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GROUNDWATER OBSERVATION NETWORK DESIGN FOR THE KANSAS GROUNDWATER MANAGEMENT DISTRICTS, U.S.A.

MARIOS SOPHOCLEOUS

Kansas Geological Survey, University of Kansas, Lawrence, KS 66044 (U.S.A.)

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ABSTRACT

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Concerns about the efficiency and economic soundness of the Kansas groundwater monitoring program led to a systematic redesign of this network, a tentative phase of which is presented in this study. The objectives of this paper include monitoring of major aquifers within each groundwater management district at a spatially more uniform level of accuracy, elimination of redundant measurements and optimization of the information gained from each observation well. The theory of regionalized variables is employed to estimate the amount of spatial variability of the water table, on which the network design is based. This study shows that it is not practical to attempt to reduce the already existing level of uncertainty uniformly throughout the various districts; to do so would tremendously increase the cost of well monitoring, which is already very high. Assuming that the currently existing network is satisfactory for the State's objectives, a reduced network consisting of one well every 6.4 km is equally satisfactory. The reduced network yields district-wide maps that do not differ significantly from those produced using the present network and at the same time it reduces the already-existing network by 18—47%. Therefore, adoption of a rearranged square well network is recommended, which is reduced to a 6.4-km spacing to achieve both a uniform level of information about the water table and a minimum required accuracy.

INTRODUCTION

During the last several decades development of groundwater-based irrigation in western and south-central Kansas has increased dramatically, resulting in severe groundwater-level declines. In western Kansas, where mining of groundwater supplies is actually taking place, county-wide levels have declined at an average rate of 0.3—1.5 m $\mathrm{yr.}^{-1}$ in the last 20 yr. (K. G. M.D.A., 1980). To find solutions to the problem of dwindling supplies in western Kansas and to help control and direct the development and use of groundwater resources, five groundwater management districts (GWMD's) have been formed in Kansas (Fig. 1). A network of groundwater observation wells has also been developed in Kansas and has been expanded through the

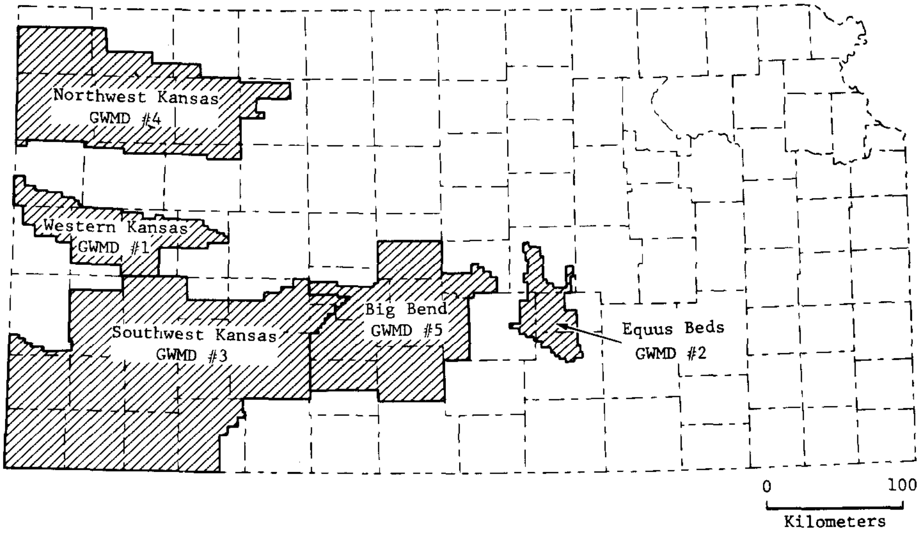


Fig. 1. Groundwater management districts (GWMD's) in Kansas.

years to monitor groundwater-level changes and to evaluate groundwater reserves. Funds allocated each year by the Kansas Geological Survey and other State agencies for collection and analysis of an expanding water-level data network increased to such an extent that concerns about the efficiency and economic soundness of the network program have been expressed. However, no systematic attempts have yet been made to determine the number and location of observation wells, the adequacy of the network for any specified purposes or its cost effectiveness.

In order to deal with some of these issues, the Kansas Geological Survey has proposed that a systematic redesign of the groundwater network in Kansas might result in some significant improvements, such as monitoring of major aquifers at a spatially more uniform level of accuracy, eliminating redundant measurements, optimizing the information gained from each observation well, and possibly decreasing the number of observation wells without significantly affecting the accuracy of the estimates.

GEOHYDROLOGIC SETTING OF GWMD's

GWMD's *1* and *3*—*5* (Fig. 1) are studied in this report. GWMD *2* (Fig. 1), the smallest in areal extent of all GWMD's ($\sim$2,023 km^2), is the subject of a separate study by Olea (1980) and, therefore, it will not be dealt with in this paper. All the studied areas belong to the High Plains region of Kansas, which is characterized by flat to gently rolling terrain consisting of fluvial and eolian sediments. The Ogallala Formation of late Tertiary age is the principal aquifer unit in western Kansas (Gutentag and Weeks, 1980; Gutentag et al., 1980) underlying all three western GWMD's *1*, *3* and *4*. It consists of poorly sorted layer of silt, clay, sand and gravel. Caliche and caliche-cemented sand and gravel zones ("mortar beds") occur at several horizons throughout the formation. In most instances, the Ogallala can be differentiated from the underlying Permian, Jurassic and Cretaceous bedrock by its hetergeneous alluvial nature (Fader et al., 1964). Unconsolidated fluvial and eolian deposits of Quaternary age that are in hydraulic connection with the Tertiary deposits (which is the case with GWMD 5) are considered to be part of the High Plains aquifer. Much of the sediments in the more recent alluvial deposits are reworked from the Ogallala Formation. Saturated thickness of the deposits ranges up to more than 180 m in southwestern Seward County, while yields to wells range up to more than $190\,\mathrm{l\,s^{-1}}$.

Precipitation is the principal source of recharge to the groundwater system in the High Plains. It ranges from less than 40 cm to ~ 77 cm, increasing eastwards across the Plains. Persistent winds and high summer temperatures cause high rates of evaporation in the High Plains. Except in sand-dune areas, where the water can readily percolate down to the water table, most of the water that enters the soil is returned to the atmosphere by evapotranspiration. Recharge to the groundwater system may be several centimeters per year in sand-dune areas; but, over the much larger part of the High Plains, recharge may average less than $1.3\,\mathrm{cm\,yr.^{-1}}$ (Gutentag and Weeks, 1980). Groundwater from the High Plains aquifer discharges naturally to streams, although there are areas where even major streams, such as the Arkansas River, are now influent because of severe water-level declines observed during the last decades.

The water-table configuration in the region shows a generally eastward slope of the water table across the High Plains. Typically, the slope of the water table, is between 1.9 and $2.8\,\mathrm{m\,km^{-1}}$. Based on average values of hydraulic gradient and aquifer parameters, the velocity of water moving through the aquifer is $\sim 3.5 \cdot 10^{-6}\,\mathrm{m\,s^{-1}}$ (Gutentag and Weeks, 1980), which is typical of sand—gravel aquifers.

Data on water levels employed in this study were obtained during January of 1979 or 1980, when the effects of seasonal pumping for irrigation were near minimum.

METHODOLOGY

The previously mentioned goals were achieved in part by geostatistical structural analysis, a statistical approach that investigates the amount of spatial variability in any surface, in this case the water table. The basic tool used in assessing this variability is the semivariogram, which is a plot of semivariance that characterizes the rate of change of a mapped variable (water-table elevation) with respect to distance. The semivariance, $\gamma(h)$, is defined as one half of the variance of the increment $[Z(x+h) - Z(x)]$, representing in this case the differences between values of the water-table elevation, Z_i, separated by a vector of distances, h, which has a specific orientation. If a total of $N(h)$ pairs of observations separated by a vector h is considered, then the semivariance is estimated, most conveniently along a line (traverse), as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

In general, the semivariance increases with increasing distance, ranging from zero when the distance h is equal to zero, to a value equal to the a priori variance of the observations (sill) at some large value of h. For a detailed exposition on such geostatistical concepts, see Matheron (1971), David (1977), Journel and Huijbregts (1978), and Delhomme (1978).

The concept of semivariogram takes into account those geological parameters that cause the estimation variance, i.e. the uncertainties in estimating water levels between wells. Such geological parameters include, among others, the continuity of the water table, the zone of influence of the water-level measurement, and the homogeneity of the deposits. The continuity is reflected by the rate of growth of semivariance with respect to distance (see section on semivariogram analysis). In a water table, changes usually occur slowly; such continuity, however, may be nonexistent in cases of perched water tables, or when different aquifers are tapped by an observation-well network. The concept of zone of influence of the water-level measurement means that any such measurement is autocorrelated with the water table up to a certain distance from the point of measurement, beyond which any prediction is completely uncertain, as such measurements are statistically independent. This distance, which corresponds to the range of the semivariogram, may vary according to the direction in which the prediction is made (anisotropy). The concept of homogeneity of the deposits means that the error associated with one estimation procedure will vary if geological conditions vary. All these geological characteristics appear quantitatively in the semivariogram, and therefore one can expect that an estimation procedure based on it can be geologically reliable.

The estimation procedure to obtain both the uncertainties in estimated water-table elevations as depicted by the standard deviation of estimation and the map of the water-table elevations is called universal kriging. In order to carry out the universal kriging procedure, the semivariogram(s) of an area must be known from a structural analysis of the data. Kriging techniques for computer contouring developed at the Kansas Geological Survey (Sampson, 1978) are used to contour the water table and to map the likely error at every estimated point in the map grid. The statistical theory from which kriging techniques are derived is known as the theory of regionalized variables.

SEMIVARIOGRAM ANALYSIS

Semivariograms taken along the main trend of the water-table configuration — which generally trends from west to east — show that the water table is extremely continuous with no abrupt discontinuities or changes in slope; they exhibit a parabolic shape, which reflects the pronounced eastward dip of the water table, and indicate that there is no distinguishable limit to the zone of influence about an observation well along this general direction. Examples of average semivariograms (at least three traverses) along a general east—west direction are shown in Fig. 2.

Semivariograms taken along a direction perpendicular to the main trend of the water table (generally trending north to south) have a good continuity at their origin but, in general, exhibit an apparent "semi-sill" or interval of almost constant semivariance. This feature, in general, results from small localized differences in water levels. Such variograms are "transitive"; that is, they exhibit moderate continuity within a local neighborhood and a random behaviour over large distances. Examples of semivariograms along a generally north—south direction are shown in Fig. 3.

In geostatistics, a neighborhood or zone of influence indicates a zone beyond which the influence of a water-level measurement disappears, that is, a zone beyond which the measurements are statistically independent. Although from the east—west-trending semivariograms a neighborhood of almost any size could be specified, most of the characteristics of the east—west semivariograms result from a pronounced dip of the water table; therefore when that trend is removed the resulting semivariance of the residuals will have a limited range depending on the size of structures present in the water-table configuration. Thus, a limited neighborhood associated with the semi-sill of the north—south semivariograms was selected for each GWMD. In order to confirm that a limited neighborhood is appropriate, semivariograms were computed for all profiles based on the estimated neighborhood for each GWMD and the fitted polynomial drift. The drift (or trend) describes the regular manner in which the variable under study (water table) behaves over the neighborhood region. Polynomials up to a degree of two were fitted, and the best-fitting polynomial was thus selected. It should be noted, however, that the estimation of the semivariogram of the residuals (i.e. the differences between the water-table elevation and the drift) is not straightforward. Before obtaining the residuals that are necessary to estimate the semivariogram, the drift must be known; but estimation of the drift requires knowledge of the semivariogram. This problem is solved recursively (Olea, 1975) by assuming a semivariogram; computing the drift and the residuals and comparing the resulting semivariogram to the one assumed; and, if necessary, adjusting the drift and/or neighborhood size. Fig. 4 represents semivariograms of the residuals from the drift for specified neighborhoods and degrees of polynomial drift. This figure shows both the experimental values calculated from the residuals themselves and the expected values calculated from the fitted polynomial model. The almost exact correspondence between the two suggests that the selection of neighborhood size and order of drift are appropriate.

Finally, before the results of the semivariogram analysis are presented, it should be noted that semivariograms are most accurate near their origin,

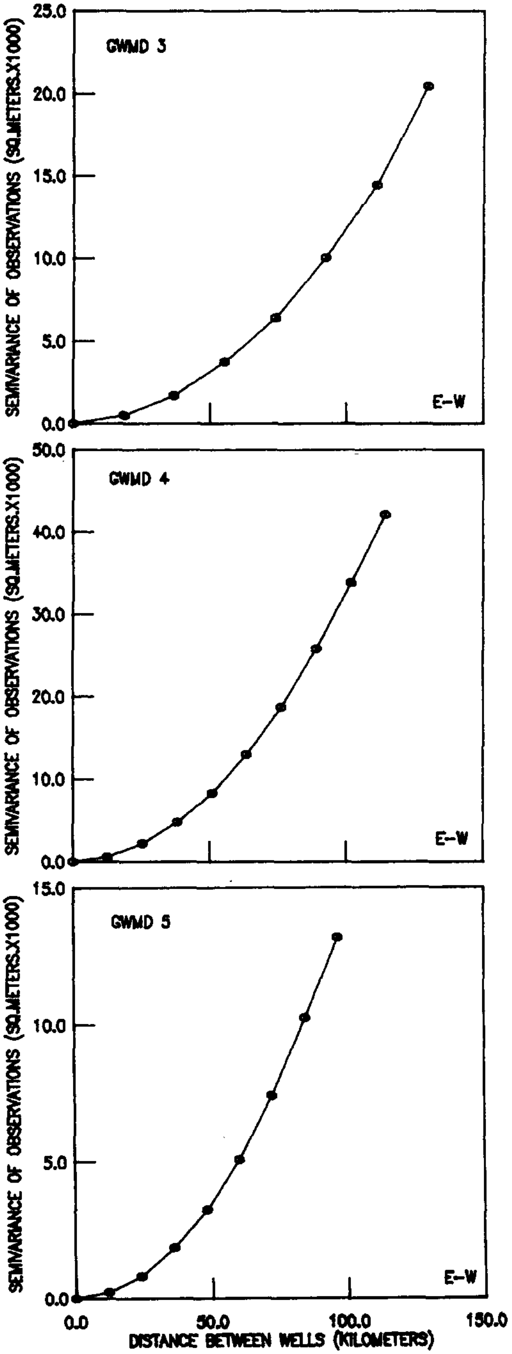


Fig. 2. Average semivariograms of water-table elevations along a general east—west direction for various GWMD's.

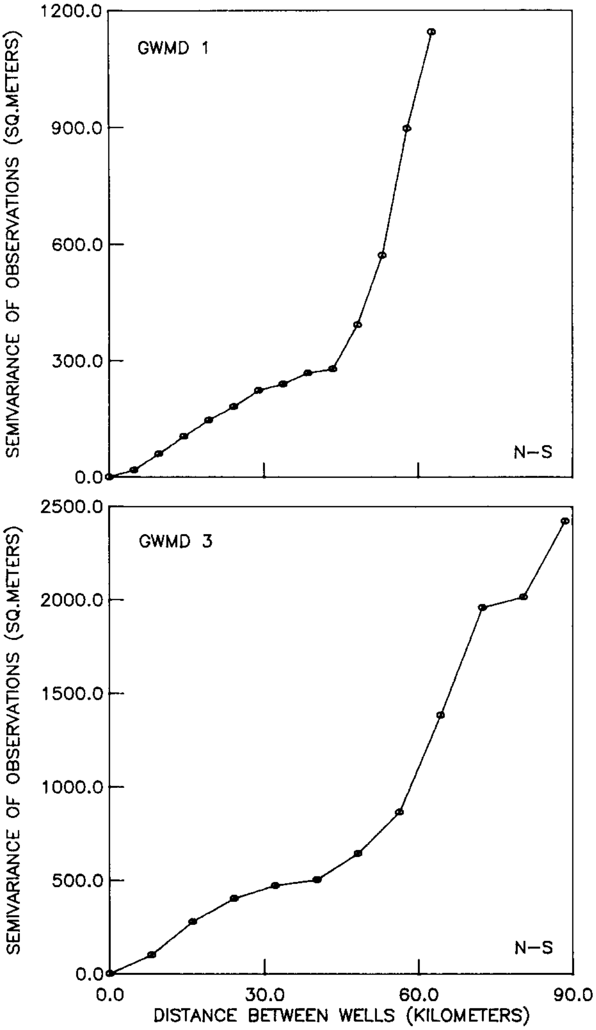


Fig. 3. Semivariograms of water-table elevations along a general north—south direction for various GWMD's. The range of the data, taken as the intersection of the semivariance and the sill, is approximately equal to 32 km for GWMD *1* and 29 km for GWMD *3*.

where the estimates are based upon the maximum number of measurements. Therefore, the interpretation of the semivariograms in this study is based on the analysis of the rate of change of the semivariance near the origin. Finding the slope of the semivariogram at the origin establishes the rate of increase of the semivariance, and is a convenient means of comparing variability of phenomena. Thus, a steep slope near the origin signifies a distribution that changes rapidly with respect to distance, indicating irregular, erratic, or discontinuous surfaces; a more gentle slope signifies a relatively slow change in semivariance, indicating a relatively smooth and regular surface.

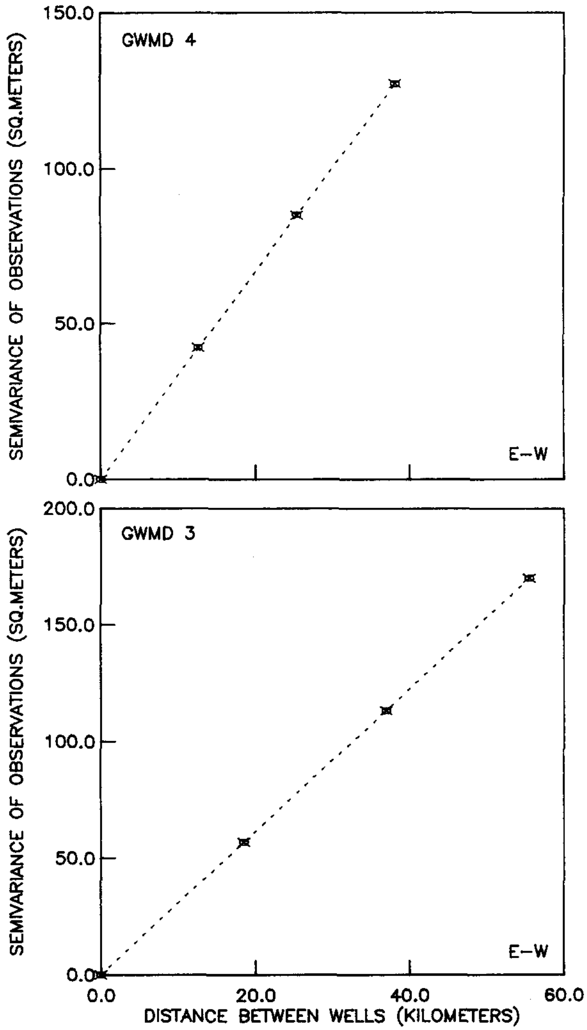


Fig. 4. Comparison between the semivariogram of the residuals from the drift (o) and the assumed linear semivariogram (X) for the average east—west semivariograms for various GWMD's. The neighborhood size contains four observations in these examples.

Therefore, since attention is restricted to measurements within the neighborhood (near the origin of the semivariogram), the semivariance $\gamma(h)$ will not be needed for distance, h, larger than the range. For such cases, a linear semivariogram of the form:

$$\gamma(h) = \omega \cdot h \qquad \text{for} \qquad h \leqslant 2r$$

which is a straight line through the origin with a slope of ω and a neighborhood of radius r, is a good approximation. Thus, to determine the semivariogram in this simplified form, all that is needed is to determine the slope

TABLE I

Summary of semivariogram and network design analyses

GWMD	Approximate area (km^2)	Semivariogram characterisitcs		Degree of polynomial drift	Number of observation wells*		Percent reduction
		slope ($m^2 km^{-1}$)	range (km)		existing net	reduced net	
1	4,856	3.6	32	1	247	132	47
3	23,156	6.5	29	2	497	347	30
4	12,784	6.3	32	1	327	241	26
5	10,214	3.9	29	1	305	241	18

Recommended well spacing in a square network: 0.155 (wells km^{-1}); recommended well density: 0.024 wells km^{-2} (2.25 wells per township).

*All wells not measured during January or which, in addition to the High Plains aquifer, penetrate into pre-Ogallala formations are excluded from this compilation.

ω and the boundary r. Because the drift should represent only the main features of the water table and not the details, the simple analytical expression mentioned previously is usually enough. These features are incorporated in a computer program, published in Olea (1977), which was used to calculate all semivariograms in this study.

Table I summarizes the results of such semivariogram analyses for all western GWMD's. From that table, one could group the four western GWMD's into two groups, based on the complexity of the water-table configuration as indicated by the slope of the semivariograms. The slopes and ranges indicated in that table are averages of several calculated semivariograms from each district. One group includes GWMD's *3* and *4* which possess more complex water-table configurations than the other GWMD's as indicated by the relatively high average slopes of 6.5 and 6.3 $m^2 km^{-1}$, respectively, of the semivariograms at their origin. [In Sophocleous et al. (1982) the average slope for GWMD *4* is an unweighted average (6.6 $m^2 km^{-1}$) as opposed to the present weighted average value of 6.3 $m^2 km^{-1}$.] The second group includes GWMD's *1* and *5* which possess a regular, relatively smooth water table as indicated by the smaller average semivariogram slopes of 3.6 and 3.9 $m^2 km^{-1}$, respectively.

Another important piece of information one can extract from semivariogram analysis is the range, which for all western GWMD's is approximately the same, 29—32 km, indicating that any water-level measurements taken within such neighborhood are correlated to each other. This information, as will be shown in the next section, is a paramount importance in network design.

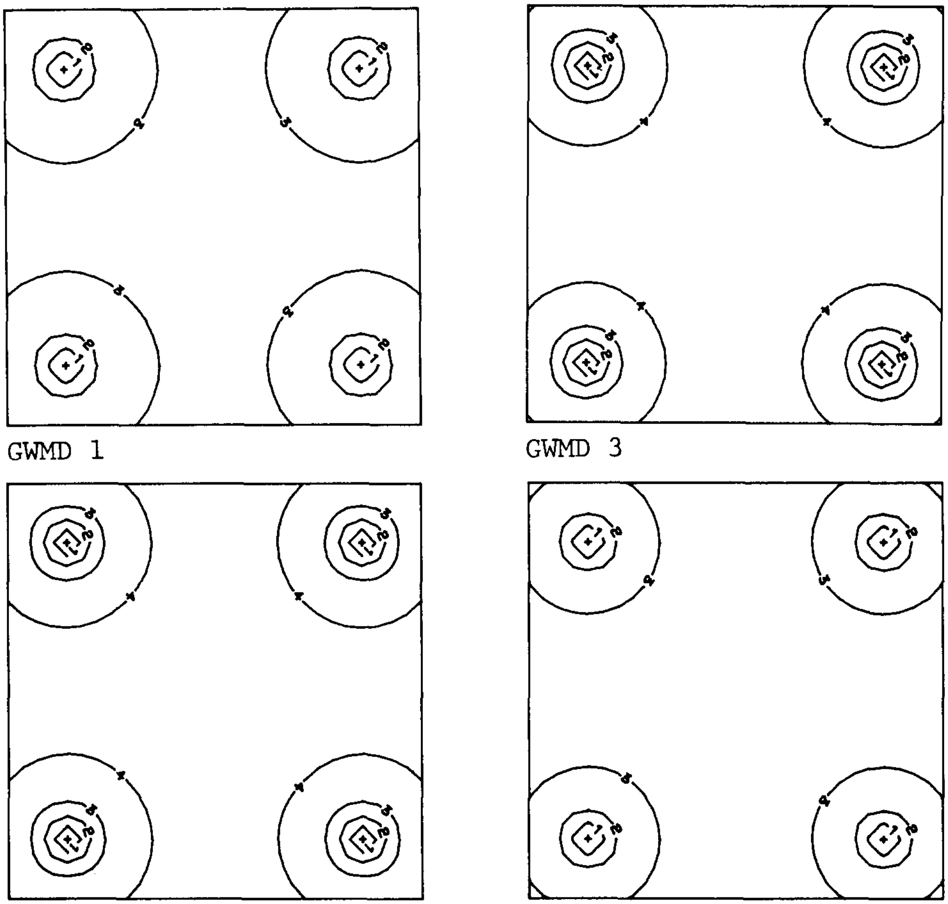
NETWORK DESIGN AND ERROR ESTIMATION

The most rational approach to a groundwater network would satisfy the following conditions: (a) it exhibits a uniform square grid that is easy to fit into the already existing land-classification system of township and range (areas of 9.7 km × 9.7 km), and also insures uniform coverage and uniform level of information about the water table; and (b) it is dense enough to provide the best answers at an affordable cost, while providing the required accuracy.

The most efficient space-covering pattern that can be devised is, for practical reasons, a regular square grid of observation wells, provided the variable of interest is isotropic in the sense that it does not change in different directions. The water table is regarded to be an isotropic surface based on the results of the average semivariograms of the residuals, which show no significant differences between the north—south and east—west semivariograms, and on a careful study of water-table maps in all GWMD's where no closed contours of preferred orientation or structure appear.

It will be shown here that reducing the already-existing average uncertainty would require a great increase in wells at a great cost. However, significant savings can be made without significantly increasing the uncertainty by reducing the number of monitoring wells. Therefore, since it is wasteful to collect more data than necessary, especially when these data make only an insignificant contribution to our understanding of the water table, the approach to observation-well-network design should be one that minimizes the number of observation wells in the network under the constraint of a minimum required accuracy.

In selecting the optimal number of observations to be used to krige a point, the screen effect (David, 1977) may be employed. Tests (Olea, 1975) indicate that a limit of sixteen observations nearest the point to be estimated are sufficient to krige that point, as they account for more than 97% of the total weights assigned to observations within the zone of influence. A square pattern (equivalent to a circular neighborhood) of four by four wells, yielding sixteen wells inside the zone of influence, was thus selected to take advantage of the autocorrelation between water-level observations and between each observation and the estimated values. This advantage is assured when the diagonal of the square pattern is equal to the range. Therefore, the spacing between wells in such a pattern, and consequently the well density, can be easily computed. For the western GWMD's of Kansas this spacing is conservatively calculated to be 6.4 km which means that for a square pattern, nine wells are required for every four townships, that is one well for each 41.4 km^2 (Table I). This represents a near minimum acceptable density of wells needed to approximately maintain the present level of accuracy in estimating the water table. The expected errors in estimates made of the watertable — estimation errors — can be calculated using the universal kriging procedure before actual measurements are made because



GWMD 1

GWMD 3

GWMD 4

GWMD 5

Fig. 5. Estimation standard deviation contours (in m) for various GWMD's, assuming a hypothetical network of observation wells spaced 6.4 km apart in a square pattern that repeats indefinitely over the area.

the estimation errors do not depend on the observed values but on the semivariogram and the configuration of the data points. Fig. 5 shows contour maps of the standard deviation of estimation (estimation error) within an area defined by four wells, which are part of an infinite regular network where wells are spaced 6.4 km apart. The standard deviation rises sharply away from the wells, reaching a maximum at the center of the square pattern, which is the most distant location from the control points (Fig. 5).

Converting such standard errors into a confidence interval, however, requires the assumption of some probability distribution for these errors. For example, if the central-limit theorem holds, a 95% confidence interval for the actual values at the center of the four-well patterns, where the water level will be estimated least reliably, will be given by $Z^* \pm 1.96\sigma_E$ where Z^* is the estimated value of the water table, and σ_E is the standard deviation of estimation or standard error. This value also represents the minimum

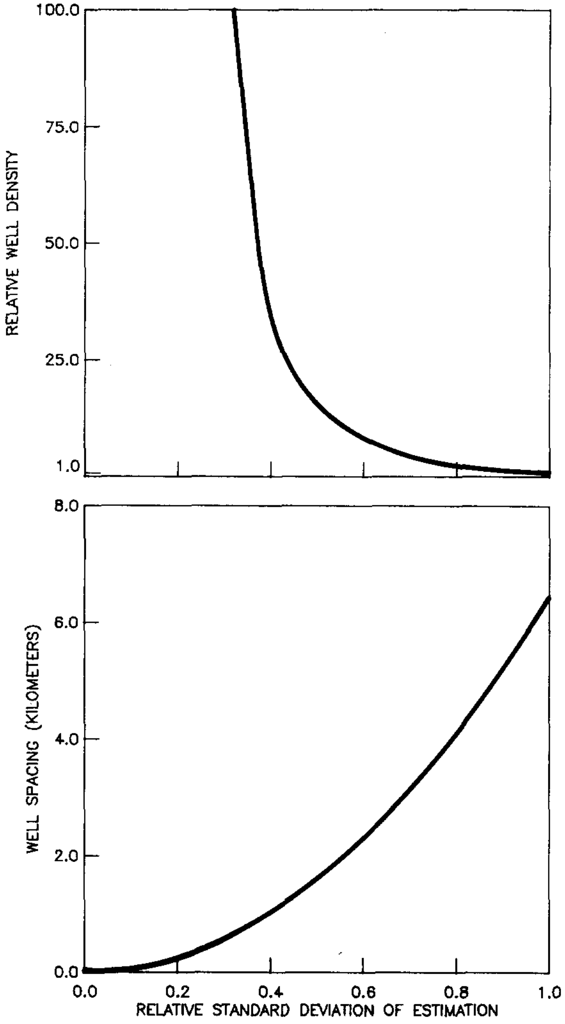


Fig. 6. Reduction in well spacing and increase in relative well density that would be required to reduce the estimation error of the water-table elevation for a 6.4-km well spacing, shown in Fig. 5, to any desired value for a linear semivariogram.

accuracy that will be obtained if the study areas are sampled on a 6.4-km grid.

Theoretical networks of observation wells may be similarly constructed using different well spacings. A sensitivity analysis can thus be conducted to test other alternative networks. The theory of regionalized variables predicts that in a contour map generated by universal kriging the estimation variance is a linear function of the distance between wells, provided the semivariance is linear, a condition held in this study. Taking these conditions into consideration, Fig. 6 was designed to calculate the spacing and relative well density that would be required to reduce to any desired level the estimated standard deviation of the water-table elevation for the 6.4-km well spacing shown in Fig. 5. For example, to reduce the maximum standard deviation at the center of a four-well pattern in a regular grid with a 6.4km well spacing by 50%, a well spacing of 1.6 km and a relative well density of sixteen times more wells relative to the 6.4-km square grid is required (Fig. 6). Even with significant increases in the number of wells, no appreciable changes in the error map will be observed. For example, doubling the number of wells in a regular network will only reduce the standard deviation of estimation by a factor of 1.2. It is thus inferred that the minimum network, consisting of wells every 6.4 km, is optimal when compared to any practically achievable sampling density, as this spacing meets the required level of accuracy with the minimum number of wells. A sparser network will result in a deterioration of the standard deviation of estimation beyond acceptable values, while a denser network will produce minor improvements in accuracy with substantial increases in the number of monitoring wells and in associated costs. For example, in GWMD *3*, a well spacing of 8 km resulted in significant differences between the existing network and the reduced network of one well for every 8 km. Such differences range up to about twice the values obtained using the 6.4-km spacing.

MAPPING RESULTS

Fig. 7a shows water-table contour maps, based on the existing pattern of wells for various GWMD's, produced by universal kriging using the SURFACE II graphics system (Sampson, 1978). Areas with data densities below a specified minimum (for this study, nine data points within a circular neighborhood for interior regions; three octant sectors of a circular neighborhood with at least one data point for boundary regions) are not contoured by the kriging technique. These maps represent the closest approximation to reality because all information available is used. Fig. 7b indicates the estimation errors given as standard deviations of estimation for the same GWMD's. Using the existing well network, such maps show the uncertainty already present in the water-level estimation process.

Fig. 8a shows water-table contour maps produced by selecting from the existing network wells that are closest to those in a regular network with wells every 6.4 km. The well-network reduction was obtained by superimposing a square 6.4 x 6.4 km pattern over the area and selecting one well per square block in a stratified pattern mode. The selection procedure retains nine wells for every four townships. The final pattern contains 18—47% fewer wells than the already existing network. It should be kept in mind, however, that a number of square blocks, in all GWMD's have no observation wells. Fig. 8b presents contour maps of the standard deviation of estimation for the reduced network of wells. Comparison of these maps

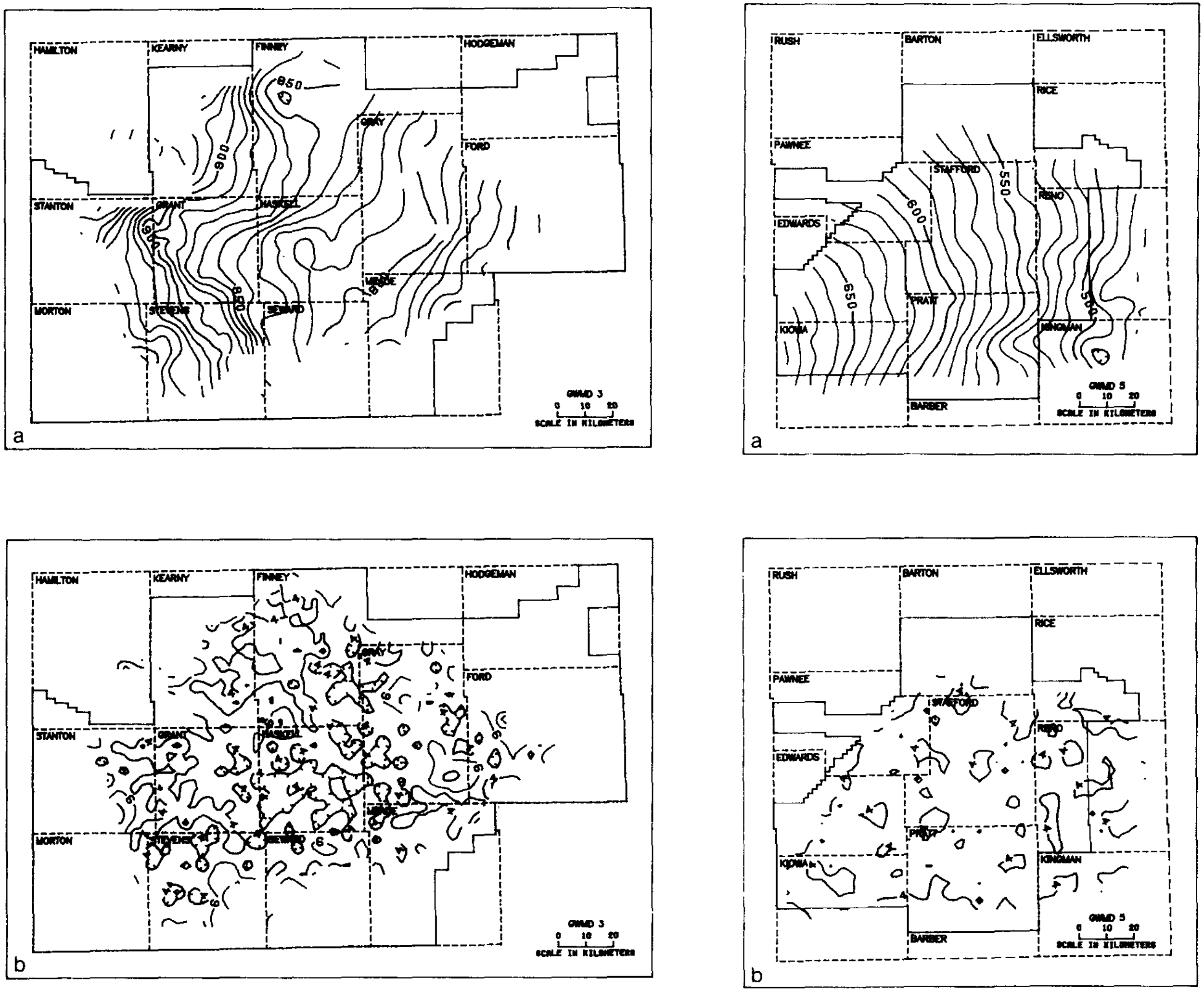


Fig. 7. January 1980, water-table maps based on the existing network (a) for various GWMD's, and their associated

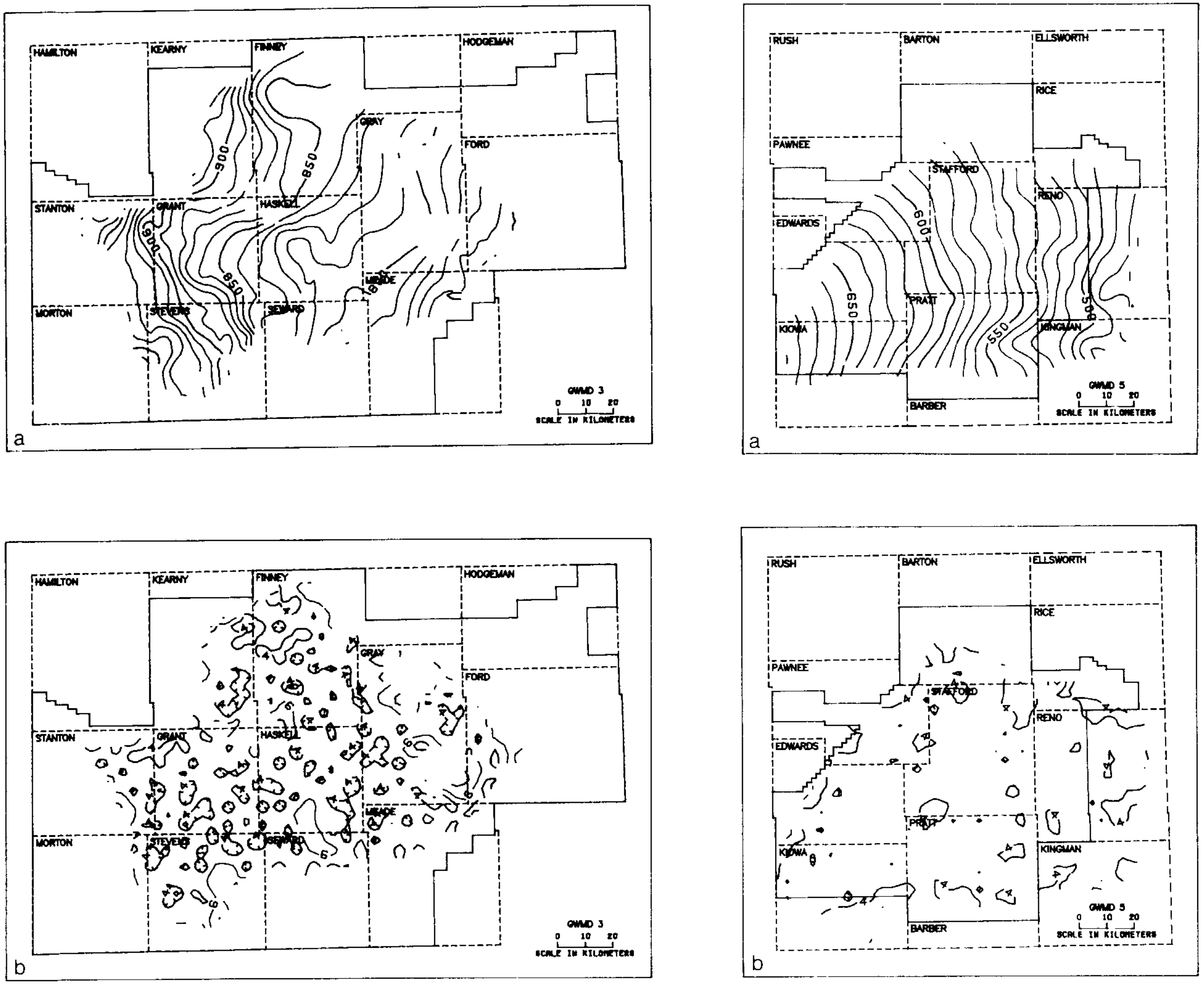


Fig. 8. January 1980 water-table maps based on a reduced network (a) for the same GWMD's shown in Fig. 7, and their associated estimation errors given as standard deviations of estimation (b). Contours are in meters.

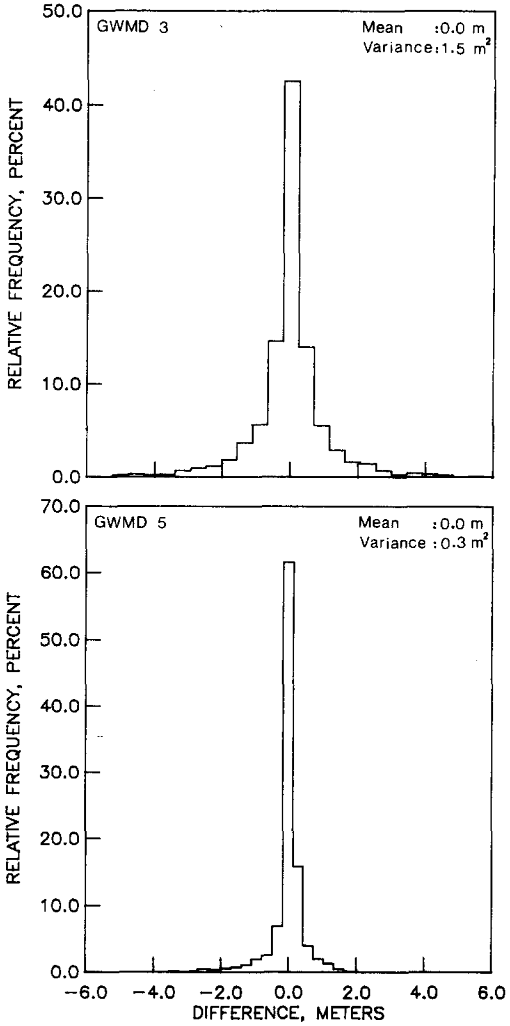


Fig. 9. Histograms of the differences in water-table elevations between the full and reduced networks shown in Figs. 7a and 8a.

with the corresponding ones for the full network (Fig. 7b) indicates that the estimation errors for both maps are very similar despite the 18–47% difference in the number of wells. It should also be noted that in both sets of maps the calculated maximum standard deviations are greater than those estimated for the ideal network (Fig. 5) because of non-regular spacing, boundary effects, and missing data for a number of blocks in the maps. Therefore establishing additional monitoring wells is recommended in the area of high standard deviations in the reduced network maps (Fig. 8b). Fig. 9 shows histograms of the differences in water-table elevations between the full and reduced networks shown in Figs. 7a and 8a. As can be readily recognized, these differences are generally small and consistent with the standard deviation maps. In a study by Sophocleous et al. (1982) the significance of the standard deviation maps is evaluated; critical areas where a certain error of estimation would have a significant impact on groundwater-reserve estimations are thus outlined.

Table I lists the total number of wells employed for each GWMD, the reduced number of wells resulting from the recommended well spacing and the density of wells for all GWMD's studied. It should be noted that in all GWMD's additional monitoring wells exist that were not measured during the month of January of the year adopted for network analysis (1979 or 1980). It should also be noted that only those wells that penetrate the High Plains aquifer exclusively were considered for analysis. No wells penetrating deeper into pre-Ogallala units, even if they were also screened at the shallower units, were considered in this study.

CONCLUSIONS AND RECOMMENDATIONS

The results and essence of this study are summarized in Table I and Fig. 6. This study shows that it is not practical to attempt to reduce the present average level of uncertainty or estimation error uniformly throughout the region, because to do so would increase the cost of well monitoring tremendously. For example, to attempt to reduce the presently existing error by 50% throughout the GWMD's would require at least sixteen times more wells than the currently existing network has. On the other hand, decreasing the existing well density to nine wells for four townships does not significantly increase the uncertainty already present in the estimation process.

Therefore, this study leads to the following conclusion. Assuming that the currently existing network is satisfactory for the purpose of predicting water-level changes related to various pumping and/or recharge mechanisms or groundwater-reserve estimations, a reduced network of one well every 6.4 km is equally satisfactory since it yields district-wide maps of no significant difference from those produced using the present network. This statement implies both a significant reduction in the number of monitoring wells (Table I) and the establishment of additional observation wells in areas where the recommended spacing requirement for the reduced network is not currently satisfied. These areas are indicated by the mapped areas of maximum standard deviation (Fig. 8b). Therefore, adoption of a rearranged square well network is recommended, which is reduced to a 6.4-km spacing or one well per 41.4 km^2 (stratified pattern) in order to achieve both a uniform level of information about the water table and the minimum accuracy required to supply scientifically valid answers to questions about groundwater resources. Such stratified pattern allows flexibility in maximizing the use of existing wells within each 41.4-km^2 area.

However, in particularly important areas, where reduced networks exist, which are denser than those recommended and where the estimated uncertainties are unacceptably high for their specific objectives, a separate network may be designed. It should be kept in mind that the objectives of various groundwater programs differ; therefore, the precision and quantity of data required for water-resource evaluation, for example, is different from that required for water-resource management and allocation, or for particular research programs. Therefore, the key problem in network design is the definition of program objective; once this is done, the procedures for attaining these objectives can be developed.

Finally, the methodology used in this study is very general and can thus be applied to any type of network analysis where the theory of regionalized variables is applicable. The uncertainty of error maps can be used, in any network, to determine where more information is necessary and to estimate the number of additional measurements that will be needed. Thus, regionalized variable theory provides criteria by which future measurements can be planned in order to achieve specified levels of reliability.

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