Precipitation Estimation in Mountainous Terrain Using Multivariate Geostatistics. Part II: Isohyetal Maps

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ABSTRACT

Values of average annual precipitation (AAP) may be important for hydrologic characterization of a potential high-level nuclear-waste repository site at Yucca Mountain, Nevada. Reliable measurements of AAP are sparse in the vicinity of Yucca Mountain, and estimates of AAP were needed for an isohyetal mapping over a 2600-square-mile watershed containing Yucca Mountain. Estimates were obtained with a multivariate geostatistical model developed using AAP and elevation data from a network of 42 precipitation stations in southern Nevada and southeastern California. An additional 1531 elevations were obtained to improve estimation accuracy. Isohyets representing estimates obtained using univariate geostatistics (kriging) defined a smooth and continuous surface. Isohyets representing estimates obtained using multivariate geostatistics (cokriging) defined an irregular surface that more accurately represented expected local orographic influences on AAP. Cokriging results included a maximum estimate within the study area of 335 mm at an elevation of 7400 ft, an average estimate of 157 mm for the study area, and an average estimate of 172 mm at eight locations in the vicinity of the potential repository site. Kriging estimates tended to be lower in comparison because the increased AAP expected for remote mountainous topography was not adequately represented by the available sample. Regression results between cokriging estimates and elevation were similar to regression results between measured AAP and elevation. The position of the cokriging 250-mm isohyet relative to the boundaries of pinyon pine and juniper woodlands provided indirect evidence of improved estimation accuracy because the cokriging result agreed well with investigations by others concerning the relationship between elevation, vegetation, and climate in the Great Basin. Calculated estimation variances were also mapped and compared to evaluate improvements in estimation accuracy. Cokriging estimation variances were reduced by an average of 54% relative to kriging variances within the study area. Cokriging reduced estimation variances at the potential repository site by 55% relative to kriging. The usefulness of an existing network of stations for measuring AAP within the study area was evaluated using cokriging variances, and twenty additional stations were located for the purpose of improving the accuracy of future isohyetal mappings. Using the expanded network of stations, the maximum cokriging estimation variance within the study area was reduced by 78% relative to the existing network, and the average estimation variance was reduced by 52%.

1. Introduction

Yucca Mountain, Nevada, is a potential location for a high-level nuclear-waste repository. The conceptual perimeter-drift boundary for the potential repository site is an area of approximately 2 square miles beneath the southern extent of Yucca Mountain. The location was selected for a potential repository site partly because of a sparsity of precipitation. Values of average annual precipitation (AAP) are desired for hydrologic studies concerning site characterization, such as water-budget analyses, groundwater-flow modeling, and the characterization of current climatic conditions. Unfortunately, reliable measurements of AAP are sparse in the vicinity of Yucca Mountain. Estimates of AAP can be calculated using more reliable measurements from surrounding precipitation stations in southern Nevada and southeastern California. Previous estimates of AAP at Yucca Mountain have ranged from 100 to 150 mm yr^{-1} (Winograd and Thordarson 1975; Quiring 1983). Montazer and Wilson (1984) used an estimate of 150 mm AAP to help estimate net infiltration at Yucca Mountain. An estimate of recharge, based

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on an AAP value of 150 mm, was calculated by Czarnecki (1985) in a model of groundwater flow of Yucca Mountain and vicinity.

This article presents the first application of multivariate geostatistical methods to the problem of estimating AAP at Yucca Mountain and the surrounding Upper Amargosa River Watershed (UARW), an area of approximately 2600 square miles centered on the potential repository site (Fig. 1). Yucca Mountain is located in the northern Amargosa Desert of southern Nevada, along the transitional boundary of the Great Basin Desert to the north and the Mojave Desert to the south. The UARW is within the southern basin and range physiographic province and includes most areas considered important for a hydrologic characterization of the potential repository site. Elevations for the mountainous terrain within the watershed range from a minimum of 2000 to a maximum of 7694 ft. A more complete description of the physiography and climate of the UARW are in Hevesi et al. (1992).

Orographic effects caused by mountainous terrain can result in a significant positive correlation between AAP and station elevation. Dingman et al. (1988) used an "elevation scale factor" to remove an observed orographic influence of elevation on AAP in Vermont and New Hampshire. Quiring (1983) and French (1986) fit regression equations between AAP and station elevation for precipitation stations in southern Nevada and southeastern California. Hevesi et al. (1992) used data from 42 precipitation stations in southern Nevada and southeastern California to compute a correlation coefficient r of .75 between the natural log of AAP and station elevation.

In this article, variogram models defined by Hevesi et al. (1992) were used to prepare two isohyetal maps of AAP for the UARW. The first map was prepared using estimates calculated with AAP data (kriging). The second map was prepared using estimates calculated with both AAP and elevation data (cokriging). The usefulness of the maps for characterizing AAP within the UARW was evaluated. The effectiveness of applying a multivariate geostatistical model, using a large sample of elevations to obtain improved estimates of AAP, was evaluated by mapping the differences in cokriging and kriging estimates and by mapping the reductions in estimation variances of cokriging relative to kriging.

The AAP–elevation correlation represented by the geostatistical model was validated using regression between estimated values of AAP and known elevations. The regression results for the estimates were compared with regression results between measured values of AAP and elevation. An independent validation of the results was made by comparing the location of the estimated 250-mm isohyet with the location of boundaries defining the occurrence of pinyon pine and juniper woodlands within the UARW.

Cokriging estimation variances were calculated for the active precipitation network to determine the effectiveness of this network for future isohyetal mappings of AAP within the UARW. To analyze the potential effectiveness of an expanded network of precip-

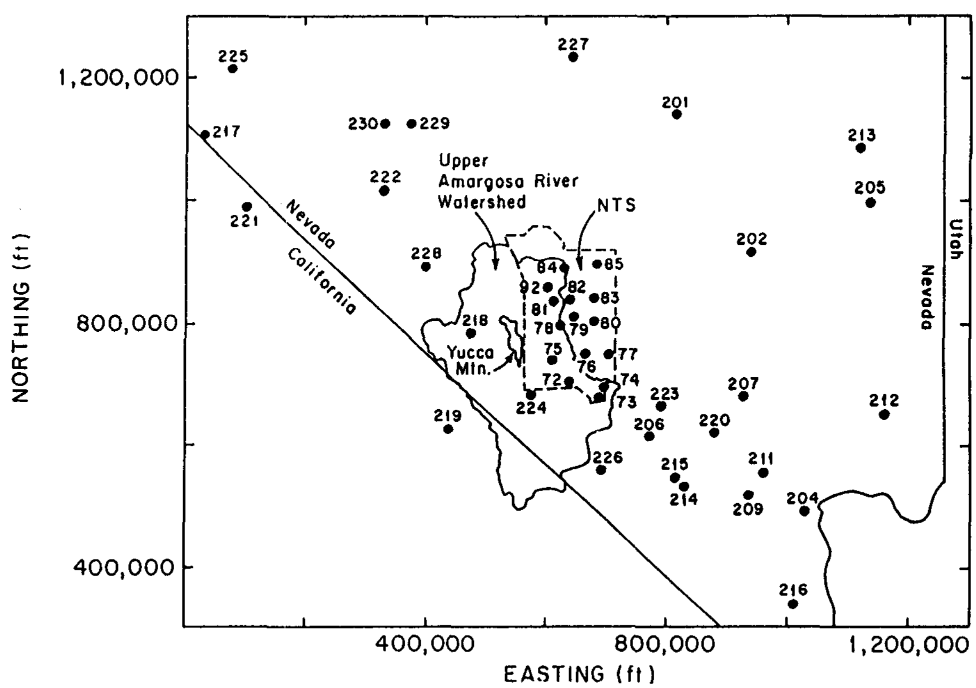

FIG. 1. Location of study area and precipitation stations from Hevesi et al. (1992).

itation stations, locations for 20 additional stations were selected by computing cokriging estimation variances for the existing network and identifying the locations of maximum estimation variances within the UARW.

2. Methodology

a. Precipitation and elevation data

Measured values of AAP from 42 precipitation stations in the southern Nevada and southeastern California region were obtained for estimating AAP (Fig. 1). The lengths of record for these stations ranged from 8 to 53 years (Table 3, Hevesi et al. 1992). The use of measurements from stations with relatively short lengths of record was necessary to obtain a sample large enough for a geostatistical analysis. The nearest station to the potential repository site (station 75, AAP = 119 mm) was located approximately 10 miles east-southeast and the farthest station (station 225, AAP = 115 mm) was located approximately 140 miles west-northwest. The sample did not include stations located on Yucca Mountain because the length of record for these stations was less than 8 years at the time of this study. Ten of the 42 selected stations were within the boundaries of the UARW (Fig. 1). Station elevations were combined with 1531 elevations recorded from topographic maps using a square grid with a spacing of 10 000 ft. This density was considered sufficient for preparing isohyetal maps of AAP for the UARW. Elevations for the grid locations ranged from −250 to 8400 ft. The grid was centered on the UARW and included a total of 747 locations within the UARW (Fig. 2, Hevesi et al. 1992).

b. Estimating average annual precipitation (AAP)

Estimates and estimation variances were calculated using ordinary kriging and cokriging (Journel and Huijbregts 1978). The variogram models selected by Hevesi et al. (1992) were defined in terms of a transformed variable, TAAP, where TAAP = ln(AAP)1000, because the 42 AAP measurements approximated a lognormal distribution, and the linear geostatistical methods used in this study required the data to be normally distributed (Journel and Huijbregts 1978). To provide minimum cokriging estimation variances, the variogram models were used to calculate estimates and estimation variances for TAAP at the same 1531 grid locations used to obtain the elevation sample. The method of sliding neighborhoods was used to calculate each estimate within a circular search neighborhood because the variogram models were defined using the assumption of quasi stationarity (Journel and Huijbregts 1978). Separate radii for the two search neighborhoods for TAAP and elevation were needed because of the inconsistent spatial distributions between the TAAP and elevation samples. Estimates were also calculated for ten precipitation stations located within the UARW that were operational at the time of this study but were not included in the sample of measured AAP because of lengths of record less than 8 years (Table 1). Eight of these stations were located on Yucca Mountain in the vicinity of the potential repository site.

To compute estimates and estimation variances for AAP, inverse transformations were made using the following equations (Cooper and Istok 1988):

$$\mathrm{AAP}^*(x_0) = K_0 \exp[\mathrm{TAAP}^*(x_0)/1000 + \sigma_k^2(x_0)/1\,000\,000], \quad (1)$$

$$\sigma_{\mathrm{AAP}}^2(x_0) = m^2\langle \exp(\sigma^2)\{1 - \exp[\sigma_k^2(x_0)/1\,000\,000]\}\rangle, \quad (2)$$

$$K_0 = \left[\frac{\frac{1}{m}\sum_{i=1}^{n} \mathrm{TAAP}^*(x_0)}{1000}\right], \quad (3)$$

where $\mathrm{AAP}^*(x_0)$ is the estimate for AAP at the point x_0, $\mathrm{TAAP}^*(x_0)$ and σ_k^2 are the estimate and estimation variance for TAAP obtained using kriging or cokriging, n is the sample size, m is the sample mean for AAP, σ_{AAP}^2 is the estimation variance for AAP, and σ^2 is the sample variance for TAAP. The parameter K_0 is used to correct for bias in the inverse transformation.

c. Evaluation of isohyetal mappings

The transformed kriging and cokriging estimates were mapped using isolines to represent the values calculated at the 1531 grid locations (isohyets are isolines of AAP). The general characteristics of the kriging and cokriging isohyetal mappings were visually compared to evaluate the influence of the elevation sample on estimates of AAP. The values and locations of maximum and minimum estimates within the UARW and the values of estimates at the eight precipitation stations in the vicinity of the potential repository site were identified. Global (area-averaged) estimates for AAP were obtained by computing the arithmetic average of AAP estimates for points within the UARW (Istok and Cooper 1988). A direct comparison of the two isohyetal mappings was made by mapping the difference between cokriging and kriging estimates. An evaluation of estimation accuracy was made by a visual inspection of the mapped estimation variances, and a comparison of relative estimation accuracy was made by mapping the percent reduction in cokriging variances relative to the kriging variances.

d. Validating kriging and cokriging estimates

Estimates were calculated for the same 1531 grid locations used to obtain the elevation sample, and this configuration permitted a regression analysis between estimated AAP and measured elevation. Regression results obtained between estimated AAP and elevation were compared with results obtained between mea-

TABLE 1. Active precipitation stations in southern Nevada and southeastern California.

Station name	Nevada central state plane coordinates: Easting coordinates (ft)	Northing coordinates (ft)	Station elevation (ft)	Years of record	Measured average annual precipitation (mm)
Regional stations					
Boulder City	1 029 489	490 470	2525	50	139
Caliente	1 133 802	995 954	4407	51	231
Las Vegas Airport	936 479	519 841	2162	33	104
Pioche	1 119 116	1 084 068	6120	44	313
Red Rock Summit	828 783	534 527	6500	8	270
Searchlight	1 009 908	338 717	3540	50	185
Beatty	472 943	785 458	3550	47	159*
Death Valley	437 164	627 537	−168	18	69
Desert Game Range	887 736	622 641	2920	42	106
Dyer	100 904	991 059	4975	31	125
Goldfield	330 981	1 015 535	5690	39	136
Mina	76 428	1 216 240	4551	53	115
Pahrump	691 717	559 004	2700	20	125
Rattlesnake	644 277	1 235 821	5912	20	163
Nevada test site stations					
Rock Valley	639 050	704 700	3400	8	157*
Desert Rock A.P.	688 100	681 750	3298	15	157*
Mercury	696 738	695 045	3770	13	159*
4JA	610 605	740 840	3422	16	119*
Cane Spring	663 600	751 000	4000	21	208
Well 5B	705 200	747 600	3080	19	128
Mid Valley	644 500	809 250	4660	13	226
Yucca	680 875	837 100	3920	25	176
40 MN	610 600	837 100	4820	18	202*
Tippipah Spring	638 650	838 600	4980	20	245
BJY	679 100	842 300	4072	22	176
Area 12 Mesa	631 400	888 900	7490	17	295*
PHS Farm	682 870	895 840	4565	8	192
Little Feller 2	602 000	858 520	5160	8	229
Pahute Mesa No. 1	566 700	909 700	6550	4	212*
Jackass Flat	610 564	743 968	3492	0	*
Yucca Mountain stations					
UZ-1	560 148	771 482	4432	4	203*
UZ-6	558 356	760 134	4915	2	176*
SAIC-60	569 155	761 832	3750	0	*
Prow	554 986	782 850	5870	0	*
RF-1	567 934	759 011	3815	0	*
Fran Ridge	573 575	754 015	4062	0	*
USW G-3	560 265	751 136	4765	0	*
Alice Point	577 000	770 000	4047	0	*

* Precipitation stations located within Upper Amargosa River Watershed (UARW) boundary.

sured AAP and elevation (Hevesi et al. 1992). The comparison was used to evaluate the geostatistical model's performance in terms of preserving the AAP–elevation correlation observed in the southern Nevada region and also to compare estimates obtained using the geostatistical model with estimates obtained using only elevation data and fitted regression equations.

For the purpose of obtaining an independent validation, the location of the estimated 250-mm isohyet was compared with the boundaries of sparse to moderately vegetated pinyon pine and juniper woodlands identified on topographic maps, areal photographs, and in the field. The occurrence of these woodlands in the UARW and vicinity was observed to be correlated with high elevations of approximately 6000 ft and above that receive relatively high precipitation and have low air temperatures. The boundaries did not include low-elevation woodlands resulting from the occurrence of springs or a shallow water table.

The selection of the 250-mm isohyet was based partly on observations by Houghton et al. (1975) concerning the relation between elevation, climate, and the distribution of plant communities in the Great Basin. Their results indicated a correlation between an elevation of 5900 ft, an AAP value of 250 mm, and the approximate lower limit for the occurrence of pinyon pine and juniper woodlands, defining the boundary between a moist-steppe and a dry-steppe climate in the Great Basin. The selection of the 250-mm isohyet was also based on the observation that, from the sample of 42 precipitation stations used in this study, all six measurements of AAP greater than 250 mm were at elevations greater than 6000 ft (Fig. 4, Hevesi et al. 1992) and were located within or directly adjacent to woodland boundaries. Unpublished investigations on the relations between elevation, AAP, and plant communities in the southern Nevada region substantiated 250 mm as a reasonable value to be correlated with the occurrence of pinyon pine and juniper woodlands (J. Emerick, personal communication, 1990).

e. *Using estimation variances to evaluate the 1990 network*

The 42 precipitation stations used to develop geostatistical models and isohyetal maps of AAP included 28 stations that were still operational in 1990 and actively collecting data at the time of this study. An additional 10 stations within the UARW that were not used for model development and estimation because of lengths of record less than 8 years were also active at the time of this study. Eight of the 10 stations were located on Yucca Mountain. A summary of the data for the total network of 38 active stations is in Table 1.

Assuming that sufficient lengths of record would be available in the future for obtaining reliable measurements of AAP at the 38 locations, the effectiveness of the network for characterizing AAP within the UARW was evaluated by mapping the cokriging estimation variances. Cokriging was applied using the 38 known locations and arbitrary, or fictitious, values of AAP. The selected values for AAP were arbitrary because only the variogram models and data locations were needed to calculate estimation variances (Journel and Huijbregts 1978). In this study the selected values consisted of the 28 measured values and 10 fictitious values of AAP for the stations with lengths of record less than 8 years (Table 1).

f. *Identifying locations for additional precipitation stations*

An investigation of potential improvements in characterizing AAP for the UARW by expanding the existing network was made using cokriging estimation variances. Beginning with the results obtained for the existing network of 38 active stations, the location for an additional precipitation station was selected by identifying the grid location with the maximum cokriging estimation variance within the UARW. The coordinates of that location were then added to the available data, and the procedure of calculating estimation variances was repeated to identify the location for the next station. The value of AAP used for each additional station was arbitrary because only the estimation variances were considered in this procedure. Locations for a total of 20 additional, or fictitious, precipitation stations were identified, and the reductions in maximum and average estimation variance for the UARW obtained using the expanded network of 38 active and 20 fictitious stations were analyzed.

3. Results and discussion

a. *Evaluation of isohyetal mappings*

The kriged isohyets defined a smooth surface that indicated a gradual increase in AAP from the southwest to northeast across the UARW (Fig. 2a). Orographic effects were indicated only as a general trend of increasing AAP toward the northeastern edge of the watershed. Kriging estimates exceeding 250 mm were obtained for one area in the northeast section of the UARW and included 1.9% of the total area within the watershed (Table 2). Estimates of less than 100 mm included 11.4% of the watershed area and occurred in the Amargosa Desert and the Funeral Mountains. A maximum estimate of 287 mm was calculated for an elevation of 7500 ft on Pahute Mesa, close to the northeastern edge of the watershed boundary, and a minimum estimate of 86 mm was obtained at an elevation of 5000 ft in the Funeral Mountains (Table 2). A global estimate of 142 mm was calculated for the total area of the UARW. Kriged estimates at the locations of the eight precipitation stations on Yucca Mountain ranged from 160 to 130 mm (Table 3). An average estimate of 143-mm AAP was obtained for these eight stations located in the close vicinity of the potential repository site.

The cokriging isohyets defined an irregular surface that was similar to the known topography, indicating a strong influence of the elevation data on the calculated estimates (Fig. 3a). Estimates exceeding 250 mm were calculated for 5.2% of the UARW (Table 2) and included several areas within the watershed: the Grapevine Mountains, the Spring Mountains, Timber Mountain, Shoshone Mountain, and the northern part of Yucca Mountain. Estimates less than 100 mm were obtained for locations in the southern Amargosa Desert and included 9.2% of the watershed area. A maximum estimate of 335 mm was obtained at an elevation of 7400 ft on Pahute Mesa, and a minimum estimate of 79 mm was obtained at an elevation of 2200 ft for a location in the southern Amargosa Desert (Fig. 3a, Table 2). The global estimate calculated for the UARW was 157 mm, 12 mm greater than the kriging global

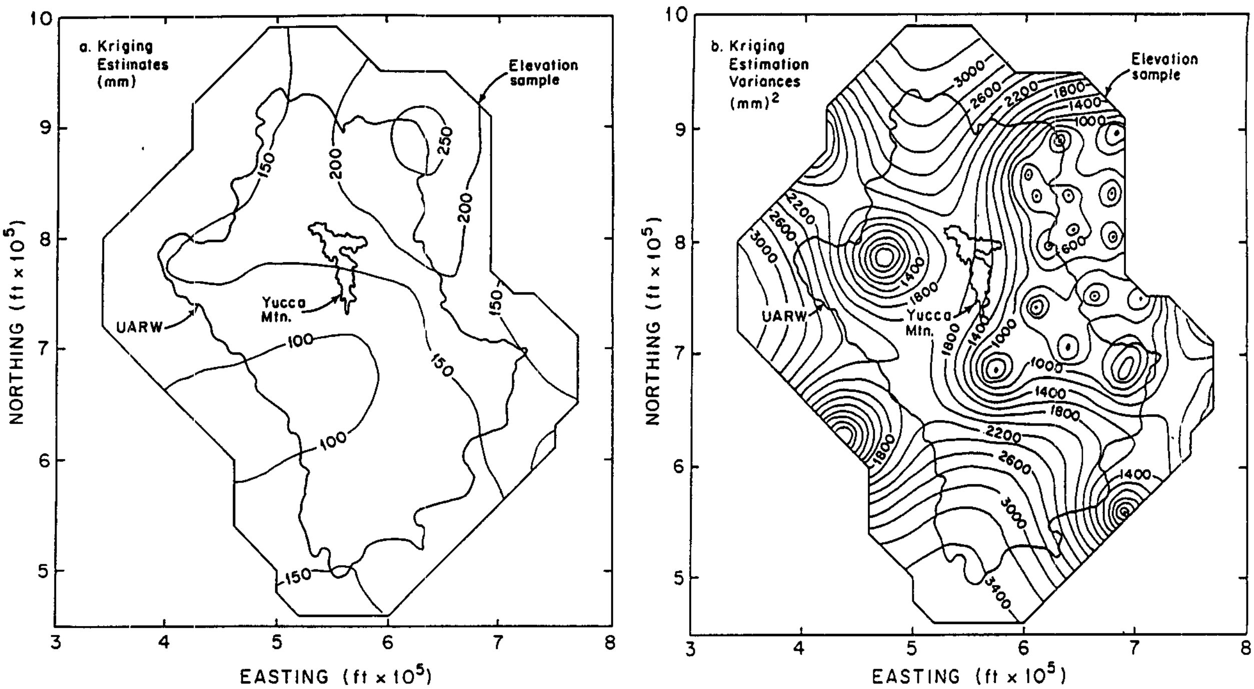

FIG. 2. (a) Isohyetal map of kriging estimates of AAP for the UARW and (b) map of kriging estimation variances for the UARW.

estimate. Cokriging estimates for the eight stations on Yucca Mountain ranged from 145 mm at an elevation of 3750 ft to 247 mm at an elevation of 5870 ft (Table 3), representing a maximum gradient of 48-mm AAP per 1000-ft elevation in the vicinity of the potential repository site. An average cokriging estimate of 172 mm was obtained for these eight stations, a 29-mm increase relative to the average kriging estimate. The maximum cokriging estimate of 247 mm was 87 mm greater than the maximum kriging estimate at Yucca Mountain. In general, significant orographic effects in the vicinity of the potential repository site were indicated by the cokriging estimates, but not by the kriging estimates, because increased AAP at the higher eleva-

TABLE 2. Summary of results for estimated AAP within the UARW.

		Estimates of AAP for 747 grid locations within UARW			
Statistic for UARW	Measured AAP from ten stations within UARW (mm)	Cokriging estimates (mm)	Kriging estimates (mm)	Cokriging estimation variances (mm^2)	Kriging estimation variances (mm^2)
Average	179	157	145	836	1808
Maximum	295	335	287	2490	3460
Minimum	85	79	86	290	256
Variance	3280	2488	1519	87 280	582 058

	Percent area of UARW within range of estimated AAP	
Range of estimated AAP within UARW (mm)	Cokriging (%)	Kriging (%)
>300	0.9	0.0
300–250	4.3	1.9
250–200	14.1	8.8
200–150	29.0	30.9
150–100	42.4	49.4
<100	9.2	11.4

TABLE 3. Estimates of AAP at ten precipitation stations within the UARW. Location coordinates for the stations are listed in Table 1.

Precipitation station name	Station elevation (ft)	Cokriged AAP (mm)	Kriged AAP (mm)	Cokriged estimation variance (mm^2)	Kriged estimation variance (mm^2)
Pahute Mesa No. 1	6550	270	214	1060	2250
Jackass Flat	3492	131	133	375	441
Prow	5870	247	160	764	1790*
UZ-6	4915	184	139	752	1710*
USW G-3	4765	165	130	783	1650*
UZ-1	4432	171	150	757	1720*
Fran Ridge	4062	151	135	698	1450*
Alice Point	4047	158	151	698	1470*
RF-1	3815	149	138	723	1580*
SAIC-60	3750	145	141	721	1570*
Average for eight stations located on Yucca Mountain	4457	172	143	737	1617

* Precipitation stations located on Yucca Mountain, in the vicinity of the potential repository site.

tions on Yucca Mountain were not adequately represented by the available sample of 42 AAP measurements.

Contours of the quantity "cokriging AAP estimate–kriging AAP estimate" conformed to contours of elevation; large positive values (cokriging estimates exceeding kriging estimates) occurred along the crests of mountain ranges, whereas negative values occurred in the basins and valleys (Fig. 4). The largest values occurred in areas of high local relief and in areas farthest from the precipitation stations. Within the UARW, cokriging estimates were 100 mm greater than kriging estimates at the Grapevine Mountains, the Funeral Mountains, the Spring Mountains, and Timber Mountain because of a lack of AAP measurements at the higher elevations of these remote and mountainous locations. Cokriging estimates were 20 mm smaller than the kriging estimates at Yucca Flat, Sarcobatus Flat, and in the southern section of the Amargora Desert. Cokriging estimates for elevation grid locations at Yucca Mountain were 20 to 80 mm greater than kriging estimates, depending on elevation.

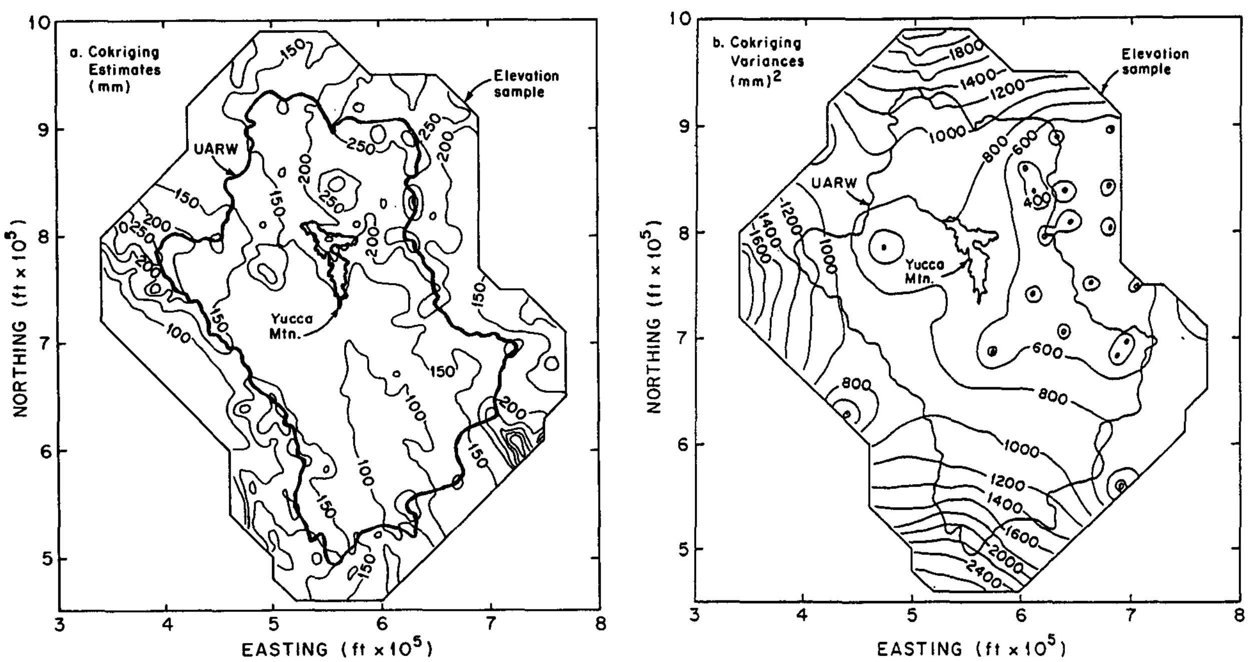

FIG. 3. (a) Isohyetal map of cokriging estimates of AAP for the UARW and (b) map of cokriging estimation variances for the UARW.

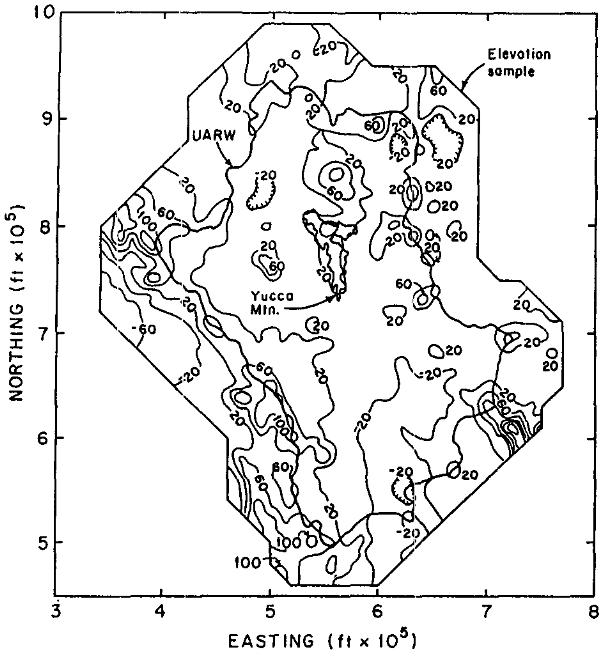

FIG. 4. Cokriging-minus-kriging estimates of AAP for the UARW.

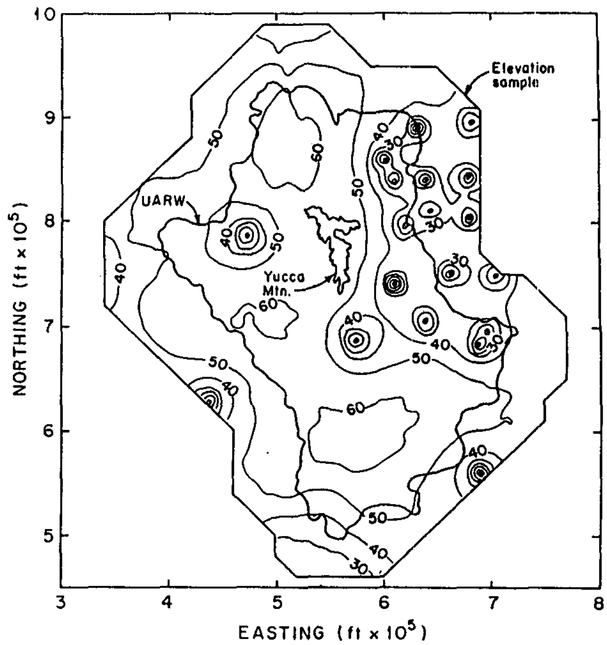

FIG. 5. Percent reduction in cokriging estimation variances relative to kriging estimation variances for the UARW.

b. Comparison of kriging and cokriging estimation variances

Kriging and cokriging estimation variances indicated similar trends in estimation accuracy throughout the UARW; small values near the cluster of stations on the Nevada test site (NTS, Fig. 1) indicated relatively high estimation accuracy, and large values at the southern, western, and northern boundaries of the watershed indicted areas of relatively low estimation accuracy (Figs. 2b, 3b). The locations of maximum and minimum estimation variances were similar for kriging and cokriging because the elevation data were located on a regular grid with a uniform spatial distribution throughout the UARW. The shape of the surface (not the magnitude) defined by kriging and cokriging estimation variances was determined primarily by the spatial distribution of the precipitation stations.

Estimation variances were reduced by 30% for cokriging relative to kriging over approximately 90% of the UARW (Fig. 5). The largest reduction of 65% resulted for a location south of Quartz Mountain, in the northwestern section of the UARW. Reductions of more than 60% were indicated for the Amargosa Desert in the south-central and western sections of the UARW, and reductions of 55% resulted at the potential repository site. In general, reductions in estimation variances of as much as 50% were indicated at distances of approximately 30 000 ft (6 miles) from precipitation stations. Reductions decreased for areas outside the boundaries of the UARW as a result of edge effects caused by the boundary of the elevation sample. Edge effects were most pronounced at the southern extent of the UARW, where the search neighborhood radius of 120 000 ft for elevation did not include any precipitation stations.

c. Validation of cokriging and kriging estimates

The scatterplot of the kriging estimates indicated a lack of correlation with elevation in the range of −250 to 3000 ft (Fig. 6). A correlation between kriging estimates and elevation was indicated for elevations above 3000 ft, along with an increase in the variability of estimates. A regression equation was fit to the data:

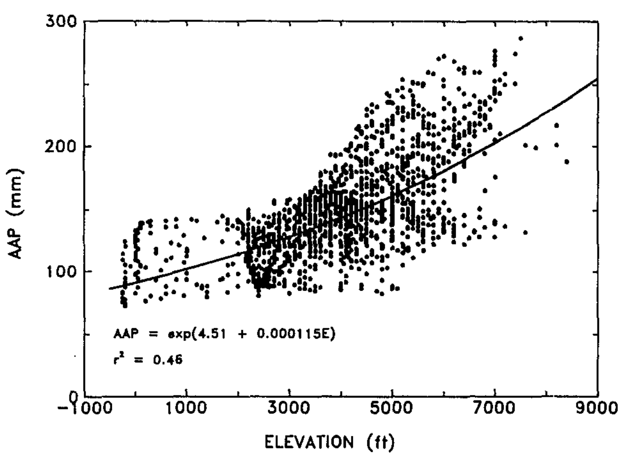

FIG. 6. Scatterplot of kriging estimates and 1531 grid elevations.

$$\mathrm{AAP}^* = \exp(4.51 + 0.000115), \quad r^2 = .46, \quad (4)$$

where AAP* is the kriging estimate for AAP (mm) at a grid location, and E is elevation (ft) of the grid location. Equation (4) indicated a smaller orographic influence [i.e., the regression parameter multiplying E in Eq. (4) is smaller] for AAP than that defined by precipitation stations in the southern Nevada and southeastern California region [Eq. (13), Hevesi et al. 1992].

The scatterplot of the cokriging estimates indicated a stronger log-linear correlation between AAP and elevation than the correlation indicated by the kriged estimates (Fig. 7). A maximum cokriging estimate of 442 mm was obtained for the maximum elevation of 8400 ft in the northern Spring Mountains, which was 155 mm greater than the maximum kriging estimate of 287 mm for an elevation of 7500 ft, and 88 mm greater than the maximum measured value of AAP for an elevation of 6100 ft in the Spring Mountains (station 215, Table 3, Hevesi et al. 1992). A regression equation was fit to the cokriging estimates and elevations:

$$\mathrm{AAP}^* = \exp(4.26 + 0.000197E), \quad r^2 = .79. \quad (5)$$

For the range of elevations representative of Yucca Mountain (3000–6000 ft), Eq. (5) defines a gradient of +31 mm AAP (1000 ft)$^{-1}$, which was the same as the observed gradient defined by the 42 precipitation stations used to develop the multivariate model (Hevesi et al. 1992). Using Eq. (5), cokriging estimates of AAP are predicted to vary 28 mm within the area of the potential repository site because the range of elevations overlying the area of the site is approximately 900 ft.

A comparison of the regression equations defined by Eqs. (4) and (5) with regression equations presented in Hevesi et al. (1992) using measured values of AAP indicated that the cokriged estimates preserved the expected relation between AAP and elevation, while the kriged estimates did not. This provided good evidence of model validation, indicating that the cross-variogram model, which was difficult to define (Hevesi et al. 1992), represented a reasonable correlation between AAP and elevation.

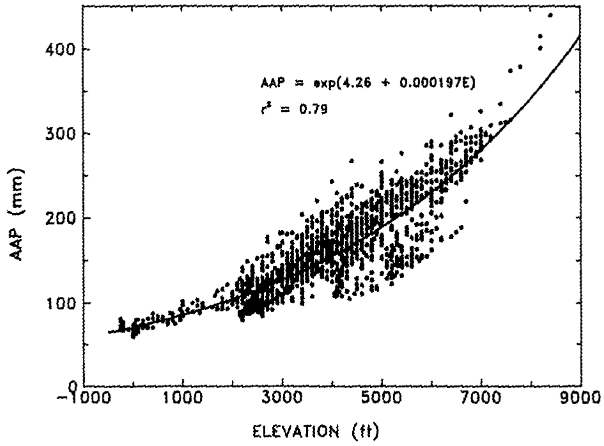

FIG. 7. Scatterplot of cokriging estimates and 1531 grid elevations.

The relation defined by Houghton et al. (1975) between climate, elevation, and vegetation indicated a stronger orographic influence on AAP in the Great Basin than did the correlation indicated by the regression curve obtained using cokriging estimates and curves obtained using measured values of AAP. The stronger correlation is partly due to lower average air temperatures in the northern Great Basin (which includes northern and central Nevada) relative to the southern Nevada and southeastern California regions. However, the lower limit for the moist-steppe climatic zone (pinyon–juniper woodland), corresponding to an AAP value of 250 mm and an elevation of 5900 ft, and the lower limit of the dry-steppe climatic zone, corresponding to an AAP value of 200 mm and an elevation of 4600 ft, indicated a relatively close fit to the regression equation defined by French (1986) for the 12 NTS stations and a reasonable fit to the regression equation defined by the cokriging estimates.

d. *Validation of cokriging and kriging isohyetal mappings*

The location of the cokriging 250-mm AAP isohyet coincided closely with the location of pinyon pine and juniper woodland boundaries for most areas, whereas the location of the kriging 250-mm isohyet did not (Fig. 8). A close match of the cokriging results with the woodland boundary was obtained for Pahute Mesa, Shoshone Mountain, Timber Mountain, Yucca Mountain, the Grapevine Mountains, and the Spring Mountains, and this indicated good estimation accuracy for these locations. The absence of the kriging 250-mm isohyet in the Grapevine and Spring mountains indicated that the expected orographic influence for these remote, mountainous locations was not adequately represented by the available sample of AAP measurements.

The 250-mm cokriging isohyet did not coincide with woodland boundaries at all locations. Cokriging estimates exceeding 250 mm occurred at elevations above 6000 ft in the Black Mountains (outside of the UARW) where pinyon pine and juniper woodlands were not observed. The cokriging estimates at these locations may have been erroneously high because of a rain-shadow effect from Telescope Peak and because there were no precipitation stations within the elevation search radius for grid locations in this area. The 250-mm cokriging isohyet did not coincide with the woodland boundary observed on the summit of Quartz Mountain, along the northwest edge of the UARW. Although the cokriging estimate of 180 mm was 40 mm greater than the kriging estimate for Quartz Mountain, a relatively low estimate of AAP was cal-

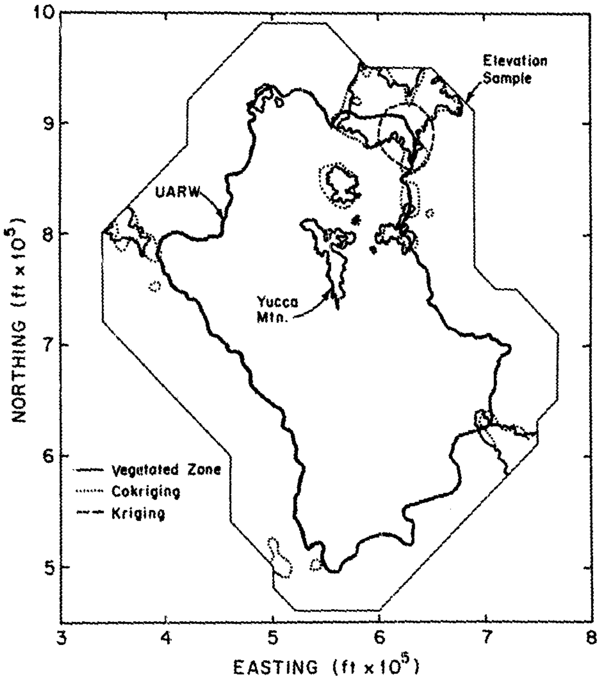

FIG. 8. Comparison of the location of woodland boundaries within the UARW and the 250-mm isohyet obtained by kriging and cokriging.

culated for this location because the measured value of 90-mm AAP at the nearest precipitation station (station 228, Hevesi et al. 1992), located within the deficit zone defined by French (1983), was also relatively low for the station elevation of 4020 ft.

e. *Usefulness of 1990 active stations for isohyetal mapping*

Cokriging variances calculated for the active network of precipitation stations indicated significant improvements in the potential accuracy of estimating AAP at Yucca Mountain and in the vicinity of the potential repository site, but many locations within the UARW indicated an increase in cokriging variances relative to the historical network because several precipitation stations were no longer active at the time of this study (Fig. 9). A maximum estimation variance of 2600 mm^2 within the UARW occurred at the southern extent of the watershed boundary, indicating an 18% increase relative to estimation variances obtained using the historical precipitation station network. High estimation variances exceeding 1600 mm^2 within the UARW were also obtained along the western and northwestern edges of the watershed boundary, resulting in as much as a 33% increase in estimation variances relative to the historical network. In general, estimation variances were less than 1000 mm^2 for 50% of the UARW, with minimum values located at Yucca Mountain and along the northeastern section of the watershed boundary. Cokriging estimation variances in the vicinity of the potential repository site were less than 400 mm^2.

f. *Usefulness of additional fictitious stations*

Twenty locations for additional precipitation stations were identified within the UARW using maximum cokriging variances: the locations were numbered to indicate the sequence in which each separate location was added to the total network (Fig. 10). The first and second identified locations occurred within the Amargosa Desert in the southern extent of the UARW, indicating this to be the most important area for locating additional precipitation stations. The Funeral Mountains, the Grapevine Mountains, Sarcobatus Flat, Quartz Mountain, and the northern extent of the Spring Mountains were also indicated as important locations for additional precipitation stations. Estimation variances obtained using the expanded network of 58 stations indicated large potential reductions in estimation variances for the northwestern, western, and southwestern sections of the UARW. In general, estimation variances were more uniform throughout the UARW relative to estimation variances obtained using the 1990 active network; variances within the UARW were less than 700 mm^2 at all locations and were less than 500 mm^2 for approximately 40% of the UARW. Maximum reductions were obtained along the southern and western sections of the watershed boundary; 12 of the 20 identified locations were on the boundary. No reduction in estimation variances occurred in the vi-

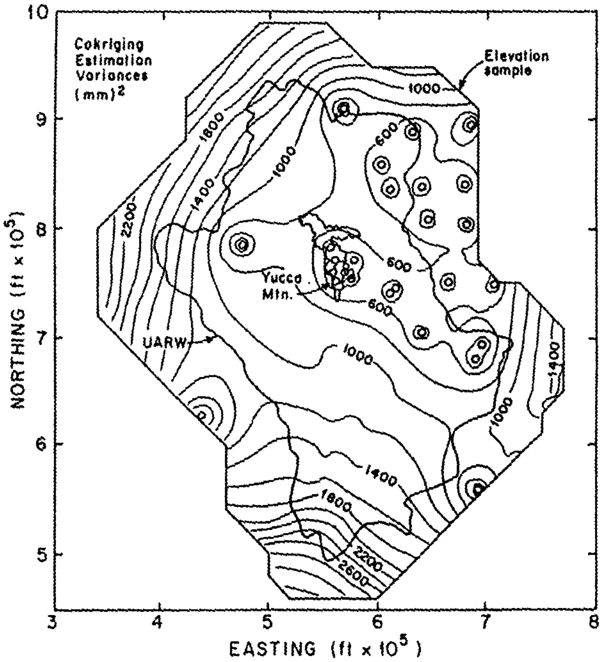

FIG. 9. Cokriging estimation variances for the UARW obtained using the 1990 active precipitation station network.

cinity of the potential repository site and throughout the entire northeast portion of the UARW because of the relatively dense cluster of active stations within the NTS and on Yucca Mountain.

The configuration of the 20 additional locations was not considered to be optimum because the locations were not identified simultaneously. For the procedure used in this study, each additional location remained fixed after it was identified, and this affected all successive locations. A procedure to simultaneously identify 20 locations from 747 potential locations was difficult because the computational time required for the large number of possible combinations was prohibitive. Alternatively, identifying locations for additional stations based on a procedure to minimize the average estimation variance within the UARW may have been more appropriate for defining optimum locations. If the average estimation variance had been minimized, identified locations would have occurred farther inside the watershed (not on the watershed boundary) because the area of influence for each additional station would be considered. The resulting configuration probably would have been more efficient because a smaller number of additional stations would provide the same level of estimation accuracy. Unfortunately, the procedure to minimize the average estimation variance also required a prohibitively long computation time. A continuing effort is being made to develop a more efficient procedure to simultaneously identify optimum locations for as many as 20 additional stations using the average cokriging variance.

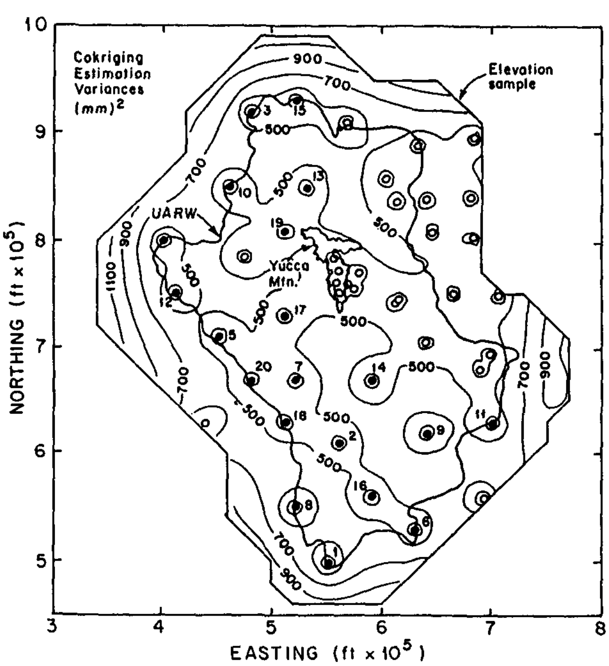

FIG. 10. Cokriging estimation variances for the UARW obtained using the 1990 active precipitation station network and 20 additional fictitious precipitation stations.

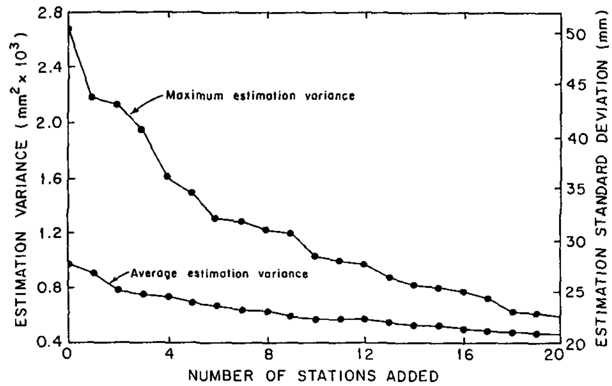

FIG. 11. Reduction in the average and maximum cokriging estimation variance for AAP within the UARW with the addition of 20 fictitious stations to the 1990 active precipitation station network.

A plot of the observed maximum and average cokriging variance was used to investigate the relative importance of each successive fictitious station in reducing estimation variances (Fig. 11). As expected, the maximum variance decreases much more rapidly than the average variance, and the addition of the first three to four stations provides the largest reductions. Using the additional 20 fictitious stations, the average estimation variance within the UARW was reduced by 52% from 974 to 464 mm^2, and the maximum estimation variance was reduced by 78% from 2690 to 597 mm^2.

4. Summary and conclusions

Kriging and cokriging were used to estimate AAP at Yucca Mountain, the potential site for a high-level nuclear-waste repository, and a surrounding 2600-square-mile watershed, referred to as UARW. The cokriging estimation procedure used the observed positive correlation between AAP and elevation, precipitation data for 42 stations in the southern Nevada and southeastern California region surrounding the site, and elevation data for 64 stations and 1531 grid locations within and adjacent to the UARW. Isohyets defined using cokriging estimates conformed closely to elevation contours and displayed the expected orographic effect of mountainous terrain within the UARW. Cokriging estimates obtained within the UARW included a maximum estimate of 335 mm for an elevation of 7400 ft on Pahute Mesa, a minimum estimate of 79 mm for an elevation of 2200 ft in the Amargosa Desert, and an average estimate of 157 mm for the area of the UARW. The cokriging average estimate was 12 mm greater than the kriging average estimate because increased AAP for higher elevations in the Grapevine Mountains, the Funeral Mountains, and the Spring Mountains was not adequately represented by the available sample of AAP measurements. The average cokriging estimate of 172 mm AAP at eight precipitation stations located in the vicinity of the potential repository site was 29 mm greater than the average kriging estimate, and the maximum cokriging estimate of 247 mm was 87 mm greater than the maximum kriging estimate for the eight precipitation stations.

Cokriging estimation variances for the UARW were reduced by an average of 54% relative to kriging estimation variances, indicating a significant improvement in estimation accuracy obtained by using elevation data. Cokriging estimation variances were reduced by 55% relative to kriging variances at the potential repository site, with maximum reductions of more than 60% occurring for large areas to the northwest and southwest of the site. Reductions of 50% were obtained at distances of approximately 30 000 ft (6 miles) from measured values of AAP.

Regression results between cokriging estimates of AAP and elevation compared favorably with regression results obtained between measured AAP and elevation, indicating that the correlation between AAP and elevation defined by the multivariate geostatistical model was reasonable. An indirect confirmation of the cokriging estimates was obtained by comparing the location of the estimated 250-mm isohyet relative to boundaries defining the occurrence of pinyon pine and juniper woodlands, which were considered to be representative of the approximate lower limit of the moist-steppe climatic zone in the southern Great Basin. In most cases, the location of the cokriging 250-mm isohyet corresponded closely to the woodland boundaries.

The potential accuracy of the 1990 network of 38 active precipitation stations for estimating AAP was evaluated using cokriging estimation variances, and locations for 20 additional stations were selected using maximum cokriging estimation variances. Analysis of the expanded hypothetical network indicated that precipitation stations were needed at low elevations in the Amargosa Desert throughout the southern section of the UARW, in Sarcobatus Flat in the northwest section of the UARW, and at the higher elevations of Quartz Mountain, the Grapevine Mountains, the Funeral Mountains, and the northern Spring Mountains. These locations would be useful for improving precipitation characterization within the UARW based on both the elevation–precipitation correlation and the spatial distribution of precipitation measurements.

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