SEISMIC RISK ASSESSMENT OF PUBLIC CULINARY WATER SUPPLY SYSTEMS IN UTAH AND RECOMMENDATIONS FOR RISK REDUCTION

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FOREWORD

The Utah Seismic Safety Advisory Council, established in 1977, is charged to prepare assessments of earthquake hazards and associated risks to life and property in the State of Utah, and to make recommendations for mitigating hazards that may be found.

This report presents an assessment of earthquake risk for public culinary water systems in Utah. The report includes recommendations for reducing risks that are deemed reasonably manageable within available resources. The recommendations are set forth as judgements of the Seismic Safety Advisory Council in terms of effectiveness of the suggested action for reducing risk to life, health, and property.

The report is divided into a summary of findings, a set of recommendations for earthquake risk reduction to water supply systems that deal primarily with policies and procedures rather than technical solutions, background information that helps one to understand earthquake effects upon water supply systems, estimates of earthquake damage to two major water supply systems in Utah, a discussion of mitigation measures for reducing earthquake effects, and a technical section which describes the methodology for making earthquake risk assessments.

The report presents an overview of earthquake risk to water supply systems rather than analysis of selected components of specific systems. Thus, vulnerabilities of particular types of components to earthquake effects are highlighted. Guidance is provided by which system operators may undertake detailed evaluations of components in their systems and can establish priorities for mitigation efforts in accordance with elements or components of greatest vulnerabilty or of greatest importance to the continuing operation of their systems. As well, guidance is given for preparing network analyses of systems in order to determine areawide effects of localized component failures that might be caused by earthquakes.

This report, like several others of similar nature dealing with various utilities, reveals the complexity of public works and quasi-public works that reach across and serve wide areas of settlement. Such systems are made up of innumerable small and not so small components that must work together for effective and reliable distribution of the utility product. To achieve areawide service, some components and some lines in the systems are more important than others in the sense that more of the service population can be affected by unplanned failures. The perspective sought from the reader, then, is of the system which is reliant upon individual components. Such a perspective helps significantly to understand how earthquakes can cause discomfort and economic loss to populations and businesses remote from the epicenters of the events. Such a perspective also helps one to realize that unnecessary earthquake risk to water supply systems and to other utility systems is, indeed, a matter in which the general public has a direct and proper interest.

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SECTION 1

INTRODUCTION

The report is divided into a summary of findings, a set of recommendations for earthquake hazards reduction, and technical sections describing Utah's earthquake environment and methods used for estimating potential risks to water systems as a result of earthquakes. Feasible methods for preventing operational problems or for reducing the negative impacts of earthquakes upon water systems then are examined within the context of selected water systems along Utah's Wasatch Front region.

Although the technical sections on methods of analysis and results utilize current seismicity data in Utah and state-of-the-art methods for earthquake damage and risk assessments, the reader must bear in mind that earthquake risk assessment is an inexact science built upon limited understanding of earthquake phenomena and effects. The technical results presented herein are largely probabilistic in nature and carry all of the imperfections implied by the term.

Earthquake damage and risk assessments commonly tend to emphasize building losses and other relatively visible effects. Earthquake safety of utility systems that are essential elements of each community's functional fabric often receives little or no attention and often is relegated to a less important status by the more spectacular and visible types of damage. Yet, the loss of a community's water supply has significant ramifications for any community's social, business, and economic fabric. Widespread inconvenience is one of the problems, but life safety and health hazards also can arise. Fire-fighting capability, that might be needed following a severe earthquake, could be impaired or lost. Contamination of potable water could result if water supply lines are broken or if negative pressure should result from loss of flow. These and other possible problems are serious enough to merit attention in earthquake preparedness studies and programs of State and local governments.

This earthquake risk assessment of public culinary water systems is the first such study that specifically addresses the seismic vulnerability of Utah's water systems in a comprehensive way. There are general studies available of earthquake risks to water systems, and at least two public water utilities in the State have incorporated some earthquake safety considerations into the designs of their systems. However, none of those studies or efforts have attempted to provide a broad earthquake risk perspective for Utah's water supply systems. This report seeks to fill that void. Although we have not attempted to evaluate earthquake risk of particular systems in every detail, we hope that the report treats each type of risk condition in sufficient detail to allow application of some obvious principles of safer design by local water utilities companies.

Recommendations made herein for earthquake risk reduction to public water supply sytems are of a policy type rather than technically specific. We leave such details to the separate operators of individual water supply systems. However, the more general purpose of safeguarding public safety, health, and welfare, cannot be left just to the operators of public water supply systems, because there exists an overriding public interest in the continuing and safe operation of these systems. In this regard, the Seismic Safety Advisory Council has observed that there are in Utah different levels of attention and consideration given to earthquake safety of water supply systems, or the lack of both, and that these variations result from concern for or indifference to the situation, as the case may be. Indifference, when present, likely is not a deliberate action in which the interested public has participated.

Because there are particular considerations for earthquake safety that are applicable to all public water supply systems in Utah, because there are certain situations involving public health in which the State has chosen to regulate the construction and operation of water supply systems, and because existing State regulatory authorities already include oversight of certain construction activities that directly affect earthquake safety of the water systems, the Seismic Safety Advisory Council has recommended strengthening certain aspects of governmental involvements and authorities. Other recommendations that are made are intended primarily for consideration by the local water utilities.

The Seismic Safety Advisory Council urges adoption and implementation of the recommendations contained herein.

SECTION 2

SUMMARY OF FINDINGS

Principal findings resulting from the seismic risk assessment of public culinary water supply systems in Utah reported herein are presented in this section without elaboration or extensive discussion. More detail is presented in Section 4 regarding expected effects of earthquakes upon facilities and components which make up a typical water supply system. These effects then are related to earthquakes of different strengths, and information upon seismicity in Utah is provided to allow correlation of general effects. In Section 5, evaluations are made of two selected water systems along Utah's Wasatch Front in order to estimate general earthquake effects upon components in a specified seismic environment. Sections 6 and 7 of the report discuss actions that can be taken to mitigate, or reduce, the effects of earthquakes to water supply systems, with occasional reference to the specific systems described in Section 5.

Recommendations for dealing with principal findings of earthquake vulnerability to water supply systems are provided in Section 3. Section 3 is organized so as to allow separation of the recommendations from the report without their seeming to be incomplete or unrelated.

Principal findings of this study are listed and discussed below. Importance of the topic was not a basis for the list sequence, and readers will note that the findings are listed more or less in order of their appearance in the subsequent sections of the report.

Seismicity In Utah

- Seismicity is common in most of the State of Utah with the possible exception of the easternmost portion of the State. The most severe and frequent earthquakes historically have occurred along a central region extending from the north central border to the southwest border. This seismic region is a part of an area that has become known as the Intermountain Seismic Belt. Geologic evidence suggests that severe seismicity in the future most likely will occur within this same region, with the Wasatch Fault Zone being the zone of greatest risk. Although the probable frequency of strong earthquakes is expected to be very low, the Wasatch Fault is said to be capable of producing earthquakes in the 7.3 Richter magnitude range. Earthquakes in the 6+ Richter magnitude range not only have occurred in historic time in the State, but Utah can expect to experience more such events in the future.

- Earthquake damage to water supply systems is determined by three factors: (1) Earthquake strength, (2) Earthquake location relative to the water supply system, and (3) Strength characteristics of the particular system component. Earthquake damage to water supply systems typically begins at a threshold level slightly higher than earthquake damage to buildings, although water supply facilities housed in buildings may have vulnerabilities comparable to typical buildings. Building vulnerability is described in greater detail in other reports prepared by the Seismic Safety Advisory Council. Earthquake damage to water supply systems tends to appear roughly at Intensity VII levels (roughly correlated with a Richter magnitude 5+ earthquake) and becomes more apparent at Intensity VIII. Severe damage will occur at earthquake Intensities IX and X.

Component Vulnerability

- Past earthquakes indicate that various components of water systems are vulnerable to damage at different intensity thresholds.

  At Intensity VII levels, poorly constructed structures housing system components may be damaged, pump stations may suffer damage, unanchored or poorly anchored equipment can be damaged, and poorly sited tanks above ground can buckle. As well, underground pipes in poor condition can rupture.

  At Intensity VIII, cast-iron and asbestos-cement water pipes can suffer as much as one break or more per kilometer. Water leakage also may effect other systems, such as buried electric cables. Unanchored or poorly anchored massive equipment, including standby generators and booster pumps, can move or become misaligned at Intensity VIII. Unanchored above-ground tanks may suffer more serious damage, and inflexible inlet and outlet connections at tanks can suffer damage.

  At Intensities VIII and IX, some ruptures can occur to more earthquake-resistant pipe, such as welded-steel, ductile-iron, pvc, and polyethylene pipes, even though pipes of such material are much safer in earthquakes than are cast-iron or asbestos-cement pipes.

  At Intensity IX, penstocks feeding hydro-electric generating facilities can be ruptured, and pipes and conduits crossing faults or other areas of possible ground displacement are vulnerable to rupture.

  At Intensity X, anchored tanks and buried reservoirs may be damaged.

- Principal populated areas of the State of Utah typically receive their water supply from storage reservoirs in the mountains to the east of the communities, and such supply conduits and major lines consequently must cross known active fault zones to reach the points of use. Major supply lines therefore are vulnerable to disruption from major earthquakes. Since neither the earthquakes nor the need to cross active fault zones can be avoided, other measures are needed to insure the availability of water supply. One such measure involves selection of alternative routes for major supply lines so that a community's water supply may be safeguarded against disruption that might be caused by failure at a single point of a major conduit. Another measure is the design of more earthquake-resistant facilities and components particularly at crossings of active faults. Still another measure involves valving or other controls appropriately located to facilitate repairs which cannot be avoided, also at fault crossings.

- Although many of Utah's communities are served by gravity-flow water systems, there are nonetheless many areas dependent upon pumping to elevated storage tanks or reservoirs. For such systems, the possiblity of power loss interrupting pumping capability requires consideration, particularly where flow may be required for fire fighting purposes. Backup generators to insure continued pumping capability, earthquake-resistant design of storage tanks and for inlet and outlet connections to the tanks, and siting of storage tanks to avoid the possiblity of downstream washouts are among the means to reduce the vulnerability of these particular systems.

- Breakage of underground pipes appears to be a prevalent problem resulting from all earthquakes commencing at Intensity VII and greater. Typical water systems, constructed and expanded over a period of many years and even decades, have many types of pipes, including asbestos-cement, cast-iron, polyethylene, polyvinyl chloride, and welded-steel. Past earthquake damage investigations reveal that some types of pipe perform much better than others in strong earthquakes. Selection of pipe material, then, becomes an important factor in reducing the number of breaks in pipes, which can result in loss of supply within the distribution system. The possibility exists, therefore, for pipe replacement programs to be implemented in which materials are selected for their earthquake resistance when replacement is made.

Mitigation Methods

- Information on how an earthquake might affect a water supply system is useful as a guide to emergency response planning and also as a guide for efforts to reduce (mitigate) damage to the system from possible future earthquakes. Mitigation measures should go hand-in-hand with emergency procedures.

- Although detailed cost evaluations of various mitigation actions were not undertaken in this report, several general observations may be made which have bearing upon the cost-effectiveness of particular actions that might be taken. Avoidance of known geologic conditions which may be susceptible to earthquake effects is one cost-effective action. Similarly, selection of flow routes for conduits and allowance for alternative flow routes may, in the future when an earthquake strikes, more than offset the initial effort and cost to provide a more secure system. Component replacement, a routine activity for most water systems operators, ought to be made after giving consideration to earthquake resistance of the components, or from the perspective of improving the system response to earthquake effects. Replacement of worn out pipe with more earthquake resistant pipe and appropriate location of valves to allow control of flows when earthquake damage occurs, such as at fault crossings, are among such measures available to reduce potential disruption of the supply system.

- Fire-flow requirements of the water supply system should receive special consideration owing to the fact that fires in built-up areas may be a common occurrence immediately after severe earthquakes. Auxiliary power for water systems dependent upon pumped supply and the safeguarding of elevated storage tanks and reservoirs also warrant careful consideration. Future fire losses could more than offset the cost of such additional equipment or design considerations.

SECTION 3

RECOMMENDATIONS FOR EARTHQUAKE RISK REDUCTION TO PUBLIC CULINARY WATER SUPPLY SYSTEMS IN UTAH

The following recommendations result from a study of the expected impact of earthquakes upon public culinary water supply systems in Utah. The study, titled "Seismic Risk Assessment Of Public Culinary Water Supply Systems In Utah," provides estimates on the extent and nature of hazards posed by earthquakes to water supply systems. In the report guidance is given for operators of water supply systems regarding components or aspects of the systems that are particularly vulnerable to disruption by earthquakes. Associated mitigation actions that might be taken to reduce those risks also are furnished.

Water supply systems are especially important to any community, both for culinary use and for purposes of fighting fires. Protection of these systems from serious damage that might be caused by earthquakes resulting in interruption of water service is an especially important consideration in those areas of the State of Utah that are within high seismic risk zones.

Although it may not be economically feasible to design new systems or to replace portions of existing water supply systems with components and facilities that are completely earthquake resistant, some actions can be taken in both design and retrofit that will reduce earthquake vulnerability, especially that vulnerability to earthquakes of small and moderate size. Such actions can be especially beneficial in reducing damage for those water supply systems in close proximity to known active fault regions, such as through the north-central region of the State of Utah.

The recommendations contained herein are general concepts rather than engineering solutions to specific problems. They also apply to a range of risk situations, some of which may not be applicable to all water supply systems. Thus, operators of particular systems will need to assess their own systems in order to decide which actions are appropriate to that particular system. Such actions will be decided, in part, in accordance with the particular geographic setting of the water supply system, the source of water supply, the system flow-path relative to suspected seismic source areas, and the particular components of the system.

1. It is recommended that evaluations of geologic hazards be included as a part of the engineering of each new water system installation, or part thereof, in the State of Utah, and that enforcement of this recommendation occur under administration of the State Department of Health which has oversight responsibility for safe drinking water standards in the State of Utah.

The purpose of this recommendation is to cause review of earthquake safety to be made for each water supply system as it is developed or expanded. The principle function of geologic investigations is to highlight earthquake risk conditions rather than to require particular types of engineering solutions for problems that may be discovered. Authority for review of geologic evaluations that is recommended be granted to the State Department of Health should be used primarily as a means to insure that earthquake risk problems, which could endanger public health, are not ignored in the design and construction of water supply systems rather than to serve as the basis for approving one particular design solution over another. Geologic investigations may be used to discover zones of earthquake risk, fault lines, and susceptible soil conditions for a water supply sytem. The follow-up review process can be used as a means to evaluate system performance under those unique geologic conditions and potential points of water service disruption. Alternative routes of water flow (system redundancy), fault crossings of major water service lines, and dependency upon pumping and tank storage are among aspects of the system that have bearing upon its performance during and after an earthquake.

2. It is recommended those water supply systems which receive their supply from more than one source be designed to provide alternative flow paths for major conduits in regions of known faults, or, if such is not possible, that parallel routing of major conduits be avoided.

The purpose of this recommendation is to insure against complete failure of water supply systems whose conduits from major supply sources necessarily must cross known faults. It is acknowledged that principal water supply lines along Utah's Wasatch Front necessarily must cross regions of faulting between the mountain supply sources and the communities situated in the valleys to the west of the Wasatch Mountains. Since this situation likely cannot be avoided for most communities, advantage can be taken out of the fact that an earthquake normally will be a localized event. Hence, alternative routes of water flow may be utilized to avoid failures of conduits side by side at fault crossings.

3. It is recommended that water supply conduits in major service lines crossing known fault areas be either designed to accommodate significant differential movement of the ground or be valved immediately above and below the points of fault crossings to allow control of water flow in case of pipe rupture during an earthquake event.

Although buried pipelines can be designed to withstand significant differential ground displacments, the cost of such designs may not be warranted for many water supply systems. Consequently, the next best alternative is to allow for the possiblity of conduit rupture at fault crossings. This can be done by valving ahead of and below the crossing so that significant downstream flooding may be avoided and so that repairs may be made expeditiously.

4. It is recommended that bypasses be provided at water treatment plants so that water flow from the source into the pipeline distribution system may be continued without interruption, primarily for fire fighting purposes, in the event that the treatment plant is rendered dysfunctional by an earthquake.

Past practices in the design of water treatment plants, as advocated by public health agencies, have been to discourage bypass capabilities at water treatment plants. Primarily, this is done to safeguard against health hazards that can occur through contamination of the water supply system. We have observed, however, that water treatment plants comprise numerous components that are especially vulnerable to earthquake damage, the consequence being that water supply flow has a high possibility of interruption at the treatment plant location. We also have observed during and immediately after a severe earthquake that the occurrence of fires is likely to be very large and the risk of conflagrations very high. An adequate water supply is extremely important in combatting this secondary effect of earthquakes. In such cases, preserving a community's buildings and facilities from fire loss may be more important than safeguarding the purity of the water supply for a brief period of time. It is for this reason that a means for bypassing the water treatment facility is recommended.

5. It is recommended for those water supply systems dependent upon pumping stations and pumping equipment that they be designed to resist earthquake damage to the pumping systems, such as could occur by building collapse or by displacement of equipment, and that back-up systems for pumping be provided in those cases when the pumping is dependent upon commercial power.

Although many communities along Utah's Wasatch Front are served by gravity flow from mountains to the east, not all areas of all systems are serviceable from gravity flow. In such cases, pumping and storage tanks are used to provide water service. Hence, the water supply may be dependent upon the availability of both an operable pumping system and electric power to drive the pumps. Since such components in a water supply system rarely have alternative means of power supply, it is especially important that these single-source systems be protected against earthquake damage and be provided with a means to insure pumping capability. Experts generally agree that a severe earthquake will cause power outages in the region of impact which may last for just a few hours to perhaps a day or more. Storage tank capacities typically are insufficient to handle water needs for extended periods of times, especially if fire fighting capability also must be preserved. The purpose of this recommendation is to provide adequate safeguards to insure the continuing availability of flow for water supply systems dependent upon pumping.

6. <u>It is recommended that inlet and outlet connections of water conveyance facilities, pump stations, water treatment plants, and storage tanks be designed to accommodate differential movement of ground and structure.</u>

One of the most frequent types of damage to water supply systems due to earthquakes occurs at the inflow connection or outflow connection of water conveyance and storage structures. Rigid inlet and outlet connections tend to rupture fairly often due to differential movement between the ground and the structure. If such ruptures occur, there is the possibility of complete drain-down unless a means is provided to protect the connection or to control the water flow. The purpose of this recommendation is to safeguard against unexpected loss of supply and also to safeguard downstream development from washout as a result of such possible draindown.

Another common tank failure occurs when the tanks shift horizontally relative to the ground. Proper anchorage at the base of the tank to foundations is required to insure against this kind of failure.

7. <u>It is recommended that pipes in the distribution network of water supply systems be of a type least vulnerable to damage by earthquakes, such as ductile-iron and polyvinyl chloride pipes. Pipes for new water systems in areas of high earthquake risk and for replacements in existing systems should be of an earthquake-resistant type whenever possible.</u>

Earthquake damage to water supply systems in the past has occurred with greater frequency to some kinds of pipes than to others. Cast-iron pipe and asbestos-cement pipe have performed less well than have ductile-iron pipe and polyvinyl chloride pipe. Welded-steel pipe also has performed very well but is less frequently used in water supply systems. Where choice exists, pipe more resistant to earthquake effects should be selected over that which is less resistant.

8. It is recommended that the operators of all water supply systems in earthquake-prone regions of the State stockpile replacement pipe and other essential components in sufficient quantity to accommodate a high occurrence of failures in a severe earthquake.

It is accepted that there may be widespread damage to underground pipes in a water distribution system as a result of a severe or even moderate earthquake. Also, given that there is also no reasonable way to avoid earthquake damage to underground systems, an alternative is to plan for prompt emergency repairs. Such repairs will require both manpower and materials. Stockpiling of necessary materials for each particular system sufficient to meet an exceptionally large number of failures, along with proper planning of manpower requirements, will provide a means to meet such emergencies.

9. It is recommended that individual components critical to the operation of water supply systems be provided with anchorage to secure the components from loss due to earth-forces.

The systematic nature of all water supply systems has been observed, and the dependency of system operation upon the correct and reliable functioning of the parts has been pointed out in this report. Due to the fact that some of these compoents critical to the system are vulnerable to displacement and consequent damage, or at least loss of function, in an earthquake, special care should be given to securing them from possible movement. Anchor bolts and bracing are the principal means to mitigate this type of loss.

SECTION 4

BACKGROUND DATA FOR ASSESSING EXPECTED EFFECTS OF EARTHQUAKES UPON UTAH WATER SYSTEMS

SEISMICITY IN UTAH

Although greater earthquake risks exist both in California and in western Nevada, Utah contains a significant segment of what scientists call the "Intermountain Seismic Belt," which has one of the "highest levels of earthquake risk in the contiguous United States" ([1], p. 2).

In addition to being described in terms of Richter magnitude, earthquakes also can be described in terms of their Modified Mercalli Intensity, which is a measure of the felt effects of the earthquake. The Modified Mercalli Intensity scale ranges from I to XII. This intensity scale enables one to identify effects of earthquakes at some distance from the point of occurrence, which at ground level is called the epicenter. At one extreme, Intensity XII, damage of the sort found only in the 1964 Anchorage earthquake or the 1906 San Francisco earthquake can occur. At Intensity VIII, some features of a water system, such as underground pipes, become vulnerable to damage. At Intensity VI or VII, some unreinforced masonry structures can suffer damage.[1]

Utah ranks high on a comparative national basis in terms of general seismicity in the region as determined from historical records and in terms of expected earthquake strengths that can cause extensive damage.

In a report by S.T. Algermissen and David M. Perkins, the contiguous United States is divided into 71 seismic zones based upon expected seismicity in each zone ([3], especially pp. 17, 18). Large areas of the United States have insufficient seismicity to be included in any specific zone. Four specific zones are applicable to Utah, namely, Zones 32, 33, 34, and 43 (See Figure 1). Zone 33 is the one of greatest seismicity and therefore greatest earthquake risk. Zones 32 and 34, in order, are less active seismically. Zone 43 is the least active. Part of the State lies in no zone, where little seismic activity is expected.

One can compare the more recently developed Algermissen and Perkins zonation map (Figure 1) with the map now in use in the 1979 Uniform Building Code (UBC) (See Figure 2). Although the UBC zones have provided the basis for designing earthquake-resistant buildings in Utah in recent years, it can be seen that the zones do not match very well the distribution of seismicity as presently understood.

Zone 33, which extends through Utah's most densely populated areas, ranks seventh among the 71 zones in the contiguous United States in terms of expected

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[1]For a further explanation of the Modified Mercalli Intensity Scale, see Appendix A and also [2], pp. 202-205. For a Scale including the empirical summaries of this report pertaining to water supply systems, see Appendix B.

number of Modified Mercalli Intensity V earthquakes per 100 years, and ties for nineteenth in terms of the expected maximum Mercalli intensity. Zones that exceed Utah seismicity lie predominantly in California, Nevada, and Montana.

Part of the basis for predicting earthquakes and their intensities comes from the historical record, which indicates considerable seismic activity in Utah ([4], pp. 703-718). From 1853 to 1975, an estimated 17 Utah earthquakes had an Intensity VII or greater ([5], p. 156). Two earthquakes, one in Richfield in 1901 and one in Kosmo in 1934, are identified as having had an intensity of IX (Cf. [6], pp. 9-20). Figure 3 shows a part of the historical earthquake record for Utah.

Recent geological findings suggest that conclusions based exclusively upon historical records may underestimate the seismicity in Utah. Using information provided by Robert Bucknam and others at the U.S. Geological Survey, Zone 33 has been divided into two subzones, Zone 33A, and Zone 33B (See Figure 4). Zone 33A, with higher expected seismic rates and higher expected maximum intensities, extends approximately 20 kilometers on each side of the Wasatch Fault.

Research findings that might enable one to define more precisely expected seismic rates and expected offsets for given locations in Zone 33A only now are beginning to accumulate. In this report, a random distribution of earthquakes in each zone has been assumed. For practical purposes, maximum fault displacements have been assumed to be less than 3 meters. Since only large, less frequent earthquakes can cause damage to water systems, and since only such large earthquakes appear to produce significant faulting offsets in Utah, both earthquakes and resulting offsets are in this report assumed to be discrete events separated by relatively long, though likely unequal, periods of quiescence or inactivity.

Since the historical record of earthquakes, taken alone, leads to estimates that are lower than those based upon the more extensive geological record, and since past reports of earthquakes are often incomplete, one can understand why the historical record of damage to water systems is not our sole basis for estimating future damage. Some reports do exist of past damage to water systems. In the Richmond earthquake of 1962 (Richter magnitude 5.7, Intensity VII), damaged flumes and irrigation channels caused minor flooding. In the 1949 Salt Lake City earthquake (Richter magnitude 4.9, Intensity VI) a 10-inch water main ruptured, leading to a loss of water in a sizeable portion of the city ([6], p. 21). According to Bruce N. Kaliser, engineering geologist at the Utah Geological and Mineral Survey (UGMS), in the Pocatello Valley earthquake of 1975, damage occurred to the Bothwell water system. Bothwell, which lies a few miles west of Tremonton, may have been in an Intensity VI area, although near-by intensities reached VIII. At such lower intensities, it shall be shown, not much damage is expected to a water system. By the same token, water systems located in parts of Utah, such as in Zone 32, where only lower intensities are expected, are relatively immune to earthquake damage. Several other Utah earthquakes probably caused damage to water systems, but general earthquake records are incomplete (Cf. [7]).

DAMAGED WATER SYSTEMS AND DELETERIOUS SOCIAL CONSEQUENCES

The disruption of a water system can lead to many types of losses, both property losses and also injuries and deaths. Damaged water system components, such as pipes and tanks, need repair or replacement. Flooding can result from damaged reservoirs. Service losses can occur that result in revenue losses and may be economically disruptive where revenue is needed for water department projects. Service losses to industries may result in lost production and wages. Added costs may occur for hauling water to homes with inadequate supplies, for emergency power to pump water, and for temporary aboveground piping. Contamination may occur, and even lead to epidemics. And, as in San Francisco in 1906 and in a few other earthquakes, fires may be uncontrollable as a result of lack of water or pressure for fighting fire ([9], p. 136; [10], p. 28).[2]

EARTHQUAKE EFFECTS UPON WATER SYSTEMS

Past earthquakes indicate that various components of water systems are vulnerable to damage at various intensity thresholds.

Estimates of the vulnerability of many of the components of a water system are based upon research often in its initial stages. Far less is known, say, about the seismic performance of aboveground tanks than about the seismic performance of buildings. Much of the literature about water systems consists of recommendations rather than systematic presentations of data, and available data come primarily in a scattered form from a few earthquakes, such as the San Fernando earthquake of 1971, the Nicaragua earthquake of 1972, the Anchorage earthquake of 1964, and various earthquakes in Japan and more recently China.

Whereas damage to buildings, especially adobe or unreinforced masonry structures, may occur at Intensity VI, damage to most water systems components, such as pipelines or buried reservoirs, is not expected for earthquake intensities less than VIII or IX. Since such higher intensities are infrequent, water systems damage is modeled in this report in terms of expected damage at a given epicentral intensity. In other words, averages of all expected losses resulting from the whole array of earthquakes over some period of time may be very misleading, since the major damage primarily is expected to occur all at once as a result of an infrequent strong earthquake. Moreover, the discrete modeling of earthquakes enables one to examine in detail the systematic effects of an earthquake upon a water system.

The major components of a water system include the following:

- dams
- penstocks and flumes
- purification facilities
- wells
- aqueducts, conduits, or main supply channels
- aboveground reservoirs or tanks

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[2]According to at least one source, the city of San Fernando was fortunate that no major fires broke out when it was without water as a result of the 1971 earthquake ([11], p. 33).

- o belowground reservoirs
- o pumping stations
- o pressure reducing valve stations
- o feeder mains
- o distribution mains

The seismic performance of dams lies outside the scope of this report.

Failures of penstocks or flumes, e.g., pipes, conduits, or channels, often designed to generate power, could lead to flood damage. In the 1971 San Fernando Valley earthquake, a power penstock in an Intensity X region had its supporting piers displaced both horizontally and vertically up to two feet. Anchor bolts failed, the pipe elongated at two expansion joints, and rivets were sheared. The penstock was back in service three days after the earthquake ([11], p. 29; [12], p. 124).

Purification facilities have been regarded as abovegrade concrete structures, whether reinforced or not ([10], p. 52). So treated, the structures vary in seismic resistance as do concrete structures generally. However, in Section 5 of this report, reasons are given for treating purification facilities as systems in themselves, of which the abovegrade parts may be less important in their functioning than other parts.

According to one report, much of the damage to the Jensen treatment plant, located in an Intensity X region in the 1971 San Fernando earthquake, was the result of the absence of a bypass from the inlet to the outlet lines. Had there been such a bypass, the "damaged inlet pipeline could have been restored to service within a short time" ([11], p. 27). Inlet and outlet connections are known to fail at higher intensities. Several authors strongly recommend that bypass lines exist at treatment plants ([9], p. 143; [10], p. 28; [34], K10).

Equipment anchorage also may affect the performance of the purification facility. According to Irving J. Oppenheim,[3] "[f]ailure of some items, such as unanchored power transformers or pumps, may be repaired before the water in storage is depleted. Other damaged components, such as sedimentation tanks and rapid sand filters, would probably require closing of the facility for longer periods of time" ([10], p. 72). Unsecured chlorine cylinders, common appurtenances in purification plants, can lead to broken connectors, damage to chlorination facilities, and release of liquid chlorine and gas ([12], p. 161; see [13], pp. 773, 774).

In the San Fernando Valley earthquake, the major impact upon wells was contamination resulting from the many broken sewer lines and septic tanks in the area ([11], p. 26; [12], pp. 148, 149). Although some earthquake damage occured to wells, such as breaks in the casing, joint rupturing, severe distortion of the casing, cracking of the pad or base of the pump, and twisting of the pump stem, irreparable damage occurred only in the region of severe

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[3]I.J. Oppenheim is professor of architecture at Carnegie-Mellon University and principal investigator of a study of earthquake risk to water supply systems funded by the National Science Foundation.

tectonic rupturing, where ground fractures are capable of conveying contaminated seepage for considerable distances from the source ([12], p. 155; [9], pp. 143, 144). Owing to contamination generally, all wells in San Fernando City were out of service ([12], p. 129).

In the San Fernando earthquake, aqueducts performed better when the lining was reinforced, when underground installation was used, and when transitions from aboveground to underground pipelines were seismically designed ([11], p. 29). Aqueducts in the San Fernando Valley were repaired for at least partial service within days, but extensive repair to the unreinforced concrete lining of bypass channels required entirely new lining ([12], pp. 123, 127). Damage to trunk lines occurred mainly at joints, due predominantly to compressive but also to tensile failures. Chief damage to the Chatsworth High line was due to its lack of design for seismic loading ([12], pp. 130-134).

From San Fernando Valley data, several conclusions may be drawn about the performance of tanks. In general, except where soil conditions are either very poor or very good, tanks evidenced damage at Intensity IX and above. Two tanks located on unyielding bedrock were undamaged in an Intensity X region. One tank located on poor soil was extensively damaged in an area of Intensity VII to VIII. But, for tanks in areas with Intensity IX or above, the predominant mode of failure was displacement leading to buckling in the base of the tank. Proper anchorage is the principal means to design against such problems ([12], pp. 135-148; [14]; [19], p. 144).

Apparently, inlet and outlet lines both to tanks and to reservoirs almost universally suffer damage in higher intensity regions. Mitigation measures are possible, such as the use of ball and socket joints ([12, p. 148; [9], p. 143). Poorly designed tank roofs can also fail at lower intensities, as with the Granada High Tank in the San Fernando Valley. Most of the tanks surveyed were probably nearly full, so that statistical data do not yield information on how the water level in a tank affects its performance. In the Managua earthquake, one empty tank performed better than those that were five-sixths full ([13], p. 775).

Loss of storage in elevated tanks and standpipes, according to I.J. Oppenheim, results in a pressure loss. Not only may a loss in service ensue, but a health problem occurs if negative pressures result, causing pollutants to enter the system ([10], p. 14). If these pollutants come from nearby broken sewer lines, serious health problems ensue.

Even though buried structures generally perform better than aboveground structures, damage can be expected to buried reservoirs at Intensity X. In the San Fernando Valley earthquake, six of eight buried reservoirs in regions of Intensity X suffered damage. Four reservoirs suffered roof damage, generally followed by cracking or bending of sidewalls. Two other reservoirs chiefly suffered horizontal cracking of sidewalls. As with other types of storage facilities, leakage in reservoirs can occur at the breaks on the inlet-outlet pipes through the cracks in the sidewalls ([12], pp. 135-148).

In the San Fernando Valley, pumping stations suffered little structural damage, although leaks in suction and discharge lines caused some temporary damage ([11], p. 29). According to Oppenheim, pumping facilities vary extremely in size and structural details ([10], p. 53). At one extreme, small reinforced-concrete box structures are only slightly vulnerable to seismic damage. Equipment anchorage or bracing also reduces seismic vulnerability. Power failure, of course, could also lead to non-functionality or temporary failure of pumping stations, especially if no emergency generators are available.

Pressure reducing valve stations, sometimes called "pressure regulators," are not themselves vulnerable to seismic shaking, unless they are in a region of ground offsets. But, such stations appear to influence the system negatively when failure occurs elsewhere. Wendall Hand, engineer at the Salt Lake City Department of Public Utilities, has provided the following account of their influence.

> Operation of pressure reducing valves (PRV's) in the system depends upon the maintenance of a higher supply pressure upstream of the valve and a regulated reduced delivery downstream.
>
> If a break upstream of a PRV occurs and water loss is sufficient to drop upstream pressure below that of downstream delivery pressure, then the PRV will function as a check valve and close off, preventing downstream delivery. In some cases, rocks and debris may enter the watermain at the break. After its repair, secondary high pressure damage may occur as rocks jam under the seat of the regulator to cause high pressure leakage. Loss of control can also occur as debris plugs the control lines of the pilot system and causes the PRV to go open and to release high pressure into the system below.
>
> If a break of sufficient volume occurs downstream of a PRV, then the pilot controls will cause the valve to open to its maximum capacity. Lime or corrosion build-up on the stem of some types of PRV's may jam the PRV in an open position. Failure to check the operating conditions of the PRV before opening valves after repairing the downstream break may result in a jammed PRV remaining wide open, releasing high pressure into the system below and causing additional breaks as a secondary cause of the earthquake.

In order to simplify a water system network, pipelines can be classified as supply mains, which transport water from the source of supply (catchment reservoirs) to the centralized point of distribution (distribution reservoirs), as feeder mains, which begin at distribution reservoirs and carry water to centralized points of distribution, and as distribution mains, which supply the individual consumer. Feeder mains can be further divided into primary mains and secondary mains, the latter of which also incidentally may supply individual consumers, either because no other main is available or the consumer in question requires a large main ([35], pp. 5, 6).

Although it is theoretically possible to discuss possible damage to every main in a system, it is convenient to discuss only damage to the supply and the larger feeder mains. In general, one may assume that the number of failures per length of pipeline of pipes with larger diameters is lower than the same failure rate for smaller pipes (see [10], pp. 74-76; [16]). This assumption is accepted here in spite of questions raised in [17], p. 259.

Pipe failures generally begin to occur at Intensity VIII. Some failures may occur at Intensity VI where pipes are in poor condition. Rates of pipe failures for intensities above VIII are poorly documented, but they may be expected to exceed the one break per kilometer roughly expected at Intensity VIII. The City of San Fernando, affected at Intensity IX and above, was out of water not only because its wells were contaminated but also because its distribution system was out of order. Liquefaction conditions also can increase greatly the number of pipe failures.

Modes of pipe failure vary according to the type of pipe. In general, all pipes are subject to joint failures, the moreso where joints are rigid. Pipe failures at crossings of faults also may occur as a result of shearing action at the face of the fault. Considerable literature is available on the design of pipes that cross active faults (see [18], [19], pp. 126-129, [20], [21]). Some pipes, such as asbestos-cement pipes, are more likely to fail by crushing. Others, such as cast-iron, are more subject to shear failure, and steel pipes can be subject to a pull-out type of failure at the joints. The most earthquake-resistant pipes appear to be ductile-iron with rubber-gasketed joints. Polyvinyl-chloride (PVC) pipes, although they may have inflexible joints, have seemed to perform well in earthquakes.

SUMMARY OF EARTHQUAKE EFFECTS UPON WATER SYSTEMS

Damage to water systems, which occurs predominantly only at higher earthquake intensities, nonetheless can be extensive at those higher intensities.

In review, one finds that most of the components of a water system are not susceptible to functional damage except at higher earthquake intensities, viz., Intensities VIII and above. When such higher intensities occur, however, damage becomes extensive, especially for facilities not designed to resist ground-shaking or not sited properly. The systematic effects of such extensive damage at higher intensities imply that fire control and other water uses may be difficult to effect without considerable repair work after an earthquake event.

An outline of expected damage at given intensities provides an initial idea of what can be expected and so of what repairs may be needed.

At Intensities VI and VII, poorly designed treatment plants may suffer structural but possibly not functional damage. Poorly designed pump stations, though, may suffer sufficient structural failure to cause secondary functional failures. Poorly sited tanks may settle and buckle. Pipes in poor condition may rupture, or come apart at joints. Hasty repair work may lead to later breaks owing to the functioning of PRV's. Some equipment may move.

At Intensity VIII, pipe failures are expected. Some poorly designed treatment plants may be rendered non-functional. Wells may become contaminated if they are too close to sewage lines that rupture. Some tanks may buckle.

Some open valves in PRV's may lead, after repair work, to further breaks. Some inlet and outlet connections may break. Heavy equipment may move.

At Intensity IX, breaks occur at inlet and outlet connections, tanks buckle, penstocks and flumes rupture, and many pipes break. Purification facilities may suffer structural and equipment damage. Small ground-surface offsets may damage structures. Aqueducts, tunnels, and conduits may suffer damage to concrete linings.

At Intensity X, even most buried reservoirs will suffer sidewall damage and possibly roof damage. Offsets may be large in some localized areas. Only components that are well-designed or well-sited can be expected to be undamaged.

Such a rough account of the seismic conditions needed to cause permanent or temporary non-functionality can, when combined with estimates of expected seismicity, enable one to determine which components of water systems and which water systems generally are more vulnerable to earthquake damage. In those zones where intensities are not expected to exceed VII, for instance, seismic damage to water systems may not be expected to be much of a problem.

In the next section, such general findings will be applied to water systems in Utah in order to determine which water systems are susceptible to water damage and what sort of damage is expected. In the next section, the general findings here are thus refined in connection with particular facilities that may exist in Utah.

SECTION 5

EXPECTED EARTHQUAKE DAMAGE TO SELECTED UTAH WATER SYSTEMS

EARTHQUAKE INTENSITIES EXPECTED IN SEISMIC ZONES IN UTAH

As indicated in the previous section, Utah may be divided into seismic macrozones in accordance with the degree of seismicity of the zone (Figure 1). Using information about the effects of earthquakes upon water systems and further information about expected earthquakes in a given zone, one can determine in a general way what damage to expect to various water systems in the State.

In Zone 32 (roughly the same as Zone U-1, Figure 4), the maximum expected earthquake, based upon the historical record, has a near-field Intensity VI ([3], p. 17). Such an earthquake would not be expected to cause damage except to poorly designed treatment plants, pipes in poor condition (even on the verge of breaking from other causes such as corrosion), or non-reinforced irrigation ditches.

In Zone 33A (Zone U-4, Figure 4), the maximum expected earthquake, based upon geological evidence, has an epicentral Intensity X. Such an earthquake could cause extensive damage to water systems.

In Zone 33B (Zone U-3, Figure 4), the maximum expected earthquake is an Intensity IX, as based upon historical records, and could cause considerable damage if the epicenter is near a water system.

In Zone 34 (Zone U-2, Figure 4), the historical record indicates Intensity VII as the maximum epicentral intensity ([3], p. 17). Such an earthquake could cause some pipes to break, some poorly sited tanks to buckle, and some structural failure at poorly designed pump stations or treatment plants.

In Zone 43 (Zone U-1, Figure 4), the maximum expected earthquake has a near-field Intensity V ([3], p. 18). Little or no damage to water systems is expected from earthquakes in these areas of the State.

Another consideration in the zones of significant seismicity that has bearing upon the risk to water supply systems is the recurrence intervals for expected earthquakes. However, estimated recurrence intervals for the different zones may be misleading unless one takes into account the diverse sizes of the zones. Zone 32 has an area of about 261,000 sq. km., Zone 33A has an area of about 14,000 sq. km., Zone 33B has an area of about 29,200 sq. km., and Zone 34 has an area of about 76,400 sq. km..

Table 1 indicates the expected recurrence intervals of epicentral intensities equaling or exceeding the given intensity somewhere in the seismic zone. Readers must recognize, in using this table, that although recurrence intervals for given intensities located in the seismic zone are a result of either having epicentral intensities in the seismic zone or attenuation from earthquakes lying outside the seismic zone, the intervals in Table 1 do not take into account attenuation from outside the seismic zone.

Not all earthquake epicenters are expected to be located within the boundaries of a water system. If all epicenters were located within the boundaries of a water system, then one would expect pipes to break about every 15 years and major damage to occur about every 56 years. Since water systems cover only a small portion of the four seismic zones, such recurrence intervals are comparatively short for expected damage.[4]

Given the wide differences in area among the various seismic zones, a more direct measure of the vulnerability of specific components within water systems comes from estimates of recurrence intervals for intensities equaled or exceeded at specific sites within a given seismic zone. Table 2 indicates such site-specific intervals for sites chosen randomly within given seismic zones. Lower values in the table imply shorter return periods for earthquakes and, hence, greater seismicity.

Table 2 indicates clearly that sites in Zone 33A are considerably more susceptible to levels of ground-shaking that cause earthquake damage. At the same time, components of water systems, such as buried reservoirs, that have high thresholds before damage is expected, are fairly resistant to earthquakes. A randomly chosen buried reservoir, with an Intensity X threshold, may be expected to suffer sidewall cracking only about every 15,000 years in Zone 33A. Reservoirs with poorly designed roof systems or those lying in a fault zone of deformation are not so comparatively immune to earthquake damage. Table 2 also indicates how improved design and siting can make a considerable difference in the expected damage to a given facility. If, for instance, an unanchored tank has a damage threshold of Intensity IX and an anchored tank has a damage threshold of Intensity X, then, in Zone 33A, the first tank may be expected to be damaged every 2,400 years while the second is expected to be damaged every 15,000 years. Proper design of facilities, which results in incremental improvements in damage thresholds, can thus make certain facilities practically immune from earthquake damage and can make other facilities three or more times less likely to be rendered non-functional. Of course, such conclusions should be taken in terms of averages for a large number of similar facilities subjected to the same earthquake conditions rather than in terms of site-specific structures. Table 2 does not provide data on the vulnerability of a specific water system, which generally covers some portion of a seismic zone.

Since it is clear that water systems in Zone 33A deserve special attention owing to the comparatively large amount of groundshaking expected in Zone 33A, recurrence intervals for two water systems in Zone 33A, the Salt Lake City system and the Salt Lake County Conservancy District system, may be used to illustrate what damage may be expected for specific water systems as a whole in Zone 33A.

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[4]Such recurrence intervals do not appear to be too different from those for the "Wasatch Front" area in [1], p. 275, an area that is much larger than Zone 33A. Geological evidence is needed to determine whether or not such large earthquakes are possible, even in the long run, in Zone 32.

For the Salt Lake City system, an earthquake of near-field Intensity X may be expected to be located within the system every 1,080 years. An earthquake originating in Zone 33A and affecting some part of the system at Intensity VIII (the damage threshold for significant pipe failure) is expected every 320 years. An earthquake originating in Zone 33A and affecting some part of the system at Intensity VII is expected every 100 years.

For the Salt Lake County Conservancy District, which covers a larger area than the Salt Lake City system (the latter covers about 94 sq. mi.; the former covers about 250 sq. mi.), an earthquake of near-field Intensity X may be expected to be located within the system every 1,050 years. An earthquake affecting some part of the system at Intensity VIII is expected every 210 years, and an earthquake affecting some part of the system at Intensity VII is expected every 65 years.

If the two systems were sufficiently far apart not to be simultaneously affected at such higher intensities, then the estimated recurrence intervals would be half the mean of the two recurrence intervals, or the resultant of taking two assumed independent events. Since the two systems have a common border, their combined estimated recurrence intervals are higher than they would be if they were distant systems. In particular, an Intensity X earthquake may be expected to be located within the two systems every 930 years, an Intensity VIII region may be expected to affect one or both of the systems every 180 years, and an Intensity VII region may be expected to affect one or both of the two systems every 56 years.

Such recurrence intervals imply not only that earthquakes large enough to damage a specific water system are somewhat infrequent in Utah, even in Zone 33A, but also that those systems that are poorly designed or that contain poorly sited facilities, where intensity damage thresholds are lower, are much more likely to be damaged, or are likely to be damaged much more often, than systems well designed and with special siting considerations.

Since systems in Zone 33A are likely to be affected much more often by higher earthquake intensities than systems in other zones, an examination of systems in Zone 33A enables one to assess what also may happen, but less frequently, to water systems in Zone 33B and Zone 34, and much less frequently, if at all, in Zone 32.

For this study, what follows is an analysis first of the Salt Lake City Water System and second of the Salt Lake County Conservancy District. Those intimately acquainted with some other particular water system should be able to adapt the analysis to that other system. The analysis here provided is general in the sense that specific consequences, such as determinations of pressure losses at a given point once pipe breaks are assumed to occur at other points, are not a matter of concern. The concern here is to indicate general problems in water systems, and how such problems may vary from one system to another, not to deal with specific facilities or specific grid problems.

EARTHQUAKE VULNERABILITY OF THE SALT LAKE CITY WATER SYSTEM

In this analysis of the earthquake vulnerability of the Salt Lake City water system, the purpose is to illustrate a methodology by which information about earthquake areal distribution, intensities, and recurrence may be used to assess possible impacts upon the water system components and from which one may derive new information about expected performance of the water system resulting from earthquake events.

Figure 5 indicates some of the main components of the Salt Lake City water system. As Figure 5 shows, the Wasatch fault traverses the middle of the system. For other water systems in Zone 33A, the Wasatch fault generally follows foothill bench areas and so typically lies above the water system grids but occurs at elevated locations where supply reservoirs and storage tanks usually are placed. As a result, a smaller proportion of tanks and reservoirs in the Salt Lake City system lie within the fault zone of deformation than in several other Zone 33A water systems. Nonetheless, at least two reservoirs in the Salt Lake City water system are vulnerable to fault-related damage.

In what follows, an analysis of the components of the Salt Lake City water system leads to an analysis of the system as a whole. The emphasis is on water supply for fire-fighting purposes. An analysis of systems as a whole, in their responses to earthquake of various expected intensities, leads in turn to various proposals for risk mitigation.

Water Sources and Purification Facilities

Salt Lake City water is supplied mainly from surface reservoirs in the mountains to the east of the city and from stream flow down from the mountains. A few wells scattered below the foothills add to the flow.

Water from surface sources comes from several streams that are diverted to conduits or pipes near the canyons that open to Salt Lake Valley, but a larger portion comes in conduits from reservoirs many miles away in the mountains. These supply lines are vulnerable to earthquake damage, and hence to service loss, at the point of entry to conduits and thereafter.

Water treatment or purification facilities at the head of the supply grid of the city present a first possibility for earthquake damage and disruption of supply, except, of course, for conduit failures ahead of the purification plants.

There are four main purification facilities for Salt Lake City water: the City Creek plant, the Parley's plant, the Big Cottonwood plant, and the Metropolitan plant (see Figure 5).

Nonfunctioning of a purification facility does not necessarily mean that alternative sources of water are unavailable in the Salt Lake City System. Figures 6, 7, 8, and 9 illustrate the comparative importance of the four plants in terms of the portions of the system that each can cover.

Figure 6 indicates those areas of the system that the City Creek Treatment Plant cannot feed. While supplying an average of 10 percent of the system's water, City Creek has a maximum flow capacity of 20 million gallons per day (MGD) in the spring. If the fire flow requirements for the system are about 45 MGD, an amount suggested by Leroy Hooten, Jr., Assistant General Superintendent of the Salt Lake City Department of Public Utilities, then the City Creek portion of the system may not even be able to meet fire flow requirements in the area that its plant can feed unless the creek is running near capacity.

Figure 7 indicates that the Parley's Treatment Plant can distribute water only as far south as 39th South. While supplying an average of about 15 percent of the system's water, the Parley's Treatment Plant has a flow capacity of about 30 MGD. It appears that the Parley's Treatment Plant is capable of providing water to a significant portion of the system after an earthquake. It also is noteworthy that the Parley's plant is distant enough from the other three plants so that one might expect it to survive an earthquake that damaged one of the other plants.

Figure 8 indicates the importance, in terms of distribution potential, of the Big Cottonwood Treatment Plant. While supplying 25 to 30 percent of the system's water, the Big Cottonwood plant has a flow capacity of 32 MGD.

As shown in Figure 9, the Metropolitan Treatment Plant can cover an even larger territory, which includes the southern portion excluded in Figure 8 and which excludes only the two north bench areas in Figure 8. The Metropolitan plant is shared with the Salt Lake County Conservancy District and supplies only about 15 percent of the Salt Lake City system's water but has a capacity of 100 MGD, or more than twice that needed for fire flow purposes ([24], p. 18).

It is evident that the two most southern plants can be expected to be more critical in an earthquake insofar as concerns water supply to Salt Lake City. To some extent, the fact that Deer Creek can also supply the city with large flows, if the Salt Lake Aqueduct remains functional, indicates that alternative supplies may somewhat diminish the critical nature of any one of the treatment plants.

The four main purification facilities appear to be designed to meet seismic Zone 2 standards, as set forth by the Uniform Building Code (UBC), in spite of the fact that the Parley's plant has precast concrete panels and the City Creek and Big Cottonwood plants were constructed in the 1950's before such standards were in effect. UBC Zone 3 standards are now applicable, and UBC Zone 2 standards appear to have been lower in the early 1950's than today.[5]

All four treatment plants are bifurcated (actually, the Metropolitan Plant is divided into three sections) so that part of the plants can be shut down to clean the tanks. All four plants have emergency power. Chlorine

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[5]Seismic zones and standards set forth in the Uniform Building Code were revised in the 1960's and early in 1970, the most recent being a change affecting portions of Utah from Zone 2 to Zone 3 and with a consequence that 1960 Zone 2 standards are lower than 1970 Zone 3 Standards. Hence 1970 UBC Zones 2 and 3 are not entirely comparable with pre-1970 UBC Zones 2 and 3.

cylinders in use typically are chained down, and chlorinators are bolted to the floors. Bypasses exist at the Big Cottonwood plant so that overflow water can be sent to the Jordan River, but the bypass valve to allow treated but unfiltered water to enter the Big Cottonwood conduit has not been in use in 15 years as a result of State health standards. According to one source, none of the plants have bypass valving ([6], p. 269). According to Vaughn Wonnacott, general superintendent at the Metorpolitan Treatment Plant, that plant has a bypass line that would permit chlorination if chlorine is available. Even though both southern plants lie somewhat close to the Wasatch fault zone, it appears that, at worst, they lie at the extremeties of the zone of deformation and may lie outside this zone.

A tour of the Big Cottonwood Treatment Plant, which is similar in construction to the other three plants, revealed that structural failure is not likely to be the chief point of earthquake vulnerability for the treatment plants themselves.

According to Leroy Hooten, Jr., the location of a nearby generating plant <u>penstock</u> and <u>flume</u> "presents a potential source of damage to the Big Cottonwood Treatment Plant." ([23], Chapter 6). The penstock and flume, owned by Utah Power and Light, and constructed in 1895, are located approximately 430 feet above the plant. Water flows through the flume and the penstock at about 10 to 32 MGD, or, on the average, between about 7,000 and 22,000 gallons per minute. Were a rupture of the penstock or flume to occur, considerable water could be released before a shut-off could occur that would flow onto the Big Cottonwood Treatment Plant. Since the flume is wooden and the penstock is steel, failure of the flume is likely to occur first. Water released in that case is not likely to damage the treatment plant itself. In the event that water cannot flow into the treatment plant from the penstock, water can still be admitted through a concrete ditch from the Big Cottonwood Creek, and so raw supply does not appear to be in jeopardy as a result of any earthquake-induced failure at the supply side.

A liquid chemical fiberglass tank outdoors and at the eastern end of the plant is likely to fail at higher intensities owing to two factors: a high height-diameter ratio for the tank, and anchor bolts that are stronger than the fiberglass to which they are connected. Such an expected failure would not render the treatment plant non-functional if the chemicals were spilled, since the chemicals are not very harmful.

Inside the Big Cottonwood Treatment Plant, chlorine tanks in use are chained down. However, reserve chlorine tanks are in cradles, and so would likely slide with extreme lateral forces. Even though chlorine can be harmful in excess amounts, damage from chlorine spills would not result in plant non-functionality.

Even though three power sources exist for the Big Cottonwood Plant, only the auxiliary power source is likely to be available after a large earthquake. One power source is within an adjacent Utah Power & Light structure constructed in 1896 that has no lateral resistance.

Failure of the reinforced-concrete portion of the plant, although unlikely, would not necessarily lead to plant non-functionality, although long-term problems of rubble in basins may need to be corrected. Instead, outlet connections, consisting of large diameter pipes, chiefly suspended, appear to be the chief point of vulnerability to earthquake forces at the plant.

Another major point of vulnerability to the plant's functioning lies in its total reliance upon electrical power systems for such processes as screening and treatment. According to Thomas Sherwood at the Big Cottonwood Plant, even though the screening process at the City Creek Plant may be manually operated, such is not the case at the Big Cottonwood Plant. If power is not supplied, water may not be able to pass through the screens, and so all water could be forced to bypass the system and go to the Jordan River.

In general, then, purification facilities can be regarded as systems in themselves, with various points of vulnerability such that non-functionality may occur under certain circumstances. If, for instance, the Big Cottonwood Plant had only the flume and the penstock as its inlet connection to the supply source, then non-functionality would be highly likely at higher intensities. If alternative sources of power were unavailable so that the only source were the 1896 generating station, then, again, non-functionality would be likely in a moderate earthquake. If there were unanchored mechanical systems where, say, power is needed to run the plant, as with an air compressor, then, once again, temporary non-functionality would be likely. By way of contrast, a system less reliant upon power, such as one having a manual means to operate the screening process, is less vulnerable to non-functionality.

Some features of purification facilities that may be vulnerable to earthquake damage do not appear to be so vital to functioning of the purification process. Extensive dollar losses could occur, say, to the aboveground masonry and concrete that might not halt purification processes, since any resulting rubble would sink to the bottom of sedimentation basins. Moreover, highly reinforced-concrete structures, such as are the treatment plant structures, can only expect an average 2.3 percent loss (as a percent of replacement cost) per 100 years as a result of ground-shaking. Loss of a more vulnerable ancillary structure, such as the fiberglass tank, would appear to have a negligible effect upon the plant operation.

For the Big Cottonwood Plant, power dependency and outlet connections appear to be the chief points of earthquake vulnerability. Rupture of outlet connections may be expected to occur at Intensities IX or X. Since power outage may be solved by alternative supplies, or else, with a short delay, as with portable power units, outlet connections appear to be the more troublesome points of vulnerability, and then only if the main artery fails or if most of the outlet connections rupture at the same time. While, then, a major earthquake could damage the Big Cottonwood plant, such a plant should perform as well as buried reservoirs--even though dollar losses to the structures may be very high.

Deep pump wells and artesian wells supply an aggregate of almost 50,000 gallons per minute of water, or about 70 MGD ([24], p. 20; [25], p. 10). Artesian wells can supply a maximum flow of 15 MGD for about four hours maximum. Yet, even though flows from wells suffice for fire flow requirements, wells are localized and cannot supply all parts of the Salt Lake City system. Figure 10 provides locations of deep pump wells and indicates sections of the system that wells generally cannot feed. Table 3 provides information about how much water deep pump wells can supply.

To determine whether or not wells can be expected to be in operation, after an earthquake, specific geologic investigations of wells are needed. According to Bruce Kaliser, engineering geologist at UGMS, Salt Lake City wells are geologically protected from contamination owing to the interlaying of fine and coarse sediments (aquicludes and aquifers).

Storage Tanks

Water storage tanks in the Salt Lake City water system have a combined capacity of about 10 MG. Being located upon the bench areas, tanks can supply water to almost all areas, although not enough water to supply fire flow needs. However, at higher earthquake intensities tanks are expected to become dysfunctional, both because inlet and outlet connections tend to fail in such structures and because tanks in the Salt Lake City system are not specially anchored to resist extreme lateral loads. Figure 11 indicates areas of the Salt Lake City water system that are dependent upon tanks for water supply. Such areas generally will be more vulnerable to loss of supply than areas dependent upon buried reservoirs or upon gravity-flow. Special design of tanks can reduce the vulnerability of such areas (Cf. [14]).

Ground Storage Reservoirs

Ground storage reservoirs in the system have a combined capacity exceeding 110 MG. Two reservoirs, the First South reservoir and the Tanner reservoir, are close to fault traces (See Figure 5). Buried reservoirs are able to supply all parts of the system except for those areas identified as being dependent upon tanks (See Figure 11). Hence, except for such areas dependent upon tanks, reservoirs outside the fault zone of deformation may be able to supply over a two-day fire flow supply in the event of a large earthquake. However, since valves at the large reservoirs lie downstream, ruptures at external connections could allow available supplies to be depleted. Hence, the failures of external connections at approximately Intensity IX may lead to a loss of valuable supplies from ground storage reservoirs. According to Duane Ford of the Ductile Iron Pipe Research Association, flexible external connections do exist that could reduce the risk of loss of such supplies.

According to Rowland Jensen of the Salt Lake City Department of Public Utilities, rupture of outlet connections, buckling of tanks, or sidewall cracking at reservoirs could lead, in some cases, to secondary flood damage, since the natural drainage zones of some reservoirs contain residences, commercial development, and streets.

Aqueducts and Conduits

The aqueducts and conduits in the Salt Lake City system are points of vulnerability to earthquake disruption, since they follow the Wasatch fault and cross it at several points (see Figure 5 and also UGMS Map No. 27, 1969). Fault offsets requiring repair to such structures could occur at Intensity IX.

The Salt Lake Aqueduct extends about 41.7 miles from the Provo River to Salt Lake City, and several segments lie very close to or within the zone of fault deformation. The chances, then, that a major earthquake will affect some portion of the entire aqueduct are somewhat higher than the chances that some particular segment of the aqueduct will be damaged. Approximately 7.6 percent of the total Salt Lake City water supply comes from the Deer Creek reservoir, through the Salt Lake Aqueduct and, as the earlier discussion of available water supplies suggests, could provide an important supply (even adequate for fire flow purposes to all areas that can be covered by the southern plants) should the southern treatment plants be rendered non-functional. Should, say, a major earthquake lead to an offset near Pleasant Grove, Utah, it becomes unlikely, because of the distance, that offset damage will also occur near the southern portion of the Salt Lake City system. It appears, then, that loss of the Deer Creek supply alone would not pose a major supply problem for the Salt Lake City system. In contrast, if one or more of the southern plants cannot operate, but if the Salt Lake Aqueduct is repaired quickly, the aqueduct has a capacity of 150 cfs., or about 100 MGD, which is well above the 45 MGD needed for fire flow purposes. The Salt Lake Aqueduct joins with the Metropolitan Treatment Plant at about 90th South, and water for the Salt Lake City system is taken off the aqueduct at 78th South, 70th South, the Tanner Reservoir, 45th South, 39th South, and the Park Reservoir ([22], Chapter 4).

The Big Cottonwood Conduit starts at the Big Cottonwood Treatment Plant and is intersected at the entrance to Big Cottonwood Canyon, at about 70th South, by the Little Cottonwood Conduit from the Metropolitan Water District's Little Cottonwood Treatment Plant. The Big Cottonwood Conduit has parallel outlets with the Salt Lake Aqueduct, for interchange of feeds. Both the Salt Lake Aqueduct and the Big Cottonwood Conduit cross the Wasatch fault barely north of 70th South and both cross an inferred fault barely south of 45th South (UGMS Map No. 27). A major earthquake could lead to fault-related damage to the lines at one or both locations.

Portions of the conduits and aqueduct that lack lateral load resistance are also vulnerable. The Big Cottonwood Conduit, a concrete line, was constructed in 1915, except for a section from 39th South to the Terminal Reservoir bend which is made of prestressed concrete and steel. Both the Little Cottonwood segment, with a rectangular cross section measuring 36" x 40", and the Big Cottonwood segment to 39th South, measuring 42" x 54", are made of poured-in-place concrete (flowline construction). Plans are underway to replace the most deteriorated segment at about 69th South near the gravel pits. There appears to be some reinforcement in the conduit. The Salt Lake Aqueduct consists of 20-foot sections of concrete pipe with slip joints. Constructed in 1951, the Salt Lake Aqueduct has a 69" diameter ([22], Chapter 6).

The construction of the Salt Lake Aqueduct and Big and Little Cottonwood Conduits does not suggest that major damage is expected on account of groundshaking, except at deteriorated sections or at the highest earthquake intensities.

In addition to consideration of construction features of the conduits and aqueduct, an assessment of their comparative vulnerability depends upon the ease and time with which repairs can be made. If damage occurs either to the aqueduct or to the conduits, no in-line valves exist to isolate the damaged area and the rest of the line downstream from the elevated side of the pipe. Instead, water must be turned off at the treatment plant or plants. Repair can consist of sandbagging or baffling to control surface water flow, but little more can be done until the line is emptied. If failure occurs to only one of the major supply lines, then the other one can be used to supply water to major portions of the Salt Lake City system. If failure should occur to both lines south of 70th South, then the Big Cottonwood Conduit still could supply large portions of the water needed in the system. If, in contrast, failure occurred north of 70th South, then large portions of the system would need to rely upon reservoir supplies (see Figure 7), and those portions of the system where reserve supplies would be depleted rapidly would soon lack supplies.

Pumping Stations

Except for the booster stations on 3rd East and about 26th South, pumping stations are generally small reinforced-concrete structures that are comparatively resistant to ground shaking. However, such pumping stations rely upon power, and only the 45th South station has auxiliary power. Loss of supply that could occur due to a city-wide power outage is indicated in Figure 12, and power loss to localized areas will result in a loss of water supply to such areas. Of special interest is the overlap in Figures 11 and 12. Areas dependent upon tanks also rely upon pumped water.

Some aspects of data contained in Figure 12 can be illustrated when there is a general power outage. According to Scott Cardwell of the Salt Lake City Water Department, when there was a general 4-hour power outage on July 4, 1976, the bench area above 35th South, the bench area in the southernmost portion of the system, and the northernmost bench area went dry. Hence, subregions of those areas indicated in Figure 12 were most affected by such a power outage.

Power also is needed for deep pump wells, for boosting of artesian sources at the 3rd East pumping station, and for purification plant operation. Hence, in spite of the predominant use of gravity flow in the Salt Lake City system, the system nonetheless is heavily dependent upon power sources. Since power outages regularly accompany earthquakes, the dependency of large portions of a water system upon power makes the water system more vulnerable to secondary earthquake losses, such as those that may occur if fire flows cannot be met.

The 3rd East pumping station, an unreinforced-concrete structure, is of a class of structures most susceptible to earthquake damage. Loss of the 3rd East pumping station would entail loss of at least artesian supplies, that being a maximum of 15 MGD for four hours. Since unreinforced-masonry structures can collapse even at Intensity VI earthquakes, the 3rd East pumping station may have one of the lowest damage thresholds in the system. Yet, although the station can provide important back-up supplies in the system, further studies would be needed to justify retrofitting such a station, since it does not appear to be as critical as other facilities.

Pressure Reducing Valves (PRV's)

The problem of pressure reducing valves (PRV's) in an earthquake situation, as suggested in the previous section, lies in how they can increase the amount of pipe breakage after repairs. As Figure 13 indicates, many of the PRV's in the Salt Lake City water system lie very close to or within the zone of fault deformation. Whether or not adjustments can and should be made to some of the major PRV's, such as to PRV number 15 shown in Figure 13, needs further investigation.

Pipe Failures

Pipe failures, here denoting failures of a sort that demand immediate repair, are not generally expected to occur until earthquake Intensity VIII is reached. As intensities increase, so do the failure rates. The Salt Lake City Department of Public Utilities contains extensive information about its pipe system, including information on sizes and materials of pipes. Although ductile-iron pipe is now being laid, except in corrosive areas in the West Valley, only about 5 percent of the system now contains such pipe. Older pipes in the system are of a variety of other types, some of which are quite vulnerable to earthquake damage. For these other sorts of pipe, one can expect an estimated one break per kilometer of pipe affected at an Intensity VIII level. In the Salt Lake City system, there are almost 1,000 miles of pipe. So, if intensities of VIII and above covered the system, more than 1,600 breaks might be expected. When an Intensity VIII covers some portion of the system, one expects each supply or feeder main affected to break in at least one place within the Intensity VIII area. At least 200 breaks might be expected if a near-field earthquake Intensity VIII were to be found in the system.

According to Rowland Jensen, there is no firm way to estimate the amount of time needed to repair pipe breaks. Repairs requiring only sleeves are faster than those requiring pipe replacement, and those requiring numerous valve shutdowns are slower than those requiring only one or two valve shutdowns. In general, were an earthquake to cause extensive pipe damage, time would be saved with a shutdown of valves far upstream. But, since only five crews currently are available for repairwork, and outside crews may be brought in to assist in repair of widespread damage, the likelihood increases that secondary damage could occur, such as may be involved with PRV's or that could be involved with broken power lines and other buried lines for other utilities.

In general, more pipe failures are expected for smaller pipes than for larger pipes, so that areas where there are, say, 3-in. pipes, such as on the North Bench, can expect more damage in the long run.

Some attention has been paid to the fact that water pipes must cross the major fault on the east side of Salt Lake City. Table 4 provides a list of major pipes that are known to cross the Wasatch fault. Even though various types of joints exist that can reduce the likelihood of failure at fault crossings, it must be borne in mind that the expected number of breaks to pipes in an earthquake large enough to cause fault offsets greatly exceeds the number of fault crossings. Because of this, perhaps only those major pipes, such as supply mains, that cross the fault deserve special joints.

The combined effects of ground-shaking and offsets, and secondary effects owing to PRV failures, make the vulnerability of a water distribution system a matter of major importance.

A more direct examination of the Salt Lake City water system's present capacity to yield fire flows also indicates possible areas of strength and of weakness in a system.

Figure 14 provides a rough criterion for determining city locations that may be more vulnerable to fires because they have not met fire flow standards. Locations with lower standards, such as residential areas, need less flow to meet such standards than do areas where, say, multi-unit apartment dwellings, larger industries, or business districts exist. The locations within the Salt Lake City water system indicated in Figure 14 did not meet the fire standards when tests were conducted in 1973 and in 1975. In some cases, inadequate flow may have been due to one or more of several factors, including insufficiently large pipes, and pipes in such poor condition that they have high friction losses and are unable to maintain sufficient "head" to meet the required flows. Some of the locations designated upon Figure 14, such as those on North Temple, may have been redesigned subsequently to meet existing standards.

In examing such deficient areas, one must bear in mind that failure to meet standards does not imply categorically that fire flows cannot be met at such locations. Rather, some locations may be deficient even if the standards were divided by two, whereas others may only be 5 percent short of such standards. In addition, one must bear in mind that in Salt Lake City, the portion of the system to the north of 21st South is ranked along with Ogden as having the best fire rating in the State. Hence, if deficiencies are prima facia evidence for points of vulnerability for the Salt Lake City water system, then other systems should exhibit even more points of vulnerability.

A General Overview Of Earthquake Vulnerability

A partial recapitulation of findings on intensity thresholds is needed before an analysis of various possible earthquakes can be made and their effects upon the Salt Lake City water system can be estimated.

At Intensities VI and VII, poorly sited tanks may buckle and pipes in poor condition may break. The wooden flume at Big Cottonwood Treatment Plant may rupture so that the creek must serve as the means of flow on the inlet side of the purification facility. The generating station at Big Cottonwood Canyon may suffer enough damage to require dependence upon other sources of power. There also is a chance that the 3rd East pumping station can collapse.

At Intensity VIII, pipe breakage becomes widespread. Some unanchored mechanical systems may cease to function. Some unanchored tanks may buckle. Liquid chemical tanks, such as the one at the Big Cottonwood facility where the height-diameter ratio of the tank is high, may break at anchor bolts. Some inlet or outlet connections may break. Some wells that are near sewage lines or cesspools may become contaminated. There may be some damage to deteriorated sections of the aqueduct or conduit lines. If no higher intensities exist, and unless some systematic effects occur, such as a widespread power outage or increased breaks, means should be available to the Salt Lake City Department of Public Utilities to make repairs and to supply water.

At Intensity IX, minor fault offsets may damage structures in the zone of deformation, such as tanks and buried reservoirs and possibly the Salt Lake Aqueduct or Cottonwood Conduits. Considerable damage occurs to pipes, and also to outlet connections. Treatment plants affected at such intensities may be rendered nonfunctional (except for bypass use if chlorine reserves exist) owing to power outage or other breakdown of mechanical systems, such as air compressors, or outlet ruptures. Tanks are expected to buckle. The penstock at the Big Cottonwood Treatment Plant may break, but water should already be washing out from the wooden flume. Damage will likely occur to deteriorated sections of the aqueduct and conduits.

At Intensity X, pipe damage may be beyond immediate repair, especially in areas where pipes are smaller or already in poor condition. Major fault offsets may damage the Salt Lake Aqueduct and/or the Cottonwood Conduits. Cracking will occur in reservoir walls, and reservoirs with poorly designed roof systems will suffer roof damage.

Such a partial recapitulation of findings on intensity thresholds enables one to examine how various earthquakes may affect the Salt Lake City water system. If all areas of the system were in an Intensity X region, which is not likely to be the case, repairs to the system might be almost insurmountable. The problem to be examined, then, is the degree of expected damage from earthquake intensities and their distributions that are more plausible.

In order to model various possible earthquakes, it is useful to employ an isoseismal map similar to that shown in Figure 15. One can assume a given earthquake epicentral intensity (expected to affect a given system over a certain number of years) and, to determine its various effects, superimpose such an isoseismal map upon a given system at various places. Having superimposed such an isoseismal map upon a given system and at a given place, one can use information about intensity thresholds to determine what damage to expect. One also can further analyze the consequences of such damage to determine the systematic effects of postulating such an earthquake. The resulting analysis comes from the use of such an isoseismal map in relation to the Salt Lake City system.

Earthquakes having epicentral Intensity VI or VII, or having an Intensity VI or VII region that enters into the Salt Lake City system, are expected much more often than larger earthquakes that could affect the system directly. Such smaller earthquakes, though, may cause only temporary problems within the system, such as some pipe breaks or some damage to poorly sited tanks. Such an earthquake could damage the 3rd East pumping station, but adequate alternative supplies should be available as long as peak water demands are not in effect.

Earthquakes having intensities of VIII or greater that affect the Salt Lake City system are expected less often than every 320 years. In such a case, some localized area will suffer extensive pipe damage, and, in such an area, each feeder main or supply main could have a break at some point. The number of breaks could be between 200 and 300 if an Intensity VIII earthquake were to have its epicenter in the center of the system. Depending upon its location, such an earthquake may cause temporary problems to deteriorated sections of the Big Cottonwood Conduit, may cause damage to some minor systems at the treatment plants, may buckle some tanks, and may lead to contamination of some wells. If the earthquake were to occur near the City Creek Treatment Plant, localized distribution problems could occur, and areas supplied by City Creek alone may be vulnerable to fires. Since localized power outages are possible, areas dependent upon power may have their supplies depleted that are in storage tanks.

In short, earthquakes having Intensity VIII regions that affect the system are likely to cause localized distribution problems and may cause problems to tanks or even to purification facilities if such exist in the Intensity VIII region. Outside the epicentral region, only a few problems are expected, such as those outlined for Intensity VII earthquakes or those resulting from power outages.

Earthquakes having areas of Intensity IX or above that affect the system are expected only every 700 or so years. Were such an earthquake, say, to strike Sugarhouse directly, the entire Salt Lake City system would be located in Intensity IX or VIII regions, and over 1,600 pipe breaks may occur. Were such an earthquake located on either end of the system, over 800 pipe breaks may still occur. A power outage would be likely, so that areas dependent upon power for supplies may have their supplies depleted. The Intensity IX region would buckle tanks and cause outlet connections to rupture. So, although buried reservoirs may be safe from earthquake damage at this intensity, ruptures at outlet connections may deplete some useful reserve supplies. If the outlet connections at the Park and Terminal Reservoirs were to rupture, 50 million gallons of reserves may be lost. Such an earthquake also could damage the Salt Lake Aqueduct or Cottonwood Conduits, especially at deteriorated sections. If such an earthquake were located in the southern portion of the system, not only might the major supply lines be damaged, but one or more of the southern treatment plants may have broken outlet connections. In such an event, reserve supplies might be needed, and much of the distribution system would need repair before even reserve supplies could be used.

Only if both southern treatment facilities are rendered non-functional, or if there are damages to the conduit and aqueduct to the north of 70th South, would there be a need to rely solely upon reserve supplies. Whatever the supply situation may be, there would be definite problems in the distribution system as well as in areas dependent upon power for pumping.

A major earthquake having epicentral Intensity X might be expected to strike some portion of the Salt Lake City water system every 1,080 years and to be located near the middle of the system every 2,000 to 3,000 years.

Were such an earthquake to lie along the fault in the southern portion of the Salt Lake City water system, the areas affected would be similar to those affected by an Intensity IX earthquake in the same area except that damage would be intensified. The availability of reserve supplies would depend upon the performance of outlet connections at reservoirs and tanks. The Tanner Reservoir likely would become dysfunctional, and pipe damage, extreme in the southern area, may extend north of Sugarhouse. Pipe damage in the northern portion of the system may negligible, so that Parley's and City Creek could supply much of the water needed to areas where pipe damage can be repaired and where tanks and reservoirs remain functional. But, both supply and distribution would be difficult to effect in the southern portion of the system.

If the break were to occur on the Warm Springs portion of the fault, then the City Creek Treatment Plant might become temporarily dysfunctional. Pipe damage would be extreme in an area up to about 3 1/2 miles from the fault, and such damage could extend south of 45th South. Tanks in the northern portion of the system would buckle and the First South reservoir might be damaged owing to a small offset. Except for areas served only by City Creek, all areas of the system could be supplied by the two southern plants (or Parley's), except where distribution is a problem.

If the break were to occur in the central portion of the Wasatch fault as it traverses the system, all but two reservoirs may still be functional as soon as outlet connections are repaired. The two southern filtration plants may become dysfunctional, and one or both of the main supply lines might be damaged by offsets and also by ground shaking. Pipe damage would be extreme, especially within 1/2 mile of the fault, and extensive damage would occur except at the western portion of the city. Many tanks would buckle, so that supplies to areas served only by tanks would be limited to drain-down supplies. Pipe damage would occur also where offsets occurred.

Hence, supplies from the southern portion of the system could be lost owing to breakage of outlet connections, possible power loss, and damage to main supply lines. The Parley's and City Creek Treatment Plants might remain functional as long as their facilities resisted intensities of VII to IX. Total pipe damage throughout the system, though, might exceed 2,000 breaks.

Such intuitive accounts of what could happen for various possible earthquakes enables one to summarize generally vulnerable points in the Salt Lake City water system, so that risk mitigation measures can be entertained.

Earthquakes having Intensities VI or VII, and that are more likely to affect the system much more often than larger earthquakes, are likely to cause damage that can be handled satisfactorily by existing repair crews in a short time unless some unusual damage occurs such as if a tank were to tear and cause flooding. Here, as in all other cases, earthquake-resistant pipes and properly sited and anchored tanks would greatly reduce expected damage.

Any earthquakes having epicentral Intensity VIII or above are likely to cause extensive pipe breakage, much of which can be reduced through the use of earthquake-resistant pipes. At the highest intensities, much pipe breakage will occur. Even in such cases, earthquake-resistant pipes would greatly reduce the time required to locate and to repair breaks.

Only two reservoirs in the Salt Lake City system appear to be specially vulnerable to earthquakes, except for inlet-outlet connections that may need to be repaired and provided that roof systems over the reservoirs are structurally sound. So, if reservoirs had flexible external connections, they could probably serve as supply sources in all earthquakes conditions. Wells, too, may serve as supply sources as long as they are safe from contamination. Tanks also might serve generally as supply sources if they are properly anchored and sited. But, since tanks in the system are not anchored, most tanks would buckle given Intensity IX or X earthquakes.

Only the areas served by City Creek are vulnerable to loss of supply in earthquakes striking the northern portion of the system. Areas served by the two southern plants are vulnerable to loss of supply in major earthquakes that are centered in the middle or southern portion of the system. These areas comprise a major part of the system. The chance of simultaneous failure at the two southern facilities, both of which can supply almost the entire system, can be greatly reduced if certain mitigation actions are taken.

Much of the Salt Lake City water system also is dependent upon power. Examinations of the vulnerabilities of power systems should also throw light upon the risks resulting from a heavy reliance upon power. Earthquake vulnerability of electric power systems in Utah is the subject of another report prepared by the Seismic Safety Advisory Council.

EARTHQUAKE VULNERABILITY OF THE SALT LAKE WATER CONSERVANCY DISTRICT SYSTEM

The Salt Lake Water Conservancy District, which covers about 250 square miles in the Salt Lake Valley and has about 235 miles of pipe (including 7/8-in. pipe) exhibits slightly different potential problems to earthquake effects than the Salt Lake City water system. First, the major sources of supply are from Little Cottonwood Creek, the Jordan Aqueduct, the Salt Lake Aqueduct, and various wells. Both the Jordan Aqueduct and the Salt Lake Aqueduct feed from the south across relatively long distance and are very close to the Wasatch fault near Pleasant Grove. If both supply lines were lost owing to an earthquake near Pleasant Grove, then the Salt Lake Water Conservancy District system would be dependent solely upon wells and flows from Little Cottonwood Creek (which are reported to vary greatly, from 8 cfs. to 350 cfs.). Second, although the Wasatch fault traverses only part of the Salt Lake Water Conservancy District system, most of the tanks near the fault and south of 90th South are used by other municipalities and so their supply source also is threatened by proximity of aqueducts to fault zones in certain locations. Third, part of the Salt Lake Water Conservancy District system is dependent upon pumping from stations that are not designed to resist earthquake forces. Except for these differences, the Conservancy District exhibits characteristics similar to those of the Salt Lake City water system: namely, a reliance upon power, a reliance upon the functioning of the Metropolitan Treatment Plant, and a potential problem of pipe breakage.

Figure 16 indicates main components of the Salt Lake Water Conservancy District system and their relation to the Wasatch fault. The Salt Lake Aqueduct follows the fault southeast of Draper. Figure 17 indicates areas of the system dependent upon tanks or reservoirs. In particular, the areas shown are dependent upon supply from either the 45th South tanks or the 62nd South tanks. Were an Intensity IX earthquake to buckle all such tanks, such areas would be without water. The same areas, it turns out, also depend upon pumping. Figure 18 shows areas that cannot be served by gravity flow from the Jordan Aqueduct. Figure 19 shows areas that cannot be served by gravity flow from the Salt Lake Aqueduct and the Metropolitan Treatment Plant. Figure 20 shows that wells can cover almost the entire system, and that tanks and reservoirs, using well supplies, also can serve the bulk of the system. Figure 17 also shows the areas that cannot be served in a general power outage.

Since the Salt Lake Water Conservancy District system covers a slightly larger portion of seismic Zone 33A than does the Salt Lake City water system, recurrence intervals for earthquakes are slightly shorter.

Epicentral Intensity X affecting some portion: 1,050 years
Epicentral Intensity VIII affecting some portion: 210 years
Epicentral Intensity VII affecting some portion: 65 years

Hence, extensive pipe damage can be expected in the system at least every 210 years.

If an earthquake of epicentral Intensity VIII were to strike the southern portion of the Salt Lake Water Conservancy District system, extensive pipe damage might be expected in the epicentral region. Only if such an earthquake were to strike in the central or northwestern regions might damage extend beyond pipe breaks. In such areas, the condition of the pumping stations might be impaired, and poorly sited tanks might fail. If both major pumping stations were to fail, then supplies to the Kearns and Hunter regions could be lost.

Intensity IX earthquakes illustrate further the vulnerability of supplies to such areas. An Intensity IX earthquake in the west central or northern areas of the system might cause many pipe failures, including possibly even a break in the Jordan Aqueduct but also might buckle tanks and make dysfunctional poorly designed structures. The Hunter and Kearns areas would be incapable of receiving water supplies unless they were obtainable from the Metropolitan Plant through one of the booster stations in the affected area. An Intensity IX earthquake on the eastern side of the system could cause many pipe failures, possibly even creating a loss in supply through the Metropolitan Treatment Plant, given the vulnerability of its inlet and outlet lines. Under such circumstances, wells could supply almost the entire area once trunk lines were repaired and given the availability of power and no contamination to wells. Aboveground tanks would not be expected to function after an Intensity IX earthquake.

An Intensity X earthquake outside the Salt Lake County Water Conservancy District system, but causing a loss of supply through the two main aqueducts, also could be handled through well supplies, if power were available.

An Intensity X earthquake near or within the system could cause extensive pipe failure. Most reservoirs would be expected to remain functional except for those with poorly designed roof systems or those in the epicentral region. The Metropolitan Treatment Plant, to repeat, may be dysfunctional, so that reliance upon wells might be necessary. If wells were contaminated by the earthquake, most of the area to the east of the Jordan River would be without a supply, except for a reservoir supply.

Hence, the Salt Lake County Water Conservancy District system has several possible points of vulnerability that appear to deserve closer examination and, possibly, improvement. Among these points of possible further review are: The security of wells from contamination in the event of a major earthquake, the pipe system, the pumping stations and tanks supplying the Hunter and Kearns areas, and the inlet and outlet connections at the Metropolitan Treatment Plant.

In the next section, possible mitigation measures for various types of vulnerability are described and discussed.

SECTION 6

MITIGATION MEASURES FOR WATER SUPPLY SYSTEMS

In the State of Utah, there is a total potable water storage capacity of at least 469 million gallons per day (MGD), of which about 121 MGD belongs to Salt Lake City, another 63 MGD to the Salt Lake County Water Conservancy District, and another 63 MGD to Ogden City. About 365 MGD of the overall 469 MGD lies in seismic Zone 33A ([30]).

In Sections 4 and 5, means to analyze water supply systems for earthquake vulnerabilities have been described. For larger water systems, more detailed analytic studies are needed than are provided here, and better data are needed for a few conditions, such as assumptions about the number of expected pipe breaks at near field Intensities IX and X. More extensive analytic studies also are presently hindered by a lack of detailed mapping of seismic surficial soil conditions in Utah, except in Davis County. Landslide potentials, liquefactions potentials, flood potentials, and the security of wells from contamination could also be included in more comprehensive studies.

The methods employed in this report, even though they are of a qualified sort, can be used, along with background information supplied by those who are intimate with each water system, in order to gain a good initial idea of how earthquakes can affect the operation of various systems. Such methods then can direct efforts to inspect various components in the system in order to gain a more exact idea of what could happen, given certain seismic conditions. For instance, in both the Salt Lake City water system and particularly in the Salt Lake County Water Conservancy District system, wells could be examined in order to determine more precisely whether they might be contaminated in an earthquake.

To know how an earthquake might affect a water supply system is useful in two ways. Such information can guide the emergency response planning of water districts. More importantly, the information can guide efforts to reduce damage to the system from possible future earthquakes. These are here called mitigation measures.

Mitigation measures should go hand-in-hand with emergency procedures. If, in emergency planning, one develops an inventory of personnel available and of supplies to cope with particular vulnerable situations, one also should check such supplies and personnel against various possible seismic conditions. For instance, if in a large earthquake one expects one break per kilometer of pipes 10" or larger, one should include in one's preparations the means to repair such failures. In turn, some of the following mitigation procedures may alleviate the need to have extremely large stockpiles of supplies or other means for coping with potentially disastrous conditions.

Recurrence intervals for earthquakes that could cause damage to Utah water systems indicate that most mitigation procedures can be handled through long-term engineering planning. Where much of the system is presently under design, as in the Salt Lake County Water Conservancy District, knowledge of lifelines engineering should be a part of the design process, so that costly retrofitting procedures need not be undertaken at a later stage. In engineering design processes generally, earthquake hazards are but one of many problems faced. However, as the analysis in Section 4 indicates, even though damaging earthquakes may occur only infrequently to a particular water system, the damage when it occurs can be disastrous if the system is not well designed. One measure that is economic for most systems within seismically active regions is to replace worn-out pipe with earthquake-resistant pipe or to lay earthquake-resistant pipe wherever possible. In all water systems in Zone 33A, loss of the distribution system, at least in some locales, is possible. If failures in the distribution system can be reduced to a minimum, then emergency work can be directed to other problems that may exist. Since Utah earthquakes have such long recurrence intervals, such pipe replacements do not need to occur overnight, but can be effected in an orderly fashion over several years. Of course, were a major earthquake to affect a system tomorrow, pipe failures could be extensive. So, judgement is needed as to the rate of replacement. Minimally speaking, and without regard to such problems as corrosive soils, pipe replacements are perfectly justified where the cost of repair for the old pipe exceeds the cost of replacement.

Other mitigation procedures entail some expense, but not the large expense of retrofitting old structures or replacing large conduits.

Among the less costly mitigation procedures, all chlorine tanks, whether in reserve or not, should be chained down, and, in general, all equipment at filtration plants should be braced to resist earthquake forces. In the main, cradles may not be satisfactory against the extreme lateral forces that earthquakes can generate, even though the equipment may be heavy. Auxiliary power generators and other equipment connected with the power system should receive special attention.

In the design of various components of a water system, attention paid to earthquake-resistant design can significantly improve the reliability of the system at much less cost than redesign of a vulnerable system. Power stations, tanks, reservoirs, filtration plants, wells, and other major components of the system all can be designed to be earthquake-resistant. All other things being equal, a gravity-flow system is preferable to a system dependent upon the use of power. Major facilities should be placed at larger distances from each other, in order to reduce odds of simultaneous failure. Regulators pose special earthquake problems that should be dealt with in the design phase. Potential contamination from the sewage system also poses many design considerations. Numerous studies indicate that geotechnical considerations also are extremely important in the construction phase of a water system. Wells, tanks, and other major components should be sited to avoid possible faulting effects (Cf. [32]).

When components of a water system are being redesigned, attention to lateral loads should play a significant role.

Other mitigation procedures depend upon the results of analyzing each system.

A more specific analysis of systems may lead to the use, in a few selected instances, of sleeve-type joints at fault crossings. According to Mike Childs at Waterworks Equipment Company in Salt Lake City, individual joints may cost about $350 for 12-in. pipe, $600 for 18-in. pipe, and $650 for 12-in. pipe, excluding labor. Such joints may resist most offsets expected at faults (Cf. [21], p. 416).

A systematic analysis also may imply the need for auxiliary power generators for certain pumping stations and even for retrofitting of buildings for some selected pumping stations. Auxiliary power generators are needed in some cases not only for outages due to earthquakes but for outages generally. Retrofitting of buildings may only be justified for those pumping stations that are very central to a system, where losses to the structure may entail area-wide losses. The 3rd East pumping station of the Salt Lake City water system, for instance, does not appear from this analysis to require retrofitting (although a more detailed analysis may provide different conclusions). Seismic retrofitting of one or more of the pumping stations for the Kearns and Granger areas, though, may well be justified due to the dependency of the areas served upon pumped supplies. Before such retrofitting takes place, an earthquake vulnerability analysis of the system and of the individual structures is needed, of course.

Earthquake analysis of the system may also indicate that some tanks may need to be anchored, or that added reserves may be needed in some areas.

Inlet and outlet connections are major sources of failures to tanks, reservoirs, and filtration facilities. However, design recommendations are available to alleviate these points of vulnerability (Cf. [14], pp. 179, 1980). Whether modification of existing connections should take place is dependent upon the role in the supply system to be played by the facility and its connections in earthquakes, upon the specific vulnerabilities of the existing structures, upon the cost of modifications, and upon the possibility of rapid repairs. For major filtration plants, at least, possibilities of modifying outlet and possibly inlet connections definitely should be examined.

Bypasses around purification and treatment processes (or, means of allowing water to flow directly into the main system) are strongly recommended at certain key filtration plants, so that negative pressures in the distribution system (which allow infiltration of contamination) do not create potential health problems and so that fire flows can be maintained. Should bypasses be used, means of chlorination should be available so that undue health risks do not occur. At the same time, general emergency plans should include ways to inform the public as to the quality of the water within the system.

In summary, earthquakes pose potentially high risks to Utah water systems. However, because earthquakes are expected to damage water systems only infrequently, risks can be minimized through sound engineering practices. Earthquake-resistant pipe can replace eventually much of the more vulnerable types of pipes. And, using an analysis of specific water systems in various possible earthquakes, those persons intimate with each system can identify and eventually rectify points of vulnerability. Except where such systems analyses indicate extreme risks, such as to poorly designed but key pumping stations, mitigation procedures should not require that huge sums of money be spent on matters that can be handled in a long-term economic fashion. The importance of inital siting and design cannot be overemphasized as means to reduce risks to water systems.

SECTION 7

METHODOLOGY OF EARTHQUAKE RISK ANALYSIS

METHOD FOR ESTIMATING RECURRENCE INTERVALS FOR EARTHQUAKES

In order to develop a broad perspective of the likely extent of damage by earthquakes in Utah and of risks to specific water systems, it is necessary first of all to estimate the frequency of earthquakes of various strengths in various locales.

In the Algermissen and Perkins study referenced in Section 4 (Cf. [3]), the United States is divided into 71 earthquake source zones. Three zones in Utah, zones 32, 33, and 34, are of importance. For each zone, the values of the coefficients a and b_I are developed and implicitly available so that one can employ the following equation.

$$(1)\ \log N = a + b_I I_O,$$

wherein N is the number of yearly occurrences with maximum intensity I_O, such that I_O is either the observed historical maximum intensity, or is determined from the equation

$$(2)\ M_C = 1.3 + 0.6 I_O,$$

wherein M_C is the Richter magnitude corresponding to I_O in equation (2). That is, I_O can be derived from data about Richter magnitudes.

For each zone, we are given the estimated number of earthquakes of Intensity V per 100 years. We also are given b_I for each zone ([2], pp. 17, 18). So, at the 90-percent probability level, we have the following information.

Source Zone	Number of Modified Mercalli Maximum Intensity V's Per 100 Years	b_I
Zone 32	17.0	-0.56
Zone 33	126.8	-0.56
Zone 34	71.0	-0.56

If we assume that there is an equal distribution of earthquakes over the years, or that the above estimates of earthquakes of Intensity V can be reduced suitably to annual estimates (where, say, there are 1.268 such earthquakes expected annually in Zone 33 at the 90-percent probability level), then we can use the above information, in conjunction with equation (1) (redefined, to apply to all intensities, not merely maximum expected ones), in order to derive values of the coefficient a. Given such assemptions, we have the following values for the coefficient a.

Source Zone	a
Zone 32	2.03
Zone 33	2.90
Zone 34	2.65

Hence, for each zone, we can derive the expected annual frequencies for earthquakes of a given intensity if we employ the following equations.

Source Zone	Frequency (N)
Zone 32	$10^{2.03 - 0.56 I}$
Zone 33	$10^{2.90 - 0.56 I}$
Zone 34	$10^{2.65 - 0.56 I}$

Given the assumption that the occurrence of an earthquake having a given intensity is equiprobable for each year during a 100-year period, then, with a 90-percent probability, we can derive the following 100-year expected earthquake occurrences by zone and by maximum intensity.

Source Zone	100-Year Frequencies With Maximum Intensity					
	X	IX	VIII	VII	VI	V
Zone 32	0.03	0.10	0.35	1.29	4.68	16.98
Zone 33	0.20	0.72	2.63	9.55	34.67	125.89
Zone 34	0.11	0.41	1.48	5.37	19.50	70.79

So, for example, in Zone 33, about 35 earthquakes of every 100 occurrences can be expected to have intensities with a maximum of VI, about 10 with a maximum of VII, and so on.

The information derived from the Algermissen and Perkins study, however, is based primarily upon historical records adjusted for gaps in data. Geological evidence, in contrast, as revealed by Robert Bucknam of the U.S. Geological survey (USGS) and as augmented by others engaged in fault investigations, indicates that the expected activity along the Wasatch fault, in Zone 33, may be greater than that expected in terms of historical records.

In particular, in order to appraise the effects of such increased activity as indicated by new geological evidence, we may assume that, along the fault line, which is about 350 kilometers in length, about one earthquake between 7.0 and 7.6 on the Richter scale may be expected to occur every 500 years. Such an earthquake would create an assumed 50-kilometer break along the fault line.

In order to estimate the seismicity of sites based upon such information, we have constructed a zone, called Zone 33A, that extends approximately 20 kilometers on each side of the fault. Zone 33A thus covers 350 km. x 40 km. Very crudely, we approximate the areas of the other zones as being 261,000 sq. km. for Zone 32, 43,200 sq. km. for Zone 33, and 76,400 sq. km. for Zone 34. If the remainder of Zone 33 is labeled Zone 33B, then Zone 33B covers about 29,200 sq. km.

An examination of the limited historical data indicates that about one-half of all earthquakes of Intensity V or greater that have occurred in Zone 33 have been located in Zone 33A. So, too, about one-half of all Intensity V's in Zone 33 have occurred in Zone 33A (Cf. [7], pp. 9-20).

In Zone 33A, we can thus assume that about 63.4 earthquakes with a maximum Intensity V are expected to occur in 100 years. Also, the slope chosen for the logarithmic curve (1), -0.52, is such that values of Intensity X and above will barely exceed a 100-year frequency of 0.20. So, the recurrence interval for an Intensity X earthquake will be slightly under 500 years. Hence, we have contructed the following 100-year frequencies for Zone 33A.

Source Zone	Intensity					
	X+	IX	VIII	VII	VI	V
33A	0.22	0.52	1.8	5.8	19.2	63.4

In order to estimate the frequencies for Zone 33B, one first subtracts the frequencies of Zone 33A from the frequencies in Zone 33. Then, because frequencies at higher intensities in Zone 33B will be too low, since geological evidence has increased those values for Zone 33A and hence for the zone in general, we fit the lower values to a logarithmic curve. So, for Zone 33B, we derive the following expected maximum frequencies.

Source Zone	Intensity					
	X	IX	VIII	VII	VI	V
33B	0.08	0.30	1.15	7.8	16.5	63.4

So far, then, estimated frequencies have been derived for each main macrozone. However, the estimate of frequencies at maximum intensities does not by itself yield specific information about the expected frequencies of a given intensity at some site within a given zone, or even about the expected frequencies in a given locale with a main zone. The seismicity at specific sites is needed in order to estimate expected losses to a given structure. The seismicity at specific locales is needed in order to estimate the frequency of earthquakes of various sizes expected to affect given municipalities.

In order to use the information about the seismicity in a zone to derive conclusions about the possible seismicity at a specific location within the zone, one needs to estimate how earthquakes with certain epicentral or maximum intensities will attenuate.

Attenuation curves have been developed in order to determine the intensity of an earthquake at a certain distance from the epicenter. From the USGS study of the Salt Lake City area (Cf. [6], p. 39), one finds the following curve.

(3) $I_o - I = n \, Log_{10} [(\Delta^2 + h)^{0.5}/h]$, wherein

Δ = the epicentral distance (km.) from I_o to I,

h = depth of focus (km.),

I_o = maximum intensity at the epicenter,

I = intensity at Δ from the epicenter, and

n = an exponent determined empirically.

According to Dr. Walter Arabasz, geophysicist at the University of Utah, a good approximation for Utah can be constructed if one lets n = 4.0.

The assumption for h can make a substantial difference. In terms of area covered, the assumption of 10 km. in depth as opposed to 5 km. in depth makes a difference of four times the area covered.

From a list of recent earthquakes in Utah that was supplied by Walter Arabasz and William Richins at the University of Utah Department of Geology and Geophysics, the mean and median of focal depths are less than 6 kilometers. A more relevant notion to the consideration of areas, the root mean square, the square root of the mean of squares, is also less than 7 kilometers. Focal depths do not seem to vary with intensity, although the sample is skewed with a preponderance of earthquakes of lower intensities. So, for this study, 7 kilometers was chosen as the focal depth.

Hence, for Utah, one can use equation (3) to determine Δ for $I_o - I = 1$, for $I_o - I = 2$, and so on.

For purposes of simplification, it is here assumed that a given intensity ceases to exist at the midpoint between two numerically successive Δ's. That is, if $I_o - I_1 = 1$, and Δ = 10 kilometers, then the maximum intensity, I_o, extends for a distance of 5 kilometers. So, too, if, for $I_o - I_2$, Δ = 21 kms., then the second highest intensity, $I_o - I$, extends from 5 kms. from the epicenter to 15.5 kms. from the epicenter.

Given the abovementioned assumptions for Utah, and given equation (3), we can derive the following values for Δ, given various differences in intensity.

I_o-I	Δ (km.)
1	10.3
2	21.0
3	38.7
4	69.7
5	124.3
6	221.3
7	393.6

Given the assumption about the use of a midpoint in order to determine the distance covered by the maximum intensity, we can, with other suitable assumptions, determine the area covered by each intensity.

In the general case, for all earthquakes except for those major earthquakes that cause a 50-kilometer break along the Wasatch fault, we assume that intensities can be mapped as a group of concentric circles, with the epicenter at the center, with the maximum intensity covering the inner circle, and with each lesser intensity found in each next outer circle. Given such a mapping of intensities, along with assumptions made about the use of the midpoint, we can estimate the area for each intensity, given a value for the maximum intensity. For a given I_o, the areas covered by I_o-I, for $0 \leq I_o < 5$, are as follows.

I_o-I	Area (sq. km.)
0	83
1	686
2	2,034
3	6,424
4	20,310
5	64,230

For a given value of I_o, one can use the above areas. If, say, I_o, the maximum intensity of an earthquake, is V, then 83 sq. km. are covered with an Intensity V, 686 sq. km. by Intensity IV, and so on.[1]

For Zones 32 and 34, which are more extensive in area, we assume that all of the relevant attenuated area (down to Mercalli Intensity VI) lies within the zone. In other words, we assume that the impact of earthquakes originating outside the zone is counterbalanced for our purposes by the attenuated areas of earthquakes that go outside the zone even though the epicenter lies within the zone.

For all cases where we can suitably regard the attenuation pattern as a sequence of concentric circles, we can derive the approximate areas of covered at a given intensity as a result of attenuation. Given expected epicentral frequencies, such areas can be derived. If, for instance, 0.11 is the expected 100-year frequency of earthquakes having Intensity X, then one can expect such earthquakes to cover 0.11 x 83 sq. km. at Intensity X, 0.11 x 686 sq. km. at Intensity IX, 0.11 x 2,034 sq. km. at Intensity VIII, and so on. Then, if we add the expected effects of epicentral Intensity X earthquakes to the expected effects of epicentral Intensity IX earthquakes, and so on, we determine the expected areas covered at a given near-field intensity for all earthquakes. In general, for Zone 32, one can use the same method to derive a table analogous to the one shown below for Zone 34.

Epicentral Intensity	Expected Frequency of Epicentral Intensity	Area for Attenuated Intensity -- Zone 34					
		X	IX	VIII	VII	VI	V
X	0.11	9	75	224	707	2,234	7,065
IX	0.41		34	281	834	2,634	8,327
VIII	1.48			123	1,015	3,010	9,508
VII	5.37				446	3,684	10,923
VI	19.50					1,619	13,377
V	70.79						5,876
Cumulative Areas in Zone 34 Covered at the Given Intensity		9	109	628	3,002	13,181	55,076

This table illustrates how the contribution of each epicentral intensity to intensities at lower levels can be established.

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[1] Attenuation curves are generally imprecise very close to the epicenter. The result here that the epicentral intensity extends about 5 km. is at least consistent with the general conclusion of William Gordon (member of the Utah Seismic Safety Advisory Council and a geotechnical engineer) that attenuation curves have not been precisely defined for the first 5 kilometers.

So, for any given intensity, the expected area covered is the expected area covered at such an intensity as the result of the attenuation of higher epicentral intensity earthquakes plus the expected area covered at the given intensity given its expected epicentral frequency. Since expected epicentral frequencies vary from zone to zone, so too will vary expected frequencies of areas covered by given intensities. For Zone 32, there are the following expected areas (in square kilometers) covered at various intensities.

Source Zone	Intensity					
	X	IX	VIII	VII	VI	V
32	3	29	159	744	3,238	13,454

The total areas in all zones and subzones can be crudely approximated as follows.

Source Zone	Area
Zone 32	261,000 sq. km.
Zone 33A	14,000 sq. km.
Zone 33B	29,200 sq. km.
Zone 34	76,400 sq. km.

For all zones, we assume that facilities and buildings are randomly distributed throughout the zone. Only for Zones 32 and 34 should one assume that areas covered by earthquakes within the zone do not extend beyond the zone (for Intensities VI and above).

For Zones 32 and 34, we can determine the expected frequencies of the occurrence of an earthquake whose area encompasses a given facility. Such an expected frequency equals the expected area covered by a given intensity and located within the zone divided by the total area within the zone. Such frequencies might be regarded as point-frequencies. So, any given site has the following expected 100-year frequencies at the following given intensities.

Source Zone	Intensity					
	X	IX	VIII	VII	VI	V
Zone 32	0	0	0.0006	0.0028	0.0124	0.0515
Zone 34	0.0001	0.0014	0.0083	0.0393	0.1726	0.7212

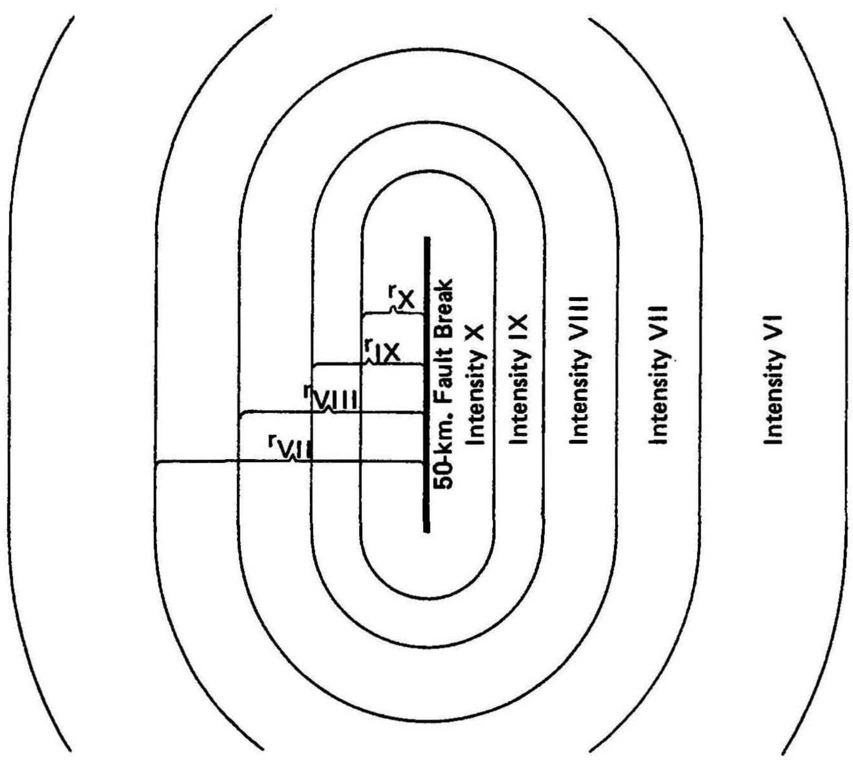
Analogous point frequencies must be derived for the other zones in order to estimate human and property losses.

However, in pursuing this methodology, two problems arise in regard to the two subzones, Zone 33A and Zone 33B. First, the subzones are small enough so that one cannot fairly assume that the amount of attenuation into the area roughly equals the amount of attenuation outside the area. Some method must be devised in order to estimate how much ground shaking attenuates ouside the subzone, and how much ground shaking enters into the subzone from other zones. Second, the attenuation pattern for an assumed 50-kilometer break along the Wasatch fault is not a pattern of concentric circles. Higher intensity earthquakes in Zone 33A, then, are regarded as attenuating more so in the pattern of rectangles having semicircles at the two ends.

For such a 50-kilometer break, it is assumed that the rectangles are formed by lines parallel to the break, and the semicircles have their centers at the ends of the break. The area covered by such an earthquake of epicentral Intensity X should be roughly as follows.

At Intensity X:	83 sq. km.
At Intensity IX:	686 sq. km.
At Intensity VIII:	2,034 sq. km.
At Intensity VII:	6,424 sq. km.
At Intensity VI:	20,310 sq. km.
At Intensity V:	64,230 sq. km.

The attenuation pattern for such a break would appear as indicated in the diagram.



The area covered at Intensity X should equal 83 sq. km., and so on. r_X is defined as the length of the perpendicular to the break measured from the break to one of the boundaries of Intensity X. In general, r_j is the length of the perpendicular measured from the break to the boundary of some Intensity j. Given the expected areas at each intensity, one can derive values of r_j for $X \geq j \geq 0$ if one knows the sum of all areas for Intensity X to Intensity j to equal $\pi r_j^2 + 100\ r_j$.

So, for instance, for Intensity X, one uses the following equation.

$$83 \text{ sq. km.} = \pi r_X^2 + 100\ r_X.$$

For Intensity IX, one uses the following equation.

$$686 \text{ sq. km.} = \pi r_{IX}^2 + 100\ r_{IX}.$$

One thus derives the following radii.

r_X = 0.79 km.

r_{IX} = 5.67 km.

r_{VIII} = 17.93 km.

r_{VII} = 40.58 km.

r_{VI} = 82.36 km.

r_V = 157.62 km.

Since Zone 33A is only 40 km. wide, the following areas in Zone 33A are ascribable at given intensities to the rectangular portion of the break.

At Intensity X:	79 sq. km.
At Intensity IX:	488 sq. km.
At Intensity VIII:	1,147 sq. km.
At Intensity VII:	207 sq. km.

At each end of the break, a semicircle is formed, with r_j as the radius out to a given intensity. For such semicircles, only the area within the width of Zone 33A is to be included. Given such areas, aspect ratios are determined in order to estimate the number of semicircles expected to lie within the length of Zone 33A. Once the earthquake occurs along a break of 50 km., the endpoints of the intensity area could occur at any point along 300 kms., given a 350-km. fault line. It was assumed that there are $(300/r_j) + 1$ possible points uniformly distributed, given r_j, of which all but one point are on the interior of the break. So, the aspect ratios are $300/(300 + r_j)$ for areas expected to lie within the length of the zone.

The determination of how much of the attenuated area lies within the width of the zone, where $r_j \geq 20$ km., can be made trigonometrically. Accordingly, the following areas were estimated to lie within the semicircles and in Zone 33A at the specified intensities.

At Intensity X:	2 sq. km.
At Intensity IX:	97 sq. km.
At Intensity VIII:	854 sq. km.
At Intensity VII:	2,224 sq. km.
At Intensity VI:	4,441 sq. km.
At Intensity V:	4,805 sq. km.

Since 0.22 such earthquakes are expected every 100 years, the areas expected to be affected by the various intensities on a 100-year basis are as follows.

At Intensity X:	18 sq. km.
At Intensity IX:	128 sq. km.
At Intensity VIII:	440 sq. km.
At Intensity VII:	535 sq. km.
At Intensity VI:	977 sq. km.
At Intensity V:	1,057 sq. km.

For maximum intensities of IX and below, typical concentric patterns were used, except that aspect ratios were again employed in order to estimate, given a uniform distribution of intensities, the percent of the attenuated areas that could be expected to lie within the zone. In particular, if $r < w \leq \ell$, given length ℓ (350 km.) and width w (40 km.), then the zone may be divided into ℓ/r units by w/r units. There are hence $(\ell/r + 1) \times (w/r + 1)$ uniformly distributed points.

The total attenuated area for all points is thus $(\ell/r + 1)(w/r + 1)\pi r^2$.

Of the four points on the corners, three-fourths of their area lies outside the zone, and of the two $(\ell/r - 1 + w/r - 1)$ other boundary points, one-half of their area lies outside the zone. So, the following aspect ratio obtains.

$$1 - \frac{\ell/r + w/r + 1}{(\ell/r + 1)(w/r + 1)} = 1 - \frac{(370 + r)}{(350 + r)(40 + r)}.$$

Where $r > w$, it is assumed that the aspect ratio is

$$\frac{2(\ell/r)}{2(\ell/r + 1)} = \frac{\ell}{\ell + r}.$$

Therefore, on the assumption that the points occur along the fault, it is determined trigonometrically what percent of the area lies within the zone. So, using both methods, one obtains the following aspect ratios for various radii.

For r = 5.15, the ratio is 0.98
For r = 15.65, the ratio is 0.98
For r = 29.90, the ratio is 0.72
For r = 54.20, the ratio is 0.40
For r = 96.77, the ratio is 0.21

Hence, the area covered

for $I_o - I$ = 0 is 82 sq. km.,
for $I_o - I$ = 1 is 754 sq. km.,
for $I_o - I$ = 2 is 2,018 sq. km.,
for $I_o - I$ = 3 is 3,692 sq. km., and
for $I_o - I$ = 4 is 6,204 sq. km.

So, the area covered at the lower intensity, the total area covered to the lower intensity minus the area covered by the higher intensities, is as follows.

For $I_o - I$ = 0, 84 sq. km.
For $I_o - I$ = 1, 672 sq. km.
For $I_o - I$ = 2, 1,264 sq. km.
For $I_o - I$ = 3, 1,674 sq. km.
For $I_o - I$ = 4, 2,512 sq. km.

Given the previously derived intensity figures based on a Modified Mercalli Intensity X, we are able to derive the accumulated areas covered in Zone 33A due to all maximum intensities by means of the following table.

Epicentral Intensity	Frequency	Near-Field Intensity					
		X	IX	VIII	VII	VI	V
X	0.22	18	129	440	535	977	1,057
IX	0.52		42	350	657	870	1,306
VIII	1.8			147	1,210	2,275	3,012
VII	5.8				474	3,900	7,332
VI	19.2					1,569	12,910
V	63.4						5,180
Cumulative Area Covered In Zone 33A		18	171	937	2,874	9,591	30,797

The values in the table above have not yet been converted into point frequencies, because adjustments need to be made for soil conditions. Seismic waves may be amplified in unconsolidated soils, so higher intensities therefore may be expected. S.T. Algermissen, K.V. Steinbrugge, and H.L. Lagorio have suggested a way to account for this effect in the methodology used here ([26]).

In [26], upon p. 77, S.T. Algermissen and others use the following intensity increments for different surficial materials.

Alluvium:	+1
Tertiary marine sediments:	0
Pre-tertiary marine and non-marine sediments:	0
Franciscan formation:	-1
Igneous rocks:	+1

That is, if all of Zone 33A were alluvium, then all previous estimates for intensities would have to be increased one intensity. I.e., if all of Zone 33A were alluvium, then 937 sq. km. would be covered at Intensity IX over a 100-year period. Values in the table above then would be increased one increment.

No map of geological surficial materials directly bearing upon attenuation presently exists for Zone 33A. With the aid of Fitzhugh Davis at the Utah Geological and Mineral Survey (UGMS), the following rough translations were made for the Utah State Geological Map.

Q (Quarternary)	=	+1
T, J, D, E, pEmf	=	0
P, K, M, PE, Tv, Tr, Tilp, Tqm	=	-1

A mapping of Zone 33A produced the following area estimates in accordance with this classification of soils.

47%	=	+1
29%	=	0
24%	=	-1.

In order to account for the effects of geological surficial materials, then, and using a suggestion made by S.T. Algermissen, one increases 47 percent of all expected intensities by +1 and decreases 24 percent of all expected intensities by -1. Thus, the following areas at expected near-field intensities result.

At Near-Field Intensity X:	94 sq. km.
At Near-Field Intensity IX:	494 sq. km.
At Near-Field Intensity VIII:	1,663 sq. km.
At Near-Field Intensity VII:	5,566 sq. km.
At Near-Field Intensity VI:	17,946 sq. km.

Given that the area of Zone 33A is 14,000 sq. km., the following point frequencies for 100 years result.

At Intensity X:	0.0067
At Intensity IX:	0.0353
At Intensity VIII:	0.1188
At Intensity VII:	0.3976
At Intensity VI:	1.2819

In estimating frequencies for the remainder of Zone 33, namely Zone 33B, it is assumed that adjustments must be made for the higher intensities, since assumptions for Zone 33A imply higher expected values for Zone 33 as a whole. In addition, aspect ratios were developed, and estimates were made of the areas attenuated into Zone 33B from Zone 33A. Given such assumptions, the following point frequencies for 100 years were obtained for Zone 33B.

At Intensity X:	0.0002
At Intensity IX:	0.0009
At Intensity VIII:	0.0111
At Intensity VII:	0.0647
At Intensity VI:	0.3767
At Intensity V:	1.5735

Thus, for Zone 33A, some account has been taken of surficial materials, whereas for the other three zones no such account has been taken. The resulting point frequencies for the four zones are found in the following table.

Source Zone	Near-Field Intensity					
	X	IX	VIII	VII	VI	V
Zone 32	0	0	0.0006	0.0028	0.0124	0.0515
Zone 33A	0.0067	0.0353	0.1188	0.3976	1.2819	--
Zone 33B	0.0002	0.0009	0.0111	0.0647	0.3764	1.5735
Zone 34	0.0001	0.0014	0.0083	0.0393	0.1726	0.7212

Given the values in the table above, one can estimate recurrence intervals for a given earthquake intensity at a given site. Since, for instance, 0.0006 Intensity VIII's are expected to occur at a given site in Zone 32 every 100 years, the recurrence interval for Intensity VIII's at a given site randomly chosen in Zone 32 is over 166,000 years. Since 0.0034 Intensity VII's or above are expected to occur at a given site in Zone 32, then the recurrence interval for Intensities VII or above is over 29,000 years at a given site.

Expected recurrence intervals for the zone as a whole also are derivable in a similar fashion. Since 0.74 Intensity IX's or above are expected every 100 years in Zone 33A, then the recurrence interval for Intensity IX's or above is 135 years.

For a subarea within the zone, recurrence intervals may be estimated if one multiplies the recurrence interval for the zone as a whole by the area of the entire zone divided by the area under consideration. Care must be taken as to how to calculate the area under consideration, since it must include all relevant epicenters.

APPLICATION OF EARTHQUAKE RECURRENCE DATA TO A WATER SUPPLY SYSTEM

The Salt Lake City water system serves as a useful illustration of the recurrence interval data developed in the previous paragraphs. The water system itself covers 94 sq. miles, or 243.5 sq. km., which is 1.7 percent of Zone 33A. However, if one is to calculate recurrence intervals for Intensity IX earthquakes, for instance, one must include a larger area, since the epicentral area may affect the water system even if the epicenter is located just outside the water system. In general, a radius of 5.15 km. (from previous calculations) may be multiplied by the length of the border of the region in order to estimate the border area that can produce earthquakes where the epicentral area enters into the system itself. If the border length for the Salt Lake City system is approximately 82 km., then the total relevant region is 243.5 sq. km. plus 82 x 5.15 sq. km., or 665.8 sq. km., or 4.8 percent of Zone 33A.

For Zone 33A, the following recurrence intervals are obtained from such calculations.

Intensity				
X	IX	VIII	VII	VI
454 years	192 years	56 years	17 years	5 years

Hence, for the Salt Lake system, the following recurrence intervals are derived:

Intensity				
X	IX	VIII	VII	VI
Special Case	4,085 years	1,191 years	361 years	106 years

For Intensity X, 51.58 sq. km. are expected to be affected every 454 years. The length of the fault is approximately 26 km. in the Salt Lake City water system area. Thus, a length of almost 129 km. of the fault could produce an earthquake affecting the area served by the Salt Lake City water system. So, the recurrence interval is 1,232 years, of 454 x (350/129) for an earthquake that might affect the system. Hence, one derives the following recurrence intervals for earthquake epicenters whose epicentral regions are within the system area.

Intensity				
X+	IX+	VIII+	VII+	VI+
1,232 years	947 years	528 years	214 years	71 years

Such figures do not take into account amplifications from large earthquakes whose epicentral regions lie outside the water system.

The above figures may be contrasted to site-frequencies that do take into account soil amplification factors.

Intensity				
X+	IX+	XIII+	VII+	VI+
14,925 years	2,380 years	622 years	179 years	54 years

Hence, soil amplification factors have a discernible effect upon estimating the occurrences of Intensity VIII's and below.

If one makes the conservative assumption that soil amplification factors apply to epicentral intensities, and if one proceeds to calculate recurrence intervals for earthquakes affecting the water system as a function of its bordered area in Zone 33A (4.8 percent of Zone 33A), then the following recurrence intervals can be used as conservative estimates for epicentral earthquakes affecting the water system.

Intensity				
X+	IX+	VIII+	VII+	VI+
1,079 years	701 years	323 years	103 years	39 years

Since for a given point, the relevant border area is about 83 sq. km. or about 0.6 percent of Zone 33A, the likelihood of an epicenter affecting a given point is about one-eighth of the likelihood of its affecting the water system in general. So, recurrence intervals seem to be less meaningful for lower intensities that can also be produced by higher intensities which attenuate into the region. A major earthquake in the middle of the zone, for instance, could cover over one-half the zone with Intensities VI and above, and could, with amplification, cover one-half of the zone with Intensities VII and above.

Inasmuch as maximum Intensity X earthquakes have been modeled in a special way, it also is possible to divide Zone 33A again into various subsections, namely, an area within 0.79 km. (1/2 mile) of the fault and an area within 5.67 km. (3-1/2 miles) of the fault. When amplification factors are taken into account, the chief differences in site-frequencies for such intensities lie in near-field Intensity X estimates, which result in the following differences.

100-year undifferentiated estimate:	0.0067
100-year within 1/2 mile of the fault:	0.0267
100-year within 3-1/2 miles of the fault:	0.0201
100-year beyond 3-1/2 miles of the fault:	0.0014

Hence, as modeled, sites relatively close to the fault are more likely to be affected by the highest expected intensity.

Since there are reasons for regarding earthquakes as discrete events for the purpose of making damage estimates, it also is useful to determine what portion of the various site frequencies are a result of earthquakes having specific epicentral intensities.

The next table indicates site frequencies at given near-field intensities as a result of various epicentral intensity earthquakes in Zone 33A.

Epicentral Intensity	Near Field Intensity				
	X	IX	VIII	VII	VI
Due To X	0.0054	0.0177	0.0292	0.0515	0.0649
Due To IX	0.0014	0.0126	0.0300	0.0488	0.0731
Due To VIII		0.0049	0.0436	0.1039	0.1690
Due To VII			0.0159	0.1407	0.3351
Due To VI				0.0256	0.4659
Due To V					0.1739

This table enables one to estimate the proportion of losses to certain components in the water system as a result of earthquakes of various sizes. A method for making such estimates is described next.

ESTIMATING EARTHQUAKE DAMAGE TO VARIOUS COMPONENTS OF WATER SYSTEMS

Statistical information on earthquake damage to buildings is much more complete than such information on earthquake damage to other facilities, such as underground pipes, underground reservoirs, tanks, and the like that make up a water supply system.

Here, some of the principal observations regarding earthquake effects on buildings will be summarized before similar findings on components of water systems are examined. The usefulness of such information on buildings is here limited to its applicability to aboveground structures at purification facilities, and to larger pumping stations. The data also provide a contrast between building losses and expected earthquake losses to other types of facilities.

In a technical paper on building losses, S.T. Algermissen and K.V. Steinbrugge have developed a figure in which earthquake losses at various intensities are estimated for different types of building contruction (Cf. [27], p. 11). In the figure, Algermissen and Steinbrugge employ a system of building classification that is based upon observed earthquake damage to different construction systems. The data are charted to indicate a percent of damage expected for a particular type of construction and for a given earthquake intensity. Using their figure and their taxonomy, one can derive estimates of average percent losses as a function of building replacement costs.

So, for example, buildings in Class 5E (the most vulnerable class, and typical, say, of such older structures as the Granite Generating Station) suffer a 35 percent average loss at Intensity IX, a 25 percent loss at Intensity VIII, and so on. The next table summarizes such loss estimates for the various types of building classes from the Algermissen and Steinbrugge figure. The reader is referred to the author's work for a complete description of the classification scheme.

Intensity	Expected Percent Losses To Buildings At Given Near-Field Intensities For Different Construction Classes									
	5E	4D	4E	4B	5D	3B,3D 4C,5C	3C,4A 5B	3A	2B	2A
X	50%	42%	37%	33%	30%	23%	18%	15%	12%	8%
IX	35%	30%	27.5%	25%	22.5%	17.5%	13%	11%	8%	7%
VIII	25%	22%	19%	18%	16%	12.5%	7.5%	6%	4.5%	4%
VII	14.5%	12.5%	11%	10%	9%	7%	2%	1.5%	1%	2.5%
VI	4%	3%	2.5%	2.5%	2.5%	2%	0	0	0	0

Using earthquake point frequency data derived previously and information from the above table, one can sum up all expected losses to given classes of buildings in given zones over a 100-year period. The next table provides the summary of expected 100-year losses (in percent) to buildings in Utah by seismic source zone and by construction class.

Source Zone	Percent of Expected 100-Year Losses To Buildings In Utah Based Upon Algermissen and Steinbrugge Classification System									
	5E	4D	4E	4B	5D	3B,3D 4C,5C	3C,4A 5B	3A	2B	2A
Zone 32	0.0011	0.0009	0.0007	0.0007	0.0005	0.0001	0.0001	0	0	0
Zone 33A	0.1545	0.1257	0.1105	0.1042	0.0967	0.0761	0.0227	0.0180	0.0129	0.0177
Zone 33B	0.0278	0.0222	0.0189	0.0182	0.0173	0.0136	0.0022	0.0018	0.0012	0.0021
Zone 34	0.0153	0.0123	0.0106	0.0101	0.0094	0.0075	0.0022	0.0013	0.0009	0.0014

From such percentage losses, and given the replacement costs of a building and its location, one can estimate the 100-year expected dollar losses, and hence the annual expected dollar losses.

The buildings associated with many purification facilities are expected to have earthquake-resistance characteristics similar to the structures included in this classification system, for instance, Class 4A. As indicated in Section 4, however, losses to structural elements may have no direct bearing upon the functionality of the entire water treatment plant.

It is also useful to use the table on site frequencies and the table on losses to buildings for given intensities together in order to estimate percentages of total expected losses that are due to earthquakes of different sizes. The next table summarizes for Zone 33A the expected impacts of various earthquakes of various sizes on overall losses to structures in different construction classes.

Epicentral Intensity	Losses As A Percent Of Overall Expected Losses For Different Construction Classes Due To Earthquakes In Source Zone 33A		
	5E,4D,4E,4B,5D, 3B,3D,4C,5C	3C,4A,5B, 3A,2B	2A
Intensity X	17% to 18%	24%	23%
Intensity IX	14% to 15%	23% to 24%	19%
Intensity VIII	22% to 23%	26%	26%
Intensity VII	23% to 25%	16% to 18%	23%
Intensity VI	14% to 17%	4% to 5%	7%
Intensity V	4% to 5%	0%	0%
Totals	100%	100%	100%

The above table illustrates clearly why, when estimating building losses, one cannot limit his consideration just to maximum probable earthquakes. For buildings, a large share of the expected long-term losses is due to moderate earthquakes which, while causing less damage on each occurrence, occur more frequently.

Evidence indicates that most components of water systems have higher damage thresholds than do buildings. Consequently, the bulk of damage to most components of water systems may be expected to occur as a result of larger earthquakes.

Evidence on pipe failures due to earthquakes is somewhat more complete than evidence on damage to other water system components. Much pipe damage is the result of tension and compression upon joints caused by the motion of the ground. In this case, flexible joints have performed better than rigid joints. Damage directly to pipes has consisted of crushing and shearing. Cast-iron water mains have evidenced cracks on the circumference and have shattered. Smaller cast-iron pipes have been broken by shear forces. Steel water mains have evidenced small holes and also blow-outs due to a combination of corrosion, internal pressure, and ground-shaking. Clay sewer mains have been crushed and have developed shear cracks (Cf. [17]). Asbestos-cement pipe may suffer breaks in pipe bodies (Cf. [34], K3, K4).

Statistical evidence suggests that rigidity of pipe joints leads to more failures. Hence, rubber-gasketed joints perform better than lead-caulked (semi-rigid) joints, which in turn perform better than cement-caulked (rigid) joints (Cf. [17], p. 254; [33], K4). There also is some evidence to suggest that pipes having both ductility and strength, such as ductile iron, steel, or polyvinyl chloride (PVC), perform better than pipes lacking ductility or strength, such as cast-iron, asbestos-cement, or clay sewer pipes. In this report and based upon such data, we have assumed that ductile iron pipe performs about four times as well as either cast-iron or asbestos-cement pipe, although much of the statisitcal evidence is too incomplete to yield definitive conclusions.

In only one report dealing with earthquake losses to water supply systems are damage rates clearly indicated in terms of near-field intensities. In that report (Cf. [28], pp. 24,25) "damage" includes not only "ruptures of pipe barrels, longitudinal cracks" and joint separation, but also joints loosening, which pose long-term problems but not necessarily immediate problems for system operators.

In other reports, attempts to show that buried cast-iron pipe performs better than asbestos-cement pipe are wanting in various needed details. In a study of the Managua earthquake, Richard Huzen provided a table which suggests that 4-in. to 6-in. cast-iron pipe performed much better than 4-in. to 6-in asbestos-cement pipe. Yet, much data was apparently missing. Although the location of the pipe in relation to near-field intensities was omitted, the overall number of failures per kilometer for cast-iron and asbestos-cement pipes were fairly comparable--0.72 and 0.88, respectively. The overall number of failures per kilometer for PVC pipe was only 0.10, but, once again, much data was missing (Cf. [29]). In a statistical study of various earthquakes, Tseuno Katayana and others state that asbestos-cement pipes were more affected than cast-iron pipes in Misawa and Naka-Furano during the 1968 Tokachi-oki earthquake (Cf. [16], p. 398). Yet, from evidence in their paper, cast-iron pipes were more affected in the Mutsu area, as well as in the overall statistics available. In their summary of the Managua earthquake, Katayama and others found that cast-iron, asbestos-cement, and galvanized-iron pipes behaved about the same (Cf. [16], p. 398).

In a summary of data on performance of buried pipe in the San Fernando water system, it is stated that 7 percent of cast-iron pipe, 47 percent of thin-walled (14-gauge) riveted steel pipe, 22 percent of all concrete-steel cylinder pipe, and 2 percent of standard steel casing pipe had to be replaced. However, almost all the replaced concrete-steel cylinder pipe existed in an area of tectonic rupture (Cf. [12], p. 182). Steel water mains performed better than cast-iron water mains outside the area of greatest ground displacement (Cf. [12], p. 185). Duane Ford, a representative of the ductile iron pipe industry and a member of the ASCE committee on lifelines engineering, has claimed that, contrary to previous reports, there was only a small amount of ductile iron pipe in service and that it was not damaged (Cf. [18], p. 4).

Based upon a survey of sewer main joints, one may conclude that flexible joints perform about twice as well as do rigid joints or encased structures. The ratio of two may be high for larger diameter pipes but lower for smaller diameter pipes (Cf. [17], p. 259).

Several studies agree that damage rates vary inversely with pipe diameter (Cf. [10], [16], Duane Ford, oral communication). In one report, though, contrary evidence is presented (Cf. [17], p. 259). However, part of the contrary evidence involves clay sewer pipes that are much more vulnerable to crushing failure. Duane Ford has suggested that pipes with smaller diameters suffer from "beam" action when the ground underneath does not support the pipe. Rigid pipes suffer from "crushing" action (Source: telephone converstation, 8-10-79).

According to Duane Ford, cast-iron and asbestos-cement pipes may fail at near-field Intensities VI or VII, but most failures begin to occur at Intensity VIII. Some types of pipe, such as ductile iron, begin to fail only at Intensity X, and then mainly because they are pulled apart.

In the Managua earthquake, there was a failure ratio of 0.36 per km. for pipes with diameters over 12 in. and composed mainly of ductile iron and some older cast-iron. Such a failure ratio may be compared with failure ratios of 1.22 per km. for 4 in. to 12 in. asbestos-cement pipe and of 1.10 per km. for cast-iron pipe (Cf. [18], p. 6). According to Adan Cajina, ductile iron pipe behaved best in the Managua earthquake and PVC behaved satisfactorily. The breaks in ductile iron pipe were "due to the longitudinal displacement caused by the tremor which shifted loose the pipe from the bell at the joint immediately near the fault" (Cf. [13], p. 774). It appears, then, that the failures in ductile iron pipe occurred in the highest near-field intensity area in the Managua earthquake.

To summarize the information from above, pipe failures generally begin to occur at Intensity VIII, although some failures may occur at Intensities VI and VII. Ductile iron pipe may perform the best, followed by PVC pipe, and then cast-iron and asbestos-cement pipe. It may be that ductile iron pipe failures occur only at near-field Intensity X, so that distribution systems composed of such pipe and with flexible joints would appear to be safe from all but the largest earthquakes. Analytical studies of pipe behavior are needed, though, to supplement incomplete statistical studies.

Oppenheim and others have used various logarithimic equations in order to estimate the number of expected pipe failures per km. (Cf. [10], [16], [28]). For average conditions, the resulting number of failures is as follows.

At Near-Field Intensity VI:	0.0001 per km.
At Near-Field Intensity VII	0.0117 per km.
At Near-Field Intensity VIII:	0.9705 per km.
At Near-Field Intensity IX:	80.9723 per km.
At Near-Field Intensity X:	6,714.29 per km.

Such results, based upon extrapolation for the highest earthquake intensities, are too high at the highest intensities. If pipes are laid in 18-in. segments, then one would expect about 182 segments per kilometer and so no more than 183 failures per kilometer. In the San Fernando earthquake, it was reported that one area contained seven breaks in a 100-foot length (Cf. [12]). In the Niigata earthquake, one liquefied area contained 18 failures over 530 meters of pipe, or about 34 failures per kilometer ([16], p. 398). In San Fernando, the following are derived averages of breaks per square mile by intensity (derived from [12]).

At Near-Field Intensity X:	22.7
At Near-Field Intensity IX:	9.4
At Near-Field Intensity VIII:	5.1
At Near-Field Intensity VII:	6.6

Given the paucity of data, then, the following estimates may be used for rough estimates of pipe failures for cast-iron and asbestos-cement pipes.

At Near-Field Intensity VI:	0.001 failures/km.
At Near-Field Intensity VII:	0.012 failures/km.
At Near-field Intensity VIII:	1 failure/km.
At Near-Field Intensity IX:	severe damage, perhaps exceeding 2 failures/km.
At Near-Field Intensity X:	extreme damage, possibly up to 32 failures/km.

For ductile iron pipes and PVC pipes, one may reduce such ratios by 75 percent and 50 percent, respectively. (Evidence that ductile iron pipes fail only at Intensity X and above needs to be further developed.) Since the above damage ratios are left inexact at higher intensities, they cannot be used to estimate number of pipe breaks. Further evidence is needed before more exact damage ratios can be developed, and then used, in conjunction with site earthquake frequencies to estimate expected pipe breaks.

Outside the San Fernando City area, it may be noted that the highest damage ratio per kilometer was 2.19 in the San Fernando Valley earthquake ([16], p. 200). It is clear from such data as above, and from the fact that as many as 7 breaks per 100 ft. occurred in San Fernando City, that pipe breakage is not a major problem until earthquake intensities approach VIII, and that pipe systems in Intensity IX and X regions may be severely damaged.

The view that pipe failures vary inversely with diameters has been developed into the following equation by Oppenheim.

MJ/MJ_{100} + 1.06 - 0.000608D, wherein

MJ = major loosened joints per kilometer

MJ_{100} = major loosened joints per km. for pipes 100 mm. in diamter ((3.94 inches)

D = diameter of the pipe (in km.)

Translated into some of the standard pipe sizes, the following ratios for MJ/MJ_{100} are obtained (Cf. [10], p. 259).

For 2 1/2" pipes:	1.02
For 6" pipes:	0.97
For 12" pipes:	0.87
For 24" pipes:	0.69
For 36" pipes:	0.50
For 54" pipes:	0.23

Such ratios indicate that one may expect about four times as many breaks per kilometer for 4-in. pipes as for 54-in. pipes and about twice as many failures per km. for 4-in. pipes as for 36-in. pipes.

In the Salt Lake City water system, there are about 6,057,000 ft. of pipe, of which only 285,000 ft. are ductile iron or PVC. About 979,000 ft. are 4-in. or smaller in diameter. About 3,452,000 ft. are 6-in. in diameter. Another 513,000 ft. are 8-in. or 10-in. in diameter. So, about 86 percent of the pipe is 10-in. or less in diameter (Cf. [24]). Hence, if damage ratios are greater for pipes with smaller diameters, and if all main trunk lines are broken at least once in a major earthquake, then one can expect even more severe breakage to smaller pipes.

Statistical evidence on pipe failures, then, does not yield definite conclusions about expected number of pipe failures but does indicate tendencies. Generally speaking, though, pipe failures become a definite problem for a water supply system when near-field intensities approach Intensity VIII.

A similar notion of the threshold at which damage may occur applies also to other components of water systems. The chief source of data comes from studies of the San Fernando Valley earthquake.

Tables 5 and 6 summarize on failures of reservoirs and tanks, respectively, caused by the 1971 San Fernando earthquake. Those reservoirs surveyed appeared to be damaged at near-field Intensity X. They suffered damage mostly to the walls and, in some cases, to roof systems. The principal mode of failure for tanks was either horizontal or vertical displacement of the tank leading to buckling near the base of the tank, and occurred at Intensity IX or above. The Granada High tank suffered roof failure, which can occur at more moderate earthquake intensities. The Sesnon tank suffered differential settlement, which also can occur at Intensity VII.

Thus, it is from data of the sort furnished in previous paragraphs that estimates of earthquake damage to water supply facilities have been made for this report. Such estimates, of course, are derived from comparative analysis rather than from quantified structural analysis and, consequently, should be considered more as indicators of expected losses rather than assured losses. The available methodologies for estimating earthquake losses to lifelines systems, such as are water supply systems, are insufficiently developed at this time to allow better estimates to be made.

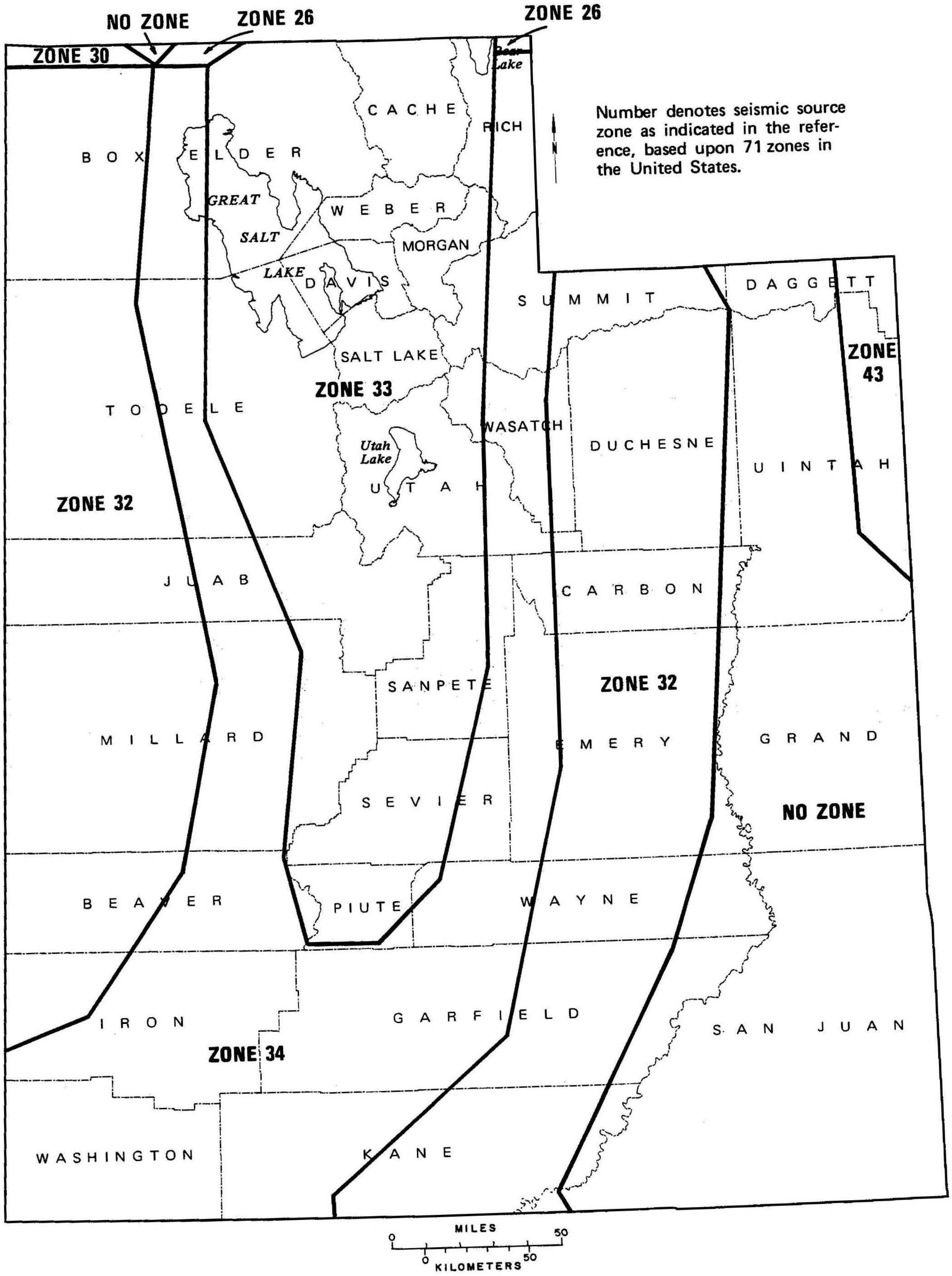


Figure 1
SEISMIC SOURCE AREAS IN UTAH
(Reference: S.T. Algermissen, and D.M. Perkins, USGS Open File Report 76-416)

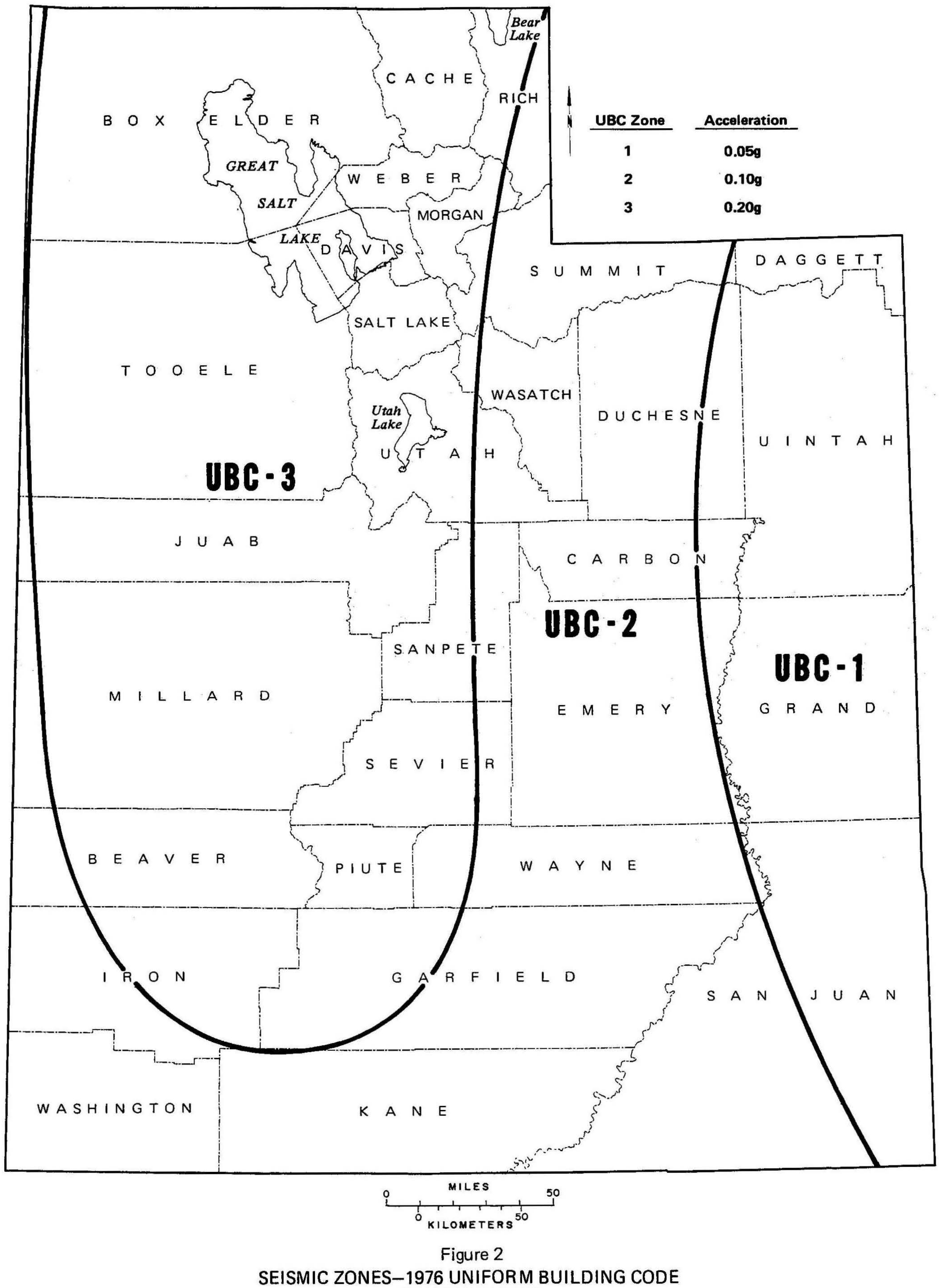


Figure 2
SEISMIC ZONES—1976 UNIFORM BUILDING CODE
STATE OF UTAH

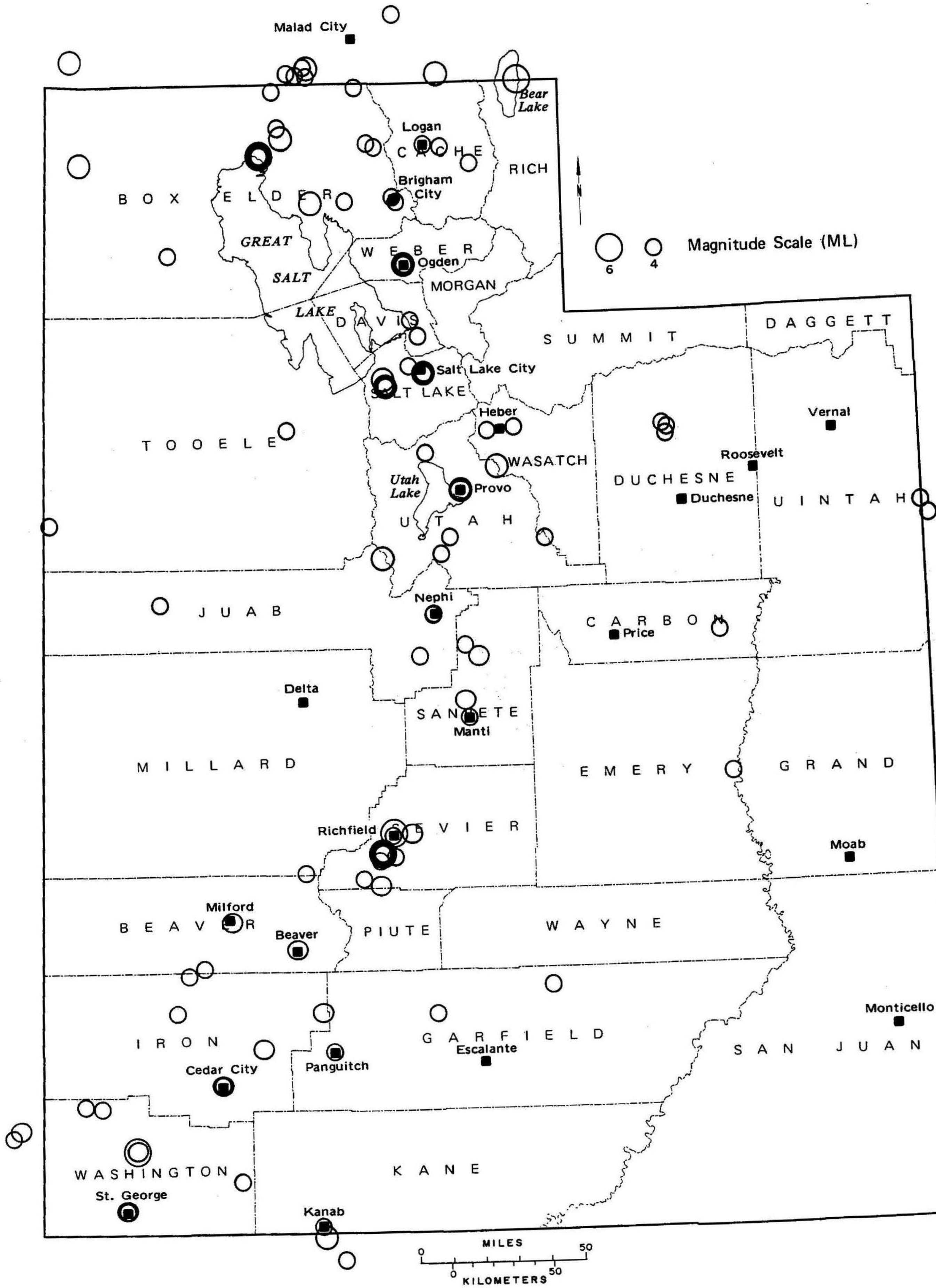


Figure 3

HISTORICAL SEISMICITY IN UTAH -- 1850 - JUNE 1978
MAGNITUDE 4.0 (INTENSITY V) OR GREATER
(Reference: *Earthquake Studies In Utah*, W.J. Arabasz, R.B. Smith, and W.D. Richins)

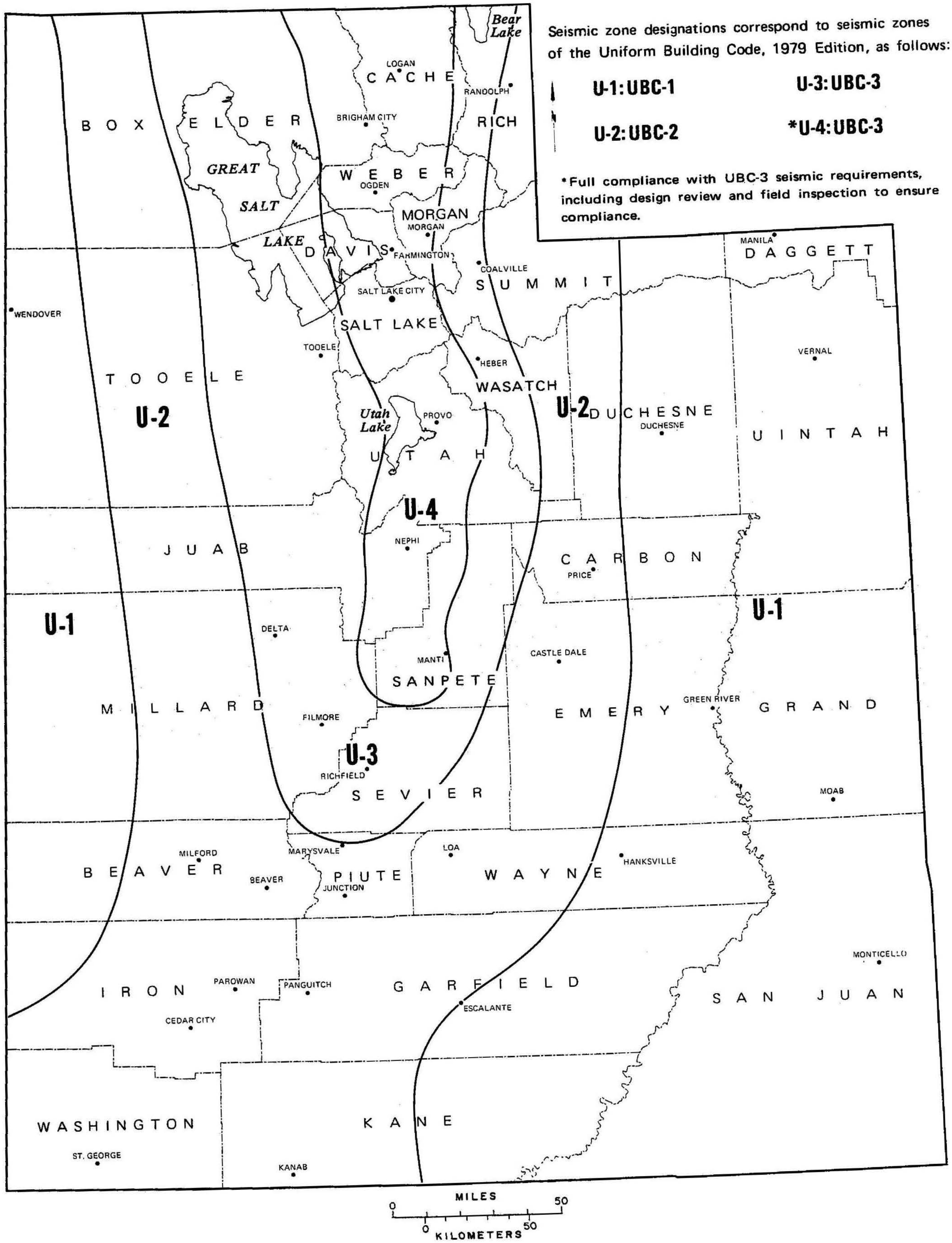


Figure 4

SEISMIC ZONES

January 1980

(Recommended by the Utah Seismic Safety Advisory Council)

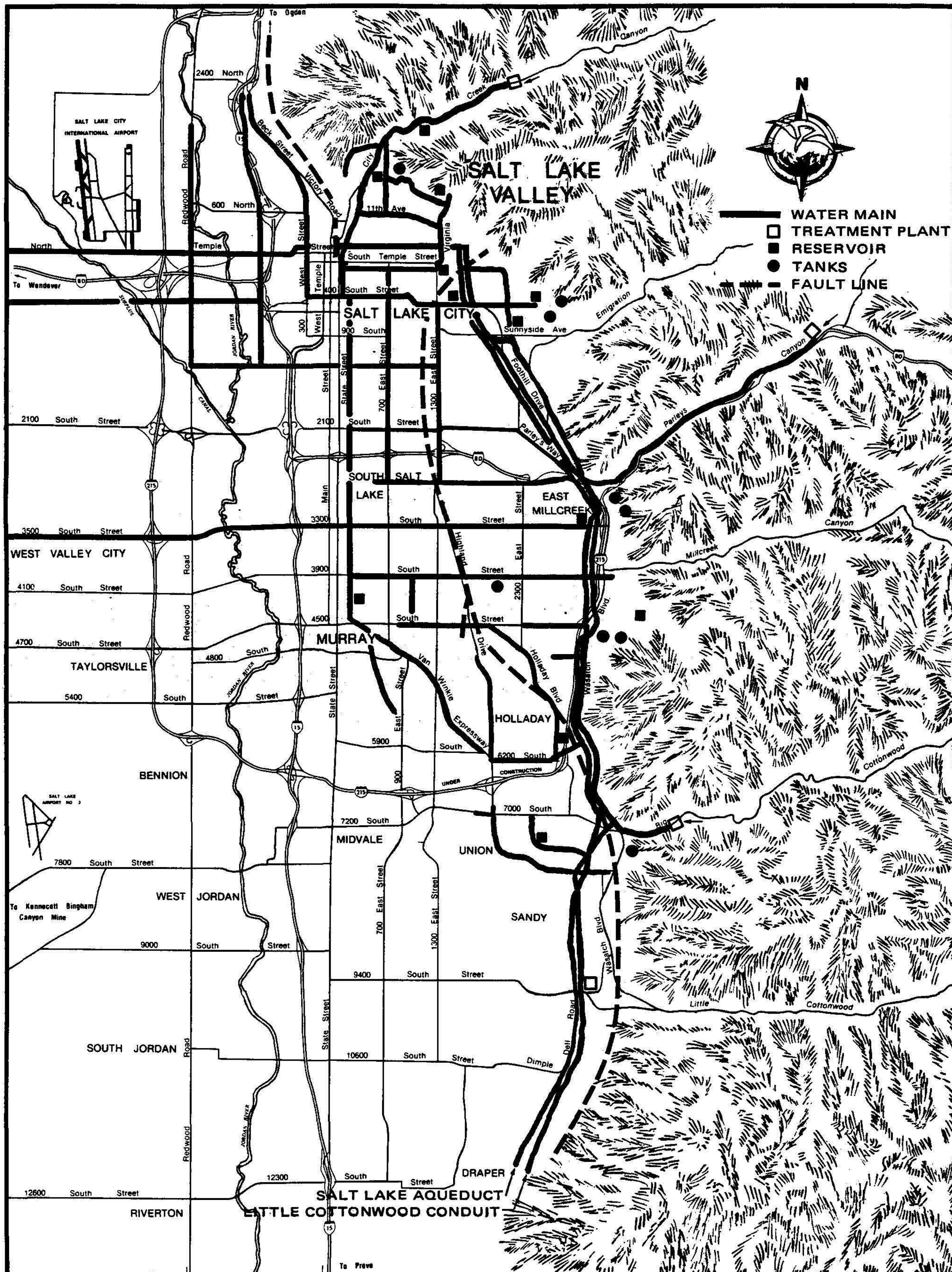


Figure 5

SCHEMATIC OUTLINE OF THE SALT LAKE CITY WATER SYSTEM
(Supply Mains Generally At Least 18-in. In Diameter)

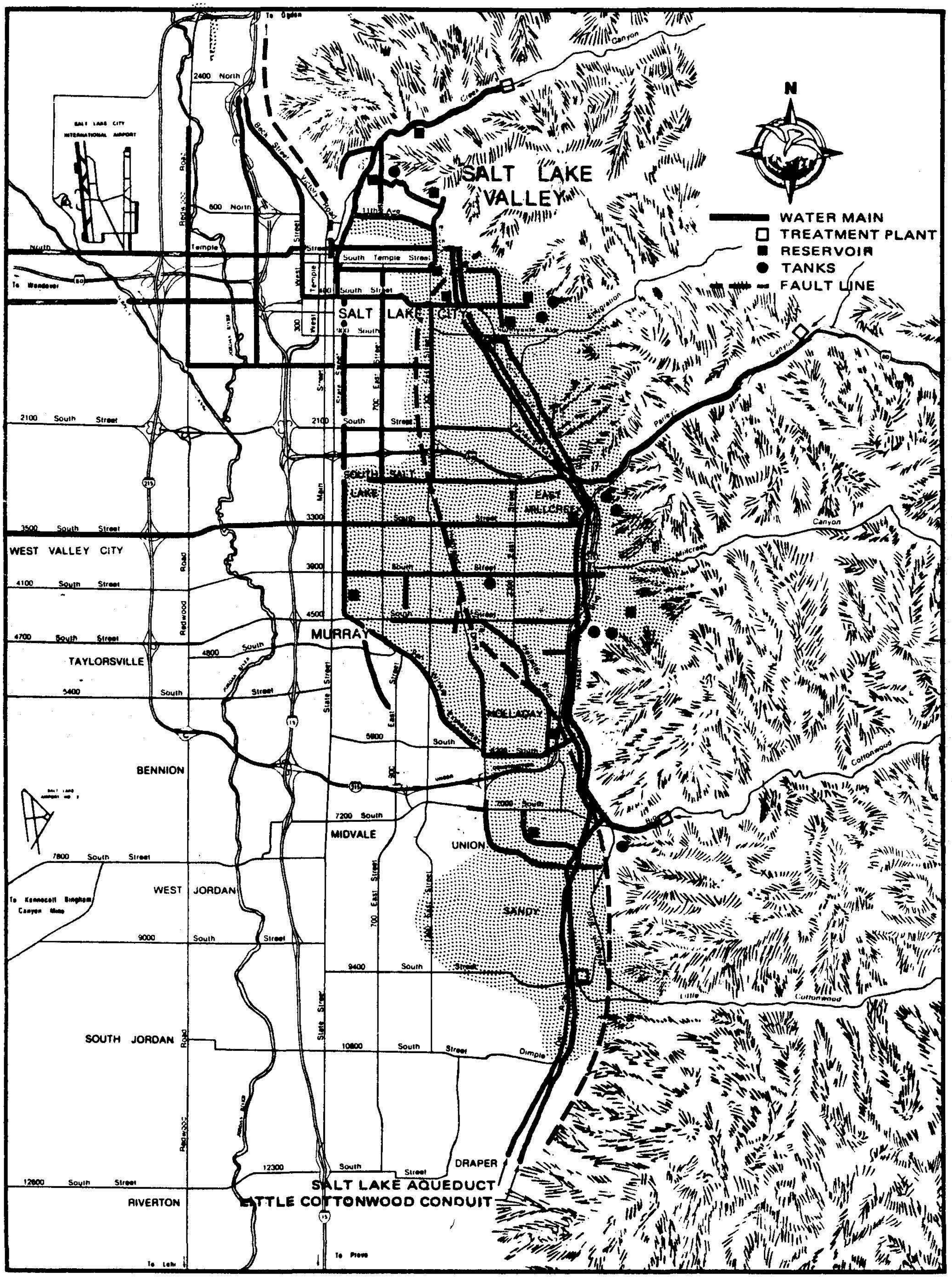


Figure 6

AREAS OF THE SALT LAKE CITY WATER SYSTEM
THAT CANNOT RECEIVE FLOWS FROM THE CITY CREEK TREATMENT PLANT

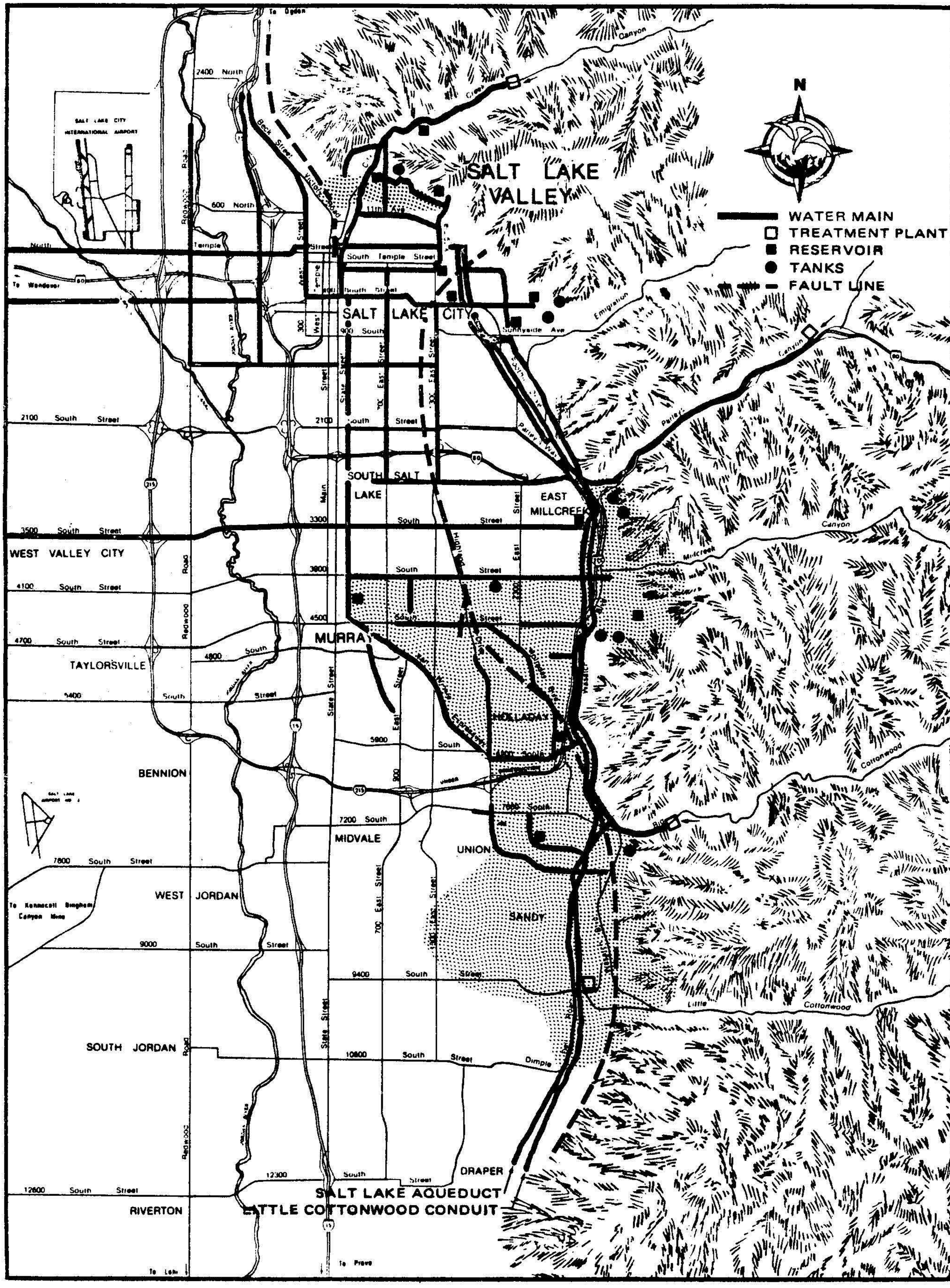


Figure 7

AREAS OF THE SALT LAKE CITY WATER SYSTEM
THAT CANNOT RECEIVE FLOWS FROM THE PARLEY'S TREATMENT PLANT

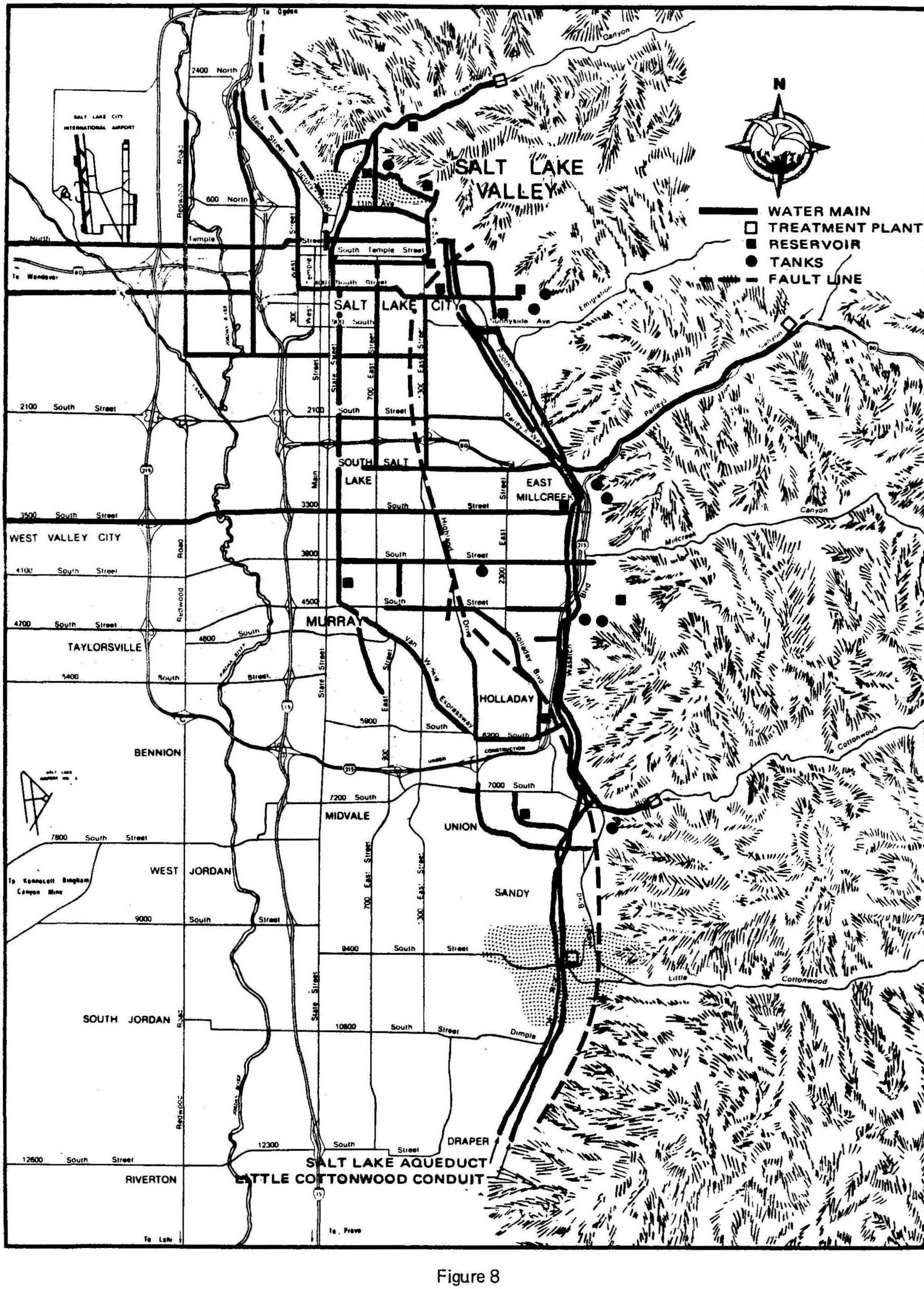


Figure 8

AREAS OF THE SALT LAKE CITY WATER SYSTEM
THAT CANNOT RECEIVE FLOWS FROM THE BIG COTTONWOOD TREATMENT PLANT

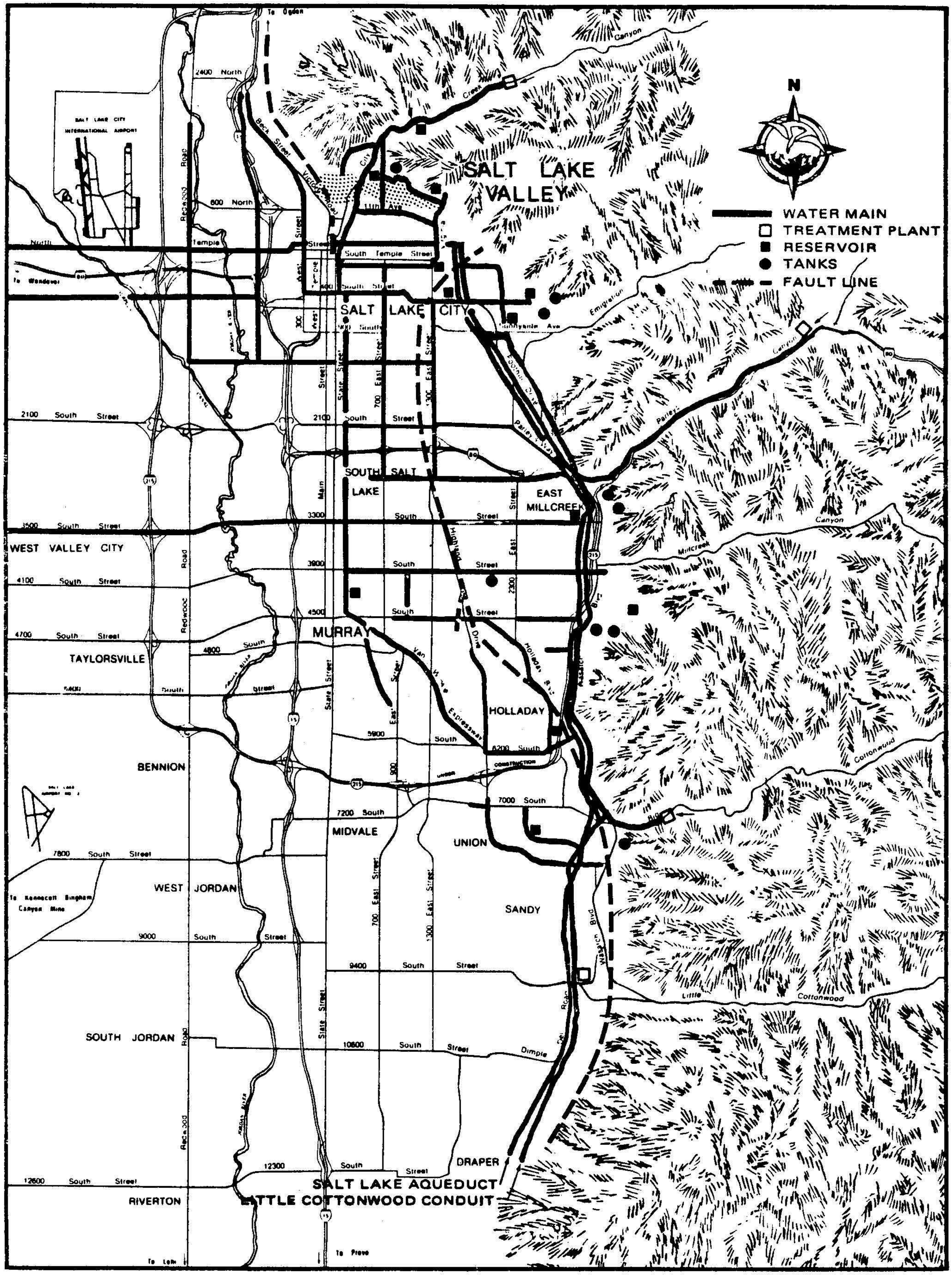


Figure 9

AREAS OF THE SALT LAKE CITY WATER SYSTEM
THAT CANNOT RECEIVE FLOWS FROM THE METROPOLITAN TREATMENT PLANT

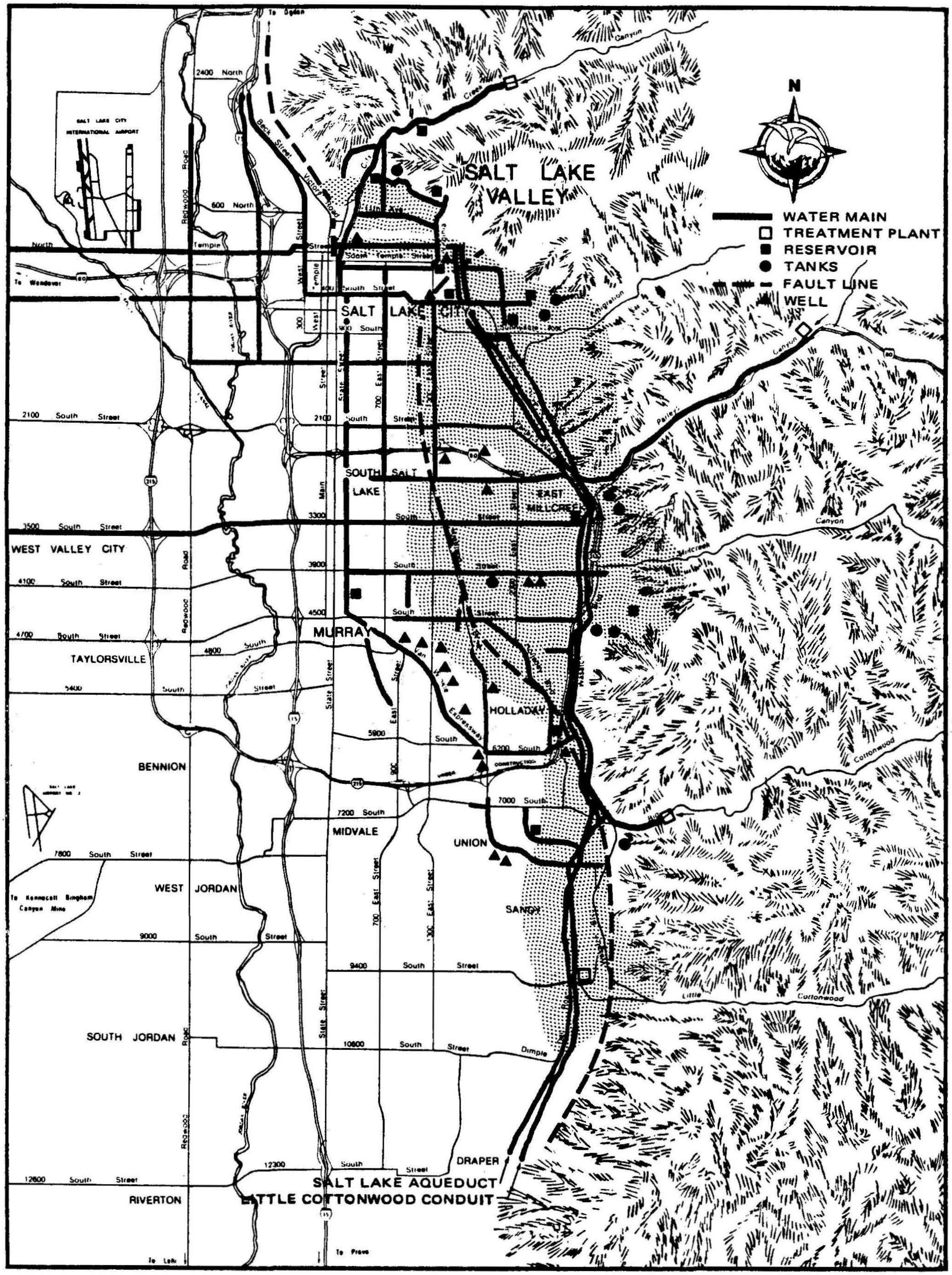


Figure 10

LOCATION OF DEEP PUMP WELLS
AND AREAS OF THE SALT LAKE CITY WATER SYSTEM
THAT CANNOT BE SERVED BY DEEP PUMP OR ARTESIAN WELLS

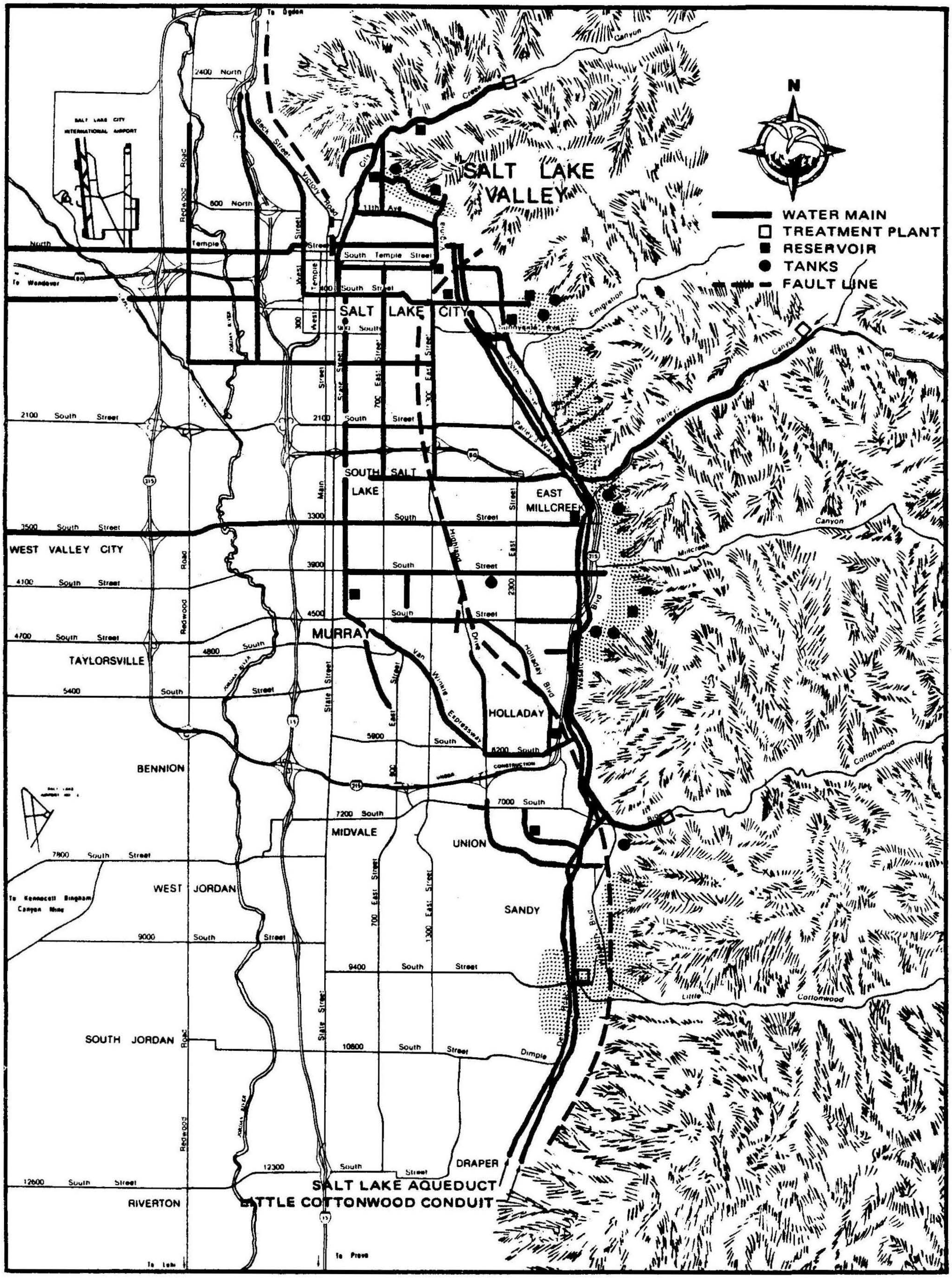


Figure 11

AREAS OF THE SALT LAKE CITY WATER SYSTEM DEPENDENT UPON TANKS FOR SUPPLY

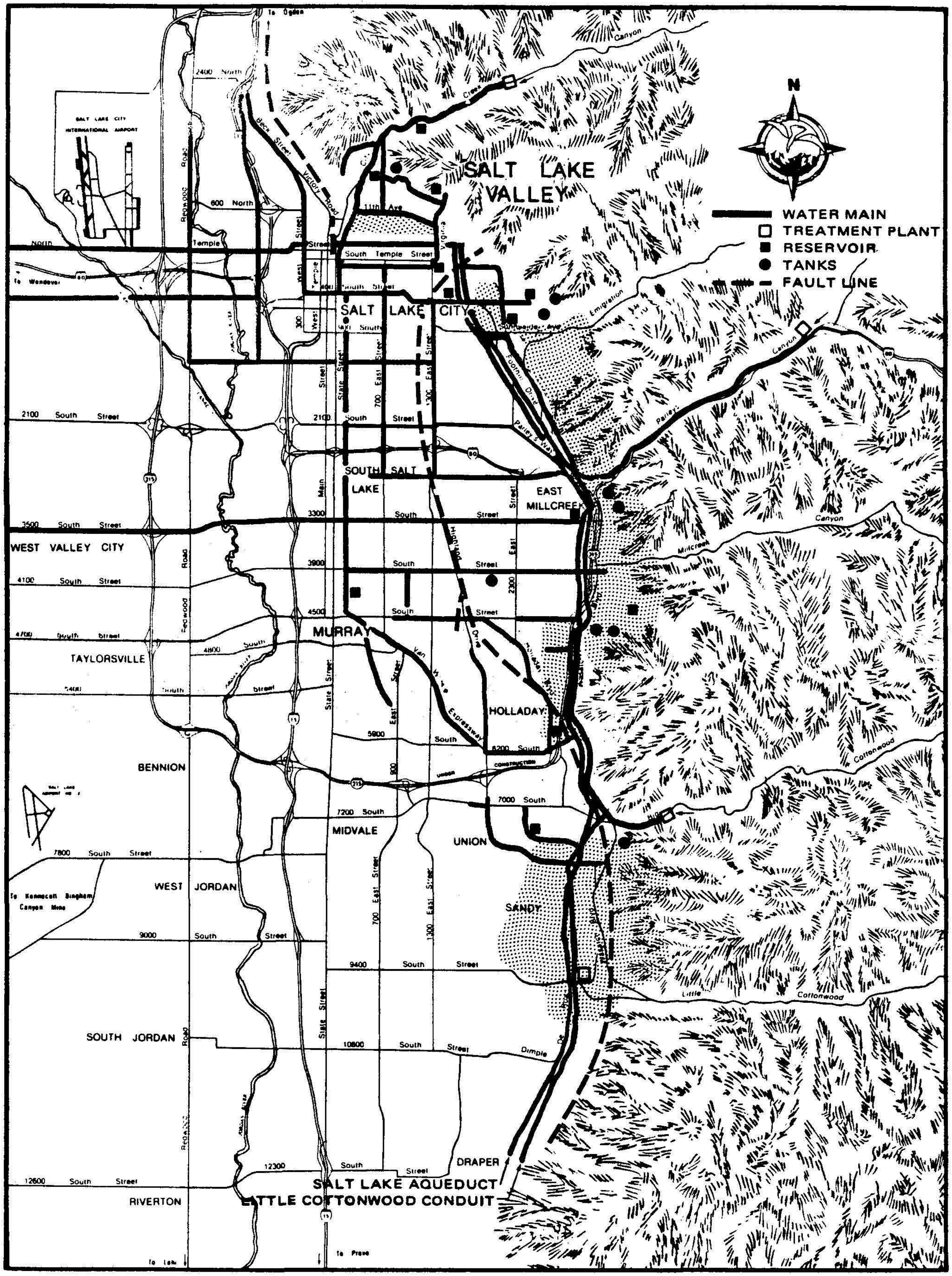


Figure 12

AREAS OF THE SALT LAKE CITY WATER SYSTEM DEPENDENT FOR SUPPLIES UPON PUMPING STATIONS

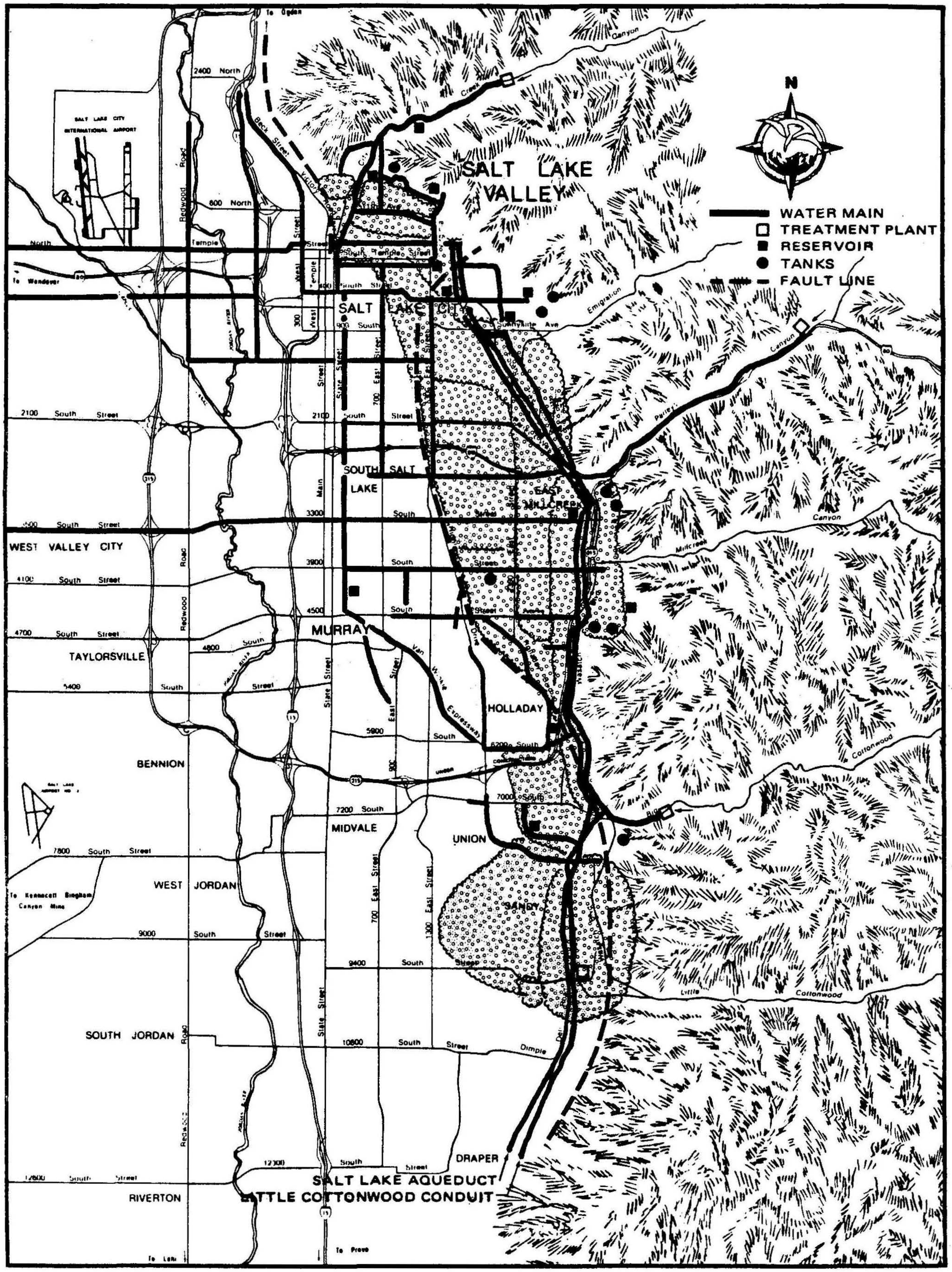


Figure 13

REGULATION ZONES FOR THE SALT LAKE CITY WATER SYSTEM (ROUGHLY DRAWN)
IN RELATION TO THE WASATCH FAULT

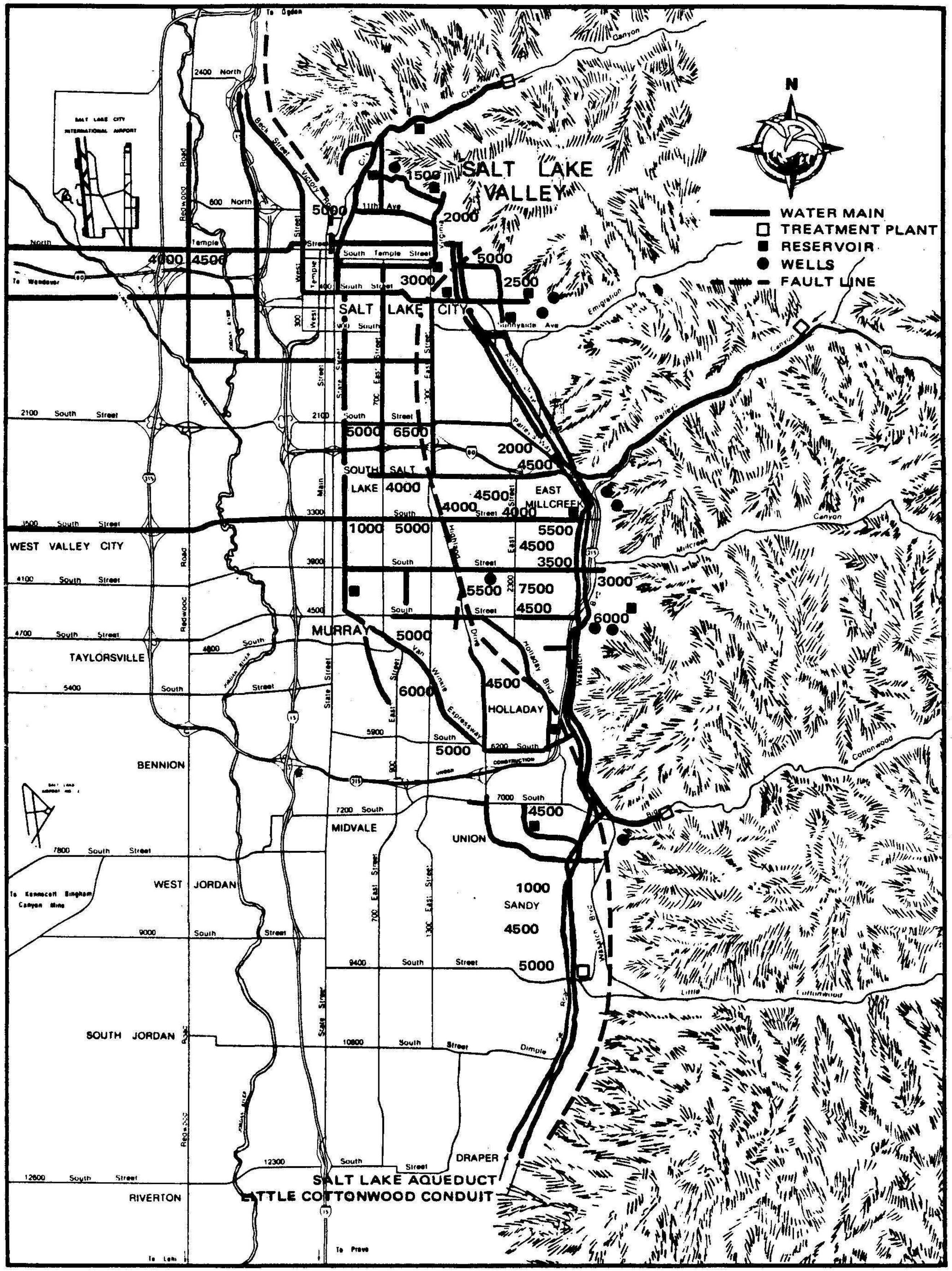


Figure 14

APPROXIMATE LOCATIONS AND FIRE FLOW REQUIREMENTS (IN GALLONS PER MINUTE AT 20 PSI PRESSURE) OF SITES IN THE SALT LAKE CITY WATER SYSTEM NOT SATISFYING 1973 AND 1975 FIRE FLOW TESTS

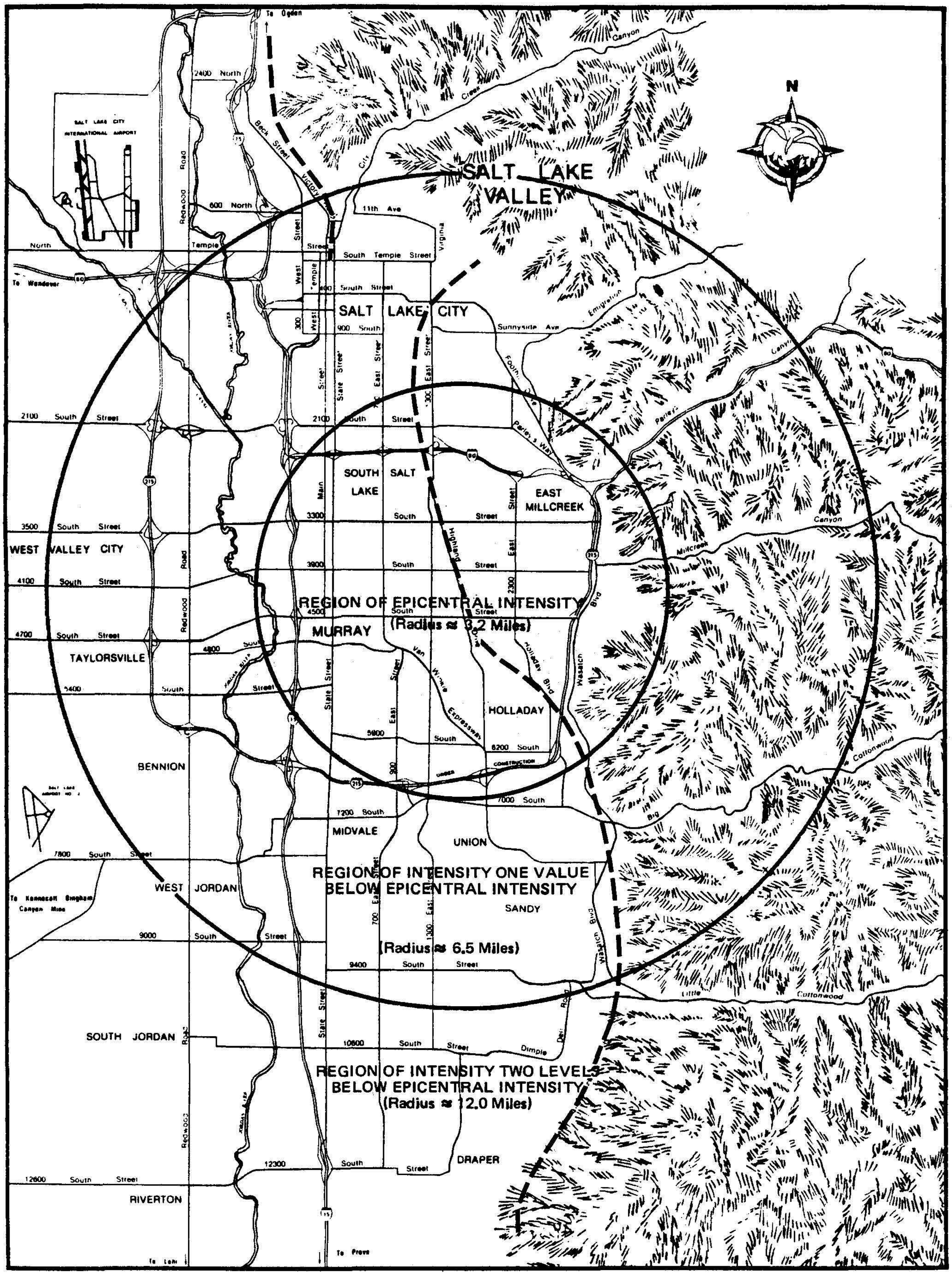


Figure 15

ISOSEISMAL MAP FOR MODELLING VARIOUS POSSIBLE EARTHQUAKES
(Epicenter For The Model May Be Located Anywhere Along Or Near Fault)

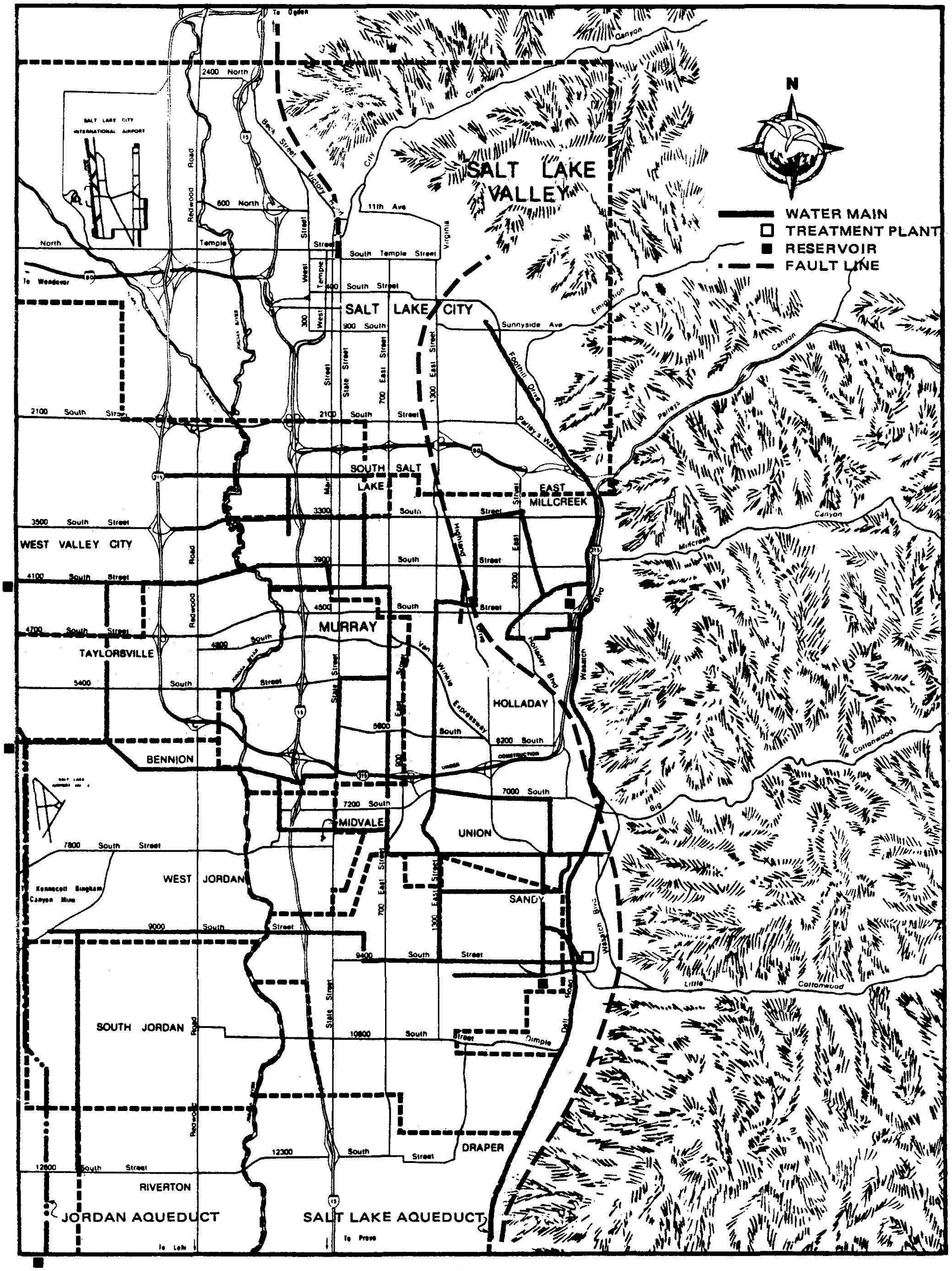


Figure 16

SCHEMATIC OUTLINE OF THE SALT LAKE COUNTY WATER CONSERVANCY DISTRICT SYSTEM

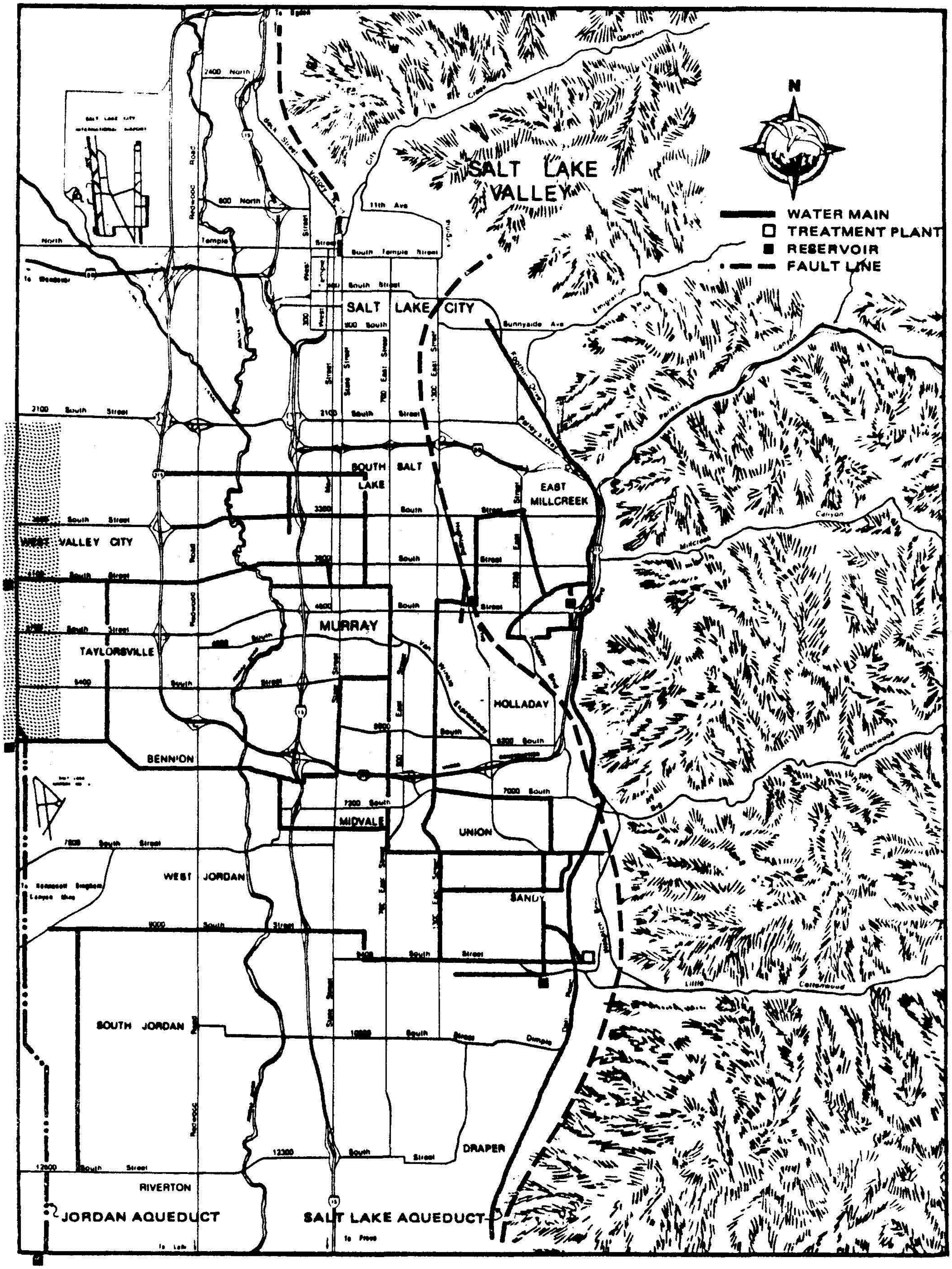


Figure 17

AREAS OF THE SALT LAKE COUNTY WATER CONSERVANCY DISTRICT
DEPENDENT UPON TANKS OR RESERVOIRS FOR SUPPLY
(Relevant Tanks Are At 45th South And 62nd South) (Identical To Areas Dependent Upon Power For Pumping)

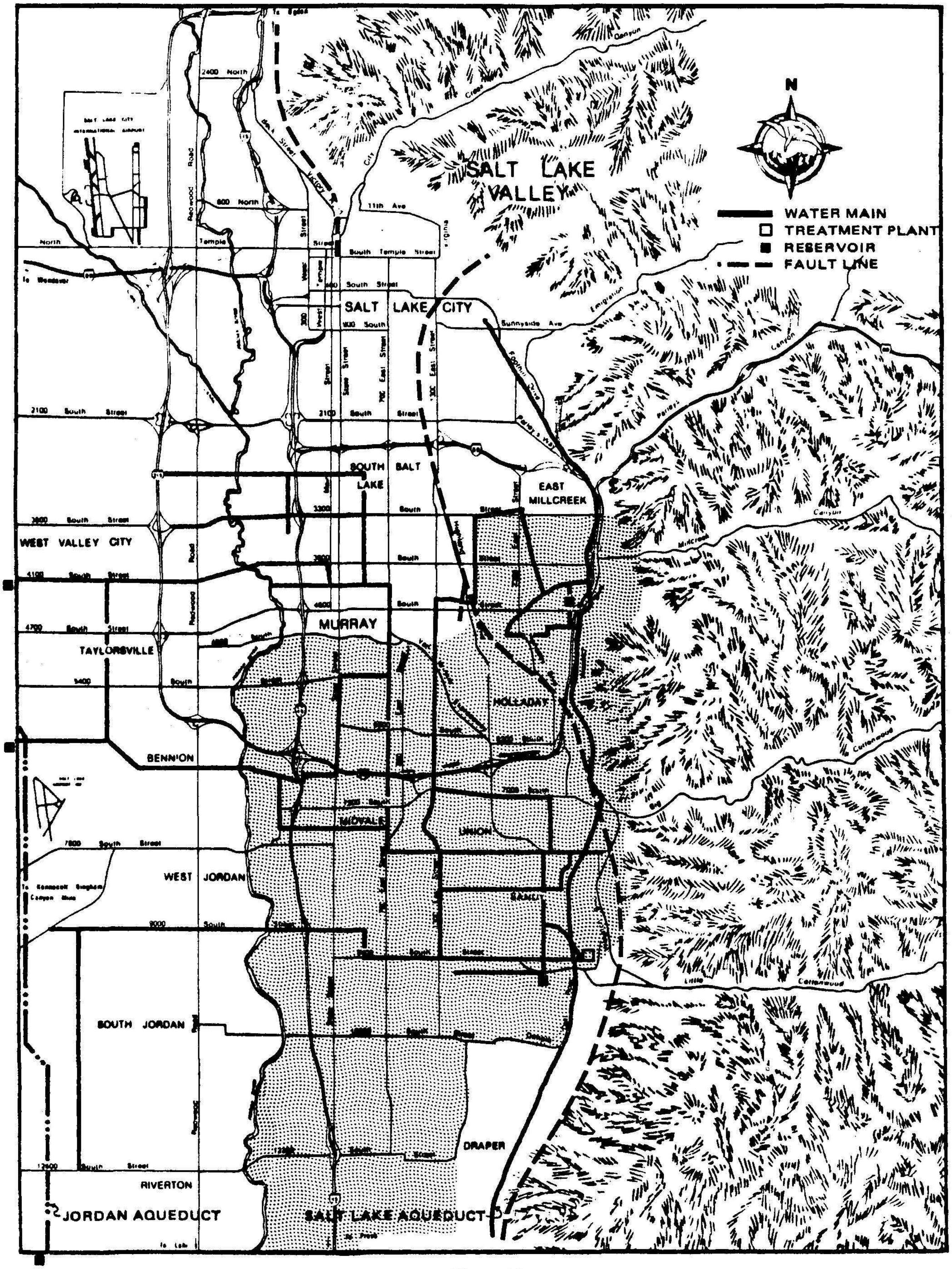


Figure 18

AREAS IN THE SALT LAKE COUNTY WATER CONSERVANCY DISTRICT
THAT CANNOT BE SERVED BY GRAVITY FLOW FROM THE JORDAN AQUEDUCT

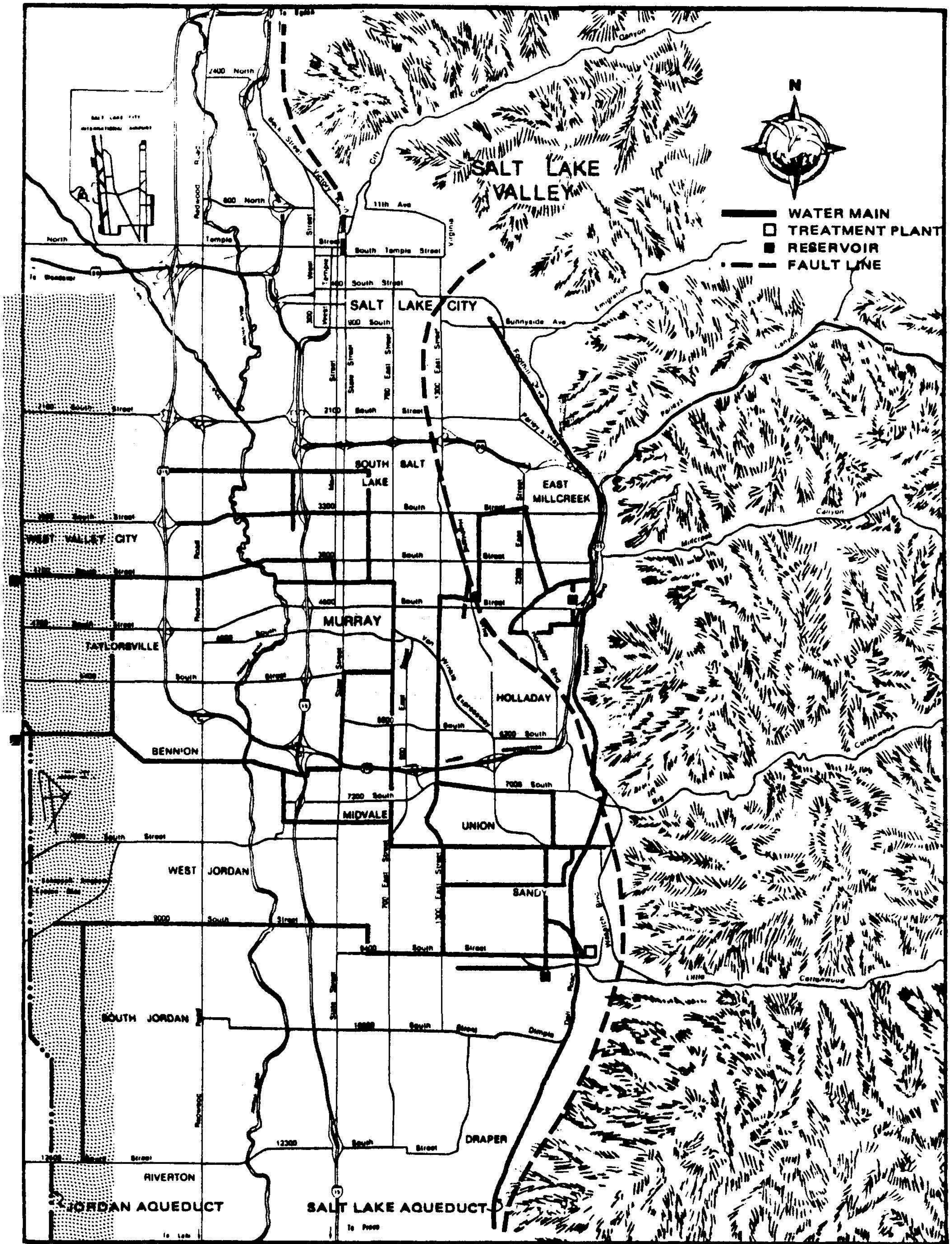


Figure 19

AREAS IN THE SALT LAKE COUNTY WATER CONSERVANCY DISTRICT THAT CANNOT BE SERVED BY GRAVITY FLOW FROM THE SALT LAKE AQUEDUCT AND METROPOLITAN TREATMENT PLANT

(Based Upon Fire Flow Use)

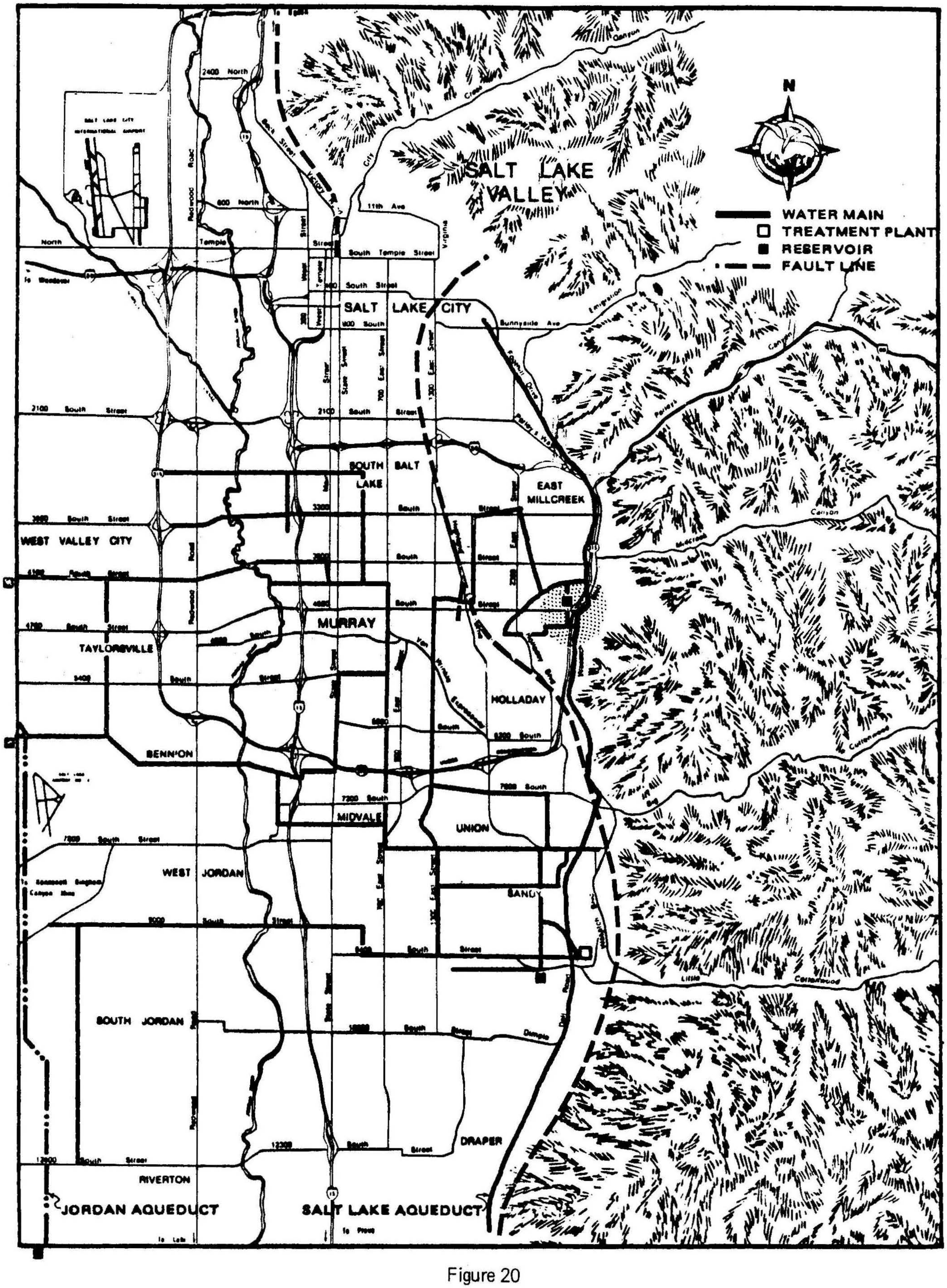


Figure 20

AREAS IN THE SALT LAKE COUNTY WATER CONSERVANCY DISTRICT THAT WELLS CANNOT SERVE

(Identical With Areas That Tanks And Reservoirs Cannot Serve)

Table 1

EXPECTED RECURRENCE INTERVALS IN YEARS
OF EARTHQUAKES WHOSE EPICENTERS EQUAL OR EXCEED
THE GIVEN INTENSITY SOMEWHERE IN THE GIVEN ZONE

Seismic Zone	Intensity Equalled Or Exceeded				
	X+	IX+	VIII+	VII+	VI+
Zone 32	3,300	770	200	56	16
Zone 33A	450	133	133	12	4
Zone 33B	1,250	260	260	11	4
Zone 34	900	190	190	14	4
Cumulations For All Four Zones	223	56	15	4	1

Table 2

EXPECTED RECURRENCE INTERVALS IN YEARS
FOR INTENSITIES EQUALLED OR EXCEEDED AT SITES
RANDOMLY CHOSEN WITHIN GIVEN SEISMIC ZONES

Seismic Zone	Intensities Equalled Or Exceeded				
	X+	IX+	VIII+	VII+	VI+
Zone 32	-	-	170,000	29,000	6,300
Zone 33A	15,000	2,400	620	180	54
Zone 33B	500,000	90,000	8,200	1,300	221
Zone 34	1,000,000	67,000	10,000	2,000	450

Table 3

DEEP PUMP WELLS IN THE SALT LAKE CITY WATER SYSTEM

Well Number	Location and/or Name	MGD*	Cfs.**
1056A	City Creek: 4th Ave. & Canyon Rd.	5.3	6.4-8.5
1061A	5th So. & 1511 E. (15th E. well)	3.0	5.0
1658	Sugarhouse Park (23rd So. 17th E.)	5.2	7.0
1063	13th E. 27th So.	5.1	<7.9>
1062	19th E. well (27th So.)	5.1	9.5
	3027 So. 27th E.	0.434	<0.7>
4	3280 So. 3580 E.	0.072	<0.1>
5	3281 So. Wasatch Dr.	0.072	<0.1>
1052	2170 Evergreen Ave.	1.8	2.8
11A	Neff's: 4060 So. 3075 E.	0.446	<0.7>
2	2700 E. Nila Way (4171 So.)	0.456	0.1
14	4280 So. 2700 E.	1.1	3.3
1657	4800 So. 9th E. (9th E. well)	1.3	2.0
1065A	Brinton Springs: 4800 So. Highland Dr.	2.6	4.0
1650	5400 So. Edgewood (Edgewood Dr.)	3.2	5.0
142A	5500 So. Diagonal Rt.	1.7	<2.6>
1655	5900 So. 18th E. (Fontaine Bleu)	6.5	10.0
1078	6200 So. 2080 E. (62nd So. well)	5.8	9.0
1652	6200 So. 2855 E. (Holladay Blvd.)	5.8	9.0
1654	Greenfield: 6750 Springbrook Way	3.6	5.5
1653	Little Cottonwood: 79th So. & 20th E.	5.2	8.0
	27th E. near 40th So.	<1.9>	2.9
1651A	2621 E. 6485 So. (Upper Ellison)	-	-
1051A	Richard's Ditch: 2400 Little Cottonwood Creek	<4.3>	<6.7>
	Approximate Totals	71.1+	112.0+

* Source: [25], p. 10.
** Source: [24], p. 20.

0.646 MGD = 1 cu. ft./sec.

Table 4

PIPES CROSSING THE WASATCH FAULT IN THE SALT LAKE CITY WATER SYSTEM

Location (See Figure 5)	Size	Material
78th South	12"	steel or ductile-iron
to Tanner Reservoir	18"	vitrified clay
45th South	12"	asbestos-concrete
39th South	20"	concrete, steel cylinder
33rd South	16"	welded steel
27th South	16"	cast-iron
21st South	18"	cast-iron
17th South	12"	--
13th South	30"	prestressed concrete & steel
5th South	36"	cast-iron
1st South	24" & 20"	cast-iron
Federal Heights	20"	cast-iron

Table 5

FAILURE MODES OF BURIED CONCRETE STRUCTURES
1971 SAN FERNANDO EARTHQUAKE [12]

Name Of Facility	Shape	Storage Capacity	Description Of Failure
Maclay Reservoir	Box	5.3 MG	Wood roof collapsed (columns were not designed to resist lateral forces).
Finished Water Reservoir	Box	--	Roof, column, and wall damage caused by horizontal acceleration of 0.4 g.
San Fernando Reservoir #1	Cylinder	0.106 MG	Roof collapsed, wall and floor lining badly cracked. Facility abandoned.
San Fernando Reservoir #2	Box	2.6 MG	Roof failure and walls cracked resulting from settlement of roof supports and sidewalls. Facility abandoned.
San Fernando Reservoir #3	Cylinder	0.113 MG	Essentially undamaged.
San Fernando Reservoir #4	Cylinder	1 MG	Only piping damaged.
San Fernando Reservoir #5	Cylinder	2.4 MG	Walls cracked due to differentials in pressure exerted at base.
Olive View	Cylinder	0.5 MG	Two circumferential rings on outside walls failed. All water drained because inlet-outlet pipe pulled apart.

Note: All facilities were located in near-field Intensity X zones, except for the Olive View facility which was in a near-field Intensity XI zone.

Table 6

FAILURE ANALYSIS OF STORAGE TANKS
1981 SAN FERNANDO EARTHQUAKE [12]

Name Of Facility	Near-Field Intensity	No Damage	Foundation Or Soil Failure	Buckling Near Bottom	Buckling Elsewhere	Shell Plate Failure	Roof Structure Failure	Anchor Bolt Failure	External Connections Severed	Deformed Tank Floor	Shell Separated From Bottom	Leakage	Beyond Repair	Repairable
Sesnon Tank	VII to VIII		●		●	●	●				●	(?)	●(?)	
Granada High Tank	VIII to IX					●	●							●
Alta Vista Tank #1	IX to X	●							●					
Alta Vista Tank #2	IX to X	●							●					
Washwater Tank	VIII to X				●			●			●		●	
Kagel Tanks (5)	IX		●	●					●				(1)	(4 of 5)
Olive View Tank	X to XI			●		●	●		●	●	●	●	●(?)	
Dexter Park Tank #1	IX								●					●
Dexter Park Tank #2	IX		●	●					●		●		●	
Dexter Park Tank #3	IX		●	●					●		●		●	
Karl Holton Bay Tank	IX			●					●		●			●

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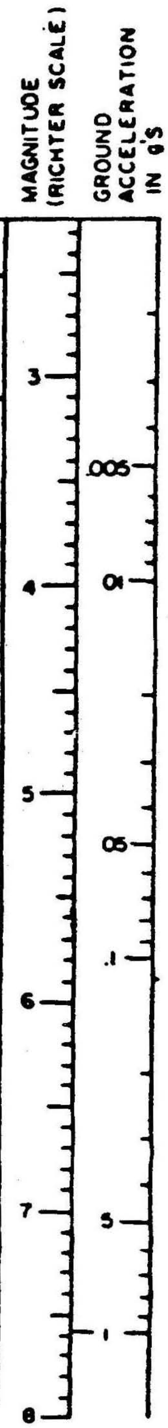
MODIFIED MERCALLI INTENSITY SCALE APPROXIMATE RELATIONSHIP WITH MAGNITUDE AND GROUND ACCELERATION

ABRIDGED MODIFIED MERCALLI INTENSITY SCALE

I	Not felt except by a very few under especially favourable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations, ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.



Modified Mercalli Intensity Scale after Wood and Neumann, 1931. (Intensities XI and XII not included).

Magnitude and acceleration values taken from Nuclear Reactors and Earthquakes, TID-7024, United States Atomic Energy Commission.

LIFELINES COMMITTEE
Seismic Safety Advisory Council

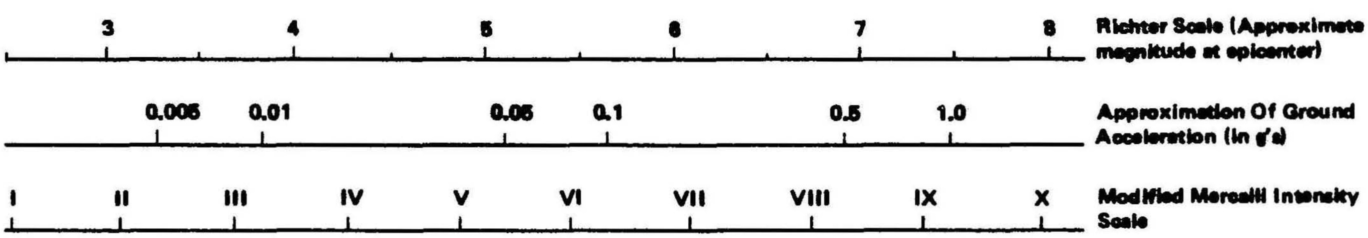
URBAN AND ENGINEERING GEOLOGY SECTION
Utah Geological and Mineral Survey

EARTHQUAKE INTENSITY SCALE FOR WATER WORKS*

(Modified Mercalli Intensity Scale, abridged)

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. *Poorly sited aboveground tanks may buckle. Pipe in poor condition may break. Unreinforced structures, including some pump stations, may suffer damage.*
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars. *Debris from unreinforced masonry pump stations may misalign pumps.*
VIII	Damage slight in specially designed structures, considerable in ordinary substantial buildings with partial collapse, great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed. *Localized intensive pipe breakage (approximately 1 break/km.) inlet and outlet connections may break. Wells may become contaminated.*
IX	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. *Ground-surface offsets may cause damage to structures. All unanchored tanks buckle. Treatment facilities may suffer structural damage. Unanchored equipment will move.*
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed, with foundations and ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. *Extreme pipe damage (up to 32 breaks/km.). Most buried reservoirs suffer sidewall and possibly roof damage.*

*Modified by Dr. C.E. Taylor and B.N. Kaliser.
Modified Mercalli Intensity Scale after Wood and Neumann, 1931. (Intensities XI and XII not included).
Magnitude and acceleration values taken from "Nuclear Reactors and Earthquakes," TID-7024, United States Atomic Energy Commission.



APPENDIX C

WATER STORAGE FACILITIES WITHIN THE WASATCH FAULT ZONE
STATE OF UTAH

RESERVOIRS

1.	East of Brigham City in mouth of Flat Bottom Canyon.	
2.	SW1/4, Sec. 17, T7N, R1W	A*
3.	SW1/4, Sec. 17, T7N, R1W	
4.	Just north of Pleasant View	
5.	SW1/4, Sec. 20, T7N, R1W	
6.	NW1/4, Sec. 27, T7N, R1W	
7.	NW1/4, Sec. 27, T7N, R1W	
8.	SE1/4, Sec. 27, T7N, R1W	A
9.	NE1/4, Sec. 34, T7N, R1W	
10.	NW1/4, Sec. 3, T6N, R1W	A
11.	SW1/4, Sec. 3, T6N, R1W	
12.	SE1/4, Sec. 15, T6N, R1W	
13.	SE1/4, Sec. 27, T6N, R1W	
14.	At mouth of Strongs Canyon, east of Odgen	
15.	NE1/4, Sec. 10, T5N, R1W	
16.	SE1/4, Sec. 15, T5N, R1W	
17.	SW1/4, Sec. 14, T5N, R1W	A
18.	SW1/4, Sec. 24, T5N, R1W	A
19.	SE1/4, Sec. 25, T5N, R1W	
20.	SW1/4, Sec. 36, T5N, R1W	A
21.	NW1/4, Sec. 25, T4N, R1W	A
22.	East of Centerville	
23.	NE1/4, Sec. 20, T2N, R1E	
24.	SW1/4, Sec. 21, T2N, R1E	
25.	SE1/4, Sec. 20, T2N, R1E	
26.	NE1/4, Sec. 29, T2N, R1E	
27.	SE1/4, Sec. 6, T1N, R1E	
28.	1st South and 13th East	A
29.	SW1/4, Sec. 14, T2S, R1E	
30.	In mouth of Bells Canyon	A
31.	SW1/4, Sec. 26, T8S, R3E	
32.	NW1/4, Sec. 34, T8S, R3E	
33.	SW1/4, Sec. 34, T12S, R1E	
34.	SE1/4, Sec. 4, T14S, R1E	

TANKS

1.	At Rice Creek Spring in the SW1/4, Sec. 22, T7N, R1W	A*
2.	At mouth of Garner Canyon NW1/4, Sec. 3, T6N, R1W	A
3.	SE1/4, Sec. 15, T6N, R1W	
4.	SE1/4, Sec. 15, T6N, R1W	A
5.	NW1/4, Sec. 23, T6N, R1W	
6.	At the mouth of Waterfall Canyon, east of Ogden	
7.	At the mouth of Strongs Canyon, east of Ogden	
8.	NW1/4, Sec. 13, T4N, R1W	A
9.	NW1/4, Sec. 25, T4N, R1W	
10.	SW1/4, Sec. 18, T3N, R1E	A
11.	SW1/4, Sec. 32, T2N, R1E	
12.	NE1/4, Sec. 6, T1N, R1E	
13.	SE1/4, Sec. 14, T2S, R1E	
14.	SW1/4, Sec. 2, T3S, R1E	A
15.	SE1/4, Sec. 11, T3S, R1E	
16.	SW1/4, Sec. 29, T6S, R3E	
17.	At mouth of Slate Canyon	
18.	SW1/4, Sec. 35, T7S, R3E	A
19.	SW1/4, Sec. 1, T8S, R3E	
20.	NE1/4, Sec. 34, T8S, R3E	

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* All listed facilities are within the Wasatch Fault Zone; those with "A" designations are actually astride fault scarps or traces.