Impact of artificial reservoirs on hydrological equilibrium

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ABSTRACT The operation of reservoirs as a function of their design purpose and mode of operation is discussed and a listing and summary of impacts produced as a result of the reservoir are given. Particular considerations are given to flood control, sediment deposition and the problems involved in flushing sediment past a dam, consequences of downstream flow modification, ecological problems produced including those for fisheries, and the legal aspects related to development of reservoirs.

INTRODUCTION

Reservoirs have been constructed since antiquity for the purpose of conservation of water. The Iranian Committee on Large Dams (Iran 1990) has assembled a description of many dams which were constructed in Iran up to more than 1000 years ago. Many others existed and some have been described by Biswas (Biswas 1967). It is obvious that these old dams were developed because of the benefit or expected benefit which accrued to those who used the water. It is entirely logical that such dams first were constructed in arid or semi-arid areas where rainfall was seasonal and agriculture and society in general benefited from the storage and subsequent use of water from the reservoir. The first dams to be constructed in mountainous areas were most likely constructed to develop power for mills, initially mechanical, and as a result were constructed at the mill site. One had the choice of building the dam at the best dam site or at the best mill site, a possible conflict in choices. With the discovery of electricity and the means of generating it from water and transmitting it to other sites, it became possible to build dams farther up in the mountains where the site conditions were more favorable for the dam and still supply electricity for distant needs. This is the pattern today.

Early cities developed along the rivers and streams because of the need for a water supply and because trade could be carried on using river transportation; the same pattern exists today. Frequent flooding undoubtedly proved to be an inconvenience and a danger particularly in regions subject to rapidly rising river crests. As a result, the concept of flood control was developed and levees were constructed to protect life and property. When the concept of building dams for storage of flood waters began is not precisely known, but serious flood-control planning using dams and reservoirs in the USA began after a disastrous 1913 flood with the creation of the Miami
Conservancy District in 1914 which was organized to develop a flood-protection system for the Miami River valley in Ohio (Woodward 1920). That report stated that two flood-retention reservoirs had been constructed on the Loire River in France in 1711 and that they had flood-storage capacities of 100 and 108 million m³ respectively.

**Benefits Derived From Reservoirs**

The benefits which are obtained from reservoirs are numerous and well known. They include: flood control downstream; establishment of a dependable water supply for municipal, agricultural, and industrial uses; generation of electricity; improvement of navigation; and recreation. For large reservoirs the benefits accrue to a broad array of people and, thus, those projects are usually constructed and operated by public or quasi-public agencies. Other smaller dams often have as their primary benefit the storage of water for private irrigation use or the generation of electrical energy and are usually constructed and operated by private companies or by special-purpose associations. Direct benefits from these special-purpose dams usually go only to stockholders of the company or to members of the association.

**OPERATION OF RESERVOIRS AND HYDROLOGICAL IMPACT**

The operation of reservoirs varies with the purpose for which the reservoir was constructed. For reservoirs with the soul purpose of providing downstream flood protection through storage of flood runoff, retention of the flood waters is short and the flood waters are released at a flow rate which does not exceed the downstream channel capacity. Impact of such reservoirs on the hydrological equilibrium is usually small since only the large peak flows are modified and flow into the reservoir is quickly released as long as it does not exceed the channel capacity. The hydrological equilibrium is only slightly altered as a result of the reservoir. For larger reservoirs the retention time is longer (frequently part of the storage is for conservation) and impact is greater. The most obvious impact usually appears downstream where use of the flood plain increases as a result of reduced flooding. The stream is usually confined to a smaller channel and often wetlands are modified as a result of streamside development.

Reservoirs that have been constructed for conservation storage include those whose purpose is hydroelectric development as well as storage for downstream use by irrigators, municipalities, and industries. The operation of such reservoirs requires that flow in excess of some minimum value be stored for later use. Thus, these reservoirs are storing water during the rainy and snow-melt periods and releasing at flow rates less than the inflow rates. The reservoir operation serves to smooth out erratic inflow patterns and provide release rates more nearly equal to the average annual flow rate of the river. However, the extent to which the river flows can be limited to the average annual value is dependent upon the reservoir storage volume and the variance of the river flows. In general it is impossible to store all of the reservoir inflow
since unusually large inflows always occur during which the reservoir must spill. Depending upon the design of the dam and its spillways and outlet works, more or less of the annual inflow can be stored. The larger the reservoir storage volume, the more the hydrological regime will be changed by storage and the reservoir operation.

The impacts of artificial reservoirs on hydrological equilibrium is profound in many cases and predominantly involves environmental issues. The current major activities in the field of dam engineering today is primarily associated with means to mitigate those impacts. In the case of new dams, concern over these impacts has greatly increased the length of time required to obtain legal permits to construct dams as well as the uncertainty of success in obtaining those permits. For existing dams the impacts have been identified and current activity is primarily associated with attempting to mitigate those impacts through modification of the dams and/or the operational policies of the reservoirs. For many old dams the mitigation is required in order to renew legal permits to own and operate the dam.

**Impacts of large reservoirs**

Introduction of storage on a stream alters the natural hydrological regime by reducing the flood peaks and releasing a streamflow which is more nearly equal to the average annual flow unless the reservoir provides for diversion either to another drainage basin or to a point further downstream. In the latter two cases the streamflow in the river downstream can be greatly reduced. In the United States before approximately 1960, it was often allowable to reduce the stream flow to zero. In any event the hydrological equilibrium is drastically changed downstream. Following is a list of impacts which are produced:

1. **Interuption of Sediment**: Sediment is stored in the reservoir with the coarsest part stored in the upstream reaches and the fine material stored further down. The flow released to the stream contains, on the average, smaller concentrations of sediment. As a result, the river downstream of the dam degrades if the bed of the river is erodible. Even if it is erodible, degradation of the bed is often limited because of armoring of the bed occurs as erosion takes place and the river carries away the small material which its velocity is capable transporting. The character of the bed material changes becoming more coarse with a resultant impact on the aquatic life. Sediment stored in the reservoir often fills at least a portion of the live storage reducing the beneficial storage and the potential benefits of the reservoir as well. Problems of aggradation can occur downstream of the dam because sediment entering from downstream contributory channels will have reduced flow to transport the sediment; the peak flood flows, which normally transport the majority of the sediment, may no longer occur in sufficient frequency and magnitude to move all sediment entering from tributaries downstream.

2. **Altered Flow Regime**: The downstream flow regime will be changed by operation of the reservoir. The sediment concentration in released flow is usually much less than that which occurred without the reservoir (for large reservoirs the water released may be essentially
clear). As a result the channel downstream has a slope which produces velocities large enough to have transport capacity greater than the concentration of the outflow. Degradation occurs near the dam and some distance downstream as a result of the imbalance between the transport capacity and concentration of the released flow. Eventually, as degradation proceeds, the channel will armor effectively stopping the erosion; or the channel slope will be reduced until equilibrium is reached.

However, the armoring of the channel bottom is followed by more aggressive erosion of the banks and as a result the stream will become wider and may tend to meander. Sediment eroded from the banks and that brought in by the tributaries may produce a sediment load that is greater than the transport capacity of the releases. Since peak flows released from the reservoir are reduced in both magnitude and frequency from that which provided flushing prior to construction of the reservoir the downstream peak flows no longer occur in sufficient number and magnitude to carry away the downstream sediment load. As a result aggradation of the channel occurs at some distance downstream from the dam may further tending to reduce the gradient of the river.

Interstices in gravel substrate used for spawning by the riparian fish population sometimes become clogged as a result of sediment deposition. As a result the eggs laid in the gravel by the spawning fish often have insufficient oxygen for survival. To reduce this impact it is necessary to release peak flows of a desired magnitude and duration from the reservoir. The establishment of the required magnitude and duration of this flushing flow is difficult at best and is highly dependent upon the type of bed material contained in the river. Without the release of flushing flows, it is possible for biocenosis to occur where nearly all the native aquatic plants and animals are eliminated or at least seriously impacted.

The reduction of downstream peak flows also allows more vegetation to grow in the main channel; as a result the resistance to flow is increased and the capacity of the channel is reduced; higher flood stages occur for a given flow than occurred prior to construction of the reservoir.

At the upstream end of the reservoir the hydrological regime of the river is also changed. Coarser sediment deposits at the upper end of the reservoir and form a delta there which impacts the active storage. If the reservoir is a storage reservoir the surface level will drop as storage is released and the upstream deposited delta becomes exposed. The river then cuts a channel through the delta. The slope of the river channel becomes flatter than it was prior to construction of the dam and, as a result, the flow capacity of the channel is reduced below that of the channel prior to development of the reservoir.

3. Altered Water Quality: If the dam is high, the reservoir contents will usually stratify with the result that flow released from the lower portions of the reservoir will often be in the order 3 to 5 °C. If this temperature is significantly colder than the original stream temperatures the downstream resident fishery will change drastically. At reservoirs on the White River in Missouri and Arkansas the resident Black Bass fishery (warm water species) was completely lost after the dams were
closed and a thriving Rainbow Trout population (a cold water species) developed (Smith 1973).

Because the surface area of the reservoir is larger than the surface area of the original stream and is often warmer there may also be an increase in evaporation volume which reduces the amount of downstream flow below that experienced before the reservoir was built.

Water quality effects produced by artificial reservoirs are frequently created by temperature stratification of the reservoir and decomposition of organic material in the reservoir. For high dams the oxidation of organic materials reduces the dissolved oxygen of the water stored in the lower parts of the reservoir. Releases made in the fall or winter after a summer of stratification and decomposition of bottom material frequently results in the release of water having zero or very low dissolved-oxygen content. Often hydrogen-sulfide gas is released as a result of decomposition of vegetation. These releases are frequently a serious problem for the resident aquatic colony below the dam. The Tucurui dam is probably the most famous of the recent examples of water quality problems that can occur as a result of construction of a reservoir (Canali et.al. 1988).

4. Interruption of Migrant Fish: Both high and low dams will interrupt free passage of fish. Although some species of riparian fish do not move far from their resident habitat others migrate during spawning periods. Both the Atlantic and Pacific Salmon migrate between the oceans and fresh-water rivers where they spawn. In the western part of the United States the Steelhead Trout also migrates between salt and fresh water, but like the Atlantic Salmon returns to the sea after spawning. Reservoirs in the eastern and western United States and Canada and in the Scandinavian countries have interrupted the spawning of these anadromous fish to the extent that in some places entire runs of Atlantic Salmon have been lost and have been replaced by Salmon raised in hatcheries.

Efforts in the United States began about 10 years ago to restore runs of Atlantic Salmon to streams in the northeast and have been expensive and only moderately successful to date (Rogers 1989). In Australia some species of fish exist that spawn in the sea and the young return to live in rivers; efforts there are now considering means to allow for passage of these fish. Fish ladders for the passage of downstream migrants have now been provided for some low dams but accommodation of upstream migration of juveniles is in the early stages of consideration (ANCOLD 1990). The passage of Atlantic Salmon using fish ladders and locks have been allowed for in Ireland and Scotland for many decades but there appears to be little data to assess the success of all of the measures used (Aitkin 1980).

SOME EXAMPLES OF PROBLEMS

The topic sessions which follow this plenary session all contain papers which describe examples of problems or solutions to problems which have been briefly covered in the preceding parts of this paper. The
following examples supplement those papers and provide some additional insights to the problems. Unfortunately problems seem to be more prevalent and easier to identify than solutions. Hopefully, the results of this conference will produce some ideas for solutions which will make the use of artificial reservoirs even more beneficial in the future by eliminating or at least reducing the impact of changes in hydrological equilibrium produced by artificial reservoirs.

COWLITZ FALLS HYDROELECTRIC DAM

The Cowlitz Falls project is to be constructed on the Lewis River in the southwestern corner of the State of Washington in the USA. The dam will be 35 m tall and will impound a reservoir about 32 km long. The drainage area above the dam is 2868 km² and produces an annual average flow of 123 m³ s⁻¹. The drainage area is mountainous and includes two volcanos, Mt. Ranier with a height of 4270 m and Mt. St. Helens which, after its May 1989 eruption, has a height of only 2700 m. The dam will house two hydroelectric units with a total capacity of 36 mw. At one time the river hosted a substantial run of Chinook Salmon and Steelhead Trout, but two dams downstream, one of which is a 172 m high arch dam, stopped the run of anadromous fish in 1968. The controlling agency for permits for the dam is the Federal Energy Regulatory Commission which oversees all hydroelectric dams in the United States. In granting the license for construction of the dam two restrictions relating to the hydrological equilibrium were made a part of the license. First, the dam and its operation had to be designed so that the presence of the dam would not increase flooding at the town of Randal at the upper limits of the reservoir. This restriction meant that sediment could not be allowed to deposit to depths upstream that would increase flooding and secondly that the reservoir would need to be lowered during floods exceeding that magnitude beyond which the backwater curve from the dam would reach the critical zone on the river.

Sediment characteristics were obtained from a limited number of suspended sediment measurements, from samples taken from the delta in the downstream reservoir, and from bars deposited along the river. Samples of bed material were collected to estimate bed-load sizes. As is common for mountain drainages the river has a gravel bottom and the sediment conveyed has a median size ranging from 0.5 to 0.8 mm. Bed load was found to be about 5% of the total load. The U.S. Army Corps of Engineers computer program HEC-6, Erosion and Deposition in Rivers and Reservoirs, (U.S. Army 1977) was used to perform sediment routing using a 50-year record of daily average flows. Hydraulic analysis of long-term sediment deposition depths and resulting water-surface profiles during floods showed that even though the dam will be only 35 m tall, long-term aggradation of the channel in the upper reaches of the reservoir could not be prevented unless the reservoir water-surface is lowered by 6.1 m from its normal maximum whenever the flow exceeds 767 m³ s⁻¹. Lowering the reservoir increases velocities in the reservoir and, thus, increases transport capacity. Since
HEC-6 is a one-dimensional simulation, it could not be used to study effects of sediment deposition near the dam. Instead a 1:46 scale model, which was used to verify hydraulic design, was used to study the effectiveness of the two 3.6 m x 4.9 m sluices located beneath the spillway bay on the left side of the dam. Using plastic pellets, 1.71 mm diameter by 3.21 mm long, with a specific gravity of 1.02 to represent the sediment, the model showed that the sluices would indeed sluice away material which reached the front of the dam. In this case the sluices will be effective because of their large flow capacity (568 m³/s), because the reservoir would be lowered to increase the velocity in the reservoir, and because the diversion channel in the bottom of the river will be left in place to trap sediment and divert it toward the sluices. For most dams the sluices are not effective in passing sediment for significant distances upstream from the dam unless strong density currents are developed by the sediment and/or the reservoir surface is lowered during passage of large flows.

The second restriction attached to the project license required that the construction of the dam not prevent the trapping of downstream migrating anadromous fish since the State of Washington was considering the re-establishment of a Chinook Salmon fishery in the river upstream of the dam. Because of the large dam downstream it would be necessary to trap adult fish downstream of the dams and transport them to the river upstream of Cowlitz Falls Dam for release. It would likewise be necessary to trap downstream migrating juveniles at the Cowlitz Falls dam and transport them to a point downstream of the dams from which they could continue their migration to the sea. It would be necessary to trap downstream migrants at Cowlitz Falls Dam because earlier tests had shown that, because of the very small velocities in this large reservoir, the downstream migrating juveniles could not find their way through the large reservoir which is immediately downstream of Cowlitz Falls. A screening concept was designed which would intercept downstream-migrating juveniles at the turbine intakes and direct them to a holding tank for later transport downstream of the dams by truck. The design would screen only the top 1/3 to 1/2 of the intake area since field studies of migrating juvenile Salmon have shown that most swim in the upper 15 to 20% of the approaching flow. The ultimate design of the screens would be based on field studies of actual migrating fish once the dam is in place and planting of the fish upstream has been accomplished.

SEDIMENT FLUSHING AND/OR REMOVAL

Probably the most serious and most common impact of reservoirs on hydrological equilibrium is that of sediment interruption. The resulting sediment deposits have seriously reduced the capacity of reservoirs in all parts of the world (ICOLD 1989). The reduction in capacity decreases the benefits of the reservoir and, if not corrected, can render the project useless. Problems for reservoirs on the Yellow River in China are probably among the most famous because of that river's extremely large suspended load; as a result a means of sluicing must be developed such as that planned for the Xiaolangdi reservoir, which
without effective sluicing would be essentially filled with sediment in 5 years or less (Hsu 1988).

The effectiveness of passing sediment through dams is not always good and, if the dam is not initially designed for passing sediment, it may become prohibitively expensive to modify the dam and outlet works to do so later. It appears that for most dams the predicted amount of sediment entering the reservoir each year is very uncertain at best. Plotted on a log-log scale data on sediment concentrations versus discharge normally scatter over more than two cycles for a particular discharge illustrating the uncertainty inherent in sediment-load prediction. However, the prediction of the volume of sediment inflow that will be experienced is very important. If the predicted inflow volume proves to be smaller than what actually occurs, no problems will occur and the life of the reservoir is extended beyond that anticipated. However, if the annual amount of deposition is underestimated, the reservoir may be rapidly filled, frequent operation problems can occur, and the project will fail to realize its expected economic worth. For the Shihmen Reservoir in Taiwan the annual prediction was 800,000 m$^3$ year$^{-1}$ when the dam was designed in 1955 but in 1964 alone the actual input was 19.5 million m$^3$. After the years of operating experience the annual input is now estimated to be 0.862 m$^3$ (Hsu et al. 1988). When sediment deposition reached the power intake structure at Shihmen Dam it became necessary to institute a dredging program in order to maintain hydropower operations.

The Public Works Department of Los Angeles County in the State of California in the USA constructed three reservoirs on the San Gabriel River in the San Gabriel Mountains for flood protection of cities in the Los Angeles Basin. The dams are San Gabriel, Cogswell, and Morris and were constructed in the early 1930’s. These dams, although constructed for flood control, are actually operated for conservation as well. Since rainfall in California is very seasonal it is possible to store water in the reservoirs at the end of the flood season and release it for downstream recharge of groundwater aquifers later during the dry season. Table 1 shows the reservoir storage capacity when constructed and as they are in 1990 (Coale 1989):

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Year Constructed</th>
<th>Drainage Area (km$^2$)</th>
<th>Original Capacity (10$^6$ m$^3$)</th>
<th>1990 Capacity (10$^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cogswell</td>
<td>1935</td>
<td>111</td>
<td>15.17</td>
<td>10.92</td>
</tr>
<tr>
<td>SanGabriel</td>
<td>1938</td>
<td>518</td>
<td>65.74</td>
<td>53.91</td>
</tr>
<tr>
<td>Morris</td>
<td>1935</td>
<td>562</td>
<td>39.84</td>
<td>27.49</td>
</tr>
</tbody>
</table>

The reservoirs are in a series on the San Gabriel River. The area in the upper part of the basin beyond San Gabriel is a pristine forested mountain area. Sediment entering the reservoir is typical of mountain streams and ranges in size from silt and fine sands to gravels. A scenic popular Trout-fishing area has developed on the river downstream.
from Cogswell Dam. About 2 million m$^3$ of sediment had been removed from San Gabriel in 1979 using conventional earth moving equipment with the reservoir drawn about 30 m. The removed sediment was placed in an engineered fill in a ravine about 2 km upstream from San Gabriel reservoir. The County of Los Angeles decided that sediment again needed to be removed from the reservoirs in 1987 because, at the rate of sedimentation experienced, the reservoirs would no longer be able to contain the design flood (100-year) by 1990. The urban area downstream from Morris dam is a highly developed residential, commercial, and industrial development which makes flood control upstream a vital concern. However, for environmental reasons, the U.S. Forest Service, which is the owner of the land around the reservoirs, decided that placing removed sediment on forest land would no longer be acceptable and refused to issue the necessary permits. The County was therefore forced to locate another disposal site and chose a number of large unused gravel quarries downstream from Morris dam. Attempts had been made to use the low-level outlets to sluice sediment from Cogswell reservoir in 1978 and had resulted in a serious citation from the State of California Department of Fish and Game for destruction of fish habitat since the slits sluiced from the reservoir had covered substantial amounts of aquatic habitat in the popular fishing stream.

The scenarios for removal of the sediment considered: wet removal using a cutter-head dredge, dry removal using conventional earth-moving equipment, and transportation of the removed sediment by slurry pipeline, trucks, conveyor belt, railway, or aerial tramway. The final scheme selected on the basis of economics utilized a 1000 m$^3$ hour$^{-1}$ floating dredge and a 45 cm diameter slurry pipeline. The slurry is to have a concentration of 30% by weight. Capital cost for the project is estimated at US$ 30 million and operational costs will be US$ 4.15 per m$^3$. The project is just beginning and will remove about 20 million m$^3$ initially. This sediment removal project is one of very few to be carried to completion in the United States and was economically feasible only because of the very serious consequences of not providing satisfactory flood protection to the downstream area.

LEGAL ASPECTS

The legal aspects of the impacts of artificial reservoirs on hydrological equilibrium are primarily related to environmental concerns. In the United States these concerns began to be raised in the early 1960's. The concerns were primarily related to the loss of fish habitat, the inundation of land, and the loss of scenic rivers. In actuality these concerns actually were initially raised in the early 1900's when the City of San Francisco began plans to build the Hetch hetchy reservoir on the Tuolome River which inundated a scenic valley in Yosemite National Park. However, it was not until about 1965 that the Environmental Protection Agency was created and the National Environmental Protection Act was passed by the Congress. That act was quite broad and led to a large number of environmental protection policies at the federal level. Many of these policies impacted the individual States
strongly. The act essentially requires that any project to be constructed in the United States must be studied for its environmental effect which requires an Environmental Impact Report. That Environmental Impact Report must identify all impacts that construction of the project will cause and must be reviewed by all Federal and State agencies concerned with any of the potential impacts. Any private person may also review and comment on the environmental report. Public hearings are usually held, and may be required to inform the public about the proposed project. If the potential impact is judged to be significant, an Environmental Impact Statement may be required. The Environmental Impact Statement references the Environmental Impact Report and must develop mitigation measures which will be undertaken to mitigate the identified environmental impacts. For the case of dams and reservoirs detailed field studies are frequently required. These field studies usually include some studies that are normally required for design such as reservoir surveys and sediment surveys but usually include many other studies such as a survey of riparian types of fish and their numbers and the extent of use of the river and the general area for recreation. This Environmental Impact Statement will be widely reviewed by Local, State, and Federal agencies as well as environmental activist groups and individuals. For a new dam the process takes several years and may result in legal action by environmental activist groups or concerned citizens who wish to stop the project and believe that the environmental impact of the project outweighs the economic benefit.

For storage dams without power facilities the environmental permits are issued by the relevant State Agencies and also by the pertinent federal agency which is usually the U.S. Army Corps of Engineers. For a dam which is to include hydroelectric power, the Federal Energy Regulatory Commission is the responsible federal agency under authority of the Electricity Consumers Protection Act. However, they cannot grant a construction license unless the required permits are granted by the pertinent State and Federal agencies.

Most developed countries have environmental laws which are similar to but not as broadly restrictive as those of the United States. Many developing countries, where most of the dam building is required, do not have such restrictive policies or environmental laws. If the necessary money is available, the project can go ahead. However, it is in obtaining the necessary capital that the environmental restrictions show up. The World Bank and other international lending institutions normally have developed a set of environmental considerations that must be met before they will agree to grant construction loans. They in effect require the preparation of an equivalent to an environmental impact report and its review and acceptance before they will agree to fund the project.

Almost no one would question that the US environmental laws have improved the environment or that protection of the environment must have a high priority. However, any one connected with the process of obtaining a permit is frustrated by the very long time required to pursue purely administrative requirements to obtain the necessary permits. The entire process has increased the cost of engineering and planning by at least 100% and often more for large complex projects. Most of the
increase in cost occurs as a result of administrative delays and not because of technical additions. Those who are planning projects feel that the entire process can and should be shortened, that they should not need to wait for months and years after preparing an Environmental Impact Statement to receive a decision as to whether or not they are going to be allowed to build their project. Whether or not such a streamlining process can and will be achieved remains to be seen. One thing that is certain is that the entire environmental process in the USA has produced several new professions the largest, most active, and most wealthy of which may the Environmental Attorney.

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