RESERVOIR SEISMIC EFFECTS

By

Wendell V. Mickey

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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ABSTRACT

Increases in seismic activity following the construction of large man-made lakes or reservoirs have been documented by studies in many regions of the world. In the United States, reservoir-related earthquakes have been reported in Washington, Nevada, California, and Montana. Of five specific sites selected for the current detailed study, Lake Mead has reservoir-related earthquakes, while Cedar Springs and San Luis, California, Flaming Gorge, Utah, and Glen Canyon, Arizona, do not. Although not complete, the Cedar Springs site was the most seismically active. To determine the seismic effects of man-made lakes requires an appropriate seismograph system in operation prior to construction, during construction, and sufficient time after construction to define adequately the seismic environment.

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The occurrence of earthquakes in the vicinity of large dams and reservoirs has been studied by many investigators in several regions of the world (Barnett, 1968; Gough and Gough, 1970-a, 1970-b; Rothé, 1968, 1969, and 1970; McGinnis, 1963).

Historically, probably the first reported concern for the effects of reservoir loading on the earth's crust was at Lake Mead (Mead and Carder, 1941).

The National Ocean Survey (formerly U.S. Coast and Geodetic Survey) has been active in monitoring the seismicity around large dams and reservoirs in the United States since establishing a station near Lake Mead in 1938.

The following instances have been reported in the literature relating seismic activity to man-made hydrologic structures (USA only):

Lake Mead, Nev., 1936-1944 - over 3000 local earthquakes, about 10 percent felt (Carder, 1945).

Eastern Washington, 1955 - "nearly 200 shocks -- geologists reported the disturbances were caused by shifting subterranean rock due to the weight of irrigation water" (USC&GS, 1955).

Washington, 1961 - Rocky Reach Dam and Entiat Lake. Several shocks felt "-- reported that the shock was due to impounding of water in newly created Lake Entiat --." (USC&GS, 1961).

Shasta Dam, California, 1944 - several shocks --- "-- believed to have been due to the settling of the bottom of Shasta Lake under pressure of stored water." (USC&GS, 1944).

Flathead Lake and Kerr Dam, Montana, 1969-1970 - over 100 quakes have been felt in the area with activity continuing to the time of this report (USC&GS, 1958; Lander, 1969).

There are many other references of implied coadunation.

Five sites in four states were selected for a detailed study of seismic characteristics near reservoirs. The sites were:

Glen Canyon, Arizona
Flaming Gorge, Utah
Hoover Dam (Lake Mead), Nevada
San Luis, California
Cedar Springs, California

Flaming Gorge and Glen Canyon

These two dams and reservoirs are grouped because the observing area overlaps and both are in the Colorado River Storage Project.

Flaming Gorge Dam, Utah (Green River), is 151 meters high with a reservoir capacity of 3,789,000 acre-feet. It was first loaded in November 1962. Seismic measurements started in June 1960.

Glen Canyon Dam, Arizona (Colorado River), is 216 meters high with a reservoir capacity of 28,040,000 acre-feet. It was first loaded in May 1963. On-site seismic measurements started in June 1960.

The station locations and the observation area are shown in Figure 1 on a background of earthquake epicenters for 1968. The major seismic activity is to the west of the two reservoirs along the more prominent tectonic features.

Figure 2 shows the cumulative number of earthquakes per month for Flaming Gorge and Glen Canyon from 1960 through 1968 at different distances from the station. If the reservoir was affecting the local seismicity, it should be apparent in the 0- to 40-km range. There was a decrease in seismic activity in this distance zone following reservoir loading. Although Glen Canyon is 65 meters higher and the reservoir seven times larger, it has much less seismic activity than Flaming Gorge. The seismicity characteristics for Glen Canyon were affected by the earthquake series during 1966 in southeast Nevada.

Extreme probability statistics are shown in Figure 3 for Flaming Gorge for 36 months. The equivalent slope is 0.89, very near that for southern California. While the area is much less active than southern California, the rate of occurrence of small to large earthquakes is similar.

Figure 4 is a contoured map using the square root of the source seismic energy which is proportional to strain release. The darker shaded areas are progressively more seismically active for the period of the present observations. The most active areas correspond to the tectonic zones trending NNE with a transverse trend from near Grand Junction, Colorado, to Price, Utah. The areas with the least seismic activity are in the vicinity of Glen Canyon (GCA) and Flaming Gorge (FGU). From September 1960 through December 1968 there were 3182 earthquakes recorded at Flaming Gorge and 1506 at Glen Canyon within a 350-km radius from each station. There were many explosions, rock bursts, and coal bumps recorded at each station, and every effort was made to exclude these data. The data were substantiated by nearby seismograph stations at Logan, Salt Lake City, Dugway, and Cedar City, Utah; Eureka, Boulder City, and Las Vegas, Nevada.

San Luis Dam

A histogram of the seismicity within 80 km of San Luis Dam, California, from November 1965 through July 1970, is shown in Figure 5. This dam is 93 meters high and was first filled in June 1965.

The number of earthquakes per month within 80 km of the station varied from 16 to 89, with an average of 52. The size of earthquakes ranged from M_L 0.2 to 5.0. The average monthly-minimum-distance earthquake was 7.2 km from the station. During the 57 month monitoring period there were 2,968 earthquakes occurring within 80 km, with 560 of these at distances of 25 km or less.

The high seismic activity of this area is influenced by a major fault system 22.5 km to the southwest.

Extreme probability techniques were used to compare nearby seismicity to the overall zone of 0 to 80 km. Figure 6 shows that the rate of occurrence is similar with identical "b" values of 0.7. When the observing area was reduced by a factor of 10 the probabilities were also reduced a similar amount.

Cedar Springs Dam Site, California

The Cedar Springs project is about 50 miles east of Los Angeles on the north edge of the San Bernardino Mountains. The seismograph station at this site started operations in February 1965. Figure 7 shows the occurrence characteristics of this site. There were 682 earthquakes within 50 km of the site during the 28-month monitoring period, ranging in size from M_L less than 1 to 3.7. This site differs from the others discussed, because it shows more seismic activity near the site than in an area three times as large but 25 to 50 km away. The other major difference is that the reservoir has not been built in this area yet. This site is near an active area of the San Andreas Fault.

Hoover Dam and Lake Mead, Nevada

Hoover Dam, 40 km southeast of Las Vegas, Nevada, was completed in 1936 with a height of 221 meters and a reservoir capacity of 32,471,000 acre-feet. A seismograph monitoring system of one or more units has been in operation near the dam from 1938 to the present time. There have been several reports written about the seismic characteristics of this area (Carder and Small, 1948; Mead and Carder, 1941; Jones, 1944; Carder, 1945; Carder, 1968).

Figure 8, which shows the seismic activity at Lake Mead from 1939 through 1951, has been especially prepared to check for periodicity and correlation of seismic activity with reservoir water level. The top curve is the average monthly water level for the period plotted from January through December, with January through September repeated so that more than one cycle is shown. Due to the reservoir recharge characteristics, the water level in Lake Mead is periodic with levels at maximum usually in July, and at minimum in April.

The second curve is the number of earthquakes for a three-month period and plotted at the center month, i.e., the first point is plotted above M for March and is 1242, the number of earthquakes which occurred during February, March, and April. The third graph is prepared like the second, but it represents the number of earthquakes which were felt during the period 1939-51. The correlation is very apparent but has a low level of significance. Using other averages, monthly combinations, or chronological earthquake and water-level statistics, the correlation is much less apparent.

Summary

The number of earthquakes per unit time per unit area is a measure of relative seismicity for the five sites. Ranked in the order of most to least seismically active the sites are as follows:

1. Cedar Springs, California
2. San Luis, California
3. Hoover Dam, Lake Mead, Nevada
4. Flaming Gorge, Utah
5. Glen Canyon, Arizona

Cedar Springs was the most seismically active, but the dam and reservoir have not been built. The seismic activity near San Luis Dam is along a fault zone which was active historically, before the dam was built. Of the five areas considered, the seismicity around Lake Mead seems to be related to the reservoir. Jones (1944) reported, "According to T. C. Mead, of the Bureau of Reclamation, no earthquakes were reported by the few local inhabitants in the fifteen-year period prior to the construction of Boulder Dam." Since 1936 there have been over 10,000 earthquakes recorded, with approximately 10 percent felt in the Hoover Dam, Lake Mead area.

Recommendations

Although four of the five examples of reservoir seismicity did not indicate effects of reservoir loading, the scientific literature is replete with references affirming a causal relationship. The best place to build a dam is in a deep narrow gorge with an upstream reservoir of sufficient dimensions and inflow potentials to make such a project feasible and economical. These optimum areas are also where past tectonic activity has been present to create the desired deep narrow gorge which is associated with faulted structures and concomitant earthquakes. Current seismic activity, however small, along the faults within the reservoir indicates a potential for fault movement.

It is recommended that a seismograph station be installed in areas of large man-made lakes, dams, and reservoirs at the time the site is proposed to provide a history of seismicity prior to construction.

If the area is seismically active, additional stations should be deployed to locate the earthquake hypocenters and, if possible, to determine the earthquake mechanisms in addition to frequency of occurrence characteristics and magnitudes. Close coordination should be maintained with the project geologists. If the earthquakes can be considered associated with surface faulting, there should be monitoring networks of stations across the fault to determine if there is movement.

The demand for water reservoirs will increase, and the construction rate of man-made lakes will increase. Mermel (1970) reported that there are 125 dams a year being built in the United States with heights greater than 15 meters. World-wide, over 300 a year are being constructed.

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CAPTIONS

Figure 1. Seismograph station map showing Flaming Gorge, Utah (FGU), and Glen Canyon, Arizona (GCA), with the area of observations within the 350-km radius circles. Also shown are stations Logan (LOG), Salt Lake City (SLC), Dugway (DUG), Cedar City (CCU), and Uinta Basin (UBD) Utah, Eureka (EUR), Las Vegas (LVN) and Boulder City (BCN), Nevada. Epicenters for 1968 earthquakes are shown.

Figure 2. Cumulative earthquakes per month from 1960 through 1968 at Glen Canyon and Flaming Gorge at different distance ranges from the station.

Figure 3. Graph shows extreme probability return period of earthquakes recorded at Flaming Gorge, Utah, for a period of 36 months and occurring within 350 km of the station.

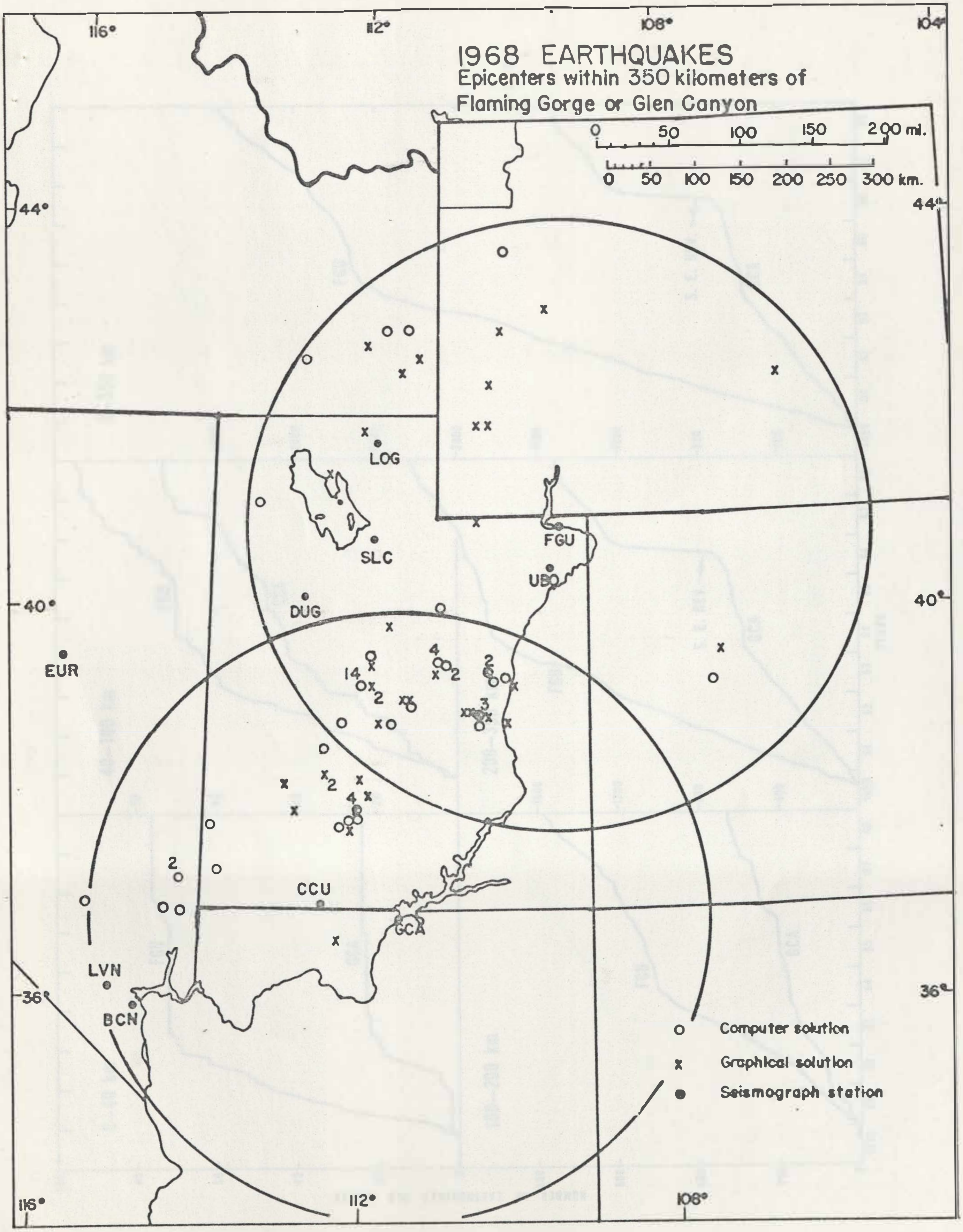
Figure 4. Contoured map of the square root of seismic source energy which is proportional to strain release. An increase in density of shading indicates an increase in strain release.

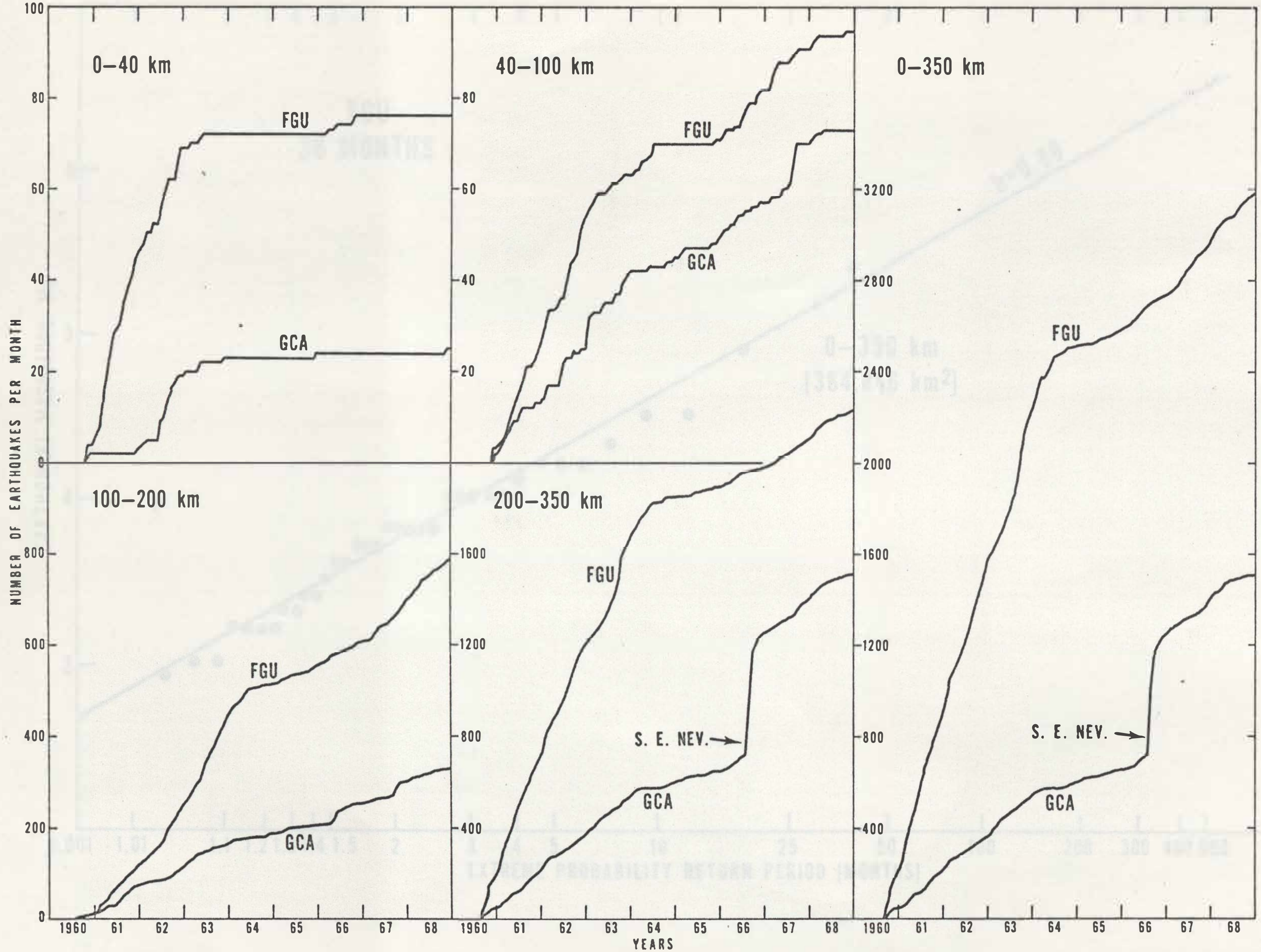
Figure 5. Number of earthquakes per month at San Luis Dam, California, from November 1965 through July 1970 in two distance ranges.

Figure 6. Extreme probability statistics at San Luis Dam for the seismicity within 0-80 and 0-25 km.

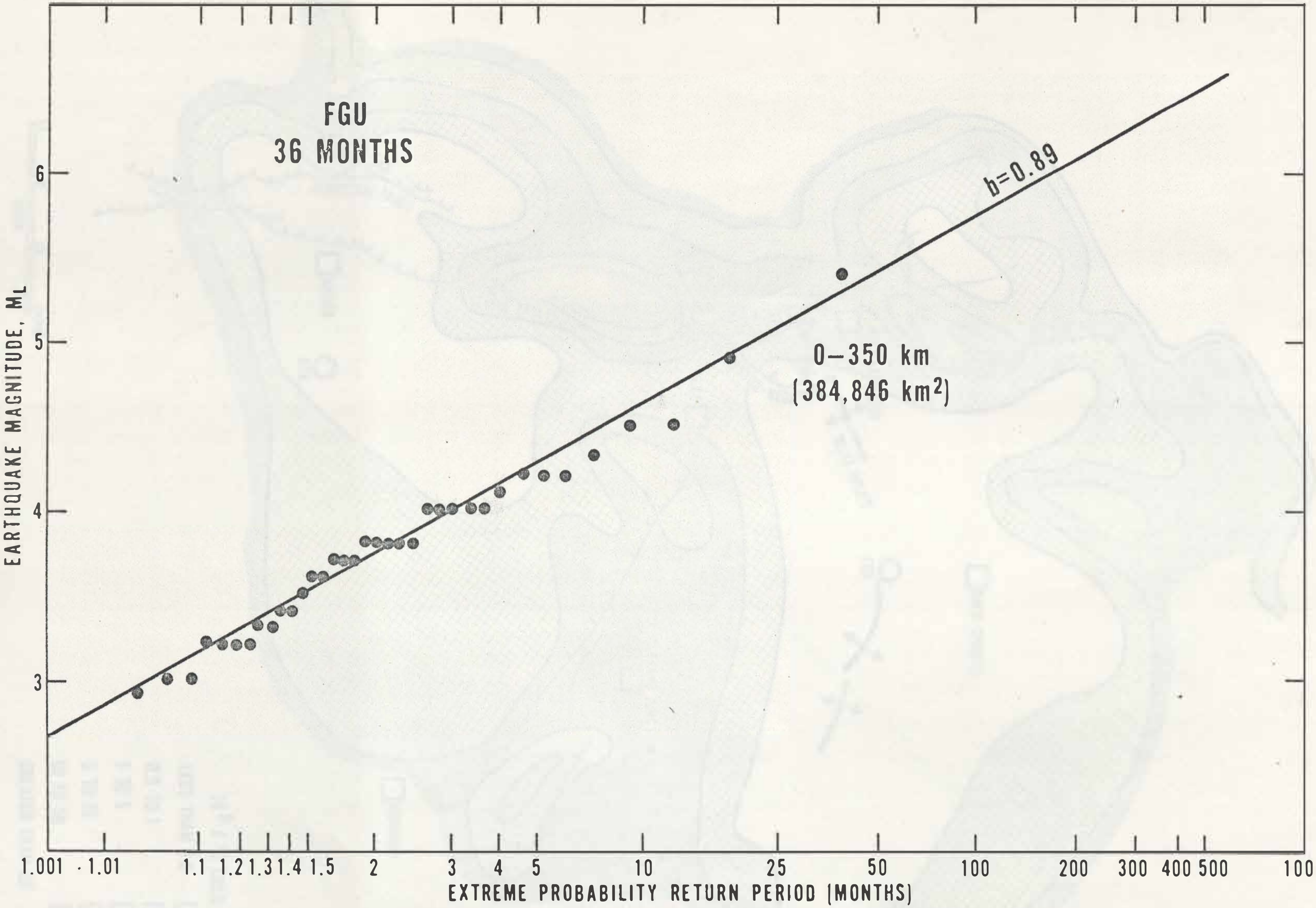
Figure 7. Earthquake occurrence characteristics in two distance ranges from Cedar Springs, California, and cumulative number of earthquakes from March 1965 through June 1967.

Figure 8. Periodicity and correlation plots of average monthly water level, number of earthquakes recorded per three-month period, and number of felt earthquakes per three-month period at Lake Mead, Nevada, from 1939 through 1951.

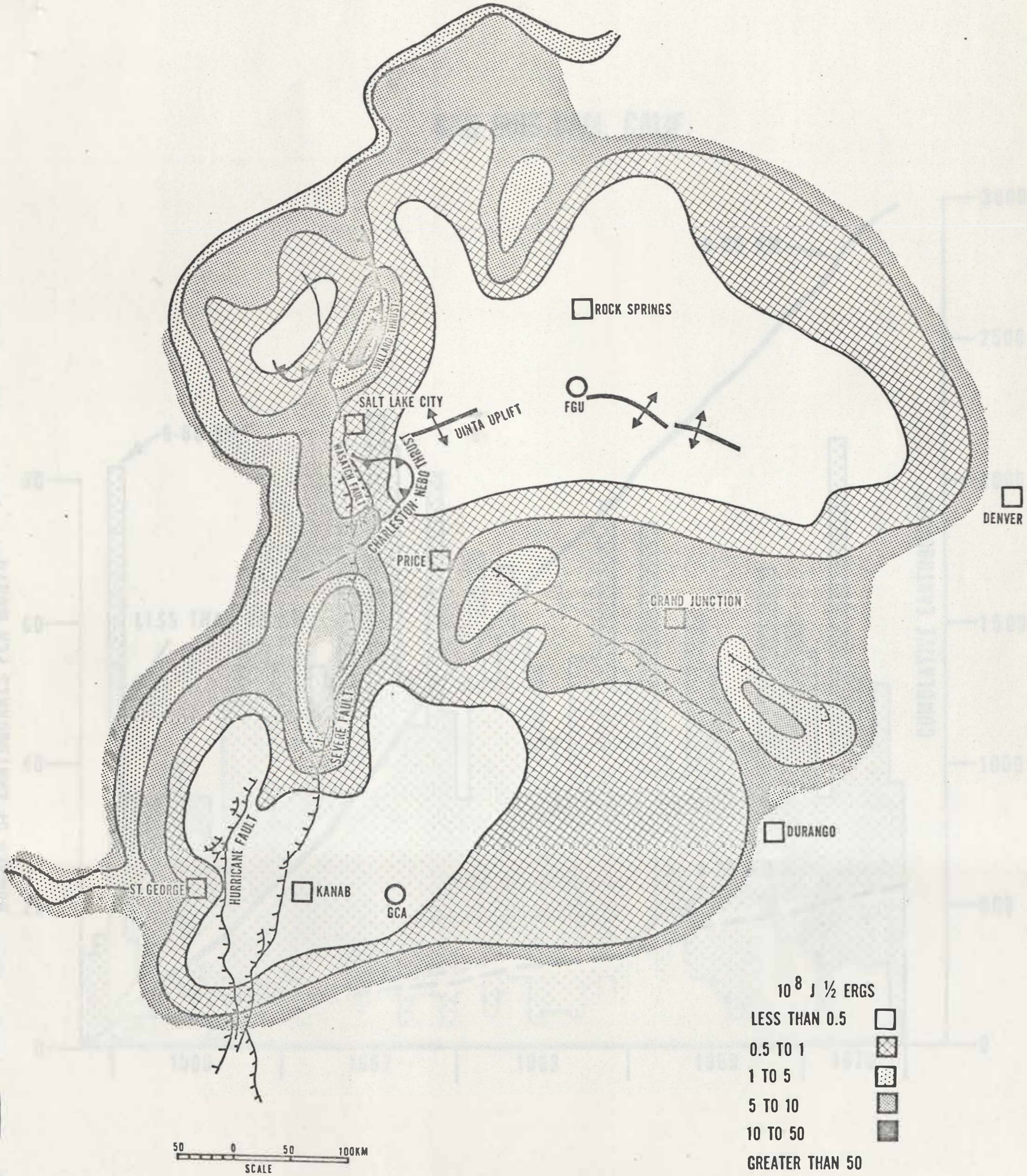

1968 EARTHQUAKES
Epicenters within 350 kilometers of
Flaming Gorge or Glen Canyon
0 50 100 150 200 mi.
0 50 100 150 200 250 300 km.
116°
112°
108°
104°
44°
40°
36°
115°
LOG
SLC
FGU
UBO
DUG
EUR
CCU
GCA
LVN
BCN
Computer solution
Graphical solution
Seismograph station



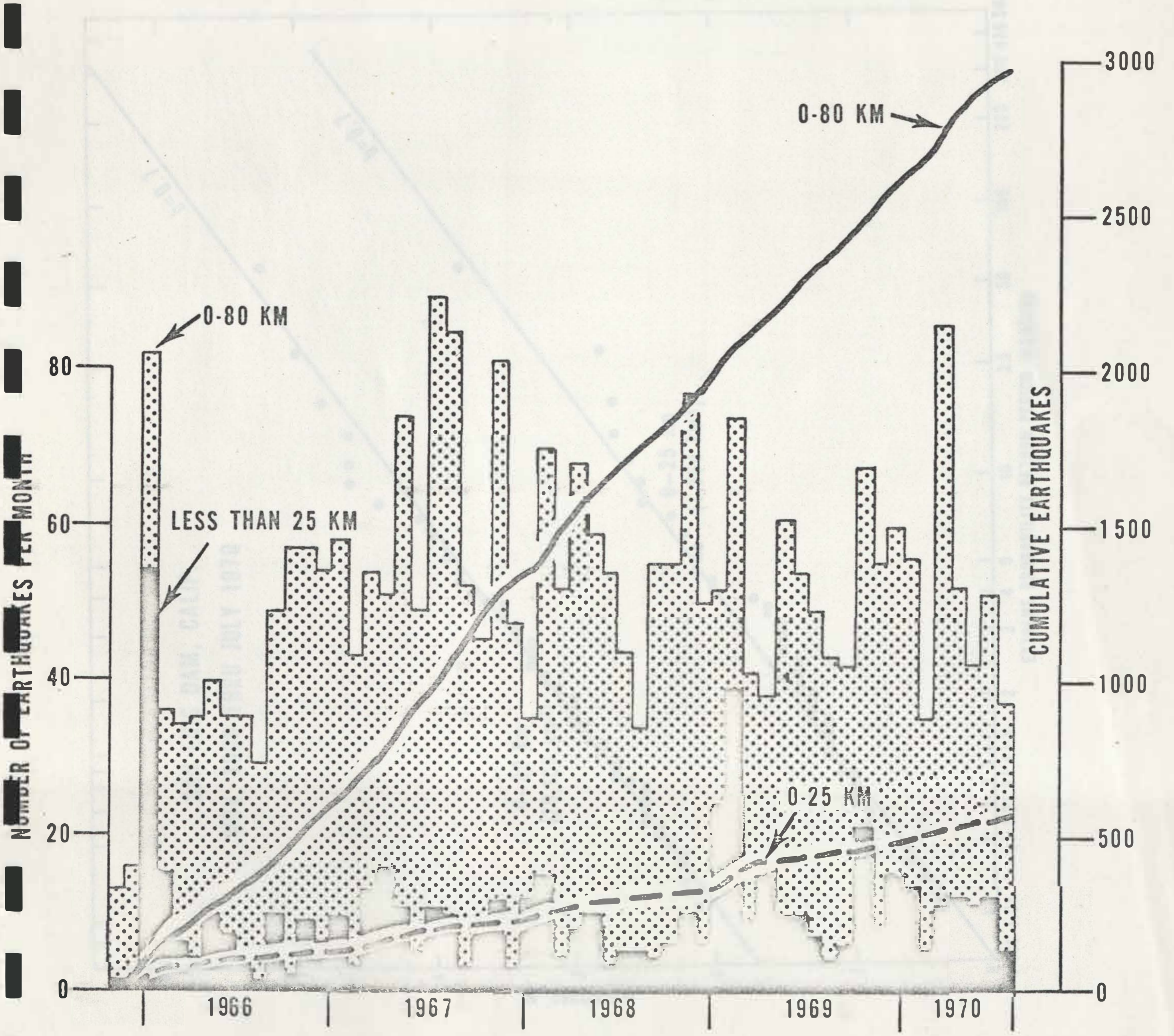
0–40 km
40–100 km
0–350 km
100–200 km
200–350 km
FGU
GCA
S. E. NEV.
NUMBER OF EARTHQUAKES PER MONTH
YEARS
1960
61
62
63
64
65
66
67
68
0
20
40
60
80
100
200
400
600
800
1200
1600
2000
2400
2800
3200

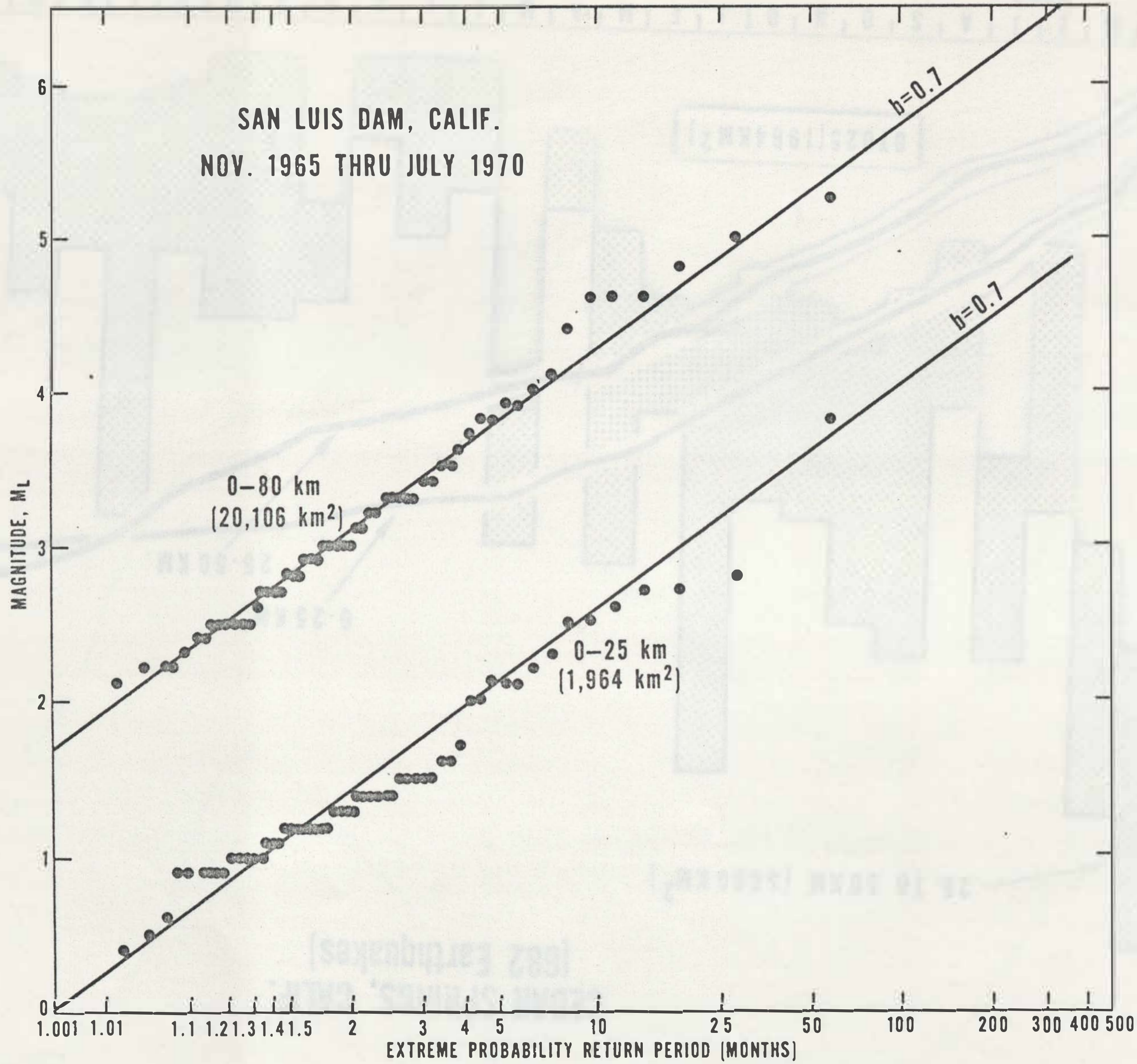


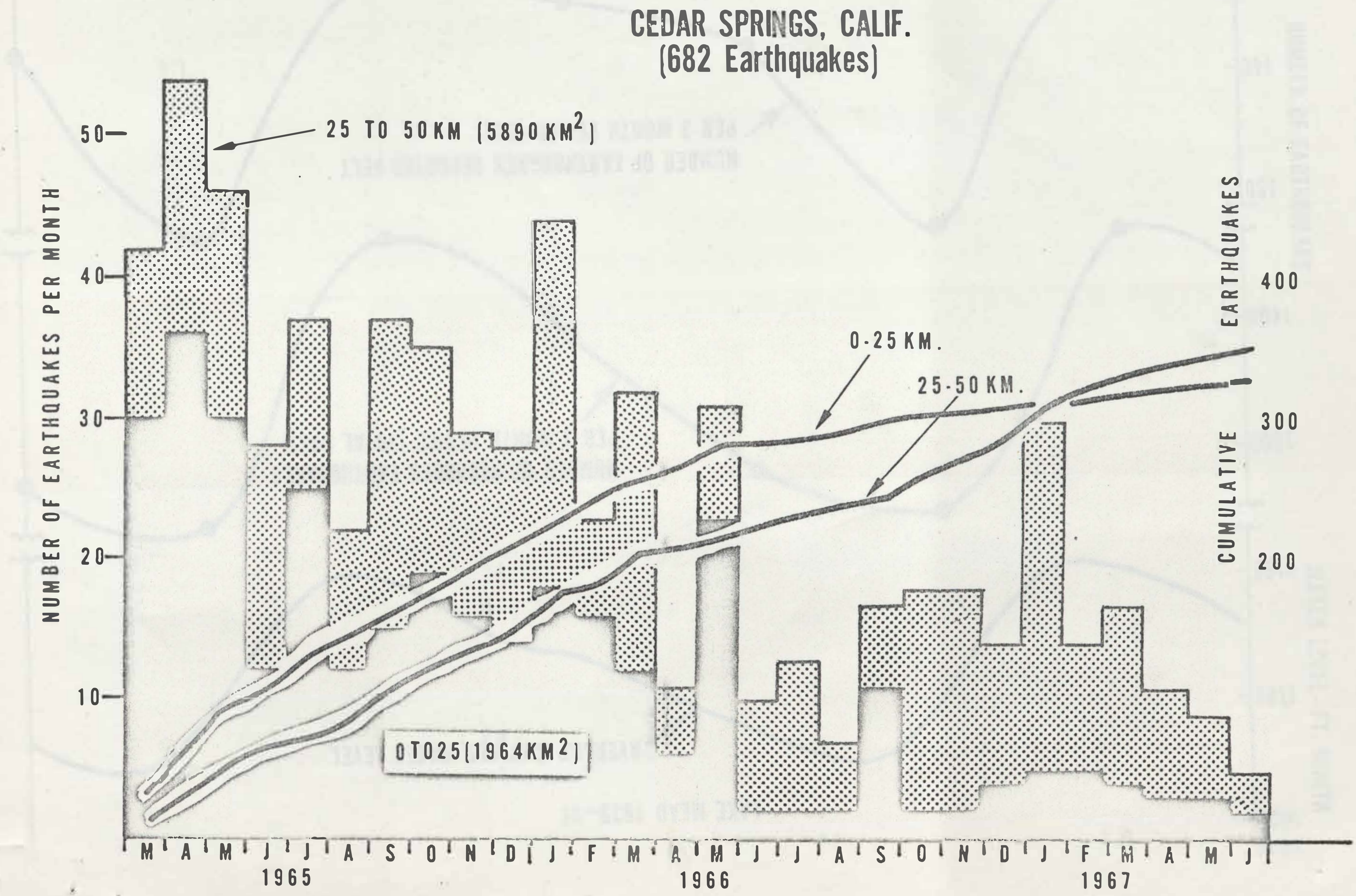
FGU
36 MONTHS
b=0.89
0–350 km
(384,846 km²)
EARTHQUAKE MAGNITUDE, M_L
3
4
5
6
1.001
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
10
25
50
100
200
300
400
500
1000
EXTREME PROBABILITY RETURN PERIOD (MONTHS)


ROCK SPRINGS
SALT LAKE CITY
UINTA UPLIFT
FGU
WILLARD THRUST
WASATCH FAULT
CHARLESTON-NEBO THRUST
DENVER
PRICE
GRAND JUNCTION
SEVERE FAULT
HURRICANE FAULT
ST. GEORGE
KANAB
GCA
DURANGO
10^8 J ½ ERGS
LESS THAN 0.5
0.5 TO 1
1 TO 5
5 TO 10
10 TO 50
GREATER THAN 50
50 0 50 100KM
SCALE

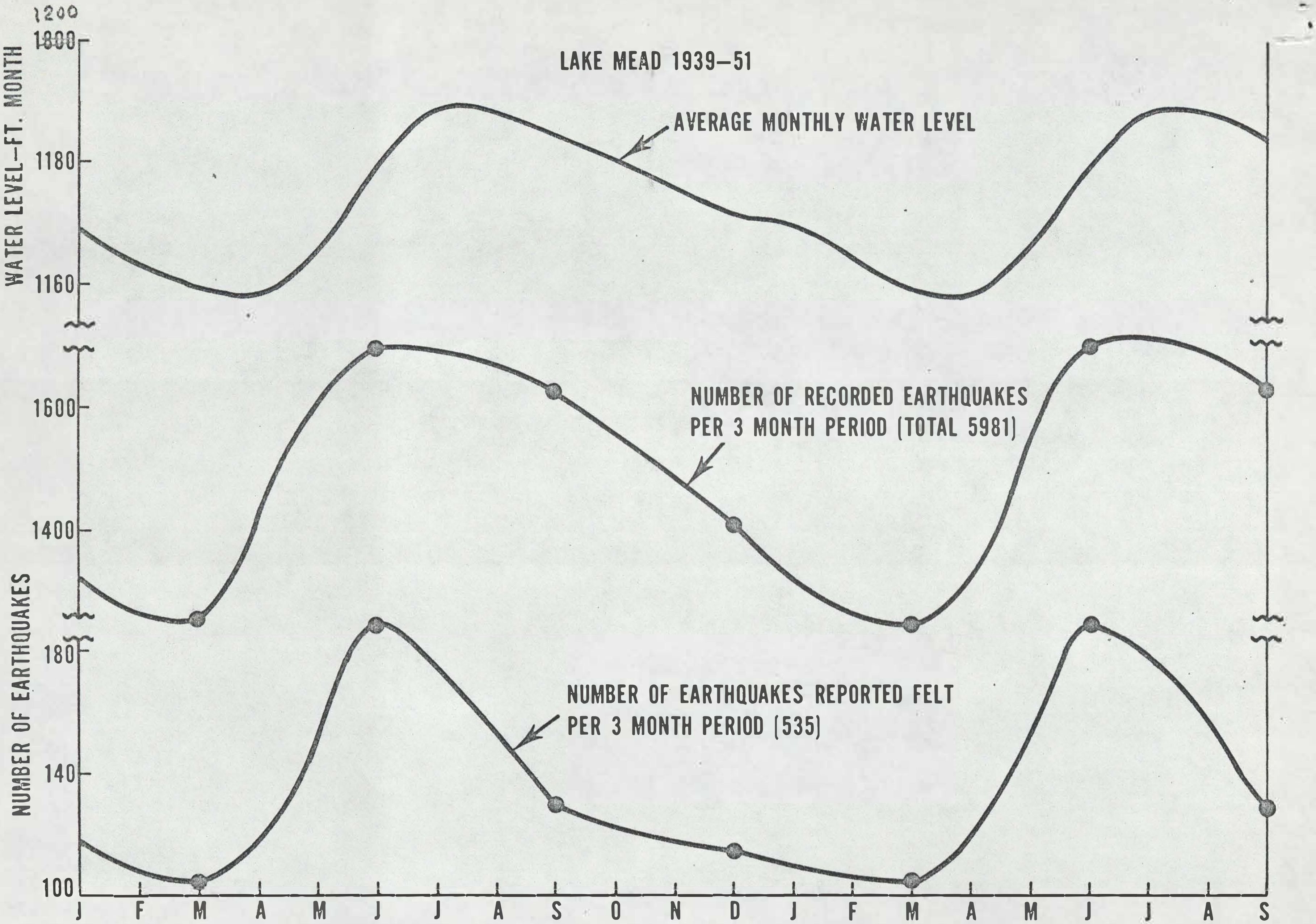
SAN LUIS DAM, CALIF.




SAN LUIS DAM, CALIF.
NOV. 1965 THRU JULY 1970
b=0.7
b=0.7
0–80 km
(20,106 km²)
0–25 km
(1,964 km²)
MAGNITUDE, M_L
0
1
2
3
4
5
6
1.001
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
10
25
50
100
200
300
400
500
EXTREME PROBABILITY RETURN PERIOD (MONTHS)



CEDAR SPRINGS, CALIF.
(682 Earthquakes)
25 TO 50KM (5890KM2)
0-25KM.
25-50KM.
0TO25(1964KM2)
NUMBER OF EARTHQUAKES PER MONTH
CUMULATIVE EARTHQUAKES
50
40
30
20
10
400
300
200
M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1965
1966
1967


LAKE MEAD 1939–51
AVERAGE MONTHLY WATER LEVEL
NUMBER OF RECORDED EARTHQUAKES PER 3 MONTH PERIOD (TOTAL 5981)
NUMBER OF EARTHQUAKES REPORTED FELT PER 3 MONTH PERIOD (535)
WATER LEVEL—FT. MONTH
NUMBER OF EARTHQUAKES
1200
1800
1180
1160
1600
1400
180
140
100
J F M A M J J A S O N D J F M A M J J A S