ANALYSIS OF THE OPERATION OF LAKE SHELBYVILLE AND CARLYLE LAKE TO MAXIMIZE AGRICULTURAL AND RECREATION BENEFITS

A joint study by

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ABSTRACT

The U.S. Army Corps of Engineers, St. Louis District, has been regulating Lake Shelbyville and Carlyle Lake on the Kaskaskia River in Illinois since the completion of the dams in 1969 and 1967, respectively. Thus far, the lakes have been operated primarily for flood control and recreation because the Navigation Channel below Fayetteville to the Mississippi River has not yet been opened. Damages to agriculture and recreation in the region of the lakes were very high during the extremely wet years of 1973 and 1974. This study was conducted to review the Corps' present regulation policy and the various inputs used in adoption of that policy. A detailed systems analysis shows that the operation of the lakes can be improved substantially.

An operating policy has been derived on the basis of results from a dynamic programming model and optimization of operating rules through a simulation model. The optimization reduces the average annual recreation damage to about 40 percent and agricultural damage to about 16 percent of that for the present operating policy under the same hydrologic, recreation, and agricultural functions over the 24-year period, 1942 through 1965. The derived policy as well as the Corps' present policy were applied to the years 1972 through 1974 for which data from actual operation of the lakes were available. The overall damages with the policy developed in this study are much lower than those with the Corps' present policy and with actual operation over these three years.

The benefits of flood control are analyzed and the two lakes are shown to reduce greatly the agricultural damages expected under natural flow conditions, that is, without the two dams. Suggestions are made for improvement in the data base and criteria, and for consideration of water supply needs, tributary flows, synthetic flows, and flow estimation in deriving an operation policy to fit the needs of the future.

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The study was made under the general supervision of Dr. William C. Ackermann, Chief of the Water Survey. Krishan P. Singh, Hydrologist, carried out the study with the advice of John B. Stall, Head of the Hydrology Section. Carl G. Lonnquist, Numerical Analyst, developed the computer programs and models. Roger H. Smith, Hydraulic Engineer of the Division of Waterways, provided liaison with the Corps of Engineers and other State departments. Many other Water Survey personnel contributed. Mrs. J. Loreena Ivens, Technical Editor, edited the report. Douglas Noel, part time Graduate Research Assistant, assisted in data handling, computations, and tabulations. John W. Brother, Jr., supervised the preparation of illustrations.

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Analysis of the Operation of Lake Shelbyville and Carlyle Lake to Maximize Agricultural and Recreation Benefits

INTRODUCTION

The Kaskaskia River and its tributaries drain an area of 5840 square miles (sq mi) lying wholly in Illinois. The river flows southwesterly in a meandering course from west of Champaign in Champaign County to its confluence with the Mississippi River 8 miles upstream of Chester in Randolph County. With the exception of a small area adjoining the lower reach near the mouth of the river, the area drained lies in the Till Plains Section (Leighton, Ekblaw, and Horberg, 1948) in the Springfield Plain and Bloomington Ridged Plain physiographic divisions. The Springfield Plain is covered by Illinoian drift laid about 200,000 years ago. The Bloomington Ridged Plain was subsequently covered by Wisconsinan drift some 20,000 years ago, and the Shelbyville Moraine marks the southern extent of this glaciation. This explains the much more rugged topography along the Kaskaskia River upstream of Shelbyville compared with that downstream.

Two multipurpose reservoirs, Carlyle Lake and Lake Shelbyville (Figure 1), were completed by the Corps of Engineers in 1967 and 1969 by building dams across the Kaskaskia River at mile 107 and 222, respectively, upstream of its confluence with the Mississippi River. These projects were authorized under the Flood Control Acts of 1938 and 1958 for purposes of flood control, navigation releases, water supply, fish and wildlife conservation, and recreation. The state of Illinois has storage allocation of 33,000 acre-feet (ac-ft) in Carlyle Lake and 25,000 ac-ft in Lake Shelbyville. Prorated over a two-year period, these reserves amount to steady withdrawals of 23 and 17 cubic feet per second (cfs), respectively. These storages were reserved for meeting future requirements of water for municipal, industrial, and rural purposes. As other links in the comprehensive development of the Mississippi River and its tributaries, the Kaskaskia Navigation Channel from the mouth of the Kaskaskia River to Fayetteville in St. Clair County and the Navigation Lock and Dam at river mile 0.8 are nearing completion. The Navigation Channel is expected to be in operation in 1978. The normal pool level upstream of the 600 x 84 ft lock is set at 368 ft above mean sea level (msl). Releases from Shelbyville and Carlyle Lakes will provide sufficient flow to assure lockage needs for navigation and maintain adequate flow depth in the channel.

Shelbyville and Carlyle Lakes

Shelbyville Dam is located at the edge of the Shelbyville Moraine which forms the southern boundary of the most recent, i.e., Wisconsinan, glaciation. The valleys are deep, narrow, and steep-sided where the river cuts through the moraine. Valley slopes remain wooded because they are too steep to cultivate. Thus, Lake Shelbyville is a fairly deep lake in a region where topographic relief is generally small. Carlyle Dam is located about one-half mile upstream of the town of Carlyle in Clinton County. The drainage area upstream of the dam, up to Shelbyville, is distinguished by its flatness and shallow entrenchment of drainage.

Leighton, M. M., G. E. Ekblaw, and L. Horberg. 1948. *Physiographic Divisions of Illinois.* Illinois State Geological Survey Report of Investigations 129. 33 p.

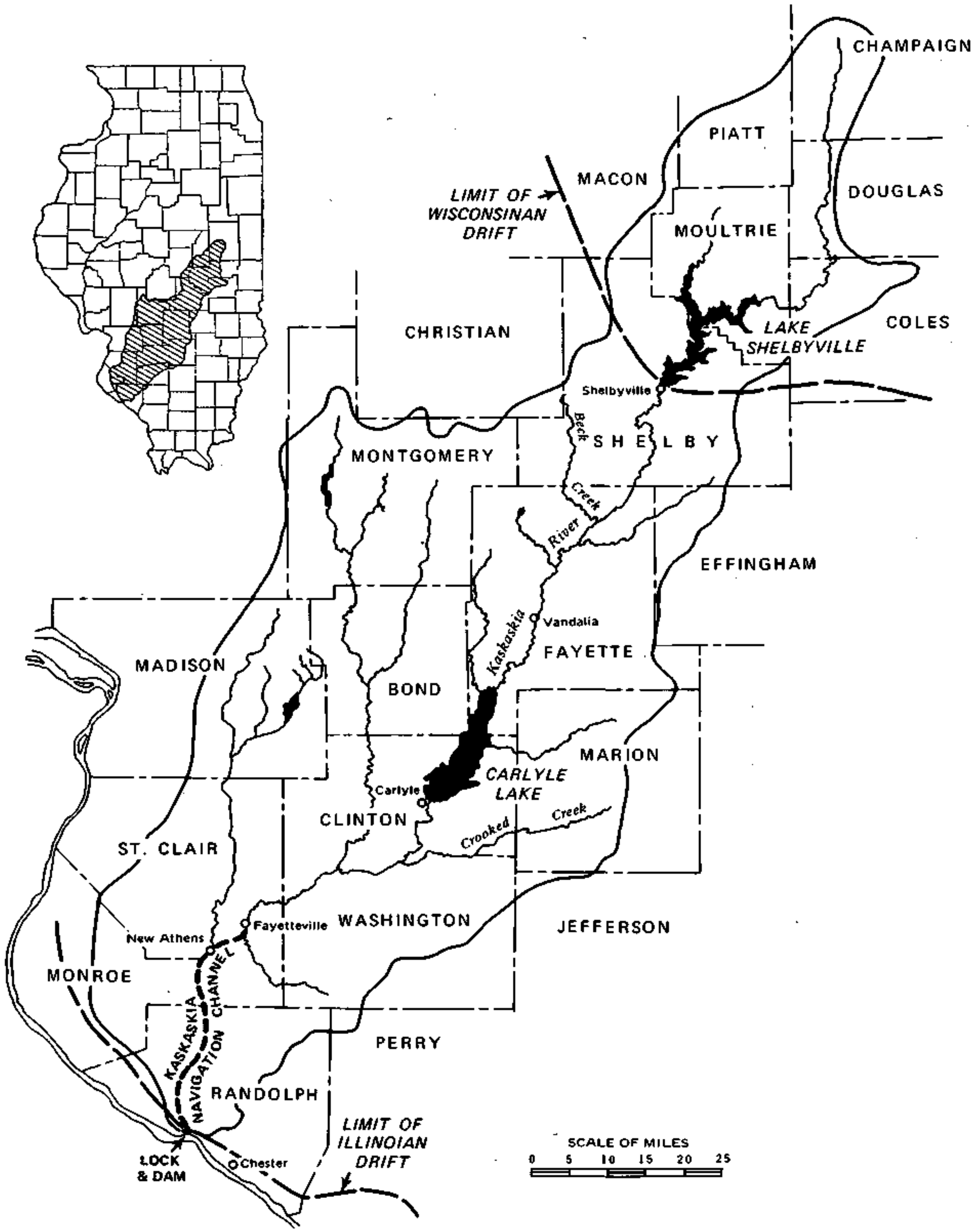

Figure 1. Location map. Lake Shelbyville and Carlyle Lake

Table 1. Physical Data

Item	Lake Shelbyville	Carlyle Lake
Drainage area above dam, *sq mi*	1,030	2,680
Top of dead storage pool		
Elevation, *ft msl*	573.0	429.0
Area, *ac*	3,000	6,700
Storage, *ac-ft*	30,000	50,000
Top of joint-use pool		
Elevation, *ft msl*	599.7	445.0
Area, *ac*	11,100	24,600
Storage, *ac-ft*	210,000	283,000
Top of flood control pool		
Elevation, *ft msl*	626.5	462.5
Area, ac	25,300	58,400
Storage, *ac-ft*	682,000	983,000
Top of surcharge pool		
Elevation, *ft msl*	638.2	467.2
Area, ac	35,800	71,300
Storage, *ac-ft*	1,005,000	1,286,000
Spillway		
Crest elevation, *ft msl*	594.0	425.0
Free-flow discharge capacity at top of flood pool, *cfs*	95,200	131,000
Discharge capacity at top of surcharge pool, *cfs*	166,100	160,000
Minimum release, *cfs*	10	50
Nondamaging flow release, *cfs*	1,800	4,000
Maximum allowable release for lake level below top of flood pool, *cfs*	4,500	. 10,000

Physical Data. The data on reservoir elevations, corresponding water surface area and storage capacities, flow releases, etc., pertinent to the regulation of the two lakes are given in Table 1. The amounts of water stored between the top of the joint-use pool and the dead storage pool are 180,000 ac-ft in Lake Shelbyville and 233,000 ac-ft in Carlyle Lake. The distribution of joint-use storage between the state of Illinois and the Federal Government is given below (Corps of Engineers, 1964).

Lake	Joint-use storage	Illinois	Federal Govt.
Shelbyville	180,000 ac-ft	25,000 ac-ft	155,000 ac-ft
Carlyle	233,000 ac-ft	33,000 ac-ft	200,000 ac-ft

Illinois has the right to withdraw water from its available reserve provided the lake surface is above the top of the dead storage (or inactive) pool. Regardless of water surface elevation, the Federal Government reserves the right to maintain the minimum downstream releases, 10 cfs from Shelbyville and 50 cfs from Carlyle.

Corps of Engineers. 1964. *Design Memorandum: Low Flow Regulation (Joint Operation)* U.S. Army Engineer District, St. Louis.

Releases up to the maximum allowable flows downstream of Shelbyville Dam can be handled by the undersluices. Higher releases necessitated by lake levels exceeding 626.5 ft msl are handled by discharges over the spillway for part-gate opening or free-flow conditions depending upon the inflow. In the case of Carlyle Dam, the undersluices can take care of a release of about 2000 cfs. Higher releases are accomplished by. partial opening of one or more tainter gates.

The minimum releases of 10 cfs below Shelbyville and 50 cfs below Carlyle are in excess of the minimum flows experienced at these locations for the last 30 years or more. The 7-day 10-year low flows, had the dams not been constructed, would have been 0.9 and 20.1 cfs (Singh and Stall, 1973). When the Navigation Channel below Fayetteville becomes operational in 1978, the minimum flow releases over and above the 10 and 50 cfs values will be governed by the additional flow needed to meet the lockage requirements and would be charged to the Federal storage reserve. A withdrawal of 13 cfs from Carlyle Lake is earmarked for Texaco-Salem water supply.

Both Carlyle and Shelbyville Dams are earthen dams with concrete spillways fitted with tainter gates. A 4.8 ft freeboard has been provided above the lake levels reached by maximum probable floods routed through the lakes.

The area submerged (or the water surface area) and storage capacity curves for the two lakes are shown in Figure 2. This information is necessary not only for analyzing lake input-output, but also for estimating the areas inundated above a certain level that would undergo damages to crops, recreation, and property.

Regulation of Lakes. The lakes are operated from a multiple-use management viewpoint. The major uses so far have been for enhancement of recreation, reduction in agricultural damages, and augmentation of low flows during dry weather conditions. The water supply and navigation requirements have so far been inoperative, but they form an integral part of any long-range regulation plan.

After the lakes became operational, it soon was apparent that the estimated channel capacities below Shelbyville and Carlyle, for nondamaging flow conditions, would have to be drastically reduced. From actual observations of inundated areas below the dams, these capacities were fixed at 1800 and 4000 cfs below Shelbyville and Carlyle, respectively, compared with 4500 and 7000 cfs assumed in the original project designs. Before the teething troubles in management of these two projects were over, the upper half of the Kaskaskia River basin experienced two of the wettest years in the last 33 years of record (October 1941 through September 1974) as indicated in Table 2.

With the experience gained over the years, the Corps of Engineers undertook a comprehensive reanalysis of the operation of these two lakes in 1969, with the results shown in Table 3. The Corps selected regulation plan 7 as the long-range plan and plan 6 as the interim plan to be used until the Navigation Channel becomes operational, say up to the year 1978.

The Problem

Carlyle Lake began filling April 1, 1967, and reached joint-use pool level in December. Therefore, the outflow from this lake can be considered as regulated from January 1968 onward.

Singh, K. P., and J. B. Stall. 1973. *The 7-Day 10-Year Low Flows of Illinois Streams.* Illinois State Water Survey Bulletin 57. 24 p.

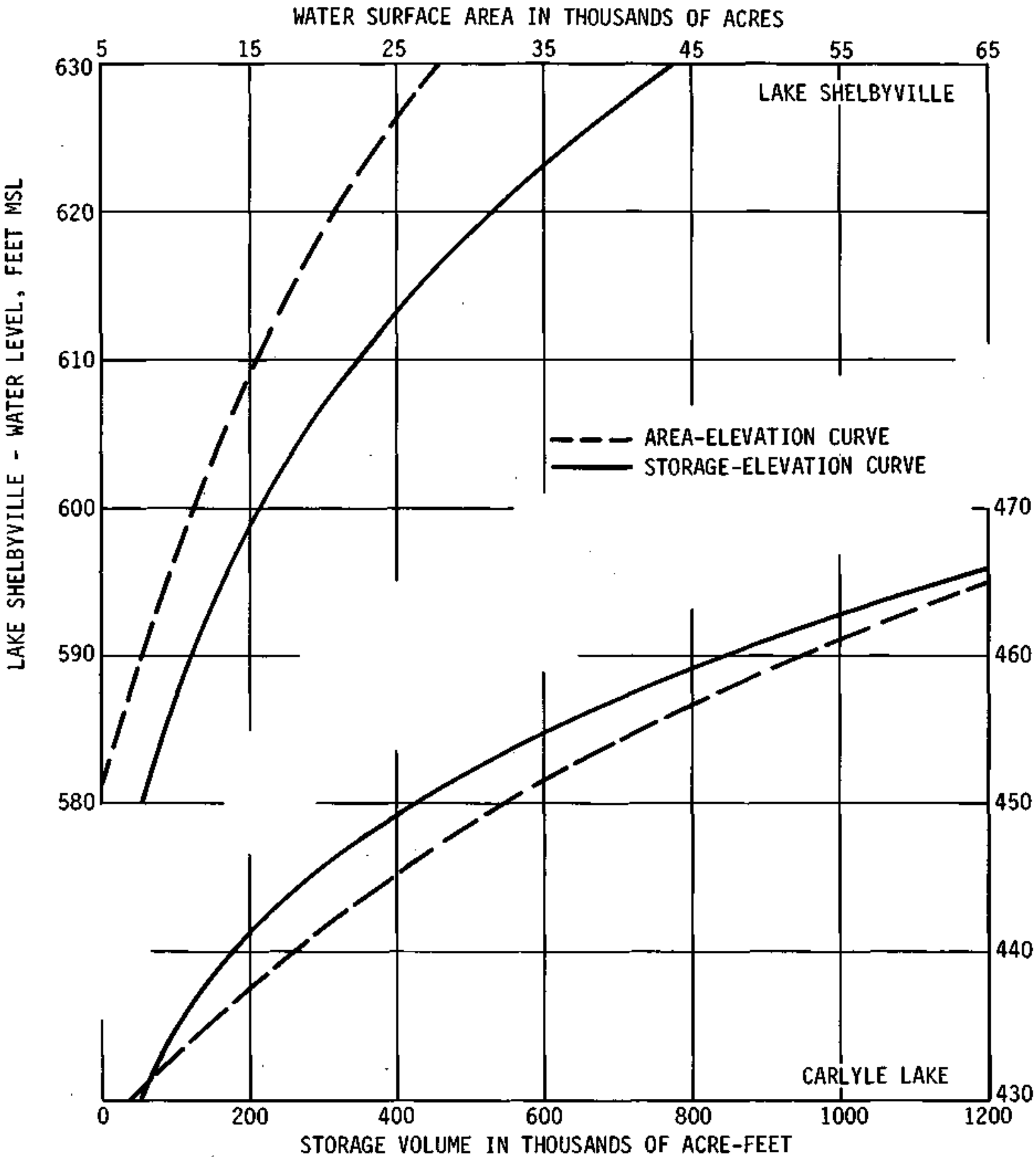

Figure 2. Water surface area and storage capacity curves for Lake Shelbyville and Carlyle Lake

Table 2. Mean Annual Flows, *in cfs,*
Kaskaskia River

Water year	At Shelbyville	At Carlyle
1942	1358	3140
1943	1207	3210
1944	662	1418
1945	815	2696
1946	915	2611
1947	963	2652
1948	675	1820
1949	805	2645
1950	1657	4246
1951	1169	2762
1952	915	2207
1953	338	706
1954	36.1	71.5
1955	291	633
1956	467	1116
1957	1212	3640
1958	953	2328
1959	707	1637
1960	611	1757
1961	486	1696
1962	997	2594
1963	300	894
1964	458	851
1965	486	829
1966	523	1435
1967	837	*2117
1968	1113	*2722
1969	741	*2220
1970	*932	*2571
1971	*545	*905
1972	*672	*1306
1973	*1754	*4248
1974	*1950	*4398
Average	835	2124

NOTE: * denotes that annual flows have been corrected for lake storage effects.

Lake Shelbyville was commissioned on June 24, 1969, and reached the top of the joint-use pool in June 1970. Thus, the releases from these lakes have been regulated for the last four years or more. Maximum lake levels and releases during the years 1971-1974 are given below. This information has been taken from the preliminary St. Louis District daily river data.

	Lake Shelbyville				*Carlyle Lake*			
	Nov. to April		May to Oct.		Nov. to April		May to Oct.	
Year	S	Q	S	Q	S	Q	S	Q
1971	590.44	810	606.37	1800	445.23	3,040	446.15	3220
1972	605.63	2110	603.35	1800	448.88	4,020	448.83	3495
1973	612.13	4490	613.63	2120	455.48	9,935	455.08	6370
1974	612.30	4500	620.27	3670	455.13	10,038	453.75	5024

S = maximum lake level attained, ft msl
Q = maximum outflow or release, cfs
Year 1971 = November 1970 to October 1971

Table 3. Results of Various Regulation Plans by the Corps of Engineers

Regulation Plan Number	1	2	3	4	5	6	7	8	9
Carlyle Lake									
Joint-use pool level, *ft*	445.0	443.0	443.0	443.0	443.0	445.0	445.0	445.0	445.0
Max flood control pool release, *cfs*	8,500	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Winter months of flood releases	Jan-Mar	Jan-Mar	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr
*Damaging flood release level, *ft*	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0
Winter drawdown level, *ft*	None	None	None	None	None	440.0	443.0	437.0	437.0
Lake Shelbyville									
Joint-use pool level, *ft*	599.7	596.0	596.0	596.0	599.7	599.7	599.7	599.7	599.7
Max flood control pool release, *cfs*	3000	4500	4500	4500	4500	4500	4500	4500	4500
Winter months of flood releases	Jan-Mar	Jan-Mar	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr	Dec-Apr
*Damaging flood release level, *ft*	612.0	602.0	602.0	610.0	610.0	610.0	610.0	610.0	610.0
Winter drawdown level, *ft*	None	None	None	None	None	590.0	596.0	585.0	590.0
Average annual damages, *in 1000 dollars*	577.8	407.9	389.6	390.6	466.1	362.4	428.1	340.1	359.3

NOTES: 1. Interim plans: 6, 8, 9; Long-range plans: 1, 2, 3, 4, 5, 7
2. *Pool elevations at which releases are increased resulting in downstream flooding
3. Release is increased linearly with increase in elevation up to the maximum allowable of 10,000 and 4500 cfs at elevations 462.5 and 626.5 ft, respectively, for the Carlyle and Shelbyville Lakes

Maximum releases during the growing period (May to October) in 1973 and 1974 were much higher than nondamaging releases and caused severe damages to crops in the bottomlands. Lake levels exceeding 610 and 450 ft in Shelbyville and Carlyle caused high crop losses in the areas inundated and substantial damage to recreation structures and facilities as well as serious curtailment of recreation activities.

The following four reaches are directly affected by the regulation of the two lakes:

1. Upstream of Shelbyville Dam: The area covered by the lake and adjoining area affected by wave erosion, above 610 ft elevation.
2. Downstream of Shelbyville Dam: The area inundated by flow releases below the dam to the confluence with Beck Creek, a distance of 35 miles; adds a drainage area of 332 sq mi.
3. Upstream of Carlyle Dam: The area covered by the lake and adjoining area affected by wave erosion, above 450 ft elevation.
4. Downstream of Carlyle Dam: The area inundated by flow releases below the dam to the confluence with Crooked Creek, a distance of 22 miles; adds a drainage area of 95 sq mi.

In addition, there are flooded areas along the Kaskaskia River below Beck and Crooked Creeks (Figure 1). The protection against flooding afforded by reservoir regulation to areas lying downstream decreases as the distance to these areas increases. Relief to such areas may come partly from improved regulation and partly from local flood control measures such as levees or flood retention reservoirs on the tributaries.

The major problems experienced in the damage reaches are described in the following paragraphs.

Flooding of Agricultural Lands. Areas under crops can be flooded both in the lake areas because of high lake levels and along the river downstream because of high releases that cause overbank flows. The severity and frequency of these damages depend on the efficiency of regulation, though damages cannot be totally avoided because of the rather moderate flood storage capacity of the lakes.

Loss of Land. Land may be agricultural, wooded, or primarily meant for recreation. In the lake areas, the shoreline is receding at places from erosion due to wave action. Some recreation facilities near the shoreline are in danger of being destroyed by advancing shore erosion. This erosion is aggravated by more frequent and rapid changes in lake levels. In the downstream reaches of the Kaskaskia River, bank erosion is a dominant feature along the numerous sharp curves and connecting lengths. Shore and bank erosion are causing loss of good land and are having an adverse effect on the environment.

Damage to Recreation. High lake levels restrict recreational use because of access problems and partial flooding of service facilities. In addition, high water levels do structural damage to some recreation facilities. Very low levels, on the other hand, can leave boating ramps high and dry, uncover unaesthestic mud flats, and greatly reduce the water area and shoreline available for recreation.

Clearance of Debris. Many trees near the shoreline in the two lakes have died because of high water levels during 1973 and 1974. Until a suitable species of trees is established along these lakes, the tree loss will continue. Uprooted, floating trees are a nuisance and a hazard for swimmers and boaters. Along the river in the downstream reaches, the trees on the banks are falling in the river because of erosion and bank cutting. At places the trees form sizeable logjams causing considerable bank cutting on both sides. This floating and partly fixed debris needs to be cleared at regular intervals not only to cut down the loss of land but also to reduce the hazard to recreation.

Sustained High Releases. Sustained water releases at about the bankfull capacity of the river below the two dams cause a host of problems. The banks are saturated and more susceptible to scour by high velocities at bankfull flows. The low-lying bottomlands do not get sufficient time to drain out through sloughs and troughs. Where these lands have tile drainage, the high water level in the river interferes with the efficient operation of tile drains. Psychologically, this situation causes farmers along the banks to fear that a good rain any day may cause water in their fields.

Backwater Effects in Tributaries. Before construction of the dams, the flood peaks in tributaries generally reached the main river when it was still rising. No doubt high tributary flows occurred when river stages were high, but not very often. The regulated flows downstream of the reservoirs over long periods of time have significantly increased the frequency of concurrence of tributary peak flows and high river stages. This has significantly increased the backwater effects, flooding more lands along the tributaries, depositing undesirable sediment over the flooded agricultural lands, and submerging and even burying some of the tile drain outlets under the deposited sediment.

Objectives of This Study

The severe damages during the past two years increased the dissatisfaction of both farmers and recreationists with the present regulation procedures. The state of Illinois allocated funds to the Division of Water Resources, Department of Transportation, to conduct an overall investigation of the regulation plans and to find if any improvements can be made *to minimize the agricultural damages and maximize the recreation benefits to the state.* Because this was primarily a hydrologic problem, the Division of Water Resources contracted with the State Water Survey through the University of Illinois to undertake such a study starting November 1, 1974, and ending June 30, 1975.

The following objectives were set forth for this study:

1. *Evaluation of Present Operating Rules.* Includes review of the basic data used by the Corps of Engineers, scope of recreation and agriculture, benefit and damage functions, interim and long-range plans for joint operation, and results of regulation from actual operation of the lakes for the water years 1972-1974.

2. *Development of Methodology for Deriving 'Optimum' Operating Rules.* Includes a search for initial operating rules by the use of dynamic programming, recreation functions, and simplified agricultural damage functions; the development of 'optimum' operating rules via simulation with detailed agricultural, recreation, and property damage and benefit functions; and the determination of the effect of water supply and navigation requirements on the 'optimum' regulation plan.

3. *Comparison of Different Regulation Strategies.* With the use of the 24-yr record (1942-1965) of daily flows at Shelbyville and Carlyle gages as published in the Water Supply Papers of U.S. Geological Survey, compares the average annual benefits with the Corps strategy, with the strategy developed in this study, and with damages to agriculture below Shelbyville and Carlyle under natural flow conditions, i.e., considering no dams were present.

4. *Comparison of Benefits with Different Strategies for the Years 1972-1974.* Compares benefits with the developed strategy, the Corps strategy, and the actual operation of the lakes based on data from regulation of Shelbyville and Carlyle Lakes for the water years 1972, 1973, and 1974, and assesses agricultural damages in those years for the river reaches below Shelbyville and Carlyle had the dams not been constructed.

5. *Suggestions for Further Improvement in Regulation Strategies.* Rigorous analytical procedures may be used to ascertain if any further improvement in overall benefits can be effected. Different flow traces of 50 years or more length may be generated and used in optimization. Better definition of area inundated vs discharge curves, more precise information on agricultural income and its variability, comprehensive study of channel hydraulics in the reaches below the dams, incorporation of bank and shore stabilization in operation strategy, and allowance for uncertainties in hydrologic and economic indicators are other features for consideration. Study may be made about the lead times required for reducing releases when tributary flows are high in order to minimize losses due to backwater effects.

EVALUATION OF PRESENT OPERATING RULES

The original plan of regulation developed during the project design study period called for outflows equal to inflows up to the channel capacities of 4500 cfs below Shelbyville and 7000 cfs below Carlyle Dam, and simple gate regulation curves for higher inflows. Field trial of this plan indicated channel capacities below Shelbyville and Carlyle to be 1800 and 4000 cfs, respectively. These low capacities dictated major modification of the operating rules with releases varying with lake levels and seasons. Each year of operation saw minor changes in the start of drawdown or rise of lake levels and in the periods for releasing certain flows.

In 1969, the Corps undertook an 'exhaustive' reanalysis of various operating plans, as was shown in Table 3. Their preferred interim plan (without navigation) is 6 and their preferred long-range plan is 7 which allows for navigation withdrawals. Interim plan 6 has been modified and this modified plan has been incorporated in the yet unapproved Master Reservoir Regulation Manual. The modified schedule of releases is shown in Figure 3. The objective is to maintain the rule curve elevation at all times. Their modified regulation differs from interim plan 6 in that the winter dump is allowed to begin October 1 instead of December 1, depending on downstream conditions, and the rule curve for Lake Shelbyville allows lowering the lake level to 590 from October 1 instead of from December 1.

The beginning of the winter dump will be governed largely by the harvesting of crops in bottomlands susceptible to flooding in the damage reaches below Shelbyville and Carlyle. The harvesting may be completed by the end of October in some years, but normally it continues to mid-November. High flows exceeding nondamaging flows of 1800 cfs and 4000 cfs cannot be released below the dams until the crops are harvested without causing tremendous agricultural losses. Moreover, the inflows during the period October to December are generally much lower than 1800 and 4000 cfs at Shelbyville and Carlyle, and beginning the winter dump in December, rather than in October, will not make much difference. The storage capacity of 94,600 ac-ft created by lowering Lake Shelbyville to 590 starting October 1, instead of December 1, could also be achieved by passing maximum allowable flows for about 10 days during the first half of December. Because of the reasons stated above and because of the nonavailability of the proposed manual, plans 6 and 7 in Table 3 are considered as the Corps present interim and long-range regulation plans.

Basic Data

The background and supporting information that went into the analysis of various operating schemes is reviewed here.

Hydrologic and Other Pertinent Data. The daily flows at the four gaging stations on the Kaskaskia River are available for use in hydrologic analyses. These data are published by the U.S. Geological Survey in their annual regional and state publications. Daily flow records are available for the following periods.

Station name and location	Drainage area, sq mi	Continuous record beginning
Kaskaskia River at Shelbyville	1030	Oct. 1940
Kaskaskia River at Vandalia	1980	Aug. 1914
Kaskaskia River at Carlyle	2680	May 1938
Kaskaskia River at New Athens	5181	Oct. 1934 (to Sept. 1971)

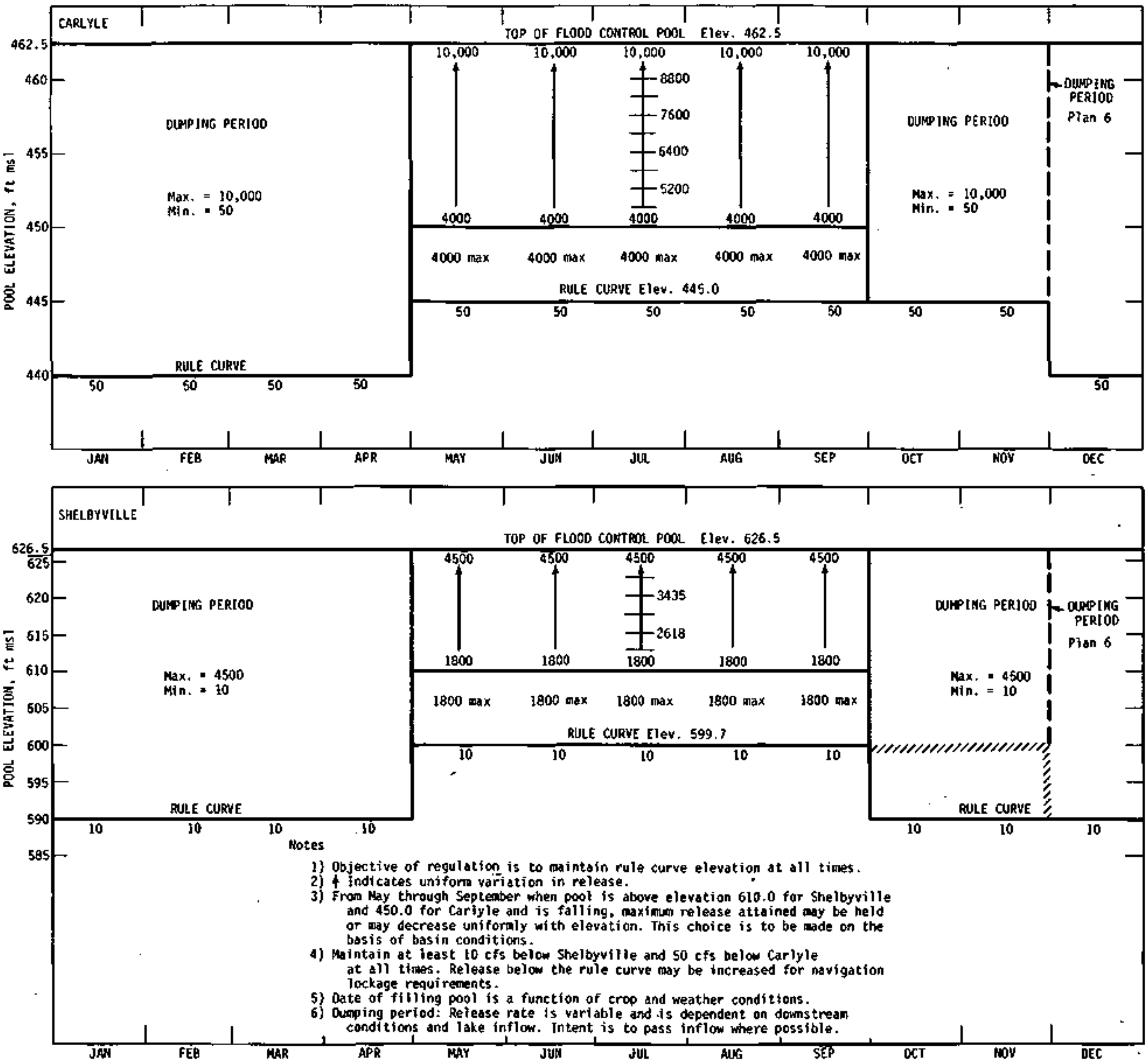

Figure 3. Corps modified interim plan (Master Reservoir Regulation Manual, U.S. Army Engineer District, St. Louis)

In simulated operation studies (Corps of Engineers, 1960) the flows for the period 1930-1959 were used. The flows at Shelbyville were derived by synthetic means for the years 1930-1940. For Carlyle Lake, the flows for the period 1930-1954 (Corps of Engineers, 1958) were used, and the flows for the years 1930-1938 were derived synthetically. In a study of low flow regulation and joint operation of the two lakes (Corps of Engineers, 1964) the flow data for the years 1935-1959 were used because the corresponding flows were available at the New Athens gage for estimating the navigation releases. In an exhaustive reanalysis of the joint operation of the two reservoirs in 1969, the streamflow data used spanned the period 1935-1967, although the 1967 data were not natural river flow data because of Carlyle Lake.

Lake Evaporation. Lake evaporation data are needed to adjust the inflows for the net precipitation (or precipitation, P, minus evaporation, E) from the lake area. Pan evaporation data observed over a number of years were available at four stations in the general vicinity of the lakes. These stations are: Washington University, St. Louis, Missouri; and Springfield, Carbondale, and Urbana in Illinois. Evaporation from the Shelbyville and Carlyle Lakes was estimated by multiplying the average monthly pan evaporation by a pan coefficient of 0.8. The average monthly evaporation and precipitation (based on 33 to 38 years of rainfall data) are given in Table 4, as used by the Corps of Engineers.

Average monthly pan-to-lake coefficients for the four locations (Roberts and Stall, 1967) vary from 0.59 to 0.77, 0.60 to 0.77, 0.59 to 0.77, and 0.60 to 0.82; the months March to Septem-

Table 4. Average Monthly Precipitation, Evaporation, and Net Precipitation, *in inches*

	Lake Shelbyville			*Carlyle Lake*		
Month	P	E	P-E	P	E	P-E
October	3.10	2.86	0.24	2.99	2.70	0.29
November	2.83	1.62	1.21	2.94	1.70	1.24
December	2.14	0.98	1.16	2.21	0.98	1.23
January	2.31	0.68	1.63	2.55	0.68	1.87
February	2.15	0.82	1.33	2.31	0.82	1.49
March	3.22	2.14	1.08	3.26	2.29	0.97
April	3.75	3.70	0.05	3.72	3.70	0.02
May	4.28	4.90	-0.62	4.51	4.74	-0.23
June	4.60	5.54	-0.94	4.35	5.35	-1.00
July	3.39	5.99	-2.60	3.39	5.85	-2.46
August	3.32	5.24	-1.92	3.38	5.12	-1.74
September	3.51	4.33	-0.82	3.14	4.18	-1.04
	38.60	38.80	-0.20	38.75	38.11	0.64

Corps of Engineers. 1960. *Design Memorandum No. 1: Hydrology and Hydraulic Analyses, Shelbyville Reservoir.* U.S. Army Engineer District. St. Louis.

Corps of Engineers. 1958. *Design Memorandum No. 1 (Revised): Hydrology and Hydraulic Analyses, Carlyle Reservoir.* U.S. Army Engineer District. St. Louis.

Corps of Engineers. 1964. *Design Memorandum: Low Flow Regulation (Joint Operation).* U.S. Army Engineer District. St. Louis.

Roberts, W. J., and J. B. Stall. 1967. *Lake Evaporation in Illinois.* Illinois State Water Survey Report of Investigation 57. Urbana. p. 19.

ber have higher coefficients than those for the remaining months. The corresponding average-over-the-year coefficient values are 0.72, 0.72, 0.73, and 0.78. The use of 0.8 pan-to-lake coefficient is considered satisfactory because of unknown seepage losses as well as lower P-E values during dry years. A difference of 0.1 inch in evaporation over a month, when the Shelbyville and Carlyle Lakes are at their normal pool levels of 599.7 and 445.0, amounts to a difference of 92.5 and 205.0 ac-ft, or 1.55 and 3.45 cfs.

Minimum Flow Releases. The low-flow releases from the Shelbyville and Carlyle Lakes, when navigation requirements are not operative, were set at 10 and 50 cfs, respectively. The Kaskaskia River Navigation Project extends from the mouth of the river to Fayetteville, and will provide navigation for a distance of 32 miles. The upstream pool level at the lock and dam, located at about the 0.8 river mile, is set at 368.0 ft msl. Lockage requirements have been estimated by the Corps of Engineers on the basis of 10 synchronous and 6 random lockages for the 600 ft x 84 ft lock per day. The river stage downstream of the lock and dam is taken as the Mississippi River stage observed at the Chester (Illinois) gaging station. According to the present Corps plan for the long-range joint-operation strategy, the minimum flow releases are governed by the larger of the two flows: the guaranteed low flows or the flows needed to meet the lockage requirements with allowance for evaporation and leakage losses.

Area and Storage Capacity. Lake area and storage capacity curves were determined by the Corps of Engineers from project topographic maps. The area and storage versus elevation curves for the two lakes are shown in Figure 2. The data on outflows and lake levels for the period of operation of these lakes indicate that these curves are generally satisfactory for the range of elevations experienced in these years.

Channel Capacities. The channel capacities or the flow conveyance capabilities of the river channel downstream of Shelbyville and Carlyle Dams without causing noticeable flooding of the low-lying bottomlands were first taken as 4500 and 7000 cfs, respectively. No evidence of any survey or theoretical work could be found to indicate how these capacities were assumed. However, the actual operation of the lakes during the first year indicated that nondamaging flows would be closer to 1800 and 4000 cfs. These figures have been used in later analyses including the reanalysis of various operating plans done in 1969.

The river reaches for which the capacities of 1800 and 4000 cfs are believed to hold are the 35-mile reach below Shelbyville to Beck Creek and the 22-mile reach below Carlyle to Crooked Creek (damage reaches 2 and 4 on page 8). These reaches were inspected by Singh and Stall together with district conservationists of the USD A Soil Conservation Service. The reach below Shelbyville was checked near four bridge sites and the flow was generally 3 to 4 ft below the top of the banks. The release from Lake Shelbyville was 1800 cfs but there was not much tributary or lateral inflow. There were a few local areas and some swales which either had some water or were wet. The Kaskaskia River downstream of Carlyle to its confluence with Crooked Creek was inspected at six places. River flow was about 1600 cfs and banktops in general were 8 ft or higher above the water. Prominent marks at about 3 ft below the banktops indicated a flow condition of 4000 cfs. Thus, when the release is 4000 cfs from Carlyle Lake, the river stage may be 2 to 3 feet below the top of the banks in this damage reach.

A casual mention was made of a limited number of tile drains emptying into the main river. However, neither the district conservationists nor their staff were aware of the location of such drains. The main complaint of farmers seemed to be the unusually long periods of sustained bankfull flows that impede drainage of bottomlands, scour the banks, uproot trees, and form log jams which further worsen the erosion.

Discharge vs Area Flooded Downstream of Lakes. The Corps obtained channel cross-sections for the two damage reaches and water surface profiles for low to medium flows. This information was augmented by data available from some historical floods. The Corps used the available information to construct area-elevation curves for various short segments throughout the length of the two reaches. Curves were then drawn, as shown in Figure 4, relating the outflow from Shelbyville and Carlyle Lakes and the area flooded in the respective damage reaches. These curves need better definition by detailed survey of the reaches as well as by inclusion of a function to account for the effects of variability of tributary inflows. Such information would be more meaningful in simulated operation because it may be possible to modify downstream releases allowing for tributary inflows.

Recreation Benefits and Damages

"Recreational operation and maintenance have the objective of providing the visitor with a rewarding recreational experience. This is done by providing maximum facility use despite water level fluctuations, offering a variety of family-oriented recreational activities, preserving the area's natural character despite development, and allowing maximum visitor use of the area without endangering themselves, other visitors, or the facilities" (Corps of Engineers, 1975). Some property along the lake shores is leased to concessionaires to provide such services as boat storage, cabins, and restaurants. There are also State Park areas operated by the Illinois Department of Conservation.

The main recreational activities in the lake areas and immediate areas downstream are: camping, picnicking, swimming, boating, water skiing, fishing, and hunting. The estimates of visitors per year for each of the seven activities at the Shelbyville and Carlyle Lakes have changed from time to time in view of the data accumulated over the years of operation as well as the steady improvement in space and time sampling of the visitor count surveys. Visitor data for the years 1971-1974 were obtained from the Corps field offices at Shelbyville and Carlyle. The Illinois Department of Conservation and its field staff helped in estimating the actual number of visitors to be used in simulation of the joint lake operation. The number of visitors used in the 1969 analysis of regulation plans, as well as those now worked out in joint consultation with the Corps and Department of Conservation, are given in Table 5. These visitor numbers are for a year in which there are no adverse high or low lake levels, and thus represent the maximum recreational potential under the present conditions of demand. The dollar value per visitor day for each activity is included in Table 5, and discussed below.

Although recreational experiences are often cited as being highly personal and variable among individuals, the economic value is, nonetheless, real and comparable to the economic value of all consumer goods — a value measured by what people are willing to give up to attain them (Fischer, Lewis, and Priddle, 1974). Resource-oriented outdoor recreation activity may involve substantial expenditures for equipment, e.g., a trailer or pickup for camping and a boat for boating, or

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Corps of Engineers. 1975. *Environmental Statement: Lake Shelbyville, Illinois.* U.S. Army Engineer District. St. Louis. p. I-16.

Fischer, D. W., J. E. Lewis, and G. B. Priddle (editors). 1974. *Land and Leisure: Concepts and Methods in Outdoor Recreation.* Maaroufa Press. Chicago. p. 167-174.

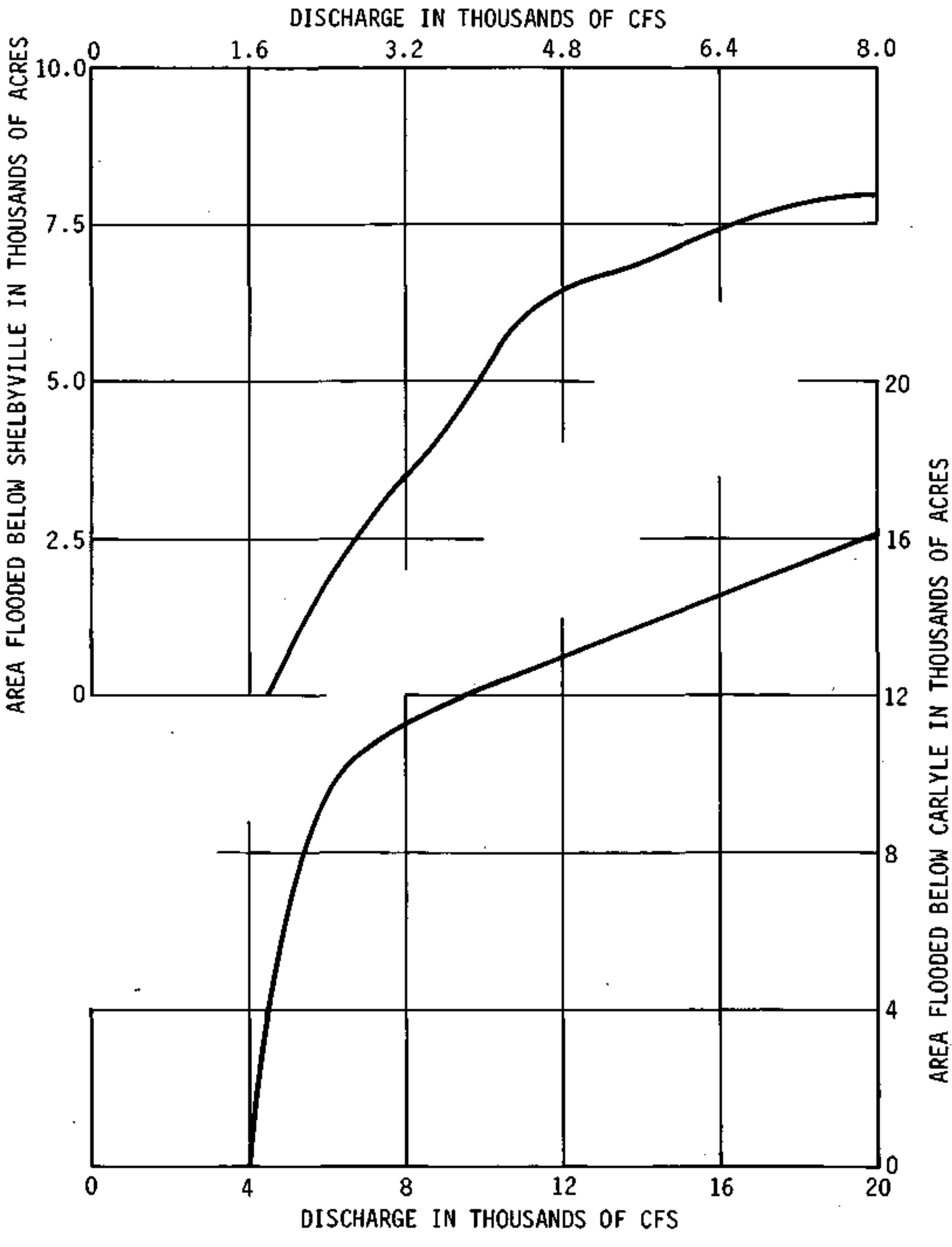

Figure 4. Area flooded versus discharge curves for damage reaches below the dams

Table 5. Yearly Number of Visitors by Recreational Activity

	Lake Shelbyville		Carlyle Lake		Dollars per recreation day
	Previous analyses	As worked out now	Previous analyses	As worked out now	
Camping		365,000	137,000	110,000	1.50
Picnicking		130,000	190,000	190,000	1.50
Swimming	475,000	400,000	140,000	100,000	1.50
Boating	952,000	300,000	200,000	200,000	1.50
Skiing	101,300	60,000	11,000	40,000	1.50
Fishing	830,000	350,000	476,000	250,000	3.00
Hunting		35,000	5,000	20,000	3.00
	2,358,300	1,640,000	1,159,000	910,000	

NOTE: Maximum recreation benefit per year equals $4.8075 million

modest expenditures, e.g., for fishing, swimming, and picnicking. Outdoor recreation has developed largely as a nonmarket commodity. Though recreation has an important economic value, economists and public administrators have been ill-prepared to include it in the social or public accounting in ways that lead to better allocation of resources. As the desirability of establishing values for recreational use of resources has become more apparent over the past few years, a number of methods have been proposed and used to some extent. These include: gross expenditure method, market value of fish method, cost method, market value method, methods based on willingness to pay, interview methods, and travel-cost method. None of these has been tested well and all have their shortcomings. The recreation day value may range from 75¢ to $30 or more. In absence of any agreed method, the Water Resources Council (1973) has suggested the following simulated prices per recreation day under the definitions given below.

Type of outdoor recreation day	Range of unit day value
General	$0.75 - $2.25
Specialized	$3.00 - $9.00

"General: A recreation day involving primarily those activities attractive to the majority of the outdoor recreationists and which generally require the development and maintenance of convenient access and adequate facilities.

"Specialized: A recreation day involving primarily those activities for which opportunities, in general, are limited, intensity of use is low, and often may involve a large personal expense by the user.

" [Recreation day:] A single unit value will be assigned per recreation day regardless of whether the user engages in one activity or several. The unit value, however, may reflect both the quality of activity and the degree to which opportunities to engage in a number of activities are provided.

"The general class, constituting the great majority of all recreation activities associated with water projects, embraces the more usual activities, such as swimming, picnicking, boating, and most warm water fishing. In view of the fewer alternatives available and the likelihood that higher total costs are generally incurred by those engaged in hunting and fishing activities compared with those engaged in other types of outdoor recreation, it may be anticipated that monetary unit values applicable to fish and wildlife recreation will ordinarily be larger than those applied to other types of recreation."

Water Resources Council. 1973. *Water and Related Land Resources-. Establishment of Principles and Standards for Planning.* Federal Register, Vol. 38, No. 174, Part III. p. 24804.

Average values of $1.50 per recreation day for camping, picnicking, boating, swimming, and skiing and $3.00 for fishing and hunting, as used by the Corps of Engineers, seem to be satisfactory for computation of recreation benefits.

Damages to Recreation. To maximize the recreational use of lakes despite water level fluctuations, numerous structural and operational techniques are employed. Some of these are (1) placing permanent structures such as picnic shelters and comfort stations at a level (610 ft for Lake Shelbyville and 450 ft for Carlyle Lake) much higher than joint-use pool, and (2) providing boat launching ramps and docks that can be operative over a considerable range of elevation (generally 585-610 ft for Lake Shelbyville and 438-450 for Carlyle Lake). Similarly, man-made swimming beaches are operable between certain pool levels, as are management practices for wildlife recreation. Information on water levels above and below which the usual number of visitors cannot fully participate in a particular recreation activity and the percentage reduction in the activity with rise or fall in levels are important for evolving a good regulation scheme. Recreation damage consists of damage to facilities and loss of enjoyment by recreationists who are unable to use the facilities. The levels and percent damage figures finally arrived at as a result of talks with the Corps and information from the Department of Conservation differ considerably from those employed by the Corps in previous analyses. The pertinent information is given in Table 6.

Distribution of Visitors over the Year. In order to obtain the number of visitors in each activity on a particular day of the month, the Corps had developed multipliers to the annual visitors for a particular activity at each of the two lakes. New multipliers were developed with the use of the recreation data from the Corps field offices at Shelbyville and Carlyle for the years 1972-1974. These are weekly multipliers because a week was considered a reasonable time unit for developing new reservoir regulation rules. The multipliers are graphed in Figure 5 for camping, picnicking, swimming, skiing, boating, and fishing at Shelbyville and Carlyle. They differ from those obtained by aggregating daily values of multipliers, used by the Corps in previous studies, to weekly values. However, over a period of one year, both daily and weekly multipliers for any activity add up to unity. Weekly multipliers for hunting are 0.036, 0.123, 0.170, 0.139, 0.119, 0.131, 0.135, 0.104, and 0.043 for weeks 3 to 11 (mid-October to mid-December) at each of the two lakes.

Computer Program for Assessment of Recreation Benefits and Damages. The purpose of the program is to compute recreation loss because of high or low water level in Shelbyville and Carlyle Lakes. The numbers of visitors lost in each activity are multiplied by the dollar value assigned to that activity and the total loss gives the recreation damage. Net recreation benefit equals the potential (or with no damages) recreation benefit minus the damages accrued over the year.

The Corps Reservoir Simulation Program yields the lake levels for each day of the year for all the years for which inflow data are available. These daily lake levels become the input to the recreation benefits program. It contains data on yearly number of visitors for each activity, daily multipliers to calculate daily number of visitors, high and low lake levels above and below which recreation loss occurs, the percent loss per foot change in lake level, and the maximum percent loss.

Visitors for activity j and day i are calculated from

$$(\text{visitors})_{i,j} = (\text{visitors in year})_j \times (\text{multiplier})_{i,j}$$

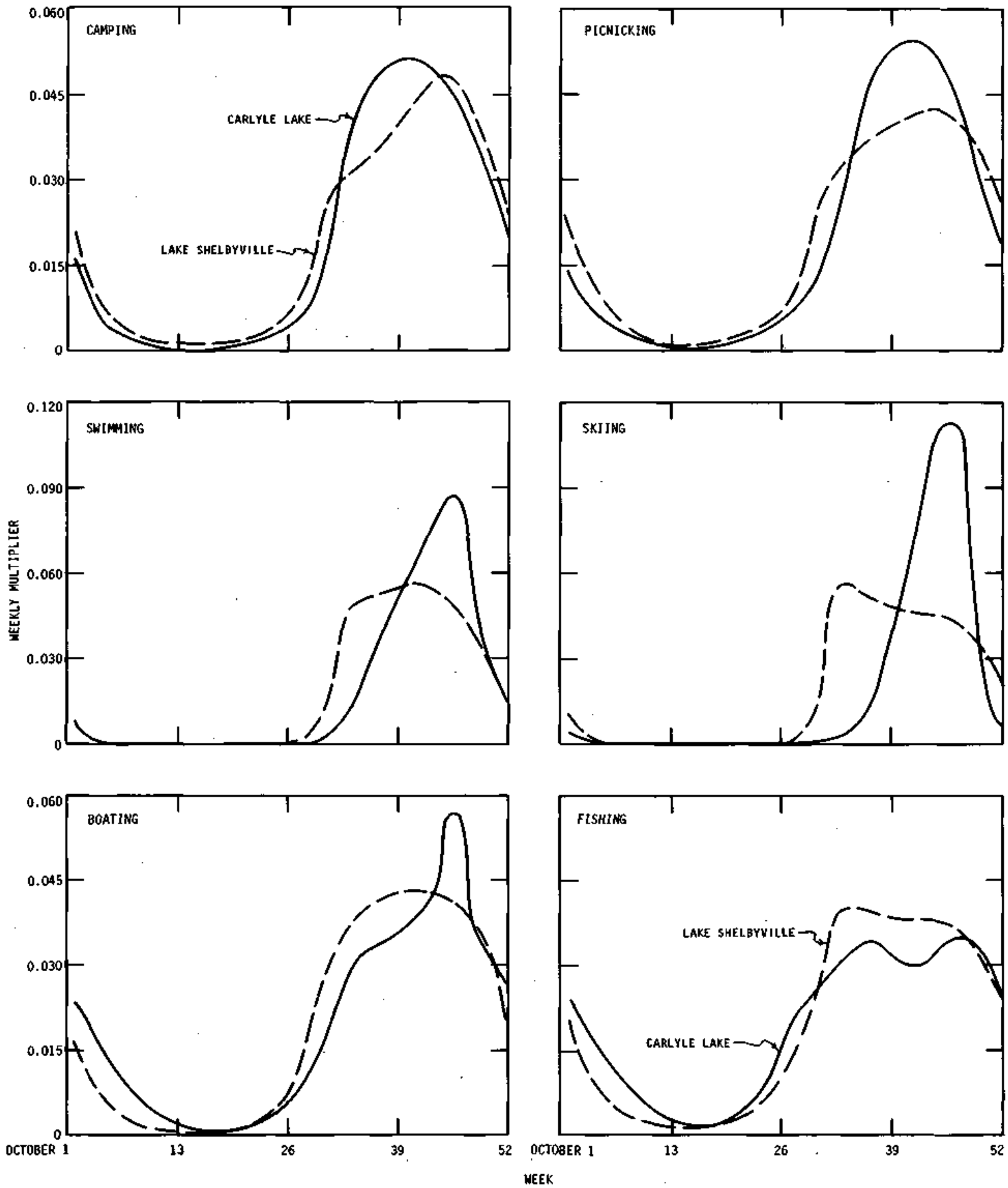

Figure 5. Distribution of visitors for various recreational activities
(Number of visitors per week equals the product of that week's multiplier
and total of visitors over the year for the recreation activity under consideration)

Table 6. Percent of Recreation Loss per Foot of Change in Lake Level

Activity	Low level*	% Loss	Max	High levelt	% Loss	Max
Old data, used by Corps of Engineers						
Shelbyville						
Camping		No loss			No loss	
Picnicking		No loss			No loss	
Swimming	595	5.0	50	603	8.33	70
Boating		No loss		603	8.33	39
Skiing		No loss		603	8.33	39
Fishing		No loss		609	37.5	75
Hunting		No loss			No loss	
Carlyle						
Camping		No loss		450	10	100
Picnicking		No loss		450	5.0	50
Swimming	438	25	100	450	20	100
Boating		No loss		450	20	100
Skiing		No loss		450	20	100
Fishing		No loss		450	8.5	85
Hunting	445	50	100	450		100
New data, used in this study						
Shelbyville						
Camping		No loss			No loss	
Picnicking		No loss			No loss	
Swimming	589	5.0	50	603	8.3	70
Boating	585	25	100	610	8.3	39
Skiing	585	25	100	610	8.3	39
Fishing	585	15	75	610	5.0	75
Hunting	589	10	100	602	3.5	95
Carlyle						
Camping		No loss		450	10	100
Picnicking		No loss		450	5.0	50
Swimming	438	25	100	450	10	100
Boating	438	25	100	450	10	100
Skiing	438	25	100	450	10	100
Fishing	438	15	75	450	6.0	72
Hunting	443	15	100	450	10	60

*Lowest lake level below which recreational loss begins
tHighest lake level above which recreational loss begins

Visitors lost because of high or low lake levels is obtained from

$$(\text{visitors lost})_{i,j} = (\text{visitors})_{i,j} \times p_j \times (\Delta E)_i/100$$

in which p is the percent visitors lost per foot of change in lake level, above or below the damage level; and ΔE is the height of lake level above damaging high level or depth of lake level below damaging lake level, in feet. If the lake level is in the nondamaging range of elevations, ΔE equals zero. In case the product of p_j and $(AE)_i$ exceeds the maximum allowable, it is set equal to the maximum.

Total recreation loss in dollars in a year

$$= \sum_{i=1}^{365} \sum_{j=1}^{7} \left\{ [(\text{visitors})_{i,j} \times p_j \times (\Delta E_i/100)] \times \$_j \right\}_s + \left\{ [(\text{visitors})_{i,j} \times p_j \times (\Delta E_j/100)] \times \$_j \right\}_c$$

in which subscripts s and *c* refer to Shelbyville and Carlyle Lakes. The program allows for a dry-out period of a duration specified by the user. The Corps documentation of the procedure indicated a 5-day drying period. For the weekly data compiled for this study, the dry-out period was taken as one week.

Damages to Agriculture

Flood control is one of the major purposes of the construction of Shelbyville and Carlyle Dams. During the water years 1942-1965, average weekly flows observed at Shelbyville exceeded 1800 cfs for 151 weeks, and weekly flows at Carlyle exceeded 4000 cfs for 178 weeks. These damage weeks constitute 12.1 and 14.3 percent of 1248 weeks in the 24 years of record. Number of damaging flow weeks during the main crop season, May 1 to November 15, are 94 and 113, respectively. The primary intent of flood control would be to reduce these crop damage weeks to a minimum or, if necessary, to restrict them to a few beginning weeks so that farmers could replant the crops. The flow control in the nongrowing period mainly consists of restricting the flows to a certain maximum and operating the lakes in a way to minimize losses from carrying storage of spring flows into the growing period.

The flood control storages, or the volume of water stored between flood control pool and joint-use pool levels, are 472,000 and 700,000 ac-ft in Lake Shelbyville and Carlyle Lake, respectively. The purpose of this storage is to store inflows that exceed downstream channel capacity (nondamaging flow in the growing season and maximum allowable during the nongrowing season) and release the stored water when inflows are less than flows allowed downstream. However, the storage of excess flows in the growing season for later releases results in sustained high, though nondamaging, flows downstream for weeks and sometimes months, causing bank erosion and back-up of water in tributaries when they have substantial flows. Drastic curtailment of releases not only poses the danger of insufficient storage available for any new high inflows but also can cause damage to recreation and crops in the lake area because of high lake levels. The object of regulation would be to minimize the overall damage to both recreation and agriculture, though a case may be made for some preferential treatment to agriculture insofar as the recreationists are more often outsiders while farmers and agriculture are the backbone of the community directly affected by the lake regulation. Also, farming is a livelihood and recreation is a spare-time pleasure activity.

Losses due to flooding of crops are of two types: loss of direct production investment (DPI) at the time of flooding, and loss of income (LI) which is not realized because of either destruction of crops before harvesting or reduced yields from late planting. The total DPI and LI values, for each of the four damage reaches, used in the 1969 reanalysis of plans by the Corps of Engineers are given in Table 7 together with the percent of area under different crops. The values of DPI and LI for a typical acre are obtained by multiplying the values for various crops in that acre by the respective fraction of acre under each crop, and adding the products.

The Corps used the Flood Hydrograph-Damage Integration (FHDI) Method (Cochran, 1960) for estimating flood damages in agricultural areas. Some details of this method are noted here.

Cochran, A. L. 1960. *Flood Hydrograph-Damage Integration Method of Estimating Flood Damage in Agricultural Areas.* Department of Army, Office of the Chief of Engineers, Washington, D.C. Unpublished note. 31 p. and 21 exhibits.

Table 7. DPI and LI Values for Four Damage Reaches

Item	Upstream of Shelbyville	Downstream of Shelbyville	Upstream of Carlyle	Downstream of Carlyle
Crop yield, *in bu/ac*				
Corn	100	90	77	85
Soybeans	35	33	25	30
Wheat	40	40	40	40
Hay *(tons/acre)*			3.0	3.5
DP I/acre, *in dollars*				
Corn	37.40	33.27	30.50	31.35
Soybeans	19.50	17.54	19.00	20.10
Wheat	13.55	13.55	19.40.	19.40
Hay			14.00	14.00
Li/acre, *in dollars*				
Corn	50.60	45.93	36.11	42.70
Soybeans	61.56	59.14	38.90	49.38
Wheat	32.45	32.45	26.60	26.60
Hay			33.40	42.80
Fraction of typical acre under				
Corn	0.15	0.50(0.60)*	0.21	0.38(0.45)
Soybeans	0.07	0.30	0.25	0.25
Wheat	0.03	0.10(0.00)	0.09(0.15)	0.05(0.00)
Hay			0.06 (0.00)	0.02 (0.00)
Timber etc.	0.75	0.10	0.39	0.30

*Numbers in parentheses show changes for this study which merged hay with wheat for areas upstream of dams and replaced wheat and hay by corn for areas downstream, as explained under step 3 below

FHDI Method. To estimate flood damages or potential flood control benefits, the requisite information comprises (1) the monetary values that are vulnerable to loss in the event of flooding, (2) the reduced monetary yields because of late planting or replanting, and (3) the monetary loss from individual flooding events depending on the dates of flooding. The method developed estimates losses from flooding of agricultural crops and takes into account major variations in damage potential with season. The main steps in applying this methodology and the salient points of our review of the Corps computer programs and information are:

Step 1. Designate appropriate limits of "damage reaches" to be used in estimating agricultural damages.

The damage reaches specified are those previously defined on page 8. Damage reaches 2 and 4 include bottomlands that are flooded from flows exceeding 1800 cfs below Shelbyville Dam and from flows exceeding 4000 cfs below Carlyle Dam.

Step 2. Designate "index gaging stations" corresponding to each damage reach for discharge or stage information needed to calculate the acreage inundated in each reach.

The stations for the four reaches are: 5-59195, Lake Shelbyville near Shelbyville; 5-5920, Kaskaskia River at Shelbyville; 5-59299, Carlyle Lake near Carlyle; and 5-5930, Kaskaskia River at Carlyle.

Step 3. Estimate the total land area below various flood levels that is considered suitable for crops and estimate the percent of that area in various crops.

The areas flooded are obtained from Figures 2 and 4, and the fractions of area in various crops in the four reaches are given in Table 7. Discussions with Soil Conservation Service district conservationists at Shelbyville, Vandalia, and Carlyle plus field inspections indicated that any wheat crops in the bottomlands are being planted above the flooding level attained by maximum allowable flows. Therefore the hay and wheat crops were merged for this study, as is also shown on Table 7.

Step 4. Collect information on crop yields per acre and their monetary value, replanting after flood occurrences, reduced crop yields and monetary values because of late planting or replanting, cost of various components of direct production investment such as plowing, disking and harrowing, seeds, planting, and cultivation.

The cost components and other pertinent information could not be obtained from the Corps of Engineers at this time. A general review of their computer program indicated that the requisite information is stored on tapes. It was not clear whether the different values and figures were changed from time to time to account for changing market conditions. Field trips were made to collect data for determining the necessary cost components. Because the developed information cannot be compared with that used by the Corps, it is presented separately in this report under Detailed Agricultural Damage Assessment.

Step 5. Compute DPI and LI distribution graphs for each type of crop considered in the study.

The DPI and LI distribution graphs are stored in matrix form in the Corps computer program. However, the values therein are old and any new analysis would require values under present conditons.

Step 6. Determine the lands flooded in the damage reaches with information developed from routing of historical inflows through a reservoir or a system of reservoirs during each 10-day period of the growing season.

The reservoir routing program of the Corps provides the areas flooded in each damage reach every day for the years of record analyzed. This output from the routing program becomes input to their agriculture damage assessment program which considers a dry-out period of 10 days after an area is flooded and also considers the effect of successive or intermittent flooding.

Step 7. Compute agricultural losses from the information developed under steps 5 and 6.

The Corps of Engineers' computer program yields the agricultural damages which are aggregated by season and year. It also summarizes the total loss for each flood event.

A general review of the computer program showed that the methodology used was similar to that outlined by Cochran (1960). However, a thorough checkup of the program could not be done in the limited time available because of a lack of description of variables used, a lack of explanation of various calculation steps, and relevant information matrices stored elsewhere. A meeting with the Corps gave an insight into what the program was expected to achieve, but step-by-step followup and checkup of functions were not possible.

Navigation Water Requirements

The navigation lock at 0.8 mile of the Kaskaskia River is 600 x 84 ft with a normal pool level of 368 ft msl (Corps of Engineers, 1964). Ten synchronous and six other lockages are assumed for an average day. It was indicated by the Corps that lockage volume was calculated by multiplying the lock area by the depth of the Mississippi River below 368 ft msl. For this purpose, the Mississippi River stage data observed at Chester, 8 miles downstream of the Kaskaskia River, were used. The daily lockage requirement was obtained by multiplying the lockage volume by 16, or the number of lockages per day, and adding an allowance for leakage and evaporation. Because the final information was not available from the Corps, the navigation requirements were computed as described below.

Daily navigation requirement, cfs

$$= 16 \times 600 \times 84 \times h \times 1.2/86400$$
$$= 11.2\,h \qquad \text{for } h > \text{zero}$$

in which h = 368.0 -Mississippi River level at Chester, ft; and 1.2 allows for 20 percent increase to account for leakage and evaporation loss. The average weekly flow requirement is translated to the weekly flow release from Carlyle, Q_{cn}.

$$Q_{cn} = 11.2\,h - (Q_{na} - Q_{cb}) \qquad \text{but} \nless \text{min flow release}$$

In the above equation, Q_{na} denotes the weekly flow recorded at the New Athens gage and Q_{cb} is the weekly flow at the Carlyle gage, the week starting 2 days earlier than that for calculating Q_{na} and 11.2 h. The analysis of available data shows that during the low flow periods, the use of weeks instead of days is satisfactory.

For the period 1942-1965 used in developing the new operation methodology and rules, the navigation flow releases downstream of Carlyle, when exceeding 70 cfs, are as shown in Table 8. Generally high navigation requirements are experienced during the months of July to December.

Interim and Long-Range Plans

The interim regulation plan differs from the long-range plan in making no allowance for navigation flow requirements and in providing substantial drawdown of reservoir levels during the winter dump period of December through April. Interim and long-range plans were selected by the Corps from a reanalysis of various regulation plans which used a trial and error procedure with reservoir levels and times of the year as variables.

Interim Plan. This plan is to be utilized by the Corps of Engineers pending completion and operation of the navigation channel. Essentially, it provides for maintaining a normal joint-use pool elevation of 445.0 and 599.7 at Carlyle Lake and Lake Shelbyville, respectively, during the months May through November. Around December 10, the end of duck hunting season, the lakes would be drawn down to elevation 440 and 590 ft to create additional storage space of 106,000 and 91,000 ac-ft for absorbing spring floods. During the months May to November, every attempt will be made to regulate flow so as not to exceed 4000 cfs from Carlyle and 1800 cfs from Shelbyville. If lake elevations exceed 450 and 610 ft, the flow releases will be increased to equalize in-pool and downstream damages.

Corps of Engineers. 1964. *Kaskaskia River, Illinois: Navigation Improvement, Design Memorandum No. 1 — Hydrology and Hydraulic Analyses.* U.S. Army Engineer District, St. Louis.

Table 8. Navigation Flow Release below Carlyle Dam, 1942-1965

Water year	Number of weeks the release, *in cfs*, is between 70-100	101-150	151-200	201-250	251-300	Total weeks
1942	2					2
1943	2	6	1			9
1944	5	5	13	4		27
1945	2	5	6	9		22
1946	2					2
1947	4	4				8
1948	8	3	3	3		17
1949	3	2	1	1		7
1950	4	3				7
1951	4	3				7
1952	2	3	1			6
1953	4	11	7	10		32
1954	6	8	5	8	18	45
1955	8	5	6	4	2	25
1956	5	8	6	10	3	32
1957	4	4	4	5	4	21
1958	5		2			7
1959	4	5	4			13
1960	7	2	2			11
1961	4	4	9	2		19
1962	7	6	2			15
1963	7	3	10	8	2	30
1964	6	4	10	8	7	35
1965	8	4	2	11	2	27
	113	98	94	83	38	426

The regulation plans have been under constant review and change from time to time. The latest modification of the plan (Figure 3) follows the above interim plan with the following exceptions.

1. The pools are to be kept at winter drawdown levels of 440 and 590 until the end of April, rather than letting them rise to joint-use pool elevations from March 15 to May 15 as planned earlier.

2. The winter dump period can start as early as October 1 if the crops have been harvested. In the 2-month period, October 1 to December 1, the rule curve elevation for Carlyle Lake would remain at the joint-use pool level of 445, but Lake Shelbyville could be drawn down to 590 if downstream conditions permit dumping of flow.

3. During the period May 1 to September 30, the release rates from the two lakes when the levels exceed 450 and 610 ft are specified in terms of the lake levels.

The latest interim plan does have the merit of creating extra storage for absorption of early spring floods, but still suffers from many other drawbacks. Some of these are considered below.

a. The regulation does not provide any interaction between Shelbyville and Carlyle storages during critical periods of very high or very low inflows.

b. The desirability of keeping lower than joint-use pool elevations during May to August to minimize damages from late floods in some years has not been tested.

c. When lake levels are above 450 and 610 in the growing period, an attempt to equalize in-pool and downstream damages by allowing damaging releases will generally lead to higher agricultural damages.

d. The difference between rule curve elevations, 440 and 445 for Carlyle and 590 and 599.7 for Shelbyville, is considerable. It will lead to considerable shore erosion and loss of land, though conditions should stabilize when beach slopes are attained.

Long-Range Plan. The long-range plan differs from the interim plan in that the rule elevations during winter dump will be maintained at 443 and 596 (instead of 440 and 590 in the interim plan) to conserve water for the navigation requirement. This should reduce the pool level fluctuations. The extra storage capacity for absorbing early May high inflows will be reduced, resulting in some more damages to agriculture and recreation.

The Corps studies of 1968-1969 indicated that the average annual damages under these plans would be:

	Average annual damage in dollars to			
	Agriculture	Recreation	Property	Total
Interim plan	155,000	203,330	4090	362,420
Long-range plan	192,470	229,250	6430	428,150

The long-range plan suffers from drawbacks similar to those for the interim plan.

Property Damage. Damage to property in the four damage reaches comprises damages to farmsteads, roads, and farm fences or other structures. The damage figures used for the four reaches are summarized below.

Damage reach	Property damage (farmsteads, fences, roads, etc.)
1. Shelbyville pool area	\$0.42 per acre flooded above 610 ft
2. Downstream of Shelbyville	\$0.30 per acre flooded in bottomlands
3. Carlyle pool area	$\$[(1800 \text{ if } c > 450) + (5000 \text{ if } c > 458) + (2000\, n \text{ if } c > 462.5)]$ in which n = number of farmsteads affected $= 15\left(\frac{c - 462.5}{2.5}\right)$ rounded off to nearest integer, but $\not> 15$ and c = Carlyle Lake level, ft
4. Downstream of Carlyle	\$0.42 per acre flooded in bottomlands

Operation Results for the Years 1972-1974

The 6 A.M. values of daily reservoir levels and outflows for the water years 1972-1974 were obtained from the Corps to review the actual operation. As mentioned previously, the years 1973 and 1974 were two of the three wettest years on record since 1942. A cursory review of the data indicated that the Corps did not adhere to its interim plan for more than half of the time. A brief summary of the actual operation results is given below.

		Max lake level, ft		Max outflow, cfs	
Water year	Lake	NGS	GS	NGS	GS
1972	Shelbyville	605.63	603.35	2,110	1800
	Carlyle	448.88	448.83	4,020	3495
1973	Shelbyville	612.13	613.63	4,490	2120
	Carlyle	455.48	455.08	9,935	6370
1974	Shelbyville	612.30	620.27	4,500	3670
	Carlyle	455.13	453.75	10,038	5024

NGS and GS denote non-growing and growing season, respectively. Had the Corps followed its own regulation plans, the damages to both recreation and agriculture would have been substantially lower as shown later under Results of Regulation 1972-1974.

DYNAMIC PROGRAMMING MODEL

Dynamic programming is an approach for optimizing mathematical representations of multistage processes. The dynamic programming principle of optimality (Bellman, 1957) states: An optimal decision has the property that whatever the initial state and decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision. The following five features (Heidari, Chow, and Meredith, 1971) characterize the problems to which dynamic programming formulation can be applied.

1. The problem must be one which can be divided into stages with a decision required at each stage. Stages may represent different weeks in determining the optimal release each week from a reservoir.

2. Each stage of the problem must have a finite number of states associated with it. The states describe the possible conditions in which the system might find itself. For a reservoir, the state may represent the amount of water stored in it or its water level at that state.

3. The effect of decisions at each stage is to transform the current state of the system into a state associated with the next stage. Associated with each potential state transformation is a return, a benefit or a damage, which indicates the effectiveness of the transformation.

4. For a given current state and stage of the problem, the optimal sequence of decisions is independent of the decisions made in the previous stage.

5.. An optimal policy is the set of decisions that optimizes the objective function which is a measure of effectiveness of the state transformations and hence the policy.

The general form of the optimum value of objective function F*, at state s(n), where n is the stage, can be written as

$$F^*[s(n), n] = \max_{u(n-1) \in U(n-1)} \left\{ R[s(n-1), u(n-1)] + F^*[s(n-1), n-1] \right\}$$

in which s(n) is the state at stage n and lies in the admissible domain, S(n), in the state space at stage n; u(n - 1) is the decision vector at stage (n - 1) and lies in the admissible domain, U(n - 1), in the decision space at stage n; and R[s(n - 1), u(n - 1)] is the return from the system due to its being in state s(n - 1) and application of a decision vector u(n - 1) in the time interval starting at stage n - 1 and lasting At or up to the beginning of stage n. The above equation is the recursive equation or functional equation of dynamic programming.

Advantages. Because of its flexibility and simplicity, dynamic programming has been applied to solve a wide spectrum of water resource problems. It is very suitable for solving multistage problems because of a simple recursive equation for optimization. Both deterministic and stochastic problems can be handled without significant changes in the algorithm. The constraints present no computation problems because at every stage, the range and level of states and decisions can be tested easily to safeguard against violation. The objective function and the system equations may be linear or nonlinear, though the knowledge of linearity can be effectively used to search for the optimum value at the extreme points of the convex policy set.

Bellman, R. 1957. *Dynamic Programming.* Princeton University Press. Princeton, New Jersey.

Heidari, M., V. T. Chow, and D. D. Meredith. 1971. *Water Resources Systems Analysis by Discrete Differential Dynamic Programming.* University of Illinois. Urbana. Hydraulic Engineering Series #24.

Disadvantages. Dynamic programming suffers from what Bellman (1957) designates as the curse of dimensionality. The high-speed computer storage memory requirement grows geometrically with the dimensions of the state domain and the quantized levels of states. If a water resources system has 5 reservoirs and thus 5 state variables, and each state has 10 quantized levels, at least a high-speed storage memory of $4(10)^5$ units is required. However, quantizing active storage at 10 levels will not give conclusive results. For a given number of states, the computer time requirement increases directly with the increase in the number of stages. Further, the decisions taken at any stage are independent of those taken earlier. The return function which depends on earlier decisions, for example, dry-out time after flooding of crop lands, additional direct production investment because of varying level of replanting operations depending on the week of flooding, etc., cannot be incorporated in the dynamic programming approach. This is tantamount to saying that the dynamic programming algorithm has no memory regarding such occurrences. The agricultural damage function will have to be simplified to use the dynamic programming formulation.

Discrete Differential Dynamic Programming. Discrete dynamic programming is made less time consuming by reducing, at each step, the portion of the region of feasibility containing an optimum solution. For example, if with each evaluation of the objective function (Nemhauser, 1966) the region of feasibility containing an optimal solution is reduced by a, $a < 1$, after n evaluations the optimal solution would lie in a region a^n size of the original region. This sequential search scheme was found by Kiefer (1953).

Various techniques have been developed in recent years to reduce dimensionality of a dynamic programming problem as well as to use sequential search schemes to reduce the computer time and make the problem more tractable. Discrete Differential Dynamic Programming, DDDP, is a successive approximation technique (Heidari, Chow, and Meredith, 1971) for determining the optimal policy for nonlinear systems. This technique reduces the computer storage requirement such that large systems can be analyzed on available equipment, e.g., the IBM 360/75 computer. It was first introduced into optimal control theory by Mayne (1966).

Hydrologic and Hydraulic Data

The hydrologic and hydraulic data inputs required for a dynamic programming formulation comprise information on reservoir levels and corresponding water surface areas and storage capacities, net precipitation on reservoir surfaces, streamflow, navigation requirements, minimum flow releases, nondamaging flow capacity of the channels, and areas flooded by high flows or lake levels.

Reservoir Data. The pertinent data on the two lakes are given in Table 1, and the area submerged and storage capacity curves are delineated in Figure 2. Damage to crops is considered for areas submerged above 610 ft in Lake Shelbyville and 450 ft in Carlyle Lake. Areas below these" elevations had been acquired for the projects.

Nemhauser, G. L. 1966. *Introduction to Dynamic Programming.* John Wiley and Sons, Inc. New York.

Kiefer, J. 1953. *Sequential Minimax Search for a Maximum.* Proceedings, American Mathematical Society, Vol.4. p. 502-506.

Mayne, D. 1966. *A Second-Order Method for Determining Optimal Trajectories of Nonlinear Discrete-Time Systems.* International Journal of Control, Vol. 3(1). p. 85-95.

Table 9. Average Precipitation Minus Evaporation (P-E) *in inches,* for Shelbyville and Carlyle Lakes

Week	Shelbyville	Carlyle	Week	Shelbyville	Carlyle
1 (Oct)	-0.02	-0.09	27 (Apr)	0.09	0.07
2	0.03	0.01	28	0.05	0.02
3	0.06	0.09	29	-0.01	-0.01
4	0.16	0.17	30	-0.05	-0.02
5	0.21	0.23	31	-0.08	-0.03
6	0.25	0.27	32	-0.11	-0.04
7	0.28	0.29	33	-0.15	-0.07
8	0.28	0.28	34	-0.16	-0.10
9	0.26	0.28	35	-0.17	-0.12
10	0.26	0.27	36	-0.19	-0.16
11	0.27	0.28	37	-0.20	-0.20
12	0.28	0.32	38	-0.23	-0.25
13	0.29	0.36	39	-0.30	-0.30
14 (Jan)	0.32	0.40	40 (Jul)	-0.48	-0.51
15	0.36	0.44	41	-0.59	-0.57
16	0.40	0.44	42	-0.61	-0.56
17	0.40	0.43	43	-0.59	-0.59
18	0.38	0.41	44	-0.55	-0.48
19	0.36	0.38	45	-0.51	-0.46
20	0.33	0.35	46	-0.46	-0.43
21	0.31	0.33	47	-0.40	-0.40
22	0.29	0.31	48	-0.35	-0.35
23	0.27	0.29	49	-0.29	-0.31
24	0.25	0.25	50	-0.23	-0.26
25	0.22	0.18	51	-0.17	-0.22
26	0.15	0.12	52	-0.11	-0.15

Net Precipitation (P-E). over Lake Surfaces. The average values of P-E for the months October to September are given in Table 4. Weekly values were derived from the monthly estimates and are listed in Table 9.

Streamflows. A statistical analysis of daily streamflows observed at Shelbyville and Carlyle river gaging stations over the years 1942-1965 indicated a satisfactory value of lag equal to 2 days, i.e., the average value of travel time from Shelbyville to Carlyle is 2 days. The daily flows were summed over 7-day periods, allowing for a 2-day late start at Carlyle, to compute weekly flows. Adjustments were made so that there were 26 weeks in each half-year.

Navigation Requirements. Weekly flow releases at Carlyle, necessary for meeting navigation water requirements for the 24-year period, 1942-1965, were calculated considering a total of 16 lockages every day and allowing a 20 percent increase in water requirement for leakage and evaporation loss. The requirement at the lock and dam near the mouth of the river lags 2 days behind the flow release from Carlyle Lake. A general indication of the magnitude of releases is provided by the data in Table 8.

Minimum Flow Releases. A minimum flow release of 10 cfs from Lake Shelbyville and 50 cfs from Carlyle Lake are specified in the projects. However, there are commitments for supplying water to Texaco and Salem totaling 13 cfs from Carlyle. Thus, the minimum flow requirement at Carlyle was raised to 63 cfs.

Flow Capacity of Channels. The nondamaging flows below Shelbyville and Carlyle in the damage reaches up to Beck Creek and Crooked Creek, respectively, are taken as 1800 and 4000

Table 10. Discharge Versus Area Flooded

Damage reach below Shelbyville		Damage reach below Carlyle	
Discharge	Area flooded	Discharge	Area flooded
cfs	*acres*	*cfs*	*acres*
1800	zero	4,000	zero
2000	750	4,500	3,500
2200	1270	5,000	6,300
2400	1830	5,500	8,250
2600	2280	6,000	9,400
2800	2720	6,500	10,100
3000	3130	7,000	10,600
3200	3530	7,500	10,900
3400	3900	8,000	11,200
3600	4300	8,500	11,500
3800	4700	9,000	11,750
4000	5140	9,500	12,000
4200	5630	10,000	12,200
4400	6090		
4600	6310		
4800	6470		
5000	6580		

With flow, F, in thousand cfs and area flooded, A, in thousand acres:

For $5 < F \leqslant 7$;
$$A = 2.58 + 0.975\,F - 0.035\,F^2$$

For $7 < F \leqslant 14$;
$$A = 4.245 + 0.620\,F - 0.0182\,F^2$$

With flow, F, in thousand cfs and area flooded, A, in thousand acres:

For $10 < F \leqslant 15$;
$$A = 0.4\,F + 8.2$$

For $15 < F \leqslant 25$;
$$A = 5.5 + 0.73\,F - 0.01\,F^2$$

cfs. However, the maximum flows allowed without exceeding the top of flood storage pools in the lakes are set at 4500 and 10,000 cfs, respectively.

Flow vs Area Flooded. In the damage reaches below Shelbyville and Carlyle, the areas flooded by discharges exceeding the nondamaging flows are given in Table 10.

Simplified Return Function

The return from the system or from the operation of the two lakes mainly includes benefits from water-based recreation, damage to agriculture because of high lake levels or high outflows, and property damage. Of these three components of return function, recreation is dependent on the state of the system (i.e., lake levels) at any stage or time with the exception of a few periods when dry-out time is needed after flooding of recreation facilities and areas. Agricultural damage depends not only on the date of flooding and the sequence of subsequent floodings, but also on the state of farming operations prior to flooding and the possibility of replanting of crops. Therefore, this function needs to be greatly modified for use in dynamic programming formulation. Property damage generally occurs during the dumping period but repairs are usually done when chances of recurrence in the same year are minimal. Thus, it is counted once a year though the flooding may show up for a number of days or weeks. The property damage is a very small portion of the return function and has been precluded from consideration here.

Recreational Benefits. The relevant data on various recreational activities, visitors per year for each activity, and the dollar value of each unit of recreational activity are given in Table 5. The weekly distributions of visitors over the year are shown in Figure 5 and for hunting are listed in the text. The data on reduction in recreation because of very high or very low lake levels at Lake Shelbyville and Carlyle Lake are contained in Table 6. All these data were used to compute the recreation component of the return function at a given state and stage of the system in the overall discrete differential dynamic programming model. The dryrout period was neglected.

Agricultural Damages. The details about the crop yields in dollars per acre are given under the heading Detailed Agricultural Damage Assessment in the next chapter. These yields in the four damage reaches are mentioned below for ease of reference.

Damage reach	Crop yields in dollars per acre of land			
	Corn	Soybeans	Wheat	Total
In Lake Shelbyville	24.30	10.36	2.77	37.43
Floodplain downstream	88.20	42.00		130.20
In Carlyle Lake	26.78	27.00	13.86	67.64
Floodplain downstream	62.78	32.00		94.78

A review of some pertinent literature (Soil Conservation Service, 1964; Regional Technical Service Center, 1972; Cochran, 1960), information gathered from district conservationists during field trips to the damage reaches, usual flooding periods as indicated by the hydrologic data, and cost breakdown in terms of fixed annual charges, direct production investments, and net profits for each crop resulted in the development of a simple distribution of agricultural damage factors for corn, soybeans, and wheat. These factors are given in Table 11. Though these factors do not reflect the incremental damages and complications due to successive or intermittent floodings, a cursory check indicated that over a number of years the average damage computed with these factors would not be considerably different from that obtained from detailed procedures.

The agricultural damages, as a part of the return function, were computed from the following four equations for the areas flooded in the four damage reaches at a given state and stage of the system in the discrete differential dynamic programming model.

In Lake Shelbyville

$$\text{Damages} = \$\,A\,(24.30\,f_1 + 10.36\,f_2 + 2.77\,f_3)$$

In floodplain downstream

$$\text{Damages} = \$\,A\,(88.20\,f_1 + 42.00\,f_2)$$

In Carlyle Lake

$$\text{Damages} = \$\,A\,(26.78\,f_1 + 27.00\,f_2 + 13.86\,f_3)$$

In floodplain downstream

$$\text{Damages} = \$\,A\,(62.78\,f_1 + 32.00\,f_2)$$

In the above equations, A is the area flooded in acres (above 610 ft for Shelbyville and 450 ft for Carlyle); and f_1, f_2, and f_3 are weekly damage factors for corn, soybeans, and wheat, respectively, for the week or stage under consideration.

Soil Conservation Service. 1964. *Economics Guide for Watershed Protection and Flood Prevention.* United States Department of Agriculture, Washington, D.C.

Regional Technical Service Center. 1972. *Economics — A Manual Procedure to Estimate Annual Crop and Pasture Flood Damages.* Soil Conservation Service, Upper Darby, Pennsylvania, 17 p.

Table 11. Simplified Distribution of Agricultural Damage Factors
(Incremental Flooding Not Considered)

Week	Damage factors: Corn	Soybeans	Wheat	Week	Damage factors: Corn	Soybeans	Wheat
1 (Oct)	0.60	0.10		27 (Apr)			0.25
2	0.30	0.05		28			0.25
3	0.15		0.06	29			0.30
4	0.05		0.06	30			0.30
5	0.02		0.10	31			0.35
6			0.10	32			0.35
7			0.10	33	0.03		0.40
8			0.10	34	0.03		0.40
9			0.15	35	0.07	0.04	0.45
10			0.15	36	0.07	0.04	0.45
11			0.15	37	0.13	0.08	0.50
12			0.15	38	0.13	0.08	0.50
13			0.15	39	0.17	0.15	0.90
14 (Jan)			0.15	40 (Jul)	0.17	0.15	0.50
15			0.15	41	0.25	0.22	0.20
16			0.15	42	0.35	0.30	0.05
17			0.15	43	0.45	0.40	
18			0.15	44	0.55	0.50	
19			0.15	45	0.65	0.65	
20			0.15	46	0.75	0.80	
21			0.15	47	0.80	0.90	
22			0.15	48	0.90	1.00	
23			0.20	49	0.95	0.90	
24			0.20	50	1.00	0.80	
25			0.20	51	0.95	0.60	
26			0.20	52	0.85	0.30	

Discrete Differential Dynamic Programming (DDDP) Model

For deriving the best operation of the system over the 1248 weeks or stages of the 24-year record, a mean trajectory of levels for each of the two lakes is assumed together with a corridor width (half the corridor width determines the upper and lower trajectory boundaries). This gives 3 state levels at which each reservoir can be at any stage and a joint operation which leads to 9 combinations: $s_h c_h$, $s_h c_m$, $s_h c_l$, $s_m c_h$, $s_m c_m$, $s_m c_l$, $s_l c_h$, $s_l c_m$, and $s_l c_l$; s and c refer to lake levels in Shelbyville and Carlyle, and subscripts h, m, and 1 denote the high, mean, and low trajectory. Starting from time zero, the system could be in any of the 9 combinations of lake levels. The system return over the first week or stage for each of these 9 levels is computed. For the second week or stage 2, for each of the initial 9 level combinations, the return is computed for each of the possible 9 levels at the end of stage 2; and the maximum return and the corresponding level give the state level the system should move to from the initial state level at stage 1 to maximize the return.

Similarly, optimum state levels for all initial state levels are determined. The optimum 9 state levels at the end of stage 2 become initial levels for determining the best level to move to in the next week. The procedure is repeated over all the stages and a traceback allows determining the best trajectory giving the maximum return for one of the 9 initial state levels. This trajectory is taken as the mean trajectory for the second iteration, keeping the corridor width the same. The iterations are repeated until there is an insignificant difference in the preceding and succeeding best trajectories or the improvement in return becomes negligible. Then, the corridor width is halved and the whole procedure is repeated. Subsequent reductions in corridor widths bring the final trajectory closer and closer to the theoretical global maximum. In this study, the final corridor width was taken as 0.004 ft.

The initial trajectory at both lakes was set at the top of the joint-use pools of 599.7 ft and 445.0 ft for Lake Shelbyville and Carlyle Lake, respectively, over all 1248 weeks. The initial corridor width was taken as 2.048 ft which was reduced to one-half after finding the best trajectory (producing maximum return) for that width. Thus, the corridor widths changed from 2.048 to 1.024, 0.512, 0.256, 0.128, 0.064, 0.032, 0.016, 0.008, and 0.004 ft.

In addition to the mode of operation explained above, the program needs system equations in terms of continuity equations governing inflow, outflow, and lake storage relationships. The constraint equations specified the minimum and maximum flow releases permissble during various weeks of the year and penalty functions defined the charges for any violation of these constraints. The weekly inflow data and the information on reservoir precipitation and evaporation permitted calculation of net inflows for the storage equation. The return function consisted of recreational benefits and agricultural damages. All data pertaining to the recreation function were stored in the high-speed memory of the computer. Areas flooded could be obtained from discharge and lake elevation information stored in matrix form in the high-speed memory. The average cost for a complete run comprising nine corridor widths was $150 with the IBM 360/75 computer.

DDDP Results

The intent of the dynamic programming formulation was to establish relationships between inflow, outflow, and lake level for the optimum trajectory over different periods of the year. The relationships so derived could then be used in generalizing the structure of an operation strategy which could be optimized via a simulation model (with detailed agricultural damage assessment subprogram) by varying the different coefficients in the relations developed. However, the output from the DDDP model in regard to weekly average lake levels over the 24-year period, given in Table 12, indicates that the optimum trajectory levels are governed mainly by the lower limit of lake levels below which recreational damages accrue. The governing lower limits in respect to the two lakes and related recreational activities are:

	Water level ft	Recreational activity	Effective period weeks
Lake Shelbyville			
	589	Swimming, hunting	29th through 11th
	585	Other activities	Remaining period
Carlyle Lake			
	443	Hunting	3rd through 11th
	438	Other activities	Remaining period

Weekly average lake levels in Table 12 show that the optimum rule level in Shelbyville is elevation 589 for weeks 26 through 11 and 585 for the remaining weeks. The period of 589 rule level starts 3 weeks in advance of that governed by recreational activity to ensure raising the level from 585 to 589 during the prior high inflow weeks. Weekly average levels are higher than the rule levels during certain weeks because of high inflows and restricted releases from the lakes,

Table 12. Average Lake Levels, *in feet,* from DDDP

Week	Shelbyville level	Carlyle level	Week	Shelbyville level	Carlyle level
1 (Oct)	589.0	442.7	27 (Apr)	589.4	438.7
2	589.0	442.9	28	589.4	438.6
3	589.0	443.2	29	589.2	438.6
4	589.0	443.2	30	589.6	538.6
5	589.1	443.2	31	589.1	438.5
6	589.0	443.2	32	589.0	439.0
7	589.0	443.2	33	589.9	439.6
8	589.0	443.1	34	590.3	440.1
9	589.0	443.1	35	590.3	440.4
10	589.0	443.1	36	590.3	440.4
11	589.0	443.0	37	590.7	441.0
12	585.1	438.7	38	591.1	441.0
13	585.0	438.4	39	592.1	441.4
14 (Jan)	585.5	438.6	40 (Jul)	592.1	442.1
15	585.8	438.8	41	592.1	442.1
16	586.0	438.9	42	591.9	442.3
17	586.0	439.0	43	591.2	442.5
18	586.1	439.0	44	590.8	442.5
19	585.8	438.9	45	590.6	442.5
20	586.3	439.0	46	590.3	442.5
21	586.4	439.0	47	590.1	442.6
22	586.1	438.8	48	589.7	442.6
23	585.9	438.7	49	589.5	442.5
24	585.7	438.6	50	589.1	442.5
25	587.1	438.5	51	589.1	442.5
26	589.2	438.5	52	589.0	442.6

extra storage of high inflows to reduce downstream damages, and storage for meeting navigation water requirements. In the DDDP model, one-fourth of the navigation requirement was met from Lake Shelbyville. For Carlyle Lake, a rule level of 443 is indicated during the hunting season, a level of 438 for weeks 12 through 31, and a transition between these two rule levels over the weeks 32 through 2 to build up storage for the navigation requirement, to reduce releases for minimizing agricultural damages, and to ensure a rule level of 443 during the hunting season.

These rule levels provide the maximum storage capacity for absorbing floods without recourse to damaging flows downstream, and give the maximum return or benefits. However, this has been possible in this formulation because of advance knowledge of inflows for the 24-year period. The optimum strategy allows raising the lake levels by storing whatever extra water is available a year or so in advance of a drought year, such as 1953-1954, and releasing substantial volumes of water from the lakes or greatly lowering their levels many weeks ahead of a major flood or high inflow. This complete and precise fore-knowledge of hydrologic inputs is never available in actual operation of a system. Thus, the optimum trajectory of levels for the 24-year period is mythical or theoretical with no chance of being achieved in actual practice.

The relation of outflow with inflow and lake level (or storage) could not be established and there was practically no new information on the structure of the desirable rule curves except that the rule levels, though varying with periods spanning several weeks, should be as close as possible to the no-recreation-damage minimum lake levels. The greater the ability to know the magnitudes of future inflows over many, many weeks the closer would be the two levels. The minimum levels provide a low bench mark, though the actual rule levels, when there is not even a few weeks advance knowledge of future inflows, would be higher. The DDDP results indicated an interaction of the lake storages during high-level high-inflow conditions. When the Carlyle Lake level was above 445 ft and high inflows were still coming in, the outflow or release from Lake Shelbyville was less than the maximum permissible, to hold down the rise in water level at Carlyle.

The maximum lake levels during the main crop season, as obtained from the optimum trajectory, are 606.66 ft at Shelbyville and 450.00 at Carlyle. There are no damages to crops in lake areas because the water levels do not exceed 610 and 450 ft, respectively, at Shelbyville and Carlyle Lakes. The flow releases during the main crop season, with the exception of one year at Carlyle, do not exceed nondamaging flows for the river reaches below the two dams.

SIMULATION MODEL AND OPTIMIZATION

A model for joint operation of Shelbyville and Carlyle Lakes can be set up with the information gathered from (1) the perusal and analysis of the characteristics of hydrologic inputs; (2) lake data on elevation, water surface area, and storage; (3) weekly distribution of recreational benefits over the year at each of the two lakes; (4) the relative intensity of crop damage in the four damage reaches with respect to change in lake levels and outflows; (5) designation of periods over which lake outflows and/or levels need to be specially controlled; and (6) benefits of storage interaction between the two lakes at high lake levels and high inflow conditions. Such a model will contain a considerable number of variables, some of which may be found to be insignificant and hence removed from the model. At the same time, the simulated behavior of the system may indicate the desirability of including some other variables not at first considered.

The simulation model, written as an interactive program for use on the time sharing computer facilities of the University of Illinois, can then be 'optimized' by systematic variation in values of the significant variables to maximize the benefits over the 24-year period. With an efficient and fast interactive program, one to two hundred trials may be run in a day at a relatively nominal cost. Before developing the structure of a simulation model, the first step was the development of an efficient and compact but detailed agricultural damage assessment procedure.

Detailed Agricultural Damage Assessment

For a detailed agricultural damage assessment program, the requisite data inputs are: the value of crops, the average crop yields for the respective damage areas, the percent area under different crops, time distribution of various farming operations for each crop, unit monetary values of these operations, direct production investment estimates, drying period for possible restarting of farming operations after flooding, loss of crops caused by flooding during growing and harvesting periods, etc. A description of these inputs and development of the damage assessment procedure are the subject matter of this section.

Value of Crops. Main crops in the damage areas are corn, soybeans, and wheat. The market price of these crops has witnessed high fluctuations during the last two or three years because of heavy exports and energy problems. Net prices for ready-to-harvest crops, as used in this study, are given below. Harvesting and transport charges to elevators do not add to or detract from the farmers' benefits.

Corn	1974 normalized price	\$1.71/bu
	6/19/75 market price	\$2.81/bu
	Assumed 1975 normalized price	\$2.00/bu
	Harvesting, transport charges, etc.	\$0.50/bu
	Net price	\$1.50/bu
Soybeans	1974 normalized price	\$4.17/bu
	6/19/75 market price	\$5.11/bu
	Assumed 1975 normalized price	\$4.40/bu
	Harvesting, transport charges, etc.	\$0.40/bu
	Net price	\$4.00/bu
Wheat	1974 normalized price	\$2.21/bu
	6/19/75 market price	\$2.91/bu
	Assumed 1975 normalized price	\$2.60/bu
	Harvesting, transport charges, etc.	\$0.50/bu
	Net price	\$2.10/bu

Table 13. Crop Yields and Area Distribution

	Corn	Soybeans	Wheat	Hay	Total
Crop yields *in bu/ac*					
Above Shelbyville	108	37	44		
Below Shelbyville	98	35	44		
Above Carlyle	85	27	44		
Below Carlyle	93	32	44		
Percent area distribution					
Above Shelbyville	15(15)*	7(7)	3(3)	0(0)	25(25)
Below Shelbyville	60 (50)	30 (30)	0 (10)	0 (0)	90 (90)
Above Carlyle	21(21)	25(25)	15(9)	0(6)	61(61)
Below Carlyle	45(38)	25(25)	0(5)	0(2)	70(70)
Crop yield *in dollars per typical acre*					
Above Shelbyville	24.30	10.36	2.77		37.43
Below Shelbyville	88.20	42.00			130.20
Above Carlyle	26.78	27.00	13.86		67.64
Below Carlyle	62.78	32.00			94.78

*The Corps of Engineers percent area distribution figures are given in parentheses

The normalized prices for 1974 (Water Resources Council, 1974) have increased by an average of about 17 percent over those for 1973. The assumed 1975 normalized prices are expected to be close to those that might be recommended for 1975. The normalized prices refer to at-elevator prices.

Crop Yields. The crop yields in Illinois have been increasing steadily since 1939 (University of Illinois, 1970). The increase has been mostly due to better fertilizers, pesticides, and higher plant populations. The trend has been extrapolated to the present time to estimate the current crop yields. The crop yields in bushels per acre, and in dollars per typical acre in each of the four reaches, are given in Table 13. The yield in dollars is obtained by multiplying component fractions of an acre under different crops with respective yields in bushel per acre and net price, and summing the products. It is obvious that in terms of the yield in dollars per acre, the best land is below Shelbyville and the worst land is above Shelbyville. The land above Shelbyville is the most productive but a low percent of it is used for agriculture because of uneven and rugged topography.

The Corps had considered a small percent of the area below Shelbyville and Carlyle under wheat crops. However, visits to the damage reaches and conversations with the district conservationists indicated that such areas were minimal because farmers planted wheat at higher elevations to save their wheat crops from high flows in spring. Accordingly, the percent area distribution was modified and hay was merged with wheat (same growing season) as shown in Table 13.

Farming Operations and Unit Costs. There is an overlap of farming operations because different parts of the farm are operated in different weeks, but a simplification is made to assume the beginning of one operation on a particular week under normal conditions. The possible periods of various farming operations, starting October 1, for corn, soybeans, and wheat are:

Water Resources Council. 1974. *Guidelines to Agricultural Price Standards.* GSA-DC-75-4008. Washington, D.C.

University of Illinois. 1970. *Productivity of Illinois Soils — Circular 1016.* Urbana.

Operations	Activity weeks Corn	Soybeans	Wheat
Plowing	31-39	34-39	1-4
Disking and harrowing	32-40	35-40	2-5
Seeds and planting	33-41	36-41	3-6
Fertilizer and spraying	35-43	38-43	3-6
Cultivating	37-45	40-45	
Harvesting	1-6	51-4	38-41

The high water table in the spring season generally precludes any land preparation activities in the month of April.

Estimated costs of the farming operations in dollars per acre (except harvesting which is not considered because of using a net price for the crops) for the 1975 conditions are: plowing—6.00; disking and harrowing—4.50; seeds and planting—8.40 to 9.20 for normal corn, 10.80 to 12.00 for early maturing variety corn, 12.00 to 13.20 for soybeans, varying with crop yields in bushels per acre, and 8.00 for wheat; fertilizer and spraying—22.60 to 25.60 for corn, 20.20 to 26.20 for soybeans, varying with crop yields, and 26.00 for wheat; and cultivating—6.00 for corn and soybeans.

Direct Production Investment (DPI) Costs. The DPI includes repeatable farming operations in case of flooding, such as disking and harrowing, seeds and planting, and cultivation. The flooded area is not rep lowed after drying before starting disking and harrowing in order to replant the crop. Some farmers fertilize in early winter and others do so at different periods of crop development. However, the fertilizer loss because of flooding of bottomlands for short durations is rather low and it can be neglected.

As an example, the preparation of DPI tables is explained for the area under corn below Shelbyville. If plowing is started in any of the weeks 31 to 39 and no flooding occurs after the operations are started, the weeks 31 to 39 can be considered as 9 states or categories of crop. The final yields because of late start, mostly caused by flooding, in dollars per typical acre are less than normal because of reduced crop yield and somewhat reduced area farmed. For the beginning three state weeks, disking and harrowing, and seeds and planting are taken to be done uniformly over a three-week period with a lag of one week between the start of the two activities. Cultivating is done over a four-week period starting 4 weeks from the beginning of planting. For the last state week, the two operations are done in the 40th and 41st week, respectively, and cultivation is completed during the 43 to 45 week period. A farmer will speed up the operations knowing that this is his last chance to raise the crops that year. In the DPI Table 14, state weeks 31-33 refer to normal corn, weeks 34-36 early maturing variety corn, and weeks 37-39 substitute soybean crop.

The DPI values for corn (and early maturing variety corn and substitute soybeans) in the bottomlands below Shelbyville are given in Table 14. It also contains the yield in dollars corresponding to each of the 9 state weeks. The information on loss due to flooding in the 46-52 week growing period as well as in the 1-6 week harvesting period is also included. Such tables were prepared for each of the crops in each of the four damage reaches. To effect economy of storage on the computer, corn and soybean DPI tables for a reach were combined into one table.

Damage Assessment Program. A brief explanation of the mechanism of the computer program developed for agricultural damage assessment follows.

1. Areas flooded: As each week's inflows are run through the system according to the specified regulation, the ensuing lake levels and outflows are known. Areas flooded in the four damage reaches are obtained as previously explained. Areas flooded and the corresponding week

Table 14. DPI for Corn (and Substitute Crops) for Typical Acre below Shelbyville

	DPI (cumulative), *in dollars,* at any week for the state week								
Week	31	32	33	34	35	36	37	38	39
31									
32	0.90								
33	3.58	0.90							
34	6.26	3.58	0.90						
35	8.04	6.26	3.58	0.86					
36	8.04	8.04	6.26	3.94	0.84				
37	8.94	8.04	8.04	7.01	3.81	0.81			
38	9.84	8.94	8.04	9.22	6.79	3.69	0.90		
39	10.74	9.84	8.94	9.22	8.93	6.57	4.38	1.32	
40	11.64	10.74	9.84	10.08	8.93	8.64	7.86	6.44	2.56
41	11.64	11.64	10.74	10.94	9.76	8.64	10.44	10.23	9.92
42	11.64	11.64	11.64	11.81	10.60	9.45	10.44	10.23	9.92
43	11.64	11.64	11.64	12.67	11.44	10.26	11.64	11.41	11.06
44	11.64	11.64	11.64	12.67	12.28	11.07	12.84	12.58	12.20
45	11.64	11.64	11.64	12.67	12.28	11.88	14.04	13.76	13.34
$ Yield/acre	88.20	88.20	88.20	81.12	75.84	71.46	84.00	80.64	75.60

Weeks 46 to 52 Loss factor due to flooding equals 1.00

Weeks 1 to 6 Loss factors 0.85, 0.65, 0.40, 0.15, 0.05, and 0.02, respectively

are the basic information fed into the damage assessment subroutine as inflow data are processed from week to week.

2. Area initialization for corn and soybeans: In order to simplify computation of areas flooded in various state weeks, the initial total area in week 31 in each of the four damage reaches is taken as 50,000 acres. This has to be more than the area expected to be flooded for the period of record. At the same time, the areas in the state weeks 32 to 40 are set equal to zero. This initialization is done to keep track of transference of area from one state week or timetable to the other because of flooding. A dry-out period of one week is allowed.

3. DPI loss: The area flooded in any week is checked against areas in that week under different state weeks and adjustments are made in the areas affected by flooding. The DPI loss for the week under consideration, say week i(i = 31, 32, ... or 45),

$$(\text{DPI loss})_i = \sum_{j=31}^{39} (\text{DPI})_{i,j} A_j$$

in which subscript j refers to the state week and A: is the area flooded in week i and state week j category.

4. Loss due to reduced yields: At the end of 45th week, the areas farmed under various state weeks 31 to 39 as well as the area that could not be farmed because of adverse conditions (stored in week 40) are known. The loss due to reduced yields and area not farmed is calculated for each of the four damage reaches.

$$\text{Loss} = \sum_{j=31}^{39} \bar{A}_j (Y_{31} - Y_j + DPI_{45,j} - DPI_{45,31}) + A_{40} (Y_{31} - DPI_{45,31})$$

in which $Y_{31} - DPI_{45,31}$ is the yield minus DPI if area had been farmed in state week 31; Y_j-$DPI_{45,j}$ is the actual yield and DPI when these are in state week j; and $\bar{A}_j$ is the area farmed in state week category j.

5. Loss due to flooding in the growing period: For the corn and soybeans composite crops, this period spans weeks 46 through 50. Flooding during any week destroys the crop in the area flooded; the loss factor is 1.0.

$$\text{Loss} = \sum_{j=31}^{39} a_j Y_j$$

in which a_j is the area flooded belonging to state week j, and Y_j is the actual yield for state week j. Loss is the loss in dollars for the week under consideration.

6. Loss due to flooding in harvesting period: For the corn and soybeans composite crop, this period covers weeks 51 through 6. The loss is computed as for flooding in the growing period but the loss factor is no longer 1 but a smaller value depending on how much crop has been harvested already.

$$\text{Loss} = L \sum_{j=31}^{39} a_j Y_j$$

in which L is the loss factor for the week of flooding under consideration.

7. Credits: Credits need to be given for any area not plowed because of being flooded throughout the weeks 31 through 39 or because of plowing capability and time constraints. Similarly, credits are due for any area not fertilized. Knowing the capabilities of performing these operations, the time schedules, and the unit costs of operations, an algorithm was devised as a part of the damage assessment program to compute these credits.

8. Net damage to corn and soybeans: Net damage equals sum of damages under items 3, 4, 5, and 6 minus credits under item 7.

9. Net damage to wheat crop: This is calculated by the same procedure, with different state weeks for wheat, from steps 2 through 8.

10. Total damage in a year: This is the total of net damage to corn and soybeans, and to wheat (where applicable) for all the four damage reaches.

It may be of interest to note that the crop yield in dollars minus DPI cost per typical acre includes: fixed annual charges, plowing and fertilizing, and net profit or income. The fixed annual charge includes allowance for capital investments in land and equipment required for farming operations involved, and any other investments that must be made whether or not farming operations are affected by floods during a particular year (such as taxes, depreciation, and drainage).

Recreation and Property Damage

The yearly number of yisitors and dollars per recreation day by recreational activity are given in Table 5. The percent visitor loss per foot of change in lake level from the low or high limits at which recreation loss begins, and the maximum percent loss allowable at the two extremes are given in Table 6. A dry-out period of one week is allowed when the level exceeds the upper damage level. The mechanics of the computer subroutine for assessment of recreation benefits and damages has already been explained (p. 18). To minimize the round-off and truncation errors, the annual recreation damage was computed. The annual benefit equals $4.8075 million minus the annual damage.

The property damage, as spelled out on page 26, was included in the computer program. Property damage from high lake levels and high river flows usually occurs during the months of

February through April. The values of the maximum damage during the year in each of the four damage reaches are added to obtain the annual property damage. Repairs are usually done at the end of the damage season.

Simulation Model Structure

The model structure depends on the physical nature of the system and the desirable operation in the best interests of various beneficial uses which are quite often conflicting. The physical system consists of Lake Shelbyville and Carlyle Lake in series, on the Kaskaskia River. The physical characteristics and capacities of these lakes have already been discussed in detail. The releases from Lake Shelbyville can be manipulated to provide some degree of interaction between the two storages. Levels in Carlyle Lake can be controlled more often by flow releases from the lake. A scheme of manipulation of lake levels and flow releases for minimization of damages to agriculture, recreation, and property can be worked out by considering the economic tradeoffs between different damages when the conflicts in use cannot be reconciled otherwise.

Agricultural Use. An analysis of farming practices and conditions, and the DPI and crop yield information for the four damage reaches, indicates the priorities for maintaining certain lake levels and releases to minimize agricultural damages. For corn and soybeans, the first priority period covers weeks 39 to 4, when the levels should not exceed 450 ft in Carlyle Lake and 610 ft in Lake Shelbyville. The flow releases should not exceed 4000 and 1800 cfs, respectively. Under these conditions the farmers are assured at least a late planted crop, reduced dollar yields, and practically 90 percent harvesting of the crop. The second priority period comprises weeks 37-38 and 5-6. If the nondamaging lake levels and flow releases are maintained during these four weeks, it gives farmers a little extra time for planting and assures complete harvesting of the crop. The third priority would be maintaining nondamaging lake levels and releases during weeks 31 to 36 so that farmers have ample time for plowing, disking and harrowing, planting, and fertilizing without making these operations a rush job.

The wheat crop is considered only in the areas above 610 ft elevation at Shelbyville and above 450 ft elevation at Carlyle Lake. The top priority covers practically the whole crop period from week 1 through 41 because of the overriding priorities for corn and soybeans which are the major crops. However, keeping the lake level below 450 ft in Carlyle will have higher priority than keeping it below 610 ft in Shelbyville because the wheat yield in dollars per acre in the Carlyle area is 4 to 5 times that in the Shelbyville area.

Recreation Use. With the exception of hunting and swimming, more than 90 percent of the other five activities (camping, picnicking, boating, water skiing, and fishing) are indulged in during the period May 1 to December 1, or weeks 32 through 9; however, the major part of this recreation occurs during the months June through October. For these five activities, the upper and lower lake levels, above or below which recreational use is adversely affected, are 610 and 585 ft for Lake Shelbyville and 450 and 438 ft for Carlyle Lake. Swimming is spread over June through October but the greater part of the activity occurs in July through September. The upper and lower lake levels desired for swimming are 603 and 589 ft in Shelbyville and 450 and 438 ft in Carlyle. Hunting is limited to a short period from mid-October to mid-December, and the upper and lower lake levels are 602 and 589 ft for Shelbyville and 450 and 443 ft for Carlyle.

The normal annual returns from these seven activities at each of the two lakes are:

Activity	Normal annual return, in thousand dollars Lake Shelbyville	Carlyle Lake
Camping	547.5	165.0
Picnicking	195.0	285.0
Boating	450.0	300.0
Water skiing	90.0	60.0
Fishing	1050.0	750.0
Swimming	600.0	150.0
Hunting	105.0	60.0
	3037.5	1770.0

It is evident that fishing provides for more than one-third of the recreation benefit at each of the two lakes. Swimming provides about one-fifth of the benefit at Shelbyville. The following priorities are indicated considering only the economics of recreation benefits.

1. First priority is holding the Shelbyville level between 589 and 610, and the Carlyle level between 438 and 450 ft during the period July through September, or weeks 40 through 52.
2. Second priority is holding the Shelbyville level between 589 and 610, and the Carlyle level between 438 and 450 ft during May, June, October, and November, or over the weeks 32 through 39 and 1 through 9.
3. Third priority is holding the Shelbyville level between 585 and 610, and the Carlyle level between 438 and 450 over the months December through April, or from weeks 10 through 31.

Because of special interest in hunting, an overriding priority may be created for keeping the Shelbyville level between 589 and 602, and the Carlyle level between 443. and 450 ft elevation, during the weeks 3 through 11 of the hunting season.

Property Damages. The property damage in the river reaches below Shelbyville and Carlyle depends upon the maximum weekly flow during a year and that in the two lake areas depends on the maximum lake levels above 610 and 450 ft elevation for Shelbyville and Carlyle Lakes, respectively. The maximum flows in the river reaches would be equal to or less than 4000 and 10,000 cfs most of the years when the inflows are regulated by the lakes. However, these flows would generally be much higher for natural flow conditions, i.e., without dams. Minimization of property damage in the lake areas calls for not exceeding the damage levels of 610 and 450 ft in these lakes.

Hydrologic Inputs. Main hydrologic input is the discharge at Shelbyville and at Carlyle observed over the 24-year period, 1942 through 1965. Secondary inputs are net evaporation over the lake surfaces and navigation requirements which become important during drought years.

The percent chance that a weekly flow may exceed the nondamaging flow at Shelbyville and Carlyle during the 24-year record is:

Period	Number of weeks	Percent chance	High flow range, thousand cfs	Period	Number of weeks	Percent chance	High flow range, thousand cfs
Lake Shelbyville				Carlyle Lake			
47 through 2	8	zero (one week 1841 cfs)		47 through 2	8	zero	
3 through 13	11	4.5	1.8-4.3	3 through 13	11	5.7	4 - 9
14 through 39	26	20.4	1.8-11.5	14 through 40	27	23.6	4 - 34
40 through 42	3	6.9	1.8-8.2	41 through 42	2	12.5	4 - 10
43 through 46	4	4.1	1.8-6.9	43 through 46	4	4.1	4 - 9

It is evident that inflows into the lakes during the weeks 47 through 2 (mid-August to mid-October) are less than the nondamaging flow releases. There is only about a 5 percent chance of inflows exceeding damaging releases over the weeks 3 through 13 (mid-October to end of December) and the high flow range is rather low. The crucial period of high inflows spans weeks 14 through 39 (January through June). There is a chance of more than 1 in 5 that any weekly inflow can exceed nondamaging flow, and further, magnitude of damaging inflow can be very high. High flows during weeks 31 through 39 cause agricultural damages. There needs to be some extra storage for absorbing the high flows in this 9-week period. The regulation strategy may allow some agricultural damages in the form of DPI losses in the first few weeks of this period (weeks 31-39), if necessary, by passing damaging flows and thus creating storage for absorbing subsequent high flows to ensure crops. It should be possible to absorb any high flows during the next three-week period without raising the lakes above the 610 and 450 ft elevations and without exceeding the nondamaging releases of 1800 and 4000 cfs, below Shelbyville and Carlyle Lakes, respectively. The chance of inflows exceeding the nondamaging flows during the weeks 43 through 46 is 1 in 25 and the inflows are not very high.

The values of net precipitation over the lake surfaces are negative over the weeks 29 through 1 (Table 9) and these can cause a maximum reduction of about 0.6 inch in lake levels during a week. Recreational loss would increase during long droughts when lake levels go below the lower damage level for recreation. The navigation requirements would also reduce the lake levels during dry years. The long-range regulation plan may allow some higher levels during certain periods to meet these requirements.

Findings from DDDP. The discrete differential dynamic programming formulation showed that although the structure of the desirable operation could not be obtained precisely, the following procedures would be desirable: (1) keeping the lake levels close to lower damage levels for recreation, practically 589 ft for Shelbyville and 438 ft (except 443 during the hunting season) for Carlyle, (2) holding back water in Lake Shelbyville to reduce inflows into Carlyle Lake during high lake level and high inflow conditions, and (3) supplying extra water from Shelbyville to Carlyle Lake during drought conditions when evaporation loss and navigation requirements are high.

Economics. For a wide range of lake levels, between the lower and upper levels beyond which the recreation is adversely affected, there is no damage to recreation. Interaction of lake storages for recreation under these conditions would not be necessary. Even at the two extremes, the damage increases at a rather uniform rate, the rate varying from week to week for moderate fall or rise in level. Generally, the damage depends on the weekly level and does not have a big one-time loss like the loss of a crop from flooding during the growing or harvesting season.

The economics of relative flood damages in the two lake areas and along the river downstream of the dams is complex. For an increase in flow of 1000 cfs above the nondamaging flow, the area flooded below Shelbyville is 2720 acres and the area flooded below Carlyle is 6300 acres. Even allowing for the higher yield per typical acre below Shelbyville, the damage below Carlyle is about double that below Shelbyville. However, an increase in water release below Shelbyville increases the inflow into Carlyle Lake by the same amount. An increased inflow of 1000 cfs for a week raises the lake level by about one-half foot, causing damages to recreation and crops in the lake area if the lake elevation is 450 ft or higher at the beginning. Thus, the relative disutility of water in the two river reaches is modified by the state of Carlyle Lake.

A comparison of agricultural damages due to high lake levels in Shelbyville and Carlyle Lakes can be made. For a 2-ft rise in Lake Shelbyville above 610 ft elevation, the added storage is 32,918 ac-ft and the area submerged is 1037 acres. The maximum dollar yield per typical acre is $2.77 for wheat and $34.66 for corn-soybeans. The same added storage in Carlyle Lake above 450 ft elevation causes a rise of a little less than 1 foot and submerges 2700 acres. Yields per typical acre from this area are $13.86 for wheat and $53.78 for corn-soybeans. The ratio of damages for the Carlyle to Shelbyville areas is 13 for wheat and 4 for corn-soybeans. Recreation activity is very small during weeks 7 through 26, which are critical for the wheat crop. The economics of relative damages warrants holding water in Shelbyville to minimize damages in Carlyle Lake during this period. During the main crop season for corn-soybeans, weeks 31 through 6, the disutility of water changes because of (1) the lower agricultural damage ratio, (2) the increased magnitude of recreational activity which is about twice as much at Shelbyville as at Carlyle, and (3) decrease in damages below Shelbyville if water is held in the lake. Reduction in agricultural damages below Shelbyville usually outweighs the recreational loss.

In formulating the model structure, various combinations of lake levels, flow conditions, stages of crop development, etc., were considered in assessing the relative disutility of water from week to week.

Simulation Model. The simulation model was structured from consideration of all different uses, functions, DDDP results, and economics, as mentioned in this section. The model equations had 21 coefficients to begin with. The computer model was written as an interactive program for use on the time-sharing computer facilities of the University of Illinois. The 'optimum' values of the significant coefficients were obtained by making about 400 runs. The average cost of a computer run was less than 30¢. The operating policy, in general, and the governing equations for releases and lake levels are specified in the next chapter, without going into the detailed procedure of getting a mix of values of significant coefficients which minimized the damage over the 24-year period of record.

SWS OPTIMUM OPERATING RULES

The operation policy obtained through optimization via simulation with weekly flows for the 24-year record, 1942-1965, minimizes the overall damages or maximizes the overall benefits under the general framework of agricultural, recreation, and property damage assessment, as spelled out in the previous chapter. The only differences indicated between the operating rules without navigation water requirement and with navigation, i.e., between the interim and long-range plans, are the rule level of 438.2 in Carlyle Lake instead of 439.25 during weeks 31 through 36 and the minimum flow release from Carlyle of 63 cfs (50 cfs minimum release and 13 cfs earmarked for Texaco-Salem water supply) instead of 63 cfs or navigation water requirement whichever is higher. In the following description of the optimum operating rules, any differences between the interim and long-range operation strategies are noted. Because the highest lake levels reached in 24 years of simulation were much lower than the top of the flood control pool, 626.5 and 462.5 at Shelbyville and Carlyle, respectively, the release policy at higher lake levels was not considered. The intent of the joint lake operation is to keep the lake levels as close to the rule levels as possible.

Various symbols used in explaining the release rules are:

E_c = level in Carlyle Lake at the beginning of week, ft
E_s = level in Lake Shelbyville at the beginning of week, ft
FRC = flow release, in cfs, below Carlyle
FRCRC = flow release as per rule level, in cfs, below Carlyle
= storage at the beginning of week minus storage at rule level plus extra storage from inflow during the week
FRS = flow release, in cfs, below Shelbyville
FRSRC = flow release as per rule level, in cfs, below Shelbyville
I_c = net inflow, in cfs, into Carlyle Lake during the week
I_s = net inflow, in cfs, into Lake Shelbyville during the week
OCMN = minimum allowable flow release, in cfs, below Carlyle
OCMX = maximum allowable flow release, in cfs, below Carlyle
OSMN = minimum allowable flow release, in cfs, below Shelbyville
OSMX = maximum allowable flow release, in cfs, below Shelbyville
T = inflow contributed to Carlyle Lake by drainage area between Shelbyville and Carlyle, in cfs

Lake Shelbyvilie

Rule Levels. These are:

595.0 for weeks 37 through 11, i.e., June 10 through December 17
590.0 for weeks 12 through 36, i.e., December 18 through June 9

Release Rules. These rules vary over three periods.

(1) Weeks 37 through 6 (June 10 through November 11)

$$\text{OSMX} = 1800 \text{ cfs} \qquad \text{if } E_s \leq 617.5$$
$$= 1800 + 300\,(E_s - 617.5) \qquad \text{if } E_s > 617.5$$

The multiplier of 300 allows linear increase in OSMX from 1800 to 4500 cfs as the lake level rises from 617.5 to 626.5 ft elevation.

OSMN = 10 cfs

The minimum flow is modified to maintain Carlyle Lake at 443 ft for hunting activity during dry years if the Lake Shelbyville level is higher than 590 ft.

OSMN = Max (10, Min (1500, Min (Deficit storage in Carlyle, Excess storage in Shelbyville above 590)))

Deficit storage in Carlyle

= storage in cfs-weeks (as per rule curve + that for releasing minimum flow below Carlyle - that at beginning of the week - that contributed by flow, T, for area between Shelbyville and Carlyle). (1 cfs-weeks = 13.88 ac-ft)

Excess storage in Shelbyville

= storage in cfs-weeks (at the beginning of week - that at 590 ft elevation + that from net inflow, I_s)

Provision of a maximum value of 1500 cfs for OSMN is more than ample for meeting the deficits. Thus, modified OSMN is the maximum of (1) old OSMN of 10 cfs or (2) minimum of 1500 or deficit or excess whichever is smaller.

FRS = Max (OSMN, Min (OSMX, FRSRC)) if $E_c < 447$; or $E_s \leq 597$ and $I_s <$ OSMX

The above statement means that flow release from Lake Shelbyville is the maximum of OSMN and the smaller of OSMX and FRSRC. The FRSRC equals the flow release during the week which will raise or lower the lake level to the rule level during the week starting from a given lake level at the beginning of the week and the value of inflow during the week.

FRS = Max (OSMN, Min (OSMX, OCMX - T)), but $\leq$ FRSRC if level and flow conditions for the former FRS are not met.

This allows reduced flow releases from Lake Shelbyville to hold down the rise in level in Carlyle Lake.

(2) Weeks 7 through 30 (November 12 through April 28)

OSMX = 4500 cfs

OSMN = 10 cfs

The OSMN is modified to meet any deficits in Carlyle Lake during weeks 7 to 11, or up to the end of the hunting season, to maintain the Carlyle level at 443 ft, if the Lake Shelbyville level is above 590 ft elevation.

FRS = Max (OSMN, Min (OSMX, FRSRC)) if $E_c < 445$

FRS = Max (OSMN, Min (OSMX, OCMX - T)) if $E_c \geq 445$

(3) Weeks 31 through 36 (April 29 to June 9)

OSMX = 1800 cfs

= 4500 cfs if $E_s > 600$ and $I_s + 400\ (E_s - 600) \geq 4500$

OSMN = 10 cfs

FRS = Max (OSMN, Min (OSMX, FRSRC))

Carlyle Lake

Rule Levels. There are 3 different rule levels for the three periods.

443.0 for weeks 37 through 11, i.e., June 10 through December 17

440.0 for weeks 12 through 30, i.e., December 18 through April 28

438.2 ***Interim*** / **439.25** ***Long-range*** } **for weeks 31 through 36, i.e., April 29 through June 9**

Release Rules. These rules are also different for the three periods.

(1) Weeks 37 through 6 (June 10 through November 11)

OCMX = 4000 cfs if $E_c \leq 454.5$

= 4000 + 750 (E_c - 454.5) if $E_c > 454.5$

This allows linear increase in OCMX from 4000 to 10,000 cfs as lake level rises from 454.5 to 462.5 ft elevation.

OCMN = 63 cfs *for interim plan*

It comprises the 50 cfs minimum release requirement and 13 cfs for Texaco-Salem water supply.

OCMN = Max (63, navigation water requirement) *for long-range plan*

FRC = Max (OCMN, Min (OCMX, FRCRC)) if $E_c < 447$; or $E_s \leq 597$ and $I_s <$ OSMX

Otherwise,

FRC = Min (OCMX, FRCRC)

(2) Weeks 7 through 30 (November 12 through April 28)

OCMX = 10,000 cfs

OCMN = 63 cfs *for interim plan*

= Max (63, navigation water requirements) *for long-range plan*

FRC = Max (OGMN, Min (OCMX, FRCRC)) if $E_c < 445$

FRC = Min (OCMX,.FRCRC) if $E_c \geq 445$

(3) Weeks 31 through 36 (April 29 through June 9)

OCMX = 4000 cfs

It is modified for high level and high inflow conditions to allow pulling down the lake levels for absorbing any later high inflows.

OCMX = 10,000 cfs if I_c + Max (zero, 1000 (E_c - 446)) > 10,000

For weeks 32 through 36,

OCMX = Max (OCMX for the current week, FRC for last week)

This allows for higher maximum flow to ensure low lake level when necessary. The DPI damages are not increased but some losses due to reduced yields because of late replanting will occur. Such losses will be considerably less than the loss of crops due to high lake level or high release in case high inflows persist beyond the 39th week.

FRC = Max (OCMN, Min (OCMX, FRCRC))

In order to minimize the chance of flooding in later weeks, the flow release in the 37th week is allowed to equal that in the 36th week, if the 36th week flow is higher than 4000 cfs and the inflow, I_c, into the lake exceeds 10,000 cfs. No extra DPI losses are involved, though there may be some reduced income because of late replanting.

COMPARISON OF SWS AND CORPS RULES

Computer programs were written for the operation strategies as laid out in the Corps interim and long-range plans, but with the recreation, agricultural, and property damage and benefit assessment subroutines as used in the SWS simulation program. The results from these computer programs allowed comparisons between the damages or benefits from the SWS and Corps operation plans. The major differences in the SWS and Corps strategies in respect to rule levels and release rules are noted here.

Rule Levels and Release Rules

Lake Shelbyville (Interim plans except as noted)

Rule Levels:

SWS 595.0 weeks 37 through 11 (June 10 through December 17)
590.0 weeks 12 through 36 (December 18 through June 9)

Corps 599.7 May 1 through November 30 (weeks 31 through 9)
590.0 December 1 through April 30 (weeks 10 through 30); 596.0 *for long-range plan*

Release Rules:

SWS OSMN = 10 cfs
OSMX = 1800 cfs, weeks 37 through 6
= 1800+ 300 (E_s - 617.5) if $E_s > 617.5$
OSMX = 4500 cfs, weeks 7 through 30
OSMX = 1800 cfs, weeks 31 through 36
= 4500 cfs, if lake level and inflow high.

The operation allows passing more flow from Shelbyville, if its level is higher than 590 ft, to Carlyle Lake to maintain the level therein at 443 for planting water fowl crops and hunting during weeks 37 through 11. Also, release from Shelbyville is reduced when the level and inflow into Carlyle are high, during weeks 37 through 30.

Corps OSMN = 10 cfs
OSMX = 1800 cfs, May 1 through November 30
= 1800 + 163.6 (E_s- 610) if $E_s > 610$
OSMX = 4500 cfs, December 1 through April 30

Carlyle Lake (Interim plans except as noted)

Rule Levels:

SWS 443.0 weeks 37 through 11 (June 10 through December 17)
440.0 weeks 12 through 30 (December 18 through April 28)
438.2 weeks 31 through 36 (April 29 through June 9); 439.25 *for long-range plan*

Corps 445.0 May 1 through November 30 (weeks 31 through 9)
440.0 December 1 through April 30 (weeks 10 through 30); 443.0 *for long-range plan*

Release Rules:

SWS OCMN = 63 cfs; Max (63, navigation water requirement) *for long-range plan* ,

OCMX = 4000 cfs, weeks 37 through 6

= 4000 + 750 (E_c - 454.5), if $E_c > 454.5$

OCMX = 10,000 cfs, weeks 7 through 30

OCMX = 4000 cfs, weeks 31 through 36

= 10,000 cfs, if high level and inflow conditions

To ensure crops, high releases are allowed during weeks 31 through 36, if necessary, incurring DPI losses but making tremendous savings by reducing the probability of no crops to a minimum.

Corps OCMN = 63 cfs; Max (63, navigation water requirement) *for long-range plan*

OCMX = 4000 cfs, May 1 through November 30

= 4000 + 480 (E_c - 450), if $E_c > 450$

OCMX = 10,000 cfs, December 1 through April 30

Comparative Damages

A measure of the relative efficiency of the SWS and Corps operation plans is obtained by comparing the net damages to recreation, agriculture, and property for each year of the 24-year period, 1942 through 1965, for both interim and long-range plans. The plans use the same hydrologic inputs, and damage or benefit assessment procedures, and differ only in the regulation policy. The damage to recreation, agriculture, or property equals the benefits under ideal conditions of no damage minus the actual benefits under the conditions spelled out by the operation plan under consideration.

Interim Plan. The annual damages to recreation, agriculture, and property for the 24 years under the SWS and Corps interim plans are given in Table 15. Some interesting statistics can be derived.

Item	SWS Plan	Corps Plan
Recreation damage		
Number of damage years	10	24
Maximum annual damage	$346,300	$626,400
Average annual damage	$ 25,800	$ 61,900
Agricultural damage		
Number of damage years	4	5
Maximum annual damage	$446,100	$2,148,000
Average annual damage	$ 32,000	$ 197,300
Property damage		
Number of damage years	22	23
Maximum annual damage	$9,700	$9,900
Average annual damage	$5,700	$7,100
Total annual damage		
Maximum	$802,100	$2,784,200
Average	$ 63,600	$ 266,300

The number of years in which moderate to major damage occurred are not much different. However, the magnitude of maximum damages to recreation and agriculture with the Corps plan are 2 to 4 times those with the SWS plan. The average annual damage with the Corps plan is 4.19 times that with the SWS plan.

Table 15. Comparative Damages — Interim Plan

	Damages in thousands of dollars								
	State Water Survey				Corps of Engineers				Natural flow*
Year	Rec	Agr	Prop	Total	Rec	Agr	Prop	Total	Agr
1	16.3		7.0	23.3	67.7		7.0	74.7	2104.0
2	111.3	162.3	7.3	280.9	493.6	1383.1	9.9	1886.6	345.8
3			6.3	6.3	0.5		6.3	6.8	19.1
4			6.6	6.6	64.2	964.8	8.8	1037.8	907.1
5			5.9	5.9	0.4		7.0	7.4	1130.2
6			6.2	6.2	64.4		6.3	70.7	1068.5
7			7.0	7.0	0.5		7.0	7.5	31.4
8			7.0	7.0	0.4		7.0	7.4	
9	10.9	8.8	8.3	28.0	12.8	88.8	8.8	110.4	1219.0
10			7.0	7.0	0.4		7.0	7.4	1990.6
11			5.9	5.9	0.3		7.0	7.3	233.9
12			3.7	3.7	0.5		7.0	7.5	90.6
13	23.7			23.7	2.1		6.7	8.8	
14	46.2			46.2	30.5			30.5	
15			5.7	5.7	0.5		7.0	7.5	
16	346.3	446.1	9.7	802.1	626.4	2148.0	9.8	2784.2	2102.9
17	22.3		7.0	29.3	69.5		7.0	76.5	2177.3
18			7.0	7.0	0.3		7.0	7.3	
19	8.9		5.2	14.1	23.8		6.8	30.6	2137.4
20		151.3	6.1	157.4	25.4	149.9	8.8	184.1	131.2
21			7.0	7.0	0.4		7.0	7.4	2.5
22			5.6	5.6	0.5		7.0	7.5	70.4
23	4.2		5.5	9.7	0.5		6.6	7.1	
24	31.0		0.6	31.6	0.7		6.9	7.6	69.6
Total	621.1	768.5	137.6	1527.2	1486.3	4734.6	169.7	6390.6	15831.5
Average	25.8	32.0	5.7	63.6	61.9	197.3	7.1	266.3	659.6

*Damage to agriculture in the reaches below Shelbyville and Carlyle Lakes without dams, *in thousands of dollars*

Included in Table 15 are the agricultural damages in the river reaches below Shelbyville and Carlyle if the dams had not been built. Maximum annual damage of $2,177,300 and annual average damage of $659,600 are indicated. The latter damage is much higher than the average annual agricultural damage in all of the four reaches (river reaches and lake areas) amounting to $197,300 with the Corps plan and $32,000 with the SWS plan.

Long-Range Plan. The annual damages to recreation, agriculture, and property over the 24-year period for the SWS and Corps long-range plans are given in Table 16. Damages follow the same pattern as in Table 15. Some interesting statistics are as follows.

Item	SWS Plan	Corps Plan
Recreation Damage		
Number of damage years	10	12
Maximum annual damage	$415,200	$648,100
Average annual damage	$ 32,300	$ 73,300
Agricultural Damage		
Number of damage years	4	7
Maximum annual damage	$492,600	$2,149,900
Average annual damage	$ 34,300	$ 220,600
Property Damage		
Number of damage years	22	22
Maximum annual damage	$10,000	$9,800
Average annual damage	$ 5,700	$6,000
Total Annual Damage		
Maximum	$917,800	$2,807,800
Average	$ 72,300	$ 299,900

Table 16. Comparative Damages – Long-Range Plan

Year	State Water Survey Rec	State Water Survey Agr	State Water Survey Prop	State Water Survey Total	Corps of Engineers Rec	Corps of Engineers Agr	Corps of Engineers Prop	Corps of Engineers Total	Natural flow* Agr
1	16.3		7.0	23.3	77.5		7.0	84.5	2104.0
2	113.7	173.9	9.1	296.7	590.1	1574.5	9.7	2174.3	345.8
3			6.3	6.3			7.0	7.0	19.1
4			6.6	6.6	75.5	1056.8	8.8	1141.1	907.1
5			5.9	5.9	27.7	94.1	7.7	129.5	1130.2
6			6.1	6.1	67.5		5.7	73.2	1068.5
7			7.0	7.0			7.0	7.0	31.4
8			7.0	7.0			7.0	7.0	
9	10.9	8.8	8.3	28.0	18.8	127.6	8.8	155.2	1219.0
10			7.0	7.0	8.4		7.0	15.4	1990.6
11			5.9	5.9			5.9	5.9	233.9
12			2.4	2.4			3.7	3.7	90.6
13	64.5			64.5					
14	77.7			77.7	18.9			18.9	
15			5.7	5.7			5.4	5.4	
16	415.2	492.6	10.0	917.8	648.1	2149.9	9.8	2807.8	2102.9
17	22.3		7.0	29.3	124.4	73.0	5.8	203.2	2177.3
18			7.0	7.0			7.0	7.0	
19	4.8		5.2	10.0	27.0		5.4	32.4	2137.4
20		148.3	5.7	154.0	76.3	217.4	6.8	300.5	131.2
21			7.0	7.0			7.0	7.0	2.5
22			5.5	5.5			5.0	5.0	70.4
23	9.7		5.1	14.8			5.0	5.0	
24	39.0		0.5	39.5			0.5	0.5	69.6
Total	774.1	823.6	137.3	1735.0	1760.2	5293.3	143.0	7196.5	15831.5
Average	32.3	34.3	5.7	72.3	73.3	220.6	6.0	299.9	659.6

Damages *in thousands of dollars*

*Damages to agriculture in the reaches below Shelbyville and Carlyle Lakes without dams, *in thousands of dollars*

The average annual damage with the Corps plan is 4.15 times that with the SWS plan. The agricultural damages for conditions with no dams are repeated from Table 15 for ease of comparison.

Lake Levels

A comparison of lake levels during major divisions of the year, as warranted by the operation rules, should yield a measure of stability of these levels for enhanced durability of recreation, reduction in lake shore erosion, and protection to farmers. The relevant information is tabulated from the computer results for the SWS and Corps plans with respect to both Shelbyville and Carlyle Lakes (Table 17). Conditions during the 37th week are the same as for the period spanning weeks 38 through 6, except that with the SWS plans, the flow release exceeded the nondamaging flow below Carlyle in one out of the 24 years used in this study.

In Lake Shelbyville, the SWS interim and long-range plans maintain the lake levels between 589.5 and 595.0 (rule levels are 590 and 595) for 85 percent or more of the weeks. For a corresponding percent of time, the range of levels with the Corps plans is 589.5 to 599.0 ft. The maximum lake level reached during the main crop season is 615.7 with the SWS plan and 614.8 with the Corps plan. The higher lake level with the SWS plan is caused by holding water in Shelbyville to reduce the rise in Carlyle Lake and thus reduce the overall damages during that period. Maximum level

Table 17. Lake Levels under Various Regulation Strategies

Weeks	Strategy	Percent of weeks lake level is equal to or less than given level *(ft msl)*									Year	*Max level *ft msl*
Lake Shelbyville		585.0	589.5	590.0	591.0	595.0	596.0	600.0	605.0	610.0		
31-36												
	Interim											
	SWS			74.3	76.4	87.5	90.3	97.9	97.9	99.3	1943	611.6
	Corps			15.3	25.0	65.3	70.8	93.1	97.9	98.6	1943	615.5
	Long-range											
	SWS			74.3	76.4	87.5	90.3	97.9	97.9	99.3	1943	611.6
	Corps						18.8	84.7	97.2	97.9	1943	616.8
38-6												
	Interim											
	SWS			30.6	36.3	84.9	87.5	93.4	97.0	98.8	1957	614.4
	†Corps			0.2	0.3	6.8	13.7	87.3	94.6	98.6	1957	614.7
	Long-range											
	SWS			26.2	33.3	84.3	86.9	93.1	96.8	98.4	1957	615.7
	†Corps						2.0	85.1	93.9	97.9	1957	614.8
7-30												
	Interim											
	SWS			72.7	76.0	96.4	96.5	97.7	98.1	98.8	1950	616.5
	††Corps			85.5	86.5	92.9	93.3	98.4	99.6	100.0		
	Long-range											
	SWS			92.1	93.5	96.1	96.3	97.0	97.4	98.4	1950	616.5
	††Corps						90.1	97.4	98.8	99.8	1950	610.3
Carlyle Lake		438.0	439.0	440.0	441.0	443.0	445.0	447.0	450.0	452.0		
31-36												
	Interim											
	SWS		57.6	76.4	77.8	86.8	91.7	96.5	100.0			
	Corps			18.8	38.9	66.7	88.2	91.7	95.8	97.9	1943	455.9
	Long-range											
	SWS		58.3	75.5	77.8	86.1	91.7	96.5	98.6	100.0	1943	450.2
	Corps					18.8	81.2	86.8	93.1	96.5	1943	457.1
38-6												
	Interim											
	SWS	2.2	6.2	13.9	17.7	84.3	89.5	95.8	98.6	100.0	1957	451.8
	†Corps			4.3	4.9	10.2	85.9	90.6	96.2	97.2	1957	457.5
	Long-range											
	SWS	3.0	4.6	8.3	14.9	83.9	89.1	95.0	98.4	99.6	1957	452.1
	†Corps				2.6	4.5	84.2	89.9	96.0	97.0	1957	457.7
7-30												
	Interim											
	SWS		1.6	70.1	71.6	96.0	98.1	99.3	100.0			
	††Corps			83.5	84.7	90.9	96.6	97.6	98.0	98.8	1950	453.6
	Long-range											
	SWS	3.1	7.3	70.5	72.6	96.0	98.1	99.3	100.0			
	††Corps				1.0	88.1	94.2	96.8	98.0	98.0	1950	455.0

*Maximum level given when damage level is exceeded
†Weeks 38-9
††Weeks 10-30

reached in the remaining periods (weeks 7 through 36) is 6.16.5 with the SWS plan, 616.8 with the Corps plan. However, these high levels occurred for only a few weeks in two of the 24 years analyzed.

In Carlyle Lake, the SWS interim and long-range plans maintain the lake levels between 438.0 and 443.0 for 85 percent or more of the weeks. For a corresponding percent of time, the range of levels with the Crops plan is 439.0 to 445.0 ft. Maximum lake level reached during the main crop season is 452.1 ft with the SWS plan and 457.7 with the Corps plan. Maximum levels reached during the nongrowing period are 450.2 with the SWS plan and 457.1 with the Corps plan. Therefore, the maximum level in Carlyle Lake is more than 5 ft higher with the Corps plan than with the SWS plan.

Flow Releases

Weekly flow release rates from the Shelbyville and Carlyle Lakes for the 24 years with the SWS and Corps plans were tabulated to develop flow-duration information. An analysis of the flow releases and percent time a flow release is equal to or less than the flow release under consideration is summarized in Table 18. The maximum flow releases and the year of occurrence are also included in the table.

During the main crop season, weeks 38 through 6, the flow releases from Shelbyville and Carlyle Lakes do not exceed the nondamaging flows of 1800 and 4000 cfs, respectively, under the SWS plans. However, these flows are exceeded about 2 percent of the time at Shelbyville and 4 percent of the time at Carlyle under the Corps plans. Damaging flow releases in this period cause tremendous losses to agriculture. With no dams, the damaging flows occur about 6 percent of the time at both Shelbyville and Carlyle. Thus, the SWS plans afford the maximum relative protection to downstream farmers, practically assuring crops except under much worse inflow conditions than encountered in the 24 years, 1942-1965.

During the winter period, weeks 7 through 30, the natural river flows observed at Shelbyville and Carlyle over the years 1942-1965 exceeded the maximum allowable of 4500 and 10,000 cfs about 4 percent of the weeks. It may be noted that the flow durations for flows up to 3500 and 8000 cfs at Shelbyville and Carlyle, respectively, are not much different under the SWS and Corps plans, nor for the condition of no dams.

For the period spanning weeks 31 through 36 (or 37), somewhat higher flows are allowed under the SWS plans than under the Corps plans. This is due to trading possible high crop losses in later weeks with relatively small losses (DPI losses) during this period under the SWS plan. Under the SWS plans, flow exceeding 1800 cfs is released for weeks 34, 35, and 36 in year 1943 at Shelbyville, and flow exceeding 4000 cfs is released for 5 weeks in 1943, 3 weeks in 1957, and 5 weeks (4 weeks under the interim plan) in 1961 at Carlyle.

Table 18. Lake Outflows under Various Regulation Strategies

Weeks	Strategy	Percent of weeks lake outflow is equal to or less than given values (cfs)						Year	*Max flow cfs
Lake Shelbyville									
		50	1000	1800	2500	3500	4500		
31-36									
	Interim								
	SWS	2.1	62.5	97.9	97.9	97.9	100.0	1943	4500
	Corps	79.2	84.7	98.6	98.6	100.0		1943	2696
	Long-range								
	SWS	2.1	62.5	97.9	97.9	97.9	100.0	1943	4500
	Corps	52.8	72.2	97.9	98.6	100.0		1943	2912
	No dams	. 1.4	69.4	84.7	90.3	93.8	95.8	1943	12464
38-6									
	Interim								
	SWS	56.2	82.7	100.0					
	†Corps	58.3	84.5	98.6	99.8	100.0		1957	2581
	Long-range								
	SWS	45.8	82.9	100.0					
	†Corps	41.0	80.7	97.9	99.8	100.0		1957	2581
	No dams	45.5	89.3	94.6	97.4	97.9	98.9	1957	11454
7-30									
	Interim								
	SWS	21.0	65.5	79.5	86.3	91.7	100.0		
	††Corps	12.5	56.5	72.6	81.2	86.7	100.0		
	Long-range								
	SWS	21.5	65.8	80.2	86.8	91.7	100.0		
	††Corps	8.9	60.7	76.2	84.3	91.3	100.0		
	No dams	16.0	62.3	80.3	88.2	93.9	96.1	1944	9837
Carlyle Lake									
		250	2500	4000	6000	8000	10000		
31-36									
	Interim								
	SWS	0.7	53.5	91.7	91.7	92.4	100.0	**	10000
	Corps	73.6	80.6	95.8	98.6	100.0		1943	6821
	Long-range								
	SWS	4.9	61.1	91.0	91.7	93.1	100.0	**	10000
	Corps	47.9	72.2	94.4	97.9	100.0		1943	7424
	No dams	4.2	69.4	77.8	87.5	92.4	94.4	1943	33429
38-6									
	Interim								
	SWS	63.7	84.3	100.0					
	†Corps	58.7	82.9	96.2	98.4	100.0		1957	7616
	Long-range								
	SWS	59.3	83.9	100.0					
	†Corps	47.9	80.7	95.8	98.1	100.0		1957	7712
	No dams	47.8	89.4	93.9	96.0	97.9	99.0	1957	16463
7-30									
	Interim								
	SWS	18.6	63.0	74.3	81.8	88.5	100.0		
	††Corps	15.5	55.4	68.3	77.2	83.7	100.0		
	Long-range								
	SWS	19.1	61.6	75.0	82.5	88.7	100.0		
	††Corps	15.3	59.7	72.2	80.8	88.5	100.0		
	No dams	18.9	61.0	75.9	84.6	91.2	95.6	1950	27673

*Maximum flow given when non-damaging flow is exceeded
** 1943, 1957, 1961
†Weeks 38-9
††Weeks 10-30

RESULTS OF REGULATION 1972-1974

The years 1973 and 1974 were two of the three wettest years during the period 1942 through 1974, as indicated in Table 2. The 6 A.M. values of lake levels and flow releases from the two lakes were supplied by the Corps. The data pertaining to the water years 1972 through 1974 were analyzed to compare the results from actual operation and operation as defined by the Corps and SWS interim plans. The 6 A.M. values of flow releases were aggregated over the week to obtain average weekly releases. From the lake levels at the beginning and end of a week, the inflow into the lake was calculated both for Shelbyville and Carlyle Lakes. The inflow to Carlyle Lake was adjusted for the effect of Lake Shelbyville in modifying the flow below the dam. These inflows or flows at Shelbyville and Carlyle formed the hydrologic input to the SWS and Corps interim plans. No corrections for net precipitation over the lakes were made because the computed flows were already adjusted for this effect at lake levels under actual operation. Any difference in inflow because of net precipitation effect changing with lake level or water surface area would be relatively minor and was not considered.

Comparison of Damages. The results obtained from computer runs for the SWS and Corps interim plans and for actual operation (with weekly releases and beginning of week lake levels) are given in Table 19.

There are no recreation and agricultural damages for the years 1972 and 1973 with the SWS plan. Under the Corps plan, there is a small amount of damage to recreation during 1973. However, for the year 1974, the damages to recreation and agriculture are $190,800 and $345,200 with the SWS plan, and $322,100 and $1,059,500 with the Corps plan. For the year 1974, the damage ratio of the Corps to SWS plan is 1.69 for recreation and 3.07 for agricultural damage.

The damages with the levels and flows for the actual operation are very high for both 1973 and 1974. The total damage in these two years is 2.69 times that with the Corps plan and 6.91 times that with the SWS plan. The damages for actual operation would be somewhat higher than those with the theoretical operation for several reasons. For example:

Table 19. Comparison of Damages, 1972 through 1974

Strategy	Year	Damages *in thousands of dollars* Rec	Agr	Prop	Total
Operation according to SWS Interim	1972			6.5	6.5
	1973			6.3	6.3
	1974	190.8	345.2	7.5	543.5
		190.8	345.2	20.3	556.3
Operation according to Corps Interim	1972			6.6	6.6
	1973	16.3		6.2	22.5
	1974	322.1	1059.5	9.8	1391.4
		338.4	1059.5	22.6	1420.5
Actual Operation	1972	1.4		0.3	1.7
	1973	580.8	1152.5	9.5	1742.8
	1974	698.7	1348.7	10.8	2058.2
		1280.9	2501.2	20.6	3802.7

1. The releases below Shelbyville may have been curtailed when tributary flows were high between Shelbyville and the confluence with Beck Creek.
2. Computer programs use weekly inflows, and damages are assessed on the basis of weekly levels and outflows. Operation on a daily basis may increase these damages somewhat because of level and release fluctuations within the week during abnormal inflows.

However, such reasons can account for only a portion of the tremendous difference between actual damages and those with the Corps interim plan.

Lake Levels. Figure 6 shows the lake levels in Shelbyville and Carlyle from week to week over the years 1972 through 1974, for actual operation and under the SWS and Corps plans. The maximum levels attained in these years are:

	Maximum level, ft					
	Lake Shelbyville			Carlyle Lake		
Year	SWS	Corps	Actual*	SWS	Corps	Actual*
1972	t599.21	599.38	605.55	t444.92	445.0	448.82
1973	601.56	605.36	613.58	446.50	449.23	455.08
1974	612.23	614.83	619.85	444.83	451.74	455.05

*Lake level at the beginning of a week
†Beginning week lake levels, 1972

Lake level fluctuations are within a narrower range with the SWS plan, and lower lake levels are maintained for longer durations of time. Incidentally, these should help in reducing both shore erosion and destruction of trees along the shoreline because of high lake levels maintained for long durations under actual operating conditions.

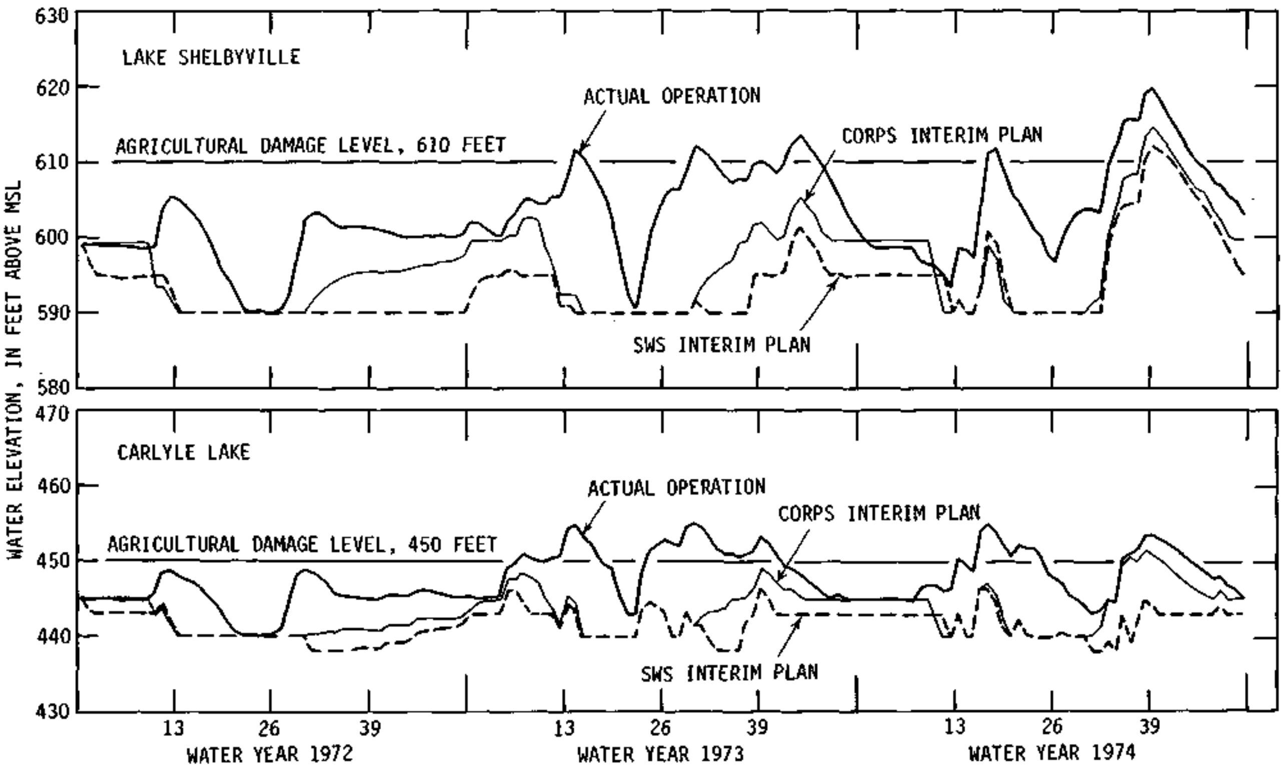

Figure 6. Levels in Lake Shelbyville and Carlyle Lake with Corps and SWS operation plans

Flow Releases. Pertinent damaging flow releases during the main crop season, weeks 31 through 6, for the SWS and Corps plans as well as for actual operation are summarized below.

Item	Year	Weeks in which damaging flow releases occur: *Shelbyville*	*Carlyle*
SWS Plan	1972		
	1973		
	1974	35	35,36
Corps Plan	1972		
	1973		
	1974	39 through 43	37 through 41
Actual	1972		
	1973	31 through 34, and 44 through 49	31 through 36, and 38 through 45
	1974	34, 36 through 47, 51, 52	39 through 51

Under the SWS plan the high releases occurred for a week below Shelbyville and for two weeks below Carlyle. There were DPI losses, but crops could be replanted and harvested without being flooded later. Releases were lower under the Corps plan but occurred during crucial weeks, so that crops could not be replanted and potential income from the flooded area was lost. Under actual operations, the damaging releases occurred over long stretches of time. The magnitude of damaging flow releases is given in Table 20.

Table 20. Agricultural Damages in Downstream Reaches, 1972 through 1974

Strategy	Year	Damages, *in thousands of dollars*: Below Shelbyville	Below Carlyle	Total
Interim				
SWS	1972			
	1973			
	1974	154.3*	151.4**	305.7
Corps	1972			
	1973			
	1974	282.3†	497.2††	779.5
Actual				
	1972			
	1973	133.7[a]	569.5[b]	703.2
	1974	471.0[c]	298.8[d]	769.8
No dams				
	1972			
	1973	875.7	1143.3	2019.0
	1974	726.6	684.5	1411.1

*Week 35; release is 4500 cfs

**Weeks 35 & 36; releases are 10,000 cfs

†Weeks 39-43; releases are 2360, 2590, 2398, 2161, 1908 cfs, respectively

††Weeks 37-41; releases are 4034, 4014, 4836, 4523, 4144 cfs, respectively

a)Weeks 31-34, 44-49; releases are 1867, 1856, 1839, 1819, 2091, 2106, 2084, 2048, 2015, 1938 cfs, respectively

b)Weeks 31-36, 38-45; releases are 5245, 6314, 6189, 4354, 4017, 4021, 4118, 4804, 5010, 4970, 4858, 4306, 4079, 4007 cfs, respectively

c)Weeks 34, 36-47, 51, 52; releases are 1867, 2051, 2234, 2354, 3402, 3451, 3011, 2748, 2616, 2174, 1947, 1862, 1840, 1857, 1822 cfs, respectively

d)Weeks 39-51; releases are 4319, 4331, 4375, 4471, 4359, 4473, 4336, 4311, 4318, 4318, 4268, 4280, 4064 cfs, respectively

FLOOD CONTROL AND OVERALL BENEFITS

The benefits to agriculture because of the flood control function of Lake Shelbyville and Carlyle Lake, as obtained from 24 years of flow data, can be calculated by considering the damages under natural flow conditions (or with no dams) as the base or datum. The combined agricultural damage for the two river reaches below Shelbyville and Carlyle under natural flow conditions averages $659,600 per year (Table 15). Because the damages in the lake areas for natural flow conditions cannot be assessed directly, the damage in the two river reaches is considered as the base. The benefits, or the damages under natural flow conditions minus damages in all four damage reaches with lake regulation, under the various plans of regulation are then calculated as shown below.

	Average annual agricultural damages and benefits in thousands of dollars		
Plan	Damages with natural conditions	Damages with regulation	Net benefits
Interim			
SWS	659.6	32.0	627.6
Corps	659.6	197.3	462.3
Long-range			
SWS	659.6	34.3	625.3
Corps	659.6	220.6	439.0

Agricultural damages in the river reaches below Shelbyville and Carlyle were computed for various regulation strategies and natural flow conditions for the years 1972 through 1974. The results are given in Table 20. The damaging flow releases under various plans and actual operation are given at the bottom of the table. Under natural conditions, a total damage of $3.430 million would have occurred over the years 1972 through 1974 compared with $1.473 million under actual operation, $0.780 million under the Corps interim plan, and $0.306 million under the SWS interim plan. Benefits to agriculture from the operation of these two lakes are evident. An improved overall regulation strategy for minimization of damages should increase the efficiency of flood control.

A relative measure of benefits with the various strategies can be obtained from the overall average annual benefits. Recreation benefit is obtained by subtracting the average annual recreation damage (Tables 15 and 16) from the potential recreation benefit of $4.8075 million.

	Average annual benefits, in millions of dollars		
Plan	Recreation	Agriculture	Total
Interim			
SWS	4.782	0.628	5.410
Corps	4.746	0.462	5.208
Long-range			
SWS	4.775	0.625	5.400
Corps	4.734	0.439	5.173

The SWS plans indicate an average increase in benefits of more than $0.2 million a year.

SUGGESTIONS FOR FURTHER IMPROVEMENT

The regulation strategies developed in this study, designated as SWS interim and long-range plans, may be further improved through a better data base, consideration of potential water supply requirements, effect of tributary inflows in the damage reaches below the dams, and testing of the strategies and perhaps further optimization with a number of generated flow sequences.

Better Data. The need for better data may be exemplified by area flooded versus discharge information at various points along the river downstream of the two dams, particularly near the confluence with the tributaries. Such information coupled with flow information for the tributaries would help in modifying the flow releases below the dams to keep the overall damages to a minimum. The extent of a damage reach below a dam needs defining, on the basis of specified criteria and considerations, because the flood control protection decreases with distance downstream from the dam. Information is needed on the advisability of changing the beginning week of the main crop season from week 31 (year starts October 1) to a later week for areas in the zone of maximum allowable flows, 4500 and 10,000 cfs from Shelbyville and Carlyle Lakes. Shifting the beginning week to week 35 may cut down the agricultural loss to one-half of that with week 31. The estimates of visitors in each recreation activity and the upper and lower lake levels at which the activity is adversely affected, need to be carefully analyzed with respect to the capacity of the recreation areas and the design of boating ramps and other recreation facilities.

Water Supply. The state of Illinois has a reserve storage of 25,000 ac-ft in Lake Shelbyville and 33,000 ac-ft in Carlyle Lake. These storages will be used for water supply to municipalities and industries and perhaps coal-conversion plants. A computer run was made on the SWS long-range plan with continuous withdrawals of 17 cfs from Lake Shelbyville and 23 cfs from Carlyle Lake over the 24-year period, 1942 through 1965. These rates of withdrawals correspond to the use of reserve storage over a period of 2 years. The total damage for the 24 years increased from $1.735 million to $2.252 million; all the increase in damage occurred to recreation. The estimates of projected requirements and their alternative costs will help in deciding whether such supplies can be met totally or partially from the lakes, depending upon the overall benefit to the state. Such a study may show the advisability of meeting water supply demands from the lake most of the years with a standby provision for dry and very dry years.

Tributary Flows. The tributary flows in the damage reach below Shelbyville are considerable when these tributaries are in flood. Under natural flow conditions, the chance of tributary flow peaks coinciding with peak flows in the river needs to be analyzed. The regulation strategy should decrease that chance during the main crop season. In actual operation, a lead time would be needed for modifying the releases from the lake. Detailed hydrometeorological studies may indicate how much in advance the storm and the associated precipitation can be predicted. If forecasts are satisfactory and give sufficient lead time, they can be incorporated in the operational strategy. Otherwise, levees, channel improvements, detention dams, etc., may be considered if necessary.

Synthetic Flows. The flow-record period of 24 years, 1942 through 1965, used in this study is only one sample out of a population of flows over thousands of years. Certainly the next 24 years' sample will not duplicate it. With the use of suitable flow generation models, a number of synthetic flow sequences at Shelbyville and Carlyle may be obtained and used for optimizing the regulation strategy. The results of simulated operations can define the damage or benefit confidence bands. Instead of using average values of precipitation and evaporation over the lake surfaces, these may be varied depending on the magnitude of flow and other pertinent variables.

Estimating Flows. In actual operation, the inflows to the lakes are estimated from day to day. The estimating procedure needs to be critically reviewed. An interaction between the day's forecast and the previous day's forecast error (the actual inflow obtained from change in storage and flow release data) can be used to improve the estimate.

Drought Forecasting. Severe droughts have occurred in the past at intervals of 10 to 20 years. They are marked by a low-flow persistence over one to three years. An analysis of the occurrence of droughts and their characteristics may help in developing some indices as precursors of severe droughts. If these indices are found satisfactory, they can be incorporated into the operation strategy to conserve water and to let lake levels rise above rule levels a year in advance of the drought year.