USE OF PRINCIPAL COMPONENTS ANALYSIS FOR STUDYING DEEP AQUIFERS WITH SCARCE DATA--APPLICATION TO THE NUBIAN SANDSTONE AQUIFER, EGYPT AND ISRAEL

by

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ABSTRACT: A methodology was developed and applied to the Nubian Sandstone aquifer beneath the Sinai Peninsula (in Egypt) and the Negev Desert (in Israel) to improve understanding of the hydrology of a deep aquifer with scarce data. Principal Components Analysis (PCA) is a statistical technique that was used to combine various multidisciplinary data in order to identify chemical and physical groups, which were used to define groundwater flow paths.

The findings of this study are in accord with the generally accepted hydrogeological conceptual model of the aquifer. However, through this study, new insights were obtained by the use of the PCA method concerning:

1) **the description of a complex flow system by grouping various qualitative and quantitative parameters;**
2) **the delineation of optimal operational zones for aquifer exploitation; and**
3) **the definition and characterization of six main groundwater flow paths from their outcrops in the southern part of the Sinai to its discharge zones in the Arava River Valley and Dead Sea area in the Negev desert. These flow paths are defined by their water categories, which are unified expressions of such properties as salinity, origin, and age of groundwater.**

This methodology is useful for analysing aquifers with scarce data and may also be helpful for studying other deep groundwater basins.

RÉSUMÉ: Une méthode d'étude a été mise au point et appliquée à l'aquifère des grès nubiens du désert du Sinaï (Egypte) et du désert du Negev (Israël) afin de connaître les écoulements dans un aquifère profond à partir d'un nombre réduit de données. L'Analyse en Composantes Principales (ACP) est une méthode statistique utilisée pour prendre en compte des données d'origines variées afin d'identifier des groupes de caractéristiques physiques et chimiques permettant de définir les axes d'écoulement souterrain.

Les conclusions de cette étude sont en accord avec le modèle hydrogéologique conceptuel généralement accepté pour cet aquifère. Cependant, dans cette étude, de nouveaux résultats ont été obtenus, grâce à l'utilisation de l'ACP, en ce qui concerne :

1) **la description d'un système d'écoulement complexe par le regroupement de différentes variables qualitatives et quantitatives;**
2) **la délimitation de zones opérationnelles optimales pour l'exploitation de l'aquifère;**
3) **la définition et la caractérisation de six axes principaux d'écoulement souterrain depuis les affleurements dans la partie sud du Sinaï jusqu'aux zones de décharge dans la vallée de l'Arava et de la région de la Mer**

Morte dans le désert du Négev. Ces axes d'écoulement sont définis par des familles d'eaux identifiées par la salinité, l'origine et l'âge des eaux souterraines.

Cette méthode d'étude est utile pour analyser des aquifères à partir d'un nombre réduit de données; elle peut aussi aider à étudier d'autres systèmes hydrogéologiques profonds.

RESUMEN: Se ha desarrollado una metodología para mejorar el conocimiento de la hidrología en acuíferos profundos con escasez de datos. Esta metodología ha sido aplicada en el acuífero de Arenisca Nubia, bajo la Península del Sinaí (Egipto) y el Desierto del Negev (Israel). El Análisis de Componentes Principales (PCA) es una técnica estadística que se usó para combinar un conjunto de datos multidisciplinares y poder así identificar características físicas y químicas, que se usaron a su vez para definir el flujo subterráneo.

Los resultados de este estudio concuerdan con el modelo conceptual generalmente aceptado del acuífero. Sin embargo, a través del uso del PCA, gracias a este estudio se pudieron obtener nuevas ideas sobre:

1) **La descripción de un sistema complejo de flujo mediante la integración de diversos parámetros cualitativos y cuantitativos;**
2) **la delimitación de las zonas de operación óptimas para la exlotación del acuífero; y**
3) **la definición y caracterización de seis caminos preferentes de flujo, desde sus afloramientos en la parte sur del Sinaí, hasta sus zonas de descarga en el Valle del Río Arava y el área del Mar Muerto en el Desierto del Negev. Estos caminos preferentes se definen a partir de una categorías de agua, que corresponden a unas expresiones que tienen en cuenta propiedades como la salinidad, origen y edad de las aguas.**

La metodología desarrollada permite analizar acuíferos con datos escasos y puede ser útil también para estudiar otras zonas con acuíferos profundos.

INTRODUCTION

The shortage of available fresh water has become a crucial problem for society. Throughout the world, shallow groundwater near industrial and high-intensity agricultural areas is threatened by various contaminated leachates generated by anthropogenic and other sources of pollution. In such areas, groundwater potential declines drastically in time (Castany, 1968; UNESCO, 1980; U.S. Environmental Protection Agency, 1990). Deep groundwater, mostly in confined aquifers, is less affected by surface contamination. Some of these deep groundwater basins are in desert areas, where they commonly constitute the main source of water (Picard, 1953; Ambroggi, 1966; Castany, 1967; Vauchez, 1967; Melloul, 1970; Issar et al., 1972; Forkasiewick and Margat, 1982). However, data on such basins are generally scarce and exploitation is expensive, compared to shallow groundwater basins. Optimal management of the aquifer may reduce these costs. To accomplish this, one requires a better understanding of the aquifer and of the groundwater flow system, e.g., geometry of the basin, hydraulic properties, quality of groundwater, water flow rates and directions, and leakage through confining beds (Castany, 1967). Even limited data based upon a small number of observation wells and a restricted budget, and measurements of a larger number of variables in existing wells, can contribute significantly to this understanding. When dealing with a small data base, it is useful to consider the groundwater environment by means of multidisciplinary studies (Gibert, 1991). In such an approach, many variables must be processed simultaneously. These include distributions of various chemical variables (Burger, 1972), isotopic variables (Fontes, 1976), as well as physical variables (distance from the source of salinization, rate of recharge, well depth, etc.).

One way of overcoming the inadequacy of classical methods to integrate chemical and physical factors in groundwater analysis is by use of Principal Component Analysis (PCA). This factor-analysis technique develops linear constructions by data reduction and facilitates the determination and visualization of certain aspects of hydrological problems, thereby helping to correlate and identify similarities between variables and observations (Laffite, 1972; Zhou et al., 1983; Davis, 1984). PCA is an effective tool for identifying and explaining groundwater evolution processes, augmenting classical statistical methods by combining chemical and physical variables (Melloul and Collin, 1992).

For 30 years, factor analysis, including PCA, has been used in many fields, including psychology and socio-economics (Harman, 1976). In the ecological sciences, factor analysis was utilized to characterize zooplankton associations of species occurring in 54 lakes in Canada and their relationship to environmental factors (Pinel-Alloul et al., 1990). The method has also been applied in stratigraphy and paleontology (Davis, 1984). In surface hydrology, an attempt has been made to identify stations with homogeneous precipitation for interpolation (Morin et al., 1979) and to determine an optimal method for reservoir management (Saad and Turgeon, 1988). In hydrochemistry, this method has been utilized to assist in understanding hydrologic processes affecting groundwater and soil salinity (Deverel, 1989) and to identify pollution sources in the coastal aquifer of Israel (Melloul and Collin, 1991).

The PCA method was applied in hydrogeology for the first time in the study of deep sandstone aquifers of the Albian Formation in the Paris basin and the Nubian Formation of the Sinai Peninsula and the Negev Desert (Melloul, 1979).

In this paper, the PCA statistical technique is used as a tool to process chemical and operational data in order to assess the nature of a deep aquifer. The main objective is to assess the suitability of this method in developing a hydrogeological conceptual model in an area with scarce data. The conceptual model describes flow paths, rates of recharge, and feasibility of exploitation, and it explains hydrogeological aspects of the aquifer (Kiraly, 1978) and processes that affect water quality in this basin.

The method is applied in this report to the Lower Cretaceous Nubian Sandstone (NS) aquifer beneath the Sinai Peninsula (in Egypt) and the Negev Desert (in Israel), as shown in figure 1. This aquifer was selected because:

1) it is a deep aquifer beneath a desert;
2) data exist from only a few observation wells;
3) substantial research has previously been carried out on this aquifer; and
4) a hydrogeological conceptual model has been generally agreed upon by many authors (Picard, 1953; Melloul, 1970; Issar et al., 1972; Kroitoru and Galai, 1978; Kroitoru, 1980; Rosenthal et al., 1978; Rosenthal et al., 1990; Hydrological Service Report, 1994).

The NS aquifer receives very little groundwater recharge, and any exploitation amounts to actual groundwater "mining". Furthermore, because little current exploitation of the NS aquifer occurs, water-quality parameters vary more over space than in time (Hydrological Service Report, 1989 and 1994).

HYDROGEOLOGICAL CONCEPTUAL MODEL

The Nubian Sandstone aquifer of Lower Cretaceous age underlies the desert of Central Sinai Peninsula and the Negev Desert. The aquifer is an extension of the sandstone formation of the African Shield that underlies Egypt and Libya and that extends westward through the Sahara Desert (Picard, 1953; McKee, 1962; Melloul, 1970; Forkasiewick and Margat, 1982; Idriss, 1989). The occurrence of fresh water in this formation was discovered 100 years ago in Algiers by Ville and Rolland (Issar et al., 1972). Since then, many wells have been drilled and the aquifer has been exploited to develop arid areas in the Sahara of Algeria, Libya, and Egypt (Ambroggi, 1966; Vauchez, 1967; Gonfiantini et al., 1974; LaMoreaux et al., 1985; Idriss, 1989).

The aquifer in the Sinai and the Negev is characterized by a thick, predominantly sandy sequence of sandstone with some intercalated clay beds. The unit is mainly terrestrial with intensive and variable colors interspersed with gritty conglomeratic sandstone that are frequently cross-bedded and mainly soft but occasionally quite hard (Bentor, 1960). The geology and structure are presented in figures 1 and 2 for the Sinai and in figure 3 for the Dead Sea region.

Outcrop areas of the aquifer are mainly in the southern part of Sinai; smaller areas occur in the northern part of the Sinai and in the Negev (near Eilat and near the Ramon area). From south (Sinai region) to north (Negev region) the following lithologic changes occur:

1) the sand component diminishes relative to the clay component;
2) the uppermost layer of the NS becomes increasingly calcareous and marly, and the proportions of alluvium and younger geological beds (Upper Cretaceous to Recent) increase, thus gradually transforming the NS unit from an aquifer to an aquitard and from phreatic to confined; and
3) the underlying unit changes from igneous rocks of Cambrian and Precambrian age to sedimentary rocks of Jurassic age (Melloul, 1970; Issar et al., 1972; Kroitoru, 1980).

Topographically, recharge areas of the aquifer occur in the high parts of Sinai, whereas its outlets are in the Arava River valley. This valley is formed by a "trough" component of the Afro-Syrian rift valley, which is a highly faulted and fissured complex, enabling a hydraulic connection between the Nubian Sandstone aquifer, and aquifers of Holocene sediments, and rocks

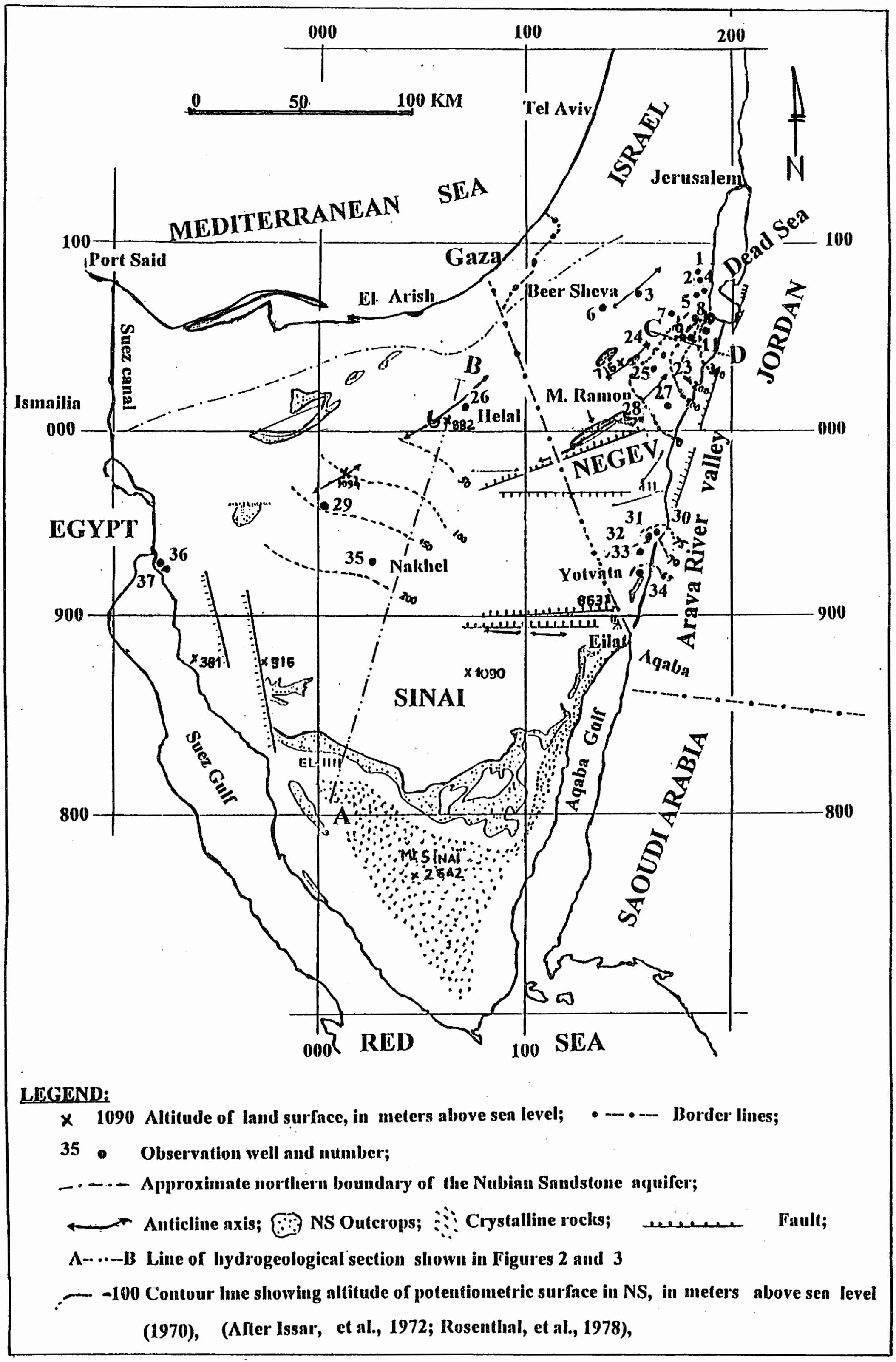


Figure 1. Hydrogeology of the Sinai Peninsula and Negev Desert, showing well locations and lines of section.

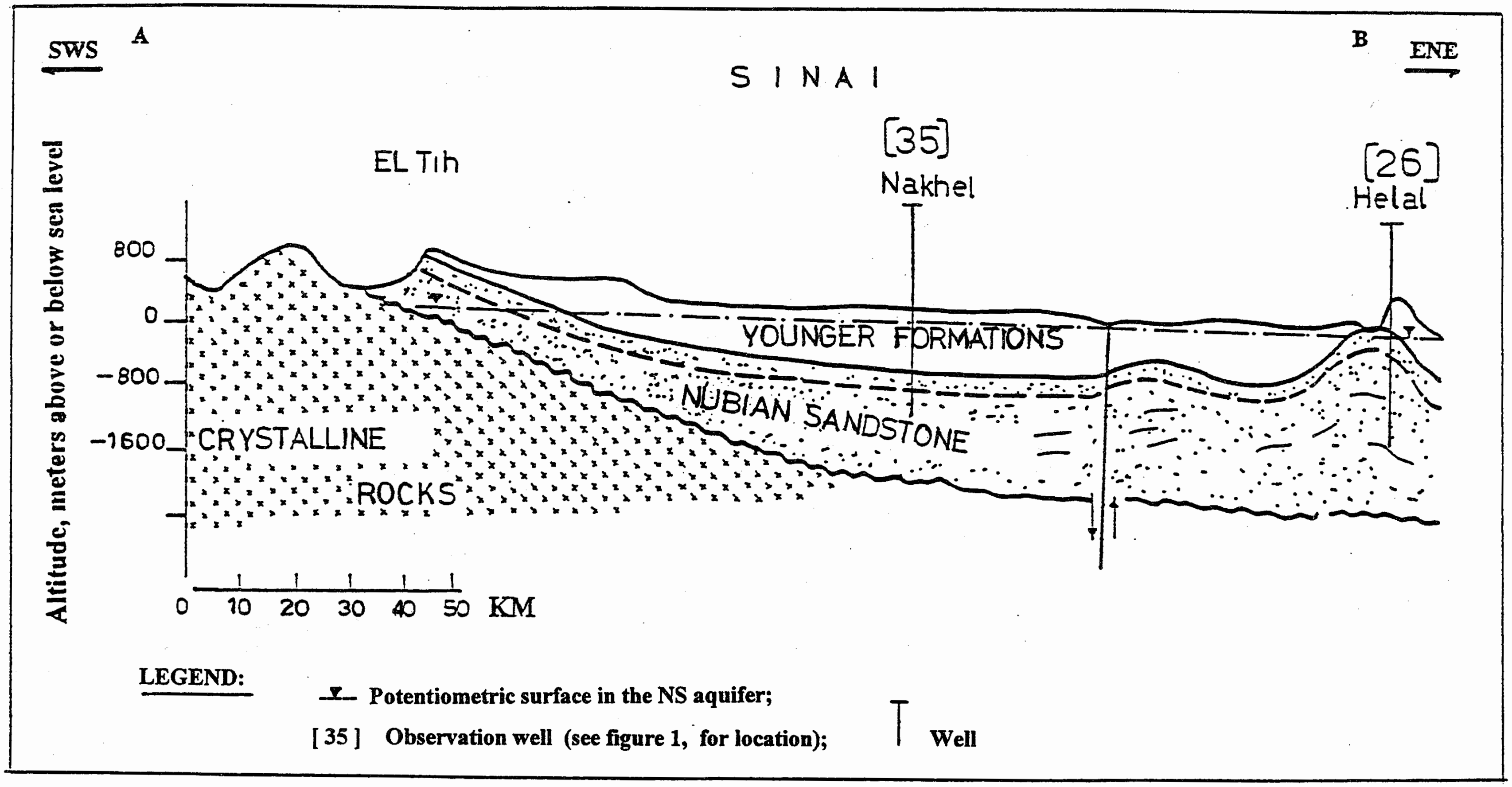


Figure 2. Hydrogeological section A-B of the Sinai Peninsula and Negev Desert (after Issar et al., 1972).

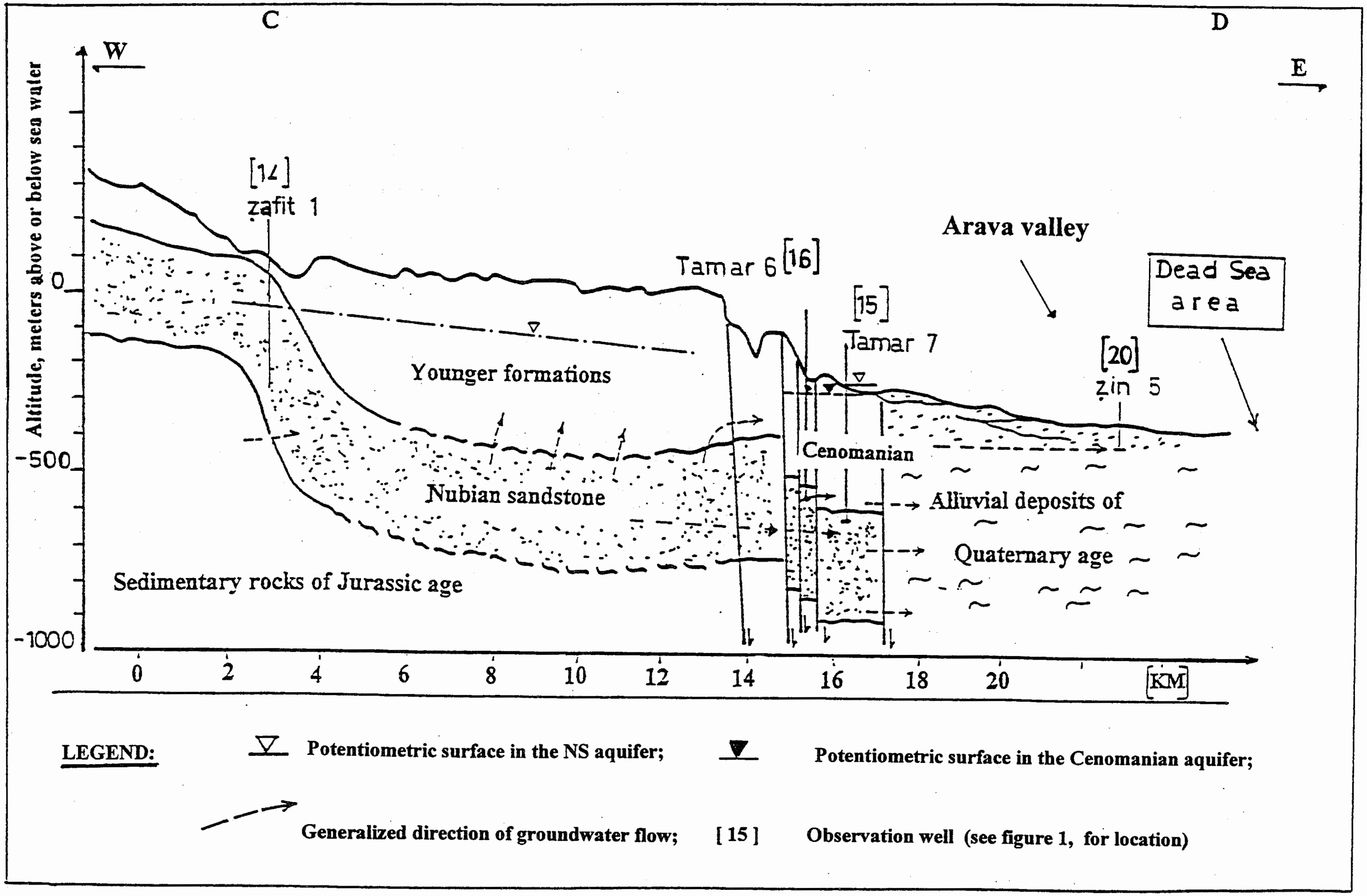


Figure 3. Hydrogeological section C-D of the Dead Sea area (after Rosenthal et al., 1978).

of Cenomanian and Jurassic age (fig. 3).

Topographically, recharge areas of the aquifer occur in the high parts of Sinai, whereas its outlets are in the Arava River valley. This valley is formed by a "trough" component of the Afro-Syrian rift valley, which is a highly faulted and fissured complex, enabling a hydraulic connection between the Nubian Sandstone aquifer, and aquifers of Holocene sediments, and rocks of Cenomanian and Jurassic age (fig. 3).

The potentiometric surface of the NS aquifer in the Arava River valley, shown in figure 3, is about 30 to 270 meters below sea level (Hydrological Service Report, 1994), whereas in the Sinai and in the central Negev it is about 100 to 200 meters above sea level (Issar et al., 1972; Hydrological Service Report, 1994). Recharge areas of the aquifer are arid environments; estimated average annual recharge is 20 to 100 mm/year (Issar et al.,1972).

According to the presently accepted model (Issar et al., 1972; Kroitoru, 1980; Rosenthal, 1990), groundwater flow is from the southern part of the Sinai north-northeastward to the Arava River valley in the Negev, which is probably the main natural discharge zone. Groundwater in the intervening region is generally confined.

The total quantity of water stored in this aquifer is estimated to be billions of cubic meters (Issar et al., 1972). However, when groundwater quality and economic constraints are considered, the quantity of exploitable groundwater is only about tens of millions of cubic meters (Hydrological Service Report, 1989).

The general concept of groundwater flow that has been adopted by most authors who have studied this aquifer includes the following:

1) a large proportion of groundwater is ancient, that is, about 10,000 to 20,000 years old;
2) the main recharge areas for the aquifer are the Nubian Sandstone outcrops that occur in the southern Sinai and smaller outcrops in the Makhtesh Ramon area in the Negev; and,
3) the general flow direction is indicated by a marked decrease in hydraulic head, accompanied by an increase in salinity, from the recharge areas in Sinai (in the south) toward the Negev (in the north), and from the Makhtesh Ramon area in the Negev towards the Arava River valley and the Dead Sea to the northeast and east.

This paper utilizes this relatively well-known aquifer as an example to check the proposed methodology in the study of such an aquifer. The paper also presents a rational way to develop a conceptual model of this kind of aquifer.

METHODOLOGY

The proposed methodology is a rational way to combine various multidisciplinary data in order to explain processes occurring in groundwater flow systems and, in order to improve efficiency of groundwater exploitation of deep aquifers with scarce data. The analysis is done by using PCA as a tool to identify chemical and physical groups, in combination with classical chemical and hydrogeological methods.

The proposed methodology and the four basic steps for developing a conceptual model are presented in figure 4 and described below.

Step 1 - Data-Bank Formation

The first step consists of collection of data from various bibliographic review sources dealing with the investigated area. Types of information include geological maps, description of structural and lithologic variability of the aquifers, and information obtained directly from the existing observation-well and pumping-well networks.

Types of data should include chemical variables (concentrations of calcium, magnesium, sodium, etc.); exploitation data (e.g., depths of wells, thickness of the aquifer, and specific-capacity data); isotopic data (oxygen 18, deuterium, carbon 14, and tritium); and hydrogeological information, such as water levels, lithology, and hydraulic parameters.

For optimal data processing, complete matrices of data should be displayed, where columns represent variables (e.g., calcium, magnesium, sulfate, and depth) and rows represent observations in space (e.g., well 21, well 23).

Step 2 - Processing and Analysis of the Data and the Formation of Groups.

The second step involves establishing relationships between chemical and physical data (e.g., exploitation data) within various regions of the aquifer. PCA is utilized to process data where a complete set of variables is available for each of the observation wells.

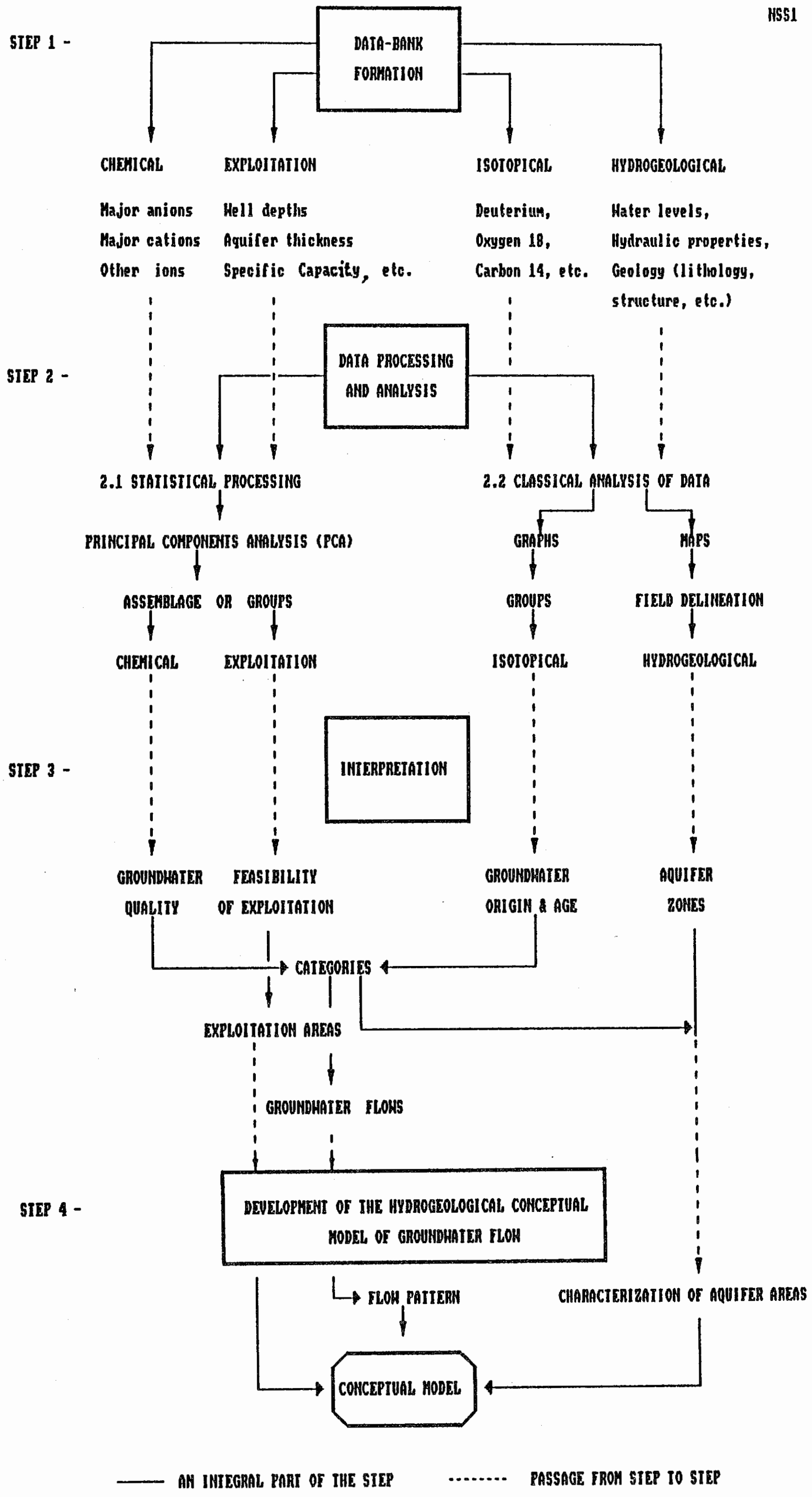


Figure 4. Diagram of the methodology.

Step 2.1 The PCA Processing

Data analysis is presented using the PCA method along with rotational transformations. PCA is a simple technique of Factorial Analysis, in which graphs are generalized, simultaneously taking into account all the elements involved, in order to achieve optimal data visualization (Laffite, 1972). The method defines a pattern of relationships by rearranging raw data, thereby reducing them to smaller sets of factors or components. This process allows the graphing of variables (v) and well-sampling sites (n) and emphasizes similar relationships between variables and sampled wells, which in turn allows establishment of connections with various properties of the data involved (e.g., proximity to salinity sources, pollution sources, and high transmissivity of the aquifer). This result is obtained by utilizing certain factor-analysis procedures.

One means of expressing these observations is to work in terms of "v" linear combinations while losing a minimum of information (Davis, 1984). The data matrix can be used as the basic input to other statistical methods for identification, e.g., factors shed light on changes in groundwater quality and properties of the aquifer (Laffite, 1972; Davis, 1984; Zhou et al., 1983).

Once a complete set of representative data has been collected for all the variables (v) and well sampling sites (n), the set is represented by a data matrix [X] of dimension v.n. The [X] matrix is then transformed to a variance-covariance matrix, which yields the principal components, which are orthogonal, that is, not correlated to each other. By themselves, these components may provide significant insight into the structure of the matrix (Davis, 1984). In fact, the solutions of the variance-covariance data matrix are given by "v" various factors. The first solution is the principal factor, F1, or the component representing the initial axis on the graph, explaining as much as possible the total variance of the observations; the second solution, F2, is the second factor, or the component representing the second axis (axis 2 on the graph), which explains as much as possible the residual variance, and so forth, for the other factors or components, each explaining less and less of the total variance. The first two components are then plotted as perpendicular axes, on which all variables and well-sampling sites involved are represented, as shown for instance in figure 5.

Specific coordinates for chemical variables, such as Ca, Mg, Cl, and NO_3, with regard to axis 1 and axis 2, are obtained by means of a varimax rotated factor matrix (Kaiser and Cerny, 1979). The samples' coordinates in regard to axis 1 (or factor F1) and axis 2 (or factor F2) are obtained in the same manner, by using factor score coefficients and standardization of the raw data. This standardization is given by the formula:

$$Z_{ij} = (X_{ij} - X)/\ s_j,$$

where:

X_{ij} = raw data of variable "j" in well sample "I",
X = a mean value of the variable X_j for all the well samples, and
s_j = standard deviation of the variable X_j for all the well samples.

Figure 5 shows that the two axes of the diagram represent the salinity of the water by axis 1 and bicarbonate and sulfate contribution by axis 2. Thus, the major ions representing water salinity occur near axis 1, and the bicarbonate and sulfate variable contribution near axis 2. This approach groups data of influential variables and well samples, thereby enabling identification of the relationship between these variables and individual well samples. By delineating the limits of the resultant assemblages of well-sample positions with regard to the axes, it is possible to note similarities of data that indicate prominent characteristics of water from the sampled sites. This delineation of observation-well assemblage limits is visual rather than statistical, simplifying the analysis of data. For instance, in figure 5, samples from observation wells located in the direction of major ions represent more saline water, while samples from observation wells located at a significant distance in the opposite direction from the arrow are fresh water.

In figure 5, the axis of the variables passes through the center of the graph. Thus, the direction of influence of each variable of well samples increases in the direction of the arrow (see, for example, well 28). When projected from its coordinates in relation to the two main axes, at right angles to the arrow for Na or Cl (which are closer to axis 1) and when extended through the centre, one can note the relatively low influence of Ca on this sample. However, projecting the position of well 28 on the arrow of bicarbonate (which is closer to axis 2) indicates the significant influence of high HCO_3 in this sample. The closer the data point's position to the axis of each variable on the graph, the stronger the correlation of this variable with the quality of water.

A similar analysis may be done for other new properties (fig. 6) in relation to other variables, such as specific capacity, depth to the top of the aquifer, and aquifer thickness. This process enables delineation of similarities, or "groups", of groundwater from observation wells in relation to the most influential variables affecting the aquifer.

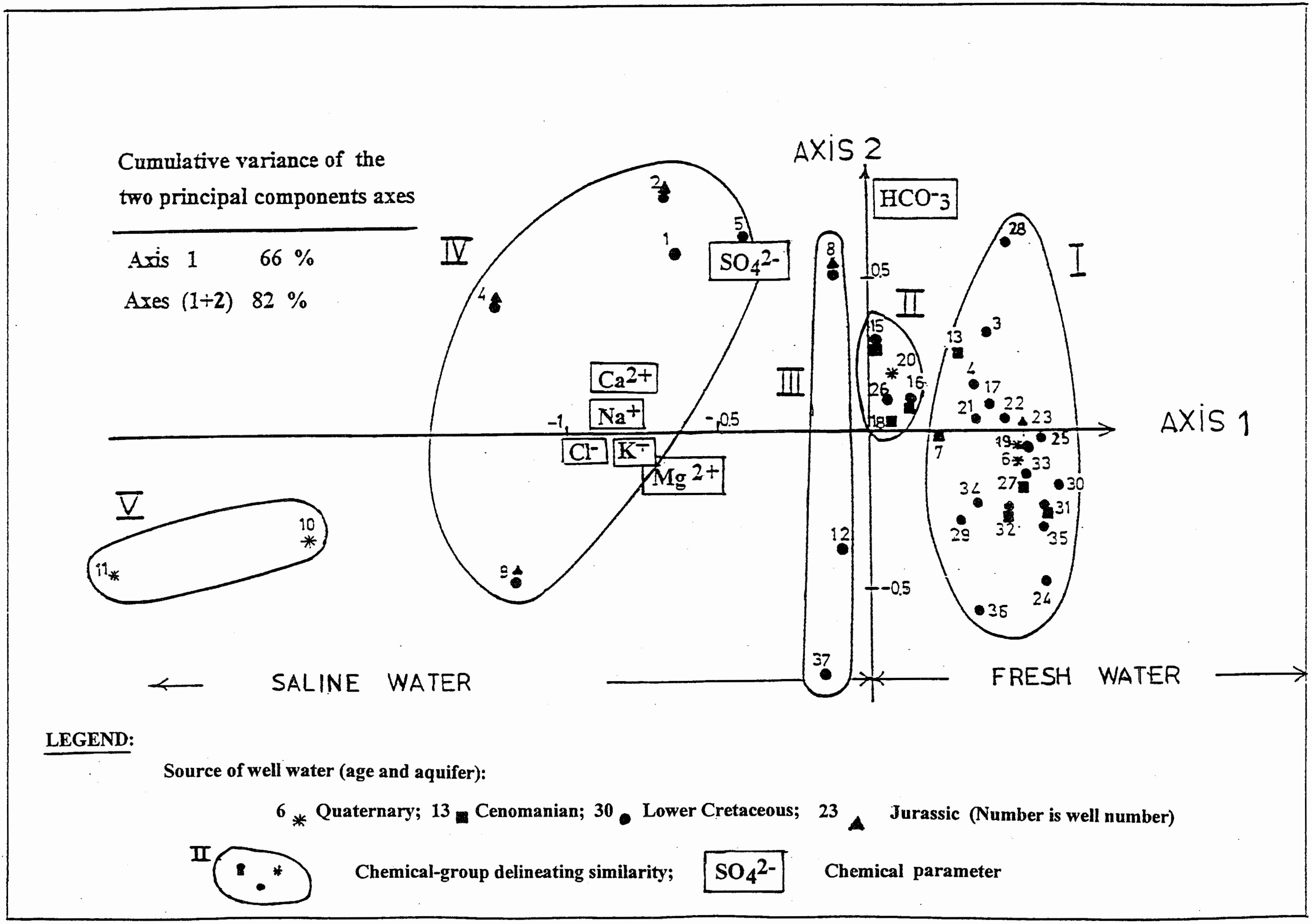
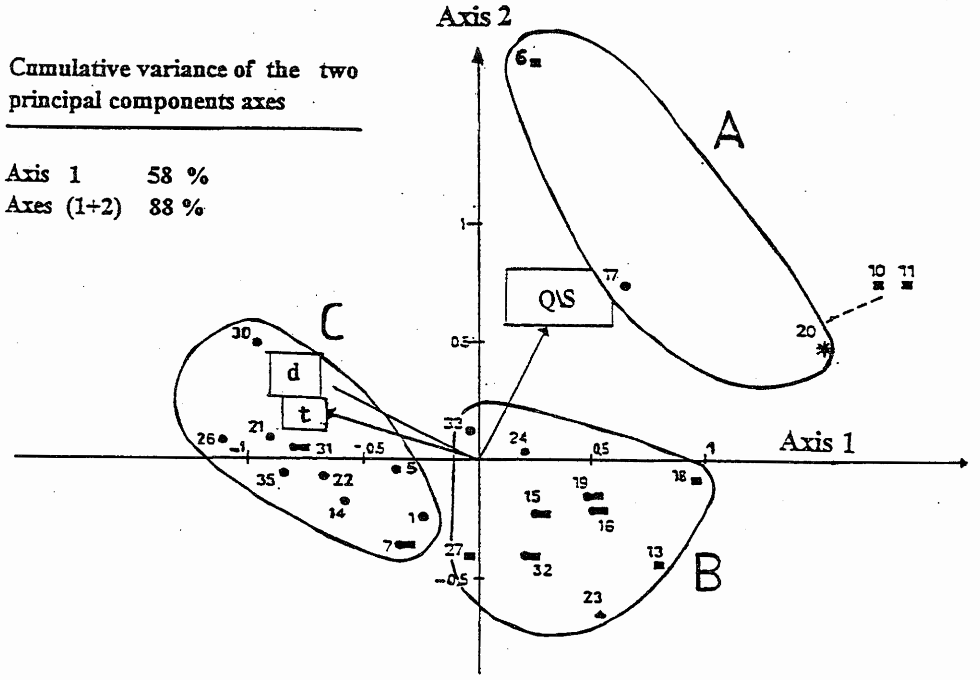


Figure 5. Chemical groups.



Cumulative variance of the two principal components axes

Axis 1	58 %
Axes (1+2)	88 %

LEGEND:

Q/S - Specific capacity [(m ^{3}/h)/m];

d - Aquifer depth [m]; t - Aquifer thickness [m]

A ◯ Group based on feasibility of aquifer exploitation

Source of well water (age of aquifer):

20 ✱ Quaternary; 18 ■ Cenomanian; 24 ● Lower Cretaceous (NS); 23 ▲ Jurassic (Number is well number)

Figure 6. Exploitation groups.

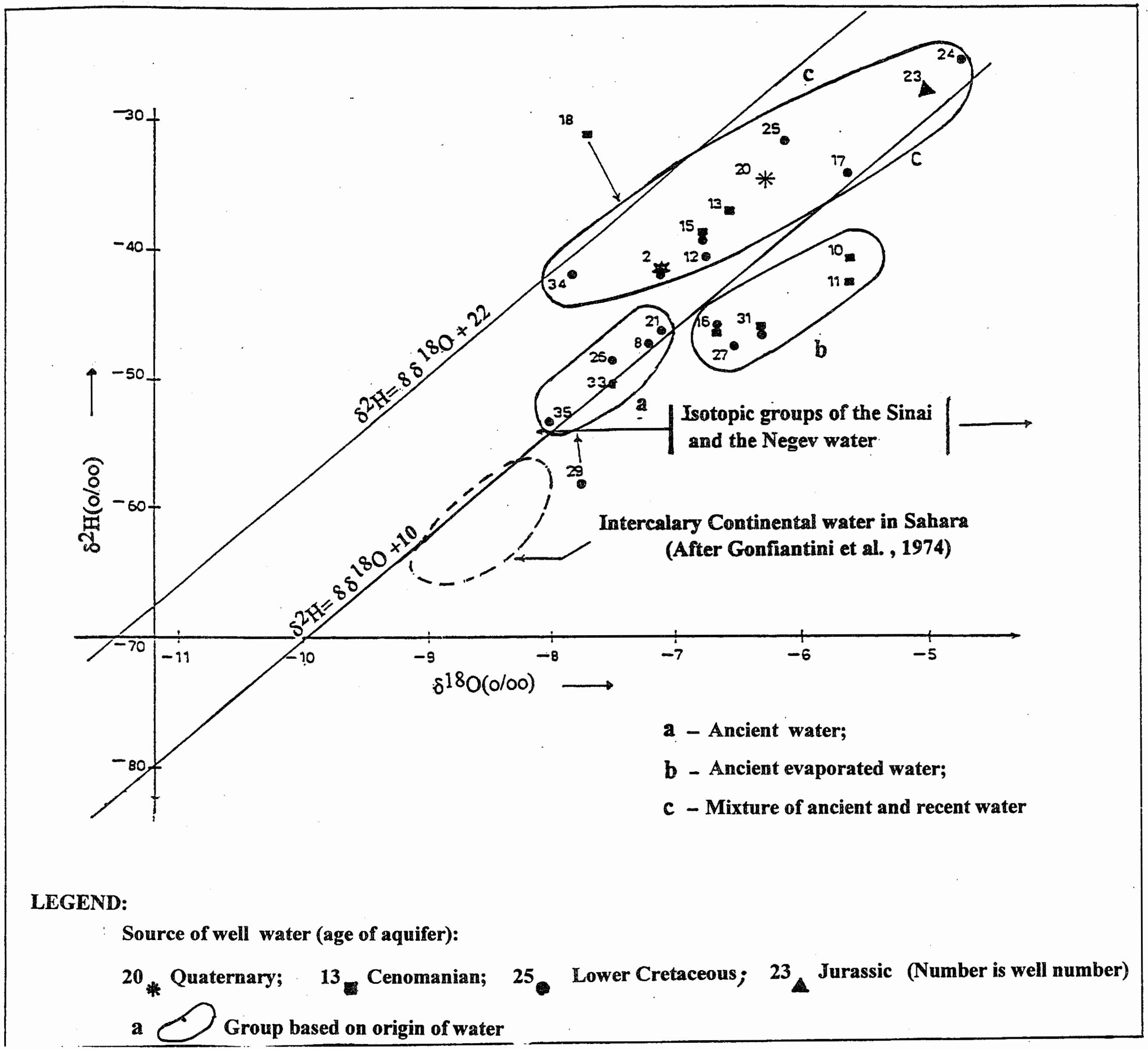


Figure 7. Isotopical groups.

The PCA method thus enables simultaneous processing of water-quality variables with physical and hydrological variables of the aquifer, as well as visualisation of and emphasis upon those variables that best explain changes in the character of water from one observation well to another within the aquifer. Thus, PCA is used as a tool that complements classical methods for processing data.

Step 2.2 Classical Manner of Analyzing Data

In the case of the isotopic variables with scarce and incomplete sets of available data, use of the PCA method is less helpful. In this case, only classical graphical representation of deuterium versus oxygen 18 was used to explain origin of the groundwater (fig. 7). Carbon 14 (observed in samples from only a few wells) was used only in special cases to estimate water age.

Additional information from hydrologic and geologic maps, showing such features as water-table configurations, hydraulic parameters, and lithology, was used in the final stages of this methodology to augment the existing data.

Step 3. Interpretation of the Results

Water Categories (C_i)

Categories of groundwater are simultaneously defined by quality, origin, and age. The quality of a given groundwater is affected by changes in chemical constituents due to processes that occur in the aquifer, such as water-rock interaction, groundwater evaporation, and relationships between fresh and saline and recent and fossil waters. The origin and age of water are obtained by means of isotopic variables, enabling a differentiation between water that was recharged during cooler climates that prevailed thousands of years ago and water that was recharged during a more recent warmer period.

By means of graphs, groundwater-quality groups (major chemical ionic data) and water from different origin and age groups (oxygen 18 and deuterium data) are combined to form water categories (C_i). This grouping is helpful in the development of the next step in the methodology.

Aquifer Zones

Aquifer zones delineate phreatic, confined or recharge zones of an aquifer. The lithological and structural information given by geologic maps and the combination of water samples from observation wells depicted in PCA groups are very helpful in defining various aquifer zones of the aquifer. For instance, low-salinity water, rich in oxides as sulfates and bicarbonates (as determined by the PCA), when also relatively young (as determined by isotopes), can assist in establishing recharge areas. Similarly, PCA groups of saline and older water, obtained from relatively deep wells in the same aquifer, assist in establishing discharge or transition zones that are little affected by recent groundwater recharge.

Operational or Exploitation Areas

The term "exploitation", as used here, relates to groundwater development and involves such parameters as total depths of wells, d (essential for approximating drilling cost), thickness of the aquifer, t (for estimating the physical importance of the aquifer), and specific capacity, Q/s (to express in general the feasibility and capacity of exploitation of the aquifer). A relatively shallow well with high specific capacity can delineate a good exploitation area of the aquifer (e.g., well 24). PCA processing of data relative to these aquifer exploitation variables leads to "well exploitation groups", as shown in figure 7. When mapped, these results may lead to delineation of operational areas, suitable for further development.

Step 4 - Development of the Hydrogeological Conceptual Model of Groundwater Flow.

In this last step in the methodology, results and interpretations of data converge to develop the hydogeological conceptual model of groundwater flow, which consists of an interpretation of groundwater flow patterns in relation to various areas and zones of the aquifer.

Flow patterns represent the major directions of groundwater flow in the aquifer. In the course of movement from recharge to discharge zones, groundwater properties change in space. These changes may be explained simultaneously by the quality, origin, and age of the water. Recharge zones are represented by specific categories of groundwater, characterizing certain segments of the flow. An undisturbed aquifer (one with no faults, leakage, etc.), would likely be one with the youngest groundwater that has the lowest salinity.

Discharge zones are represented by water of other categories that occur elsewhere in the area. In this case, an undisturbed aquifer would likely be one having older groundwater with higher salinity than that of the recharge areas.

It is assumed here that a connection exists between water coming from the recharge zone and that arriving at the discharge zone. In the case of a groundwater basin composed of a confined aquifer recharged in part from a phreatic aquifer where the water level is higher than its discharge zones, flow in the aquifer is characterized by two water categories. The first involves the fresher and more recent water from the phreatic zone, whereas the second includes more saline and older water in its discharge zones. More complex flow phenomena include leakage from neighboring aquifers, evaporation, mixing of entrapped saline and fossil waters, etc. In this case, more water categories must be added to explain these properties of the flow.

Complementary hydrogeologic data such as geologic structure, lithology, groundwater levels, and hydraulic parameters, enable more exact mapping of aquifer zones and the various groundwater flow patterns. Superimposing exploitation zones on these flow patterns can delineate the most effective operational regions, where further groundwater exploitation of the aquifer may be recommended. Together, these steps result in the construction of the hydrogeological conceptual model of the aquifer.

RESULTS

The methodology illustrated in figure 4 was applied to the NS aquifer of the Sinai Peninsula and the Negev Desert, as represented in figures 1, 2, and 3. Most of the data are from the NS aquifer, but some are from the Quaternary, Cenomanian, and Jurassic aquifers, which in some areas have hydraulic contact with the NS aquifer by means of the numerous faults and fissures that characterize the Arava region. The investigation is based on data from 37 wells (Melloul, 1979).

The application of the PCA method to process data generated three groups of observation wells, based on:

1) chemical component (fig. 5);
2) feasibility of aquifer exploitation (fig. 6); and
3) origin of water when utilizing the classical method (fig. 7).

The processed data are summarized below.

Chemical Groups

The quality of groundwater is defined in figure 5 on the basis of major chemical ions, such as magnesium, calcium, potassium, sodium, and chlorides, as the main parameters of axis 1. The major variables that are closer to axis 2 are bicarbonates and sulfates.

The boundaries between various chemical groups, shown in table 1 and illustrated by figure 5, are arbitrarily chosen. All these data refer to the two main PCA axes, which explain almost 82 percent of total variance. The chemical characteristics of each of these groups of groundwater are summarized as follows:

1) Groups I and II represent the less saline, or relatively "fresh" water. Group I waters have cations that range from 21 to 50 meq/l, and Group II waters have cations that range from 51 to 65 meq/l. They include samples from the Lower Cretaceous rocks of the Sinai and the other aquifers in the Arava River valley, south of the Dead Sea. All the well numbers of these groups are given in table 1.
2) Groups III, IV, and V represent more saline waters. The salinity increases from Group III (66 to 83 meq/l cations) to Group V (161 to 291 meq/l cations), with high sulfate content for Group IV.

Most of the wells involving these groups are in the western part of the Dead Sea, whereas those with the highest salinity are near Mt. Sdom, a salt diapir (wells 9, 10, and 11 in figure 1). Data from wells in Groups III, IV, and V are from three aquifers, the Lower Cretaceous (NS), Cenomanian, and Jurassic, generally representing three different lithologies.

Analysis of the chemical constituents of the groundwater and lithological environments indicates a connection between salinity of the groundwater and the lithology of the aquifer.

Aquifer Exploitation Groups

Feasibility levels for aquifer exploitation are shown in table 1 and in figure 6 by such relevant variables as thickness (t) and depth (d) of aquifer as the main parameters of axis 1, and by specific capacity (Q/s) as the most representative parameter of axis 2.

By processing these physical data in a manner similar to that of the chemical data, well assemblages were arbitrarily delineated. The criteria were chosen on the basis of the hydrological significance of the axis.

An examination of these results shown in figure 6, indicates that the two main PCA axes explain almost 88 percent of total variance and that the well locations of Group B are of particular interest (as given in table 1); the wells that belong to this group have a relatively shallow well depth (100 to 400 m) and a medium specific-capacity value (in comparison to Groups A and C). Most of the water samples of Group B are also characterized by relatively low salinity. This process is helpful in demarcating areas where further exploitation of the aquifer is feasible.

Isotopic Groups

The origin of groundwater (e.g., ancient water, recharge by recent rainfall, and/or evaporated fossil or recent waters) was determined by means of the graphical representation of deuterium versus oxygen-18, expressed as per mil deviations from SMOW (d o/oo). The age of water that is more than 20,000 years old (and a maximum about 50,000 years) was obtained by means of carbon-14 values, given as percentages of modern carbon. This information was obtained only in wells 17, 22, and 35 and is used here as complementary data that are indicative of water origin. The delineation of water origin shown in table 1 and illustrated with classical graphics in figure 7, enables differentiation among three isotopic groups of groundwater (Groups a, b, and c).

Group a

The data points of this group (table 1) are very close to the line characterizing the ancient water of the Sahara Intercalary Continental aquifer in Algeria (fig.7), with deuterium levels between -55 and -65 and oxygen-18 between -8 to -9 (Gonfiantini et al., 1974), and the NS aquifer in the Sinai and the Negev. This water was recharged 10,000 to 20,000 year ago, when these areas had a temperate climate (Gat and Dansgaard, 1972; Issar et al., 1972; Gat and Issar, 1974). Water of this group probably has low 14C content, on the basis of data from well 35, in the central part of the Sinai Peninsula (fig.1).

Group b

The data points of this group (table 1) are also very close to the line characterizing the ancient water of the Sinai Peninsula and the Negev Desert (fig.7). The slope of the trend of data points in Group b (fig. 7) is less than the slope of the line for $8\delta^{18}O + 10$, which characterizes ancient groundwater that has been affected by evaporation (Gat and Dansgaard, 1972; Issar et al., 1972; Gat and Issar, 1974). Most of the wells of this group (e.g., wells 10, 11, and 16) are located in a highly faulted region south of the Dead Sea area (fig.8). Due to these faults, this ancient water originating in the Lower Cretaceous aquifer may also occur in Cenomanian aquifers (fig. 3).

Table 1. Chemical, exploitation, and isotopic well groups.

Group	Observation wells	Remarks
Chemical groups		**Range of cations (meq/l)**
I	3, 6, 7, 13, 14, 17, 19, 21, 22, 23, 24, 25, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36	21-50
II	15, 16, 18, 20, 26	51-65
III	8, 12, 37	66-83
IV	1, 2, 4, 5, 9	84-160
V	10, 11	161-291
Exploitation groups		**Hydrogeological data**
A	6, 7, 10, 11, 20	Large values of specific capacity, Q/s
B	13, 15, 16, 19, 23, 24, 27, 32, 33	Medium values of Q/s and small values of depth, d, and thickness, t
C	1, 5, 7, 22, 26, 30, 31, 35	Small values of Q/s, d, and t
Isotopic groups		**Interpretation of data**
a	8, 21, 29, 26, 29, 33, 35	Minimal amount of oxygen 18 and deuterium; near the line characterizing ancient water
b	10, 11, 16, 27, 31	Located below the line of ancient water affected by evaporation process
c	2, 12, 13, 15, 17, 18, 20, 23, 24, 25, 34	Located between the lines of ancient and recent water affected by mixture process

Group c

Data points for this group (table 1) are shown in figure 7 between the lines for $8\delta^{18}O + 10$ and $8\delta^{18}O + 22$; the lower line characterizes ancient water, and the upper is representative of recent Negev waters (Gat and Dansgaard, 1972; Issar et al., 1972; Gat and Issar, 1974). Data of this group plot on a line with a gentler slope than the line that represents recent water. Water from wells of this group (e.g., wells 15 and 20) are probably a mix of ancient water and recent water. These occur in various aquifers, ranging in age from Lower Cretaceous to Quaternary, that are hydraulically connected by faults (fig. 3).

Hydrogeologic information, such as water-table levels, hydraulic parameters, and lithology, were used to complement the above data, in order to delineate phreatic areas and/or zones of recharge of the aquifer.

INTERPRETATION AND DISCUSSION

Water Categories (C_i)

Water Categories integrate both chemical and isotopic properties of groundwater. Six water categories were delineated as follows; well numbers involved are shown in table 2:

1) C1 and C4 represent fresh and saline water, respectively, belonging to ancient water;
2) C2 and C5 represent ancient fresh and saline water, respectively, that have undergone evaporation or are even mixed with evaporated water; and
3) C3 and C6 represent fresh and saline water, respectively, that may be mixtures of recent and ancient waters.

The integration of these groundwater categories within their appropriate geological context is helpful for characterizing aquifer zones and groundwater flow.

Aquifer Zones

The hydrogeological conceptual model describes flow paths, or major directions of groundwater flow, in the aquifer and the evolution of groundwater from recharge zones to discharge zones. This evolution of groundwater in space may be explained simultaneously by the quality, origin, and age of the water. Each aquifer zone may be represented by one or more water categories.

Table 2. Water categories and groundwater flow paths.

Water category	Chemical and isotopic group	Observation wells
C1	(I + II) a	21, 26, 29, 33, 35
C2	(I + II) b	16, 27, 28, 31
C3	(I + II) c	13, 15, 17, 18, 20, 23, 24, 25, 30, 34
C4	(III + IV + V) a	8
C5	(III + IV + V) b	10, 11
C6	(III + IV + V) c	2, 12

Flow path	Water categories	Observation wells
F1	C3	34
F2	C2, C3	31, 33
F3	C2	27, 28
F4	C1, C3, C4	17, 21, 23, 24, 25, 26, 35
F5	C2, C3, C5, C6	10, 11, 12, 13, 15, 16, 20
F6	C1, C4, C6	2, 8, 26, 29
F7	?	36, 37

In this study, no data are available regarding outcrops of the NS rocks in the Sinai. The only available data are at well 35 (Nakhel well), which belongs to C1 category, representing ancient fresh water located about 100 km from the Sinai outcrops. Therefore, the recharge zones are delineated only by outcrops on geologic maps (fig. 9).

Groundwater samples from this well have relatively low salinity (Group I in figure 5) and are about 20,000 years old (Group a in figure 7). Groundwater of this aquifer depth. The location of this well group defines well is from a deep and confined portion of the aquifer. The location of this well is, therefore, characteristic of a confined transition zone of the NS aquifer.

The water sample from observation well 13, located along a fault and in an area of low topography and potentiometric head (fig. 8) in the Arava River valley, is

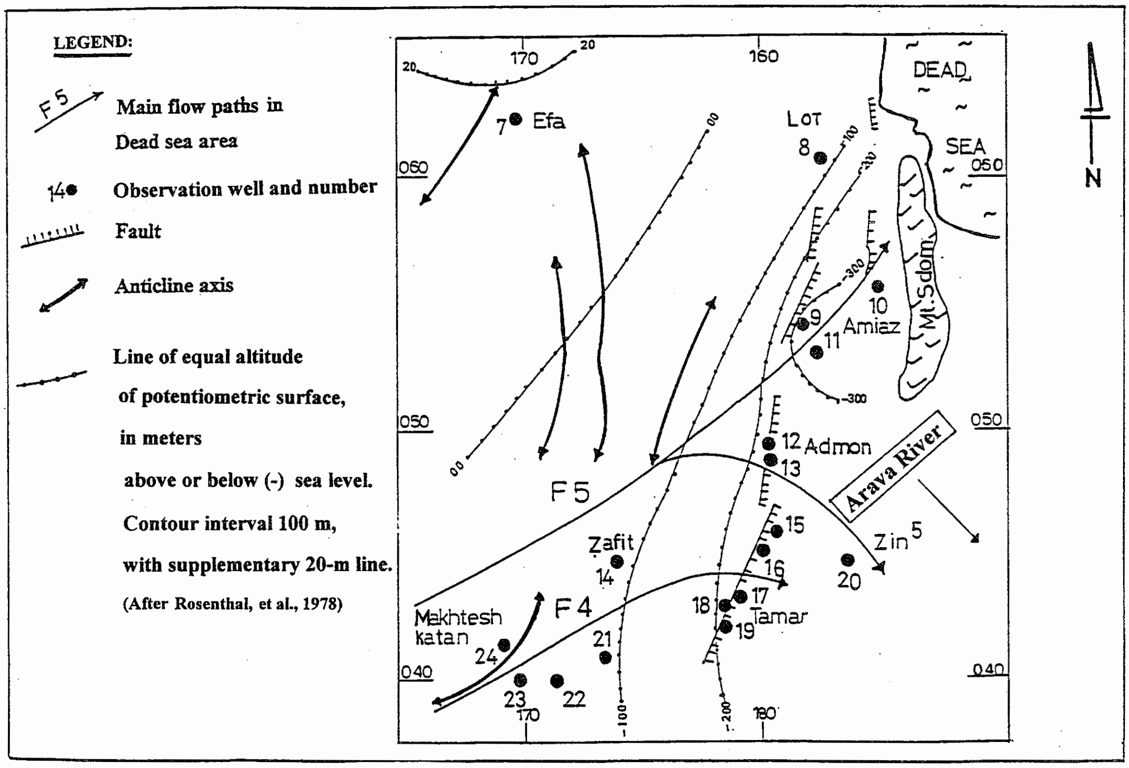


Figure 8. Hydrogeology and major groundwater flow paths in the Dead Sea area, Negev Desert.

defined here as belonging to water category C3 (table 2).This category represents water with relatively low salinity (chlorides) but richer in oxides (sulfates and bicarbonates); therefore, it is a mixture of recent and ancient water that has undergone evaporation (isotopic Group c in figure 7). This category defines one of the discharge zones of the NS groundwater in the Arava River valley.

Exploitation Areas of the Aquifer

Operational areas that are delineated by the exploitation groups can be derived from figure 6. In this figure, the observation wells of Group B are representative of wells that have relatively high specific capacity, moderate aquifer thickness, and shallow the most feasible region for aquifer exploitation. For instance, well 13 belongs to the well group having the highest feasibility for exploitation in the aquifer (Group B in figure 6). It has a relatively small depth (about 141 m from the ground surface) and a high specific capacity (19 m^3/hour/meter drawdown). When the position of this well is projected onto a geologic map, an area is defined that is favorable for further exploitation of the aquifer.

Groundwater Flow Paths

Major groundwater flow paths may be explained by the evolution of one or more of the aquifer's water categories. This approach assumes that a connection exists between water from the recharge zone, through the transition zone, and to the discharge zone. Aquifer zones and flow paths are illustrated in figures 8 and 9. All of these constitute the hydrogeological conceptual model of the NS aquifer.

Seven groundwater flow paths are distinguished (table 2 and figures 8 and 9). Flows paths F1 to F6 discharge into the Jordan Valley. Of these, the shortest is F1, which begins in the southeastern portion of the Sinai NS outcrops and ends at the discharge zone, in the Eilat region. F6 is the longest groundwater flow path. It begins in the southwestern Sinai and ends at the discharge zone in the northern Negev, near the Dead Sea. Flow paths F1, F2 and F3 are characterized by relatively low salinity, whereas F4, F5, and F6 are saline to highly saline. Flow path F7 is characterized by only one water category, discharging into the Gulf of Suez.

In the southern Sinai, groundwater that occurs from 100 km (well 35) to 200 km (well 26) north of the NS

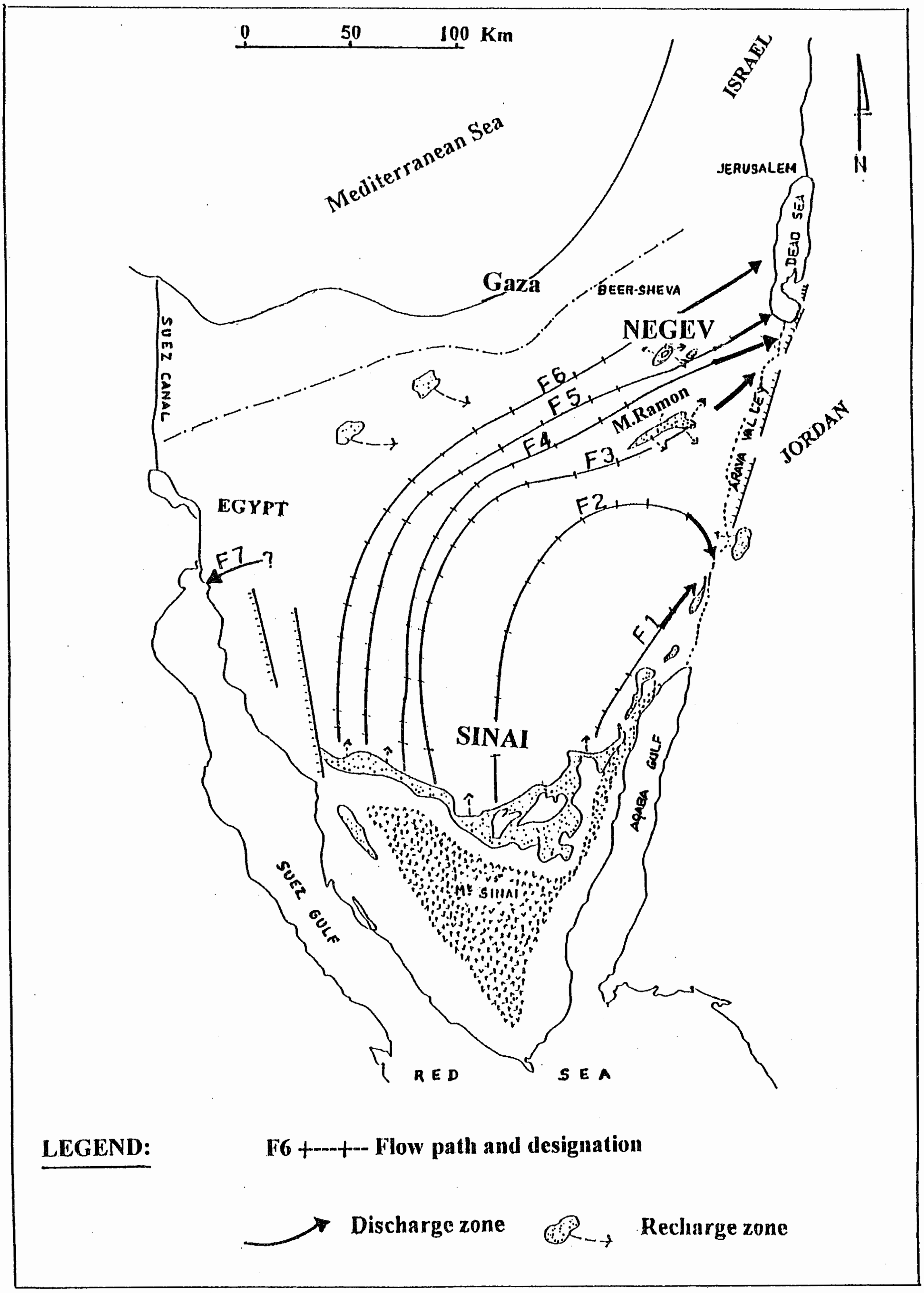


Figure 9. Hydrogeological conceptual model of groundwater flow in the Nubian Sandstone aquifer, Sinai Peninsula and Negev Desert.

aquifer outcrops has low salinity and originates from the NS aquifer (fig. 1). From the northern Negev to the Arava River valley, new sources of water likely come from recharge through the Negev NS outcrops (Makhtesh Ramon area in figures 1 and 9), from inflow of recent water from the Quaternary aquifer (from Jordan's eastern bank), and from faults (fig. 9). From the Sinai NS outcrops to the Negev, groundwater salinity increases, due mainly to the facies change from sandstone to clay in the Lower Cretaceous aquifer of the Sinai and the Negev (Melloul, 1970; Issar et al., 1972; Kroitoru, 1980). From the Negev to the Arava River valley, more radical changes in categories of water probably occur both in quality and origin, especially near the discharge zones. These changes are due mainly to mixing of water from several aquifers, as a result of the presence of the multitude of faults that occur in the Arava River valley south of the Dead Sea (fig. 3).

Despite the heterogeneity that characterizes these areas, groundwater-flow evolution can be distinguished from outcrops to discharge zones on the basis of changes in water categories. For instance, flow path F4 is defined in table 2 by three categories of water: C1, C3, and C4. C1 includes water from well 35, which is closer to the outcrops of the Sinai, and well 26, located 100 km farther north than well 35. Water from these two wells is ancient (see Group a in figure 7), but water from well 35 is less saline than that from well 26 (see Groups I and II in figure 5).

This ancient groundwater was recharged from rain that fell 20,000 years ago on the NS outcrops in the Sinai. Since then, groundwater has flowed with gradually increasing salinity, but without any other marked alterations (remaining category C1), beneath the Sinai to the central part of the Negev. From there to the northern Negev, the aquifer received additional recharge from water entering the NS outcrops in the Makhtesh Ramon area (fig. 9), changing in water category from C1 to C3. From there to discharge zones in the highly faulted Arava River valley, some mixing of groundwater of various qualities and origins occurs, further altering its category to C4.

CONCLUSIONS

The findings from this study are in accord with a generally accepted hydrogeological conceptual model. This agreement corroborates the efficiency of the methodology utilized in this study. This methodology presents a systematic way to develop a conceptual model of deep aquifers with relatively scarce data. The PCA method treats a complex flow system by grouping various qualitative and quantitative parameters. Statistical PCA contributes to developing a conceptual model by:

1) categorizing water as a unified expression of such properties as salinity, origin, and age of groundwater;
2) delineating optimal operational zones for aquifer exploitation, and
3) defining and characterizing groundwater flow paths in order to distinguish factors involved in the evolution of groundwater along various flow paths.

Development of a hydrogeological conceptual model in this manner prepares the way for delineating specific groundwater flow paths and for identifying the most feasible areas for aquifer exploitation, and it offers explanations regarding water quality and the history of the aquifer's recharge.

ACKNOWLEDGMENT

The author is greatly indebted to Mr. Martin Collin for his help in editing this paper.

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