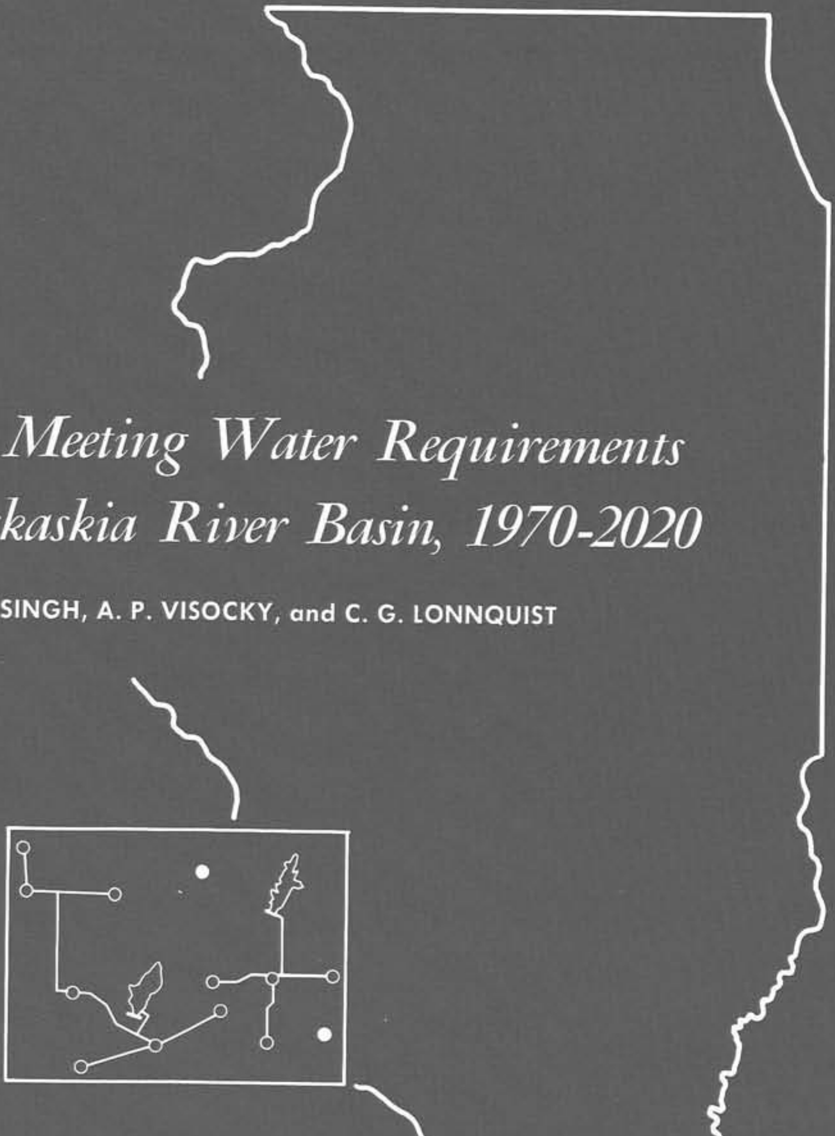
REPORT OF INVESTIGATION 70

STATE OF ILLINOIS

DEPARTMENT OF REGISTRATION AND EDUCATION



Plans for Meeting Water Requirements in the Kaskaskia River Basin, 1970-2020

by K. P. SINGH, A. P. VISOCKY, and C. G. LONNQUIST

ILLINOIS STATE WATER SURVEY

URBANA

1972

REPORT OF INVESTIGATION 70

AUG 26th 1818

Plans for Meeting Water Requirements in the Kaskaskia River Basin, 1970-2020

by K. P. SINGH, A. P. VISOCKY, and C. G. LONNQUIST

Title: Plans for Meeting Water Requirements in the Kaskaskia River Basin, 1970-2020.

Abstract: Two alternative economical plans are indicated by this systems study of available groundwater and surface water sources to provide an adequate and economical water supply for each town in the Kaskaskia River Basin through the year 2020. Plan 1 includes 6 reservoirs (excludes Carlyle and Shelbyville Reservoirs) serving 58 towns, groundwater supply for 43 towns, and river water for 4 towns. Plan 2 includes 2 reservoirs (Shoal Creek and Carlyle Reservoirs) serving 63 towns, groundwater supply for 40 towns, and river water for 2 towns. Cost elements of a water supply system, for which appropriate cost functions are provided, were grouped under costs of raw water production, treatment, and transmission to the storage tank location. Minimum-cost water supply systems were obtained by optimizing the sum of these three costs. It was found that only 50 towns in the basin have adequate groundwater potential to meet the 2020 requirements and that groundwater supply is generally more economical than water supply from reservoirs.

Reference: Singh, K. P., A. P. Visocky, and C. G. Lonnquist. Plans for Meeting Water Requirements in the Kaskaskia River Basin, 1970-2020. Illinois State Water Survey, Urbana, Report of Investigation 70, 1972.

Indexing Terms: cost optimization, groundwater, population growth, reservoir yield, surface water, systems study, transmission costs, treatment costs, water production costs, water requirement, water supply.

STATE OF ILLINOIS
HON. RICHARD B. OGILVIE, Governor

DEPARTMENT OF REGISTRATION AND EDUCATION
WILLIAM H. ROBINSON, Director

STATE WATER SURVEY DIVISION
WILLIAM C. ACKERMANN, D.Sc., Chief

URBANA
1972

Printed by authority of the Stale of Illinois-Ch. 127, IRS, Par. 58.29
(4-72-1500)

CONTENTS

Plans for Meeting Water Requirements in the Kaskaskia River Basin, 1970-2020

by K. P. Singh, A. P. Visocky, and C. G. Lonnquist

ABSTRACT

A systems study of available groundwater and surface water sources to provide an adequate and economical water supply for each town in the Kaskaskia River Basin through the year 2020 was performed.

The Kaskaskia River Basin covers an area of 5840 square miles in south-central Illinois. Water supply from the groundwater sources meets only a portion of the basin requirements, and the supply from existing small reservoirs is not adequate to meet future requirements. To alleviate future water shortages, the state has reserved storage in the Shelbyville and Carlyle Reservoirs - two recently completed large reservoirs in the basin.

An analysis of town water requirements and populations yielded a stable relation which enabled transformation of population estimates to water requirement estimates for the six decade years 1970-2020.

Three types of water sources were considered: groundwater from drift and shallow bedrock wells, surface water from existing and potential reservoirs, and water from the Kaskaskia River. General constraints were 1) that seasonal variations in water requirement would be within ± 50 percent of the yearly average and diurnal variations would be taken care of by the storage in elevated tanks, and 2) that a town would have water supply from only one source, namely, the source that provides a supply which is not only adequate but also most economical.

Cost elements of a water supply system, for which appropriate cost functions are provided, were grouped under cost of raw water production, cost of treatment of raw water, and cost of transmission of water to the storage tank location. Minimum-cost water supply systems were obtained by optimizing the sum of these three costs.

It was found that only 50 towns in the basin have adequate groundwater potential to meet the 2020 requirements and that groundwater supply is generally more economical than water supply from reservoirs.

Two alternative economical plans for meeting the water requirements of 105 towns in the basin were indicated by the study. Plan 1 includes 6 reservoirs (excludes Carlyle and Shelbyville Reservoirs) serving 58 towns, groundwater supply for 43 towns, and river water for 4 towns. Plan 2 includes 2 reservoirs (Shoal Creek Reservoir No. 4 and Carlyle Reservoir) serving 63 towns, groundwater supply for 40 towns, and river water for 2 towns. The reserve in Shelbyville Reservoir would be available to meet any water requirements from new industries, rural areas, and irrigation.

INTRODUCTION

The Kaskaskia River Basin has an area of 5840 square miles 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.

Water supplies from groundwater aquifers in the basin meet only a small portion of the total water requirement. In many cases, the supplies from rather small existing reservoirs are not adequate for future needs of towns they serve. Recurrent droughts in the basin area further reduce the yields from these reservoirs at times when water is needed most.

Increase in population with time will worsen the existing water supply conditions. In order to alleviate water shortages for municipal, industrial, and rural needs, the state has purchased storage allocations of 33,000 acre-feet (29.5 million gallons per day) in the Carlyle Reservoir and 25,000 acre-feet (22.3 mgd) in the Shelbyville Reservoir. These large reservoirs built on the Kaskaskia River have been completed recently. The storage allocations or water reserves can be used in an integrated plan of basin water supply.

The Kaskaskia River Basin has 115 small- to medium-sized towns, but four of these are supplied by nearby towns within the basin *(see table 1)* so that the study list includes 111 municipalities. Further, five of these are considered in a separate category because they obtain their water supplies from outside the basin. These include four municipalities in St. Clair County—Belleville, O'Fallon, Shiloh, and Swansea—whose water requirements make up almost one-third of the basin total and are being met by the East St. Louis and Interurban Water Company using Mississippi River water. The fifth town supplied from outside the basin is Humboldt, in Coles County, which obtains water from Mattoon.

At present (1970) 57 towns are using groundwater, 48 towns use surface water and outside sources, and 6 towns do not have a municipal water supply. Some of the towns using groundwater are looking for additional water sources to supplement existing supplies.

Water requirement forecasts are based on population forecasts, the accuracy of which decreases as the length of the time horizon increases. For a time period of 50 years, as used in this study, the range of error can be considerable. For the towns of the Kaskaskia Basin, an analysis of town water requirements and populations indicated that the relation between the two has been rather stable so far. This can be attributed to lack of local concentrations of industry and to a direct relation between the town population and its level of industrialization. Therefore, a unique relation between water requirement and population was assumed to hold for analyzing the adequacy of various water sources available in the basin and in arriving at economical combinations of the various supply systems.

General constraints imposed for the analysis include: 1) seasonal variations in water requirement would be within ±50 percent of the yearly average; 2) variations in requirements during the day would be taken care of by the storage in elevated tanks; and 3) a town would have water supply from only one source, namely, the source from which water supply is not only adequate but also most economical. For comparison of costs from various sources, water costs were calculated at the location of municipal elevated storage tanks.

Three types of water sources — groundwater from drift and shallow bedrock wells, surface water from existing and potential reservoirs, and water from the Kaskaskia River (for towns already using it) — are available for meeting the basin water requirements over the 50-year study period. A study of spatial distribution and potential of these water sources in relation to the location of towns and the magnitude of their water requirements was helpful in delineating areas where one source or the other would be not only adequate but also more economical.

This study was undertaken to evolve economical plans for basin water supply and to indicate clearly how the water reserves in the Carlyle and Shelbyville Reservoirs can be used in such plans. To accomplish these objectives a systems approach was warranted for both groundwater and surface water supply sources.

Basic to the systems approach is a model — a symbolic representation of a real life situation. The model can be for a groundwater supply system having elements representing wells, pumps, the treatment plant, the conveyance line, and their operation and maintenance. It may be for a surface water supply system having elements representing the reservoir, treatment plant, transmission network, and their operation and maintenance. The network may be a small one, serving only one town, or a big one, serving scores of towns. Minimum cost systems from these models could be obtained by linear programming techniques if the overall objective function were a linear one, subject to certain linear constraints. However, in water supply systems, as formulated in this study, the objective function and the constraints are not linear. Therefore, recourse was made to simulation which is fundamentally an iterative solution methodology.

This report presents first the basin water requirements estimated for the six decade years 1970-2020. The next section provides the appropriate cost functions for all of the cost elements involved in producing and treating raw water and transmitting the water to the storage tank location. The adequacy and cost of the water sources are then related, after which the two economic plans for basin water supply are presented and discussed. Notations used through the report are listed in the back, page 23.

Acknowledgments

This study was conducted under the general supervision of Harman F. Smith, Head of the Hydrology Section, and Dr. William C. Ackermann, Chief, Illinois State Water Survey. Computer facilities at the University of Illinois were used in carrying out the various analyses and systems studies. Mrs. J. Loreena Ivens and Mrs. Patricia A. Motherway edited the final report, and John W. Brother, Jr., and William Motherway, Jr., prepared the illustrations.

WATER REQUIREMENTS

Estimates of water requirements for a town during a specified number of years depend on the population projections during these years and a suitable function for converting the population projections to water-requirement estimates. Population projections for all the towns in figure 1 have been made by the use of: 1) Department of Business and Economic Development town populations for the years 1960, 1967, and 1980, and county populations for the years 1960, 1967, 1980, and 2020; 2) estimates of urban population as a percentage of total population of a county extrapolated to 2020 from the data for the period 1900 to 1967; and 3) straight-line interpolation between 1980 and 2020 projections.

A logarithmic plot of the average yearly consumption in gallons per day and the population served indicates that the same population-water requirement function is applicable to both 1960 and 1967, years for which satisfactory data are available for most of the towns in the Kaskaskia

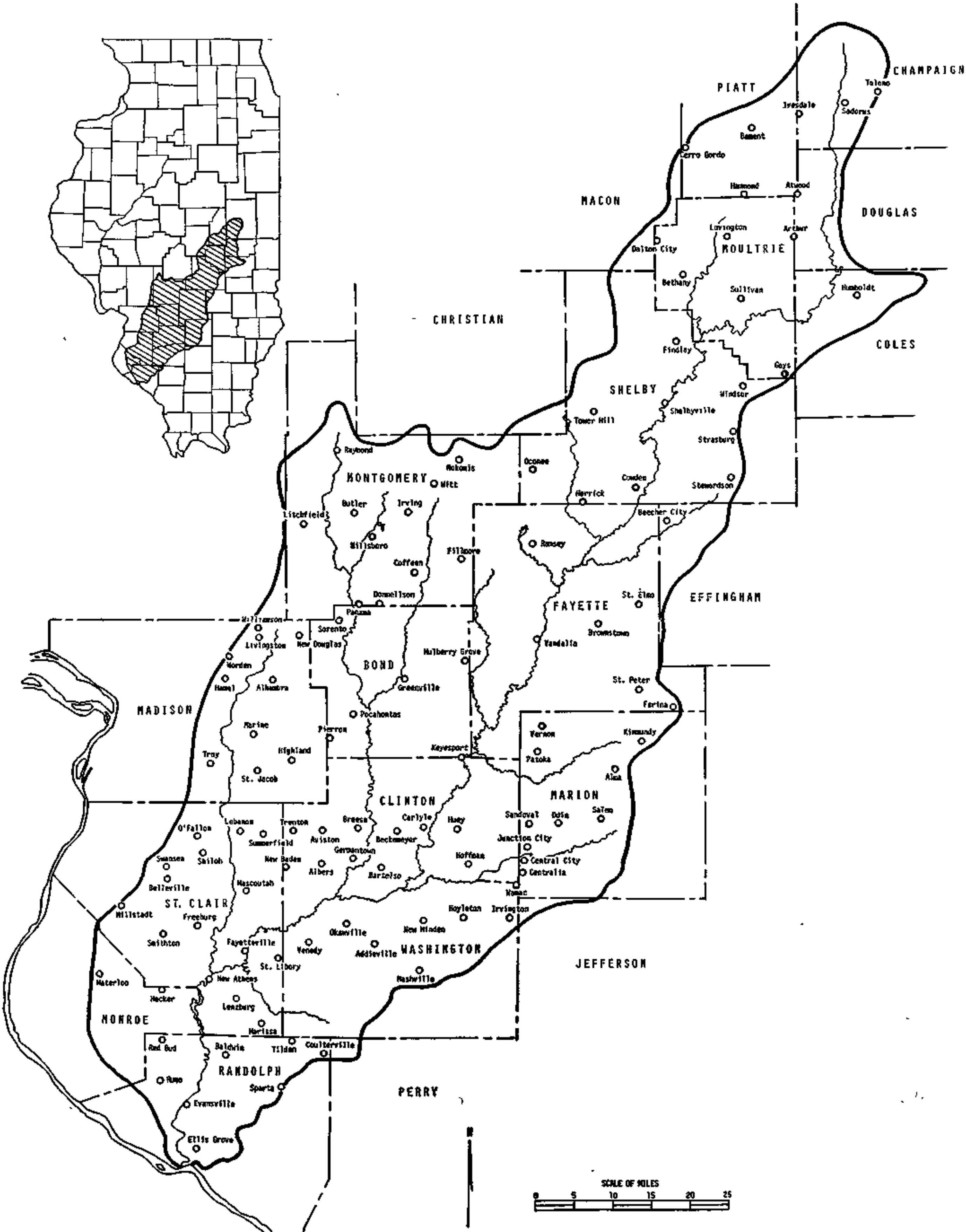


Figure 1. Towns in the Kaskaskia River Basin

River Basin and nearby areas. The stability of this function with time is attributed to leveling-off of domestic consumption, some reduction in unaccounted-for water losses, an increase in metering of service connections, and leveling-off of or even reduction in unit consumption by industries because of technological advances such as water reuse. The adopted function, as shown in figure 2, is

$$Q = 11.0\, P^{1.252} \tag{1}$$

in which Q is the average yearly consumption in gallons per day (gpd) and P is the population. The scatter about the adopted line is small except for towns with less than 1000 population in the southern part of the basin, where water use is less because of poor groundwater aquifers and the relatively high cost of developing surface water supplies for small population towns. Population projections have been transformed to water requirement estimates by the use of equation 1.

The estimated average water requirements for all the towns in the study area are given in table 1 for the years 1970, 1980, 1990, 2000, 2010, and 2020. Where there will be a decrease in population in 1980 and 1990, the water requirement was considered to be the same as in 1970.

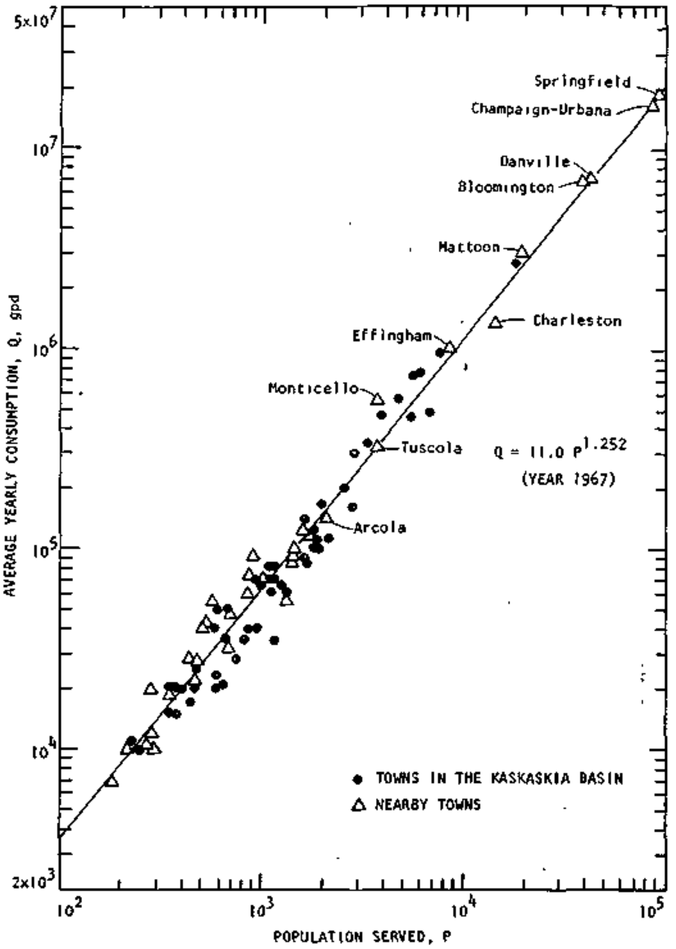


Figure 2. Average yearly consumption versus population served

COST ELEMENTS OF A WATER SUPPLY SYSTEM

For comparison, the water costs from the various sources were calculated at the location of the municipal elevated storage tanks. Costs of subsequent pumping to the tank and the distribution system and of maintaining suitable in-line pressures are common to all alternatives, and thus are excluded from the comparison. The water-supply source must be adequate to provide 1.5 times the average water requirement in order to meet seasonal variations. Variations in requirement during a day are taken care of by the storage in elevated tanks. Further, any one municipality can have its water supply from only one source, since a conjunctive use of groundwater and surface water for a single small- to medium-sized municipality is generally not economical. A municipality will use that water source which provides a water supply that is not only adequate to meet the anticipated water requirements but also most economical.

Under these guiding constraints, the cost elements of a water supply system were considered under three main headings: 1) cost of production of raw water, 2) cost of treatment of raw water, and 3) cost of transmission of water to the storage tank location. The magnitude of these costs as a percent of the total cost varies with the type of water source, degree of treatment required, and distance over which water is transported. In addition, the relative economies of scale vary with the magnitude of water requirements.

Three types of water sources have been considered in determining the most economical plan for meeting the water requirements of towns dependent on the in-basin water sources: 1) groundwater from drift and shallow bedrock wells, 2) surface water from existing and potential reservoirs, and 3) Kaskaskia River water for towns already using it. For the sake of uniformity, all cost functions are based on 1964 dollars. Conversion to 1970 dollars can easily be done by multiplying by a suitable factor based on cost indexes of 1970and 1964.

Cost of Production of Raw Water

Groundwater from Drift and Shallow Bedrock Wells

Groundwater sources within the basin are found generally in two types of aquifers — glacial drift deposits and shallow

Table 1. Estimated Water Requirements for Towns in Basin

(Requirements in 1000 gallons per day)

Town	1970	1980	1990	2000	2010	2020
Addievillc	12 1	13 9	18 1	22 5	27 0	31 7
Albers	45.8	60 4	76 1	92 4	108 9	125 8
Alhambra	44 1	60 4	72 1	84 2	97 8	111 7
Alma	14 2	14 2	14 2	16 0	18 4	20 9
Arthur	158 9	191.6	221 3	251 9	291 5	332 2
Atwood	174.5	278 6	342 7	409 3	472 7	537 9
Aviston	70 9	102 5	129 1	156 8	184 7	213.5
Baldwin	16 2	16 2	20 4	24 7	29 7	34 8
Bartelso	28 1	38 7	48 7	59 2	69 7	80 6
Beckemcyer	83 6	100 0	125 8	152 8	180 0	208 1
Beecher City	24 8	26 3	33 1	40 2	47 3	54 6
Bement	154 1	202 5	249 1	297 6	343 6	391 0
Bethany	76 7	80 4	91 9	103 6	119 5	135 9
Breese	251.7	309 6	390 1	474 0	558 3	645 2
Brownstown	54 1	72 3	93 3	115 4	135 8	156 9
Butler	10 3	10 3	11 5	13 7	16 0	18 3
Carlyle	287 2	334 7	421 6	512 3	603 6	697 7
Central City	110 8	124 3	150 0	176 6	202 7	229 5
Centraha	2063.1	2387 4	2881 0	3392 3	3893 4	4408 0
Cerro Gordo	90 9	115 6	142 3	169 9	196 2	223 3
Coffeen	19.0	19 0	19 0	19 0	20 6	23 7
Coulterville	58 2	58 2	64 2	77 8	93 4	109 6
Cowden	34.2	38 0	49 1	60 8	72 1	83 8
Dalton City	16 8	16 8	17 5	23 1	26 7	30 3
Donnellson	11 7	11 7	12 2	14 5	16 9	19 4
Ellis Grove	8 0	8 0	8 6	10 4	12 5	14 6
Evansville	56 4	61 2	76 7	92 9	111 6	131 0
Farina	47 8	56 5	73 0	90 2	106 2	122 6
Fayetteville	16.5	19 3	22 9	26 5	30 3	34 3
Fillmore	16 6	16 6	19 1	22 8	26 5	30 4
Findlay	59.0	75 5	97 7	121.0	143 4	166 6
Freeburg	183 4	228 7	270 7	314 1	359 5	406 1
Gays	10 0	10 0	10 1	13 7	15 8	17 9
Germantown	92 0	123 7	155 8	189 2	223 0	257 7
Greenville	462 2	509 6	617 1	728 5	853 5	982 4
Hamel	27 2	37 3	44 5	51 9	60 3	69 0
Hammond	38.0	52 7	64 8	77 4	89 4	101 7
Hecker	32 1	52 7	64 0	75 7	89 2	103 1
Herrick	19 1	19 1	21 0	26 0	30 8	35 8
Highland	581 4	699 0	834 5	974 6	1131 6	1293 1
Hillsboro*	545 1	559 2	683 4	812.4	948 1	1087 9
Hoffman	19 1	27 0	34 0	41 3	48 7	56 3
Hoyleton	40 5	56 5	73 5	91 4	109 8	128 9
Huey	13 5	18 1	22 8	27 7	32 6	37 7
Irving	34 9	38 7	47 3	56 2	65 6	75 3
Irvmgton	31 2	43 7	56 9	70 7	85 0	99 8
Ivesdale	15 7	15 7	15 7	16 0	17 9	19 9
Junction City	12 0	12 0	12 0	13 7	15 7	17 8
Keyesport	23 0	25 0	31 5	38 3	45 1	52 2
Kinmundy	38 7	38 7	38 7	41 9	48 1	54 4
Lebanon	329 5	431 9	511 3	593 3	679 0	767 0
Lenzburg	20 4	20 4	23 6	27 4	31 3	35 4
Litchfield	814 0	866 0	1058 4	1258 1	1468 2	1684 6
Livingston	79 9	100 7	120 3	140 5	163 1	186 4
Lovington	69 9	69 9	73 6	95 8	110 5	125 6
Marine	82 7	119 2	142 3	166 2	193 0	220 5
Marissa*	151 8	159 7	189 1	219 4	251 2	283 8
Mascoutah	383 5	455 2	538 9	625 3	715 7	808 4
Millstadt	158 6	183 8	217 6	252 4	288 9	326 4
Mulberry Grove	41 2	41 2	48 1	56 8	66 6	76 7
Nashville	239 8	267 0	347 4	431 8	518 9	609 0
New Athens	180 9	220 5	261 1	302 9	346 7	391.6
New Baden	129 1	156 9	197 6	240 1	282 9	327.0
New Douglas	25 2	32 4	38 7	45 1	52 4	59 9
New Minden	11 4	16 2	21 1	26 3	31 6	37 1
Nokomis*	230 2	230 2	279 5	332 2	387 7	444 8
Oconee	14 2	17 5	22 6	27 9	33 1	38 5
Odin	71 5	71 5	73 4	86 4	99 2	112 3
Okawville	99 5	142 9	185 9	231.1	277 7	325 9
Panama	24 9	24 9	29 8	35 4	.41 3	47 4
Patoka	32 0	32 0	37 1	43 7	50 2	56 8
Pierron	26 3	30 7	37 2	43 9	51 4	59 1
Pocahontas	40 0	40 0	48 1	56 8	66 6	76 7
Ramsey	70 1	93 0	120 1	148 5	174 8	201 9
Raymond	63 4	73 9	90 3	107 3	125 3	143 8
Red Bud	196 8	248 2	311 4	377 3	453 1	531 5
Ruma	7 4	9 4	11 8	14 3	17 2	20 2
Sadorus	18.7	18 7	21 5	24 5	27 5	30 6
Salem	592 6	592 6	691 8	814 6	934 9	1058 4
Sandoval	74 5	74 5	74 5	82 2	94 3	106 7
St Elmo	123 0	141 9	183 3	226 6	266 7	308 0
St Jacob	44 3	61 2	73 0	85 3	99 0	113 1
St. Libory	17 9	19 3	22 9	26 5	30 3	34 3
St Peter	32 2	46 0	59 3	73 3	86 3	99 7
Shelbyville	581 9	731 0	945 6	1170 6	1387 8	1612 1
Smithton	43 4	51 9	61 5	71 3	81 6	92 2
Sorento	34 1	34 1	37 2	43 9	51 4	59 1
Sparta	305 7	310 7	389 8	472 3	567 2	665 5
Stewardson	43 7	51 2	66 2	81 9	97 2	112 9
Strasburg	31 3	39 4	51 0	63 1	74 8	86 9
Sullivan	333 6	333 6	375 4	457 6	528 0	600 3
Summerfield	15 7	15 7	16 5	19 1	21 9	24 7
Tilden	44 8	44 8	51 2	62 1	74 6	87 5
Tolono	147 7	189 6	218 7	248 6	279 3	310 6
Tower Hill	41 5	43 7	56 6	70 1	83 1	96 5
Trenton	179 4	220 5	277 8	337 5	397 6	459 5
Troy	242 4	365 8	436 8	510 1	592 3	676 9
Vandalia	772 1	1025 9	1324 8	1638 1	1927 8	2226 6
Venedy	7 7	7 7	9 5	11 8	14 2	16 7
Vernon	9 8	9 8	11 1	13 0	14 9	16 9
Wamac	89 7	89 7	101 9	120 0	137 7	155 9
Waterloo	639 9	1005 3	1221 0	1444 7	1701 7	1966 8
Williamson	21 8	28 3	33 8	39 4	45 8	52 4
Windsor	75 2	79 6	103 0	127 6	151 2	175 5
Witt	69 3	69 3	82 4	98 0	114.4	131 3
Worden	102 9	140 1	167 3	195 3	226 8	259 2
Total	14666 4	17485 2	,21292 4	25400 4	29614 6	33956 0
Water supply from outside of basin						
Belleville	6785 5	7784 0	9215 8	10693 9	12238 7	13823 9
Humboldt	19 5	22 4	26 7	31 1	35 6	40 1
O'Fallon	714 1	1112 0	1316 6	1527 7	1748 5	1975 0
Shiloh	59 1	78 8	93 3	108 3	123 9	139 9
Swansea	378 7	520 4	616 1	715 0	818 3	924 3
Total	7956 9	9517 6	11268 5	13076 0	14965 0	16903 2

***** Hillsboro supplies water to Schram City and Taylor Springs; Marissa supplies Old Marissa; and Nokomis supplies Coalton.*

bedrock formations. Drift deposits of large water potential usually are associated with existing or buried river valleys. This type of aquifer is found predominantly in the upper one-fourth of the basin and at several locations along the Kaskaskia River in the lower half of the basin. Principal bedrock units developed for groundwater supplies in the lower three-fourths of the basin include thin Pennsylvanian sandstones and Mississippian limestones.

Case-history studies of groundwater supplies have been made by the State Water Survey previously for several areas and municipalities within the basin. Estimates have been made of potential yields or practical sustained yields of existing well fields. In addition, studies on a broader regional basis, which include all of the study area, were made as part of a statewide comprehensive water-resource investigation, as a guide to groundwater planning and development. Aquifer location, expected well yield, and estimated potential yield were outlined in the report.[1] These studies as well as information from Water Survey files provided useful data.

Evaluation of local groundwater resources within a study area involves an attempt to answer the question: Can the local peak water requirement be met by local groundwater resources? On the basis of available groundwater information, including well test data and studies mentioned above, an estimate has been made of the potential aquifer yield in the vicinity of each of the 111 towns listed in table 1. Well fields capable of developing the potential yields have been designed by idealized-aquifer and mathematical-model techniques, image-well theory, and appropriate drawdown equations.[2] In areas where the aquifer potential is greater than the anticipated peak requirement in 2020, well fields have been designed to develop only the peak requirement.

Pertinent data used in the computer program for calculating the cost of groundwater for each town are given in table 2. Data include the well diameter, in inches, and the well type indicated by T and G for tubular and gravel-packed wells, respectively, the choice depending on common local usage. Other data in table 2 are average long-term well yield, q_w, in gpm; well depth, d_w, in feet; estimated long-term pumping level, d_p, in feet below ground level; aquifer potential yield, Q_y, in gpd; distance from the well field to the elevated storage tank, L_f, in miles; and elevation

Table 2. Data for Computing Groundwater Costs

Town	Well Diameter (inches)	Well Type*	q_w (gpm)	d_w (ft)	dp (ft)	Q_w (gpd)	L_f (miles)	H_e (ft)
Addieville	6	T	7 0	120	40	50,400	2 5	0 0
Albers	6	G	30 0	60	35	44,000	0 0	0 0
Alhambra	8	G	170 0	80	35	245,000	4 0	40 0
Alma	6	T	8 0	100	45	35,000	0 5	0 0
Arthur	6	G	50 0	90	66	1,080,000	1 8	0 0
Atwood	8	G	250 0	100	75	1,800,000	2 3	0 0
Aviston	8	G	180.0	70	40	260,000	1 0	30 0
Baldwin	6	G	130 0	65	15	188,000	3 0	80 0
Bartelso	6	G	50 0	55	20	144,000	1 0	0 0
Beckemeyer	6	T	5.0	225	90	25,000	0 8	0 0
Beccher City	6	G	75 0	33	17	108,000	4.0	80 0
Bement	8	G	225.0	140	95	1,296,000	0.5	0 0
Bethany	6	G	60 0	70	50	432,000	3 0	35 0
Breese	6	T	5 0	225	90	25,000	0 8	0 0
Brownstown	6	G	10 0	50	25	60,000	1 0	0 0
Butler	6	G	20 0	50	35	29,000	2 5	0 0
Carlyle	6	G	6 0	50	40	30,000	0 3	0.0
Central City	6	G	10 0	30	15	72,000	1 5	0.0
Centralia	6	T	10.0	100	60	130,000	2 0	10.0
Cerro Gordo	6	G	50 0	30	16	144,000	0.5	0 0
Coffeen	6	G	20 0	100	60	58,000	2 0	30 0
Coulterville	6	T	2 0	80	45	10,000	2 0	50 0
Cowden	8	T	200 0	55	30	288,000	1 0	80 0
Dalton City	6	G	60 0	80	65	86,500	1 5	5 0
Donnellson	6	G	10 0	35	20	29,000	1 5	20 0
Ellis Grove	6	G	40 0	90	45	58,000	2 5	170 0
Evansville	6	T	25 0	350	275	216,000	2 5	0 0
Farina	6	T	10 0	150	95	90,000	1 0	0 0
Fayetteville	6	G	75 0	90	65	108,000	0 0	0 0
Fillmore	6	G	37 0	45	15	54,000	0 5	20 0
Findlay	8	G	260 0	170	122	375,000	0 0	0 0
Freeburg	6	G	24 0	50	35	105,000	3 0	-10 0
Gays	6	T	10 0	110	100	28,800	0 5	0 0
Germantown	6	G	55 0	50	20	400,000	1 0	20 0
Greenville	8	G	170 0	90	58	750,000	0 8	17 0
Hamel	6	G	55 0	113	90	80,000	2 5	15 0
Hammond	8	G	200 0	87	30	295,000	0 0	0 0
Hecker	6	T	5 0	160	125	22,000	0 5	0 0
Herrick	6	T	100 0	80	38	144,000	4 0	70 0
Highland	6	G	20 0	50	35	220,000	3 5	90 0
Hillsboro	6	G	20 0	100	60	100,000	1 0	0.0
Hoffman	6	G	100 0	100	30	144,000	4 0	16 0
Hoyleton	6	T	3 5	100	75	10,500	0 5	0 0
Huey	6	G	100 0	85	40	144,000	0 0	0 0
Irving	6	T	7 0	180	100	30,300	0 5	0 0
Irvington	6	T	7 0	200	140	10,500	0.0	0 0
Ivesdale	6	T	50 0	90	35	72,000	0 0	0.0
Junction City	6	T	10 0	100	45	29,000	0 0	0 0
Keyesport	6	G	15 0	25	22	22,000	0 0	10 0
Kinmundy	6	T	10 0	100	35	43,200	1 0	0 0
Lebanon	8	G	200 0	45	25	290,000	0 5	55 0
Lenzburg	6	T	4 0	300	115	18,000	1 5	0 0
Litchfield	6	G	20 0	75	60	58,000	1 0	0 0
Livingston	6	G	100 0	140	80	289,000	1 0	20 0
Lovington	6	G	100 0	115	90	432,000	0 5	0 0
Marine	6	G	100 0	90	75	144,000	2 0	40 0
Marissa	6	T	3 5	50	45	5,100	1 5	40 0
Mascoutah	10	G	560 0	95	50	1,613,000	5.0	10 0
Millstadt	6	T	17 5	300	240	158,000	3.0	0.0
Mulberry Grove	6	T	15 0	40	30	45,000	1 5	60 0
Nashville	6	T	5 0	190	135	22,000	1 5	10 0
New Athens	6	G	120 0	80	65	346,000	2 5	30 0
New Baden	10	G	350 0	55	20	506,000	6.0	0 0
New Douglas	6	G	11 0	35	15	96,000	1 5	10 0
New Minden	6	T	6 5	170	125	57,000	2 0	0.0
Nokomis	6	G	110 0	40	28	320,000	0 5	5 0
Oconee	6	T	5 0	50	30	7,200	0 0	0 0
Odm	6	T	10 0	100	35	43,200	1 0	10 0
Okawville	6	G	100 0	70	20	576,000	3 0	30 0
Panama	6	G	19 0	25	15	28,000	0 5	60 0
Patoka	6	G	15 0	62	52	87,000	2 0	0 0
Pierron	6	T	5.0	100	80	50,500	3 5	-10 0
Pocahontas	6	G	20 0	35	20	144,000	1 5	90 0
Ramsey	8	T	150 0	40	30	216,000	1.3	70 0
Raymond	6	G	100 0	40	25	288,000	1 0	0 0
Red Bud	6	T	30 0	285	235	173,000	3.0	0 0
Ruma	6	T	40 0	315	186	58,000	1 0	0 0
Sadorus	6	T	50 0	115	80	144,000	0.0	0 0
Salem	6	T	10 0	100	45	43,200	1.0	10 0
Sandoval	6	G	30 0	100	60	173,000	1 0	10 0
St Elmo	6	G	20 0	50	35	87,000	4 0	50 0
St. Jacob	6	T	10 0	200	135	44,000	2 0	0 0
St Libory	6	G	100 0	65	30	144,000	2 0	10 0
St. Peter	6	T	6 0	150	85	44,000	2 5	0 0
Shelbyville	10	G	300 0	70	39	2,592,000	5.0	100 0
Smithton	6	T	8 0	200	145	47,000	1.0	0 0
Sorento	6	T	6 0	75	50	26,000	1 5	0 0
Sparta	6	T	9 0	275	235	78,000	3 0	30 0
Stewardson	8	T	150 0	50	20	220,000	1 0	0 0
Strasburg	6	T	70 0	40	25	101,000	5 0	20 0
Sullivan	8	G	300 0	120	70	1,510,000	3 0	55 0
Summerfield	6	G	6 0	60	47	9,000	0 5	0 0
Tilden	6	T	2 0	80	45	10,000	2 0	0 0
Tolono	8	G	200 0	180	142	1,152,000	0 0	0 0
Tower Hill	6	T	10.0	50	20	29,000	1 5	80 0
Trenton	6	T	10 0	240	175	200,000	3 0	-10 0
Troy	12	G	700 0	115	30	1,008,000	9 5	125 0
Vandalia	10	G	350 0	55	25	505,000	2 0	65 0
Venedy	6	G	50 0	50	35	72,000	1 0	50 0
Vernon	6	G	20 0	55	40	29,000	1 0	5 0
Wamac	6	T	4 0	100	70	23,000	2 0	0 0
Waterloo	6	T	15 0	260	115	108,000	2 3	0 0
Williamson	6	G	20 0	25	15	87,000	3 0	0 0
Windsor	6	T	50 0	100	90	144,000	1 0	-10 0
Witt	6	T	75 0	40	20	108,000	1 5	20 0
Worden	6	T	30 0	45	25	216,000	3 5	70 0
Belleville	6	T	40 0	400	330	58,000	0 0	0 0
Humboldt	6	T	10 0	30	18	28,800	1 0	0 0
O'Fallon	6	T	30 0	50	35	44,000	1 0	0 0
Shiloh	6	T	30 0	50	35	44,000	1 0	100 0
Swansea	6	T	40 0	400	370	58,000	0 0	0 0

* *T = tubular; G = gravel packed*

difference between the ground level at the elevated storage tank and that at the well field, H_e, in feet.

Costs of groundwater for the years 1970, 1980, 1990, 2000, 2010, and 2020 were obtained by means of a suitable computer program having the following main features.

Total Number of Wells, N_{wt}. This includes the number of wells to meet the water requirement plus standby wells. The number of wells, N_w, to meet the water requirement, Q, for different years is obtained by

$$N_w = \frac{\text{water requirement in gpd}}{q_w \times 1440} \times 1.5 \qquad (2)$$

rounded off to the next higher integer. The multiplier 1.5 allows 50 percent excess requirement over the mean. The maximum number of wells that an aquifer can sustain, N_m, is given by

$$N_m = Q_y/(q_w \times 1440) \qquad (3)$$

rounded off to the next lower integer. If N_w is equal to or less than N_m, the groundwater supply is adequate. Provision is made for standby wells as

$$N_{wt} = N_w + 1 \qquad \text{if } N_w \leq 3 \qquad (4)$$

$$N_{wt} = N_w + 2 \qquad \text{if } N_w > 3 \qquad (4a)$$

When N_w exceeds N_m, the groundwater supply is inadequate to fully meet the requirement. However, the cost of available water supply is calculated by replacing N_w by N_m in equation 4.

Cost of Wells, C_w. The costs of wells and interconnections (if wells are far apart, the cost of interconnections is adjusted in the transmission cost) for the two types of wells[3] adjusted to 1964 dollars are

$$C_w = 850\ d_w^{0.289}\ N_{wt}/1.1 \qquad \text{tubular} \qquad (5)$$

$$C_w = 680\ d_w^{0.408}\ N_{wt}/1.1 \qquad \text{gravel packed} \qquad (5a)$$

The factor 1.1 converts 1966 dollars[3] to 1964 dollars. The expected life of a well is 20 years.

Cost of Pumps and Motors, C_{pm}. The design head, H_d, for the pump equals d_p + 25 feet; the addition of 25 feet of head allows for pumping to the treatment plant. The pump and motor cost[3] in dollars is given by

$$C_{pm} = 5.629\ q_w^{0.541}\ H_d^{0.658}\ N_{wt}/1.1 \qquad q_w \leq 100 \quad (6)$$

$$C_{pm} = (800 + 7.309\ q_w^{0.453}\ H_d^{0.642})N_{wt}/1.1 \quad q_w > 100 \ (6a)$$

for submersible turbine and vertical turbine pumps, respectively. The cost of $800 is for the motor housing in the case of vertical turbine pumps. The useful life of a pump is assumed to be 12.5 years.

Annual Operation, Maintenance, and Repair (OM&R) Cost on Wells and Pumps, C_{op}. The OM&R cost in dollars is approximated by

$$C_{op} = 100 + 75\ N_{wt} \tag{7}$$

Annual Electrical Charges for Pumping, C_e. The total for kilowatt hours per year, kwh, is calculated as

$$\text{kwh} = \frac{Q \times 0.1337 \times 62.4 \times H_d \times 365.24}{550 \times 3600 \times E_g} \times 0.746 \tag{8}$$

$$\text{kwh} = 0.0011476\ Q\ H_d/E_g \tag{8a}$$

in which E_g is the average overall efficiency during the year for pumping groundwater, taken as 0.6. The kwh is converted to C_e by use of the prevalent electric rate schedule as given for transmission cost.

Hence, the total annual cost of untreated groundwater, *TCG,* is

$$TCG = C_w\,(CRF)_{20} + C_{pm}(CRF)_{12.5} + C_{op} + C_e \tag{9}$$

in which the subscripts 20 and 12.5 refer to the useful life in years for wells and pumps, respectively, for calculating capital recovery factors *(CRF)* for various rates of interest. The computer program yields annual cost, *TCG,* the available water supply in gallons per day, and the cost of water in cents per 1000 gallons.

Surface Water from Existing and Potential Reservoirs

The state of Illinois has a reserve water supply of 22.3 mgd in the Shelbyville Reservoir and 29.5 mgd in the Carlyle Reservoir — the two biggest reservoirs in the Kaskaskia River Basin. The price of raw water from these reservoirs is taken as 5 cents per 1000 gallons. In addition to these two large reservoirs, there are many existing reservoirs and potential reservoir sites.[4,5] A preliminary study showed which reservoirs should be considered for this study. Factors of consideration included reservoir yield, the water requirement in the service area, and the extent of the service area.

Costs of raw water from the 24 reservoirs listed in table 3 and shown in figure 3 have been computed by the following procedure adapted for a computer program.

Net Reservoir Capacity. Annual reservoir capacity loss because of sedimentation can be read from a graph *(Stall,[6] figure 21)* when drainage area and reservoir capacity are known. A single equation has been fitted to this graph:

$$\text{capacity loss} = 0.0191\ A^{-0.1478\ (\log_{10} A)^{0.44}} \tag{10}$$

in which capacity loss is in inches per year and *A* is the drainage area in square miles. Net reservoir capacity equals reservoir capacity minus capacity loss over a period of 40 years.

Net Reservoir Yield. Net yield from a reservoir is obtained by subtracting evaporation loss from the gross reservoir yield during a period of critical drawdown. Gross yield of a reservoir depends on the magnitude of net reservoir storage, the drainage area of the stream above the reservoir, the mean flow of the stream, and the associated risk of getting a lesser yield. In this study, the risk implied is that the reservoir yield may be less than the desired yield once in 40 years on the average. Reservoir yield can, at the most, equal the mean flow of the stream if sufficient reservoir storage is provided to ensure no spills from the reservoir under any conditions.

Table 3. Hydrologic Data for Existing and Potential Reservoirs in Basin

Waterway location*	Maximum storage *(ac-ft)*	Maximum pool area *(acres)*	Watershed *(sq mi)*	Mean annual runoff *(cfs/sq mi)*	Weights for evaporation	
					Springfield	Carbondale
1 Bear Creek	7280	625	25.0	0.72	0.58	0.42
2 Branch of Plum Creek	4200	420	4.5	0.78	0.22	0.78
3 Camp Creek	9100	680	18.4	0.72	0.58	0.42
4 Coal Creek	9860	510	10.8	0.60	0.70	0.30
5 Davidson Creek	9250	750	18.0	0.75	0.42	0.58
6 Dry Fork	16640	960	20.5	0.64	0.59	0.41
7 E. Fork Kaskaskia River	53300	3200	96.1	0.75	0.45	0.55
8 Elkhorn Creek	13140	1460	52.2	0.80	0.29	0.71
9 Horse Creek (Monroe Co.)	21700	1480	33.0	0.73	0.32	0.68
10 Horse Creek (Randolph Co.)	35333	2650	84.0	0.85	0.27	0.73
11 Little Creek	14080	704	12.2	0.60	0.66	0.34
12 Mud Creek	4200	600	14.0	0.76	0.27	0.73
13 Ogles Creek	9900	540	15.0	0.72	0.45	0.55
14 Plum Creek	17520	1460	90.0	0.85	0.25	0.75
15 Ramsey Creek	3630	320	12.0	0.62	0.72	0.28
16 Richland Creek	10500	700	39.5	0.64	0.65	0.35
17 Rockhouse Creek	5700	380	19.5	0.72	0.34	0.66
18 Rock Spring Branch	5740	410	5.9	0.68	0.45	0.55
19 Shoal Creek Res. No. 4†	15500	1412	115.0	0.56	0.70	0.30
20 Silver Lake†	10400	740	47.5	0.64	0.52	0.48
21 Spanker Branch	8000	800	14.5	0.64	0.46	0.54
22 Stone Creek	4380	365	7.0	0.72	0.54	0.46
23 Sugar Fork	4400	440	13.2	0.64	0.54	0.46
24 W. Fork Richland Creek	6160	370	6.1	0.70	0.38	0.62

* *Numbers refer to reservoirs shown on figure 3*
† *Existing reservoir*

Reservoir yield and net reservoir storage can be considered in terms of percentage of mean flow to derive a general equation for the Kaskaskia Basin. These data[6] for percent draft rate or reservoir yield as percent of mean flow, *p,* pertaining to a 40-year recurrence interval; the net reservoir storage as percent of mean flow, *S;* and the drainage area, *A,* of the reservoirs in the Kaskaskia Basin were used to derive the relation

$$S = C_p A^{n_p} \tag{11}$$

in which *C* and *n* are a coefficient and an exponent respectively, and the subscript *p* refers to the percent draft rate. Table 4 contains values of *C* and *n* for *p* ranging from 5 to 100. Knowing *S* and *A,* the computer program interpolates the proper value of *p* for which *C* and *n* satisfy equation 11.

The evaporation loss during a critical drought, occurring at an average of once in 40 years, is calculated from 1) the critical drawdown duration, T_C, in months for a given value of *p* (table 4) and 2) the net evaporation data at Springfield and Carbondale (table 5). Net evaporation equals evaporation loss from the reservoir surface minus precipitation in inches of water falling directly on the lake surface

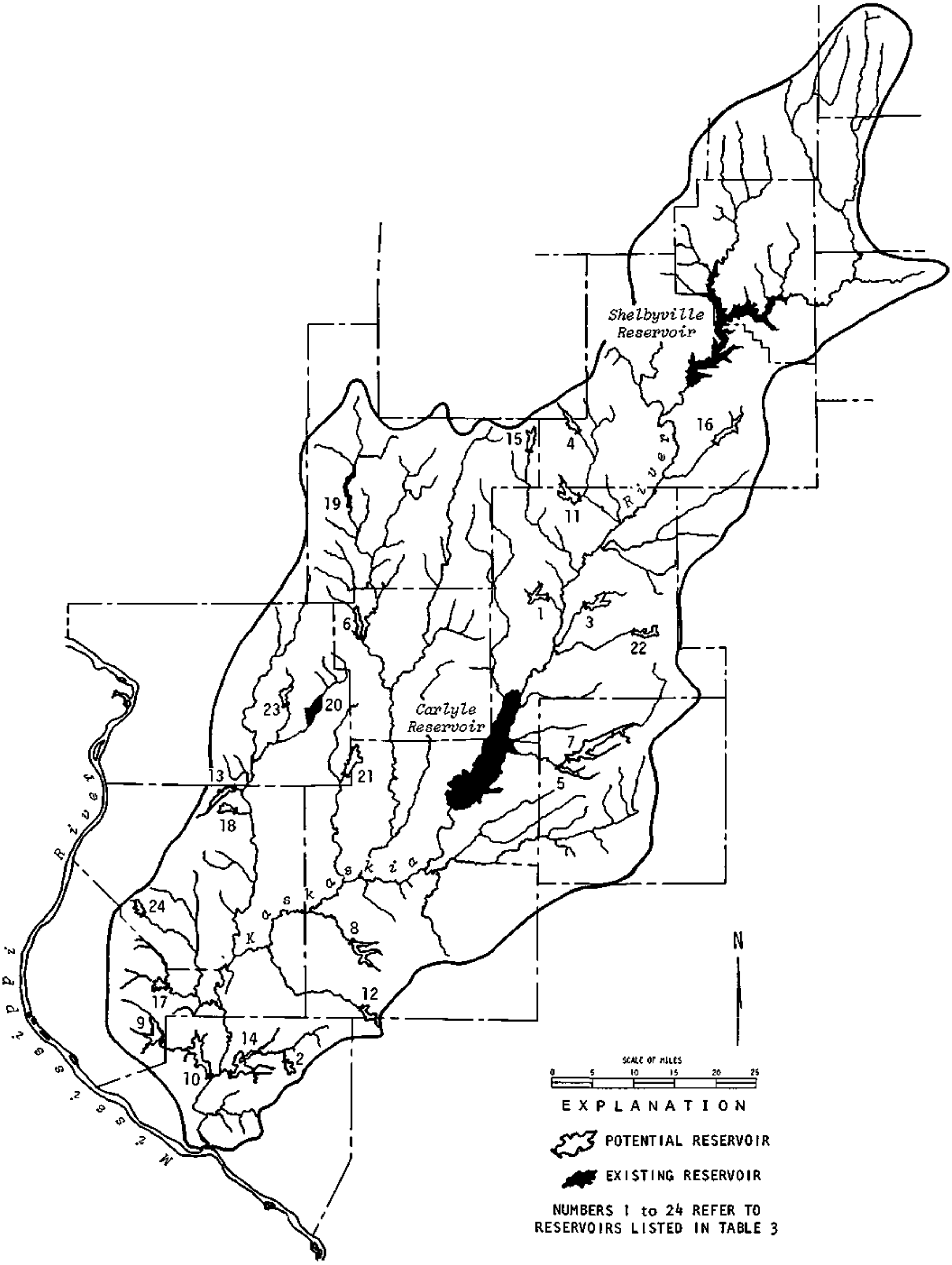


Figure 3. Reservoirs analyzed for surface water supply

Table 4. Data for Computing Reservoir Yield

p (%)	C	n	T_c (mo)
5	7.0	-0.1670	10
10	14.0	-0.0980	14
15	21.0	-0.0645	15
20	28.0	-0.0442	16
25	35.0	-0.0335	17
30	43.0	-0.0270	19
35	53.0	-0.0220	26
40	66.5	-0.0177	33
45	83.0	-0.0149	40
50	100.0	-0.0122	44
55	118.0	-0.0100	48
60	138.0	-0.0080	50
65	159.0	-0.0065	52
70	181.0	-0.0052	53
75	203.0	-0.0040	54
80	226.0	-0.0029	55
85	249.0	-0.0019	56
90	272.0	-0.0010	57
95	296.0	-0.0003	58
100	320.0	-0.0000	59

Table 5. Net Evaporation from a Lake Surface

T_c (mo)	Net evaporation (inches) Springfield	Carbondale
10	27	20
11	25	19
12	27	15
14	36	24
16	41	28
18	46	27
20	47	27
22	44	24
24	41	23
26	46	27
28	50	29
30	55	28
32	54	26
34	51	22
36	47	18
38	51	21
40	55	24
42	62	27
44	63	26
46	60	22
48	55	16
50	59	18
52	64	20
54	68	21
56	68	22
58	67	16
60	61	12

during the critical drawdown period. The relative weights for computing the weighted evaporation from the data at the two towns are included in table 3. The effective surface area for evaporation is 0.65 A_8, where A_8 denotes the pool area in acres.

Net reservoir yields in millions of gallons per day at various percent draft rates, *p*, starting from the maximum for the reservoir under consideration, are obtained by subtracting evaporation losses from the respective reservoir yields.

Cost of Raw Water. This includes the costs of reservoir. land, relocations, intake tower, and the associated *OM&R*. It is assumed that only half of the net reservoir yield can be utilized for water supply, the balance being reserved for low-flow augmentation, recreation, and other purposes. Accordingly, only one-half of the reservoir, land, relocations, and *OM&R* costs are charged to water supply. Cost of the intake tower and its *OM&R* are fully charged to water supply,

i) Reservoir Cost, *RC*. From an analysis of costs of existing reservoirs and estimated costs of some planned reservoirs (excluding the Shelbyville and Carlyle Reservoirs), a relation has been derived between reservoir cost in dollars and gross storage:

$$RC = 6250\ S_g^{0.87} \tag{12}$$

in which S_g is die gross storage in acre-feet for a given percent draft rate under consideration.

ii) Land Cost, *LC*. Reservoir storage and surface area in the Kaskaskia Basin are related[7] by

$$A_s = K\ S_g^{0.87} \tag{13}$$

in which A_8 is the pool area in acres. The constant, *K*, is evaluated from maximum values of A_8 and S_g in table 3, and is used for computing A_8 for lower values of S_g. Land cost in dollars is given by

$$LC = 1.5 \times 260\ K\ S_g^{0.87} \tag{14}$$

in which average cost of land is taken as $260 per acre including shrub and forest clearance, and the factor 1.5 indicates that the land required is 1.5 times the reservoir surface area.

iii) Relocation Cost, *RLC*. Costs are incurred for building access roads and relocating railroads, highways, and oil and gas lines. If their lengths in miles are denoted by L_a, L_r, L_h, and L_{og}, respectively, the relocation cost in dollars is obtained from

$$RLC = 80{,}000\ L_a + 200{,}000\ (L_r + L_h) + 60{,}000\ L_{og} \tag{15}$$

iv) Intake Tower Cost, *ITC*. The cost in dollars of the intake tower, *ITC*, at the reservoir is given by

$$ITC = 30{,}000 + 3000\ x \tag{16}$$

in which *x* is the water supply in mgd.

v) Investment Cost, *IWS*. The investment cost chargeable to water supply, *IWS*, in dollars then becomes

$$IWS = 0.5\ (RC + LC + RLC) + ITC \tag{17}$$

vi) *OM&R* Cost, *OMRWS*. The *OM&R* cost chargeable to water supply, *OMRWS*, in dollars is

$$OMRWS = 5000 \qquad IWS \le 10^5 \tag{18}$$

$$OMRWS = 0.05\ IWS - 0.025(IWS - 10^5) \qquad 10^5 \le IWS \le 10^6 \tag{18a}$$

$$OMRWS = 0.05\ IWS - 0.025(IWS - 10^5) - 0.01\ (IWS - 10^6) \qquad IWS > 10^6 \tag{18b}$$

Therefore, the annual cost of raw water from the reservoirs, *RWCR*, in dollars is given by

$$RWCR = IWS \times CRF + OMRWS \qquad (19)$$

in which *CRF* represents the capital recovery factor at 4, 6, or 8 percent for a 40-year period.

The computer program tabulates annual raw water cost, the water supply in millions of gallons per day, and the raw water cost in cents per 1000 gallons. This information is utilized later in the program for computing the raw water cost for the water requirements in different years and for varying sizes of the service network.

Kaskaskia River Water

Cost of raw water obtained directly from the river includes cost of the intake tower and of its *OM&R.* Cost of the intake tower, *1TC,* is the same as that for the existing and potential reservoirs. *OM&R* cost is taken as 5 percent of *ITC.* Annual raw water cost, *RWCKR,* in dollars is

$$RWCKR = ITC\ (CRF + 0.05) \qquad (20)$$

in which *CRF* denotes the capital recovery factor at 4, 6, or 8 percent interest for a 40-year period. Cost of transporting water from the intake tower to the treatment plant is included in the transmission costs.

Cost of Treatment of Raw Water

Groundwater from Drift and Shallow Bedrock Wells

The groundwater treatment includes iron removal, softening, and chlorination. The investment cost of a treatment plant,[8] *ICTPG,* in dollars is given by

$$ICTPG = 115{,}000\ Q_d^{0.63} \qquad (21)$$

in which Q_d is the design plant capacity in mgd. For purposes of this analysis, Q_d equals the average water requirement for any given year. Useful life of a treatment plant is 25 years.

Annual operation, maintenance, and repair *(OM&R)* cost[8] excluding taxes and insurance, designated as *OMRTPG,* in dollars is expressed by

$$OMRTPG = 0.05783\ ICTPG \qquad (22)$$

Equation 22 assumes *OMRTPG* as a fixed proportion of *ICTPG* for usual utilization factors or ratios of mean daily pumpage to design plant capacity. According to Koenig,[9] this proportion increases with increase in Q_d because of relatively large economies of scale in construction of treatment plants. For a utilization factor of unity, equation 22 is modified to

$$OMRTPG = 0.08069\ ICTPG\ (Q_d^{-0.02074}) \qquad (23)$$

Total annual cost of groundwater treatment, *TCTPG,* in dollars is obtained from

$$TCTPG = ICTPG \times CRF + OMRTPG \qquad (24)$$

in which *CRF* denotes the capital recovery factor.

The computer program tabulates annual treatment costs, water requirements in gallons per day and the treatment costs in cents per 1000 gallons for the years 1970, 1980, 1990, 2000, 2010, and 2020.

Surface Water from Existing and Potential Reservoirs

The surface water treatment includes chemical coagulation, sedimentation, rapid sand filtration, and chlorination. The investment cost of a treatment plant,[8] *ICTPR,* in dollars is given by

$$ICTPR = 267{,}900\ Q_d^{0.65} \qquad (25)$$

Annual *OM&R* cost, *OMRTPR,* in dollars is obtained from

$$OMRTPR = 0.08069\ ICTPR\ (Q_d^{-0.02074}) \qquad (26)$$

Total annual cost of surface water treatment, *TCTPR,* in dollars is

$$TCTPR = ICTPR \times CRF + OMRTPR \qquad (27)$$

in which *CRF* denotes the capital recovery factor.

The computer program tabulates annual treatment costs, water requirements in gallons per day, and the treatment costs in cents per 1000 gallons for the years under study.

Kaskaskia River Water

The cost of treatment of raw water from the Kaskaskia River is the same as for the surface water impounded in the reservoirs. Therefore, equations 25, 26, and 27 are used in computing the treatment costs.

Cost of Transmission of Water

In a groundwater supply system serving one town, water will be transported from the well field to the treatment plant and from there to the location of the elevated storage tank. If the system serves two or three towns, treated water has to be transported from one town to the other. The transport of water is achieved by transmission pipelines and suitable pumping stations to overcome the frictional and other head losses.

For a reservoir water supply system, the number of branches or transmission lines in the network, their diameter and length, and the size of pumping stations depend on the number of towns, their water requirements, the road distance between them, and the topography of the service area. In a river water system, water is transported from the intake tower to the location of the elevated storage tank and any other town served. Thus, it is only the size and scope of the transmission network that differs from one supply system to the other.

A computer program has been developed to calculate the minimum cost of transmission for any size network, given the water requirements for the towns served, the geometry of the network, the branch lengths, and the elevation difference between the two ends of a branch. The program optimizes each branch of the network, and prints out the amount of flow in gallons per day, the most economical diameter for the branch pipeline, the annual cost of water transmission, and the transmission cost in cents per 1000 gallons for each branch as well as for the whole network.

To keep corrosion troubles to a minimum, all pipes whether cast iron, ductile iron, or steel should have a cement lining. The useful life of these pipes is 100 years or more. The amortization period, *N*, has been taken as 50 years for computing the capital recovery factor, *CRF*, by

$$CRF = [0.01\, i\, (1 + 0.01\, i)^{N}] / [(1 + 0.01\, i)^{N} - 1] \qquad (28)$$

for interest rates, *i*, of 4, 6, and 8 percent. According to Adams,[10] the average service life of electric power pumping equipment is 36.7 years. Since most of the booster pumps in the pumping stations will be operated around the clock, a useful service life of 25 years has been used in this study.

The following cost components and functions are used in the computer program for calculating the transmission network costs.

Pipeline Construction Cost, C_1. This covers the cost of pipe, transportation, installation, valves, and other appurtenances that are integral parts of a transmission line.[22] C_1 in dollars is calculated from

$$C_1 = 2160\, D^{1.2}\, L \qquad (29)$$

in which *D* is the inside diameter of pipe in inches, and *L* is the length of branch under consideration in miles. Equation 29 applies to pipe sizes varying from 4 to 48 inches in diameter and hydraulic pressures as conventionally used in municipal water supply systems.

Pipeline Cost, C_2. This annual cost in dollars is expressed by

$$C_2 = 10\, D\, L \qquad (30)$$

The major portion of this cost is for repairing any leaks or breaks in the pipeline.

Easement Cost, C_3. The pipeline is usually laid in the right-of-way of state or county roads, highways, or rail lines. A 15-foot wide permanent easement and a total 30-foot wide construction easement are sufficient for laying pipes up to 48 inches in diameter. Easement cost in dollars is given by

$$C_3 = 1700\, L \qquad (31)$$

Pumping Station Cost, C_4. This includes the cost of pumping equipment and the station. Cost of pumping equipment depends on the horsepower of the equipment installed. The installed horsepower varies with the magnitude of water supply, the frictional and static heads, the firming or the standby factor, and the overall efficiency of the equipment at peak load.

A general study of the monthly pumpage rates indicates that the average ratios of the maximum and minimum monthly pumpage rates to the mean monthly pumpage rate over the year are 1.1 and 0.9, respectively. During a month, the daily water requirement varies from the monthly mean. The transmission system has to accommodate these variations through increased carrying capacity of a supply line supplemented by a suitable storage capacity at the supply point or town. The pipeline is designed to carry a maximum of 1.5 times the average water requirement, *Q*, for the year. Thus, the maximum head, *H*, for the pumping station is

$$H = H_f + H_s \qquad (32)$$

$$H = H_0\, (1.5)^2 + H_s \qquad (32a)$$

$$H = 2.25\, H_0 + H_s \qquad (32b)$$

in which H_f represents the friction head for the varying flow rate, H_0 is 1.05 times the frictional head loss (based on Colebrook and White equation) for the water requirement, *Q*, in gallons per day (the multiplier 1.05 allows for the losses in bends, etc.), and H_8 denotes the static head or the difference in elevation at the end and beginning of the network branch under consideration. If $H \leq 0$, the flow is by gravity and no pump station is required.

Installed horsepower at the pumping station, P_i, is calculated from

$$P_i = 0.2634\, Q\, H\, J/E \qquad (33)$$

in which *E* is the overall efficiency at peak load, and / is the firming factor or the standby factor. The value of / is obtained[12] from

$$\begin{array}{rl} x \leq 2.0 & J = 2.08 - 0.18\,x;\ J \leq 2.0 \\ 2.0 < x \leq 5.0 & J = 1.9666 - 0.1233\,x \\ 5.0 < x \leq 10.0 & J = 1.42 - 0.014\,x \\ 10.0 < x \leq 20.0 & J = 1.30 - 0.002\,x \end{array} \qquad (34)$$

in which *x* equals *Q* divided by 10^6, or the flow in mgd.

It is assumed that a pumping station will boost the pressure a maximum of 300 feet of water. If the total head, *H*, exceeds this limit, two or more pumping stations will be needed. The cost of pumping stations, C_4, in dollars is expressed by

$$C_4 = 17{,}000(H/300) + 135\, [nP_s^{1.01} - (P_i - nP_s)^{1.01}] \qquad (35)$$

in which n equals the integer part of the ratio *H*/300 and P_8 refers to the installed horsepower when *H* is 300 feet in equation 33.

Pumping Cost, C_5. The cost of energy depends on the horsepower actually expended at the actual pumping rate. With varying flow rate during the year, the pumping cost varies from day to day and must be "integrated" over the year to obtain the annual pumping cost. The varying flow rate is simulated by *Q* (1 + 0.5 sin *9)*, where *9* varies from 0 to 2Π, and the minor variation in the friction factor is neglected. The pumping under these conditions is considered for the following four situations:

$(H_f)_{min} + H_s \geq 0$ (figure 4a)
$(H_f)_{min} + H_s < 0;\ H_0 + H_s \geq 0$ (figure 4b)
$(H_f)_{max} + H_s > 0;\ H_0 + H_s < 0$ (figure 4c)
$(H_f)_{max} + H_s \leq 0$ (figure 4d)

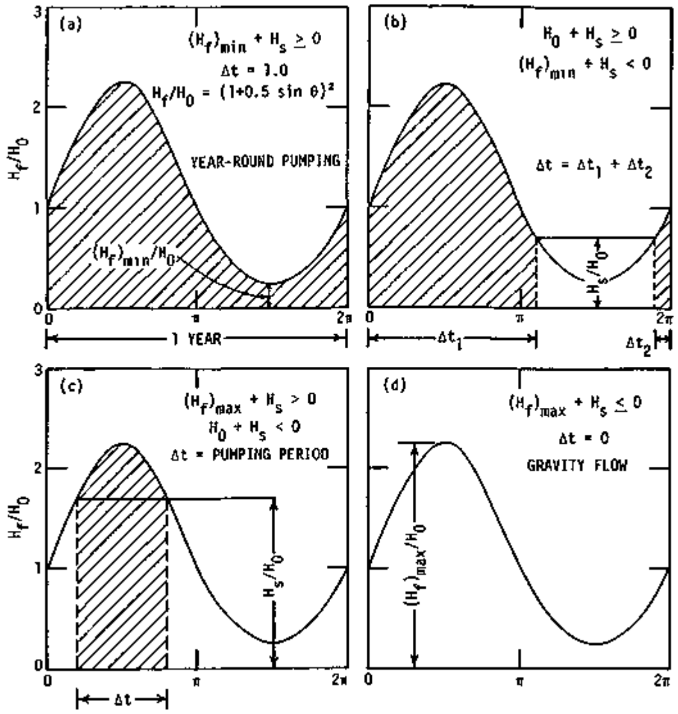


Figure 4. Types of pumping situations

The ratio of energy consumption for varying flow to that for the constant flow is denoted by E/E_0, and the subscripts f and s are used for energy consumption due to frictional and static heads, respectively. These energy ratios in respect to the frictional and static heads are evaluated by carrying the integration over the pumping period and are given by

$$(E/E_0)_f = p_f = \int QH_0 (1 + 0.5 \sin \theta)^3 \, d\theta / \int QH_0 \, d\theta$$

and (36)

$$(E/E_0)_s = p_s = \int QH_s (1 + 0.5 \sin \theta) \, d\theta / \int QH_s \, d\theta$$

The conversion factor for converting product of Q and H_0 or of Q, and H_s to yearly energy consumption in kwh is denoted by k and is expressed as

$$k = (0.1337 \times 365.24 \times 62.4 \times 0.7457) / (550 \times 3600 \times E_a) \qquad (37)$$

Average overall efficiency during the pumping period is denoted by E_a. Total energy consumption in terms of kwh per year is computed by multiplying the energy ratios, p_f and p_s, with their respective constant-Q energy consumptions. Thus, the total energy consumption in kwh per year is given by

$$\text{Total kwh per year} = k \, Q \, (p_f H_0 + p_s H_s) \qquad (38)$$

The kwh per year amounts are converted to annual pumping cost, C_5, by use of the present rate schedule of the Illinois Power Company:

For the first	1,000 kwh/month	3.0¢/kwh
For the next	4,000 kwh/month	2.0¢/kwh
For the next	20,000 kwh/month	1.5¢/kwh
For all over	25,000 kwh/month	1.0¢/kwh

Pumping Station OM&R Cost, C_6. The cost includes oiling, painting, routine checking, servicing, and repairs to or renewal of worn-out parts. By the use of data from Koenig,[12] C_6 in dollars is approximated by

$$C_6 = 850 \, P_i' + 8 \, [nP_s'^{1.05} + (P_i' - nP_s')^{1.05}] \, \Delta t \qquad (39)$$

in which $P_i' = P_i \times 0.85/J$; $P_s' = P_s \times 0.85/J$; Δt = pumping period as a fraction of the year; and multiplier 0.85 converts the installed horsepower to firm wire horsepower.

The total annual cost of transmission for any branch, *TCT,* is

$$TCT = (C_1 + C_3) \, (CRF)_{50} + C_4 \, (CRF)_{25} + C_2 + C_5 + C_6 \qquad (40)$$

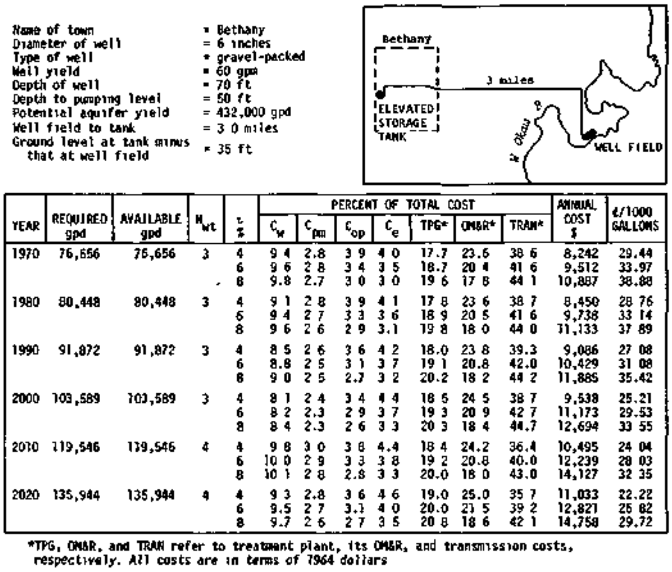
in which subscripts 50 and 25 refer to the amortization period in years for the pipeline and pumping station, respectively. The total for the entire network is obtained by summing up *the* individual costs of all the branches in the network.

ADEQUACY AND COST OF WATER SUPPLY SYSTEMS

Groundwater Supply Systems

The three computer programs for the three cost elements have been merged to compute the cost of treated groundwater delivered at the location of the elevated storage tank. A sample of the computer output for Bethany is given in figure 5. Groundwater costs for all the towns have been calculated for interest rate, *i,* of 4, 6, and 8 percent for the years 1970, 1980, 1990, 2000, 2010, and 2020. These costs are listed in table 6 for i = 6 percent. The cost figures are marked by an asterisk when the available water supply (i.e., two-thirds of the potential aquifer yield) is inadequate to meet the water requirement. Because the cost remains the same in subsequent years for this limited supply, the cost figures are not repeated in the succeeding columns. The overall multiplying factors for obtaining costs at 4 and 8 percent interest rate from those in table 6 are 0.874 and 1.136, respectively.

This study shows that the potential groundwater supply is adequate to meet the water requirements at 50 towns (including Donnellson and Troy for which the deficit in the year 2020 is less than 1 percent). However, the cost of groundwater varies widely, depending on the distance of the well field from the elevated storage tank, the static head, the well yield, the depth of well, and the pumping level. Figure 6 indicates the variation in water cost with water



Name of town = Bethany
Diameter of well = 6 inches
Type of well = gravel-packed
Well yield = 60 gpm
Depth of well = 70 ft
Depth to pumping level = 50 ft
Potential aquifer yield = 432,000 gpd
Well field to tank = 3 0 miles
Ground level at tank minus that at well field = 35 ft

YEAR	REQUIRED gpd	AVAILABLE gpd	N_{wt}	i %	PERCENT OF TOTAL COST C_w	C_{pm}	C_{op}	C_e	TPG*	OM&R*	TRAN*	ANNUAL COST $	¢/1000 GALLONS
1970	76,656	76,656	3	4	9 4	2.8	3 9	4 0	17.7	23.6	38 6	8,242	29.44
				6	9 6	2 8	3 4	3 5	18.7	20 4	41 6	9,512	33.97
				8	9.8	2.7	3 0	3 0	19 6	17 8	44 1	10,887	38.88
1980	80,448	80,448	3	4	9 1	2 8	3 9	4 1	17 8	23 6	38 7	8,450	28 76
				6	9 4	2 7	3 3	3 6	18 9	20 5	41 6	9,738	33 14
				8	9 6	2 6	2 9	3.1	19 8	18 0	44 0	11,133	37 89
1990	91,872	91,872	3	4	8 5	2 6	3 6	4 2	18.0	23 8	39.3	9,086	27 08
				6	8.8	2 5	3 1	3 7	19 1	20.8	42.0	10,429	31 08
				8	9 0	2 5	2.7	3 2	20.2	18 2	44 2	11,885	35.42
2000	103,589	103,589	3	4	8 1	2 4	3 4	4 4	18 5	24 5	38 7	9,538	25.21
				6	8 2	2.3	2 9	3 7	19 3	20 9	42 7	11,173	29.53
				8	8 4	2.3	2 6	3 3	20 3	18 4	44.7	12,694	33 55
2010	119,546	119,546	4	4	9 8	3 0	3 8	4.4	18 4	24.2	36.4	10,495	24 04
				6	10 0	2 9	3 3	3 8	19 2	20.8	40.0	12,239	28 03
				8	10 1	2 8	2.8	3 3	20.0	18 0	43.0	14,127	32 35
2020	135,944	135,944	4	4	9 3	2.8	3 6	4 6	19.0	25.0	35 7	11,033	22.22
				6	9.5	2 7	3.1	4 0	20.0	21 5	39 2	12,821	26 82
				8	9.7	2 6	2 7	3 5	20 8	18 6	42 1	14,758	29.72

*TPG, OM&R, and TRAN refer to treatment plant, its OM&R, and transmission costs, respectively. All costs are in terms of 1964 dollars

Figure 5. Typical computer results for a groundwater supply system

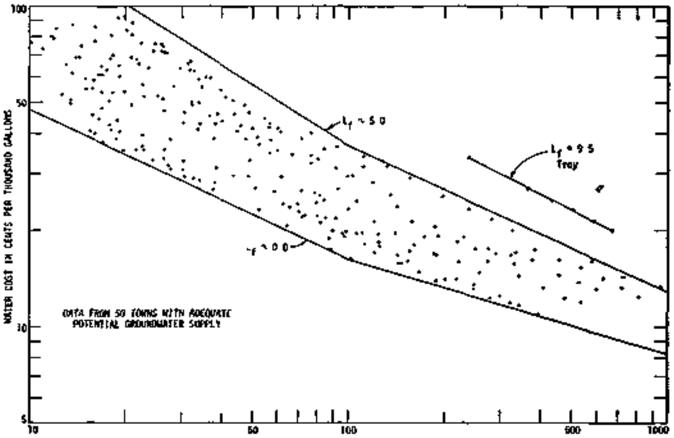


Figure 6. Variation in cost of groundwater

Table 6. Cost of Groundwater Supply Systems

(Costs in 1964 dollars, i = 6 percent)

(Cost in cents per 1000 gallons)

Town	1970	1980	1990	2000	2010	2020
Addicville	104 45	100 71	81 28	77.38	70 69	62.44
Albcrs	29.06†					
Alhambra	51 98	42 58	38 55	35.64	33 42	31.18
Alma	54 99	54.99	54 99	58 76	53 19	48 72
Arthur	21.30	19.15	18 39	17 75	16 81	15.59
Atwood	18 98	16 00	14 32	13.09	12.25	11 93
Aviston	25 43	21 28	18 72	16 90	16 09†	
Baldwin	100.49	100 49	83 71	72.09	62 75	55 86
Bartelso	38 02	31.12	29 50	26 34	24 08	22 36
Beckemeyer	73.78†					
Beecher City	77.98	74.49	62 73	54 68	49.05	44 81
Bement	15 94	13.98	13 60	12 43	11 57	10 88
Bethany	33 97	33 14	31 08	29 53	28 03	25 82
Breese	73 78†					
Brownstown	41 20†					
Butler	109 01	109 01	101 21	88 09	77 93	70 04
Carlyle	52 63†					
Central City	38 00†					
Centraha	35.36†					
Cerro Gordo	18 49	18 03†				
Coffeen	69 47	69 47	69 47	69 47	69 47	63 86
Coulterville	204 18†					
Cowden	41 16	38 48	32 87	29 10	26 55	24 56
Dalton City	65.11	65 11	63 35	51 77	46 89	43 01
Donnellson	85 23	85 23	85 23	74.49	66 27	60 20†
Ellis Grove	181 99	181 99	178 12	150 93	129 60	113 74
Evansville	42 84	40.78	40 04	36 16	33 86	31.65
Farina	40 22	37 90	37 41†			
Fayetteville	44 38	40 20	36 26	33 19	30 70	28 66
Fillmore	48.03	48 03	44 14	39 47	35 85	32 98
Findlay	25 07	21 82	19 00	17.03	15 65	14 57
Freeburg	34 06†					
Gays	77 03	77 03	76 11	61 30	55 45	50 78
Germantown	21 73	19.49	17 17	16 69	15 79	14 66
Greenville	10 72	10.44†				
Hamel	57.89	46.53	41 48	37 72	37 35 †	
Hammond	27.80	23 10	20 64	18 80	17 47	16 38
Hecker	68 22†					
Herrick	93.24	93 24	89 32	75 56	66 46	59 60
Highland	32.11†					
Hillsboro*	30.69t					
Hoffman	92 80	70.53	59 33	51 67	46 29	42 27
Hoyleton	99 72†					
Huey	49 53	41 06	35 62	31 72	28 86	26 61
Irving	53 92†					
Irvington	75.33†					
Ivesdale	40 58	40 58	40 58	40 12	37 44	35 18
Junction City	52 67	52 67	52 67	50.29	45 88	42 32
Keyesport	39.41†					
Kinmundy	43,37†					
Lebanon	14.36†					
Lenzburg	106 47†					
Litchfield	35.51†					
Livingston	24 21	23 39	21 08	19 32	17 84	16 67
Lovington	22 75	22 75	22.14	19 44	19 56	18 23
Manne	28 19	26.29†				
Marissa*	232 46†					
Mascoutah	17.38	16.01	15 31	14 10	13 17	12 47
Millstadt	38.32†					
Mulberry Grove	47.94†					
Nashville	87.99†					
New Athens	20.59	18 62	18 24†			
New Baden	33 02	29 14	25 52	23 31	21.74	19 90
New Douglas	52 01	49 06	43 26	40 89	36 97	35 41
New Minden	104 37	85 57	80 46	72 25	66 33	58 77
Nokomis*	13 09†					
Oconee	78.76†					
Odin	44 24†					
Okawville	29.40	23 66	20 34	18 82	17 36	16.62
Panama	48.63†					
Patoka	49.88	49 88	45 35	45.73	41 59	38 32
Pierron	84 28	77.71	72.35†			
Pocahontas	43.53	43 53	38 67	34 93	34.56	31 77
Ramsey	27 35	23 75	20 85	18 88†		
Raymond	23 65	21.92	20 01	19 50	17 90	16 61
Red Bud	32 85†					
Ruma	113.69	94 23	79.45	69 07	60 43	54 31
Sadorus	38 67	38 67	35 56	33 04	30 96	29 20
Salem	44 52†					
Sandoval	26 10	26.10	26 10	25 65	26 73	24 81
St. Elmo	45 88†					
St Jacob	56 80†					
St. Libory	68 28	64 45	56 84	51 05	46 46	42.77
St. Peter	69 68†					
Shelbyville	16 02	14 29	13 14	11 98	11 13	10 44
Smithton	53 81†					
Sorento	68 25†					
Sparta	57 46†					
Stewardson	29 57	27 01	23 49	21 15	19.62	18 15
Strasburg	68 07	57 60	48 48	42 73	41.31†	
Sullivan	16 95	16 95	15 93	14 44	13 59	13 09
Summerfield	98 98†					
Tilden	185 99†					
Tolono	15 65	13 92	14 05	13 17	12 43	11 81
Tower Hill	66.44†					
Trenton	38 23†					
Troy	33 24	26 78	24 42	22 90	21 32	19 93†
Vandalia	14 03†					
Venedy	108 86	108 86	93 91	78 94	68 72	61 09
Vernon	79 63	79 63	73 62	65 22	59 07	54 12
Wamac	106 26†					
Waterloo	38 20†					
Williamson	68 65	56 34	49 63	46 73	42.22	38.74
Windsor	23 91	23.22	21.24†			
Witt	25.04	25.04	24 67†			
Worden	33 67	28 21	27.72†			
Belleville	31.87†					
Humboldt	49 02†					
O'Fallon	36 17†					
Shiloh	44 94†					
Swansea	32 4 †					

** Hillsboro supplies water to Schram City and Taylor Springs; Marissa supplies Old Marissa; and Nokomis supplies Coalton.*

† Cost is given for the available water supply (i.e., two-thirds of the potential aquifer yield) when it is inadequate to meet the water requirement.

requirement, Q. If the potential aquifer yield is adequate and the well and other parameters remain the same, the water cost decreases with increase in Q. The lower curve for $L_f \sim 0.0$ (i.e., when the distance from the well field to the elevated storage tank is negligible) yields the minimum cost of groundwater from drift wells with yields of 100 gpm or more. The curve is steeper for Q less than 100,000 gpd because of proportionately greater standby allowance for wells in a small well field and other factors. The upper curve for $Lf \sim 5.0$ has the same trend as the lower one, but it is relatively steeper. The spread between the two curves increases for lower values of Q because of smaller yields and large depths of bedrock wells. The cost curve for Troy indicates the relative increase in cost when L_f equals 9.5 miles.

This study shows that 1) 50 towns have adequate groundwater potential, 2) 48 towns do not have adequate groundwater supply to meet even the 1970 requirement, and 3) 13 towns will run out of groundwater supply in the next 40 years. The 50 towns with potential groundwater supply sufficient to meet the water requirements in the year 2020 are shown as full dots in figure 7. The remaining towns are shown by open circles and are labeled by the year in which the water requirement cannot be met for the first time.

Surface Water Supply Systems

The three computer programs for the cost elements — cost of production of raw water, cost of treatment of raw water, and cost of transmission of treated water to the location of the elevated storage tanks — have been combined to compute the cost of a surface water supply system. Two types of surface water sources, reservoirs (existing and potential) and the Kaskaskia River, have been considered.

Table 3 lists 24 existing and potential reservoirs excluding the Shelbyville and Carlyle Reservoirs. The number of towns that can be served by any one of these reservoirs depends on the available supply from the reservoir, the water requirements of the towns to be served, and physical factors affecting the cost of transmission network. This involves optimizing the sum of three costs (designated as reservoir, treatment, and transmission costs) for a minimum cost system. Further, a town with adequate groundwater supply is included in a surface water supply system if the cost of the groundwater supply is greater than the increase in cost of the surface water system when that town is added to it. Surface water from the Kaskaskia River has been considered only in respect to towns already using it; these towns are Carlyle which supplies Beckemeyer, New Athens which supplies Lenzburg, and Evansville which supplies Ellis Grove.

A comprehensive use-analysis of potential surface water supplies from the 24 reservoirs listed in table 3 involved about 300 different network sizes and configurations. The most economical surface water supply systems are given in table 7, together with the water requirements and the water costs for i = 6 percent.

Table 7. Economical Surface Water Supply Systems

(Costs in 1964 dollars, i = 6 percent)

Supply system	1970	1980	1990	2000	2010	2020
1 East Fork Kaskaskia River Reservoir						
Cost in ¢/1000 gallons	33 69	31 50	28 56	26 27	24 55	23 10
Water supply in 1000 gpd	4964	5723	6983	8349	9698	11085
2 Plum Greek Reservoir						
Cost in ¢/1000 gallons	50 30	44 15	40 08	36 89	34 11	31.93
Water supply in 1000 gpd	1831	2360	2861	3392	3990	4607
3 Rock Spring Branch Reservoir						
Cost in ¢/1000 gallons	53 70	46 34	42 76	39 46	36 88	34 90
Water supply in 1000 gpd	345	448	528	612	701	792
4 Shoal Creek Reservoir No. 4						
Cost in ¢/1000 gallons	35 67	35 03	31 76	29 09	27 10	25 35
Water supply in 1000 gpd	1900	1998	2441	2911	3401	3905
5 Silver Lake						
Cost in ¢/1000 gallons	39 71	35 26	32 35	29 88	27 87	26 12
Water supply in 1000 gpd	909	1148	1371	1601	1860	2126
6 Spanker Branch Reservoir						
Cost in ¢/1000 gallons	53 66	46 84	41 38	37 32	34 52	31 98
Water supply in 1000 gpd	548	693	873	1061	1249	1440
Carlyle Reservoir System						
Cost in ¢/1000 gallons	40 56	37 60	34 62	32 33	30 54	28 99
Water supply in 1000 gpd	9018	10874	13245	15778	18394	21087
Carlyle-Beckemeyer System						
Cost in 6/1000 gallons	24 03	22 52	20 19	18 44	17 15	16 12
Water supply in 1000 gpd	371	435	547	665	784	906
New Athens-Lenzburg System						
Cost in¢/1000 gallons	32 94	29 83	27 32	25 28	23 61	22 24
Water supply in 1000 gpd	201	241	285	330	378	427

Note: ***Reservoir numbers refer to figure 9.***

Surface water supply from the Kaskaskia River was found to be economical for the Carlyle-Beckemeyer and New Athens-Lenzburg systems, but not for Evansville and Ellis Grove which can obtain groundwater more economically. For the five towns now dependent on water supply sources located outside the basin, those outside sources were found to be most economical for meeting the future requirements. Keyesport, located on the northwest shore of Carlyle Reservoir, was found to be most economically served by an independent system using reservoir water, because of its distance from other towns on the Carlyle Reservoir system. The remaining 105 towns are served economically either by groundwater or by surface water supply systems. Part of the computer output with respect to the Spanker Branch Reservoir water supply system is shown in figure 8.

Analysis of the Shelbyville and Carlyle Reservoir water supply systems shows that water supply from the Shelbyville Reservoir is not economical because the reservoir is located in the northern part of the basin where groundwater supply is adequate and more economical. Towns to the south of the reservoir not only are widely spaced requiring long transmission lines but also have relatively smaller water requirements. However, the reserve storage in the Shelbyville Reservoir will be available to meet the water requirements of new industries, expanded rural needs, and irrigation. Requirements for these uses cannot be predicted by the method used in this study.

All towns with inadequate groundwater supplies could be served by the Carlyle Reservoir water supply system alone, but it is more economical to use the Carlyle system in conjunction with Shoal Creek Reservoir No. 4. The details of the Carlyle system with this division of supplies are given in table 7. Foreseeable rural water supply needs also can be met by the Carlyle system; this would be done by in-

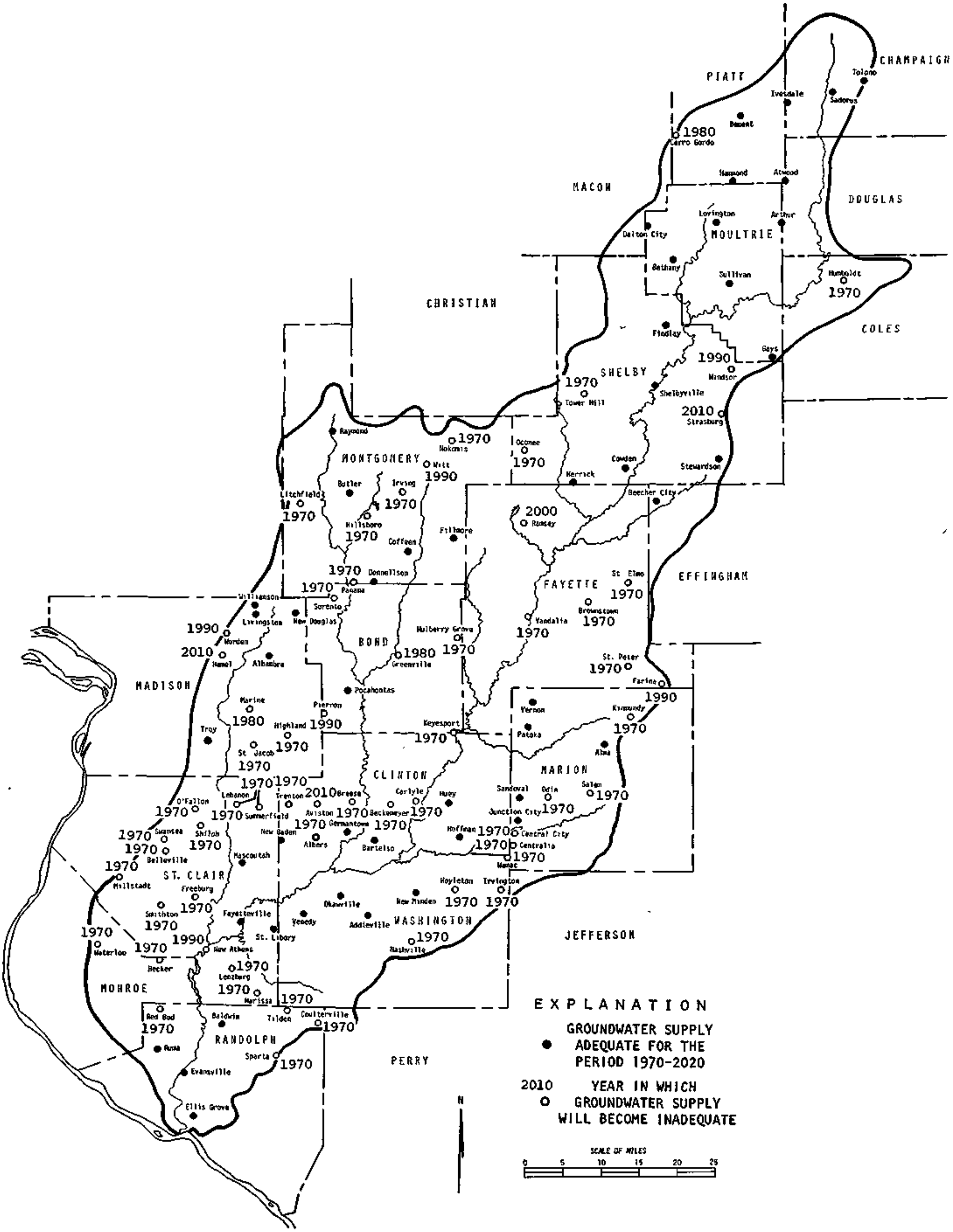
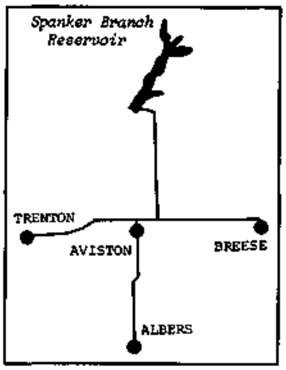


Figure 7. Adequacy of groundwater supply for water requirements through 2020

Gross reservoir capacity = 8000.0 ac-ft
Max. water surface area = 800.0 acres
Drainage area = 14.5 sq mi
Average streamflow = 0.64 cfs/sq mi
Weights for evaporation:
Springfield = 0.46
Carbondale = 0.54
Length of access road = 1.0 mi
Railroad relocation = 0.0 mi
Highway relocation = 0.0 mi
Oil & gas line relocation = 0.0 mi

40-year silt load = 382.98 ac-ft
Evaporation from reservoir = 0.330 mgd
Average inflow = 5.995 mgd
Gross reservoir yield = 3.271 mgd
Net reservoir yield = 2.941 mgd
Maximum available water for supply = 1.470 mgd



YEAR	REQUIRED gpd	i %	CENTS PER THOUSAND GALLONS				ANNUAL COST $
			RES*	TRT*	TRAN*	TOTAL	
1970	547,732	4	17.06	13.20	14.30	44.56	89,133
		6	20.79	14.48	18.39	53.66	107,351
		8	24.83	15.88	22.67	63.38	126,793
1980	692,999	4	14.46	12.12	12.46	39.04	98,806
		6	17.64	13.30	15.90	46.84	118,553
		8	21.08	14.59	19.63	55.30	139,959
1990	872,930	4	12.22	11.15	11.06	34.43	109,784
		6	14.93	12.24	14.21	41.38	131,940
		8	17.85	13.43	17.35	48.63	155,054
2000	1,060,691	4	10.76	10.39	10.08	31.23	120,995
		6	13.15	11.41	12.75	37.31	144,562
		8	15.74	12.52	15.64	43.90	170,068
2010	1,249,388	4	9.83	9.79	9.16	28.78	131,338
		6	12.03	10.76	11.73	34.52	157,516
		8	14.40	11.81	14.40	40.61	185,298
2020	1,444,019	4	8.98	9.29	8.46	26.73	140,987
		6	10.99	10.21	10.78	31.98	168,646
		8	13.16	11.21	13.29	37.66	198,595

*RES, TRT, and TRAN refer to reservoir, treatment plant and its OM&R, and transmission costs, respectively. All costs are in terms of 1964 dollars.

Figure 8. Typical computer results for a surface water supply system

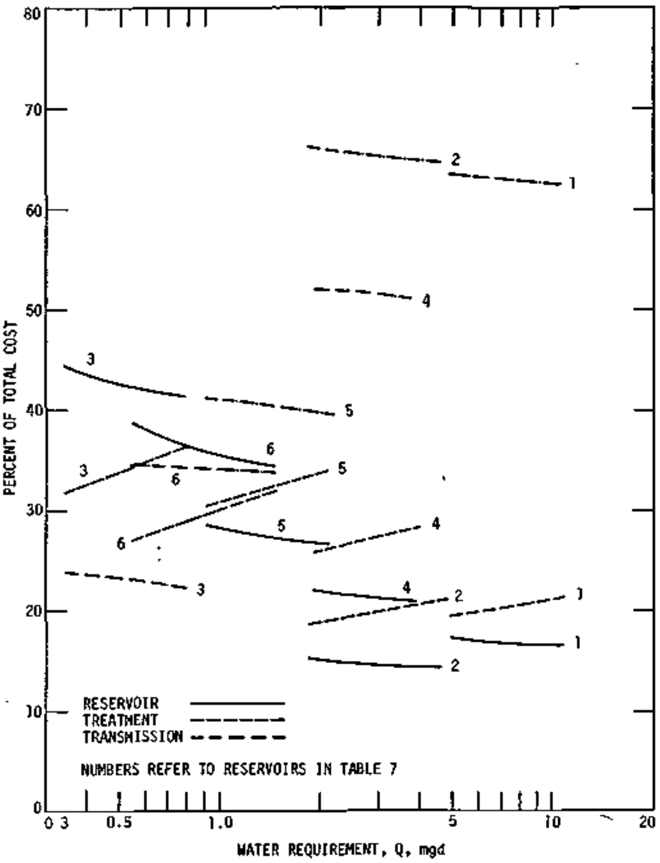


Figure 9. Cost components of reservoir water supply systems

creasing the capacity of the transmission network and supplying water to the farm communities by suitable community lines and laterals.

Costs of reservoir, treatment, and transmission as a percentage of total costs *(i* = 6 percent) are plotted in figure 9 for the six reservoirs listed in table 7. It is evident that the percent cost decreases with increase in water requirement for the reservoir and for treatment, but it increases for transmission. Some differences in position of the curves are caused by location and water requirement of towns served in relation to the location of reservoirs.

The towns served by the various surface water systems would be:

East Fork Kaskaskia River Reservoir. Alma, Brownstown, Central City, Centralia, Farina, Greenville, Hoyleton, Irvington, Junction City, Kinmundy, Mulberry Grove, Nashville, New Minden, Odin, Patoka, St. Elmo, St. Peter, Salem, Sandoval, Vandalia, Vernon, and Wamac (22 towns).

Plum Creek Reservoir. Baldwin, Coulterville, Freeburg, Hecker, Marissa, Millstadt, Red Bud, Smithton, Sparta, Tilden, and Waterloo (11 towns).

Rock Spring Branch Reservoir. Summerfield and Lebanon (2 towns).

Shoal Creek Reservoir No. 4. Butler, Donnellson, Hillsboro, Irving, Litchfield, Nokomis, Oconee, Panama, Ramsey, Sorento, Tower Hill, and Witt (12 towns).

Silver Lake. Alhambra, Hamel, Highland, Marine, Pierron, St. Jacob, and Worden (7 towns).

Spanker Branch Reservoir. Albers, Aviston, Breese, and Trenton (4 towns).

Carlyle Reservoir System. Albers, Alhambra, Alma, Aviston, Beckemeyer, Breese, Brownstown, Carlyle, Central City, Centralia, Coulterville, Farina, Fayetteville, Freeburg, Greenville, Hamel, Hecker, Highland, Hoffman, Hoyleton, Huey, Irvington, Junction City, Kinmundy, Lebanon, Marine, Marissa, Millstadt, Mulberry Grove, Nashville, New Minden, Odin, Patoka, Pierron, Red Bud, St. Elmo, St. Jacob, St. Libory, St. Peter, Salem, Sandoval, Smithton, Sparta, Summerfield, Tilden, Trenton, Vandalia, Vernon, Wamac, Waterloo, and Worden (51 towns).

TWO PLANS FOR BASIN WATER SUPPLY

Two plans for meeting the full water requirements of 105 towns in the Kaskaskia River Basin from 1970 through 2020 have been finalized, using the most economical combination of groundwater and surface water supply systems. The five towns (Belleville, Humboldt, O'Fallon, Shiloh, and Swansea) which receive their water supply from outside the basin are not included in these plans. Keyesport can have its independent water supply from the Carlyle Reservoir.

Plan 1

According to this plan shown in figure 10, the six reservoirs in table 7 will serve 58 towns, the two river systems will serve 4 towns, and the remaining 43 towns will be served by groundwater systems. Of the latter, 36 towns will have independent systems and 7 towns will be served by single systems combining two or three towns. In the *Bement-Cerro Gordo* and *Livingston-Williamson* groundwater systems, Bement and Livingston will fully supply the water requirements at Cerro Gordo and Williamson, respectively. The *Shelbyville* groundwater system will supply Shelbyville, Strasburg, and Windsor from Shelbyville well fields up to the year 2010 but the water supplies at Strasburg and Windsor will be augmented from local groundwater sources in the year 2020.

Total costs and water supplies for Plan 1 are listed in table 8 for *i* = 4, 6, and 8 percent for the years 1970, 1980, 1990, 2000, 2010, and 2020. There are 43 towns on the groundwater systems and 62 towns on the surface water systems. The groundwater supply is about 25 percent of the total water supply, but the cost of groundwater supply is about 19 percent of the total cost.

Plan 2

This plan shown in figure 11 includes only two reservoirs — Shoal Creek Reservoir No. 4 (which is also included in Plan 1) and Carlyle Reservoir. The number of towns served by groundwater supply systems reduces to 40 because Huey, Hoffman, Fayetteville, and St. Libory are served more cheaply from the Carlyle Reservoir while the groundwater supply becomes cheaper for Baldwin. Only two towns, New Athens and Lenzburg, would use Kaskaskia River water since Carlyle and Beckemeyer are served economically by the Carlyle Reservoir because of their proximity to the reservoir site. Thus, this plan has 63 towns on the reservoir systems— 12 of them on the Shoal Creek Reservoir No. 4 and 51 on the Carlyle Reservoir.

Total costs and water supplies for Plan 2 are given in table 9 for the three rates of interest and the six years of reference. A comparison of costs in tables 8 and 9 shows that the Plan 2 costs exceed those of Plan 1 by 9.1, 7.5, and 6.1 percent for interest rates of 4, 6, and 8 percent, respectively, in the year 2020. The percent increases are only 2.7, 2.0, and 1.2 for the year 1970. If the Carlyle raw water sale rate was reduced from 5¢ to 3¢ per 1000 gallons, Plan 2 would be more economical than Plan 1.

Table 8. Basin Water Supply Plan 1

(Costs in 1964 dollars)

Supply system	Number of towns	1970	1980	1990	2000	2010	2020
At 4 percent interest			*Annual cost in 1000 dollars*				
Groundwater systems							
Independent	36	234	256	280	307	331	355
Others	7	78	86	96	107	117	125
Surface water systems							
Reservoirs	58	1233	1347	1487	1629	1769	1905
River	4	50	55	61	67	72	78
Total	105	1595	1744	1924	2110	2289	2463
At 6 percent interest							
Groundwater systems							
Independent	36	271	296	323	353	382	408
Others	7	93	102	114	126	137	146
Surface water systems							
Reservoirs	58	1502	1637	1807	1975	2145	2307
River	4	57	62	69	75	82	88
Total	105	1923	2097	2313	2529	2746	2949
At 8 percent interest							
Groundwater systems'							
Independent	36	311	340	369	402	435	465
Others	7	108	120	133	146	159	168
Surface water systems							
Reservoirs	58	1790	1945	2147	2344	2542	2735
River	4	64	70	78	85	92	99
Total	105	2273	2475	2727	2977	3228	3467
Requirements			*Water. supply in 1000 gallons per day*				
Groundwater systems							
Independent	36	2543	3120	3729	4434	5147	5879
Others	7	1035	1297	1645	2009	2363	2728
Surface water systems							
Reservoirs	58	10497	12370	15057	17927	20898	23959
River	4	572	676	832	995	1162	1333
Total	105	14647	17463	21263	25365	29570	33899

Note: *See figure 10 for map of Plan 1.*

Table 9. Basin Water Supply Plan 2

(Costs in 1964 dollars)

Supply system	Number of towns	1970	1980	1990	2000	2010	2020
At 4 percent interest			*Annual cost in 1000 dollars*				
Groundwater systems							
Independent	33	225	247	270	296	320	343
Others	7	78	86	96	107	117	125
Surface water systems							
Reservoirs	63	1314	1458	1641	1826	2011	2189
River	2	21	23	25	27	29	31
Total	105	1638	1814	2032	2256	2477	2688
At 6 percent interest							
Groundwater systems							
Independent	33	261	285	311	340	368	394
Others	7	93	102	114	126	137	146
Surface water systems							
Reservoirs	63	1583	1749	1958	2172	2388	2594
River	2	24	26	28	31	33	35
Total	105	1961	2162	2411	2669	2926	3169
At 8 percent interest							
Groundwater systems							
Independent	33	299	327	356	387	420	449
Others	7	108	120	133	146	159	168
Surface water systems							
Reservoirs	63	1867	2057	2296	2542	2785	3024
River	2	27	30	32	34	37	39
Total	105	2301	2534	2817	3109	3401	3680
Requirements			*Water supply in 1000 gallons per day*				
Groundwater systems							
Independent	33	2492	3053	3647	4336	5035	5752
Others	7	1035	1297	1645	2009	2363	2728
Surface water systems							
Reservoirs	63	10919	12872	15686	18690	21794	24992
River	2	201	241	285	330	378	427
Total	105	14647	17463	21263	25365	29570	33899

Note: *See figure 11 for map of Plan 2.*

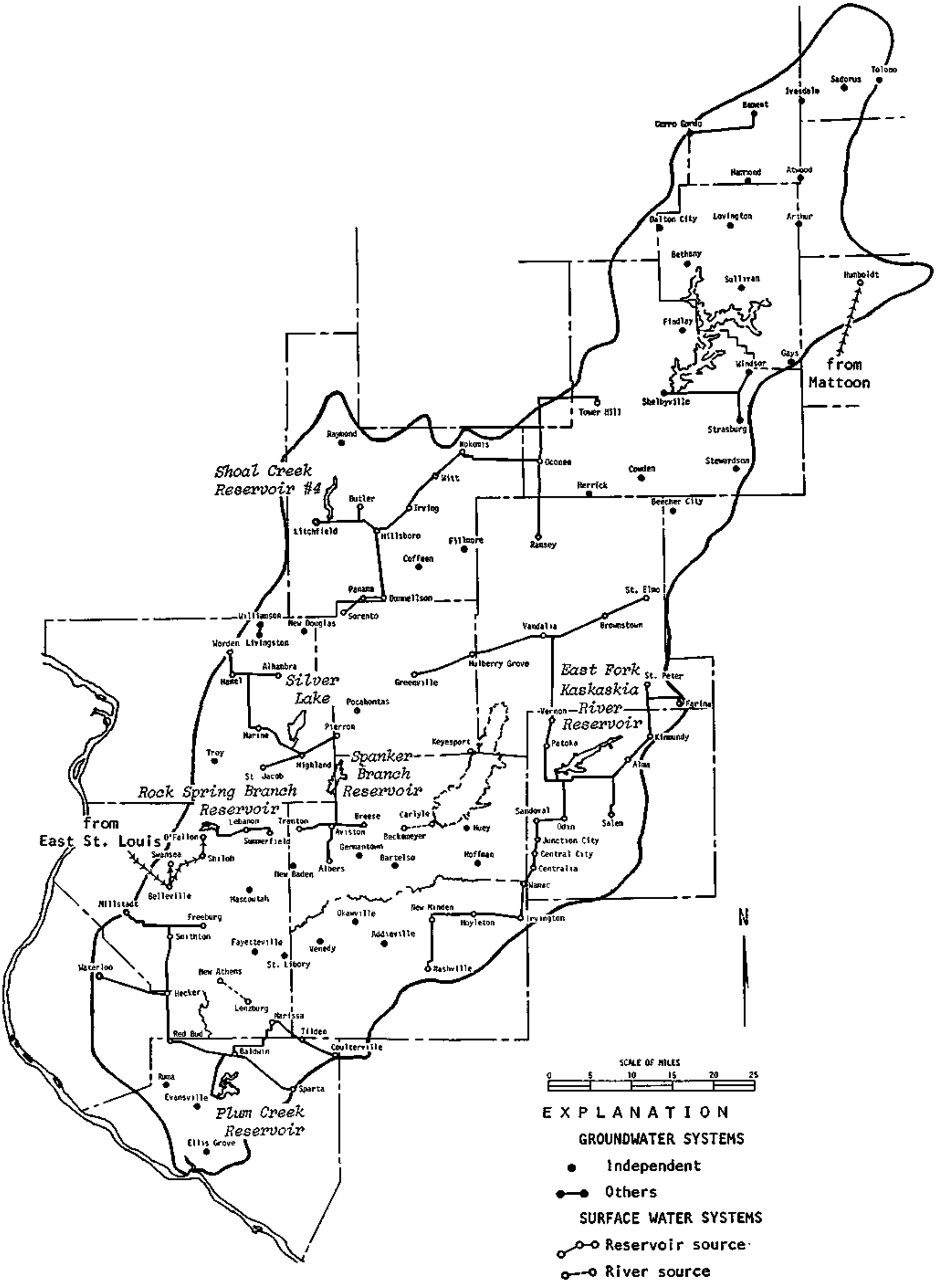


Figure 10. Kaskaskia River Basin water supply Plan 1

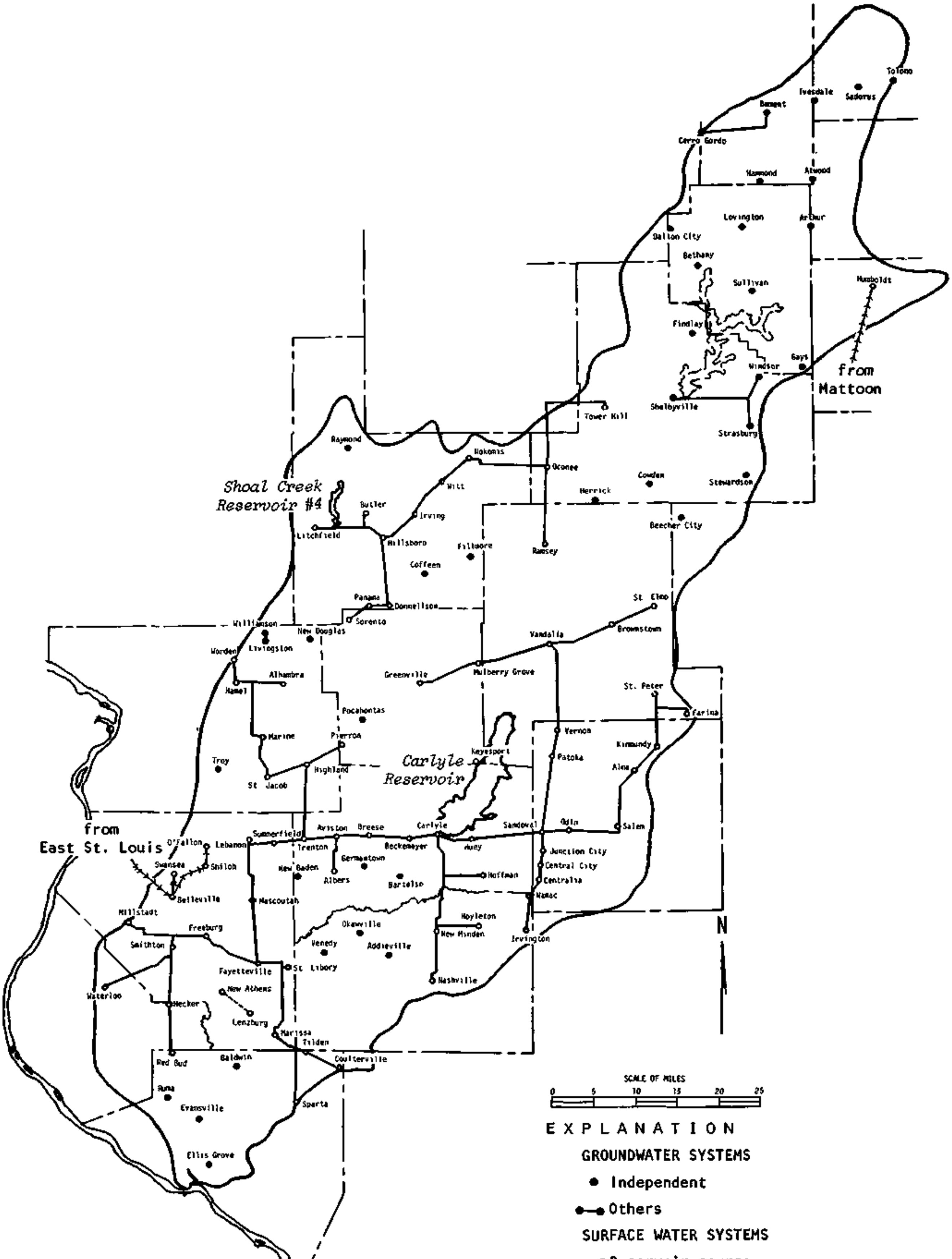


Figure 11. Kaskaskia River Basin water supply Plan 2

Variable Cost Index

Plan costs as given in tables 8 and 9 are in terms of 1964 dollars or in terms of the 1964 cost index. The construction costs have increased rather sharply during the last eight years. If we assume the cost index for 1970 to be 1.3 times that for 1964, the percent increase works out to 4.7 per year. The increase in cost index increases the plan costs proportionately with the exception of Carlyle raw water sale rate, which is taken as a constant 5¢ per 1000 gallons. The comparative costs for Plans 1 and 2 are given in table 10 for the three rates of interest and the six years of reference. For a 30 percent increase in cost index, Plan 2 costs exceed those of Plan 1 for the year 2020 by 5.5, 4.4, and 3.6 percent for *i* = 4, 6, and 8 percent, respectively. The costs for the year 1970 are practically the same for the two plans.

Table 10. Effect of Cost Index Increase on Plan Costs

(50 percent of reservoir cost charged to water supply)

		Annual cost in 1000 dollars					
	i	1970	1980	1990	2000	2010	2020
1964 cost index							
Plan 1 *(see table 8)*	4	1595	1744	1924	2110	2289	2463
	6	1923	2097	2313	2529	2746	2949
	8	2273	2475	2727	2977	3228	3467
Plan 2 *(see table 9)*	4	1638	1814	2032	2256	2477	2688
	6	1961	2162	2411	2669	2926	3169
	8	2301	2534	2817	3109	3401	3680
30 percent increase							
Plan 1	4	2074	2267	2501	2743	2958	3202
	6	2500	2726	3007	3288	3570	3834
	8	2955	3218	3545	3870	4196	4507
Plan 2	4	2080	2299	2569	2846	3119	3379
	6	2500	2751	3062	3383	3703	4004
	8	2942	3235	3590	3955	4321	4669
50 percent increase							
Plan 1	4	2393	2616	2886	3165	3434	3695
	6	2885	3146	3470	3794	4119	4424
	8	3410	3713	4091	4466	4842	5201
Plan 2	4	2375	2622	2927	3240	3548	3840
	6	2859	3144	3496	3860	4221	4561
	8	3369	3702	4105	4520	4934	5328
80 percent increase							
Plan 1	4	2871	3139	3463	3798	4120	4433
	6	3461	3775	4163	4552	4943	5308
	8	4091	4455	4909	5359	5810	6241
Plan 2	4	2816	3106	3464	3830	4190	4530
	6	3398	3732	4146	4574	4998	5396
	8	4010	4402	4877	5366	5853	6316

Plan costs for the 50 and 80 percent increases in cost index are also given in table 10. For the prevalent rates of interest, i.e., 6 and 8 percent, the costs of Plan 1 and 2 are not much different.

Reservoir Cost Allocation

In computing the cost of raw water from reservoirs, 50 percent of the reservoir cost has been charged to water supply, which equals one-half of the net reservoir yield for a drought of 40-year recurrence interval. Impounded water not used for water supply will be used for recreation, low-

75, and 100 percent of the reservoir cost is charged to water supply. If 75 percent of the reservoir cost is charged to water supply, the cost of Plan 2 is nearly the same as or less than Plan 1. When full reservoir cost is allocated to water supply, Plan 2 costs less than Plan 1 for the three interest rates and the six years of reference. If the 1970 cost index is used in conjunction with 75 percent of reservoir cost chargeable to water supply, Plan 2 is more economical than Plan 1.

Table 11. Effect of Reservoir Cost Allocation on Plans 1 and 2

(Costs in 1964 dollars)

		Annual cost in 1000 dollars					
	i	1970	1980	1990	2000	2010	2020
When 50 percent of reservoir cost is charged to water supply							
Plan 1 *(see table 8)*	4	1595	1744	1924	2110	2289	2463
	6	1923	2097	2313	2529	2746	2949
	8	2273	2475	2727	2977	3228	3467
Plan 2 *(see table 9)*	4	1638	1814	2032	2256	2477	2688
	6	1961	2162	2411	2669	2926	3169
	8	2301	2534	2817	3109	3401	3680
When 75 percent of reservoir cost is charged to water supply							
Plan 1	4	1706	1864	2055	2251	2440	2624
	6	2062	2247	2477	2705	2935	3151
	8	2441	2658	2926	3192	3459	3714
Plan 2	4	1658	1834	2054	2280	2502	2714
	6	1986	2187	2439	2698	2957	3202
	8	2331	2564	2850	3165	3439	3720
When 100 percent of reservoir cost is charged to water supply							
Plan 1	4	1815	1981	2181	2386	2585	2779
	6	2198	2393	2635	2876	3119	3347
	8	2608	2836	3119	3400	3684	3955
Plan 2	4	1676	1853	2074	2301	2524	2738
	6	2009	2201	2463	2725	2986	3232
	8	2359	2594	2881	3178	3474	3758

Capacity Expansions

Groundwater systems are practically the same in the two plans. Thus, the effect of capacity expansions on the annual costs needs to be investigated only for the surface water systems. A surface water system is designed to meet the water requirement for a number of years to come. This means that the initial capacities of treatment plants and transmission networks are larger than initially needed, but capacity expansions will be needed after a certain number of years. The actual staging will depend on cost optimization. The raw water cost from the six reservoirs will, therefore, be more when capacity expansions are considered. However, the cost of raw water from Carlyle Reservoir has been assumed constant.

SUMMARY

The following inferences can be made as a result of this study:

1) Water requirements for towns in the Kaskaskia River Basin can be satisfactorily approximated by a power relation with population alone.
2) Groundwater and surface water supply systems can be modeled and optimized for water requirements varying with time to obtain suitable combinations of these systems for arriving at economical plans of basin water supply.
3) Only 50 towns in the basin have adequate groundwater potential to meet the 2020 water requirements; 48 towns do not have adequate groundwater supply to meet the present requirements, and the remaining towns will run out of groundwater in the next 40 years.
4) Unit cost of groundwater decreases with increase in water requirement, Q, and increases with increase in distance of well field from the storage tank, L_f. The minimum groundwater costs, when $L_f \sim 0.0$, for $Q = 0.01$, 0.1, and 1 mgd are 48, 16, and 8¢ per 1000 gallons, respectively. For $L_f \sim 5.0$ miles, these costs can be as high as 153, 38, and 14¢ per 1000 gallons.
5) A minimum-cost surface water supply system is obtained by optimizing the sum of reservoir, treatment, and transmission costs. When the number of towns on the supply network increases, the reservoir and treatment portions of the unit cost decrease with increasing water requirement, but this is offset by the increases in cost of the transmission portion.
6) The Shelbyville Reservoir is located in the northern part of the basin, which has adequate and relatively cheap groundwater supply. Water transport from the Shelbyville Reservoir to towns to the south requires long transmission lines. These factors make water supply from this reservoir uneconomical for municipal water requirements when compared with other groundwater and surface water supply systems. However, the reserve storage in the Shelbyville Reservoir will be available to meet water requirements of new industries and rural areas, and for irrigation. These requirements cannot be anticipated by the method of prediction used in this study.
7) In both of the proposed basin water supply plans for 105 towns in the Kaskaskia River Basin, the groundwater supply systems account for about 25 percent of the total water supply, but the cost of groundwater supply is about 19 percent of the total cost. Thus, where adequate groundwater sources are available to establish well fields within a reasonable distance of the towns, groundwater supply will generally be more economical than surface water supply.
8) Basin Water Supply Plan 1 *(see figure 10)* has 43 towns on groundwater, 4 towns on river water, and 58 towns on reservoir water supply systems. The reservoirs include two existing reservoirs — Shoal Creek Reservoir No. 4 and Silver Lake — in addition to four potential reservoirs on E. Fork Kaskaskia River, Plum Creek, Rock Spring Branch, and Spanker Branch. Basin Water Supply Plan 2 *(see figure 11)* has 40 towns on groundwater, 2 towns on river water, and 63 towns on reservoir water supply systems. This plan includes two existing reservoirs — Carlyle Reservoir serving 51 towns and Shoal Creek Reservoir No. 4 serving 12 towns.
9) Costs of both the plans are nearly the same in terms of 1970 dollars, i.e., for a 30 percent increase over the cost index of 1964. One-half of the reservoir cost has been charged to water supply because one-half of the net reservoir yield is used for water supply. If more than 50 percent of the reservoir cost is charged to water supply, Plan 2 becomes more economical than Plan 1. If the cost of Carlyle water is considered fixed, Plan 2 will become still more economical in relation to Plan 1 because no staging or capacity expansions are needed for the Carlyle Reservoir.

According to Plan 2, water supplies from the Carlyle Reservoir will range from 9 to 21 mgd for the period 1970 to 2020. Rural water supply needs can be met by increasing the capacity of the transmission network and supplying water to the farm communities by suitable community lines and laterals. The reserve supply of 29.5 mgd in the Carlyle Reservoir should be adequate to satisfy this increased water requirement. In case there is new industry requiring large water supplies or there are rural and irrigation water demands unanticipated at present, the Shelbyville water reserve of 22.3 mgd will be available. This can be easily routed if needed to the Carlyle Reservoir via the Kaskaskia River, or farther downstream, and the demands can be met through an expanded network or by a new network whichever is more economical.

REFERENCES

1 *Water for Illinois, a plan for action.* 1967. Illinois Department of Business and Economic Development, Springfield, 452 p.

2 Walton, W. C. 1962. *Selected analytical methods for well and aquifer evaluation.* Illinois State Water Survey Bulletin 49, p. 1-30.

3 Gibb, J. P., and E. W. Sanderson. 1969. *Cost of municipal and industrial wells in Illinois, 1964-1966.* Illinois State Water Survey Circular 98, 22 p.

4 Roberts, W. J., R. Hanson, F. A. Huff, S. A. Changnon, Jr., T. E. Larson, et al. 1957. *Potential water resources of southern Illinois.* Illinois State Water Survey Report of Investigation 31, 100 p.

5 Dawes, J. H., and M. L. Terstriep. 1966. *Potential surface water reservoirs of south-central Illinois.* Illinois State Water Survey Report of Investigation 54, 119 p.

6 Stall, J. B. 1964. *Low flows of Illinois streams for impounding reservoir design.* Illinois State Water Survey Bulletin 51, 395 p.

7 Dawes, J. H., and M. Wathne. 1968. *Cost of reservoirs in Illinois.* Illinois State Water Survey Circular 96, 22 p.

8 Illinois State Water Survey. 1968. *Cost of water treatment in Illinois.* Technical Letter 11, 7 p.

9 Koenig, L. 1967. *The cost of water treatment by coagulation, sedimentation, and rapid sand filtration.* Journal American Water Works Association v. 59: 290-336.

10 Adams, J. C, Jr. 1964. *Determination of service life of mass plant items.* Journal American Water Works Association v. 56:884.

11 Singh, K. P. 1971. *Economic design of central water supply systems for medium sized towns.* Journal American Water Resources Association v. 7:80-85.

12 Koenig, L. 1964. *The cost of conventional water supply.* Office of Saline Water, Department of the Interior. Chapters 9-10 in Final Report, OSW Contract 14-01-0001-298, prepared by Louis Koenig Research, San Antonio, Texas.

NOTATIONS

A = drainage area in square miles
A_8 = reservoir pool area in acres
C = a coefficient
C_1 = transmission pipeline construction cost
C_2 = annual cost of pipeline *OM&R*
C_3 = easement cost for transmission line
C_4 = pumping station cost
C_5 = annual pumping cost
C_6 = pumping station *OM&R* cost
C_e = annual electrical charges for pumping groundwater
C_{op} = annual *OM&R* cost on wells and pumps
C_{pm} = cost of pumps and motors for wells
C_w = cost of wells
CRF = capital recovery factor
D = inside diameter of pipe in inches
d_p = estimated long-term pumping level in feet below ground level
d_w = depth of well in feet
E = overall efficiency at peak load for pumping stations, energy consumption in pumping at a varying flow rate
E_a = average overall efficiency during the pumping period
E_0 = energy consumption in pumping at a constant flow rate
E_g = average overall efficiency during the year for pumping groundwater
f = frictional head effect
H = maximum head at a pumping station in feet
H_0 = head loss in friction and bends, etc., in feet at a constant flow rate
H_d = design head for the pump, in feet (equals $d_p + 25$ feet)
H_e = elevation difference between the ground level at elevated storage tank and ground level at well field in feet
H_f = head loss in friction and bends, etc., in feet for a varying flow rate
H_8 = static head in feet
ICTPG = investment cost of a groundwater treatment plant
ICTPR = investment cost of a surface water treatment plant
ITC = cost of intake tower
IWS — investment cost chargeable to water supply
i = interest rate in percent
J = firming factor or standby factor
K = a constant
k = conversion factor
L = length of transmission line in miles
L_a = length of access road in miles
L_f = distance from the well field to elevated storage tank in miles
L_h = length of highway needing relocation in miles
L_{0g} = length of oil and gas lines needing relocation in miles
L_T = length of railroad needing relocation in miles
LC = land cost of area required for a reservoir
N = amortization period in years
N_m = maximum number of wells with a given q_w that an aquifer can sustain
N_w = number of wells to meet the water requirement
N_{wt} = total number of wells
n = an exponent, integer part of the ratio $H/300$
OM&R = operation, maintenance, and repair
OMRTPG = annual *OM&R* cost for a groundwater treatment plant
OMRTPR = annual *OM&R* cost for a surface water treatment plant
OMRWS = *OM&R* cost chargeable to water supply
P = population

P_2 = installed horsepower at a pumping station
P_8 = installed horsepower when head is 300 feet
p = percent draft rate or reservoir yield as percent of mean flow, also used as a subscript to A and C, ratio of E to E_0
Q = average yearly water requirement or consumption in gallons per day (gpd)
Q_d = design capacity of a treatment plant in million gallons per day (mgd)
Q_v = aquifer potential yield in gpd
q_w = average long-term well yield in gallons per minute (gpm)
RC = reservoir cost
RLC = cost of relocating railroads, highways, and oil and gas lines, and of building access roads
$RWCKR$ = annual cost of raw water from the Kaskaskia River
$RWCR$ = annual cost of raw water from a reservoir
S = net reservoir storage as percent of mean flow of the impounded stream
S_g = gross reservoir storage in acre feet for a given percent draft rate
T_c = critical drawndown duration for a reservoir in months
TCG = total annual cost of untreated groundwater
TCT = total annual cost of transmission for any branch
$TCTPG$ = total annual cost of groundwater treatment
$TCTPR$ = total annual cost of surface water treatment
x = water supply in mgd
At = pumping period as a fraction of the year
6 = angle in radians