# The Problem of Converting Precipitation Into Infiltration

(The Characterization of Yucca Mountain Vadoze Zone
Waste Isolation Potential)

by

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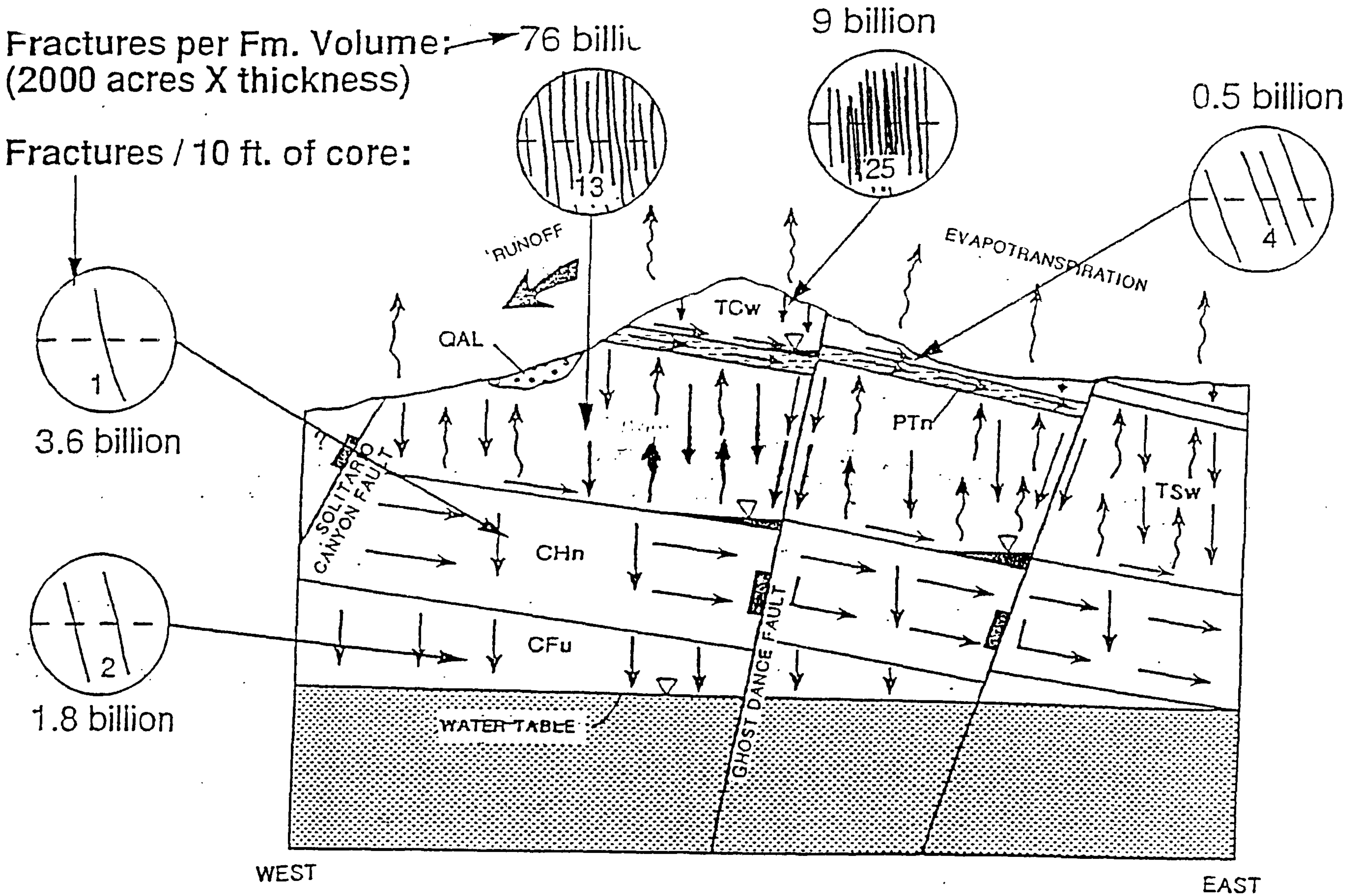
Vadose (Unsaturated) Zone Hydrogeology at Yucca Mountain

# General Concerns

- The DOE site-selection and investigative program to date has been based on unconservative assumptions with respect to the vadose zone.
- Vadose-zone hydrology remains essentially unknown. The database released by DOE is extremely sparse, and does not establish hydrologic processes at the site.
- The vadose zone is highly fractured from the uppermost welded tuffs to the water table. This promotes rapid vertical travel times for liquid and gas phase fluids.
- Vadose-zone hydrology at the site is probably extremely complex and can not be confidently characterized in the absence of site-specific data.
- To date, the DOE has not demonstrated data collection techniques suitable for confidently characterizing the hydrology of the vadose zone at the site.
- Moisture available for recharge occurs at the site, but it is not equally distributed in time or space. Confident recharge estimates can not be established at the Yucca Mountain site with the existing database and available methods.




| | |
|---|---|
| QAL | ALLUVIUM |
| TCw | TIVA CANYON WELDED UNIT |
| PTn | PAINTBRUSH NONWELDED UNIT |
| TSw | TOPOPAH SPRING WELDED UNIT |
| CHn | CALICO HILLS NONWELDED UNIT |
| CFu | CRATER FLATS (Undifferentiated) UNIT |

LIQUID-WATER FLOW

WATER-VAPOR FLOW

NORMAL FAULT

WATER TABLE

POSSIBLE PERCHED-WATER ZONE

Modified from the SCP (DOE, 12/88)

# Database with Respect to Fracture Flow

- Core data indicates each stratigraphic unit is highly fractured in the vadose zone.
- There is evidence of active soil-gas circulation within the vadose zone at Yucca Mountain. Blowing wells on a seasonal basis indicate high degrees of fracture network continuity with large volumes of fracture porosity at depth and very rapid transport times of soil air.
- Hydraulic conductivity data from core indicate variable but very small hydraulic conductivities for the rock matrix of welded volcanic tuffs, and much larger hydraulic conductivities for the bedded tuffs.
- Moisture content of core samples suggests fracture flow.
- Saturation encountered in drilling suggests perched water and fracture flow.

# Properties of Hydrogeologic Units Within the Unsaturated Zone*

## Yucca Mountain, Nevada

| Hydrogeologic Unit | Thickness Range, m | Porosity | Saturated Hydraulic Conductivity mm/yr | Saturation (percent) |
|---|---|---|---|---|
| Tiva Canyon welded | 0 - 150 | 0.12 | 0.73 | 67 |
| Paintbrush nonwelded | 20 - 100 | 0.46 | 3285 | 61 |
| Topopah Spring welded | 290 - 360 | 0.14 | 1.10 | 65 |
| Calico Hills nonwelded (vitric) | 100 - 400 | 0.37 | 1460 | 90 |
| Calico Hills nonwelded (zeolitic) | | 0.31 | 2.92 | 91 |
| Crater Flat unit (undifferentiated) | 0 - 200 | 0.23 | 18.25 | 88 |

*Table 1 of P. Montazer & W.E. Wilson, 1984, USGS, WRIR84-4345.

## APPARENT FLOW REGIMENS WITH ASSUMED STEADY RECHARGE RATES

| Hydrogeologic Unit | Saturated Hydraulic Conductivity mm/yr. | | | Assumed Steady Recharge Rate mm/yr. matrix flow (M) fracture flow (F) | | | |
|---|---|---|---|---|---|---|---|
| | | | | 0.5 | 1.0 | 5.0 | 10.0 |
| Tiva Canyon, welded | 0.31 [c] | 0.73 [b] | 1.0 [a] | M/F | M/F | F | F |
| Paintbrush, nonwelded | 109 [b] | 3,300 [a] | 12,300 [c] | M | M | M | M |
| Topopah Spring, welded | 0.05 [c] | 0.06 [b] | 0.70 [a] | M/F | F | F | F |
| Calico Hills, nonwelded (vitric) | 55 [b] | 85 [c] | 107 [a] | M | M | M | M |
| Calico Hills, nonwelded (zeolitic) | 0.01 [b] | 0.50 [a] | 0.63 [c] | M/F | F | F | F |
| Crater Flat unit (Undifferentiated) | 18.25 [b] | 22.0 [a] | 88.0 [a] | M | M | M | M |

DATA SOURCES:
[a] Environmental Assessment, 1986, DOE/RW-0073.
[b] USGS, WRIR84-4345, 1984.
[c] SAND 84-1471, 1984.

# WHAT IS EFFECTIVE MOISTURE?

EFFECTIVE MOISTURE IS THAT PART OF THE BASIN HYDROLOGIC BUDGET THAT ESCAPES DIRECT EVAPORATION OR EVAPOTRANSPIRATION IN THE CATCHMENT BASIN, AND REACHES THE HYDROLOGIC SINK(s) OF THE BASIN.

IN THE SEMI-ARID AND ARID BASINS OF THE GREAT BASIN, EFFECTIVE MOISTURE IS MOST READILY QUANTIFIED AT THE GROUND-WATER DISCHARGE AREAS AND SURFACE-WATER SINKS IN THE BOLSONS.

# BACKGROUND REGIONAL RELATIONSHIPS

## *Evidence for Infiltration in the Great Basin Environments*

Precipitation = Runoff + Evaportranspiration + Infiltration

Precipitation < Potential Evaportranspiration

As observed in the bolsons environments, the following is true for extensive areas of Northwestern Nevada, Northeastern Nevada, South Central Nevada, and Southern Nevada:

Evaportranspiration $\leq$ Precipitation

and

Runoff $\geq$ 0 (ephemeral water on playas)

Infiltration $\geq$ 0 (dynamic ground-water flow systems and ground-water discharge)

**Conclusion**

Factors related to how precipitation occurs in time and space, and terrane hydrogeological characteristics determine both infiltration and runoff. All factors generally are poorly known in time and space and *probably can not be confidently* measured at Yucca Mountain due to the very small values involved, distribution in time and space, and hydrogeological heterogeneity.

## QUANTITATIVE EVIDENCE OF PLENIPLUVIAL EFFECTIVE MOISTURE

### *REGIONAL AND SUBREGIONAL EVIDENCE*

EXTENT OF PLUVIAL LAKES (CENTRAL AND NORTHERN NEVADA)

EXTENT OF PLENIPLUVIAL GROUND-WATER DISCHARGE DEPOSITS (S. NEVADA)

### *YUCCA MOUNTAIN SITE SPECIFIC EVIDENCE*

DIRECT QUANTITATIVE EVIDENCE NOT AVALIABLE

MUST ESTABLISH INDIRECT EVIDENCE OF PLENIPLUVIAL PROCESSES RELATED TO FRACTURE FLOW, PERCHING, SHALLOW SATURATION, THE PROBABLE MANIFESTATIONS OF THE PLENIPLUVIAL CLIMATE AT THE SITE.

AGE DATING OF PLENIPLUVIAL EVIDENCE MUST SEPARATE QUATERNARY PROCESSES FROM OLDER HYDROLOGIC MANIFESTATIONS.


FIGURE 8. View of the Pre-Lahontan bar (A) in the south end of Long Valley, and an alluvial deposit of approximately the same age (B). This is the best well preserved example of a shoreline feature above Lahontan age shorelines (L) in a non-overflowing basin, and it may be related to local warping and/or faulting, or regional tilt. In Newark Valley, adjacent to the west, similar old shore features are preserved along the southeast embayment of Lake Newark.

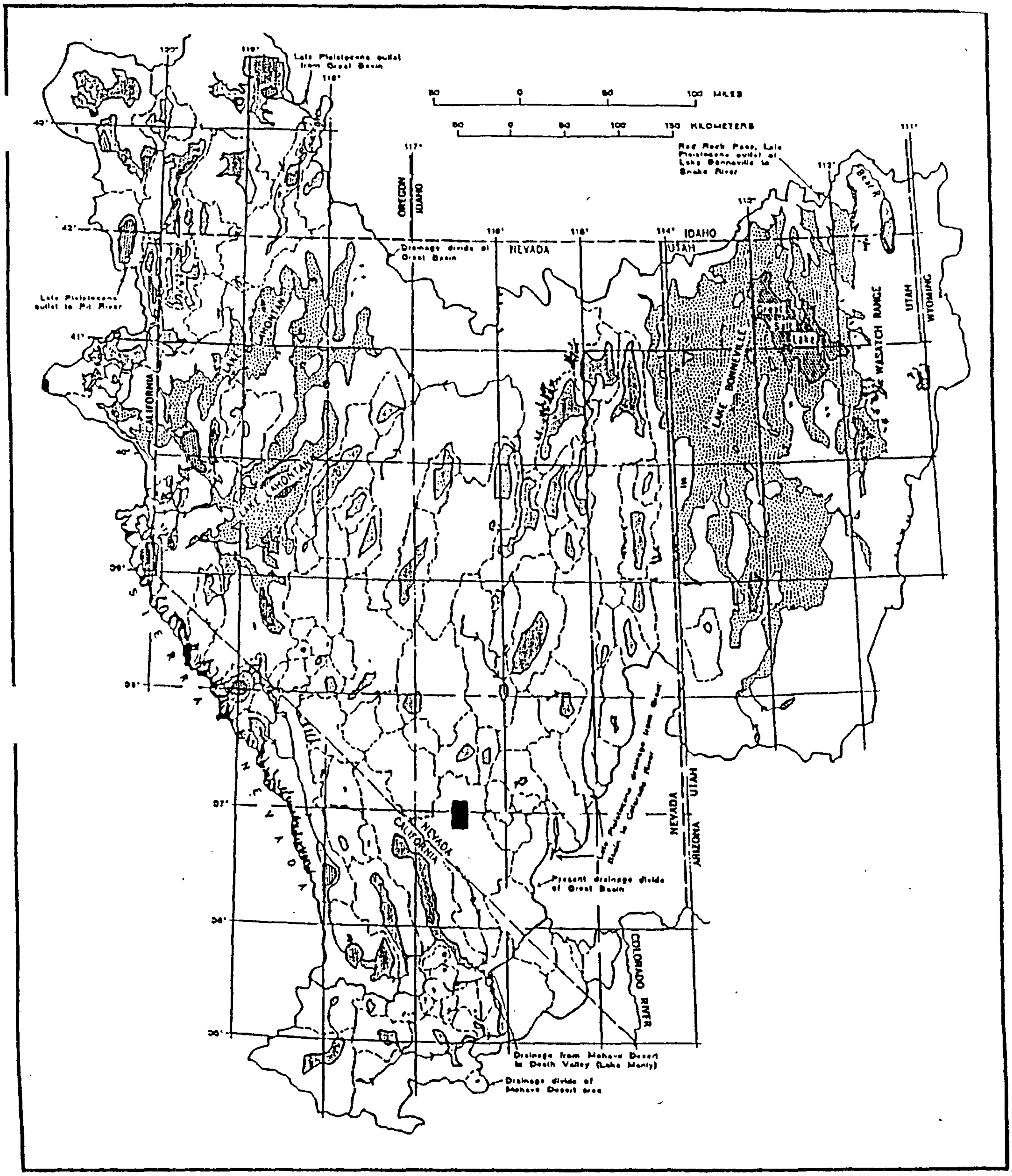
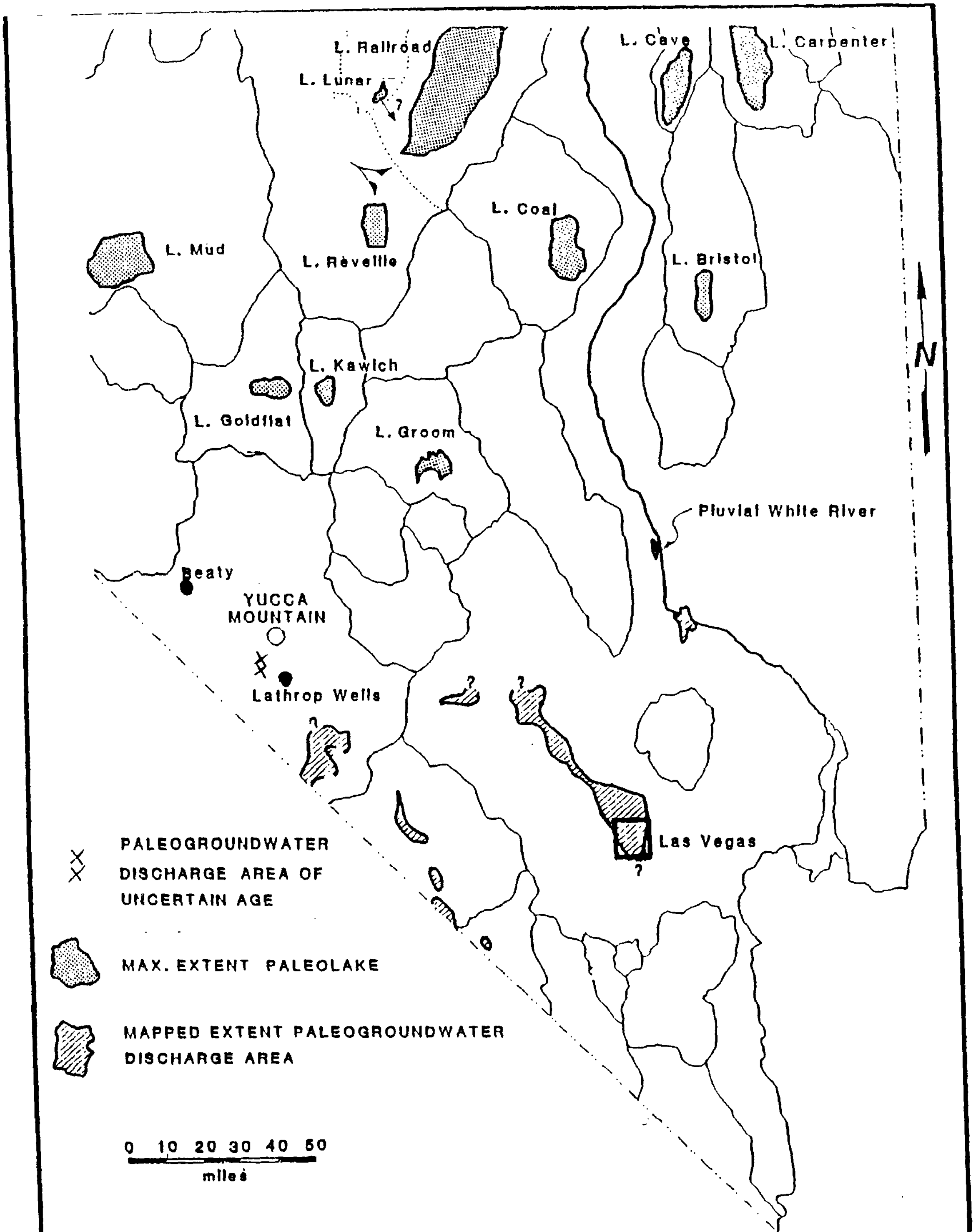
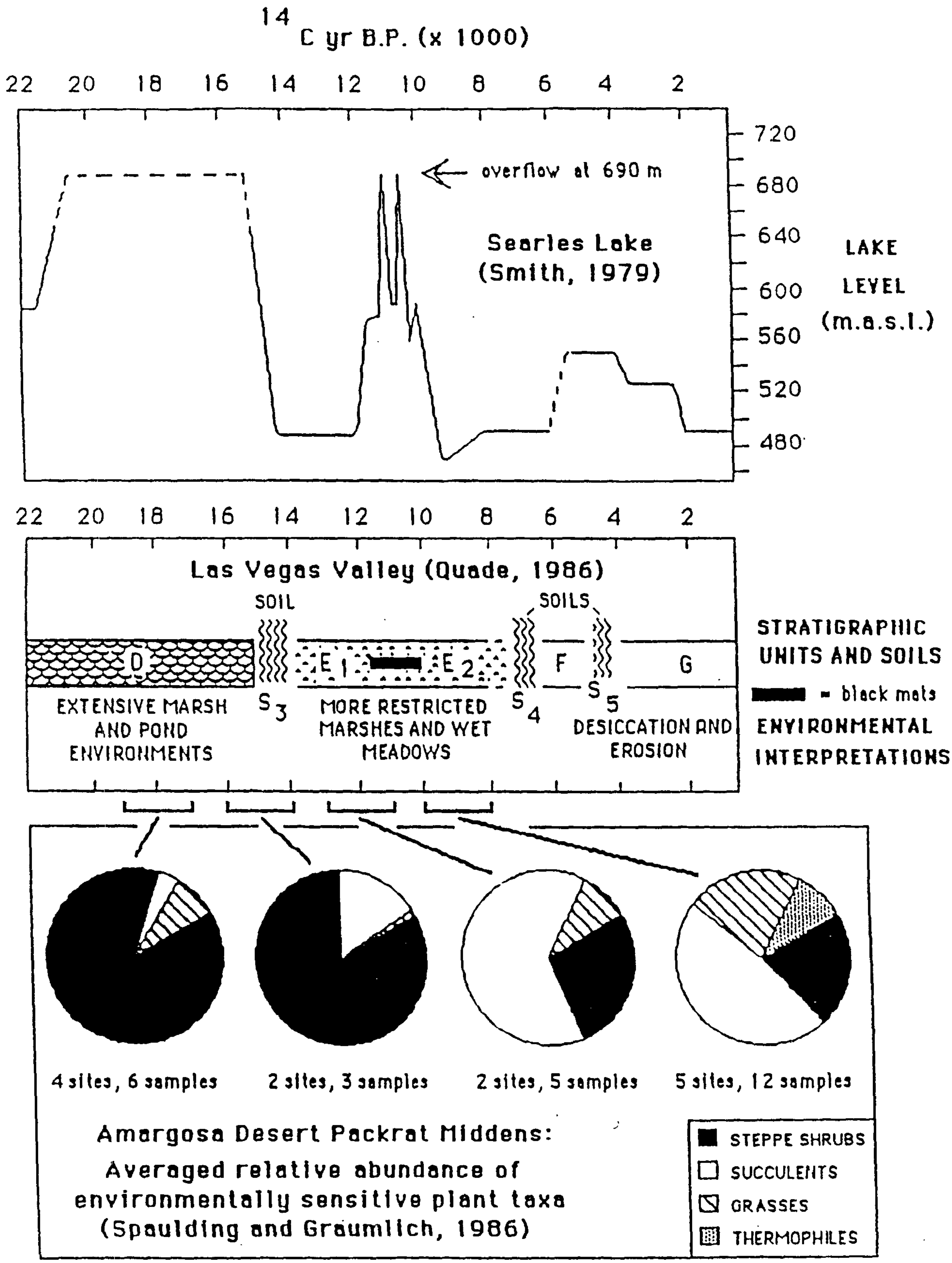



Figure 3. Plenipluvial Pleistocene lakes in the Great Basin (after Morrison, 1965; modifications from Mifflin and Wheat, 1979).




LATE QUATERNARY PLENIPLUVIAL HYDROLOGY

(MODIFIED FROM MIFFLIN AND WHEAT, 1979; MIFFLIN AND QUADE, 1988)


14 C yr B.P. (x 1000)
22 20 18 16 14 12 10 8 6 4 2
720 680 640 600 560 520 480
overflow at 690 m
Searles Lake (Smith, 1979)
LAKE LEVEL (m.a.s.l.)
Las Vegas Valley (Quade, 1986)
SOIL
SOILS
D
E1
E2
F
G
S3
S4
S5
EXTENSIVE MARSH AND POND ENVIRONMENTS
MORE RESTRICTED MARSHES AND WET MEADOWS
DESICCATION AND EROSION
STRATIGRAPHIC UNITS AND SOILS
= black mats
ENVIRONMENTAL INTERPRETATIONS
4 sites, 6 samples
2 sites, 3 samples
2 sites, 5 samples
5 sites, 12 samples
Amargosa Desert Packrat Middens:
Averaged relative abundance of environmentally sensitive plant taxa (Spaulding and Graumlich, 1986)
STEPPE SHRUBS
SUCCULENTS
GRASSES
THERMOPHILES

# SITE-SPECIFIC EVIDENCE

- Glass alteration occurs well above the present water table. Some appears to be related to a paleowater table and some, well above the zone of complete alteration, to perched water.

- Fractures have secondary mineral coatings and fillings precipitated from aqueous solutions.

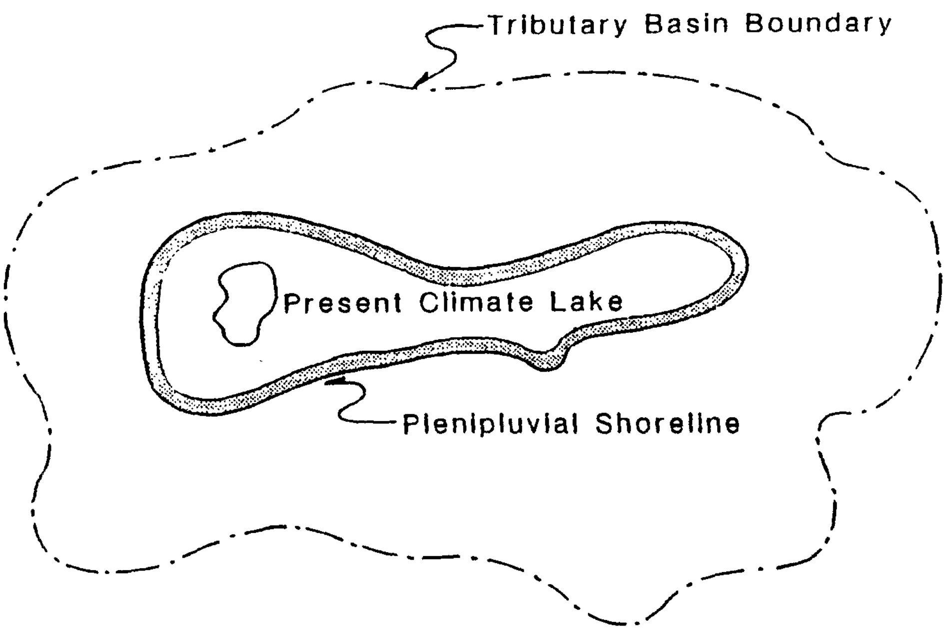
- The macro-fossil evidence (packrat middens) reflects the timing of vegetation community changes, the approximate climate related, and, locally, phreatophytic plant fossils which require perennial saturation at root level.

# REGIONAL EVIDENCE

- Former extent of pluvial lakes in the Great Basin.

- Change in effective moisture (runoff and recharge) was about a one order of magnitude increase (10x modern).

- Extensive areas of ground-water discharge deposits in the Yucca Mountain region indicate greater discharge flux and rise in water tables up to several hundred feet.




Moisture into the lake = Moisture out

$$(A_T R_T) + (A_L P_L) = A_L E_L$$

or by rearranging and factoring,

$$A_T R_T = A_L(E_L - P_L). \qquad (1)$$

where,

$A_T$ = tributary area of the basin (total basin area minus lake area),

$R_T$ = combined runoff of surface and ground water per unit area per unit of time,

$A_L$ = maximum lake area as indicated by the highest shore,

$P_L$ = precipitation directly upon the lake per unit area per unit of time, and

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A useful form of Equation 1 is obtained when the runoff ($R_T$) is stated in terms of climatic parameters; average basin precipitation per unit area per unit of time ($P_T$) minus average tributary basin evapotranspiration per unit area per unit of time ($ET_T$):

$$R_T = P_T - ET_T \qquad (2)$$

By substitution of Equation 2 into Equation 1, the continuity equation is put into terms of the product of measurable paleohydrologic areas and quasiclimatic parameters:

$$A_T(P_T - ET_T) = A_L(E_L - P_L) \qquad (3)$$

or

$$Z = \frac{A_L}{A_T} = \frac{P_T - ET_T}{E_L - P_L} = \frac{R_T}{E_L - P_L} \qquad (4)$$

**(from Mifflin & Wheat, 1979)**

Estimates of modern hydrologic indices based on ephemeral surface water on playas and groundwater discharge can be approximated by modifying Equation 4 to :

$$Z_M = A_E(E_P - P_B) = A_T(R_S + R_G)$$

or

$$Z_M = \frac{A_E}{A_T} = \frac{R_S + R_G}{E_P - P_B} \qquad (5)$$

where, $A_E$ = Area necessary to evaporate the combined surface water ($R_S$) and ground water ($R_G$) reaching the basin floor,

$E_P$ = Potential evaporation, and

$P_B$ = Modern basin precipitation.

Calculations over the tributary area always yield less than 1 inch per year and usually less than half inch per year where estimates of groundwater discharge have been made (Mifflin, 1968; Nevada Hydrologic Atlas, 1972). Examination of the surface-water runoff map of Nevada (Nevada Hydrologic Atlas, 1972) demonstrates a mean of less than 2 inches of surface runoff distributed over tributary basins; usually it is considerably less than 1 inch. Thus, a maximum modern hydrologic index for northeastern Nevada can be approximately evaluated as follows:

$$Z_M = \frac{R_S + R_G}{E_P - P_B} = \frac{1 + 0.5}{40 - 10.5} = \frac{1.5}{28.5} = 0.053$$

Ruby Valley (56 in plate 1), on the east side of the Ruby Mountains, constitutes one of the moistest closed basins in northeastern Nevada. This basin has a well-developed perennial paludal body of water called Ruby Marsh nourished by a number of large carbonate rock springs which yields a hydrologic index of 0.026 when the marsh area is used for a measured lake area in Equation 4. The marsh measurement provides a direct comparison to the pluvial index of Ruby Valley. This value omits about an equal amount of groundwater and surface-water discharge (hay meadows, areas of phreatophytes, playa and marsh) in the northern half of the valley north of Ruby Marsh. This northern Ruby Valley runoff is not as distributed in time nor as concentrated as the spring flow of the Ruby Marsh System. Thus, if the total runoff to the entire valley is considered, the modern hydrologic index would be about 0.05 or approximately that calculated as maximum hydrologic index for northeastern Nevada.

In northwestern and southcentral Nevada all modern indices are smaller, and only in a few extreme northwestern basins (and in a number of basins occurring just beyond the Nevada line in California) do conditions suggest modern hydrologic indices of similar magnitude. In these latter basins the playas are more frequently occupied by water or are playa lakes, and groundwater discharge from large areas of phreatophytes suggest a half inch or so of groundwater discharge.

In the drier areas, the following evaluation of Equation 5 gives an idea of a maximum hydrologic index for southcentral Nevada:

$$Z_M = \frac{R_S + R_G}{E_P - P_B} = \frac{.5 + .25}{44 - 8} = \frac{.75}{36} = 0.02$$

In southern Nevada, the following might be expected:

$$Z_M = \frac{R_S + R_G}{E_P - P_B} = \frac{.5 + .25}{54 - 5} = \frac{.75}{49} = 0.012$$

All evaluations of modern hydrologic indices using Equation 5 yield values not directly comparable to the values obtained in Equation 4 for pluvial indices. The prime reason direct comparison is misleading is the artificial way in which the basin shape has been circumvented in Equation 5. All surface water ($R_S$) and groundwater runoff ($R_G$) does not concentrate into one localized perennial body of water due to basin shape. If surface water runoff ($R_S$) and groundwater runoff ($R_G$) could be measured at the edge of the playas, both would drop to very small values because of evapotranspiration losses upgradient; therefore, an important part of the numerator in Equation 5 would be embodied in $ET_T$ in Equation 4.

TABLE 9. Comparison of evaluated pluvial climates with annual extreme variations of Climatic Division means, 1931–1960.

| Climate Division | Evaluated Climate Temp/°F $P_L$/inches | Annual Temperature (°F) High Mean Low | Annual Precipitation (inches) High Mean Low |
|---|---|---|---|
| SCO (ENWN) | 42.5 | 50.4 | 17.38 |
| | | 46.7 | 12.28 |
| | 21.75 | 44.5 | 6.86 |
| NWN | 45 | 53.0 | 12.75 |
| | | 49.8 | 8.30 |
| | 13.5 | 47.5 | 3.90 |
| NEN | 42 | 50.9 | 16.45 |
| | | 45.9 | 10.53 |
| | 19 | 42.6 | 7.47 |
| SCN | 45.5 | 55.0 | 12.77 |
| | | 51.7 | 6.72 |
| | 10.2 | 49.7 | 3.10 |
| SN | 58.5 | 67.3 | 11.37 |
| | | 63.5 | 5.10 |
| | 8* | 61.9 | 1.40 |

*Value from Table 7 based on adjusted curve of Figure 22.

Mifflin And Wheat 1979

**Climate Change Supplemental Discussion, M.D. Mifflin**

Figures 7 and 8 of the following viewgraph diagrammatically illustrate ground-water flow systems relationships often observed in the semi-arid and arid terranes of the Great Basin. Areas of important recharge are usually in the higher mountainous terranes, and zones of extensive lateral flow occur where recharge is minor or absent. Effective moisture, as measured at the basin lowland (bolson) is constituted by ground-water discharge through evapotranspiration in the areas of phreatophytes and short lived ephemeral water bodies on playas in all but a few of the many basins. In the *least* arid hydrographically closed basins, effective moisture, as measured in the bolsons, may occur as one or combinations of the following hydrologic features: major spring areas, perennial lakes, perennial marshes, perennial streams, playa lakes (ephemeral) and extensive communities of phreatophytes. In Figure 7 the *Zone of Active Discharge* is the area where effective moisture for a basin would be determined by measuring total evapotranspiration from the hydrologic features.

Figure 8 diagrammatically illustrates several hydrogeologic environments, including one that approximates the hydrogeologic setting of Yucca Mountain. This occurs at the topographic divide between the zones entitled *Drained Closed Basin* and *Regional Sink*. The approximating analogy is a deep, essentially uniformly sloping water table with ground-water flow passing from below a topographic high into a basin with ground-water discharge derived from interbasin flow through bedrock.

In my opinion, neither present nor past effective moisture can likely be *measured with much confidence directly* at the Yucca Mountain site. The modern values of effective moisture and net recharge are likely to prove *smaller* than the measurement accuracies of site specific methodologies, and prolonged site specific monitoring (30 - 60 years) would probably be necessary to locally record and evaluate the importance of extreme precipitation events which are suspected to be very important in determining net recharge under the existing arid climate. In such settings, processes and evidence of net recharge can be documented, but effective moisture measured as net recharge has never been convincingly measured at the "repository" field scale. Plenipluvial effective moisture, because of the widespread regional paleohydrologic evidence and hydrographically closed basin hydrology, may prove to be quantitatively more tractable than the attempts being made to quantify present net recharge at Yucca Mountain.

A concept is sketched in the second viewgraph that addresses terrane saturation and configuration of flow based on the availability of effective moisture and terrane transmissivity. This concept coupled with direct observations of terrane responses to modern variations in climate gives considerable insight when attempting to interpret the plenipluvial paleohydrologic evidence in the Great Basin. In all rock terranes in the Great Basin, the arid and semi-arid climates that occur throughout extensive areas of the basins and lower mountainous terrane do not provide enough effective moisture (and net recharge) to influence the local position of saturation. The small amounts of net recharge are often not sufficient to produce potentiometric mounding. Not all terrane is necessarily

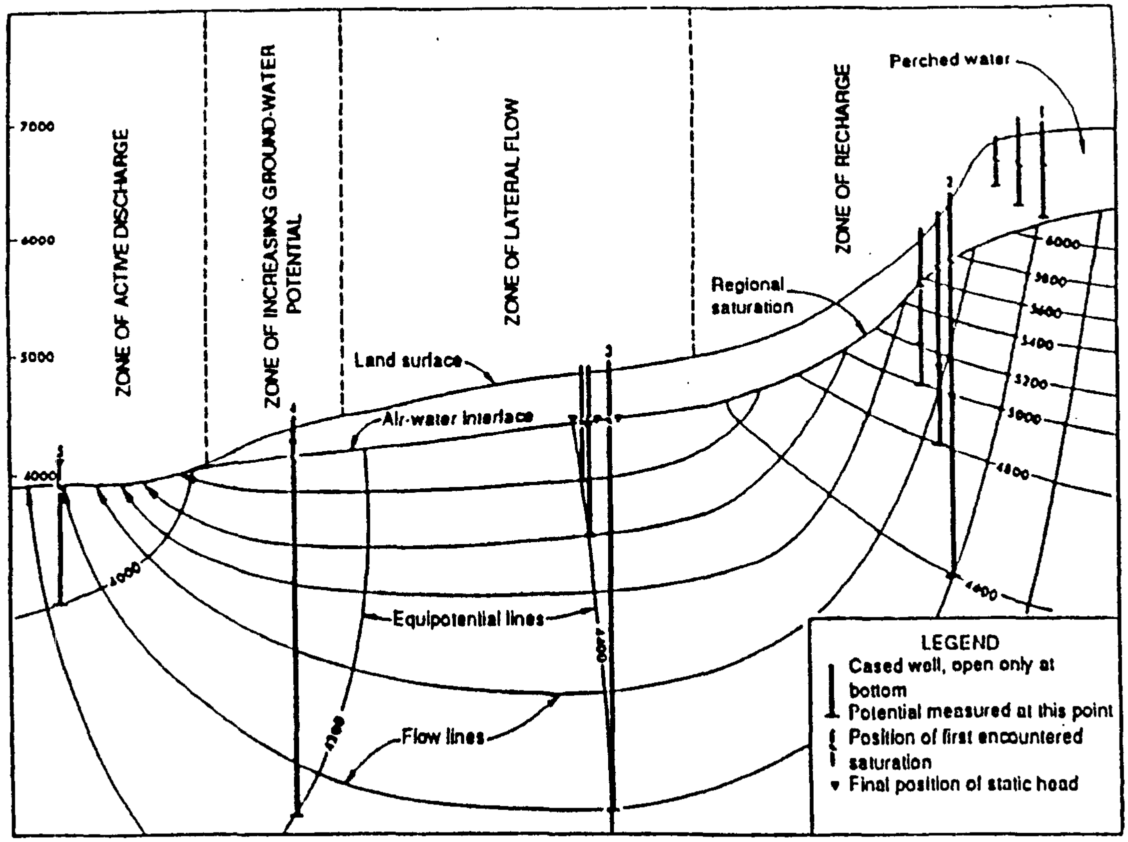



Figure 7. Idealized sketch of fluid potential relationships in Great Basin flow systems (after Mifflin, 1968).

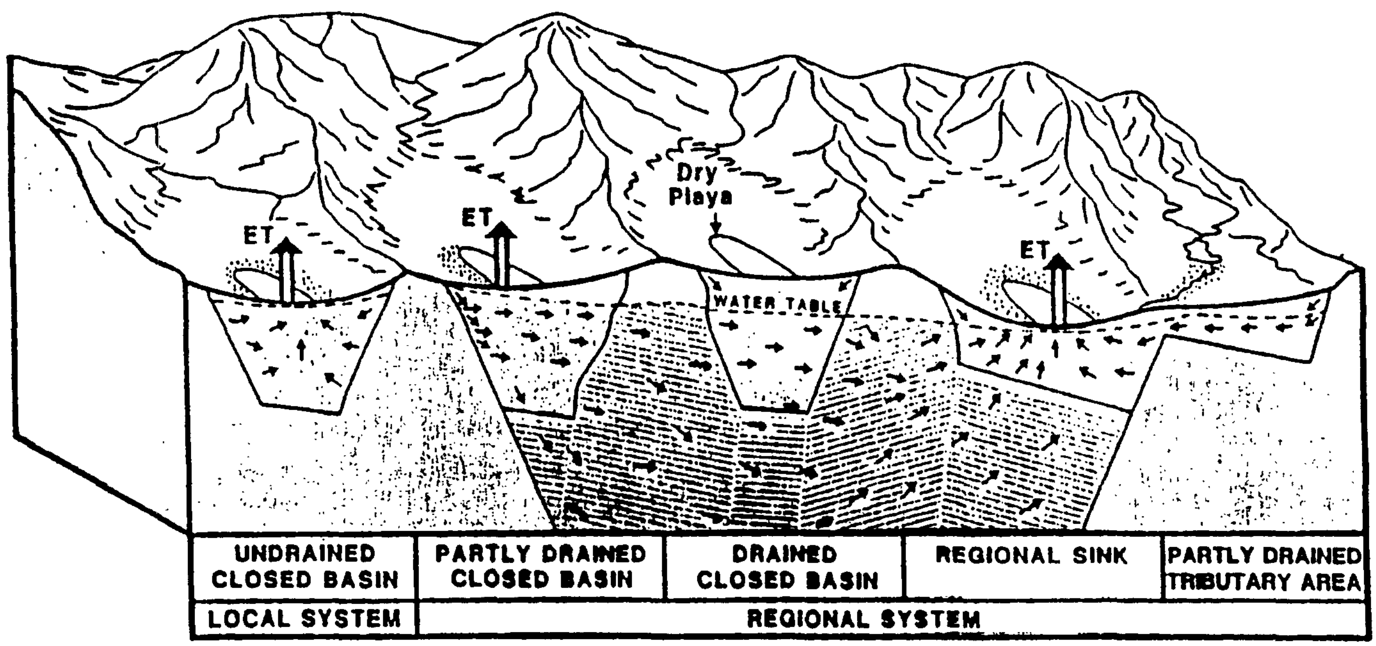


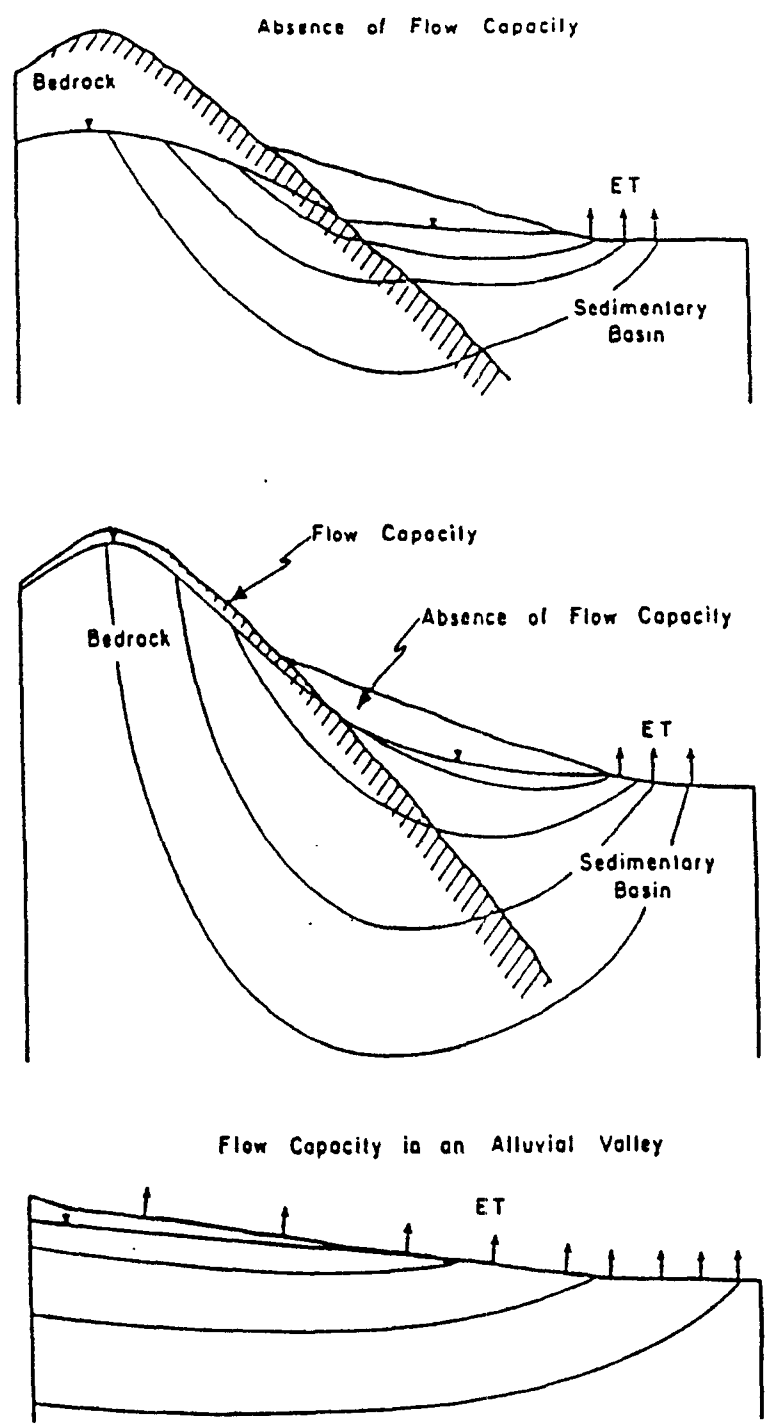

Figure 8. Observed configurations of ground-water flow in the Great Basin (modified after Eakin and others, 1976). ET, evapotranspiration.

(FROM MIFFLIN, 1988)

Qmax > Qpresent

Bedrock : Qmax = Qpresent
Basin : Qmax > Qpresent

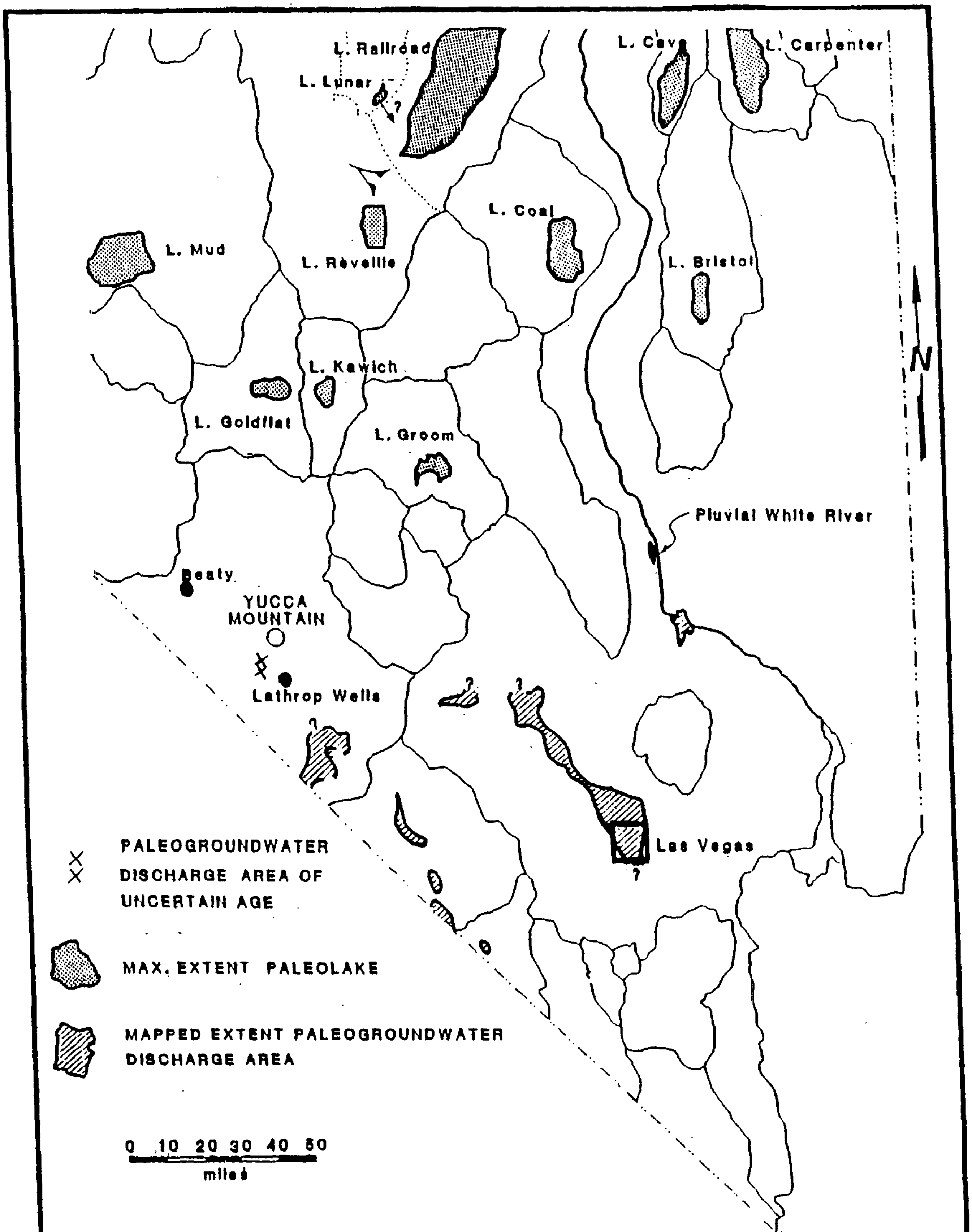
Qmax ≈ Qpresent




**Concept of terrane capacity for ground-water flow, diagrammatic sketches (after Mifflin, 1968).**

created equal with respect to transmissivity and net infiltration, however, and the more transmissive rock types may accept significantly more net recharge than others. When more effective moisture was produced by a pluvial climate, these transmissive rock types played an important part in how the changing availability of effective moisture translated into net recharge and runoff. An example illustrates this in the relatively least arid part of the Great Basin, the Ruby Mountains in northeastern Nevada. The northern part of the mountain range is mostly crystalline rock terrane, and after the spring period of direct snow melt runoff, perennial streams, springs, and seeps are nourished by *rejected recharge* in the mountain block (and *net* recharge is much smaller than *total infiltration*). In contrast, the southern extension of the Ruby Mountains are carbonate rock terrane and there is little or no perennial flow in seeps, springs, or streams in a large part of the mountain block, even though other terrane factors are similar to the northern Ruby Mountains composed of crystalline rocks. Most of the infiltration becomes *net* recharge, and the configuration of saturation and flow is sketched in the upper diagram. The middle diagram illustrates the configuration of saturation and pattern of flow for the crystalline rock terrane where the regional saturation mounding in the mountain block is closer to landsurface and at landsurface in the mountain block drainage bottoms. These relationships are discussed because the volcanic tuff sequence at Yucca Mountain is intermediate in terms of accepting increased effective moisture and transmissive capacity, and the following discussion indicates the Ruby Valley/Ruby Mountain region appears to be an analog climate of the plenipluvial climate of Southcentral Nevada.

The lower sketch of the viewgraph illustrates a situation where net recharge and flux is great enough in the alluvial basin to cause extensive ground-water discharge, a condition that occurred during plenipluvial climates in some basins in Southern Nevada (see the following viewgraph entitled LATE QUATERNARY PLENIPLUVIAL HYDROLOGY). Extensive areas of highly distinctive fine-grained deposits outline the areas of former ground-water discharge. The most extensive areas of such deposits occur in the basins adjacent to high mountains dominated by carbonate rock terrane.




LATE QUATERNARY PLENIPLUVIAL HYDROLOGY

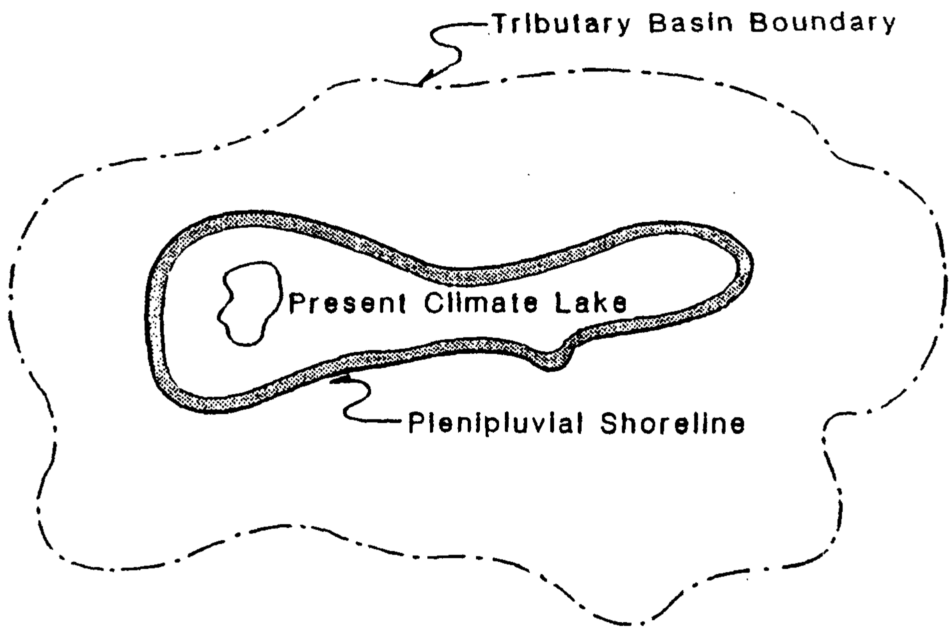
(MODIFIED FROM MIFFLIN AND WHEAT, 1979; MIFFLIN AND QUADE, 1988)

The following three viewgraphs demonstrate the methodology Mifflin and Wheat (1979) used to reconstruct plenipluvial climates in the various subregions of Nevada based on plenipluvial high lake stand shoreline evidence in the hydrographically closed basins. The first viewgraph establishes the quantitative relationships of climatic and hydrologic parameters to the effective-moisture evidence (the hydrologic index) when dealing with arid and semi-arid climates in a Great Basin setting.

The following viewgraph shows mean annual temperature/mean annual precipitation curves and mean annual temperature/runoff curves. The temperature/precipitation curves constructed on the basis of regional climate records (triangles) and individual climate station records (dots) that help to extend the curves and establish a bounding envelope. Most long term precipitation records are from stations located in the basin lowlands and thus the envelope curve approach, as precipitation is greater in the mountains. The underlying assumption Mifflin and Wheat (1979) adopted to reconstruct the plenipluvial climates by using these temperature/precipitation curves is that plenipluvial climates were similar to modern Great Basin climates in terms of mean annual temperature with respect to mean annual precipitation. This underpinning assumption has subsequently been supported by a relatively large database of dated pollen and plant macrofossils from packrat middens in the southern Great Basin. These records show that the last pluvial climate cycle shifted typical Great Basin plant communities to lower elevations by about the amount predicted by the Mifflin and Wheat plenipluvial climate reconstructions. The istopic signatures of pedogenic soil carbonates in the Yucca Mountain area also tend to support a similar or greater magnitude of downward shift in plant communities during the Quaternary. However, there is evidence for both colder "dry" and temperate "wet" conditions within the total sample record, and both variations of pluvial climate could produce the measured plenipluvial paleohydrologic conditions of markedly increased effective moisture. Such independent indicators of climate or parameters of climate are extremely valuable and help to constrain climate reconstructions based on effective moisture evidence.

The lower curves of the viewgraph demonstrate the relationships of mean annual basin runoff with respect to mean annual basin precipitation at varied mean annual temperatures. These runoff functions are based on Shumm (1965) and are derived from stream-gauge records throughout the U.S.. They allow estimates of basin runoff from plenipluvial climates characterized by mean annual temperature and mean annual precipitation. These functions show how sensitive runoff (a measurable manifestation of effective moisture in climates more humid than most Great Basin climates) is to temperature and precipitation.

The third parameter of climate used by Mifflin and Wheat (1979) is lake evaporation. The curves were established by measured evaporation from the deep water lakes in the Great Basin. To estimate plenipluvial lake evaporation rates, the curves were used by assuming a lapse rate of 3.5°F/thousand feet of altitude change to adjust from the observed lake evaporation rates to the plenipluvial evaporation rates corresponding to the plenipluvial mean annual temperatures. Thus, a 6°F cooler plenipluvial climate (the approximate change required to establish the maximum extents of the pluvial lakes) would have a lake

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or by rearranging and factoring,

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or

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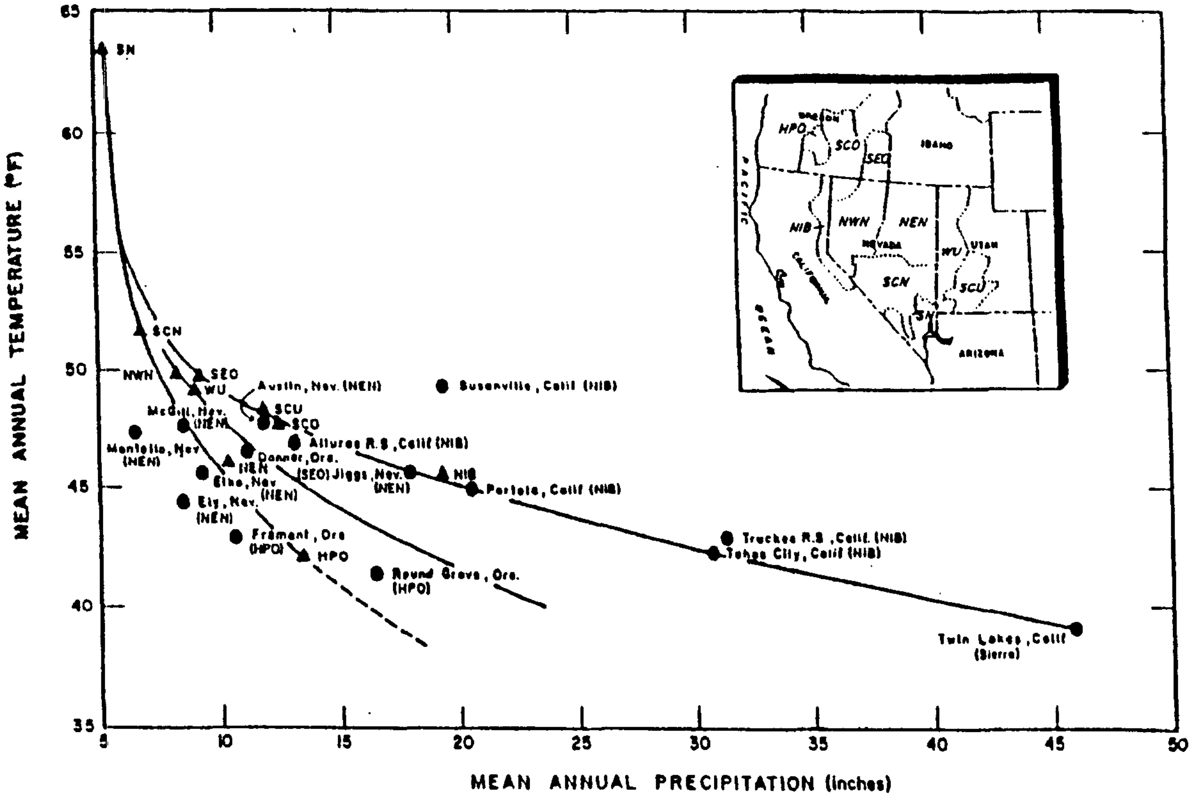
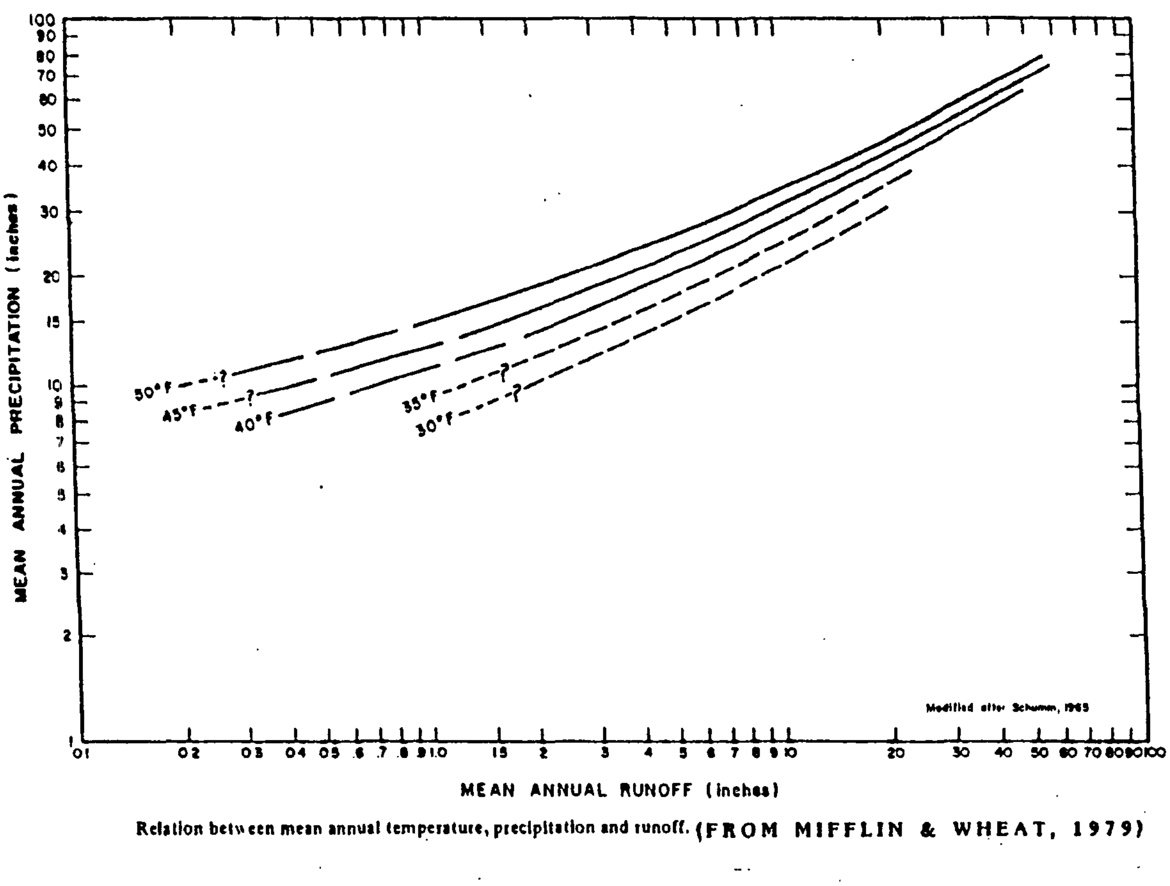
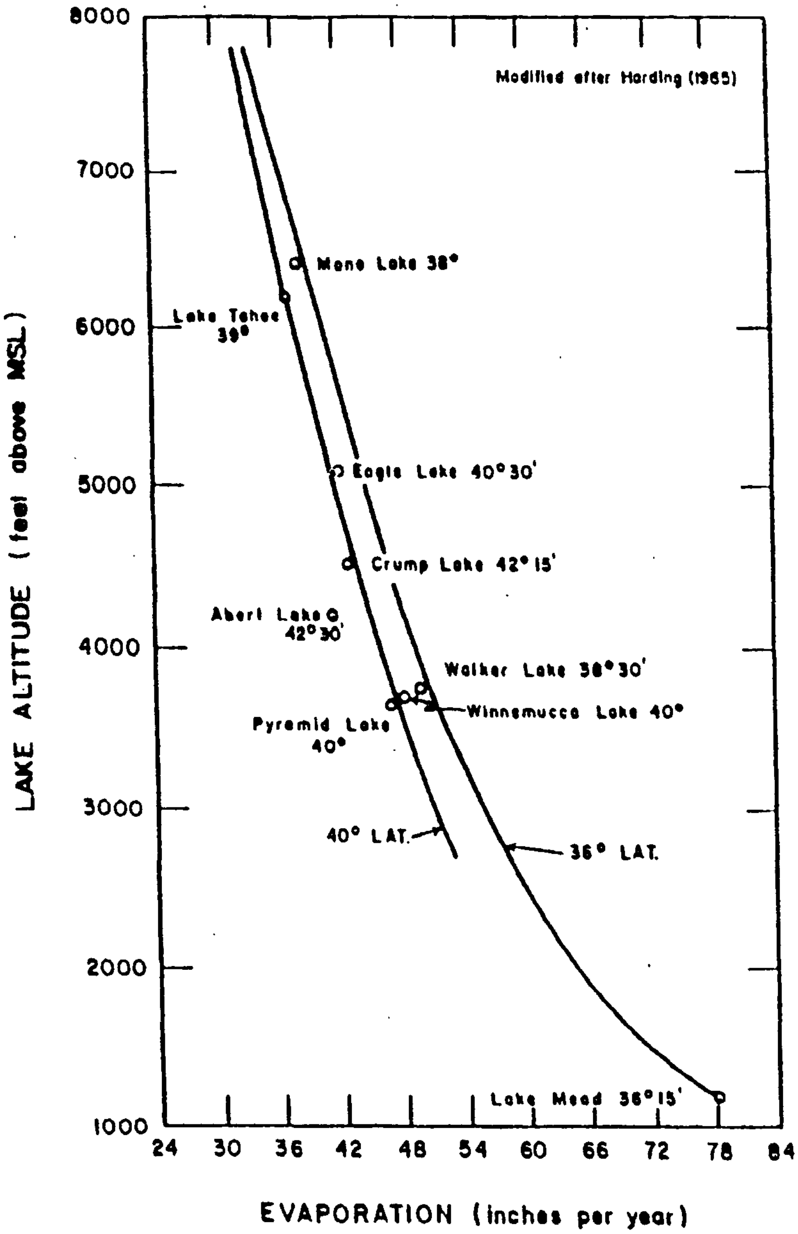
(from Mifflin & Wheat, 1979)




Relation of mean annual temperature to mean annual precipitation based on State Climatic Divisions, 1931 – 1960.




Relation between mean annual temperature, precipitation and runoff. (FROM MIFFLIN & WHEAT, 1979)



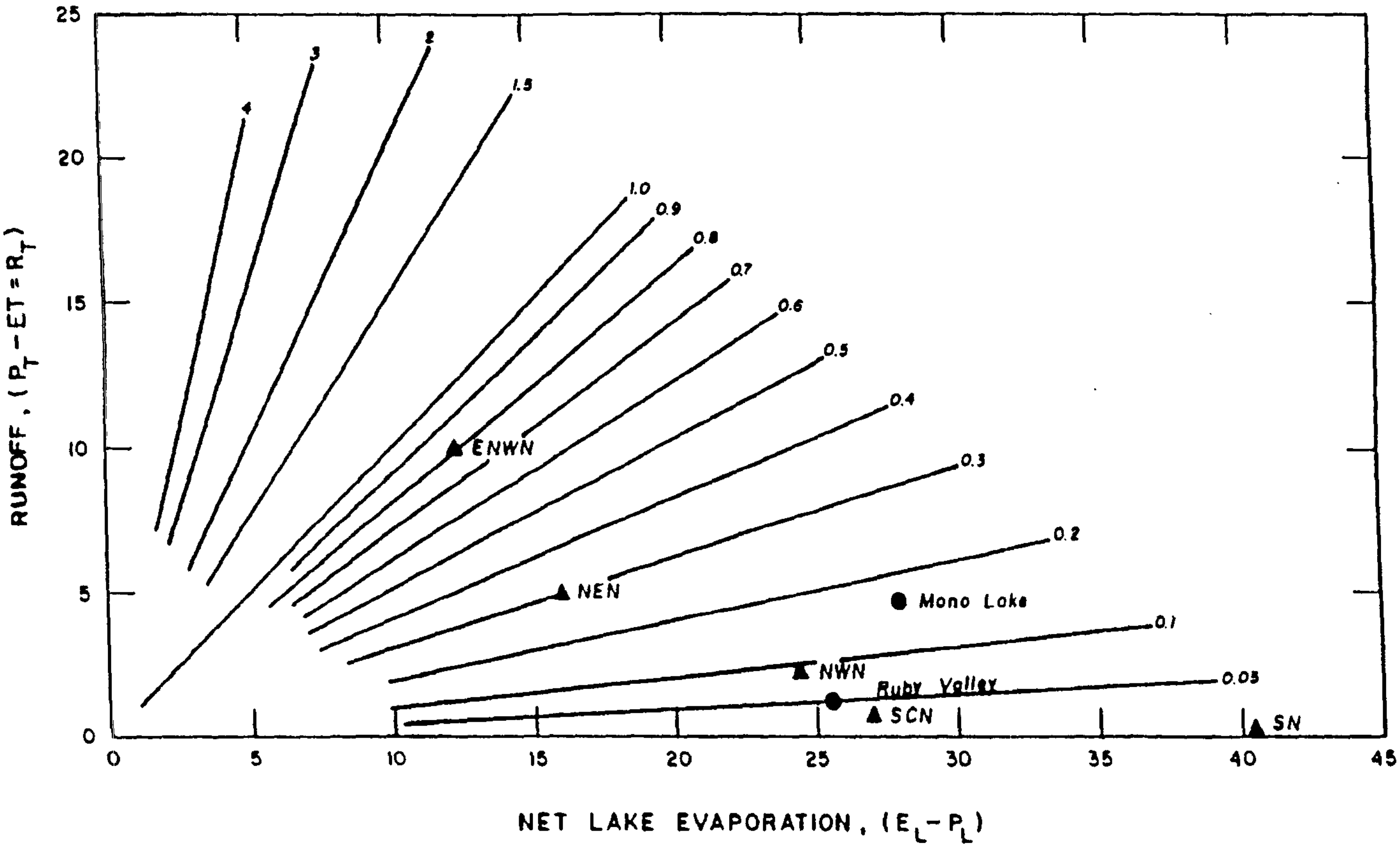

Mean annual evaporation from large lakes.
(FROM MIFFLIN & WHEAT, 1979)

evaporation rate equivalent to a lake surface altitude about 1,714 feet higher due to the lower mean annual temperature.

Values from the curves (basin and lake precipitation, basin runoff, and lake evaporation) allow for plenipluvial climates to be reconstructed in terms of mean annual temperature, precipitation, and deep lake evaporation if the basin had a plenipluvial lake that did not overflow. The numerical value of the hydrologic index (a ratio established on the basis of physical evidence of the maximum paleolake area and basin catchment area) allows for the plenipluvial climate reconstruction by using Equation 4 as mean annual temperature is adjusted downward to a value which produces the observed plenipluvial hydrologic index.

The comparison of the subregional reconstructed plenipluvial climates and associated effective moisture/hydrologic indices and two Great Basin modern climates and associated effective moisture/hydrologic indices is made in the last viewgraph. The modern climates (plotted as dots) of Mono Lake Valley and Ruby Valley can be compared on the basis of hydrologic indices of the modern lake area (Mono) and marsh areas (Ruby and Franklin) respectively. The plenipluvial reconstructed subregional climates of Northwestern Nevada and Southcentral Nevada (plotted as triangles) are very similar to the modern climate of Ruby Valley located in Northeast Nevada subregion based on the modern hydrologic index of that valley and the average plenipluvial indices of the two subregions. The modern climate of Mono Lake Valley does not appear to be a close climatic analog (homoclimate) of a plenipluvial climate in most of Nevada because of the higher modern evaporation rate. However, several southern Nevada basins with low elevation valleys but high bounding mountain ranges (Spring Mountains and Sheep Range) were the sites of extensive areas of ground-water discharge during plenipluvial climates and may well have had pluvial climates more like the modern Mono Lake Valley where the basin evaporation rate is relatively high. Mifflin and Wheat did not find a confident way to reconstruct the Southern Nevada subregion plenipluvial climate due to the total absence of former pluvial lakes.

Two important relationships that apply to the Yucca Mountain issue of climate change become apparent when studying the viewgraph. Hydrologic indices measure *effective moisture* and not climate, as there are many possible combinations of precipitation and temperature that could produce the same numerical value of hydrologic index. The second important relationship is that one particularly moist basin, Ruby Valley in Northeast Nevada, yields a modern hydrologic index similar to plenipluvial hydrologic indices of Northwestern and Southcentral Nevada subregions, and has a modern climate similar to the reconstructed plenipluvial climates of those subregions. The plenpluvial climate reconstructions indicate the modern climate of the Ruby Valley is a possible homoclimate of the plenipluvial climates in Southcentral Nevada, the subregion that includes Yucca Mountain. The Ruby Valley modern hydrologic index at about 0.05 is numerically equal to the plenipluvial indices of three basins bordering the Yucca Mountain drainage basin on the north (Mifflin and Wheat, 1979, Plate I, and Appendix):




Comparison of full pluvial climates to modern climates using hydrologic indices.

(FROM MIFFLIN & WHEAT, 1979)

| Basin/Pluvial Lake Name | Plenipluvial Hydrologic Index |
|---|---|
| Gold Flat/Gold Flat | 0.04 |
| Kawich/Kawich | 0.07 |
| Emigrant/Groom | 0.05 |

Evaluation of the climate change issue at Yucca Mountain requires determination of *effective moisture* of the Quaternary plenipluvial climates at the site. The change in effective moisture at the basin scale of measure is indicated by the plenipluvial hydrologic indices. The two basins where plenipluvial hydrologic indices were compared with modern hydrologic indices were Ruby Valley (pluvial Lake Franklin) and Mono Valley (pluvial Lake Russell) in Mifflin and Wheat (1979, p. 45-46):

| Basin/Pluvial Lake Name | Hydrologic Index | |
|---|---|---|
| | Modern | Plenipluvial |
| Ruby Valley/Lake Franklin | ~0.05 | 0.6 |
| Mono Valley/Lake Russell | 0.17 | 1.11 |

These data (and other relationships discussed in Mifflin and Wheat) suggest approximately one order of magnitude of *increase* in *effective moisture* during the plenipluvial climate as a *net measure in the bolson* (the hydrologic sink for both the surface and ground-water systems). Other quantitative comparisons have not been made for the many hydrographically closed basins where pluvial lakes occurred and modern climate ground-water/surface water budgets have been established by reconnaissance studies; they could also be made, with about the confidence level of the plenipluvial climate reconstructions due to uncertainties associated with the Maxey-Eakin estimating technique, the manner in which ground-water discharge estimates are established.

The determination of plenipluvial ground-water discharge estimates in the Southern Nevada subregion basins (where perennial pluvial lakes were absent) may add additional insight on the magnitude of Quaternary pluvial climate effective moisture at Yucca Mountain. The plenipluvial hydrologic indices are *net* measures of effective moisture at the hydrologic sink of the basin, and therefore measure the surface and ground water that escaped evapotranspiration throughout the entire basin and arrived at the bolson lowland. As terrane characteristics, as well as *local climate*, have important impact on *net recharge* in a site specific sense, it is important to recognize and determine the quantitative importance of terrane characteristics with respect to evaluating effective moisture at Yucca Mountain. One important terrane characteristic that seems to have influenced plenipluvial effective moisture in Southern Nevada is the dominant carbonate rock type in the highest mountain terrane.

Terrane capacity for flow determines hydrologic responses as effective moisture varies because of climate change. In much of the Great Basin, the existing semi-arid and arid climates do not create enough effective moisture (net infiltration) to exceed the transmissive capacity of the terrane. Generally very little of the infiltrated effective moisture is lost or rejected in mountains as seeps, springs, or as baseflow of streams within the mountains and basin margins (little or no evapotranspiration losses occur from the ground-water systems above the bolson hydrologic sinks). Only the highest mountains in northern and central Nevada, and some adjacent basins, display terranes at or near their transmissive capacities. A change in climate that produces greater effective moisture in these latter highest mountain and basin terranes can not markedly change the flux in the ground-water flow systems, and the increased effective moisture would be manifested as a marked increase in annual surface-water runoff reaching the basin lowlands. However, mountainous terranes composed of the most transmissive rock types (carbonate and some volcanic rock terrane) are often not at their transmissive capacity even in some of the higher terrane of Nevada, and would accept and transmit greater recharge in response to more effective moisture. The distribution of paleodischarge deposits indicate the combination of increased effective moisture, distribution of high mountain terrane, and rock types of the mountainous terrane markedly expanded the distribution and increased the amount of ground-water discharge in some of the basins. The patterns of some interbasin ground-water flow seems to have been changed as well.

The distribution and areal extent of paleoground-water discharge deposits in Southern Nevada/adjacent California basins appear to be consonant with the paleolake effective moisture data from the rest of the Great Basin *if* the highest terranes in the subregion were very efficient in allowing markedly increased net recharge, and the configurations of interbasin flow of the carbonate-rock flow systems within the region were modified by the markedly increased fluxes through the flow systems. This is a preliminary interpretation, and in some basins these paleodischarge deposits extend over very large areas when compared to the modern discharge areas. Paleodischarge deposits are difficult to accurately map, date, and interpret because several pluvial cycles are represented (important differences in age) and the varied aged deposits all "look" very similar. In most basins they occurred in more or less the same localities throughout much of the Quaternary, but the older deposits are often not well exposed. In order to establish a quantitative measure of *effective moisture* represented by deposits of equal age, the total area, the hydrologic character of the deposits (marsh, wet meadow, spring, etc.) and a mean annual temperature must be established. In addition, due to the interbasin nature of the involved ground-water flow systems, a *regional* analysis may be required to correctly compare modern discharge with plenipluvial discharge. Investigations on the paleodischarge deposits have been in progress since the early 1980's (work by Quade and others).

The Mifflin and Wheat (1979) studies were accomplished in the 1960's to the mid-1970's, well before the advent of the Yucca Mountain repository program. The reconstructed plenipluvial climates seem to be remarkably well supported by the latest pluvial cycle packrat midden evidence. The central issue, however, is not the details of plenipluvial climate (precipitation and temperature); it is the amount of increase in effective moisture that would change the hydrology of the vadose zone at Yucca Mountain. The current best estimate, about an order of magnitude increase in infiltration at the site, would ensure that most of the increase would percolate by fracture flow, and extensive zones of perched water would be likely. Suggestive site specific features that supports this interpretation are the abundant calcite fracture fillings and zones of glass alteration *above* both the modern and interpreted plenipluvial water tables.