MULTI-DAM SYSTEMS AND THEIR OPERATION

J.J. Cassidy
Consulting Hydraulic and Hydrologic Engineer, Concord, California, USA

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Summary

Dams and reservoirs are planned and constructed to provide benefits in the form of flood damage reduction, water for irrigation, water for industrial and municipal use, generation of electricity and or enhancement of navigation. The dams may be designed to achieve a single beneficial purpose or multiple benefits. Efficient and timely operation of the dams is required to manage water effectively, insure safety of the dams, and to achieve the benefits for which the projects were designed. Multi-dam systems are composed of a variety of dams whose functions interact through use of the water stored in the reservoirs. The water may be used multiple times in a series of dams and reservoirs or only once in the case of a single dam. Operation of multi-dam systems can be very complex if a large number of dams are involved and the dams have multiple purposes. Digital computers, computer programs, and real-time data acquisition systems are desirable if not absolutely necessary to efficiently operate multi-dam systems, particularly systems where multiple purposes are designated for use of the water. Environmental restrictions are common in the operation of dams and can include water-quality concerns and the enhancement of aquatic life in the reservoirs and in the

streams of the watershed.

1. Introduction

The distribution of water throughout the earth varies significantly from area to area. Annual depth of rainfall varies from near zero in the great deserts of the world to several hundred millimeters in the wetter areas such as Cherrapunji, India. In addition, the depth of rainfall is not uniform throughout the year in many regions and distinct variation occurs between years. Initially, civilization developed along rivers and streams where a dependable supply of fresh water was available. However, as local and international economies have developed over centuries, settlements have tended to develop in areas where natural resources could be economically utilized, and where annual flooding would not interrupt the pattern of life. In order to support life it was ultimately necessary to compensate for the fact that water was not always available at the desired location in adequate quantities or at the right time. The logical solution was to develop a reservoir where water could be stored during periods when the river or stream flowed with excess water and to utilize the stored water at future times when the normal stream flow could not satisfy society's needs. A dam constructed to create the needed reservoir was the logical development.

As dams developed they have become larger with larger reservoirs. The purposes for constructing the dams have expanded to include the multiple benefits for irrigation, navigation enhancement, municipal and industrial supply, energy generation, flood damage reduction, and recreation. As these purposes have expanded the need for better methods of operation of dams has expanded as well. The various legal and environmental ramifications for appropriation of water and the multitude of owners in a multi-dam multiple purpose system require detailed real-time operation to optimize the benefits. The complexity of ownership requires detailed daily accounting of water used and stored. Efficient operation can only be achieved if the operator has access to current data for streamflow and rainfall in the basin, and for reservoir contents at all dams in the system.

Daily operations of dams concentrate on efficiently managing water to store all that can be stored subject to legal and environmental restrictions. The ultimate goal is to efficiently manage the operation in order to maximize the benefits that are achieved from the water in the system. In addition, it is vital to carefully manage the system during passage of extreme floods in order that the dam remains safe and downstream flooding is minimized.

Where ever the word project is used throughout this monograph the reader should understand that a project implies a dam or dams and associated reservoirs and the downstream uses such as irrigated lands or reaches of the river where enhancement of navigation takes place.

2. Historical Development of Dam Operation

The earliest known dams were constructed approximately 4000 years ago. In approximately 2000 BC, water was diverted from the Nile River during periods of flooding to an existing off stream depression. Water was conveyed to the depression through a constructed canal and was controlled by two dams. Water for irrigation was released from the depression as needed during the growing season. Marib dam was constructed in what is now Yemen sometime between 1000 BC and 700 BC. An earth dam 21 meters high was constructed in Sri Lanka in 500 BC and is still in use today. These ancient dams had to be very small with a unique purpose. Their operation had to be very simple. Most of these early dams probably failed early and often as a result of having inadequate or no spillways and no readily usable outlet works by which releases from the dam could have been reliably controlled. Outflow from the reservoir was probably initiated by partial breaching of the dam and it was quite likely that outflow could not be stopped until the reservoir was empty.

Continuous developments in science, engineering, and construction have made it possible to construct larger and more durable dams, most of which now have more than one beneficial purpose. With water being so important for sustaining and enhancing life, the extensive development of dams throughout the world is not at all surprising.

The earliest dams were small and had a unique purpose, to store water for use in times of need. The needs were generally for a drinking supply and/or irrigation. As science and engineering developed and economies broadened, additional uses for dams were envisioned. If water could be stored during times of flood, then logically the potential for downstream flooding could be reduced. With developments in metallurgy and manufacturing, first water wheels and then hydraulic turbines and generators were developed and the possibility for generation of electricity was realized. It also became possible to manufacture and fabricate large gates and valves so that releases from the reservoirs could be reliably controlled. Significant developments in the design and manufacture of construction equipment, made the development of large irrigation systems possible and created large demands for water. All of these developments made it desirable and possible to operate dams with more flexibility with the result that beneficial uses of dams has been enhanced, reliability of operation has been increased, and dam safety has been improved.

2.1 Operation to Meet Beneficial Uses

As a result of the modern developments, and reliable operating systems, dams could be constructed to successfully provide multiple benefits for society. A list of those benefits includes:

- Municipal and industrial supply
- Irrigation
- Generation of electricity
- Flood damage reduction
- Improvement of downstream navigation
- Recreation

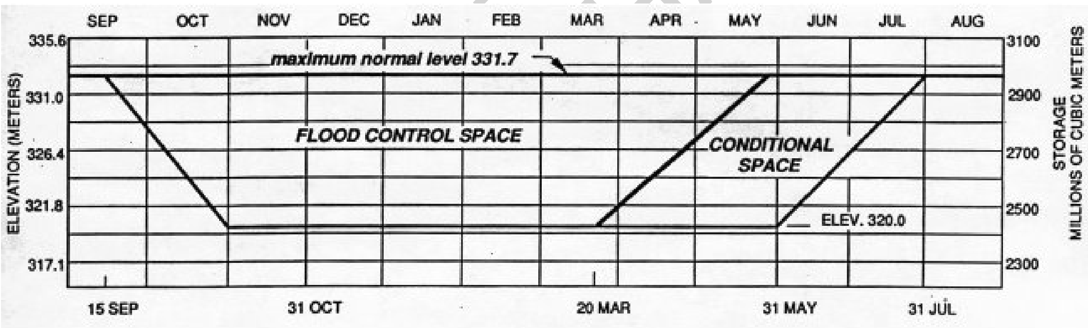
The beneficial purposes of municipal and industrial supplies and irrigation are essentially self explanatory in that water is stored in the reservoir whenever available and is released later as needed to meet downstream demands.

Generation of electricity requires installation of turbines and generators which together produce electrical power in accordance with the following equation:

$$P = E\,Q\,\gamma\,H \qquad (1)$$

where P is power, Q is the flow rate through the turbine, γ is the unit weight of water, H is the vertical distance between the elevations of the reservoir water surface and the tailwater surface, and E is the combined efficiency of the generator and turbine. Hydropower is particularly beneficial in that it is a clean process and does not deplete a natural resource. In addition, hydroturbines and generators can be brought on line quickly so that they can be used to meet either peak or base-load energy requirements as necessary.

If space in the reservoir is allocated particularly to flood storage, at least a portion of the inflowing flood waters can be stored and the rate of release to the downstream river can usually be less than the peak of the incoming flood. The effect of storing flood waters in the reservoir is to reduce the magnitude and extent of downstream flooding and the resulting damage. In the past this beneficial purpose was commonly referred to as Flood Control which could be thought of as inferring that completion of the dam would prevent any future downstream flooding. The modern terminology, Flood Damage Reduction more clearly describes the role of the reservoir in the storage and later release of flood waters. Figure 1 graphically displays the way in which operation of a reservoir makes it possible to reduce levels of downstream flooding from those which would occur if there were no dam in place.



FLOOD CONTROL OPERATION AND UTILIZATION OF FLOOD CONTROL SPACE

1. Whenever water is stored in the Flood Control Space it shall be released as rapidly as possible without causing flows in the Stanistaus River at Orange Blossom Bridge to exceed 227 cu. meters/sec.
2. Whenever water is stored in the Conditional Flood Control Space released shall be made at sufficient rate, based on anticipated snowmelt runoff, so that the pool elevation will not exceed 331.7 meter subject to the limitations in paragraph 1 above.

Figure 1: Flood Peak Reduction Accomplished by Dam Operation

Improvement of Navigation by dams can be accomplished in two ways. Some dams are relatively low and navigation locks are constructed as part of the project. The presence of the dam increases the depth of flow in the reach of the river upstream of the dam enhancing the use of that reach of the river for navigation by boats and barges. These types of dams are “run-of-the-river” dams in that the flow rate released through each dam is equal to the inflow rate for most operations and the water level in the reservoir is maintained at a near constant elevation. Navigation is improved downstream of large dams by storing water in the reservoir during periods of high flow and releasing water during low-flow periods in order to maintain downstream river depths favorable to navigation.

Recreational use of reservoirs varies greatly from reservoir to reservoir. . Releasing water to maintain desired water levels in the river downstream can enhance the recreational use of the river. Recreational benefits can be great in developed countries where available leisure time allows many days of boating, fishing and swimming in the reservoir. However, recreational use can add to the gross national product of some developing countries as well. For example, Lake Kariba on the Zambesi River between Zimbabwe and Zambia, attracts a large number of tourists who rent house boats for comfortable safaris to see wild game along the shores of the Lake

Storage of flood waters and later release allows maintenance of specified instream flow rates downstream from a dam. This is sometimes considered to be a benefit, particularly for rivers which have little or no flow during long periods of the year. Attention given to environmental considerations in the past three decades has made maintenance of instream flows more important than ever. Instream flows may be required to enhance fish or animal habitat downstream from the dam. For example, when Shasta Dam was completed in 1938 on the Sacramento River in California, USA, little consideration was given to the need to provide water for maintenance of aquatic life in the Sacramento River far downstream from the dam. However, in the early 1990s legislation was passed that now requires the annual release of 980 million cubic meters of water for the enhancement of aquatic conditions in the downstream-most reach of the river.

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