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The Effects of Dams, Reservoirs And Levees On River Forecasting

Richard M. Greening

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U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
U.S. WEATHER BUREAU

Weather Bureau Technical Memorandum ER-16

Second Edition

THE EFFECTS OF DAMS, RESERVOIRS AND LEVEES ON RIVER FORECASTING

Richard M. Greening

EASTERN REGION HEADQUARTERS
SCIENTIFIC SERVICES DIVISION
TECHNICAL MEMORANDUM NO. 16

GARDEN CITY, NEW YORK
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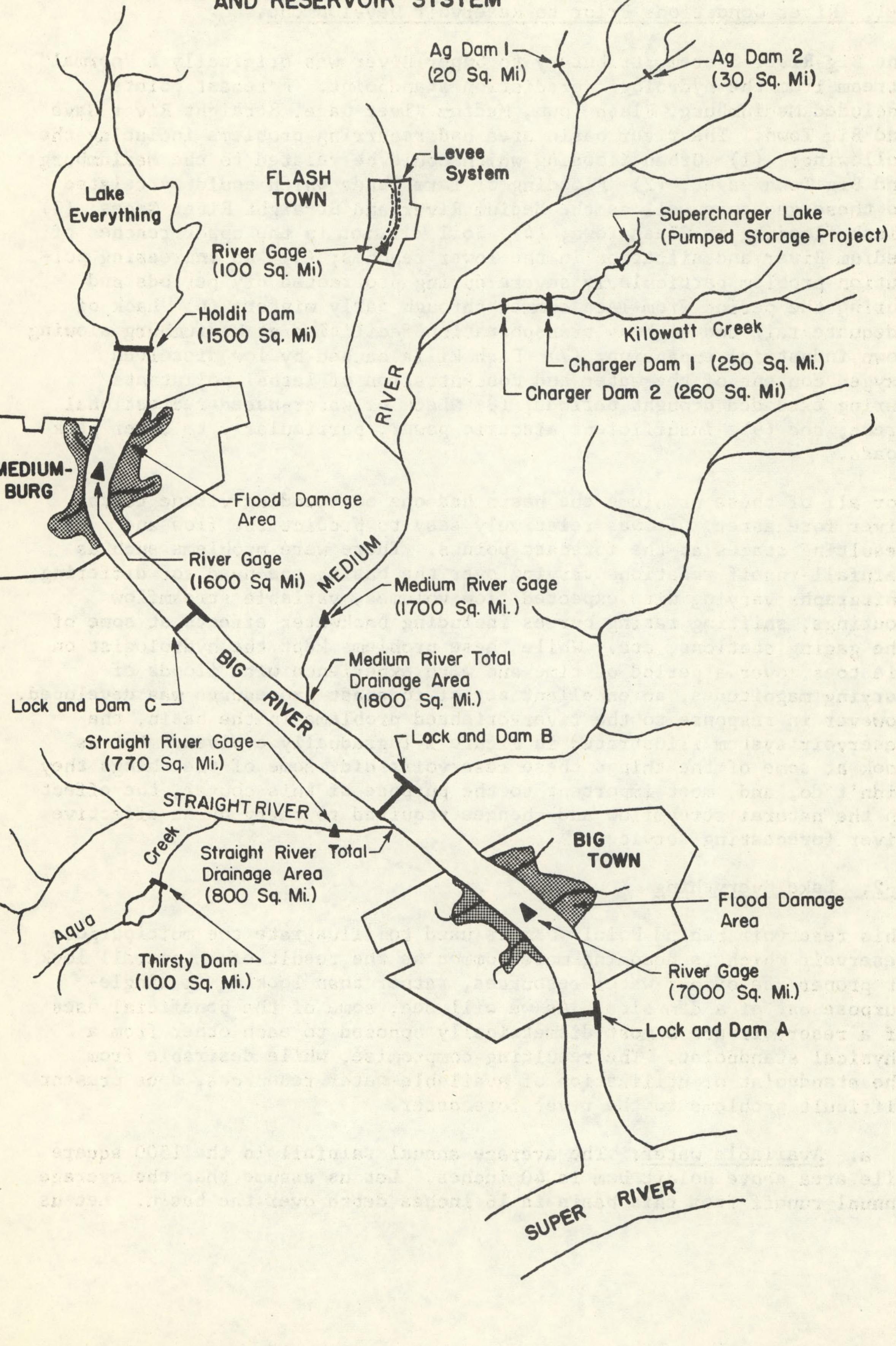
CONTENTS

INTRODUCTION

Technical Memorandum Number 16 was written primarily for inclusion in the U. S. Weather Bureau Hydrologic Public Service Course. This memorandum discusses the effect of man-made controls on river flows and river forecasting. The river system portrayed with its various types of controls and forecast problems is entirely hypothetical. Most of the problems that are incurred when man disturbs natural drainages are thus demonstrated in a single river system.

Fig 1-1 DIAGRAM OF "BIG RIVER" HYPOTHETICAL RIVER BASIN AND RESERVOIR SYSTEM



1-1. River Conditions Prior to Reservoir Development.

The Big River System, tributary to Super River was originally a "normal" stream from the hydrologic prediction standpoint. Forecast points included Mediumburg, Flash Town, Medium River Gage, Straight River Gage and Big Town. The river basin area had recurring problems including the following: (1) Urban flooding which could be related to the Mediumburg and Big Town gages; (2) Flooding of farm lands which could be related to these gages as well as the Medium River and Straight River Gages; (3) Flash flooding in Flash Town; (4) Soil erosion in the upper reaches of Medium River and siltation in the lower reaches; (5) an increasing pollution problem particularly severe during protracted dry periods and during the period from late summer through early winter; (6) Lack of adequate rail and highway transportation facilities at Mediumburg slowing down industrial expansion; (7) Fish kills caused by low dissolved oxygen content of the water and concentration of lethal pollutants during extended drought periods; (8) Lack of water-based recreational areas; and (9) Insufficient electric power, particularly to cover peak loads.

For all of these problems the basin had one outstanding virtue to the river forecaster. It was relatively easy to predict the flow and resulting stages at the forecast points. There were problems such as rainfall-runoff relations varying over the basin, the need for differing unitgraphs varying with expected flow volumes, variable streamflow routings, shifting rating curves including backwater effects at some of the gaging stations, etc. While these problems kept the hydrologist on his toes, over a period of time and with experience with floods of varying magnitudes, an excellent set of forecast procedures was developed. However in response to the river-oriented problems in the basin, the reservoir system illustrated in Figure 1-1 gradually evolved. Let us look at some of the things these reservoirs did, some of the things they didn't do, and, most important to the purpose of this course, the effect on the natural streamflow and changes required to carry on an effective river forecasting service.

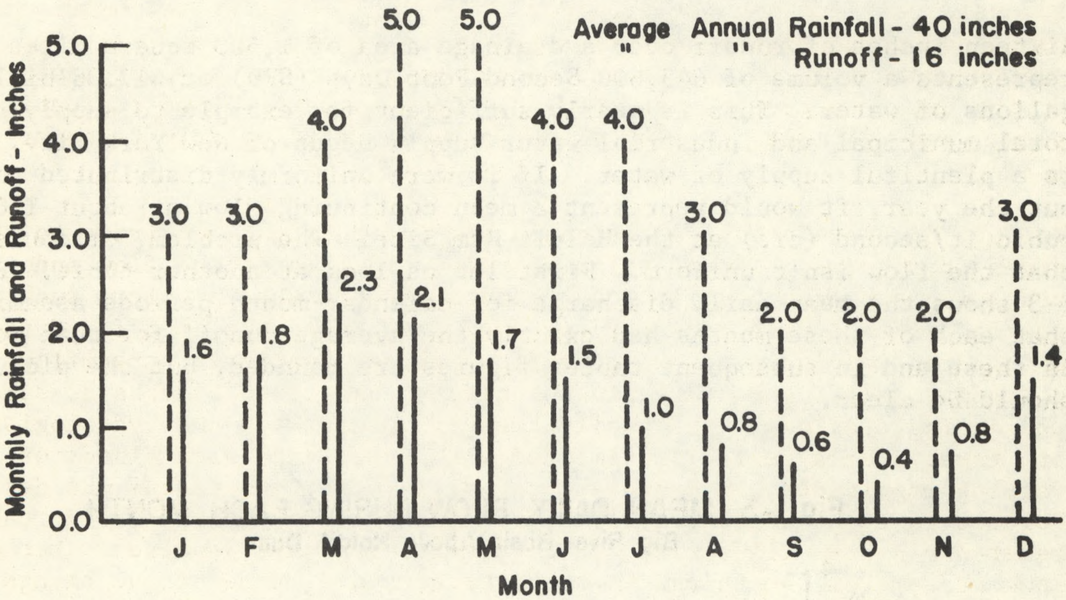
1-2. Lake Everything

This reservoir behind Holdit Dam is used to illustrate the multipurpose reservoir which is becoming more common as the result of an overall look at proper use of our water resources, rather than looking at single-purpose use of a dam site. As we will see, some of the beneficial uses of a reservoir are almost diametrically opposed to each other from a physical standpoint. The resulting compromise, while desirable from the standpoint of utilization of available water resources, does present difficult problems to the river forecaster.

a. Available water: The average annual rainfall in the 1500 square mile area above Holdit Dam is 40 inches. Let us assume that the average annual runoff from this basin is 16 inches depth over the basin. Let us further assume that the presence of the reservoir has no effect on the amount of water available at the damsite. This is not strictly correct, because evaporation from the lake surface will be higher than that of the natural terrain prior to the presence of the lake. This would make slightly less water available when the reservoir is in operation, but for purposes of illustration we will ignore this refinement. The distribution of these average values is illustrated in Figure 1-2.

Fig I-2 MEAN MONTHLY DISTRIBUTION OF AVERAGE RAINFALL (¦) AND RUNOFF (|)

Big River Basin Above Holdit Dam



Before proceeding further, let us define units and relate them to each other.

Cubic foot per second (cfs) - A volume of flow past a point of one cubic foot in one second.

Second foot day (SFD) - A flow of 1 cfs for a period of one day. (Also commonly referred to as day second foot or DSF.)

One SFD = 86,400 cu. ft. $\left(\frac{1\ ft^3}{sec} \times \frac{60\ sec}{min} \times \frac{60\ min}{hr} \times 24\ hr = 86{,}400\ ft^3\right)$

1 Cubic Ft. = 7.48 Gallons. Therefore 1 SFD = 646,000 Gallons.

1 inch of water (or runoff) over an area of one square mile = $2{,}323{,}200\ ft^3$ = 26.9 SFD or 17.38 million gallons.

For the 1,500 square miles of drainage area above Holdit Dam

26.9 X 1,500 = 40,350, so

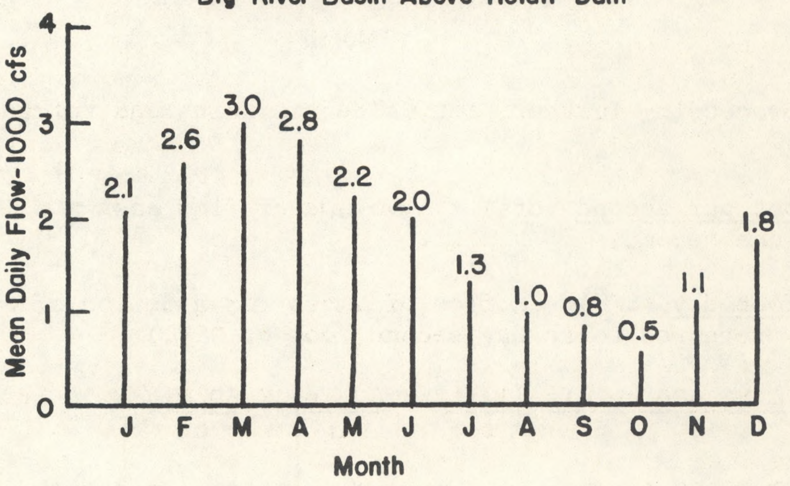
1 inch of Runoff = 40,350 SFD or about 26.07 Billion gallons.

Another term commonly used, particularly in the West, is Acre Foot (AF). This is defined as the volume necessary to cover one acre to a depth of one foot. 1 AF = 43,560 ft^3 $\frac{43,560}{86,400} = .504$. 1 Acre Foot = 0.504 SFD or roughly 1/2 SFD. This gives a standard of comparison if you see this term used with reference to reservoir storage or volume needed for irrigation purposes, etc.

Sixteen inches of runoff over a drainage area of 1,500 square miles represents a volume of 645,600 Second Foot Days (SFD) or 417.06 billion gallons of water. This is nearly sufficient for example to supply the total municipal and industrial water supply needs of New York City. This is a plentiful supply of water. If it were uniformly distributed throughout the year, it would represent a mean continuing flow of about 1769 cubic ft/second (cfs) at the Holdit Dam Site. The problem, of course, is that the flow isn't uniform. First let us look at another table. Figure 1-3 shows the mean daily discharge for calendar-month periods assuming that each of these months had exactly the average runoff for that month. In these and in subsequent tables figures are rounded, but the picture should be clear.

Fig 1-3 MEAN DAILY FLOW DURING EACH MONTH

Big River Basin Above Holdit Dam

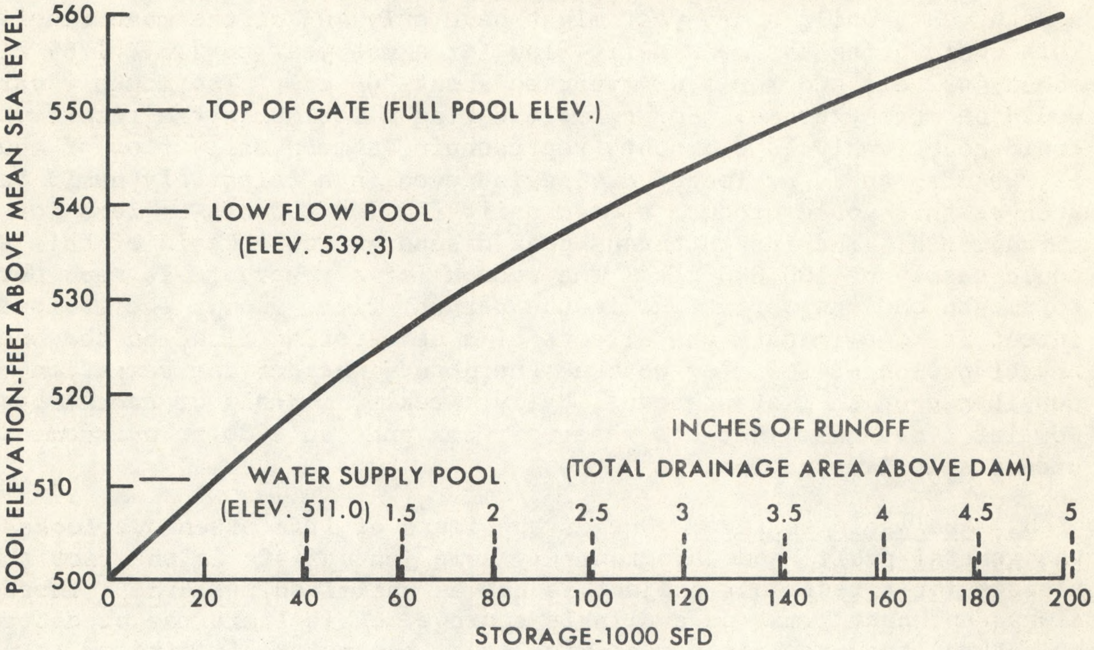


This graph gives average variation in the flow throughout the year. Even if "average" runoff conditions occurred, the mean daily discharge would vary from about 3000 cfs in March to 500 cfs in October instead of a nice smooth flow of about 1800 cfs throughout the year. Now let us look at more interesting values than the mean. Without getting far out of the realm of reason a wet year may have 2.5 times the runoff of a mean year, while a dry year might have only 40% of the mean runoff. This would bring the mean daily flow for a wet year to 2.5 X 1769 cfs, or about 4422 cfs and for a dry year to about 708 cfs. The monthly variation would be more extreme. For example during a wet March the runoff volume could conceivably be 10 inches representing a mean daily flow of about 12,900 cfs, and a prolonged dry period even in a relatively humid basin such as this could produce a mean daily flow of 100 cfs or less for a given month. The instantaneous peak discharge for a basin of this size could easily be 100,000 cfs. The reason for a reservoir is thus obvious - to smooth out the variations in the natural river flow. The obvious intent is to eliminate the effects of a devastating flood on the one hand and of prolonged low flow on the other hand, whether the variation be considered on an instantaneous, daily, weekly, monthly or annual basis. Now let's see just what the reservoir can and can't do to overcome this undesirable fluctuation.

b. Available storage. One of the facts of life often overlooked by the general public and unfortunately some journalists is the fact that storage for a reservoir project is not an unlimited resource. There is always an upper limit on available storage. This limit may be determined by natural topographic characteristics of the reservoir site or it may be imposed by economic practicalities, but it is always present. If the terrain is relatively flat, it is not practical to flood a large portion of the valley which would likely be excellent farmland. On the other hand if the valley terrain is narrow and rugged on both banks of the stream, then cities, railroads, highway road beds, etc. tend to follow the valley floor. Thus the economic benefits of the reservoir do not justify all the resettlement involved in the construction of a completely adequate reservoir. Let us say that a careful topographic survey and economic study have disclosed that a total storage of 200,000 SFD or approximately 396,000 Acre Feet is available between elevations 500 ft MSL (bed of river) and 560 ft MSL (maximum allowable height of reservoir). The relation between elevation and storage for a reservoir is often depicted graphically as in Figure 1-4.

The dam will likely be designed to allow some 10 ft of reservoir elevation above the top of gates to allow for the probable maximum flood, but the reservoir is invariably operated to prevent water flowing over the gates and the elevation 550 ft is thus considered the "Full Pool Level". Thus for operational purposes the available storage is 148,000 SFD. Since one inch of runoff over the 1500 square mile drainage area is 40,350 SFD of volume, we have an available storage of some 3.67 inches of runoff up to the full pool level. This is a large reservoir for this size drainage basin. Now let us look at the purpose for which the storage will be used and see how the available storage is to be distributed for the different reservoir functions.

FIG. 1-4 ELEVATION-STORAGE CURVE
LAKE EVERYTHING RESERVOIR



c. Allocation of storage. As indicated earlier the reservoir will serve several purposes. Let's look at some of the potential uses and resulting decisions necessary in future operations. For subsequent considerations keep the following simple formula in mind, change in storage = inflow minus outflow or $\Delta S = I - O$. This is a basic consideration which can be manipulated many ways, but not overlooked.

1. Flood Control. A single-purpose flood control operation would be to keep the reservoir bone dry except in times when surface runoff is occurring. The gates would then be closed until the runoff period was over. The reservoir would then be emptied at a rate which would not be harmful further downstream and we would return to a bone dry reservoir until the next runoff period. If this were possible we would have flood control storage of 3.67 inches available nearly all the time. This would be sufficient for all but the most extreme floods. Another possibility would be to release at a limited rate during the flood to increase available storage for the maximum flood period. For example if a continuous flow of 10,000 cfs were released for one week this would make available an additional 70,000 SFD of flood control storage available or 1.74 inches of runoff. This would make a total available storage plus controlled flow of 5.41 inches *if* a release of 10,000 cfs were allowable. This would be an excellent flood control reservoir which would effectively eliminate all but the most severe floods and could be operated to reduce those. Of course runoff events

do not always space themselves conveniently to allow for emptying the reservoir between times, among other possible factors to consider, but let us now look at the reduction in flood control benefits necessitated by other proposed uses of the reservoir.

2. Water Supply. For this single-purpose the reservoir would be kept as full as runoff conditions permitted. This would reduce pumping costs to withdraw water from the reservoirs. It would also effectively eliminate virtually all flood control benefits of the reservoir. To build a reservoir this large solely for water supply purposes would be unrealistic economically, so a decision is required as to how much storage to allocate for this purpose. Let us make some simplifying assumptions for purposes of illustration. First assume the water supply will be used for Middleburg and environs with a total population of 700,000 people. At present the average per capita consumption of water for all purposes nationwide is about 150 gallons per day. This includes home, industrial, agricultural and all other uses. For an industrialized city, such as Middleburg, the average consumption might approximate 250 gallons per day. Let us assume this consumption, to avoid further complication, and assume uniform distribution throughout the year. After a study of past flow records, it was decided to design for possible serious drought conditions indicating a minimum average daily inflow for six months of 150 cfs. This would be a total volume of inflow for 6 months of about 27,400 SFD or equivalent volume of about 0.68 inches of runoff. With the assumed consumption rates for 700,000 people, of 250 gallons per capita per day, the consumption for 6 months would be about 31.9 billion gallons or about 1.23 inches of runoff. If we accept this as the design criterion, we will have to allot the difference between consumption and inflow (1.23 inches - 0.68 inches Runoff) of 0.55 inches of storage or about 22,200 SFD for water supply storage.

What does this mean? It means that the water in storage would never deliberately be drawn down to less than 22,200 SFD of storage to provide for an assured water supply for users. This would be poor planning in that no increase of average consumption or no population growth rate has been considered. Also such factors as evaporation and seepage losses have not been considered. As pointed out this is an idealized example. Let us look back to Figure 1-4. A storage of 22,200 SFD would represent a pool elevation of about 511.0 ft. So we will call 511.0 ft the Water Supply Pool Elevation. We have now reduced our storage available for flood control from the original 3.67 inches to 3.12 inches.

3. Low flow augmentation. One of the major benefits anticipated from the Lake Everything Reservoir is the assurance of reliable flow downstream from the dam. This is beneficial in many respects; it alleviates pollution problems, it enhances development of fish and other aquatic life and vegetation, it allows for reliable river navigation further downstream and offers potential for recreational facilities by eliminating the unsightly mud flats formerly in evidence during low flow periods, making small boat travel feasible, etc. It also enhances

property values along the streams. After some study a flow of 450 cfs is determined as the desirable minimum flow and is established as the minimum release through the outlet works at Holdit Dam.

Using the same design criterion as for water supply needs, let us assume the natural low flow conditions without the dam would be for an average flow at the damsite of 150 cfs for 6 months. Actual flow conditions might vary during this period say between 500 cfs and 50 cfs, but the average must be considered to determine necessary volume. When the reservoir is designed, we cannot consider this volume of flow in determining how much volume is needed to provide the 450 cfs daily flow for low flow augmentation. Why not? Simply because this volume has already been reserved for water supply purposes. We must assume that the water needed to augment flow is in addition to that needed for water supply. An average daily release of 450 cfs for this 6 month period represents a total volume of about 82,000 SFD of storage to be reserved (allocated is the usual term) to augment low flow. This would be about 2.04 inches of runoff over the basin. Since 0.55 inches (22,200 SFD) of storage have already been allocated for water supply, this low flow augmentation storage would be on top of that amount making a total requirement of dedicated (reserve) storage of 2.59 inches (104,200 SFD) for these 2 purposes. Going again to Figure 1-4 this would represent a pool elevation of about 539.3 ft. This reduces our flood control storage from the original 3.67 inches to 1.08 inches. The elevation of 539.3 ft we will identify as the Low Flow Pool Elevation, and if the design assumptions are accepted, we will never deliberately draw the pool down below that level.

4. Other possible storage conditions. In some reservoirs it might be deemed advisable to provide additional storage above the water supply and low flow requirements to assure a sizeable lake for recreational and aesthetic purposes. If this were done it would necessarily further deplete the flood control storage available. Let us assume that Lake Everything will have adequate water available stored for water supply and flow augmentation use to satisfy most (never all) avid conservationists and recreationists and leave it as Lake "Nearly" Everything to avoid further complication.

Another possible use for the reservoir storage would be for irrigation. This feature of a reservoir is diametrically opposed to flood control. Perfect flood control would require no storage whatsoever during the maximum runoff season while for irrigation purposes every possible drop should be retained behind the reservoir to release to the parched crops in the hot dry summer. While some supplementary irrigation is desirable in even such a moist climate as Florida, the Big River Basin is a climatic area where storage for irrigation purposes would normally not be seriously considered and we will not include irrigation storage in our hypothetical reservoir design.

Storage of water for generation of hydroelectric power is another possibility which might be considered. For efficient power generation the difference in elevation between the pool behind the dam and the river level below the dam (this elevation difference is called the "head") should be kept as large as possible. In other words the lake should be as full as possible for power purposes while for flood control it should be as empty as possible. Since power can be marketed and sold for a profit the question of whether to sacrifice some flood control storage for power generation is often not an easy question to resolve. A compromise often results which provides neither the best possible power dam or flood control dam, but keeps the most tax payers happy. In the case of Lake Everything we will assume that the economics in favor of flood control storage win out and not include power as a consideration. In addition to making it easier for a reservoir operator or a river forecaster to sleep nights, this assumption avoids a further complication in preparing the example for this course. We will have more on a hydroelectric dam when we come to the Charger Dam System on Kilowatt Creek.

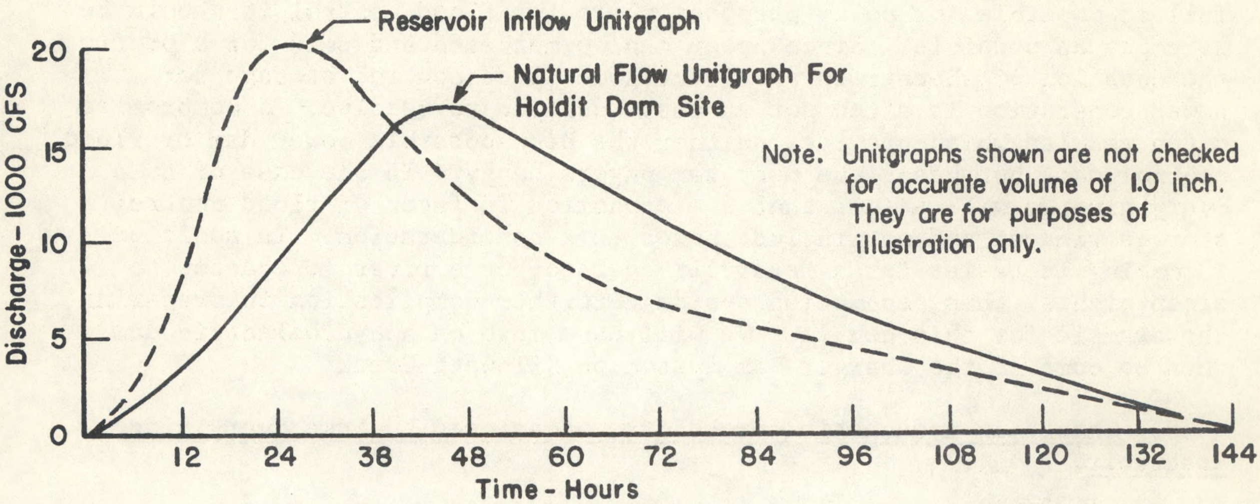
d. <u>Change in forecasting procedures occasioned by Lake Everything Reservoir</u>.

1. The first change would be in the unit hydrograph or unitgraph which was valid for natural flow conditions. As defined earlier in the course, basically the unitgraph is the flow at a gaging point resulting from one inch of runoff occurring in a particular time period over the drainage area above that gaging point. This is a basic tool used in river forecasting. For one thing the rain falling directly on the water surface of the lake would instantly show up as reservoir inflow. Also at the farthest reaches of the lake, flow would enter the reservoir and almost immediately show up as increased storage and therefore a higher elevation at the dam. Under natural conditions the dampening effect of valley storage in the river channel would delay this flow at the damsite. The effect of this "lost valley storage" can be illustrated by a simple experiment in the home. Water poured in the upper end of an empty bath tub slowly flows toward the drain. If the tub already has water in it the same inflow will produce a rapid rise at the opposite end. Figure 1-5 shows the hypothetical 12 hour unitgraph for 1 inch of runoff before and after the completion of the reservoir.

Note that the volume would be the same, but the unitgraph peak would be earlier and somewhat higher. This would not necessarily be true of any dam but would depend on basin shape, slopes, storage characteristics of the reservoir, etc. In a drainage area of this size it would be quite common. In any event, some change will occur, due simply to the reservoir being there. This is extremely difficult to evaluate theoretically and it is usually necessary to experience a few river rises after the reservoir stores water until a completely reliable inflow unitgraph can be developed.

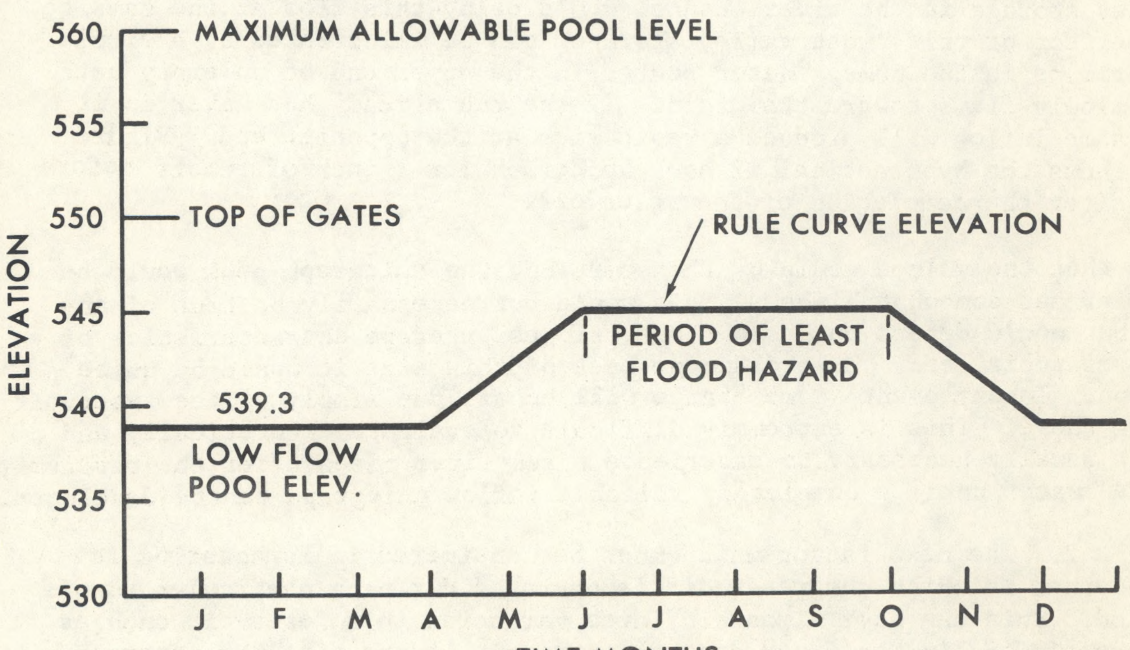
2. The next factor which must be considered in forecasting is the manner in which the reservoir is operated during a particular runoff period. This can have almost infinite variation in a reservoir such as this one with limited flood control storage. At the time the reservoir is designed, an optimal level varying during the year is developed, and

Fig I-5 12 HOUR UNIT HYDROGRAPHS FOR HOLDIT DAM SITE



the reservoir is kept as near this level as feasible depending on streamflow conditions. This operational criterion is known as a rule curve. A hypothetical rule curve is shown in Figure 1-6 for Lake Everything.

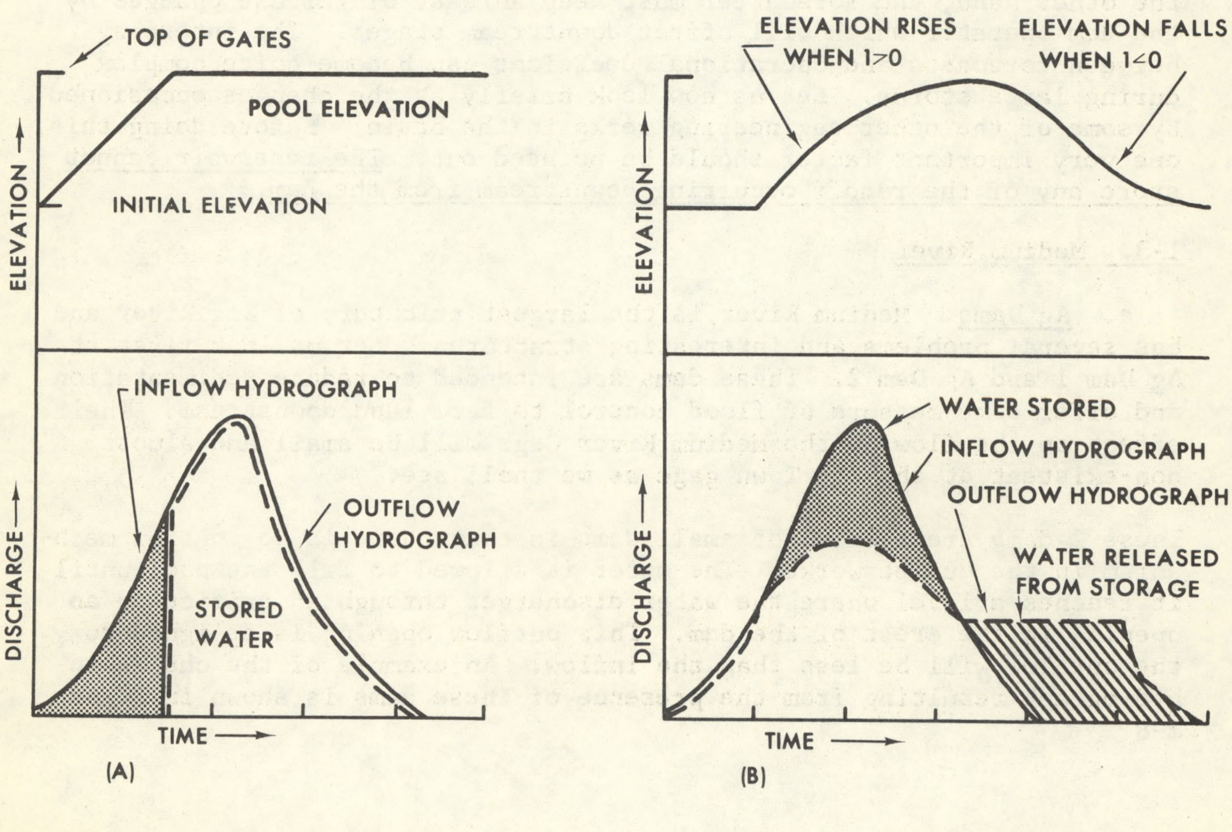
FIG. 1-6 RULE CURVE-LAKE EVERYTHING



In this rule curve, during the period December 1 through March 31, when flood hazard is greatest, the pool level is kept at the Low Flow Pool Elevation of 539.3 ft to allow the maximum 1.08 inches of runoff of flood control storage. On April 1 the pool level is allowed to rise to a maximum of 545 ft from June 1 through September 30 since the flood threat would be diminished and it is necessary to store as much water as possible for the season when outflow would normally be greater than inflow. On October 1 the pool level is dropped gradually to the 539.3 ft level. This rule curve is only a guide to be strived for. Flow conditions seldom permit the level to be exactly what the rule curve states. However if the pool filled during February, for example, releases would be scheduled to bring the level down to 539.3 as rapidly as possible to make the flood control storage available again. Likewise if the elevation were at 535 ft in August, all available runoff above the 450 cfs minimum release would be stored to bring the pool back up to the 545 ft rule curve elevation.

Suppose that runoff occurs in excess of the storage available. There are several possible ways of handling this depending on the operating criteria set up when the reservoir is designed. Figure 1-7 shows two ways of operating. In both of these operations the inflow runoff is identical and is greater than the available storage up to the top of the gates. The initial elevation is the same in both cases. In (a) the reservoir is allowed to store water until the top of gates is reached.

FIG. 1-7 RESERVOIR OPERATION-LAKE EVERYTHING



At this point the outflow must be made equal to the inflow or the water will flow over the gates anyway with possible damage to the gate structures. This is a fairly typical operation for a small reservoir intended for water supply or power generation, and any flood control storage achieved is a matter of chance. Whether the flood crest was different from the natural flood crest would depend on the changes in flow characteristics produced by the presence of the reservoir, plus the timing of the event. If the reservoir filled after the inflow peak, the flood crest might be reduced substantially. If it filled prior to the crest there would be no change in the natural flow hydrograph.

In (b) a more typical operation for a reservoir such as Lake Everything is shown. In this operation a maximum safe release is allowed consistent with preventing complications downstream. As long as the inflow exceeds this release, the pool will rise ($\Delta S = I - O$). The release is continued after the inflow drops off until the reservoir returns to its initial level which allows storage for further runoff.

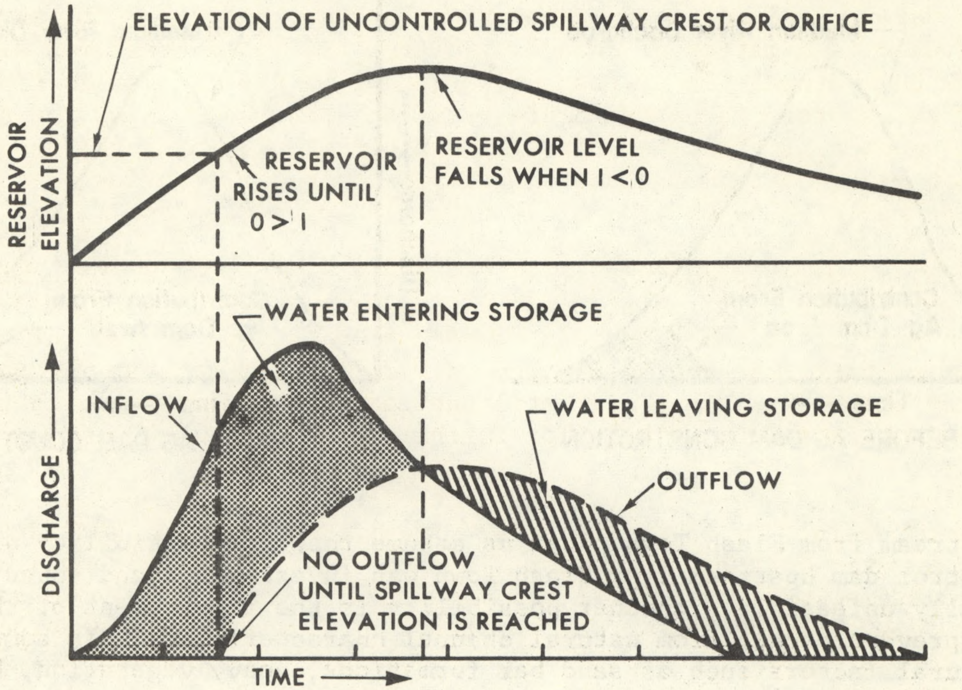
At this point, we will not go into the complexities involved with balancing out the effect of this flow on the downstream areas. There are many ways of operating the reservoir for flood control. We have shown that the forecasting problem has changed considerably and become more complex as a result of Holdit Dam. The operators of large dams need forecasts of inflow in order to make the most intelligent use of their ability to control outflow. Forecasts of flows from any tributaries that may enter Big River between the dam and Mediumburg are also important so that releases added to these flows will not cause floods at Mediumburg. On the other hand, the forecaster must keep abreast of release changes by the dam operator which will affect downstream stages. The interplay between forecasts and operational decisions can become quite complex during large storms. Let us now look briefly at the changes occasioned by some of the other engineering works in the basin. Before doing this, one very important factor should be pointed out. <u>The reservoir cannot store any of the runoff occurring downstream from the dam</u>.

<u>1-3. Medium River</u>.

a. <u>Ag Dams</u>. Medium River is the largest tributary of Big River and has several problems and interesting structures. Let us look first at Ag Dam 1 and Ag Dam 2. These dams are intended to reduce sedimentation and offer some measure of flood control to farm land downstream. Their effect on the flow at the Medium River Gage will be small and almost non-existent at the Big Town gage as we shall see.

These 2 dams are typical of small dams in that there is no control mechanism in the outlet works. The water is allowed to fill the pool until it reaches a level where the water discharges through an orifice or an opening in the crest of the dam. This outflow opening is designed so the outflow will be less than the inflow. An example of the change in hydrograph resulting from the presence of these dams is shown in Figure 1-8.

FIG. 1-8 TYPICAL OPERATION OF 'AG' DAM

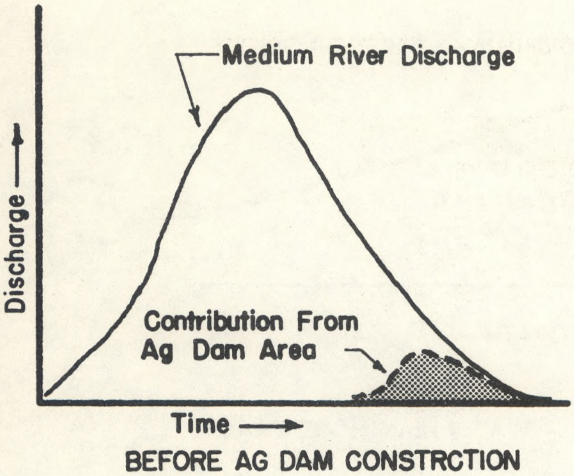


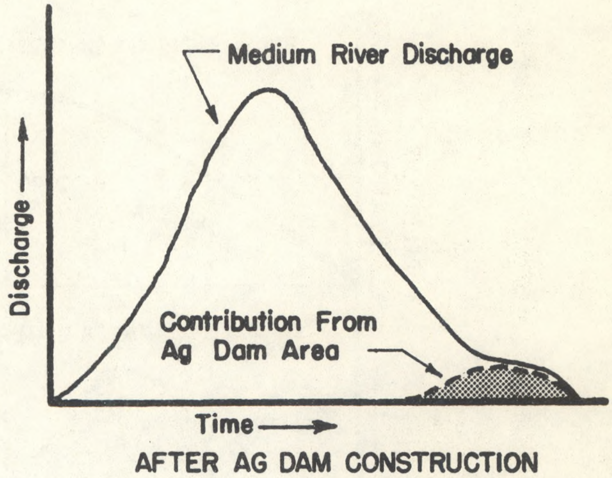
This type of reservoir can be extremely effective in reducing sedimentation, erosion and flooding for a short distance below the dam. The flood control effect diminishes rapidly as you go downstream due to the small size of the drainage area above the gage and correspondingly small volumes of water involved. In this instance the drainage area above the Medium River gage is 1800 square miles and above the two Ag Dams is only 50 square miles or less than 3% of the entire Medium River Gage drainage. Also since the dams are in the extreme headwaters, the contribution from this area above the dams arrived at the Medium River gage well after the flood crest. Figure 1-9 illustrates this minimal effect for a flood with uniform runoff above Medium River gage.

In some actual basins there is a sufficient number of this type of dam to present a significant forecast problem. Although the drainage areas of many are typically much smaller than the examples used here their summation can be critical. This is especially true since the forecaster rarely has definite knowledge of the timing of uncontrolled spill.

b. Flash Town. It should be evident that all of the reservoirs constructed on the Big River System have exactly no effect on the flash flood problem at Flash Town. Whatever problem existed prior to reservoir construction would still exist after completion of the system. The flash flood problem is a highly localized phenomenon and any structural attempts to solve the problem would have to be made in the immediate vicinity and

Fig I-9 EFFECT OF AG DAMS ON FLOW AT MEDIUM RIVER GAGE



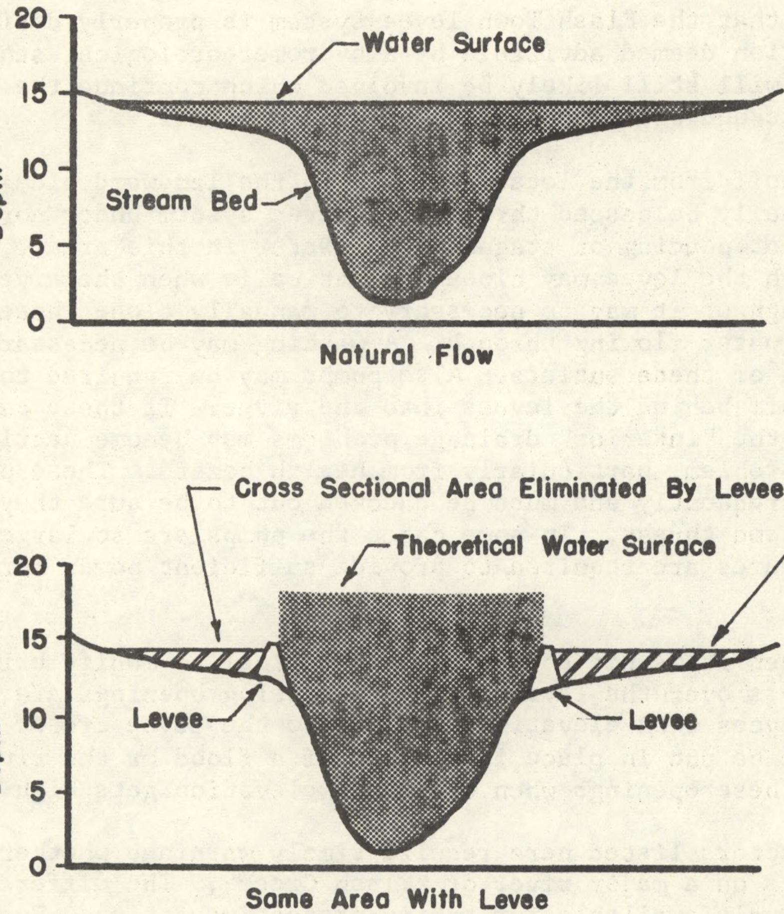


upstream from Flash Town. Let us assume that the possibility of a flood control dam upstream from Flash Town was investigated and found economically unfeasible. Another possibility is the improvement of the channel to prevent backup from natural channel characteristics. In some areas natural factors such as sand bar formations, heavy vegetation, bends in the river, etc. have slowed the flow and caused a partial damming effect which can be cleared out. Another possibility is a levee or flood wall system to prevent the water from reaching potential damage areas. Or a combination of these latter two possibilities may be employed.

In most instances the improvement of the channel is only a partial solution. Frequent overflow in low areas is often cut down drastically, but for a major flood the reduction in stage may be very slight. The river has a tendency to return to its natural conditions unless continuing dredging and vegetation control is employed. A further problem is to prevent encroachment by building and other commercial activity in the flood plain resulting from a sense of false security occasioned by the channel work. Unless flood plain zoning accompanies this work the end result may be a more serious flood problem than previously experienced.

The levee system is often an economical means of providing flood relief. Unless carefully designed and carefully maintained, however, this method can become dangerous. Some privately constructed levees may be built with the crest of the levee at the height or only slightly above the maximum flood height of record. If building proceeds behind this levee, a serious problem may result. For one thing there is no assurance that a greater flood won't occur at any time, overtopping the levee nor that the levee will not fail in a lesser flood. Another factor which may not be considered or properly evaluated is the fact that the elevation of the water surface will usually be higher for the same discharge because of the constriction of the river channel. Figure 1-10 illustrates this principle.

Fig I-10 EFFECT OF RIVER CONSTRICTION



The discharge is the product of cross sectional area of the stream and velocity of flow, or expressed mathematically Q=AV. If the discharge and velocity are reasonably constant the cross sectional area of the water will also remain constant. If the natural area is restricted the result is an increase in elevation of the water surface in order to occupy the same area. Of course, the theoretical water surface illustrated would not occur. The water would simply overtop the levee unless it could be protected by emergency sandbagging protection. This factor should be obvious but locations exist where a flow of 30% of the flood of record would overtop the levee system. In practice the velocity would be increased and the same flow could be passed through a smaller cross sectional area. Also the channel bed may scour out due to the higher velocity of flow. This would result in a different cross sectional area and conceivably even lower stages for the same flow than before levee construction. These factors would not <u>ordinarily</u> compensate for the diminishing of cross sectional area and an increase in elevation occasioned by the levee construction is quite common. All this should be considered in proper design of a levee system. Other factors must also be considered such as the effect on accelerated flow downstream from the levee.

Let us assume that the Flash Town levee system is properly designed with a crest elevation deemed advisable by a hydrometeorological study. Two other factors will still likely be involved which continue the need for river forecasts and alerts based on expected rainfall.

1. Runoff from the local drainage on the landward side of the levee will usually be passed through the levee system under normal conditions to prevent ponding or stagnation of water in this area. These outlets through the levee may close automatically when the river elevation gets high enough or it may be necessary to manually close these off to prevent flood water flowing through. A warning may be necessary for timely closure of these outlets. Also pumps may be required to pump out the storm runoff behind the levees into the river. If these pumps are not provided, the "interior" drainage problems may become nearly as serious as the flood problem, particularly from health hazard. These pumps are often used infrequently and must be checked out to be sure they are ready to meet any flood threat. In some cases the pumps are so large that emergency measures are required to provide sufficient power for their operation.

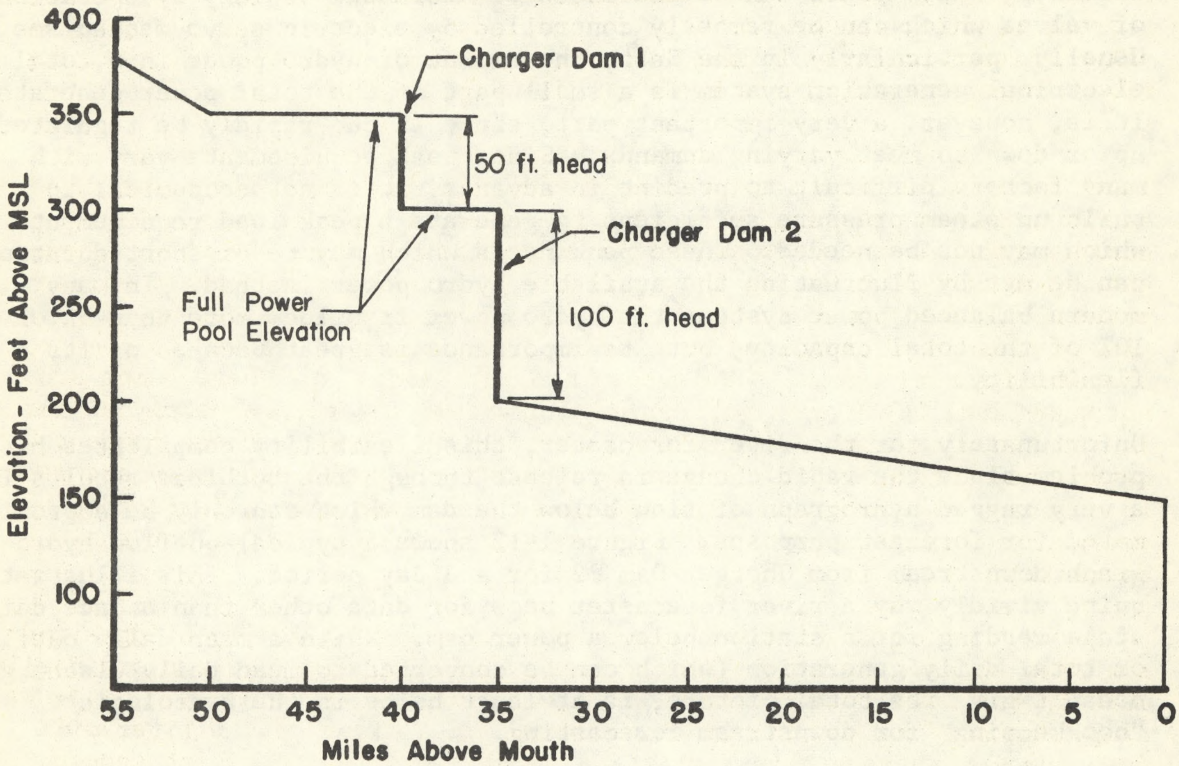
2. Often it is not economically practical to modify bridges and highways to pass over the levee system. Crossing openings are ordinarily left in the levees with elevations well below the levee crest. Gates or stop logs must be put in place in advance of a flood or the river will flow through these openings when the water elevation gets high enough.

Both of the factors listed here require timely warnings whether the levee system is on a major river or "Flash Creek". The difference is in the time intervals available for taking protective action. For a major river system several days may be available. For Flash Creek the crest may occur from 3 to 6 hours after the end of short heavy rain or serious flooding may occur even during longer periods of rain. The levee system has thus required changes in the forecast procedure due to the change in channel conditions. It has not eliminated the need for warnings. If anything flood plain encroachment has probably occurred since the levees were built and the flood problem is potentially more serious.

c. Charger Dam and Supercharger Lake. We now come to the hydroelectric operations which were conveniently skipped in describing Lake Everything. Figure 1-11 represents a cross section of Kilowatt Creek from the mouth to a point upstream of Charger Dam 1.

This figure shows one obvious reason why these dams were built where they were. Note that from mile 50 to mile 35 the natural river falls from an elevation of 350 ft to 200 ft, a fall of 150 ft in 15 miles or an average of 10 ft per mile. From mile 35 to the mouth the slope is a more gentle 50 ft in 35 mile or an average of about 1.43 ft per mile. If the water

Fig I-11 PROFILE OF KILOWATT CREEK
TRIBUTARY TO MEDIUM RIVER
BIG RIVER SYSTEM



in the steep slope area can be stored and converted to electrical energy by running through turbines this represents money in the bank. Other factors are of course considered, such as needs for power, distance of transmission lines required from source to user, topography and geology of the proposed reservoir area, value of inundated property, cost of moving roads, bridges, railroads, etc.

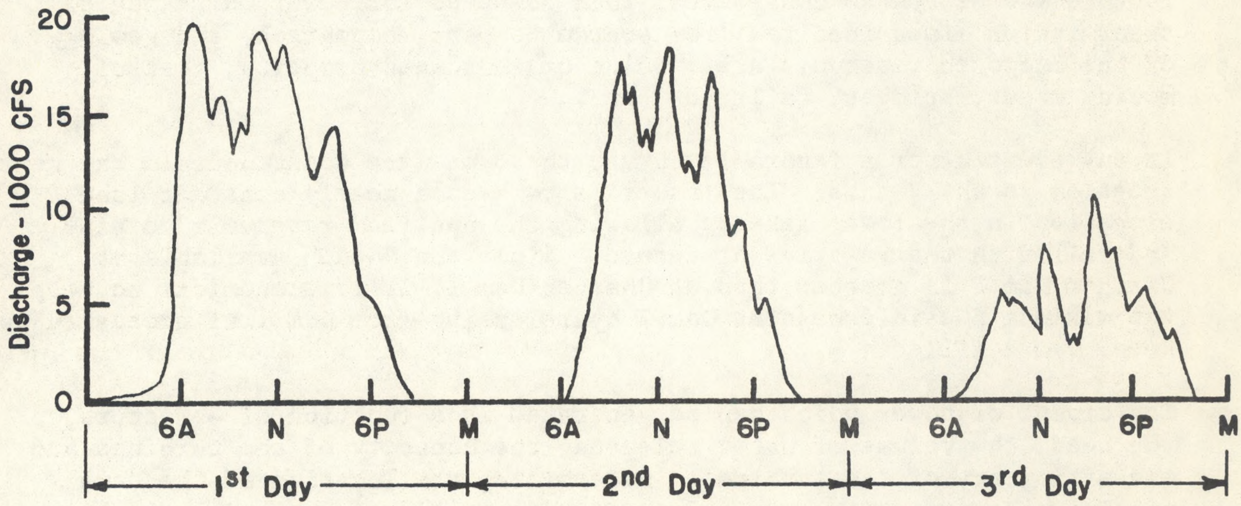
In any event after a favorable survey the dams were constructed. The next question is why 2 dams? The answer is to keep a nearly constant lake elevation in the lower lake by allowing the upstream reservoir to rise and fall with the vagaries of nature. Since the "head" available at Charger Dam 2 is greater than at Charger Dam 1, it is economical to keep the maximum possible head at Dam 2 by releasing from Dam 1 if necessary to keep Dam 2 filled.

The amount of power which can be generated is a function of 4 factors, the head, the volume of water released, the capacity of the turbines and the efficiency of the turbines. Determining the location of the dams, turbine capacity at each, size of gates to provide for passing flow in excess of lake and turbine capacity, etc. is a complicated matter in itself which we won't go into for this course.

The big advantage of hydroelectric power is that it is instantly available to meet varying load requirements. In contrast to a thermal plant where several hours may be required to build up steam pressure to drive the turbines, hydro power can be increased or decreased rapidly by operation of valves which can be remotely controlled by electric servo-mechanisms. Usually, particularly in the East, the amount of hydro power in a total electrical generation system is a small part of the total power generated. It is, however, a very important part, since it can rapidly be regulated up or down to meet varying demands. Since peak requirements vary with many factors difficult to predict in advance, it is not economical to build up steam pressure sufficient to generate a peak load requirement which may not be needed. These peak needs which may be of short duration can be met by fluctuating the available hydro power instead. In many modern balanced power systems the hydro power is seldom more than 5% or 10% of the total capacity, but its importance is great because of its flexibility.

Unfortunately for the river forecaster, this flexibility complicates his problem since the rapid change in release through the turbines results in a very ragged hydrograph of flow below the dam which can only be approximated for forecast purposes. Figure 1-12 shows a typical outflow hydrograph downstream from Charger Dam #2 for a 3 day period. This illustrates quite vividly why a river forecaster begs for data other than a once daily stage reading for a station below a power dam. While a mean daily outflow or total daily generation (which can be converted to mean daily discharge) doesn't give the total picture, it at least helps in the hydrologic "bookkeeping" for downstream forecasting.

Fig 1-12 HYDROGRAPH OF OUTFLOW FROM CHARGER DAM NO. 2



For forecast purposes, the storage in Charger Dam 2 will usually be negligible since it is kept nearly full at all times, but it is necessary to keep track of storage available in Charger Dam 1 since when or whether it fills during a rise has an important effect on the forecast hydrograph below the dam.

Several facts of life in the normal operation of a hydro reservoir must be kept in mind by the forecaster. A few of these are as follows:

1. If a reservoir has a sizeable volume of storage, the Agency (Private or Federal) distributing the power to users will usually try to commit the sale of power in advance. Unless forced by unusual circumstances the operators will not deviate too much from the mean daily volume of flow committed in advance although hourly fluctuations are great. This type of committed power is called prime power and sells at a price several times that of power delivered during a period of excess flow which was not anticipated.

2. Peak demands for power come during working hours and this is when hydro power sells for a premium due to the flexibility mentioned earlier. For this reason the hydro plant is usually completely or nearly completely shut down during night time hours and weekends and the system utilizes thermoelectric generating systems in order to save the valuable hydro power for daylight peak load demands. During a prolonged high flow period, the hydro plant will be operated at night rather than "waste" the water through flood gates but the price received per kilowatt is only a fraction of that during daylight hours.

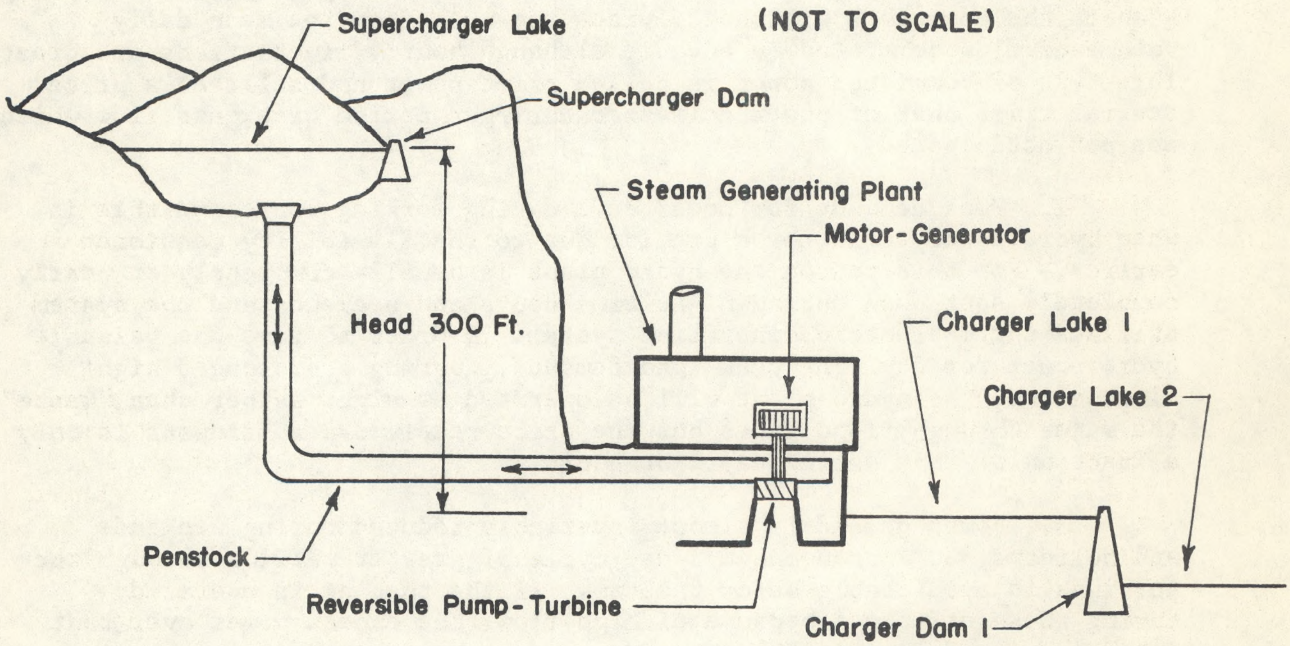
3. Power demand is almost invariably reduced during weekends and holidays, so a pronounced 5 day cycle of greater outflow through the turbines is predictable below the dam. If the turbine is operated during these off times because of high flow, the excess power over that scheduled in advance is known as "dump" power and brings a lower price than the "prime" power.

4. The operators invariably try to arrive at the end of a runoff period with a full reservoir. If they release through the turbines in advance of anticipated runoff which doesn't occur they will lose money. Since the release was of dump power they receive little for this and a lower head left in the reservoir represents potential energy lost which could have been converted to money in the bank during prime power periods. If the forecast was right and had been used to operate, money could be saved since they might have to waste water through the flood gates if the reservoir fills and the inflow is greater than the turbine capacity.

5. Dumping in advance may effectively reduce a flood peak, but it is difficult to convince an operator to take a chance unless he has great faith in the river forecaster, (or his own estimate agrees with that of the forecaster).

This course does not intend to go into sufficient detail to point out various operations which might result in operation of a hydro dam. Since the outflow must be forecast in order to predict the downstream flow, a knowledge of hydro operations plus a number of calculations to successfully consider these factors is necessary. As in most predictions of the vagaries of nature, particularly where man has considerable regulation, experience not easily programmed on a digital computer is invaluable.

Fig I-13 DIAGRAMMATIC SKETCH OF SUPERCHARGER LAKE POWER FACILITY



Supercharger Lake. As mentioned, the bulk of power in a sizeable electric generating system is usually produced by driving turbines by steam pressure. The steam may be produced by burning coal, oil or natural gas or by nuclear reaction. In the Supercharger Lake system a happy combination of hydro and steam generated power is utilized. This is known as pumped storage and is becoming an increasingly popular means of generating electricity when topographic conditions are right. A lake is not required, a sizeable river will serve as well, but we will use the water stored in Charger Lake 1 for illustrative purposes.

Supercharger Lake is created by damming a small creek on a plateau some 300 ft above Charger Lake 1. The lake does not have to be large. Since a high head exists, the volume of flow does not have to be large to generate substantial amounts of electricity.

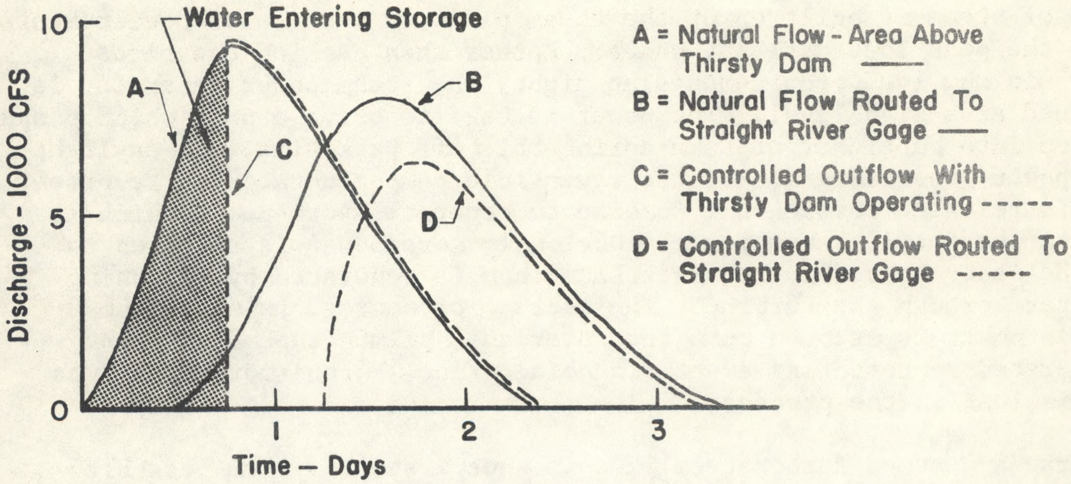
Anyone who has fired a boiler knows that it takes more fuel (and time) to build up a good head of steam than to maintain it for a few hours. A head of steam is built up at the steam plant to meet power requirements during the peak load daylight hours. Rather than banking the fires during minimum load requirements at night, the steam power generator is continued at a high level. The power is used to drive a pump which pumps water up into Supercharger Lake during this off peak time. In daylight prime power generating hours, the reversible pump-generator is reversed. Water is released through the turbine to generate hydro-power which is added to the total system power. Obviously more power is required to pump the water up to Supercharger Lake than is generated by returning the water through the turbine. The secret, of course, is that "dump" or cheap power is used to pump the water and "prime" expensive power is generated representing a net financial gain. Furthermore almost no water is lost in the process.

Of course a weather forecaster likes to have a storm system pass his forecast area and keep moving. Likewise the river forecaster likes for water to pass on downstream and eventually to the ocean. This pumped storage water keeps coming back necessitating extra bookkeeping to keep track of the total basin flow. Obviously power plant operators are more interested in making a profit than in keeping down the frustration level of the river forecaster.

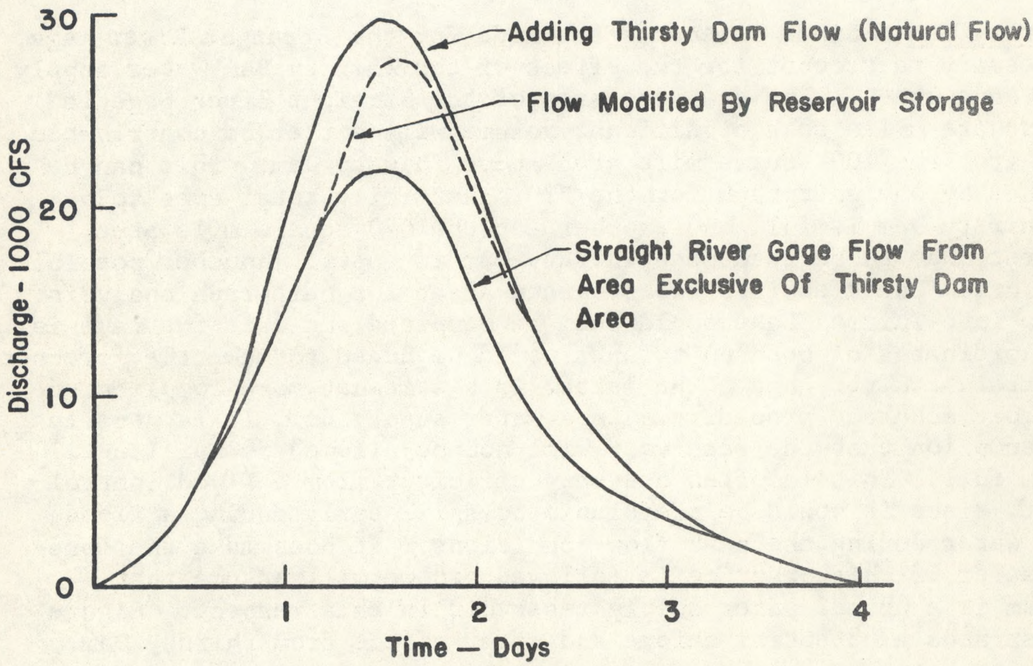
1-4. Thirsty Dam. Since forecasts are made for the Straight River gage, it is necessary to account for the effect of the Thirsty Dam water supply system on Aqua Creek. The drainage area of the Straight River gage is only 770 square miles so a significant volume will either be contributed or stored from the 100 square mile area above Thirsty Dam. This can be accomplished by one unitgraph for the 770 square mile total area to be used if Thirsty Dam is full and another for the 670 square mile area below Thirsty Dam to be used when Thirsty Dam is empty. Another possible way is to break the area into two separate areas for unitgraph analysis. The inflow into Thirsty Lake would then be computed and once the lake is full, the ordinates of both unitgraphs would be added to make the forecast for the Straight River gage. The latter is a somewhat more complicated, but also more accurate procedure. In a water supply dam, it is usually a safe assumption that the reservoir will not be allowed to spill until it is brim full. This is often not very efficient from a flood control standpoint, since it would be preferable to spill early during a flood and store water during the peak flow conditions. It does make the forecasting easier if this practice is followed, so we will assume that Thirsty Dam is a normal water supply reservoir in this respect. Figure 1-14 illustrates a potential before and after effect from Thirsty Dam.

Figure 1-14a shows the effect of the Dam after the water from this area travels through the valley storage between the dam and the Straight River gage. In this case it is assumed there is no difference between the natural inflow and the inflow when the reservoir is in existence. This is a simplifying assumption for purposes of illustration. It is also

Fig I-14 EFFECT OF THIRSTY DAM STORAGE



(a) EFFECT OF DAM ON FLOW ARRIVING AT STRAIGHT RIVER GAGE

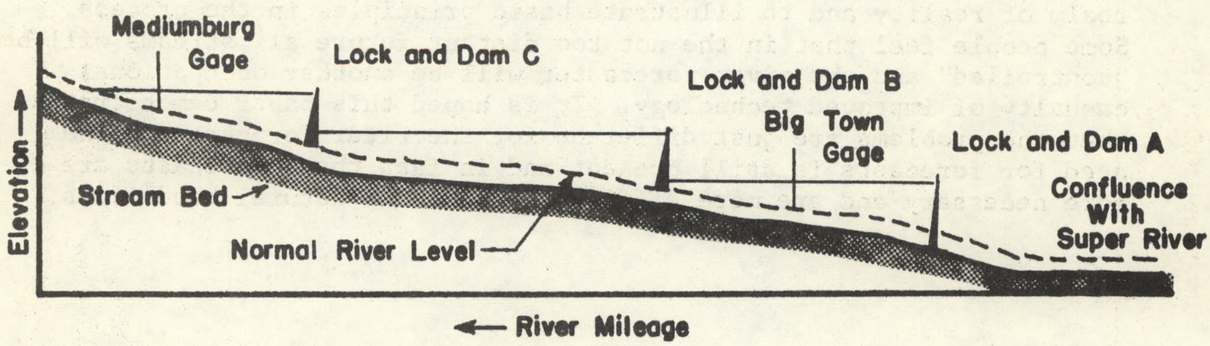


(b) EFFECT OF DAM ON TOTAL STRAIGHT RIVER GAGE FLOW assumed no outflow from the dam occurs until 18 hours after the beginning of the storm and then outflow equals inflow, again a reasonable simplifying assumption. Curve B represents the flow arriving at Straight River Gage from the area behind the dam during natural conditions and Curve D during controlled conditions.

Figure 1-14b illustrates the natural flow from the area exclusive of the dam drainage and then adds on the natural flow from above Thirsty Dam and the controlled flow. Since the area exclusive of the dam drainage is nearly 7 times as large, the volume would be about 7 times as great if runoff were uniform over the whole drainage. Obviously we have distorted the illustration by having proportionally more flow from the Thirsty Dam drainage area. Even with this distortion the effect of Thirsty Dam in this hypothetical case is relatively minor, but it does have to be considered if an accurate forecast is to be made from the Straight River Gage.

<u>1-5. Locks and Dams A, B, and C</u>. We will give somewhat short shrift to these navigation locks and dams. The obvious purpose of the dams was to create a navigable channel throughout the river from the mouth to the Mediumburg area. Prior to the lock and dam construction there were shoals in the river in some stretches which prevented reliable navigation.

Fig 1-15 RIVER PROFILE OF BIG RIVER



The providing of water by the navigation dams allowed for a reliable year round navigation. Depending on the design and operation of the gates at these dams, there would be some changes in the channel hydraulics which would have to be evaluated. In this example there should be adequate water available for low flow augmentation from Lake Everything to insure reliable navigation channels during low flow conditions. In some rivers this is not the case and flow must be estimated as much as 2 weeks in advance to determine how full the barges can be loaded for their long trip.

There are other problems which may be occasioned by the locks and dams. Often dock and warehouse facilities are built below maximum flood levels to minimize costs in loading and unloading. Also low lying industry may develop close to these dock facilities which would increase the hazard of flood losses. The rating curves at both the Mediumburg and Big Town Gages would be affected by backwater from the lakes formed. This necessitates changing these rating curves (graphs of river stage vs stream discharge) and making discharge measurements very difficult due to the flat slopes of the water surface. Ice may form more readily in these lakes due to the decrease in water velocity. Ice may also form jams at the dams and be more of a hazard due to the increased number of boats and possible damage to the gates and lock mechanisms. Pollution may become more of a problem in low flow conditions, since the water would not be free flowing as in the past.

We won't go into details on any of these factors, but it can be seen that these locks and dams do change natural flow conditions and result in a number of additional factors which must be evaluated by the river forecaster.

CONCLUSION. The vagaries of nature are always difficult to understand and to predict. When the human element is added the problem invariably becomes more complex. This technical memorandum in a few pages obviously could not go into great detail on the effects of man made regulation of river flow. Also the idealization may be considered as an over simplification by some. The author has tried to keep the examples within the realm of reality and to illustrate basic principles in the process. Some people feel that in the not too distant future all streams will be "controlled" and the river forecaster will be another occupational casualty of improved technology. It is hoped this paper demonstrates that the problems are just different for the river forecaster. The need for forecasts is still present and in fact these forecasts are even more necessary and are more difficult than under natural conditions.