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OPTIMIZING WATER QUALITY USING SMALL RESERVOIRS[1]

by

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We must use every means available to protect and improve our environment--including our water resources. Small reservoirs, too, should be designed and built to have an optimum effect on the quality of our environment. They are key conservation measures and can be used to accomplish important objectives in the systems approach to the conservation of soil, water, and agricultural chemicals.

In our attempts to improve water quality in reservoirs and streams, we must give primary consideration to sediment, our greatest pollutant (9, 14, 17, 21). Wadleigh (20) and others (6, 13, 19) have indicated the large volume of sediment transported in U.S. rivers. Furthermore, many agricultural chemicals are transported from the fields where they are applied, into drainage systems adsorbed or in association with sediment (1, 13, 14, 16, 17).

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Small reservoirs can be designed and built at specific locations to optimize their water quality and/or the water quality downstream. This report enumerates and discusses available design options and their effects on water quality.

WAYS TO USE SMALL RESERVOIRS TO OPTIMIZE WATER QUALITY

Small reservoirs can be designed to optimize water quality by properly selecting: (1) their location, (2) their size, and (3) their spillway design and location. The engineer or designer must know the primary purpose (objectives) of the structure and their priorities if it is a multipurpose reservoir. The purpose could be: (a) recreation, like swimming, boating, and fishing; (b) water supply for domestic or irrigation uses; (c) flood control; (d) erosion and nutrient control; or (e) a combination of these (multipurpose reservoir). Maintaining high water quality in the reservoir could, at times, conflict with high quality water requirements downstream.

Reservoir Location

If the reservoir's main purpose is for recreation and/or water supply, good water quality is required and we should select the site accordingly. Using Figure 1 as an idealized and simplified illustration, we would place the reservoir on the forest or grass tributary, if the drainage area will provide enough water. If more water is needed, the reservoir would have to be located further downstream and we might have to control the quality of water coming into this downstream reservoir with other small reservoirs on the feedlot and row crop tributaries.

For flood control, reservoirs should be located so they intercept most of the storm runoff above the flood plain or facility to be protected. Of course, when we control the flow of water, we trap the sediment (1, 12, 14, 16), associated nutrients, and other chemicals.

Some small reservoirs are built to control gullies and to trap sediment from these gullies. These small reservoirs are usually built at locations where their waters extend up to the gully overfalls. Some small reservoirs are also built to serve as debris basins, which also improves the water quality downstream.

In a multipurpose reservoir, we can have conflicting objectives which can complicate the situation. We then must optimize our design according to the priorities established of the objectives.

If we want to improve the water quality at a certain point in a channel system, the reservoir should not be located far upstream from that point. Water with a low sediment concentration that is released into an erodible channel system that previously reached equilibrium under a much higher sediment concentration will probably erode the channel sides and bottom until the sediment load again reaches equilibrium. The sediment concentration may approach that of pre-reservoir construction--depending on runoff velocity, soil, and channel conditions (4, 6, 7, 14, 15, 18).

In this discussion, we assumed that a good reservoir site is always available, which is not the case for many watersheds. Good sites are an important natural resource and must not be wasted. Furthermore, economics is always a factor controlling reservoir planning and construction.

Reservoir Size

The objectives of reservoirs, expected storm runoff, and sediment yields are important factors in determining the reservoir size. Recreation reservoirs must be large enough to accomodate their expected use, whereas water supply reservoirs must store enough water to last through the longest expected drought during their "design" lives. Flood control reservoirs must be large enough to store the "design" storm runoff, but reservoirs designed to control erosion and nutrient loss can be quite small. Storage capacity must also be allocated for the sediment deposition expected during the life of the reservoir. These capacity requirements are distinct, and some are accumulative. The larger the capacity, the greater the opportunity for the deposition of sediment and associated chemicals (3, 11). In multipurpose reservoirs, the sediment trapped during flood detention will lower the quality of reservoir water allocated for other purposes.

In a trap efficiency (percentage of inflowing sediment that is trapped in the reservoir) study of three central Missouri reservoirs (11), we found that a decrease in "dead" storage or permanent pool capacity decreases trap efficiency significantly (similar to that demonstrated by Brune (2)). This decreased trap efficiency allowed more sediment to be discharged downstream. Increasing the reservoir "dead" storage capacity improved the water quality downstream.

Spillway Design and Location

When storm runoff enters a reservoir (Figure 2, point A), the large sediment particles and aggregates are deposited because of reduced flow velocity (5). The remainder of the inflow moves along the bottom of the reservoir until it reaches an elevation of equal density with the reservoir water (point B). The density of the storm inflow depends on its temperature and sediment concentration. The sediment concentration usually is the important parameter in most reservoirs, however, because the temperature difference between storm inflow and reservoir water is usually not large. Only 1000 ppm of sediment is needed to equal the density difference caused by the reservoir water's being 10°F cooler than the inflow in the 50 to 80°F range. When the density of the inflow becomes equal to that of the reservoir sediment-water mixture, it flows horizontally (point B) into the reservoir like a wedge and raises the water in the reservoir above it. In a full reservoir with a surface discharge principal spillway, the upper level of water, the highest quality water in the reservoir, would be discharged.

Many combinations of dimensions, types, and locations for reservoir spillways are available to accomplish various objectives. The combination to use depends on the primary objectives and the trap efficiency needed to accomplish them.

The depth of withdrawal and size of spillway control the detention time of storm runoff. The elevation of the withdrawal point will determine the volume of runoff that will remain in the reservoir (permanent pool) until it is displaced by succeeding runoff events. Figure 3 shows the relationship between spillway pipe diameter and relative discharge time on Callahan reservoir, near Columbia, Missouri.

High quality water downstream--If the major objective is to provide high quality outflow, then the sediment trap efficiency should be high. Thus, the detention time of storm flow in the reservoir should be long enough to provide opportunity for deposition of the sediment and attached chemicals. If detention time is decreased from an average 30 to 2 days in central Missouri reservoirs (10, 11), the average trap efficiency will decrease from 90 to 82 percent.

Several spillway options are available, including bottom spillways and surface principal spillways. If we don't want to store water, but want to remove sediment from the storm runoff, we can use some type of bottom spillway (dry reservoir) or a desilting basin. Figure 4 shows a small reservoir in western Iowa with such a spillway. This reservoir was designed as a flood-retarding structure with no permanent storage. It traps all of the coarse sediment and aggregates and permits most of the fine sediment and nutrients to be discharged from the reservoir.

Figure 5 shows an example of the most effective device for removing sediment from runoff--the Farmer's Ditch Desilting Basin near Bronson, Iowa. The desilting basin, which covers about 225 acres, has a drainage area of 22.9 square miles. Such basins can be built only where the topography is flat, since the runoff must be spread over a large area. The maximum depth of water is shallow, so the sediment particles do not have far to settle to be deposited. When the sediment has been deposited, higher quality water is manually released to the channel downstream. In 3.8 years between 1941 and 1945, about 468 acre-feet of sediment was deposited in this basin, and the average depth decreased from 3.5 to 1.7 ft. Of course, the chemicals attached or adsorbed to the sediment were also trapped.

Figure 6 shows the more common type of flood control reservoir with a surface discharge principal spillway--Callahan Reservoir, C-1, near Columbia, Missouri. Table 1 shows physical data pertaining to this reservoir and its contributing watershed, with similar data on two other central Missouri reservoirs.

These reservoirs trapped sediment, nitrogen (N), and phosphorus (P), as shown in Table 2. These percentages varied from year to year, depending on storm runoff and other factors. Sediment trap efficiency depended upon detention time of runoff, volume and rate of runoff, sediment yield, and reservoir capacity (11). Phosphorus trap efficiency in Callahan reservoir depended upon the sediment and P concentrations of

TABLE 1. - Physical data of three Missouri reservoirs and their watersheds[1/]

Reservoir Characteristics	Ashland	Bailey	Callahan
Surface area (acres)	16	10(13)	23(70)
Capacity (acre-feet)	186	56(93)	185(1,017)
Water depth (feet)	27(27)	14.5(17.5)	18.7(37.6)
Shape factor[2]	3.74	2.01	3.71
Date of construction	1937	1965	1967
Watershed Characteristics			
Area (acres)	2,480	235	3,600
Weighted average land slope. . . . . (percent)	6.0	3.8	5.9
Soil texture	Clay loam to Silt loam	Clay loam to Silt loam	Clay loam to Silt loam

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1/ Numbers in parentheses apply to the reservoir at emergency spillway elevation.

2/ Shape factor is the length of the reservoir divided by the diameter of a circle of equal area.

inflow, rate and volume of runoff, and sediment concentration of outflow (12).

Table 2 shows that nitrate-N (NO_3-N) trap efficiency averaged from 24 to 66 percent for the three reservoirs and was not related to hydrologic variables. More than half the annual averages of ammonium N (NH_4-N) trap efficiency were negative (9 of 16) which indicated more NH_4-N left than entered the reservoirs. This could indicate that some N was converted to NH_4-N while in the reservoir. Ammonium N is only a small percentage of the N budget, and the increase of NH_4-N in the outflow is insignificant.

High quality reservoir water--If our primary objective is to retain high quality reservoir water, we usually design a very large reservoir so that the anticipated storm runoff can be contained and some relatively good quality water will remain. When surface flow principal spillways are used, the best water (surface water) is discharged first, and almost all of the sediment and associated nutrients are trapped. With this larger capacity, the trap efficiency will also be higher, and more sediment and nutrients will be trapped each year.

We are studying a different type of spillway for small reservoirs that we think is a desirable alternative (11). This is an automatic bottom-withdrawal spillway (Figure 7). It provides an entirely different approach and a different and expanded opportunity to control water quality. This spillway enables us to retain the higher quality water in the reservoir,

Table 2

Reservoir Trap Efficiency Summary (1970-1975) of Sediment, Phosphorus, and Nitrogen
Plus
Rainfall, Runoff, and Sediment Yield Data

Reservoir	1970	1971	1972	1973	1974	1975	Weighted Avg. (1970-1975)
<u>Ashland</u>							
Trap Efficiency %							
Sediment	--	97	99	85	98	88	94
NO_3	--	55	93	12	25	17	24
NH_4	--	-71	-19	-59	-17	20	-33
Precip. (in.)	42.0	27.2	33.3	50.9	42.8	42.8	
Runoff (in.)	--	2.2	1.8	15.5	8.9	7.2	7.12
Sediment Yield (t/a/yr.)	3.73	.57	.68	1.80	3.86	.91	1.93 1.56 for '71-'75
" (acre ft)							
<u>Bailey</u>							
Trap Efficiency %							
Sediment	79	93.5	83	85	89	93	90
NO_3	--	0	75	51	26	74	66
NH_4	--	0	55	-9	-5	-116	10
Precip. (in.)	40.8	27.7	30.6	56.0	42.7	37.2	
Runoff (in.)	--	4.2	2.3	22.6	20.5	9.2	11.8 '71-'75
Sediment Yield (t/a/yr.)	.44	.47	.14	2.6	2.22	1.15	~~1.17~~ 1971-1975 Avg = 1.32
<u>Callahan</u>							
Trap Efficiency %							
Sediment	93	85	91	87	88	74	88
$P_{Tot.}$ Sed.	--	--	--	78	80	55	77
$P_{Tot.}$ Sol.	--	--	--	46	49	07	43
NO_3	58	54	29	34	33	45	40
NH_4	60	07	19	-28	-16	48	19
Precip. (in.)	43.8	25.3	30.4	59.8	41.5	38.1	
Runoff (in.)	9.1	2.0	1.8	24.5	12.7	8.7	9.8 in
Sediment Yield (t/a/yr.)							3.3

since reservoirs equipped with this spillway will trap mainly large sediment particles and aggregates. It has a lower trap efficiency, because of decreased detention time of storm runoff and because there is no permanent or "dead" storage. Unlike other bottom-withdrawal spillways, it does not drain the entire reservoir (unless desired), nor does it require the operation of control valves to open and close drainage ports to bypass density currents.

The automatic bottom-withdrawal spillway (Figure 7) will start discharging when the reservoir water level rises above the apex of the bottom of the spillway pipe. This pipe primes and siphoning starts when the water level rises about 1 1/2 to 2 pipe diameters above this apex. When the reservoir is discharging, the sediment laden water will be discharged as soon as it reaches the spillway intake (usually located at the lowest point in the reservoir). The siphoning action of this spillway is controlled by an air vent on a pipe connected near the apex of the spillway pipe (Figure 7). The elevation of this vent determines when siphoning action stops, thereby controlling the depth of drawdown. By changing the length of the vent pipe and/or the elevation of the vent, we can vary the reservoir water level over a wide range of elevations. We can even empty the reservoir in this way.

The cleaner surface water remains in the reservoir with the automatic bottom-withdrawal spillway (Figure 8B), unless the storm runoff raises the reservoir water level above the emergency spillway level. After the return to near-normal stage, the bottom-withdrawal reservoir contains mostly clean water (Figure 8B, 3), while the surface-discharge reservoir contains mostly sediment-laden water (Figure 8A, 3).

Advantages of the automatic bottom-withdrawal spillway over other spillways are:

1. The useful life of the reservoir is increased because more sediment is discharged.
2. A smaller and more economical reservoir can be designed and built when the primary objective is high quality reservoir water.
3. Downstream channel degradation will be reduced because the downstream sediment yield will approach that of the pre-reservoir condition.
4. The reservoir water quality is improved; it discharges water with the highest sediment concentration, lowest oxygen (O_2), and highest organic matter content. Preliminary data indicated that an aerator at the outlet end of the spillway pipe will increase the dissolved O_2 to greater than 6 ppm, improving the downstream water for fisheries and recreational use.
5. The normal operating level of the reservoir water surface can be changed easily and held within a narrow or wide range of elevations by varying the length of the vent pipe and the elevation of the vent. This feature makes it easier to control the aquatic weeds around the edge of the reservoir (8).

6. It operates automatically, with no valves to open or close.
7. Once the spillway pipe is primed, the reservoir water level can be lowered to any desired elevation.
8. This system can be manually primed, if necessary, to drain the reservoir.

The closer we can locate the bottom-withdrawal or any other spillway intake to the entrance of flow (sediment) into the reservoir, the greater the opportunity to bypass sediment. As bottom slope increases between the head waters and intake, the amount of sediment that the density currents will carry to the spillway increases. The discharge of these density currents will enable us to retain high quality water in the reservoirs.

SUMMARY

Small reservoirs can be built to improve water quality within reservoirs or in downstream channels. They are effective because they control the sediment content in the water and associated chemicals.

A clear understanding of the main objectives of proposed reservoirs is essential. For multipurpose reservoirs, the highest priority objectives must control reservoir design. Small reservoirs can be designed to control water quality by carefully selecting reservoir sites, capacities, and spillway designs.

We are studying a different automatic bottom-withdrawal spillway that is very versatile and can improve water quality in small reservoirs. It provides a means to control reservoir trap efficiency of sediment and associated chemicals. Several desirable features are: (1) the useful life of the reservoir is increased; (2) a more economical reservoir can be built when the primary objective is high quality reservoir water; (3) downstream channel degradation will be reduced; (4) the reservoir water quality is improved, which improves the recreation and fishing potential; (5) it is automatic; and (6) once the spillway pipe is primed, the reservoir water level can be lowered to any desired level, easily changed, or maintained within a wide or narrow range of elevations.

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Figures

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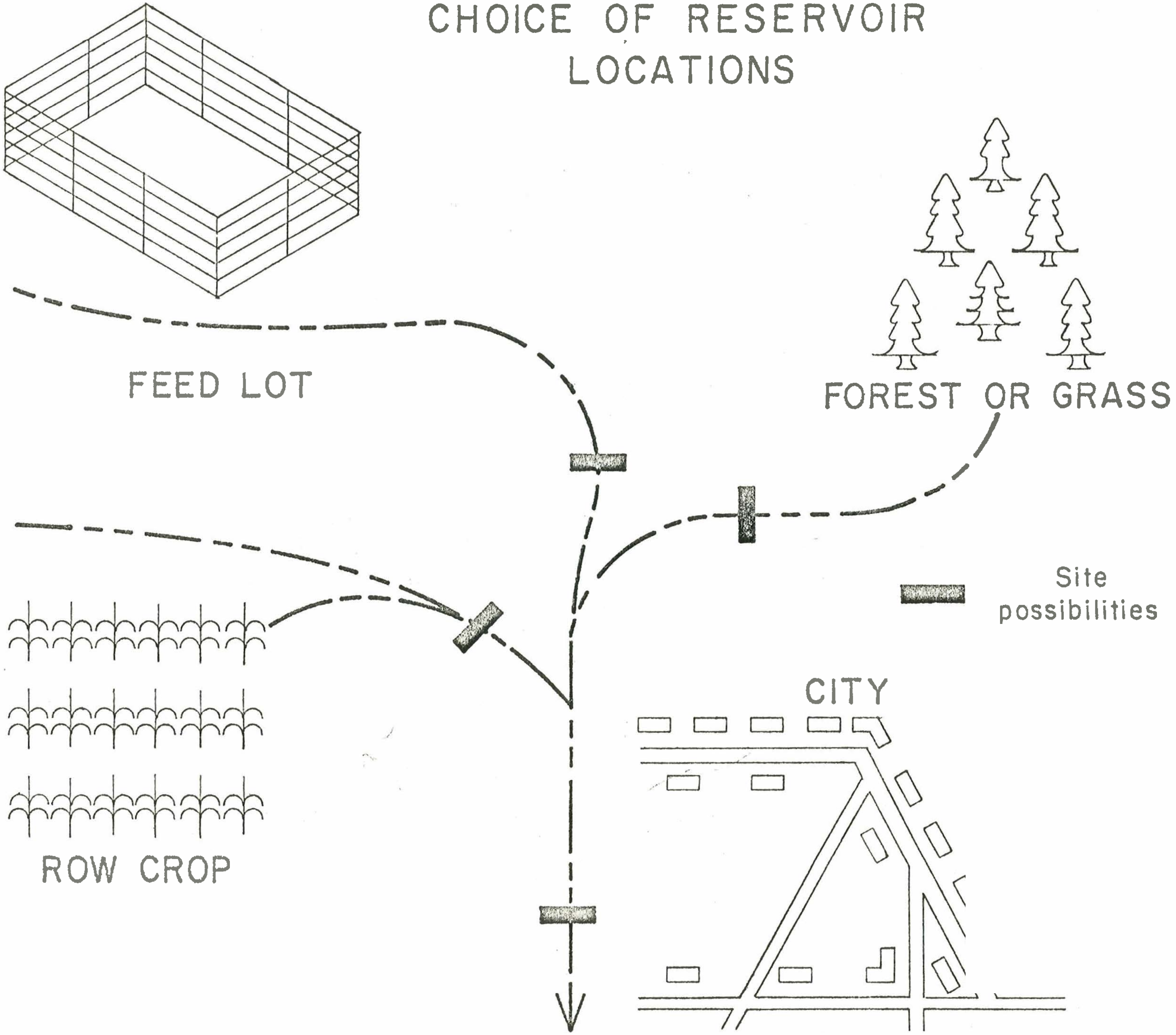
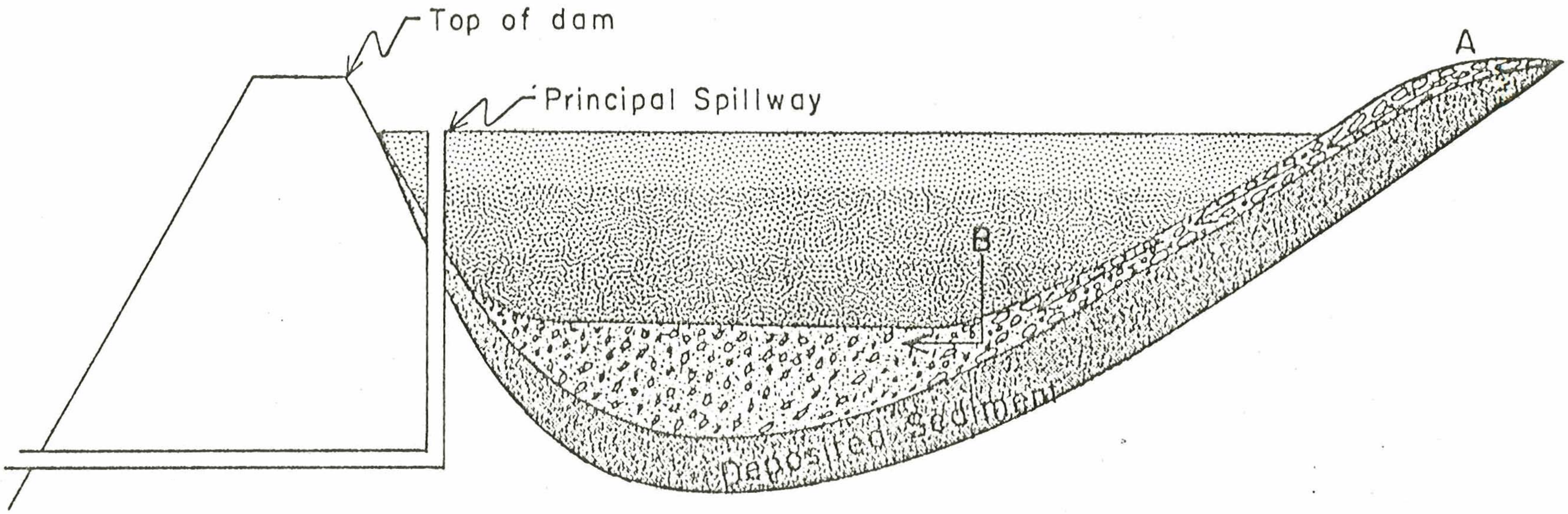
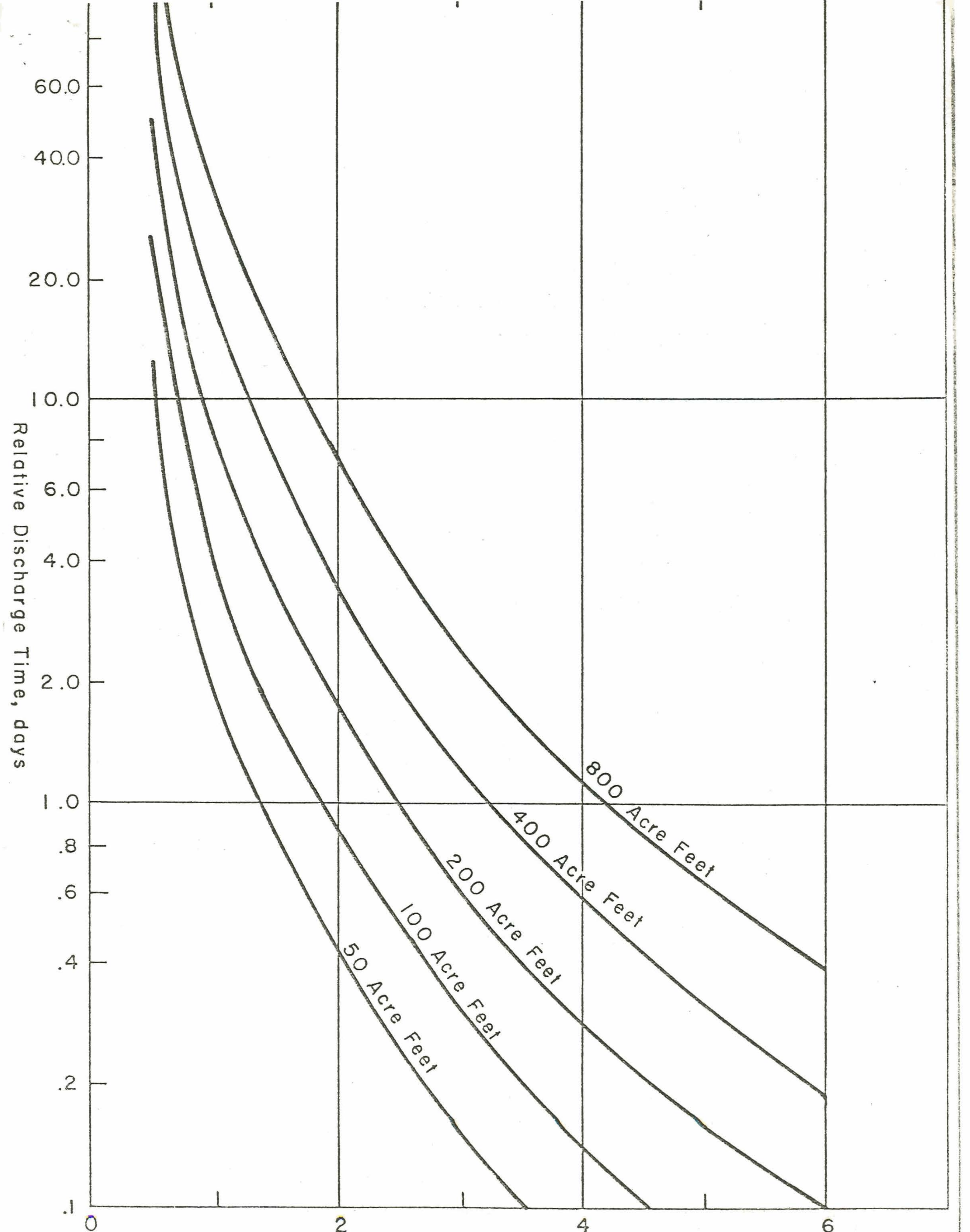
CHOICE OF RESERVOIR LOCATIONS





DEPICTING STORM RUNOFF MOVING INTO AND IN A RESERVOIR


Relative Discharge Time, days
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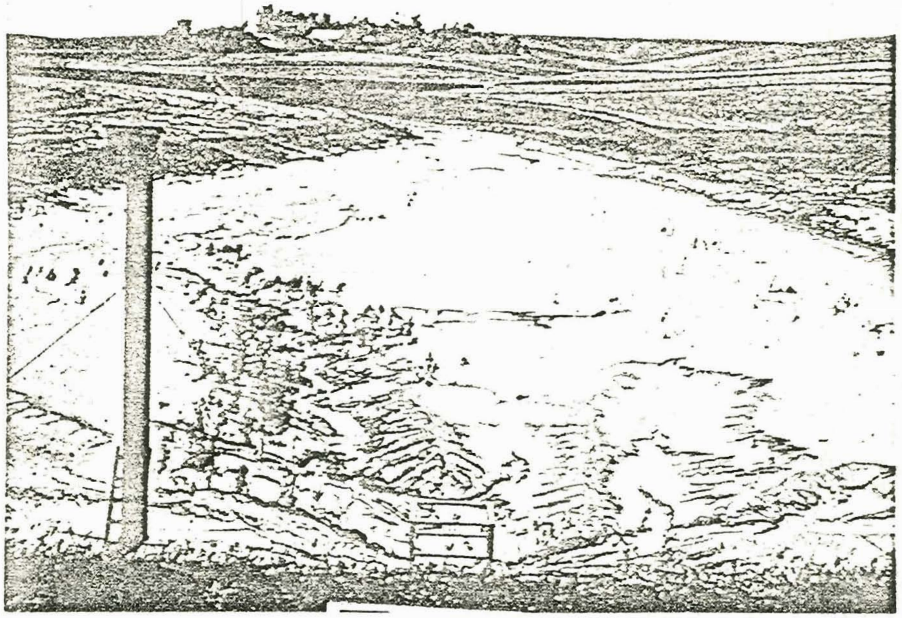
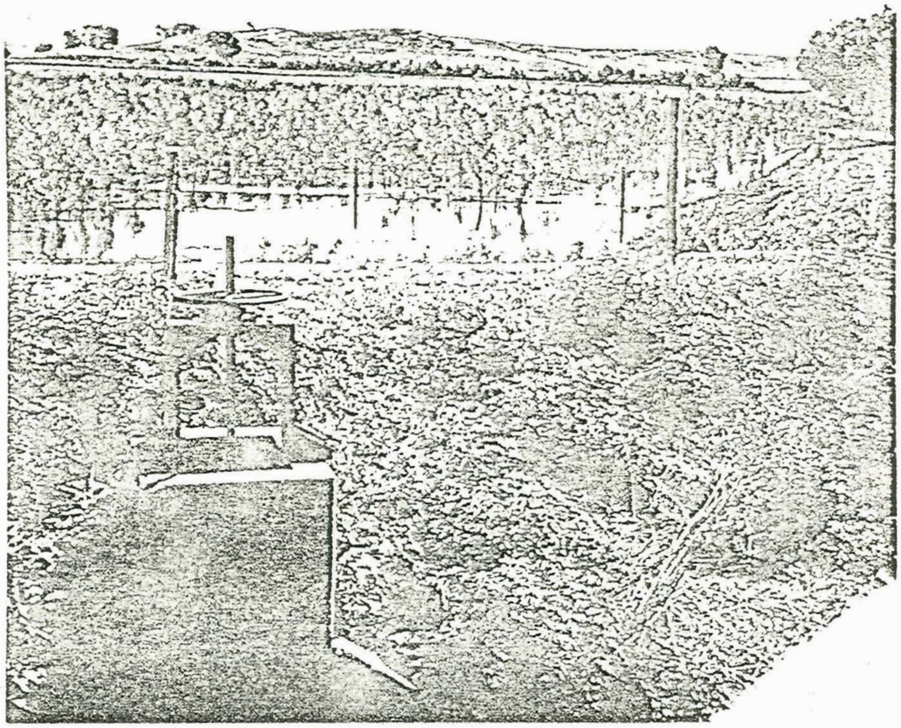
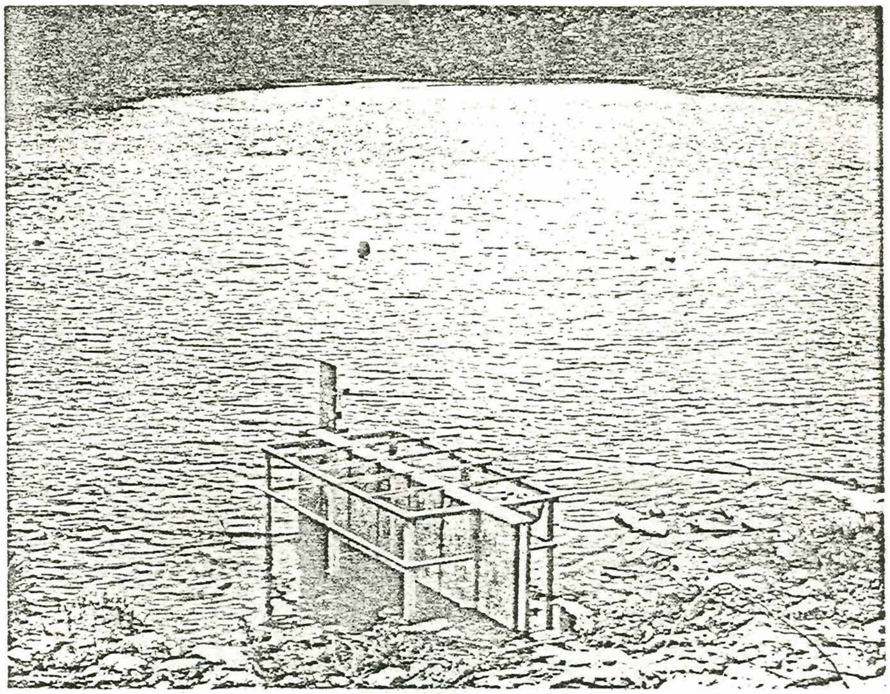
40.0
20.0
10.0
6.0
4.0
2.0
1.0
.8
.6
.4
.2
.1
0
2
4
6
800 Acre Feet
400 Acre Feet
200 Acre Feet
100 Acre Feet
50 Acre Feet



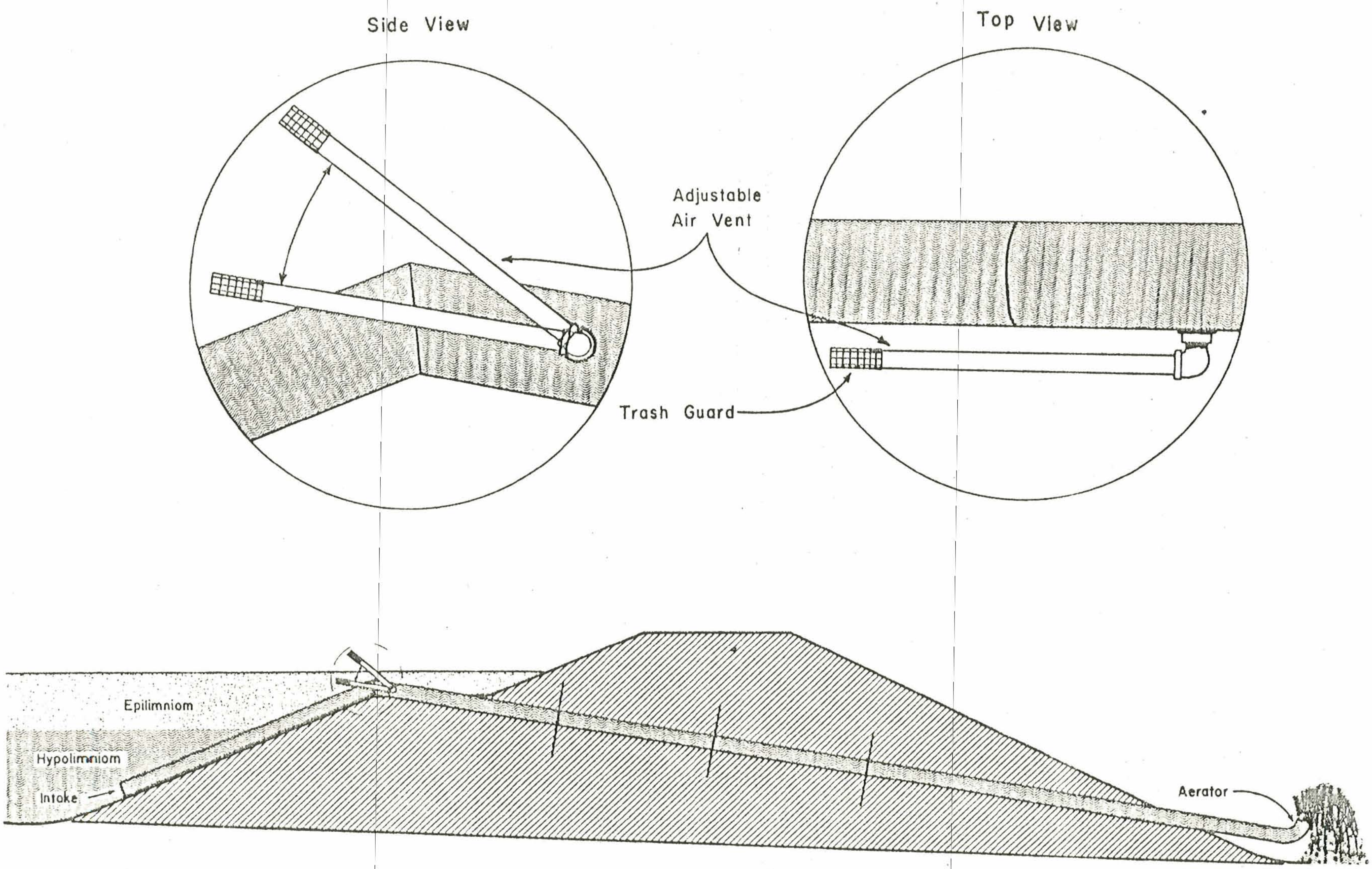
RETARDING STRUCTURE, THEOBOLD GULLY "C"--JUNE 1950



FARMERS DITCH-OLD DESILTING BASIN BRONSON, IOWA
JUNE 1949



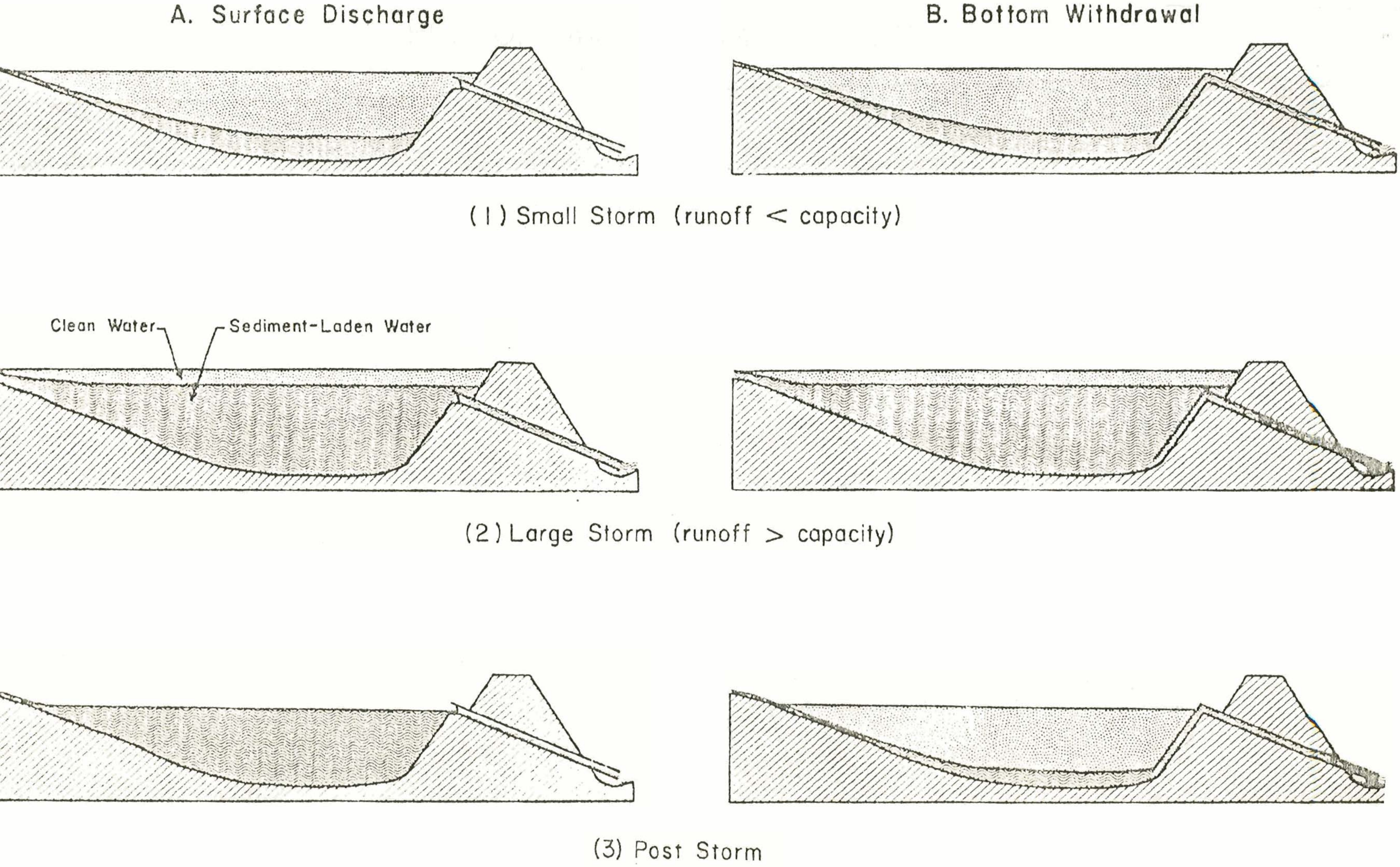
PRINCIPAL SPILLWAY-CALLAHAN RESERVOIR C-1,
NEAR COLUMBIA, MISSOURI



BOTTOM WITHDRAWAL SPILLWAY

USDA, AGRICULTURAL RESEARCH SERVICE
COLUMBIA, MISSOURI

Designed by: David L. Rausch Date 9-2-73
Drawn by: Joel A. [illegible] Date


A. Surface Discharge
B. Bottom Withdrawal
(1) Small Storm (runoff < capacity)
Clean Water
Sediment-Laden Water
(2) Large Storm (runoff > capacity)
(3) Post Storm