APPENDIX L

CALCULATIONS FOR STORAGE EFFECTIVENESS ANALYSIS

L-1. Introduction.

This appendix summarizes the calculations used to develop the storage effectiveness indices for the example reservoir systems discussed in Section 5-14f. Figure L-1 shows the storage-elevation curves for the various reservoirs. Note that the reservoir elevations on Figure L-1 are expressed in terms of net head in order to simplify the examples. The other data assumptions are summarized in Table L-1. In each case, the monthly firm energy requirement is assumed to be constant at 14,800 MWh and the critical drawdown period is eight months in length.

TABLE L-1
Characteristics of Storage Projects

	Reservoirs A, B, and C	Reservoir D	Reservoir E	Reservoir F
Total Storage at full pool, 1000 AF	280	280	280	280
Power storage, 1000 AF	200	200	200	200
Head at full pool, ft.	100	100	150	50
Head at minimum pool, ft.	60	60	90	30
Average inflow, cfs 1/	1,000	1,000 2/	1,000	1,000

1/ Assumed to be constant for all eight months
2/ 500 cfs for Case 4

L-2. Case 1: Upstream Reservoir in Tandem.

a. General. Paragraphs 5-14f(3) through (6) describe the computation of the storage effectiveness index for drafting from the the downstream reservoir (Reservoir A) in the example of two identical reservoirs located in tandem (Figure 5-53). Following are the computations for drafting the required storage from the upstream reservoir (Reservoir B).

b. Draft of Reservoir B.

(1) Energy Shortfall. Drafting storage from Reservoir B to meet the shortfall would be analyzed in the same way as drafting Reservoir A. Since no draft is required in this case from Reservoir A, the full 100 feet of head would be available for generating with inflow, and the resulting generation in the first month would be

$$\text{kWh} = \frac{(1000\text{ cfs})(100\text{ feet})(0.85)(720\text{ hours})}{(11.81)} = 5{,}200\text{ MWh.}$$

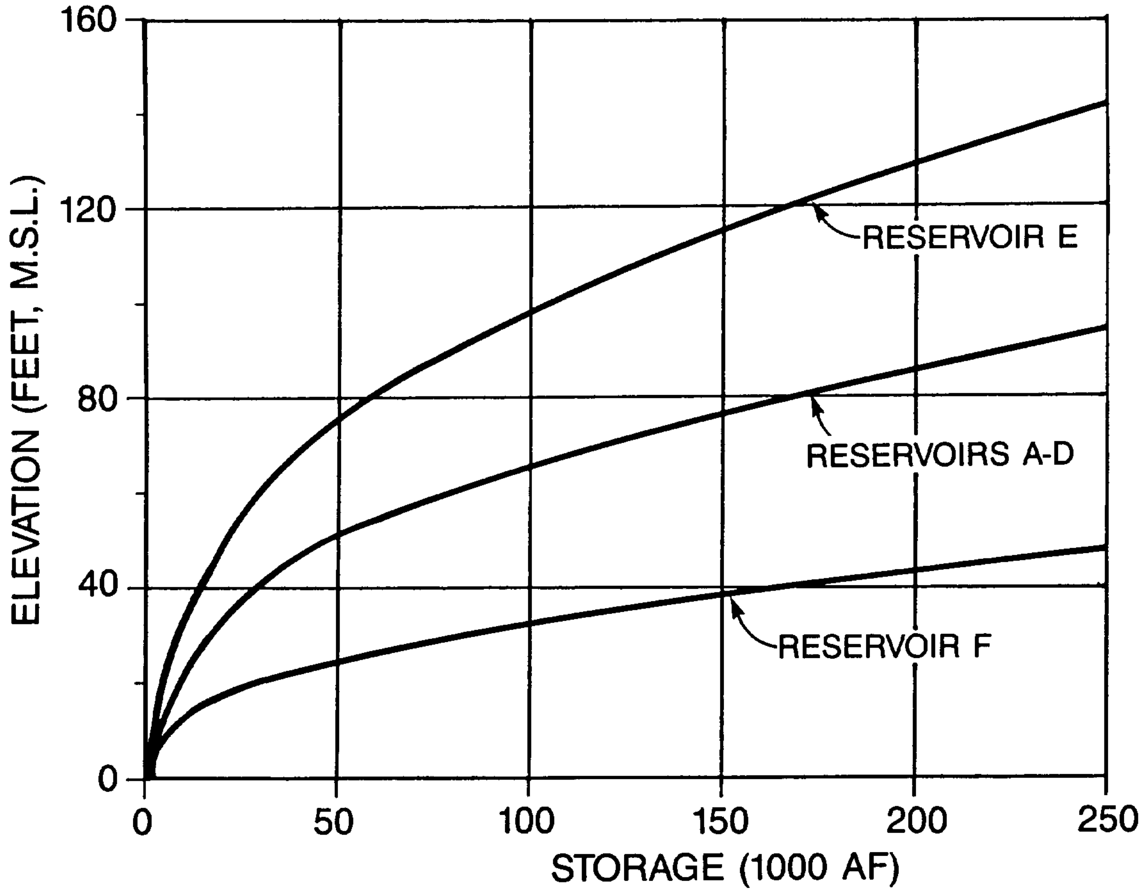

Figure L-1. Reservoir storage-elevation curves

Since storage drafts from Reservoir B pass through both powerplants, less storage would have to be drafted to make up the shortfall than was required from Reservoir A. Hence, an average head of 98 feet is assumed. The generation from inflow at Reservoir B would therefore be

$$\text{kWh} = \frac{(1000\ \text{cfs})(98\ \text{feet})(0.85)(72\ \text{hours})}{11.81} = 5{,}100\ \text{MWh.}$$

The resulting energy shortfall would be

$$(14{,}800 - 5{,}200 - 5{,}100) = 4{,}500\ \text{MWh.}$$

(2) <u>Required Draft.</u>

The average flow required to produce this generation would be

$$Q = \frac{(4{,}500{,}000\ \text{kWh})(11.81)}{(198\ \text{feet})(0.85)(720\ \text{hours})} = 439\ \text{cfs.}$$

Note that since this flow passes through both powerplants, the effective head is (100 + 98) = 198 feet. The 439 cfs corresponds to a storage draft of (439 cfs)(59.5 AF/cfs) = 26,100 AF. The end-of-period storage would be (280,000 - 26,100) = 253,900 AF, which corresponds to an end-of-period head of 96 feet (see Figure L-1). The average head would be (0.50)(100 + 96) = 98 feet (which verifies the initial assumption), and the head loss in subsequent months would be 4 feet.

(3) <u>Subsequent Energy Loss.</u> The resulting generation loss in subsequent months would be

At-site unregulated inflow = 1000 cfs

$$\text{Releases from Reservoir B} = \frac{(200{,}000 - 26{,}100\ \text{AF})}{(59.5\ \text{AF/cfs})(7\ \text{months})} = 417\ \text{cfs}$$

Storage releases from Reservoir A would not pass through Reservoir B, so the four foot head loss would apply only to the at-site unregulated inflow plus the storage releases from Reservoir A, which would be an average discharge of (1000 + 417) = 1,417 cfs. The resulting generation loss would be

$$\text{kWh} = \frac{(1{,}417\ \text{cfs})(4\ \text{ft})(0.85)(7 \times 720\ \text{hours})}{11.81} = 2{,}100\ \text{MWh.}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir B would be

$$\frac{2,100 \text{ MWh}}{4,500 \text{ MWh}} = 0.47.$$

L-3. Case 2: Two Identical Reservoirs in Parallel.

a. General. Reservoirs C and D are identical (Figure 5-55), and inflows to both are the same, so both reservoirs would be drafted equally (see also Section 5-14f(10)).

b. Energy Shortfall. The generation from inflow would be computed as follows:

$$\text{kWh} = \frac{\text{QHet}}{11.81} = \frac{(\text{Avg. inflow})(\text{Avg. head})(0.85)(720 \text{ hours})}{11.81}$$

	Reservoir C	Reservoir D
Average inflow	1,000 cfs	1,000 cfs
Est. avg. head	98 feet	98 feet
Generation	5,100 MWh	5,100 MWh

The energy shortfall to be met from storage draft would be (14,800 - 5,100 - 5,100) = 4,600 MWh, or 2,300 MWh from each reservoir.

c. Required Storage Draft. The discharge required from each reservoir to meet the energy shortfall would be computed as follows:

$$Q = \frac{11.81(\text{kWh})}{\text{Het}} = \frac{11.81(2,300,000 \text{ kWh})}{(98 \text{ feet})(0.85)(720 \text{ hours})} = 453 \text{ cfs.}$$

This corresponds to a storage draft of (453 cfs)(59.5 AF/cfs) = 26,900 AF.

End-of-period storage = 280,000 AF - 26,900 AF = 253,100 AF
End-of-period head = 96 feet (From Figure L-1)
Average head over period = (0.5)(100 + 96) = 98 feet 1/
Loss in head = (100 - 96) = 4 feet.

1/ This agrees with the initial assumption

d. Subsequent Energy Loss. The subsequent energy loss at each reservoir during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200,000 AF - 26,900 AF) = 173,100 AF

$$\text{Average cfs from storage} = \frac{(173{,}100\ \text{AF})}{(7\ \text{months})(59.5\ \text{AF/cfs})} = 416\ \text{cfs}$$

Average inflow = 1,000 cfs
Total average discharge = (1,000 cfs + 416 cfs) = 1,416 cfs
Head loss = 4.0 feet

$$\text{kWh} = \frac{(1{,}416\ \text{cfs})(4\ \text{feet})(0.85)(720\ \text{hours})(7\ \text{months})}{11.81} = 2{,}100\ \text{MWh}$$

e. Storage Effectiveness Index. The storage effectiveness index would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(2{,}100\ \text{MWh})}{(2{,}300\ \text{MWh})} = 0.91$$

L-4. Case 3: Parallel Reservoirs, One with Downstream Powerplant.

a. General. Reservoirs C and D are identical, but a run-of-river plant with 30 feet of head is located downstream of Reservoir D (Figure 5-56 and Section 5-14f(11)).

b. Draft Reservoir C.

(1) Energy Shortfall. The generation from inflow would be computed as follows:

$$\text{kWh} = \frac{\text{QHet}}{11.81} = \frac{\text{(Avg. inflow)(Avg. head)(0.85)(720 hours)}}{11.81}$$

	Reservoir C	Reservoir D
Average inflow	1,000 cfs	1,000 cfs
Est. avg. head	97 feet	130 ft. 1/
Generation	5,000 MWh	6,700 MWh

1/ 100 feet at Reservoir D plus 30 feet at run-of-river plant

The energy shortfall to be met from storage draft would be (14,800 - 5,000 - 6,700) = 3,100 MWh.

(2) Required Storage Draft. The discharge required from Reservoir C to meet the energy shortfall would be computed as follows:

$$Q = \frac{11.81\text{(kWh)}}{\text{Het}} = \frac{11.81\text{(3,100,000 kWh)}}{\text{(97 feet)(0.85)(720 hours)}} = 617 \text{ cfs.}$$

This corresponds to a storage draft of (617 cfs)(59.5 AF/cfs) = 36,700 AF.

End-of-period storage = 280,000 AF - 36,700 AF = 243,300 AF
End-of-period head = 94 feet (From Figure L-1)
Average head over period = (0.5)(100 + 94) = 97 feet 1/
Loss in head = (100 - 94) = 6 feet.

1/ This agrees with the initial assumption

(3) Subsequent Energy Loss. The subsequent energy loss at Reservoir C during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200,000 AF - 36,700 AF) = 163,300 AF

$$\text{Average cfs from storage} = \frac{\text{(163,300 AF)}}{\text{(7 months)(59.5 AF/cfs)}} = 392 \text{ cfs}$$

Average inflow = 1,000 cfs
Total average discharge = (1,000 cfs + 392 cfs) = 1,392 cfs
Head loss = 6 feet.

$$\text{kWh} = \frac{(1{,}392 \text{ cfs})(6 \text{ feet})(0.85)(720 \text{ hours})(7 \text{ months})}{11.81} = 3{,}000 \text{ MWh.}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir C would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(3{,}000 \text{ MWh})}{(3{,}100 \text{ MWh})} = 0.97$$

c. Draft Reservoir D.

(1) Energy Shortfall. The generation from inflow would be computed as follows:

$$\text{kWh} = \frac{\text{QHet}}{11.81} = \frac{(\text{Avg. inflow})(\text{Avg. head})(0.85)(720 \text{ hours})}{11.81}$$

	Reservoir C	Reservoir D
Average inflow	1,000 cfs	1,000 cfs
Est. avg. head	100 feet	98 + 30 feet
Generation	5,200 MWh	6,600 MWh

The energy shortfall to be met from storage draft would be (14,800 - 5,200 - 6,600) = 3,000 MWh.

(2) Required Storage Draft. The discharge required from Reservoir D to meet the energy shortfall would be computed as follows:

$$Q = \frac{11.81(\text{kWh})}{\text{Het}} = \frac{11.81(3{,}000{,}000 \text{ kWh})}{(98 + 30)(0.85)(720 \text{ hours})} = 452 \text{ cfs.}$$

This corresponds to a storage draft of (452 cfs)(59.5 AF/cfs) = 26,900 AF.

End-of-period storage = 280,000 AF - 26,900 AF = 253,100 AF
End-of-period head = 96 feet (From Figure L-1)
Average head over period = (0.5)(100 + 96) = 98 feet 1/
Loss in head = (100 - 96) = 4 feet.

1/ This agrees with the initial assumption

(3) Subsequent Energy Loss. The subsequent energy loss at Reservoir D during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200,000 AF - 26,900 AF) = 173,100 AF

$$\text{Average cfs from storage} = \frac{(173{,}100 \text{ AF})}{(7 \text{ months})(59.5 \text{ AF/cfs})} = 416 \text{ cfs}$$

Average inflow = 1,000 cfs
Total average discharge = (1,000 cfs + 416 cfs) = 1,416 cfs
Head loss =

$$\text{kWh} = \frac{(1{,}416 \text{ cfs})(4 \text{ feet})(0.85)(720 \text{ hours})(7 \text{ months})}{11.81} = 2{,}100 \text{ MWh.}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir D would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(2{,}100 \text{ MWh})}{(3{,}000 \text{ MWh})} = 0.70$$

L-5. Case 4: Parallel Reservoirs with Unequal Flow.

a. General. Reservoirs C and D are identical, but Reservoir D has an inflow equal to half of the inflow at Reservoir C (Figure 5-58 and Section 5-14f(13)).

b. Draft Reservoir C.

(1) Energy Shortfall. The generation from inflow would be computed as follows:

$$\text{kWh} = \frac{\text{QHet}}{11.81} = \frac{(\text{Avg. inflow})(\text{Avg. head})(0.85)(720 \text{ hours})}{11.81}$$

	Reservoir C	Reservoir D
Average inflow	1,000 cfs	500 cfs
Est. avg. head	92 feet	100 feet
Generation	4,800 MWh	2,600 MWh

The energy shortfall to be met from storage draft would be (14,800 - 4,800 - 2,600) = 7,400 MWh.

(2) Required Storage Draft. The discharge required from Reservoir C to meet the energy shortfall would be computed as follows:

$$Q = \frac{11.81(\text{kWh})}{\text{Het}} = \frac{11.81(7{,}400{,}00 \text{ kWh})}{(92)(0.85)(720 \text{ hours})} = 1{,}552 \text{ cfs.}$$

This corresponds to a storage draft of (1,552 cfs)(59.5 AF/cfs) = 92,400 AF.

End-of-period storage = 280,000 AF - 92,400 AF = 187,600 AF
End-of-period head = 84 feet (From Figure L-1)
Average head over period = (0.5)(100 + 84) = 92 feet 1/
Loss in head = (100 - 84) = 16 feet.

1/ This agrees with the initial assumption

(3) Subsequent Energy Loss. The subsequent energy loss at Reservoir C during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200,000 AF - 92,400 AF) = 107,600 AF

$$\text{Average cfs from storage} = \frac{(107{,}600 \text{ AF})}{(7 \text{ months})(59.5 \text{ AF/cfs})} = 259 \text{ cfs}$$

Average inflow = 1,000 cfs
Total average discharge = (1,000 cfs + 259 cfs) = 1,259 cfs
Head loss = 16 feet

$$\text{kWh} = \frac{(1{,}259 \text{ cfs})(16 \text{ feet})(0.85)(720 \text{ hours})(7 \text{ months})}{11.81} = 7{,}300 \text{ MWh}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir C would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(7{,}300 \text{ MWh})}{(7{,}400 \text{ MWh})} = 0.99$$

c. Draft Reservoir D.

(1) Energy Shortfall. The energy shortfall would be the same as for drafting Reservoir C, or 7,400 MWh.

(2) Required Storage Draft. The required storage draft from Reservoir D would be the same as from Reservoir C, or 187,600 AF. The loss in head would also be 16 feet.

(3) Subsequent Energy Loss. The subsequent energy loss at Reservoir D during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200.000 AF - 92.400 AF) = 107,600 AF

$$\text{Average cfs from storage} = \frac{(107{,}600 \text{ AF})}{(7 \text{ months})(59.5 \text{ AF/cfs})} = 259 \text{ cfs}$$

Average inflow = 500 cfs
Total average discharge = (500 cfs + 259 cfs) = 759 cfs
Head loss = 16 feet

$$\text{kWh} = \frac{(759 \text{ cfs})(16 \text{ feet})(0.85)(720 \text{ hours})(7 \text{ months})}{11.81} = 4{,}400 \text{ MWh}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir D would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(4{,}400 \text{ MWh})}{(7{,}400 \text{ MWh})} = 0.59$$

L-6. Case 5: Parallel Reservoirs of Unequal Slope.

a. General. Reservoirs E and F are of equal capacity, but Reservoir E has a head when full of 150 feet and Reservoir F has a head when full of 50 feet (Figure 5-59 and Section 5-14f(14)). The storage-elevation curves are shown on Figure L-1.

b. Draft Only Reservoir E.

(1) Energy Shortfall. The generation from inflow would be computed as follows:

$$\text{kWh} = \frac{\text{QHet}}{11.81} = \frac{(\text{Avg. inflow})(\text{Avg. head})(0.85)(720 \text{ hours})}{11.81}$$

	Reservoir E	Reservoir F
Average inflow	1,000 cfs	1,000 cfs
Est. avg. head	145 feet	50 feet
Generation	7,500 MWh	2,600 MWh

The energy shortfall to be met from storage draft would be (14,800 - 7,500 - 2,600) = 4,700 MWh.

(2) Required Storage Draft. The discharge required from Reservoir E to meet the energy shortfall would be computed as follows:

$$Q = \frac{11.81(\text{kWh})}{\text{Het}} = \frac{11.81(4{,}700{,}000 \text{ kWh})}{(145)(0.85)(720 \text{ hours})} = 626 \text{ cfs.}$$

This corresponds to a storage draft of (626 cfs)(59.5 AF/cfs) = 37,200 AF.

End-of-period storage = 280,000 AF - 37,200 AF = 242,800 AF
End-of-period head = 141 feet (From Figure L-1)
Average head over period = (0.5)(150 + 141) = 145 feet 1/
Loss in head = (150 - 141) = 9 feet.

1/ This agrees with the initial assumption

(3) Subsequent Energy Loss. The subsequent energy loss at Reservoir E during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200.000 AF - 37,200 AF) = 162.800 AF

$$\text{Average cfs from storage} = \frac{(162{,}800\ \text{AF})}{(7\ \text{months})(59.5\ \text{AF/cfs})} = 391\ \text{cfs}$$

Average inflow = 1,000 cfs
Total average discharge = (1,000 cfs + 391 cfs) = 1,391 cfs
Head loss = 9 feet

$$\text{kWh} = \frac{(1{,}391\ \text{cfs})(9\ \text{feet})(0.85)(720\ \text{hours})(7\ \text{months})}{11.81} = 4{,}500\ \text{MWh}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir E would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(4{,}500\ \text{MWh})}{(4{,}700\ \text{MWh})} = 0.96$$

c. Draft Reservoir F.

(1) Energy Shortfall. The generation from inflow would be computed as follows:

$$\text{kWh} = \frac{\text{QHet}}{11.81} = \frac{(\text{Avg. inflow})(\text{Avg. head})(0.85)(720\ \text{hours})}{11.81}$$

	Reservoir E	Reservoir F
Average inflow	1,000 cfs	1,000 cfs
Est. avg. head	150 feet	45 feet
Generation	7,800 MWh	2,300 MWh

The energy shortfall to be met from storage draft would be (14,800 - 7,800 - 2,300) = 4,700 MWh.

(2) Required Storage Draft. The discharge required from Reservoir F to meet the energy shortfall would be computed as follows:

$$Q = \frac{11.81(\text{kWh})}{\text{Het}} = \frac{11.81(4{,}700{,}000 \text{ kWh})}{(45)(0.85)(720 \text{ hours})} = 2{,}016 \text{ cfs.}$$

This corresponds to a storage draft of (2,016 cfs)(59.5 AF/cfs) = 120,000 AF.

End-of-period storage = 280,000 AF - 120,000 AF = 160,000 AF
End-of-period head = 40 feet (From Figure L-1)
Average head over period = (0.5)(50 + 40) = 45 feet 1/
Loss in head = (50 - 40) = 10 feet.

1/ This agrees with the initial assumption

(3) Subsequent Energy Loss. The subsequent energy loss at Reservoir F during the remaining months in the critical drawdown period would be computed as follows:

Remaining storage = (200,000 AF - 120,000 AF) = 80,000 AF

$$\text{Average cfs from storage} = \frac{(80{,}000 \text{ AF})}{(7 \text{ months})(59.5 \text{ AF/cfs})} = 192 \text{ cfs}$$

Average inflow = 1,000 cfs
Total average discharge = (1,000 cfs + 192 cfs) = 1,192 cfs
Head loss =

$$\text{kWh} = \frac{(1{,}192 \text{ cfs})(10 \text{ feet})(0.85)(720 \text{ hours})(7 \text{ months})}{11.81} = 4{,}300 \text{ MWh}$$

(4) Storage Effectiveness Index. The storage effectiveness index for Reservoir F would be the ratio of the subsequent energy loss to the generation from storage in the given period, or

$$\frac{(4{,}300 \text{ MWh})}{(4{,}700 \text{ MWh})} = 0.91.$$