Selected Flood Summaries and Cost Estimates in Arizona

by Susan M. DuBois and Brian R. Parks

As explained in the previous *Fieldnotes* issue (v. 10, n. 4, p. 6), the term "flood" is often used synonomously with *runoff* and *erosion* as the cause of major damage related to heavy precipitation. Here it has been loosely applied where excerpts of source material have been quoted. However, all of the events in the chart did include periods of overbank flow (flooding) on portions of the floodplains.

Flow rates in the washes or rivers are expressed in cubic feet per second (cfs). A useful analogy for visualizing such quantities of water and rates of flow is a 3 ft wide by 5 ft long by 2 ft deep bathtub, filling to the rim in 30 seconds at 1 cfs; 1 sec at 30 cfs; 1/30 sec at 300 cfs.

Flood events presented below were selected with regard to the following criteria: 1) all resulted in either great monetary or human loss (or both); and 2) the events had a wide geographical and temporal distribution. These 15 events comprise only a small portion of the 103 *documented* floods which occurred between 1872 and 1981. [Other destructive storm runoff (not summarized below) also occurred in the following locations: Yuma—March 1884; Nogales—June 1887; Clifton—December 1906; Upper Gila River—September 1926; Safford—September 1944; statewide—December 1965; Phoenix—June 1972; central and eastern Arizona—October 1972; statewide—February 1978].

DATE	AREA DAMAGED	DRAINAGES	LOSSES *(Millions of $)*†	SOURCES
February 1890*	Statewide	All major	$ 6,636	3, 4, 15, 17
February 1891	Statewide	All major	28,575	2, 4, 5, 6, 15, 26
January—May 1905	Clifton, Upper Gila Valley	Gila River San Francisco River	37,750	5, 9, 13, 16, 20
January 1916	Statewide	Salt River Gila River Colorado River Rillito River	2,382	5, 6, 7, 15, 26
August 1940	Tucson	Santa Cruz River	960	2
July 1954	Globe Miami	Pinal Creek	3,553	10
September 1962	South Central Arizona	Santa Cruz River Santa Rosa Wash	9,310	2, 12, 22
August 1963	Prescott	Granite Creek	1,441	1
September 1964	Tucson	Rillito River Santa Cruz River	6,411	14
December 1966	Grand Canyon	Crystal Creek Chuvar Creek	5,040	8, 19
September 1970	Santa Cruz Basin North Central Arizona	Tonto Creek Santa Cruz Verde River Oak Creek	10,860	18, 21
September 1976	Bullhead City	Silver Creek	7,440	10
October 1977	Santa Cruz Basin	Santa Cruz River	56,160	2, 22, 23
December 1978	Central and Eastern Arizona	Gila River Salt River San Francisco River	85,020	2, 24, 25
February 1980	Phoenix	Salt River	40,607	2, 4, 11

†In this column losses have been adjusted to 1979 dollars using the Gross National Product Implicit Price Deflator.
*See summaries of these events below.

February 1890

Heavy rains caused the Santa Cruz, Salt, Gila and Colorado Rivers to overflow. The Tempe bridge and miles of track between Maricopa and Yuma washed out. Farmland and irrigating systems, mostly in the upper Gila valley, were destroyed. The wood and earthen Walnut Grove Dam (110 ft high, 400 ft wide) 20 mi. S of Prescott on the Hassayampa River overflowed and burst on 2-22/90. Approximately 50,000 acre ft of water were released as a "wave 100 ft high" destroyed everything in its path, including several mining camps and an uncompleted smaller irrigation dam. Between 70 and 100 deaths were reported. The dam failed after its spillway became clogged with vegetation and water overflowed its crest. Damage estimate includes *only* cost of Walnut Grove Dam.

February 1891

Heavy rains starting on 2/15/91 created some of the largest estimated flows on major drainages in Arizona: Bill Williams River at Planet on 2/21/91 was 200,000 cfs; San Francisco River at Clifton called the "highest to date"; Salt River at Phoenix was 300,000 cfs; Gila River near present day Gillespie Dam on 2/22/91 was 250,000 cfs (greatest known flow to date); Colorado River at Yuma on 2/25/91 was 300,000 cfs. [In comparison to these flow rates, Salt River Project releases in February 1980 were 78,000 to 180,000 cfs.] In 1891, all towns along these rivers were affected. Clifton was under much water; all bridges and nearby irrigation systems were destroyed. At Globe "many buildings were damaged or lost." At Phoenix the Salt River was 18 ft above normal. The railway and its bridges were destroyed. Below Phoenix the Gila River was 2-3 mi. wide in places. At Yuma "every structure of consequence not completely destroyed was surrounded by water." Other localities reporting damage include Prescott, Holbrook, Cottonwood, Ft. Thomas and Ft. Apache. At this time Phoenix and Yuma had populations of 2,000 each. In Arizona no large flood control structures were in existence. The $28,575,000 damage estimate is for Yuma and its surroundings only.

January 1905—May 1905

Above average precipitation during this period caused widespread flooding throughout central and eastern Arizona. In January floodwaters damaged many acres of farmland and inundated several towns in the upper Gila River valley. Clifton experienced its "most disastrous flood in history"; the town was heavily damaged; all bridges across the San Francisco River were destroyed and the area was isolated for several weeks. During February, Phoenix had 4.64 in. of rain; Cave Creek overflowed its banks for the second time in two months covering the state capitol grounds. The Salt River at Phoenix was reported to be the "highest since the 1891 flood." Heavy rains continued through March and April producing flood stages on the Salt, Gila and Little Colorado Rivers. On May 2, the Norman Dam, located 7 mi. upstream from St. Johns on the Little Colorado River, burst, flooding farmland and drowning livestock downstream from St. Johns. The city itself received little damage. Loss of irrigation water impounded behind the dam affected farming throughout the valley until the new and larger Lyman Dam was constructed. [In April 1915, heavy rains caused this new dam to break, inflicting at least 8 deaths and great damage downstream as far as Holbrook.]

January 1916

January went on record as the wettest month since the establishment of the Arizona Climatological Service in 1892. "Between 4 and 6 in. of rain fell in the Gila valley lowlands. Two separate storm systems converged over Arizona during the month; the first from 1/15/16 to 1/21/16 soaked the ground; the second from the 1/26/16 to 1/30/16 caused heavy damage. The Salt River at Tempe on 1/19/16 was 18.7 ft [flood stage is 7 ft]. Flow on the same day was 100,000 cfs. Other flows for the month include 100,000 cfs in the Salt River below Roosevelt; 90,000 cfs in the San Francisco River at Clifton on 1/19/16; 100,000 cfs on 1/19/16 in the Gila River at Safford; and 130,000 cfs in the Gila River at Coolidge Dam on 1/20/16. Cities damaged along the Salt and Gila River valleys included Chandler, Tempe, Phoenix, Gila Bend and Yuma. Yuma experienced the worst damage; "81 buildings reported consumed". On 1/22/16 Colorado River flow at Yuma was 220,000 cfs; the Gila River flow at Dome (20 mi. E of Yuma) was 200,000 cfs. The damage figure does not include Yuma's losses.

August 1940

Summer monsoons brought 2.94 in. of rain to Tucson in August, producing floods on 8/13/40 along Tucson Arroyo and Rillito and Santa Cruz Rivers. Flow data on 8/13/40 show the Rillito at 13,200 cfs and the Santa Cruz at 11,300 cfs. The Rillito River flowed 200 yds beyond its banks in places. Most damage occured near Tucson Arroyo, including flooding of the Tucson Gas and Electric Company which caused a blackout. Southern Pacific track and bridges at Fairbank (near Tombstone) were washed out. [Other damaging floods in Tucson and the surrounding area within this decade include 9/43, 8/45, and 7/48, with a combined loss of $1,381,100].

July 1954

On 7/20/54 and 7/29/54 flash floods caused serious damage to Miami and Globe. Monthly rainfall totals for Miami and Globe were 3.36 in. and 2.77 in. respectively. At Miami the flood piled up cars and damaged a number of business establishments. Globe suffered when a wall of water came down Pinal Creek and flooded the business section with several feet of water. New cars were reportedly washed out of a showroom and destroyed. Twenty-five businesses were destroyed; 40 others damaged, and 126 families claimed losses in a two block section of Globe.

September 1962

Heavy rains which fell from 9/26/62 to 9/28/62 in Pinal and Pima Counties resulted in severe flooding, predominantly in agricultural areas: Sells received 4-6 in.; Tucson, 3.5 in.; the Tucson Mountains (near the Desert Museum), 5.95 in.; Marana, 4.6 in; and Avra valley, 6 in. Peak stream flows include 17,000 cfs on the Santa Cruz River at Cortaro and an amazing 53,000 cfs on the Santa Rosa Wash. [Estimated peak flow of a 100-yr. flood is 41,200 cfs.] Near Eloy a flat area known as Green Reservoir formed a lake 40 sq. mi. by 8 mi., "five foot cotton disappeared beneath water." The water destroyed dikes while flooding thousands of acres of farmland. The towns of Maricopa and Stanfield were evacuated because of high water in the Santa Cruz River. Sells experienced its "worst flood in memory" and many of the 70 surrounding Indian villages became isolated as a result of the storm.

August 1963

The third storm of the month hit north-central Arizona on 8/19/63, dropping 1-4 in. of rain on the Prescott area. The four tributaries of Granite Creek poured 7,000 cfs of water into Prescott; "higher flows may have occurred in the past 50 years, but none caused nearly as much damage." In 1963 the population of Prescott was 13,000 [by 1978 19,000]. Much of the damage occurred in residences along the narrow valleys. The creek channels were constricted by developments. When rains came, drainages were of insufficient size to carry the runoff. In places the creeks were 200 ft wide, whereas *before* the flood their channels were only 20-30 ft wide. Two miles of sewer line were completely washed out and another section, 6 mi. long, was damaged. Residential, commercial and business properties were also damaged. The governor declared Prescott a disaster area.

September 1964

The storm of 9/9 to 9/11/64 resulted in a maximum total precipitation of 6.73 in. over the Santa Catalina foothills and Sahuarita. Peak discharges on local streams include 13,000 cfs at Tucson and 14,000 cfs at Continental, both on the Santa Cruz River; 9,420 cfs at Tucson on the Rillito River; and 9,960 cfs near Vail on Pantano Wash. Flooding occurred predominantly in two areas: 1) from Continental to Sahuarita the Santa Cruz River was one mile wide over half the distance, inundating many areas of ripe unpicked cotton 2) from Marana to Chuico, water overflowed dikes and flooded 35 sq. mi. of floodplain. Much lateral erosion and downcutting occurred along the Santa Cruz River. For example, at the Ajo Way Bridge the river bed was 2-3 ft lower than the level after the 9/61 flood and 8 ft lower than it was in 1958 when the bridge was constructed.

December 1966

The sparsely populated eastern Grand Canyon experienced flooding of a rare magnitude from 12/4-12/7/66. Although few gaging stations are located in the area, rainfall totals collected during the storm indicate that great precipitation occurred in several localized areas: at Tuweep, 6.05 in.; at Jacob Lake, 6.60 in.; at Bright Angel Ranger Station, an estimated 12 in.; and at the North Rim entrance station, an estimated 14 in. Peak discharges include 3,000 cfs on Nankoweap Creek and 4,000 cfs on Bright Angel Creek, which destroyed the gaging station. Extensive mud and debris flows along the uninhabited drainages of Dragon, Crystal, Lava, Nankoweap, Kwagunt and Shinumo Creeks caused little economic loss but damaged several archeological sites and altered stream geometries. Other flood related losses, mainly in the

Bright Angel Creek drainage, included a powerhouse, pumping station, newly constructed water line, camp grounds and facilities.

Mudflows occurred on the undeveloped and unpopulated Crystal Creek. Loss of life and many more buildings would have been expected if similar mudflows had occurred along Bright Angel Creek. Cooley (1977) states, "the floods of December 1966 probably were greater than any since the general abandonment of the eastern Grand Canyon by the Pueblo Indians about A.D. 1150."

September 1970

On 9/4–9/6/70, an intense storm resulted in flooding throughout the Santa Cruz River basin, in the Four Corners area, and especially central Arizona. The Mogollon Rim area and the Santa Catalina Mountains each received more than 5 in. of rain; Payson reported 5.36 in. on 9/3/70; Tonto Creek fish hatchery received 5.63 in. on 9/6/70; and Sasabe reported 4.36 in. on 9/4/70. Peak discharge data includes 53,000 cfs and 44,000 cfs on the Tonto Creek near Roosevelt and Gisela, respectively; 24,700 cfs on Oak Creek near Cornville; 7,750 cfs on Sabino Creek near Tucson and 19,000 cfs on the Agua Fria River near Mayer. The cities of Buckeye, Tucson, Payson, Wickenburg, Phoenix and Scottsdale (where 250 homes were evacuated) reported damages. Twenty-three deaths occurred along Tonto Creek where many people were vacationing over Labor Day weekend. On 9/8/70 the Mesa Tribune reported, "Tonto Creek exploded into a churning boiling mass of water, rocks and full grown trees which crested at over 30 ft in depth in the flat areas." Also the fish hatchery, summer cabins, mobile homes and nearby roads were destroyed along Tonto Creek.

September 1976

Tropical storm Kathleen dropped 2–5 in. of rain on Bullhead City and the surrounding area, 9/11/76. Flash flooding and mud flows occurred on 8 major washes leading into Bullhead City from the surrounding mountains. The Silver Creek crossing of state route 95 was cut into "a 20–40 ft deep canyon by the raging waters." The rains cut off all overland assistance to the city and caused an estimated $3 million in damages, $2.5 million of which was private property loss. The Governor's office declared the city a disaster area on 9/21/76. A second storm on 9/24/76 dropped an additional 2–5 in. of rain, causing another $2–3 million in damages.

October 1977

Heavy rains of 10/6–10/10/77 brought by tropical storm Heather caused severe flooding in the Santa Cruz and San Pedro River basins. The heaviest rains fell in the vicinity of Nogales where the official total was 8.3 in. [Unofficial totals reported for the area are 12 in.] Peak discharges on the Santa Cruz River were the largest ever recorded at USGS gaging stations: 12,000 cfs near Lochiel; 33,000 cfs near Nogales; 28,000 cfs at Continental; 23,700 cfs at Tucson and 24,500 cfs at Cortaro. Other peak flow data include 23,700 cfs on the San Pedro River near Tombstone and 4,000 cfs on the Nogales Wash at the Old Tucson highway. Santa Cruz, Pima and Pinal Counties were declared disaster areas on 10/9/77. Damage was concentrated along the Santa Cruz River floodplain and its tributaries. A total of 12,000 acres of agricultural land was damaged in these counties. In Nogales, flooding displaced 54 families along Nogales Wash. A total of 160 residences were damaged or destroyed along the Santa Cruz River. Coronado National Forest suffered over $1 million damage to roads and bridges. Tucson, Green Valley, Sahuarita and Marana also reported damages due to flooding.

December 1978

Precipitation in the Gila River drainage basin on 12/16–12/20/78 ranged 1–10 in. causing the most costly runoff event in Arizona's history. Reported stream discharge data for 12/19/78 include 56,000 cfs on the San Francisco River at Clifton; 100,000 cfs on the Gila River near Safford; 140,000 cfs on the Salt River at Phoenix, and 126,000 cfs on the Gila River at Painted Rock Reservoir. Graham, Greenlee, Navajo and Maricopa Counties were declared federal disaster areas. Serious damage occurred in the upper Gila River valley between Pima and Duncan where 75 homes were destroyed. Sixty eight percent of the homes in Little Hollywood (near Safford) were destroyed; 2,000 people in Safford were evacuated and $12 million worth of damage to agricultural land was reported. The Phoenix metropolitan area was also affected by heavy runoff where a total of $56 million of damage occurred; 30% of this damage was caused to roads and bridges. Also damaged were Tucson, Summerhaven, Green Valley, Marana, Clifton, Thatcher, Pima, Scottsdale, Glendale, Tempe, Winslow, Williams and Gila Bend. There were 12 reported deaths from the storm.

February 1980

Damage totals for the mid-February *"flood"* are still incomplete, but expected to be higher. The Phoenix metropolitan area experienced its second major runoff event in two years, resulting in the evacuation of 6,000 people, and leaving only two of the ten area bridges open. Discharges for the Salt River at Phoenix ranged between 78,000 cfs and 180,000 cfs during the peak flow. Mesa, Scottsdale, Tempe, Glendale and Buckeye also reported damage.

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Index to Fieldnotes: March 1971 to March 1981

The following data indicate references listed under Volume-Number, Page; for example, 11-1, 1 represents volume 11, number 1, page 1.

A Decade of Fieldnotes

by H. Wesley Peirce

The first issue of our quarterly publication, *Fieldnotes*, rolled off the presses ten years ago in March 1971. At the rate of 48 pages each year, we have published 480 pages over this ten year span.

One of the reasons for developing *Fieldnotes* was to give wider visibility and recognition to the Bureau as a research and service agency of the state of Arizona. Our contacts with newspapers, television and radio stations, state and federal agencies, companies, universities, various civic groups, individual scientists and lay persons, have substantially increased over the past decade. We attribute much of this to recognition gained through *Fieldnotes*. Also, it provides a mechanism for timely response, as well as an outlet for selected geologic and mineral or energy related information that might otherwise be greatly delayed, never compiled or remain buried in files.

As with most endeavors there have been both pains and pleasures. In general, we are very pleased with the way *Fieldnotes* has been received and supported. The effort seems worthwhile.

Ten years ago, filling a 12-page quarterly issue was a burden. We rotated the editorship among our small cadre of professional staff and published many short items, some original and some gleaned from our readings and contacts with other organizations. Finally, along with the growth in federal agency research grants, came a full-time, permanent editor. More recently, the emphasis has been on the sharing of original research done by Bureau personnel.

Once in a while we slip in an item intended to re-emphasize the extent to which we humans are wedded to mother earth. Philosopher Will Durant wrote: "Civilization exists through geological consent. . . ." This is an important ecological truism too easily forgotten in the everyday hustle of modern life. Its meanings and implications should be probed and the results widely shared.

Thinking ecologically, we in the Bureau recognize that Arizona, like any other state, is not an independent entity capable of self support. What happens elsewhere might significantly affect Arizonans. Perhaps the best recent example is OPEC (Organization of Petroleum Exporting Countries), a totally foreign entity. Have we been immune from their actions? Is there a connection between OPEC pricing and the fact that more of Arizona is under petroleum lease and associated intensive geologic investigation than ever before?

Fieldnotes is the vehicle we use to share such geologically related "goings on" with the citizens of Arizona.

To us, this is an exciting place. Great gaps remain in our knowledge of the real, three dimensional Arizona. Over the next decade, through *Fieldnotes*, we will attempt to share some of the excitement that inevitably accompanies the search for and acquisition and application of new knowledge and insights about this special piece of earth. In large part, the shape of the state's future depends upon it.

NATIONAL/REGIONAL EVENTS

American Association of Petroleum Geologists and Society of Economic Paleontologists & Mineralogists:
Rocky Mountain Section Meeting, Albuquerque, April 12–15, 1981 Annual Meeting, San Francisco, May 31–June 3, 1981

Geological Society of America:
Rocky Mountain Section Annual Meeting, Rapid City, April 16–17, 1981
Annual Meeting, Cincinnati, Nov. 2–5, 1981

New Mexico Bureau of Mines—Forum on the Geology of Industrial Minerals, Albuquerque, May 13–15, 1981

American Geophysical Union—Spring Meeting, Baltimore, May 25–29, 1981

Association of Earth Science Editors—Annual Meeting, Denver, Oct. 4–7, 1981

PUBLICATIONS

"On May 3, 1887, a major earthquake shook much of the southwest United States and Mexico, an area of nearly two million square kilometers. This seismic event, with an estimated magnitude of 7.2 caused 51 deaths in northern Sonora, and major destruction of property in southeast Arizona, as well as adjacent portions of Mexico . . ." So begins the 112-page Special Paper No. 3, recently completed by the Bureau of Geology and Mineral Technology. The study is entitled, *The 1887 Earthquake in San Bernardino Valley, Sonora: Historic Accounts and Intensity Patterns in Arizona*, co-authored by Susan M. DuBois and Ann W. Smith. The cost is $6.00. This volume may be purchased from the Bureau's Publication Desk, 845 N. Park Ave., Tucson (near the U of A campus) or by mail (with a handling charge of 20% of the total order).

The research project was funded by the U.S. Geological Survey, the U.S. Nuclear Regulatory Commission and the State of Arizona.

ARIZONA TREASURES — Mining, Mining Camps, Mines (fact and fable), Prospecting and Treasure Hunting: A selected bibliography of materials in the Arizona Department of Library, Archives and Public Records, Research Division. This 43-page document was compiled by Marianna Hancin while she was a graduate student in Library Science at the University of Arizona. Copies may be obtained, at no charge and while the supply lasts, from the Department of Library, 1700 West Washington, 3rd Floor, Phoenix, AZ 85007.

UPS and DOWNS

A Reply to "Is There a Casa Grande Bulge and Will It Cause Earthquakes in Arizona?"

by *Thomas L. Holzer*

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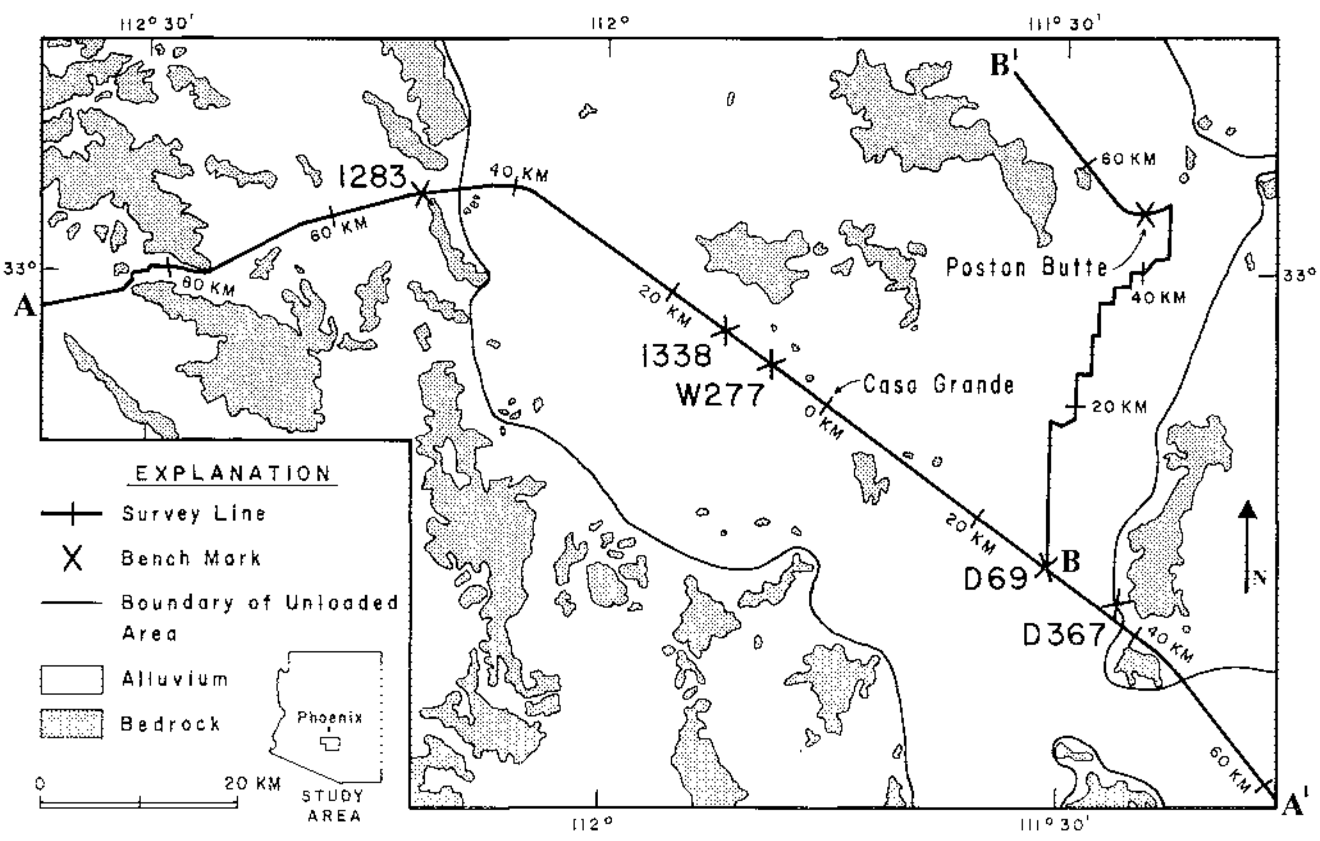
In late 1979 an article by Dr. Thomas Holzer, "Elastic Expansion of the Lithosphere Caused by Groundwater Depletion," appeared in the Journal of Geophysical Research. This frontier scientific work relates to man-induced land movements in Arizona, especially near the well-known subsidence region of south-central Arizona. A response to certain ideas presented in Holzer's paper, written by personnel of the U.S. Water and Power Resources Service (formerly the Bureau of Reclamation), appeared in a recent issue of Fieldnotes under the heading: "Is There a Casa Grande Bulge and Will It Cause Earthquakes in Arizona?" The Bureau of Geology and Mineral Technology offered Dr. Holzer an opportunity to reply to this and he has done so in the following article.

Although the subject matter is both technical and interpretive, relying as it does on the precision of measurement as well as theoretical considerations, it was the Bureau's decision to share this ongoing frontier work with its readers even though the last word has yet to be written. Such is the nature of new knowledge.

INTRODUCTION

In the September 1980 issue of *Fieldnotes*, Raymond and others (1980) question the hypothesis of crustal expansion caused by depletion of groundwater in south-central Arizona (Holzer, 1979). In particular, they question the analysis of leveling data that supported the hypothesis. Their questions, however, appear to be based on 1) misunderstandings of how geodetic data are collected and reduced and 2) misinterpretation of Holzer (1979). Before responding in more detail to the issues they raise, a review of the original article is in order. In Holzer (1979), the mass of water impounded behind Lake Mead, where measurement showed an elastic crustal depression of 17.8 cm in response to the load imposed by the water, was compared to the masses of groundwater that have been removed from several areas in the United States. The comparison revealed that in two areas, south-central Arizona and the southern High Plains of Texas, more water had been removed than was impounded at Lake Mead. Hence, crustal uplift of a few centimeters caused by elastic crustal expansion was anticipated in these two areas. Because actual magnitudes of uplift depend on the area over which unloading is distributed as well as the mass change, Holzer (1979, equation 2) derived an index to take this into consideration. Comparison of indices (Holzer, 1979, Table 1) suggested that a maximum uplift approximately equal in magnitude to half (actually 58%) of the maximum depression at Lake Mead occurred in south-central Arizona from 1915 to 1973. Raymond and others (1980) propose that the theoretical uplift is larger, equal to 74%, but this is based on their comparison of a value of uplift computed from the index formula with the measured depression at Lake Mead.

On the basis of this comparison, Holzer (1979) evaluated precise leveling data from south-central Arizona to determine if such an uplift could be detected. Leveling data collected in 1948 and 1967 suggested that indeed detectable uplift had occurred in areas near Casa Grande and possibly near Florence. Analysis of potential random and systematic surveying errors suggested that the observed uplift was statistically significant at least near Casa Grande. The magnitude of uplift measured at these two locations was also compatible with theoretically computed estimates of uplift based on the distribution of groundwater pumpage in south-central Arizona (Holzer, 1979, table 5). Raymond and others (1980)



Map showing locations of area unloaded by groundwater depletion, survey lines A-A' and B-B', and key bench marks (modified from Holzer, 1979).

question the geodetic evidence for uplift, claiming the surveying was not sufficiently accurate to measure it. They question it on the following bases: "1) unadjusted data with varying degrees of accuracy are compared, 2) data points are widely spaced and may have been disturbed or destroyed in some cases, 3) elevational changes are computed in relation to a single bench mark, and most importantly, 4) leveling errors were evaluated by nominal accuracy methods which yield minimal values of one half of the permissable error."

DISCUSSION OF LEVELING DATA

Before I respond to their questions, it is instructive to review briefly how precise leveling data are collected and the nature of errors associated with their collection. The leveling data at issue were collected by the U.S. Geological Survey and the National Geodetic Survey (formerly U.S. Coast and Geodetic Survey) from 1905 to 1977. The leveling process used by these agencies adheres to rigorously defined procedures and uses special precise equipment. The leveling is assigned an order and class on the basis of the standards used. The intent of the procedures is to minimize systematic error and to cause random error to self cancel. In the leveling process, the survey lines are divided into sections defined by adjacent bench marks. In the leveling considered here, each section is double run, i.e., leveled back and forth between each bench mark pair. The difference between the backward and forward runnings is the misclosure. The misclosure must be less than a certain value defined by the order and class of leveling, or the section must be releveled. The accuracy of the leveling, if errors are truly random, will tend to be better than the allowed misclosures because of the tendency of these errors to self-cancel rather than to accumulate. For example, First order, Class I leveling permits section misclosures of 3 mm $(K)^{1/2}$, where K is the length of the section in kilometers. The National Geodetic Survey, however, from analysis of many leveling results, estimates that leveling to First-order, Class I standards currently has a standard error of 0.5 mm $(K)^{1/2}$ (Federal Geodetic Control Committee, 1974, Table 1). Before publishing the results from these level surveys, both the U.S. Geological and National Geodetic Surveys adjust their data in order to make the new elevations consistent with elevations from pre existing surveys peripheral to the newly surveyed network or line and to distribute accumulated survey error within the new network.

The first and fourth questions raised by Raymond and others (1980) are most easily discussed together. Two separate issues are raised the use of adjusted versus unadjusted data and survey error. Raymond and others (1980) imply that the use of unadjusted data was inappropriate because they use published adjusted elevation data to argue that subsidence rather than uplift occurred during the period, 1948 1963, in the area near Casa Grande. Evaluation of small crustal movements on the basis of published adjusted elevations is apt to be misleading without careful analysis of the assumptions that were made in the adjustment. For this reason, published, adjusted data are seldom used in investigations of crustal movements. A classic example of how published adjusted data can mask real movement is the discovery of the first example in the United States of land subsidence caused by groundwater withdrawal. Indication of movement due to land subsidence in the Santa Clara Valley, California, initially was interpreted by the National Geodetic Survey to be survey error and was adjusted out of the published elevation data. It was only after a second releveling that land subsidence was recognized (Tolman and Poland, 1940). By using unadjusted data as was done in Holzer (1979), computed changes of elevation of a given bench mark depend only on survey error and vertical crustal movements on the leveling line. No other assumptions are hidden in unadjusted data, other than possible rod miscalibrations.

Raymond and others (1980) are incorrect when they state Holzer (1979) used the "nominal accuracy between points" formula published by the Federal Geodetic Control Committee (1974) and that Holzer (1979) did not take into account the varying precision of the data over time. Holzer (1979, p. 4694) states that the formula for the "standard deviation for random error" was used, but incorrectly cited Table 4 instead of Table 1. Moreover, the texts in both tables (Holzer, 1979) are explicit about which formula was used. Raymond and others (1980) are correct when they note that the precision of leveling has improved over the 1905 77 time period covered by the data that were used. This improvement resulted from refinements in procedures and equipment. I took this into account by using for all surveys the standard error formula that applied to the earliest (1905) survey, 2mm $(K)^{1/2}$ (Vanicek and others, 1980), rather than using the formula 0.5 mm $(K)^{1/2}$ cited in the Federal Geodetic Control Committee (1974, Table 1). This was done because the error formula published in the Committee report applies only to post-1974 surveys. The practical significance of this is that the calculated standard deviations I cited are conservative, i.e., they tend to overestimate the random error. If formulae appropriate to the vintage of leveling are used (Vanicek and others, 1980), smaller random errors are indicated so that the observed uplift becomes even more statistically significant than was originally reported. For example, the 1948–1967 indicated uplifts of 6.3 and 7.5 cm at bench marks W277 and Poston have an uncertainty (two standard deviations) for random error of ± 2.4 and ± 4.1 cm, respectively instead of ± 3.7 and ± 6.4 cm originally reported by Holzer (1979, Table 5). Holzer (1979) also recognized evidence for possible systematic error in the leveling data. Because the analysis of this error is not questioned, the reader is referred to Holzer (1979) for discussion. It is worth noting that even according to the error analysis by Raymond and others (1980), the observed uplift of 6.2 cm of bench mark 1338 is greater than their estimated error of ± 4.8 cm. Raymond and others (1980) are incorrect when they imply that Holzer (1979) noted a crustal uplift of 6.2 cm at bench mark D367 from 1948 to 1967. Bench mark D367 was not set until 1967.

The second question raised concerns the wide spacing of bench marks and their disturbance and destruction. The spacing between bench marks for which elevation changes were computed is significant because cumulative distance along the leveling line from the reference bench mark determines the accuracy of computed elevation changes (Raymond, R. H., oral communication, 1980). This effect is considered in the formulae for random and systematic errors that were used in the accuracy analysis in Holzer (1979). As noted previously, the observed uplift is statistically significant. Bench-mark destruction should have no effect on the accuracy of surveys, but does decrease the resolution of the observed uplift because the number of bench marks is diminished at which changes of elevation can be computed. Obviously, if the uplift had been observed at a single bench mark, any conclusions would be very tenuous because a single mark might have been unrecognizably disturbed. Uplift is indicated, however, by several bench marks in both the Casa Grande and Florence areas (Holzer, 1979, Figs. 4A and 5). Raymond and others (1980) also cite bench mark disturbance as a problem, but mention only one example, bench mark 1338 (also stamped T277). According to National Geodetic Survey records, this mark was disturbed prior to June 1948 when it was recovered. The disturbance was tilting of the pipe on which the tablet was set. The mark, however, presumably was firm. The releveling in 1948 was done in July, and the National Geodetic Survey noted no additional disturbance of the mark during recovery in 1967. Hence, the computed change of elevation at bench mark 1338 from 1948 to 1967 would appear to be unaffected by disturbance. Disturbance might affect the change of elevation computed at 1338 for the period 1905–1948. I inspected this mark on March 6, 1977, finding it in good condition. In any case, the disturbance of this mark should not have affected computed changes of elevation of other marks along the line for both the 1905–48 and 1948–67 periods.

Referencing of the elevation changes to a single bench mark, 1283, also was questioned by Raymond and others (1980) on the basis that the mark may have been unstable although no evidence for such instability was presented. This question ignores the evidence to the contrary, namely the observation that bench mark 1283 is part of a 45 km long segment of the leveling line along which movements were small to negligible from 1905 to 1967 (Holzer, 1979, p. 4693). Any bench mark or an average of several bench marks within this segment could have been used as a reference mark. Bench mark 1283 was selected because of its proximity to the area of uplift. The practical effect of selecting a more distant mark would be to diminish the statistical significance of the measured uplift. Raymond and others (1980) also "suggest that bench 1283 should not be considered absolutely stable as Holzer suggested." According to Holzer (1979, p. 4692), "the absolute elevation of bench mark 1283 is unknown, so that the terms uplift and subsidence are relative to bench 1283. Because a presumably localized crustal phenomenon is being examined, however, conclusions from the present investigation should not be affected by lack of an absolute reference."

SEISMICITY

A potential effect from man-induced changes of stress in the earth's crust is to trigger seismicity (Raleigh and others, 1976; Yerkes and Castle, 1976; and Castle and others, 1980). Mechanisms proposed for this seismicity include changes of surface load and changes of effective stress caused by pore-pressure changes. Particularly relevant to south-central Arizona is an earthquake sequence in New York that was attributed to crustal unloading caused by a quarry operation (Pomeroy and others, 1976). Most examples of man-induced seismicity appear to be triggered phenomena because, in general, the man-induced stress changes are very small relative to the inferred tectonic stress. By analogy to the problem of reservoir-induced seismicity (Castle and others, 1980), evaluation of the potential for man-induced seismicity in south-central Arizona requires consideration of the present stress state and how it is altered by groundwater withdrawal. Because south-central Arizona has been aseismic historically and the magnitude of the man-induced stress change is small, approximately 1 bar, the probability of man-induced seismicity appears small. However, man-induced seismicity has been observed in areas of low natural seismicity (e.g., Lake Mead; see Packer and others, 1977). Hence, the level of natural seismicity is not a completely reliable indication of whether or not man-induced seismicity may occur. In addition, as stated in Holzer (1979, p. 4679), "it may be pertinent that previously unexperienced seismicity may have occurred in south-central Arizona in the 1970s (Peirce, 1975; Yerkes and Castle, 1976). Although the cause of the seismicity is controversial—some have attributed it to sonic booms channeled by the atmosphere (Peirce, 1975) — it may be related to the unloading described here."

Raymond and others (1980) argue that unloading due to groundwater withdrawal is unlikely to induce earthquakes in south-central Arizona. They argue that "if earthquakes may result from unloading ... then earthquakes should have followed loading at Lake Mead and comparable areas" and cite experience at Lakes Powell and Mead. This reasoning is fallacious. If a stress change in one direction tends to promote failure and seismicity, then a stress change in the opposite direction should tend to promote stability. Accordingly, the decrease of local seismicity observed near Lake Powell after impoundment or loading (Mickey, 1973), which Raymond and others (1980) cite as evidence against the possibility of man-induced seismicity following unloading in south central Arizona, actually supports the possibility of man-induced seismicity in unloading situations. This deduction of course ignores the effects of differences in the state of stress between areas. Loading can increase stability under some stress states and decrease it under others (e.g., see Snow, 1972). Experience at Lake Mead, where seismicity increased after impoundment or loading (Carder, 1970), is opposite to that at Lake Powell. Although Raymond and others (1980) attribute the seismicity to increased pore pressures caused by hydraulic connection between underlying rocks and the reservoir, other investigators have concluded that "the post-impoundment seismicity may be the result of stresses *generated by the weight* of Lake Mead" (Packer and others, 1977, p. 39–40, emphasis added). These two examples cited by Raymond and others (1980) serve only to demonstrate that our understanding of the seismicity related to the impoundments at Lakes Mead and Powell is incomplete and does not provide an adequate basis for rejecting the possibility of man-induced seismicity in south-central Arizona.

CONCLUSIONS

The questions raised by Raymond and others (1980) concerning the validity of the measured uplift from 1948 to 1967 are without support and are based on misunderstandings of how geodetic data are collected and reduced and on a misinterpretation of Holzer (1979). In fact, even by their own analysis the uplift near Casa Grande is a valid observation. Admittedly, the uplift is small relative to potential error. This concern led to the extensive discussion of error by Holzer (1979). By conventional analysis of error, however, the 1948–67 uplift near Casa Grande is statistically significant.

Raymond and others (1980) also have not argued convincingly that man-induced seismicity will not be associated with the unloading in south-central Arizona. Their argument against man induced seismicity in south central Arizona, which is based on experience at Lakes Powell and Mead, can be challenged. In fact, the effect observed at Lake Powell argues for potential man-induced seismicity in south-central Arizona. By analogy to the problem of reservoir-induced seismicity, evaluation of the potential for man-induced seismicity in south-central Arizona requires consideration of the present stress state and how it is altered by groundwater withdrawal.

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STATE TRUST LANDS — 1979–1980

The State of Arizona, through the Arizona State Land Department, administers the "state trust lands" which amount to 13% of the total lands that make up the state. Income generated by the state trust lands goes to the common schools and 14 other beneficiaries. In fiscal year 1979–1980 (July 1, 1979 to June 30, 1980) $24,549,917 was generated, representing an increase of 25% over the preceding year. Income is produced from state trust lands by leasing, issuing permits and by selling minerals, land and timber, in addition to other activities.

Most of the state lands were under lease during 1979 and 1980. Because the Land Department employs multiple-use practices, some lands were covered by more than one type of lease. In fact, there were 13, 617 active leases in 1979–1980, totaling 17,164,604 acres. The total amount of state trust land is almost 9,582,000 acres. Leases are granted for "minerals," "common mineral materials," oil and gas, geothermal, agriculture, commerce and grazing. Prospecting permits and special use permits are also granted by the Land Department. "Mineral" leases are for metals, such as copper, gold, uranium, etc., whereas "common mineral materials" (also known as industrial minerals) are for sand and gravel, decomposed granite and building stone, etc. "Common mineral materials" are sold by the Land Department at public auction with the highest bidder receiving the right to extract the materials.

Revenues from state trust lands that were generated by mineral resources or related activities made up almost half of the total. Copper contributed the largest amount, as can be seen from the summary below:

MINERAL-RELATED INCOME	
Royalties from copper leases	$7,995,000
Royalties from other mineral leases	111,926
Royalties from common mineral materials	954,893
Oil and gas leases	1,822,144
Mineral leases and prospecting permits	288,597
Geothermal leases	61,567
Rentals on mineral leases	31,892
Total	$11,266,019

OTHER INCOME	
Agriculture leases	$2,664,962
Grazing leases	1,244,578
Rights-of-way	1,100,930
Commercial leases	1,019,330
Land sales (principal)	4,776,553
Land sales (interest)	1,039,899
Other	1,437,646
Total	$13,283,898

STATE TRUST LANDS GRAND TOTAL $24,549,917

The above information was summarized from the State Land Department's 1979–1980 Annual Report. Additional information may be obtained from the Land Department, 1624 West Adams St., Phoenix, AZ 85007.

Geology Along the Lower Salt River

The Bureau has contracted with Water and Power Resources Service (WPRS, formerly the Bureau of Reclamation) to produce a strip geological map at a scale of 1:24,000 along the Salt River from Roosevelt Dam downstream to just below Granite Reef Dam. The project falls under WPRS' safety of dams program, and is designed to provide basic lithologic and structural data for a mile-wide strip on both sides of the river, to assist in first-order planning procedures for WPRS-related projects on the river. The upstream two-thirds of the project is complete with the final report in preparation, while work on the downstream one-third was under way in February 1981.

Fieldnotes

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