. Monitor water quantity, key water quality indicators and sediment discharge.
3. Develop pre-and post- implementation hydrology, sediment budget, and water quality.
4. Simulate channel response (bed elevations and key characteristics such as width-depth ratios.
5. Predict habitat response to changing conditions and corresponding influences on key indicator species.

8. Conclusions

Large dam projects can bring extensive benefits and economic prosperity to regions. These benefits are estimated based on the best information available at the time of the design. There are few instances when the expected benefits are analyzed several years after implementation to ensure that these benefits are achieved and the investment of governments and tax payers were warranted. Examples have been raised herein, but this may be a biased sample, as forensic studies are only usually triggered when an obvious problem arises.

Conversely, anticipated problems are frequently compensated for by non in-kind mitigation measures. It is then difficult to draw direct comparisons between the loss of a resource and the benefit of the compensatory mitigation action.

In addition to the predicted problems, there are also unanticipated consequences, which may take many years to be recognized.

There is a need for standardization of post implementation monitoring protocols on large dam projects. These data sets could then be used to anticipate long-term problems and based on international experience, approaches to resolve or minimize adverse impacts can be developed. The monitoring data can be coupled with operational rules designed to incorporate greater flexibility to optimize the various benefits, whilst minimizing impacts. This type of adaptive management can be a powerful tool if all the interested parties participate.

Technology can play a major role in this adaptive management. Real time computer models, remote sensing of meteorological data through satellites and other technology such as NEXRAD can assist in management decisions. If the interested parties can agree on the technology and predictive ability of the models, then the decisions are based on policy and the weighting that the decision group places on various outcomes.

Finally, there is also a need to incorporate a decommissioning strategy in the planning of any new large dam project. The estimated cost of this refurbishment or de-commissioning should be included in the life cycle costs.

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