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UNE ÉTUDE INTEGRÉE DE LA QUANTITÉ ET DE LA QUALITÉ DE L'EAU SOUTERRAINE DANS LA PARTIE BASSE DU BASSIN DE LA SANTA LUCIA, URUGUAY

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RÉSUMÉ

Ce travail identifie et analyse les aspects variés et concomittants que prennent les caractéristiques quantitatives et qualitatives de l'eau souterraine du bassin sédimentaire de la Santa Lucia, Uruguay. Ce bassin comprend le bassin hydrologique de la partie basse des rivières San José et Santa Lucia, et la région côtière adjacente au Rio de la Plata.

Les données physiques et chimiques sont documentées d'une façon systématique et les relations observées décrites en conséquence. Les informations rassemblées par les diverses méthodes inter-disciplinaires sont aussi intégrées. Des structures plus simplifiées sont données sous forme de modèles conceptuels descriptifs et de modèles mathématiques.

La disponibilité de ressources suffisantes en eau souterraine a été établie par l'étude de la potentialité de l'aquifère (formation sédimentaire) en se basant sur les caractéristiques comme la perméabilité, la transmissivité et la productivité spécifique. Tous ces paramètres ont été présentés sous forme de carte d'isovaleur et une zone relativement favorable est indiquée du côté sud-est, sur ces cartes. La fluctuation des niveaux d'eau souterraine a été analysée à partir des enregistrements du niveau d'eau effectués au cours d'une période de huit mois (1987 et 1988). Des réseaux d'écoulement ont été construits à partir de ces données. La variation moyenne du niveau statique de l'eau observée entre les mois de l'année 1988 est de 0.35 cm. L'écart entre les niveaux moyens des puits aux minimum et maximum pour la même année est de 1 à 3 mètres. L'écoulement souterrain local se fait vers les vallées. L'écoulement régional est du nord vers le sud.

Les différents facteurs hydrologiques contribuant à l'arrivée et à l'écoulement de l'eau sont comparés. Une évaluation de la recharge nette de l'aquifère a été établie à partir de calculs de bilans hydrologiques. Les données (1980-1988) ont indiqué un surplus d'eau dans 80% des régions considérées.

La réaction de l'aquifère au pompage de l'eau (30 m^3/jour) a été analysée selon un modèle en écoulement transitoire, pour une région spécifique située au sud-est de la zone étudiée. Le modèle indique un rabbattement de 38 centimètres pour une période de 365 jours.

Les caractères isotopique et chimique des eaux souterraines sont étudiés. Les raisons des groupements chimiques des échantillons d'eau sont discutées par analyse factorielle en mode Q et par d'autres méthodes d'analyse classique des données. Les paramètres chimiques les plus importants, comme les nitrates et les chlorures sont présentés sous forme de carte d'isovaleur. Une carte de qualité de l'eau souterraine est préparée par la superposition de ces cartes d'isovaleur. En somme, la qualité des eaux souterraines ainsi que des eaux de surface est à l'intérieur des limites acceptables, sauf pour les nitrates qui sont très élevés dans plusieurs des puits.

Deux problèmes principaux associés à la contamination des eaux souterraines, l'un artificiel (usage excessif d'engrais), l'autre naturel (l'intrusion "d'eau de mer" provenant du Rio de la Plata) sont traités d'une facon détaillée. L'effet, à long terme, de l'usage constant d'engrais (contamination par les nitrates) a été analysé à l'aide d'un modèle conceptuel dit de "source diffuse". Le problème d'intrusion et le risque possible associé à l'exploitation d'eau souterraine dans les zones côtières sont discutés; des solutions pratiques sont proposées à l'aide des paramètres physiques et chimiques analysés dans cette étude. Présentement, on n`a pas trouvé d'indication sérieuse de contamination de l'aquifère par l'intrusion de l'eau salée, sauf pour la contamination de l'eau souterraine ainsi que l'eau de surface aux alentours de Delta del Tigre, à cause de la migration du Rio de la Plata vers l'amont de la rivière Santa Lucia.

Une carte des ressources d'eau a été réalisée en superposant la carte de la qualité de l'eau et les autres cartes comme la carte géologique, la carte de transmissivité et la carte de débit spécifique. Cette carte résume les évaluations portant sur la quantité et la qualité de l'eau souterraine dans la zone d'étude. Les zones de captage potentiel sont sélectionnées en se basant sur de telles évaluations. On en tire les applications pratiques de cette étude. Les développements des ressources en eau souterraine sont aussi discutés. On peut affirmer par ce travail l'existence d'un aquifère, vers le sud, contenant une eau souterraine suffisante en quantité et de qualité acceptable pour l'exploitation à grande échelle.

RESUMEN

Este trabajo identifica y analiza los aspectos inseparables y variados de las características cuantitativas y cualitativas del agua subterránea de la cuenca sedimentaria del río Santa Lucía, Uruguay. Esta cuenca comprende la cuenca hidrológica de la parte baja de los ríos San José y Santa Lucía y la región costera adyacente al Río de La Plata.

Los datos físicos y químicos se documentaron sistemáticamente y las relaciones observadas son descritas en consecuencia. Se integraron las informaciones recogidas por les diversos métodos interdisciplinarios. Algunas estructuras más simplificadas se presentan bajo forma de modelos conceptuales descriptivos y de modelos matemáticos.

La disponibilidad de recursos suficientes en agua subterránea fué establecida mediante el estudio de la potencialidad del acuífero (formación sedimentaria), basándose sobre las características como la permeabilidad, la transmisividad y la productibilidad específica. Todos estos parámetros son representados gráficamente, en forma de cartas de isovalor. Se identificó una zona relativamente favorable que se encuentra indicada en el lado sud-este, en estas cartas. La fluctuación de los niveles del agua subterránea se analizó a partir de los registros del nivel del agua efectuados en un período de ocho meses (1987-1988). Las redes de filtración fueron elaboradas a partir de estos datos. El promedio de la variación estática observada entre los meses del año 1988 es de 0.35 cm. La diferencia entre los promedios de niveles mínimos y los niveles máximos de los pozos por el mismo año es de 1 a 3 metros. La filtración subterránea local se dirige hacia los valles. El flujo regional se produce del norte hacia el sur.

Se compararon los diferentes factores hidrológicos que contribuyen al aporte y a la filtración del agua. Se estableció una evaluación del recargo neto del acuífero a partir de los cálculos de presupuesto hidrológico. Los datos (1980-1988) indican que existe un superávit de agua en 80% de las regiones consideradas.

Se analizó la reacción del acuífero al bombeo del agua (30 m^3 /jour), según un modelo de flujo transitorio, en una región específica situada hacia el sur. El modelo indica una disminución de 38 centímetros por un período de 365 dias.

Se estudió la caracterisación isotópica y química de las aguas subterráneas. Los resultados del muestreo de agua fueron reagrupados en grupos químicos (modo Q) y se presenta una discusión sobre las razones que justifican los reagrupamientos químicos de los muestreos de agua y de los agrupamientos obtenidos a través de otros métodos de análisis clásico de datos. Se presentan cartas de isovalor de los parámetros químicos más importantes, como los nitratos y los cloruros. El mapa de calidad de las aguas subterráneas fué preparado superponiendo las cartas de isovalor. En resumen, la calidad de las aguas subterráneas así como de las superficiales se encuentran al interior de los límites aceptables, a excepción de la concentración de nitratos que es muy elevada en varios pozos muestreados.

El trabajo analiza detalladamente dos problemas asociados a la contaminación de aguas subterráneas, uno de origen artificial, ligado al uso excesivo de fertilizantes y el segundo de origen natural, ligado a la intrusión del agua de mar proveniente del Río de La Plata. Analizamos por medio de un modelo conceptual llamado de "fuente difusa", el efecto a largo plazo del uso constante de fertilizantes (que provocan la contaminación por nitratos). El documento discute el problema de intrusión y las posibilidades de riesgo asociadas a la explotación del agua subterránea de las zonas costeras; se proponen soluciones prácticas a partir del análisis de los parámetros físicos y químicos encontrados en este estudio. No se encontraron indicaciones serias de contaminación del acuífero à partir de la intrusión del agua salada, a excepción de la zona situada en torno al Delta del Tigre, a causa de la migración del Río de la Plata contra la corriente del río Santa Lucía. En esta zona existe contaminación por agua salada tanto en el agua subterránea como en el agua superficial.

Superponiendo la carta de calidad del agua, la carta geológica, la carta de transmisividad y la carta de débito específico se produjo una carta de recursos de agua. Esta carta resume las evaluaciones sobre la cantidad y la calidad del agua subterránea en la zona de estudio. Las zonas potenciales de captage fueron seleccionadas basándose sobre estas evaluaciones. Se discute el desarrollo de recursos de agua subterránea y las aplicaciones prácticas de este estudio . A partir de este trabajo, se puede afirmar que existe en el sur, un acuífero que contiene agua subterránea en cantidad suficiente y en calidad aceptable para la explotación en gran escala.

ABSTRACT

This work identifies and explicitly reports the various inseparable aspects of quantity and quality characteristics of the groundwater in the Santa Lucia Sedimentary Basin, Uruguay. This basin comprises the lower parts of the hydrologic basin formed by the San Jose and Santa Lucia rivers and the coastal zone adjacent to the Rio de la Plata.

The various physical and chemical inputs and outputs are systematically documented and the relations observed accordingly described. The informations gathered by various interdisciplinary methods are integrated. Simplified frameworks are provided in the form of descriptive conceptual models and mathematical models.

The availability of adequate groundwater resources has been assessed by studying the potentiality of the aquifer (sedimentary formation) from the point of view of its hydraulic properties, like permeability, transmissivity and specific yield. All these parameters are presented in the form of contour maps, which indicate a relatively favorable zone towards the south eastern part of the basin. The fluctuation of groundwater levels has been studied from water level records of eight months (1987 and 1988). Flownets have been constructed from the data. The average change in static water level between two consecutive months for the year 1988 had been 0.35 cm. The difference between the average minimum and the average maximum water levels of the wells for the same year varied between 1 and 3 meters. The directions of the local groundwater flows are mostly towards the valleys. The regional groundwater flows are north to south.

The different hydrologic factors contributing to inflow and outflow are compared. Net recharge into the aquifer has been assessed from hydrologic budget calculations. The nine years (1980-1988) data have shown water gain in 80% of the region considered.

The response of the aquifer to pumping has been analyzed by applying the calculated parameters, such as permeability, infiltration and specific yield into a transient groundwater flow equation. A model has been applied to a specific region in the south eastern part of the studied area; a drop of head of 38 centimeters has been calculated corresponding to groundwater pumpage of 30 m^3/day over a period of 365 days.

The isotopic and chemical behavior of the groundwaters and some surface waters are intensively studied. The reasons for the chemical groupings of the water samples are discussed from Q - mode factor analysis and other methods of classical hydrochemical data interpretations. The most important chemical parameters, like nitrates and chlorides are presented in the form of contour maps. A groundwater quality map is prepared by superposing these contour maps. In general, the quality of the groundwater and also the surface water are within the acceptable range, except for the high nitrate (100 - 200 mg/l) in a number of wells.

Two main problems, associated with artificial (intensive use of fertilizers) and natural ("seawater" intrusion from Rio de la Plata) contamination of the groundwater are dealt with in detail. The effect, in time, of constant use of fertilizers (nitrate contamination), has been studied by a non-point pollution conceptual model. The problem of seawater intrusion and the possible risk associated with exploitation of groundwater in the coastal areas are discussed, with solutions given to practical examples in using the physical and chemical parameters found from the study. Presently, no contamination of the aquifer has been detected by salt water intrusion , except for the surface water and groundwater contamination around Delta del Tigre due to the upward migration of Rio de la Plata along the Santa Lucia river.

A water resource map has been prepared by the superposition of water quality map with other maps, like geological map, transmissivity map and specific yield map. This map summarizes the assessments made on the general groundwater quantity and quality of the area. Potential well field areas are selected based on such assessments. Practical applications of the study are extracted and groundwater resource developments discussed. This study affirms the existence of an aquifer, towards the south, which contains an appreciable quantity of groundwater of a reasonable quality that could be used for large scale exploitation.

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INTRODUCTION

1.1 The Major Hydrogeological Problems

This study forms a major part of the joint study program (geology and hydrogeology of the Lower Santa Lucia Basin, Uruguay) conducted by the DI.NA.MI.GE. (Direccion National de Mineria Y Geologia), Uruguay and UQAM (University du Quebéc à Montréal), Canada.

The absence of a comprehensive hydrogeological investigation, prior to this study, has necessitated a systematic hydrogeological survey including a clear description of the hydrogeological phenomena.

This work integrates the essential hydrogeological elements in the evaluation of possible groundwater resource areas, both from the point of view of quantity and quality. It provides recommendations on development and proper utilization of groundwater. Immediate solutions to various hydrogeological problems, such as groundwater pollution problems associated with the use of fertilizers is accorded prime importance. The problems of " sea water intrusion" are also discussed and solutions provided. This work will assess and predict the possible hydrogeological problems associated with the exploitation of groundwater in the sedimentary formations, where numerous wells are in operation, with the view to analyze the budget of natural balanced inflow-outflow patterns.

This study can be used as a base for future target - oriented studies, such as bore well constructions, irrigation plans, construction of dams, etc.

1.2 Objectives

The main objectives of this study are:

. To develop a scientifically sound methodology, which enables to obtain the maximum possible hydrogeologic information in a situation where data are scarce;

. To upraise scientific understanding of the natural phenomena that govern groundwater quantity and quality;

. To evaluate the potentiality of the sedimentary unit (Raigon Formation) from the point of view of large scale groundwater exploitation in order to supply the desired amount of groundwater of a reasonable quality for the city of Montevideo, as well as the rural population;

. To provide recommendations on the most efficient use of the available groundwater resources of the area.

1.3 Location and Accessibility

The study area lies in the south western part of Uruguay, which includes the southern part of the "department" of San Jose and small segments of the departments of Montevideo and Canelones.

The area is divided into two parts:

1) The southern part of Santa Lucia river basin, which includes the southern extremities of rivers San Jose and Santa Lucia and 2) the adjacent coastal zone, whose southern limit is Rio de La Plata.

Figure 1.1 shows the location of the country of Uruguay, Santa Lucia river basin and the study area. The total area covered in this study is about 3000 square kilometers.

The area is traversed by asphalted roads, "ruta 1" in the south and "ruta 11" in the north, joined by "ruta 3" and "ruta 5" respectively. Almost every part of the area is accessible by dry weather roads.

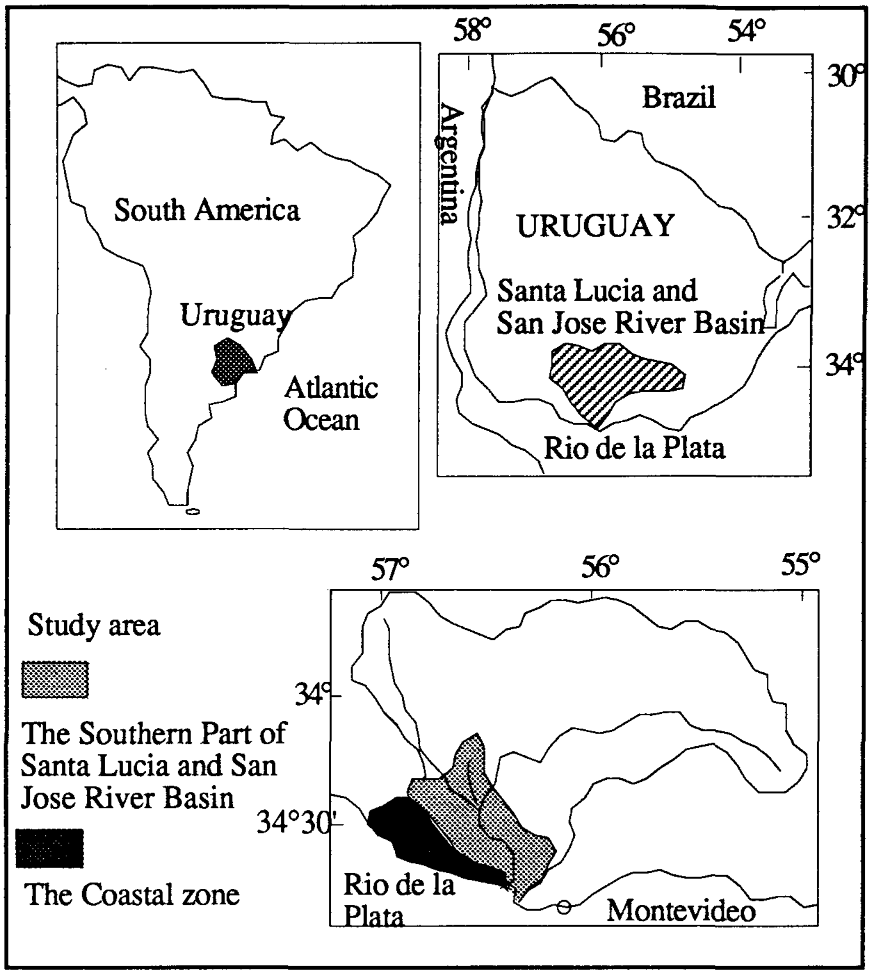


Fig. 1.1. Location map of the study area

1.4 A General Overview of the Previous Work and Present Work

The geology of the area has been extensively studied, since 1987, by DI.NA.MI.GE. geologists (M. Perez, M.J. Spoturno, J. Da Silva, C. Suarez, R. Arriguetti , and E. Medina) and their UQAM collaborators (G. Prichonnet and J. La Haye).

The hydrogeology of the area has been studied since 1987, by the hydrogeology team of the DI.NA.MI.GE. (L. Cardoso, M. Staff and R. Carion) and by UQAM - Marc Durand and the author with the participation of C. Hillaire-Marcel and P. Pagé in isotope hydrology and hydrochemistry respectively.

Some groundwater studies have previously been conducted by various governmental institutions and international organizations. Although these studies were carried out for other reasons, some relevant hydrogeological information was obtained.

In particular, groundwater feasibility studies of the present area have been carried out by OEA (Organizacion de los Estados Americanos), IGU (Instituto Geologico del Uruguay) and OSE (Obras Sanitarios del Estado). Most of the well information, referred to as drilled wells in this report (see Table 1 in the appendix) were obtained from IGU and OSE.

In conjunction with this work, the hydrogeology team of the DI.NA.MI.GE. has independently executed several field work programs, such as collecting water samples for chemical and isotopic analyses and water level measurements.

The author has, in collaboration with the DI.NA.MI.GE., spent about six and half months in the field as follows: May - June 1988, November-December 1988 and July - November 1989. Water samples were collected from selected wells and surface waters, with particular preference given to those areas which have groundwater pollution problems. Geological and hydrogeological observations were made. Pumping tests from borewells and from large diameter wells* and well tests were also conducted.

*Pumping tests of large diameter wells are refered to in this text as being equivalent to "slug test", after Kruseman and de Ridder, 1979.

Comparable Studies in Other Parts of the World

Several studies similar in nature to the present work are being held in different parts of the world. However, the hydrogeological problems encountered in this study being diverse (groundwater contamination from agricultural and industrial waste, "salt water intrusion", etc.), a methodology, that is capable of solving all the problems has been envisaged. No work has so far been encountered, that coincides with all the problems encountered and the method of approach discussed in this study. However, this study can be considered similar to other hydrogeological basin studies in its basic approach and system of analysis. For example, the Regional Aquifer-System Analysis Program of the U.S. Geological Survey are studying regional aquifer systems in order to establish background information of geology, hydrology and geochemistry of the important aquifer systems in the United States. Such information is needed to develop an understanding of groundwater flow systems and support groundwater resources management (Reston, 1986). In most of these studies, groundwater flow systems are studied by simulation techniques and the potentiality (quantity and quality) of the aquifer system analyzed.

The purpose of the present study is basically similar to the above mentioned program. However, it is different in the scope of understanding and the degree of precision of the information envisaged. In this thesis, more precise information is required from an area which has presumably less information than most of the regional aquifer studies in the United States. This study tries to overcome all the shortcomings due to data shortage by using alternative methods and comparing informations drawn from various investigatory methods. Any method if used in an appropriate way could be of some help. The disadvantage to using different methods is perhaps associated with the amount of effort involved. However, this thesis is a proof that it can be done if it should. This study has necessitated the analysis of hydrologic factors based on sub-division of the area into minor hydrogeologic sub-domains (for example, Bajar, 1971, Haile-Meskale, 1983). On top of this, hydrochemical and isotopic factors are incorporated. Due to the complexity of the hydrogeological problems considered and the absence of relevant background informations a wide variety of data had to be handled. This required a strict methodology, which develops a scientific understanding while at the same time provides the required informations.

1.5 Methodology

A variety of hydrogeological problems were tackled during this study and a great deal of information collected. Development of a basic methodology or strategy has thus become a priority task for an effective use of the information needed to solve the particular hydrogeological problems in question.

This work attempts to implement and integrate various interdisciplinary aspects related to hydrogeology, with the aim of drawing the maximum possible information from each, studying the interrelationships and extracting the most valuable for practical usage.

The major interdisciplinary aspects integrated into the comprehensive model discussed in this report are: geology, hydrology, geomorphology, climatology, isotope hydrology and hydrochemistry.

The major information gleaned from each and their inter-relationships are presented in a simplified form as in the following flow chart (see Fig. 1.2).

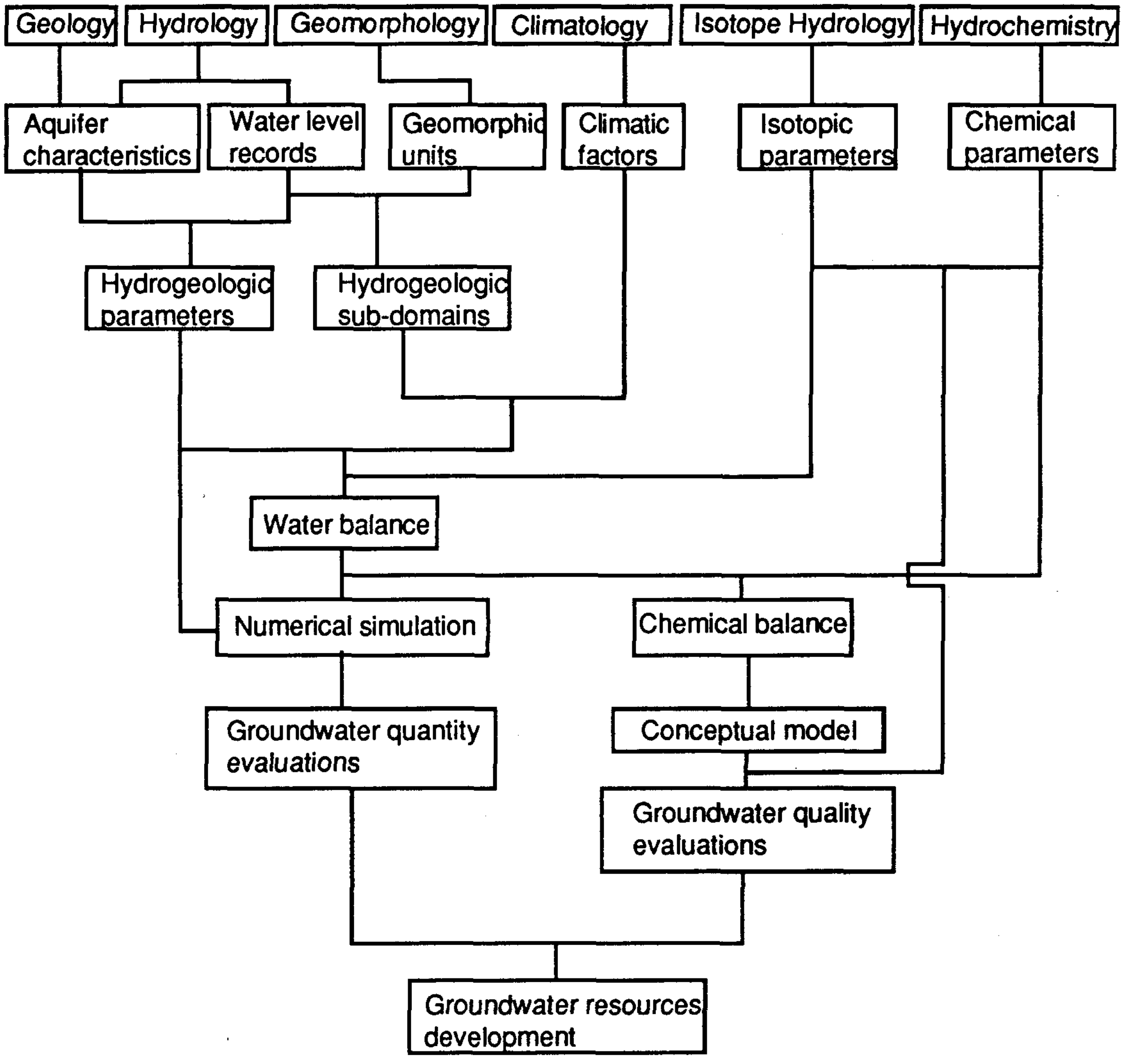


Fig. 1.2. A simplified flow chart of the methodology followed in an integrated study of the quantity and quality of groundwater in the lower Santa Lucia Basin.

The types of informations envisaged from the major interdisciplinary aspects are briefly discussed:

Geology (in chapter 2): The main informations drawn from the geological data are grain size distributions of the lithologic units which can be used to distinguish between the potential aquifer (Raigon Formation) and the aquicludes or aquitards. Aquifer parameters like permeability are qualitatively evaluated based on the general stratigraphic descriptions of the formations, whereas further detailed description of the geologic logs has enabled quantitative evaluation (estimations) of permeability values. The structural data have helped in determining the potentiality, direction and the movement of groundwater (see chapter 4).

Hydrogeomorphology (in chapter 3): The major landforms which influence the occurrence and movement of groundwater are identified. The major groundwater regions are deduced from a geomorphological map (see Fig. 3.1).

A base map was compiled from nine topomaps at 1: 50,000 scale, from which important features like rivers, roads, towns and the topographic contours were traced (see Fig.3.2). Additional information, such as possible location of springs (or seepages), small dams and marshy areas have facilitated hydrogeomorphic interpretations. The identification of marshy areas and vegetated regions is an important step in the calculation of the amount of water loss by upward seepage from groundwater evapotranspiration.

Hydrology (chapters 4 to 7): Aquifer characteristics, such as permeability, storativity and transmissivity, were determined from pumping tests in bore wells and large diameter wells and well tests (see chapter 4). A number of hydrologic parameters, such as groundwater discharge and groundwater velocity were determined from the water level measurements (see chapter 5).

Climatic factors have been statistically analyzed and used to separate relatively dry periods from relatively wet periods (see chapter 6). Parameters, such as actual and potential evapotranspiration were calculated from climatological data.

Evaluations of the quantity of groundwater becomes possible after integrating the different parameters. Some of the hydrogeologic parameters, such as groundwater discharge deduced from geology and hydrology, were used in conjunction with climatic factors, in calculating water balance in each of the hydrogeologic subdomains (see chapter 7). The hydrogeologic subdomains (see Fig.7.1) were constructed by the superposition of the geomorphic units with the average water level map.

The changes in storages obtained, from the water balance calculations at each hydrogeologic subdomain, were used as input values while numerically simulating transient groundwater flows. The resulting groundwater model has been evaluated and rechecked by comparing its output with the measured water levels.

Evaluation of the quantity of groundwater was made by observing the response of the model to possible climatic changes and/or to a given quantity of groundwater removal, that would meet the requirements of possible future use.

Isotope hydrology (in chapter 8): The stable isotopes of oxygen-18 and carbon-13 and the radio isotopes of carbon-14 and tritium were analyzed. The stable isotopes were used mainly to obtain information on the source of the waters. The radio isotopes were used mainly in determining the ages of groundwater.

Hydrochemistry (in chapter 9): The major ions determining the chemical characteristics of the waters, at various seasons, were analyzed both in the field and in the laboratory. The information thus obtained were analyzed with the aim of understanding the groundwater pollution problems. Groundwater quality evaluations (see chapter 11) were made from the analyses of the chemical parameters.

Conclusions and recommendations are made regarding future groundwater resource development, based on the above mentioned quantity and quality evaluations.

1.6 General Background

1.5.1 Geological Setting

The lower Santa Lucia Basin forms a part of a large geostructural intracratonic depression known as the Santa Lucia graben. The study area is located in the western part of this graben, where the sedimentary formations filling the graben are relatively thin (not exceeding 100 meters) in the western part (Oligocene to Pleistocene) when compared to the ones in the eastern part (Cretaceous to Pleistocene) which attain a thickness of 1000 meters or more.

Basement rocks, consisting mainly of gneisses, amphibolites, micaschists and micaceous quartzites (Preciozzi , 1985) are exposed in the northern part of the area. The sedimentary formations, consisting mainly of Oligocene - Pleistocene deposits, are of continental and marine (marine to brackish) origin. They unconformably overly the basement rocks and, are themselves overlain locally by recent, unconsolidated surficial deposits (eolian, fluvials and colluvials).

The sedimentary formations gently dip towards the south east, where they attain their maximum thicknesses. In general, the sedimentary formations pinch out towards the north. Concentration of coarser materials (small pebbles, rock debris up to large boulders) were locally observed at the base of the formations.

The basin is limited in the south by Rio de La Plata, which is an important continental outlet discharging its fresh water to the Atlantic Ocean. Some important seepages (springs), including Luis Pereyra, San Grigorio, Mauricio and Rio Del Tigre, emerging from the western part of the surface water divide, supply a large quantity of fresh water to the Rio de La Plata.

Later geomorphic events have divided the sedimentary basin into two distinct parts: An area dominated by the Rio de La Plata (the coastal zone) and an area dominated by the two young river valleys of Santa Lucia River and San Jose River (the southern part of the Santa Lucia Basin). A major surface water divide separates the later from the coastal areas.

1.5 .2 Climate

The country of Uruguay, being located between 30 to 35 degree south and 53 to 58 degree west, is a tropical region with a hot to temperate climate (Martinez , 1985). The climatic factors in the study area are, more or less, similar to the rest of the basin with some modifications being caused by proximity to the ocean. The mean annual rainfall is about 950 mm. The mean annual temperature is about 17 ° C., with minor fluctuations in the monthly averages, the maximum being 24 ° C in January and the average minimum 11° C in July.

1.5.3 Water Requirements

The total population in the study area, according to the 1985 census is 66,412. The total number of animals including cows, oxen, horses and sheep is about 585,000.

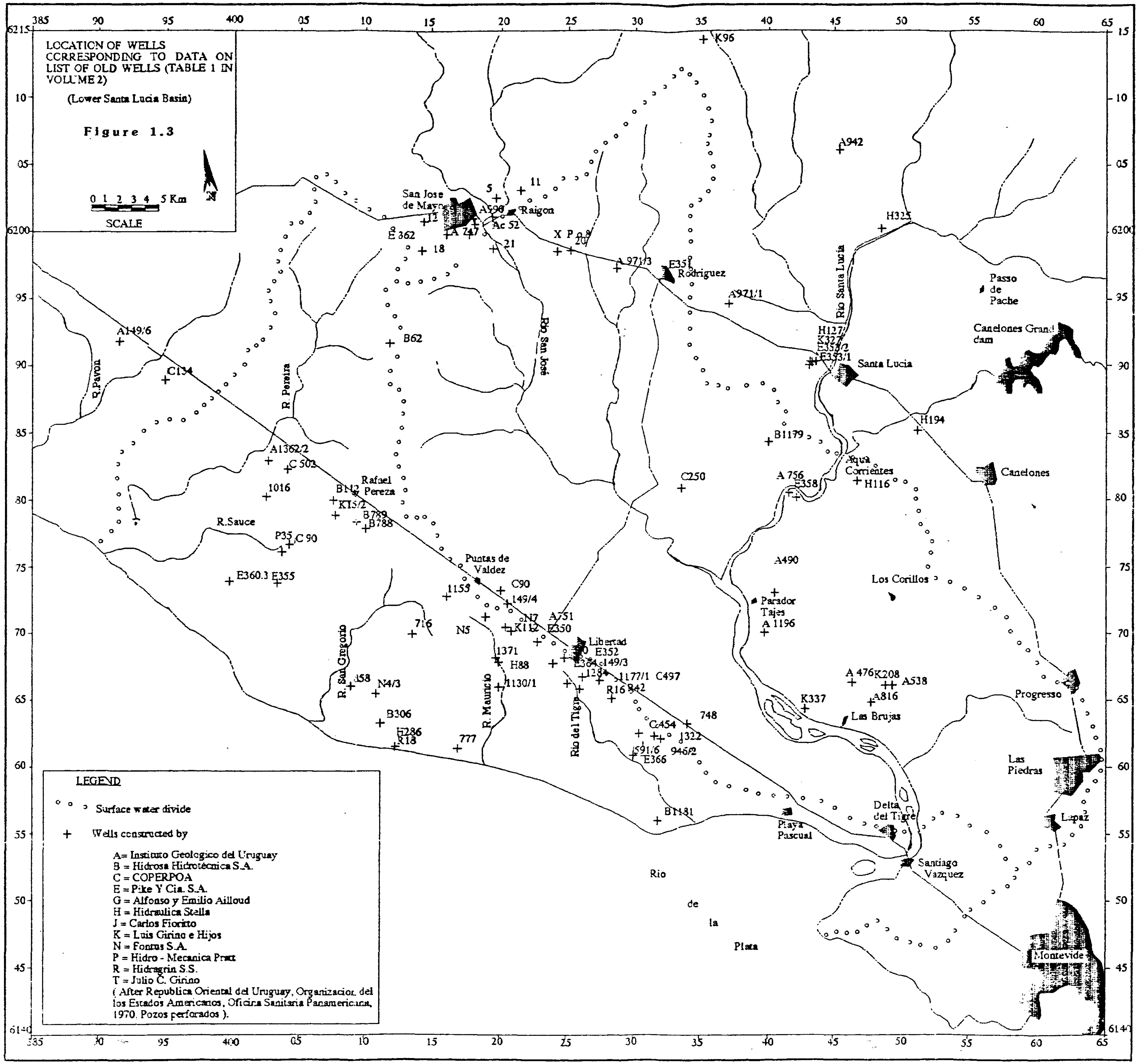
The main occupation of the rural population is agriculture and livestock. The principal crops are corn, oats, potatoes, orange and citrus fruits. Most of the industries are located along the road one "ruta uno".

The major water supply of the people for domestic, agricultural and livestock purposes is largely from groundwater. A number of excavated wells and deep borewells (several hundred) have been drilled in the sedimentary formations, most of which are concentrated along road "ruta 1". The well information compiled from old wells are presented in a table (see Table 1 for the descriptions and Fig.1.3 for the locations). The total depth of most of the wells is between 30 and 40 meters, and the static water level between 10 and 12 meters. Most of these shallow wells are excavated by hand and are tapped either by hand pumps, or by wind pumps. Centrifugal pumps are often used for wells less than 7 meters of depth to water. Relatively deeper wells are equipped with submersible pumps.

Other sources of water supply include rivers and small ponds. The average discharge of the two important rivers of Rio Santa Lucia and Rio San Jose is 732 million m^3/year and 683 million m^3/year respectively (UNESCO, 1979). Ponds have been built in depressions, where rain water is collected along small dry streams supplementing the water needs of the people.

The total population of Montevideo is about one and half million. Since 1973, there has been a rapid increase in the growth of industry, while the water supply, especially in some parts of Montevideo has deteriorated. Some wells have run dry and it has become more and more difficult to obtain new wells with appreciable yield. The major part of the water supply for the city of Montevideo is from surface water at Aguas Corrientes, where about 450, 000 m^3 of water per day is piped after passing through various stages of purification systems. The towns between Aguas Corrientes and Montevideo also benefit from this water.

Figure 1.3



LOCATION OF WELLS CORRESPONDING TO DATA ON LIST OF OLD WELLS (TABLE 1 IN VOLUME 2)

(Lower Santa Lucia Basin)

Figure 1.3

LEGEND

° ° ° Surface water divide

\+ Wells constructed by

A= Instituto Geologico del Uruguay
B = Hidrosa Hidrotécnica S.A.
C = COPERPOA
E = Pike Y Cia. S.A.
G = Alfonso y Emilio Ailloud
H = Hidraulica Stella
J = Carlos Fioritto
K = Luis Girino e Hijos
N = Fontus S.A.
P = Hidro - Mecanica Pratt
R = Hidragrin S.S.
T = Julio C. Girino
(After Republica Oriental del Uruguay, Organizacion del los Estados Americanos, Oficina Sanitaria Panamericana, 1970. Pozos perforados).

1.5.4 Groundwater Pollution Problems

The danger of groundwater pollution has become a serious problem in the Santa Lucia Basin in recent years. The major sources of contamination are related to the use of fertilizers, pesticides and fungicides. Some local contamination is also caused by domestic and industrial wastes.

It has been observed in the field that wells used for drinking purposes are located adjacent to and at times within farm areas, such as potato farms where fertilizers are intensively used. Some of these wells were also observed to be close to animal barns and drainage wastes.

Due to the scattered population pattern (a group of one or two families living at a farm and other small groups living at another farm), the consequence of high nitrate levels on the health of the population might not have been felt very acutely. However, it is apparent that the health of some of the farm dwellers is affected and may continue to be affected, unless preventive measures are taken to solve groundwater pollution problems of the area. These preventive methods will be given towards the end of this thesis, and it is hoped that the authorities concerned will act accordingly.

Chapter 2

GEOLOGY

2.1 The Structural Development of the Santa Lucia Basin

Several authors, including Martin et al. (1978), Goni and Hoffstter (1964) have presented a general framework for the structural development of the Santa Lucia basin. Figure 2.1 shows the general outline of the geology of the Santa Lucia basin.

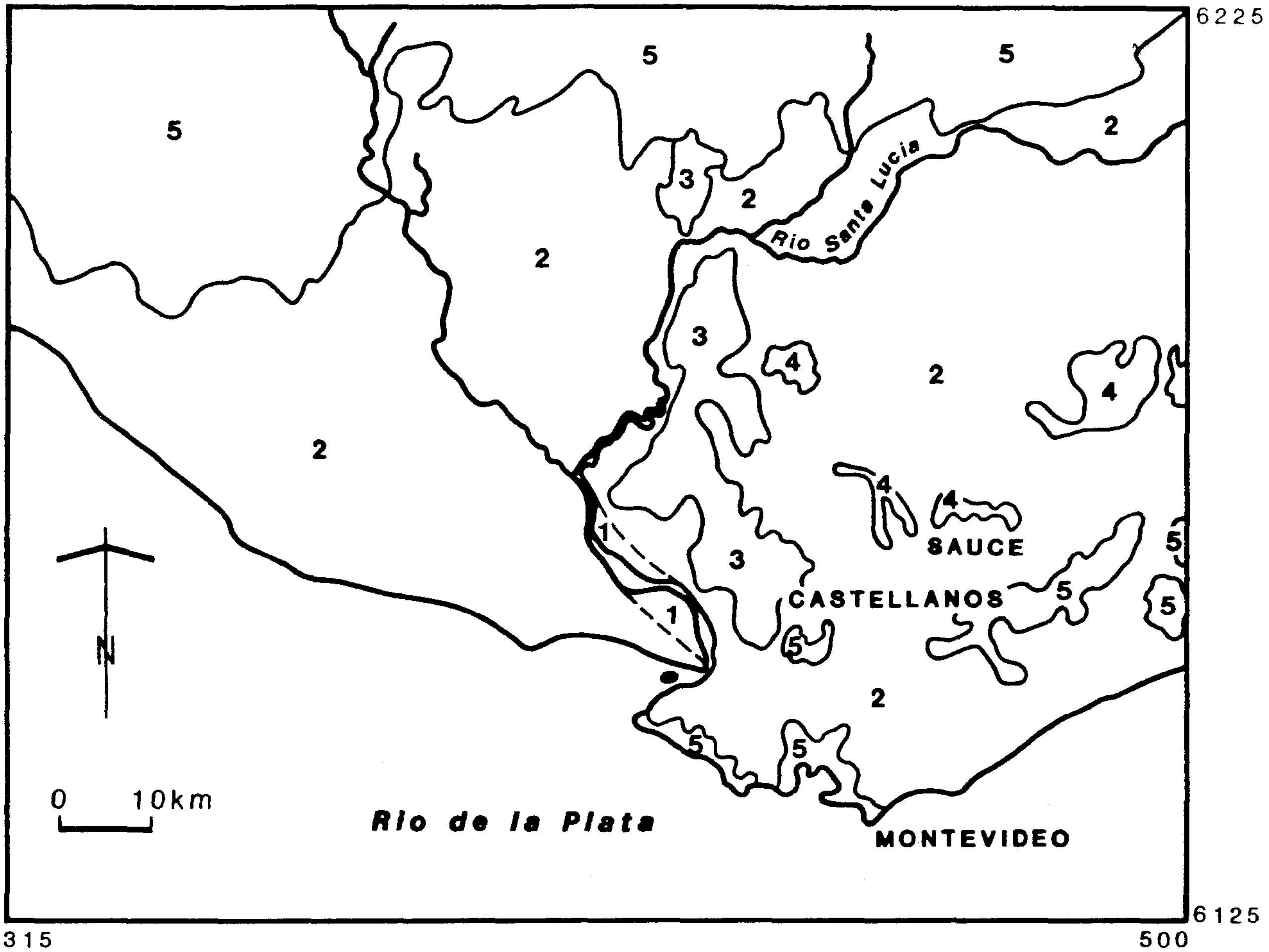
The Precambrian rocks of Uruguay belong to the South American Platform, which is one of the oldest tectonic region in South America. It is limited in the south, in Argentina, by the Patagonian Platform, which is a relatively young platform, whose basement stabilized from the middle Paleozoic onwards.

Martin et al. (1978) have indicated that the greatest stability of the South American Platform was marked by marine sedimentation during the Silurian and Devonian, mixed character during the Carboniferous, followed by continental during the Permian and Triassic. The basement of the South American Platform consolidated between the end of Precambrian and the Cambrian.

Severe tectono-magmatic reactivation took place from Jurassic and possibly from Triassic onwards. This gave rise to faulted basins, located in particular near the coast. These basins were then filled with marine sediments from the Albian-Aptian onwards. Intense tholeiitic magmatism occurred over all the platform, with particularly well preserved lava flows (Martin et. al., 1978).

Figure 2.1

A simplified Geological Map of the Lower Santa Lucia Basin. After Preciozzi F. et al., 1985



LEGEND

1: Alluvium (Recent)

2: Libertad plus Raigon Formations (Pleistocene-Pliocene)

3: Fray Bentos Formation (Oligocene)

4: Migues Formation (Lower Cretaceous)

5: Basement Rocks (Precambrian)

The formation of the Santa Lucia basin could be associated with the tectonism that affected the South American Platform. Van Der Hammen (1959) has made a study of fossils and age determinations from drilled logs at Castellanos (east of Las Piedras). According to this study, the Santa Lucia tectonic depression probably started towards the end of Jurassic or Lower Cretaceous (145 - 140 million years ago).

Larson & Ladd (1973) relate the creation of this intracratonic depression to the opening of the south Atlantic (crustal separation of the continent of Africa from South America began between 125 and 110 m.y. ago).

Post Cretaceous tectonism has produced, at some places, eruptive lavas (hypersthinite basalts). The fact that these lavas have pillow structure and are rich in sulfides indicates submarine flows (Goni and Hoffstter, 1964).

This tectonic activity, which produced lava flows, is most probably related to the formation of Santa Lucia depression. The basaltic lava flows belong to the Puerto Gomez Formation. They are found filling up the lowest parts of the depression interstratified with the sediments; outcrops of the Puerto Gomez Formation are found towards the eastern limit of the Santa Lucia graben, towards Minas town.

The graben was filled with continental deposits known as the Miguez Formation, followed by successive continental and marine deposition. The later constitute the sedimentary deposition of the area studied.

The Miguez Formation, which consists of fine to medium grained, stratified, argillaceous sandstones (Preciozzi, 1985), constitutes a major part in the eastern part of the basin. Deep bore holes drilled by the IGU (Instituto Geologico del Uruguay) and ANCAP (Administracion Nacional de Combustibles, Alcohol Y Portland) indicate thicknesses of 2400m, at Sauce (north east of Montevideo), and 1636m, at Castellanos, both in the "department" of Canelones.

Although the Miguez Formation forms a pile of thick sediment, at certain sites within the graben, it is totally absent at other parts; for example, it is not encountered in the western part of the basin. Basement outcrops are encountered within the graben in the eastern part of the basin.

The Santa Lucia depression could then be viewed as a major tectonic depression which embodies other tectonic faults of secondary importance producing minor grabens and horsts within the major depression. Gravimetric surveys and thickness measurements of sediments from deep borehole drillings indicate the existence of such graben horst relations.

The longitudinal and transverse dimensions of the Santa Lucia tectonic depression is 120 Km. by 45 Km. respectively (Bossi & Umpierre, 1975). The eastern extension of the graben goes up to Minas, where it is interrupted by north-south running faults. Its western limit goes up to Arazati, or may even extend further west, towards Colonia.

Gravimetric survey, as well as drill informations, indicate progressive thinning of the total bulk of sediments towards the west (study area). In particular, the thick continental Cretaceous sediment belonging to the Miguez Formation is probably absent, or occupies very limited (lowermost) parts of the depression. The overlying Oligocene Fray Bentos Formation is observed, at places in the north (around the town of San Jose) in contact with the basement rocks.

Such progressive thinning of the lowermost Miguez Formation towards the west may be explained by eastwardly plunging graben, which progressively deepens towards the east; the graben and horst relations within the main graben are compartmented by north-south faults.

A possible fault running north - south along the Santa Lucia river at Parador Tajes has been deduced from a step forming topography. It should be noted that although the present topography and thickness of sediments are largely influenced by the morpho-tectonics of the basement topography, the sediments themselves remain unaffected by tectonism, since the tectonic events occurred during the Lower Cretaceous. Post tectonic erosion and deposition have obscured the basement topography, filling up its irregular parts, thus resulting in a more or less uniform and gently dipping, flat topography.

However, the topography of the basement rocks could be viewed with reference to the tectonical activities discussed above. The thicknesses of the the sedimentary formations is largely dictated by the underlying topography of the basement rocks.

2.2 Litho-Stratigraphic Units and Their Relative Permeabilities

The geological units in the western part of the Santa Lucia Graben are Oligocene to Pleistocene sedimentary units, overlying crystalline basement rocks. The sedimentary units are covered, in very restricted zones, by recent unconsolidated surficial deposits (marine, eolian and alluvials).

In the foregoing discussion, concise description of each of the sedimentary units will be given, with particular reference to their permeability characteristics. Most of the geological details are obtained from the works of Preciozzi (1985), Prichonnet et al. (1987) and La Haye (1988).

2.2.1 The Basement Complex (Precambrian)

The basement rocks outcrop towards the north of the study area (north of San Jose town) and towards the south east, around Montevideo. The most widely occurring basement rocks are those of the Montevideo Formation, which are composed of gneisses, amphibolites, micaschists and micaceous quartzites. Some of these basement rocks, like the late post-tectonic granitoids, exposed towards the southwest of the town of Florida, are relatively poor in fractures, hence they are considered as groundwater barriers.

The undifferentiated granitoids and the Paso del Dragon Formation, which occur towards the north are separated by northeast to southwest running faults. In general, the principal fault directions within the basement rocks run northeast to southwest. These faults may divert groundwater from entering into the sedimentary formations. However, the existence of north-south joints and/or faults of secondary importance (as has been inferred from landsat images), may help in facilitating easy entrance of groundwater into the sedimentary formations.

The basement rocks were observed to be highly weathered towards the north (north of the town of Florida). Relatively thick (up to 2 meters), residual soils were observed in contact with the unweathered part of the basement rocks.

Towards the south, the altered products of the basement rocks are transported and deposited mostly along river courses, where a thickness of up to 3 meters was observed. The debris of materials derived from the basement rocks and reworked recent materials are also extensively distributed over the alluvial plain, towards the south.

The materials of the altered basement rocks consist of poorly sorted, rounded to sub-rounded boulders, gravels and pebbles with clayey silt. They contribute an additional secondary porosity to the basement rocks.

From the point of view of permeability, the altered basement rocks facilitate the percolation of groundwater. Due to their limited areal extent and vertical thicknesses, however, they are not considered as forming a separate aquifer unit. In general, it would be logical to expect a certain amount of horizontal groundwater leakage into the adjacent sedimentary formations due to the fracture systems and intensity of weathering of the basement rocks.

2.2 .2 The Fray Bentos Formation (Oligocene)

This formation consists of very fine, well sorted sandstone and loess with argillaceous and calcareous cement. It is characterized by its fleshy red to brown colour. Some calcite concretions occur (north west of Canelones) in its upper part. This formation is largely exposed towards east of Santa Lucia river. At Parador Tajes, the formation is locally lithified to compact quartzitic sandstone. This formation is also exposed around the town of San Jose, where it unconformably overlies the basement rocks. The deposition of this formation took place in continental semi-arid environment (Preciozzi, 1985). Its thickness varies from few meters up to ninety meters. The semi consolidated materials of this formation are highly weathered in some places.

Due to the predominance of fine materials (≥ 60% of lutites, Perez, 1990), the Fray Bentos Formation can be regarded as semi-permeable to impermeable.

2.2.3 The Camacho Formation (Miocene)

This formation consists of fossiliferous, massive and poorly sorted fine to coarse sand. It outcrops towards the western part of the study area near Arazati, where it is characterized by its well defined beds of clayey silt and sometimes by few beds of fossiliferous limestone in borehole 1394/1 (Prichonnet et al., 1987). This unit has also been identified by Perez (1990) from lithological descriptions of two other bore hole logs (see geologic cross-section in Fig. 2.2).

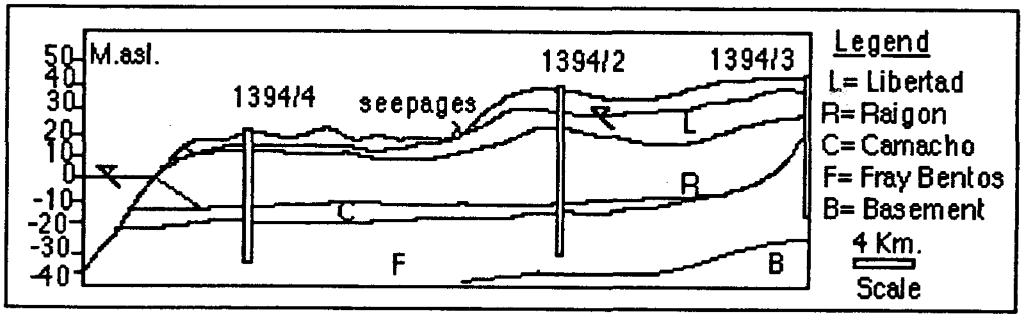


Fig. 2.2. A north to south (from south of San Jose town to Rio de la Plata) geological cross section and the position of average water table for the year 1988 (see Fig.2.3 for the location of the section).

The thickness of this formation (around 10 meters) diminishes towards the eastern part, where Fray Bentos Formation is observed to directly underlie the Raigon Formation.

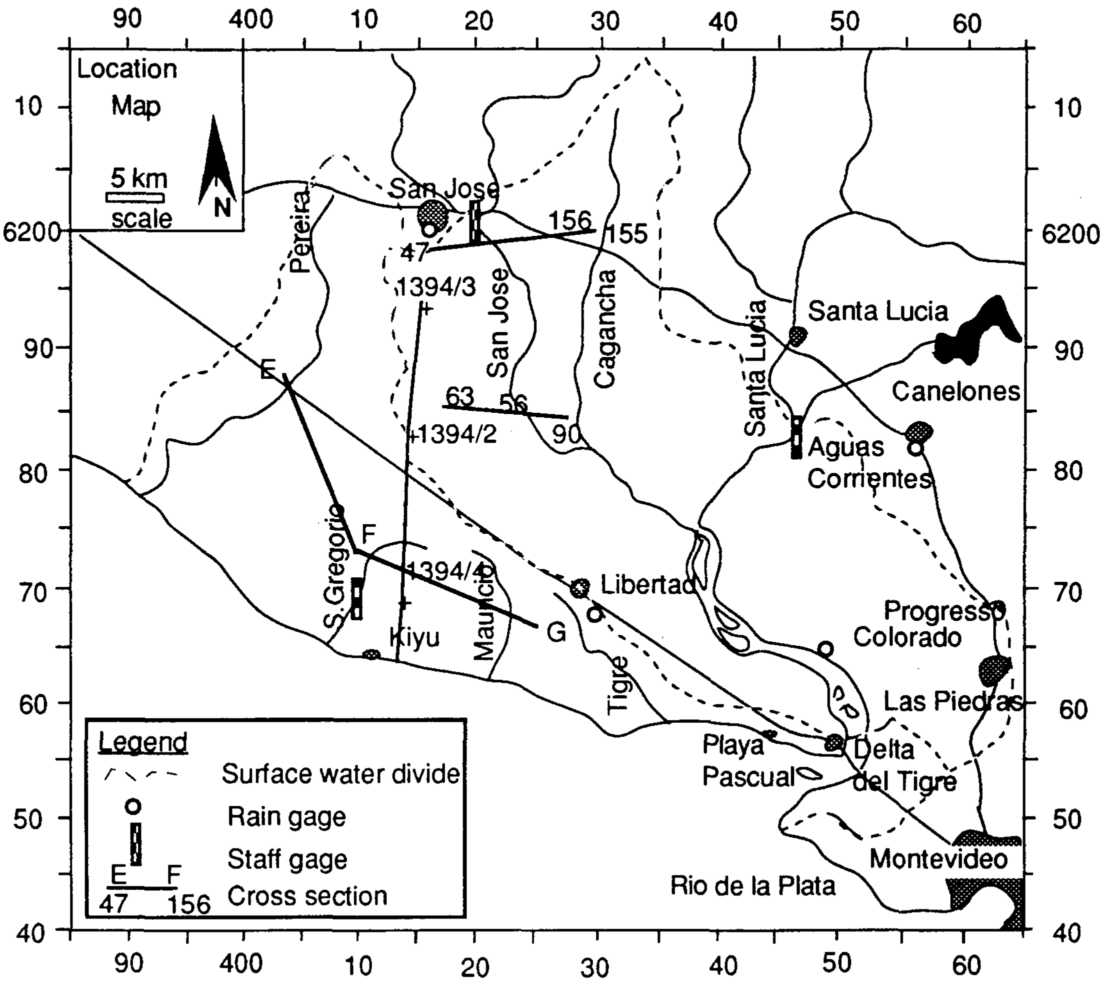


Fig. 2.3 Location of sections, climatic and hydrologic stations of the Santa Lucia Basin.

Due to the absence of extensive clayey materials within the Camacho Formation, it may have a better permeability than that of the Fray Bentos Formation. In general, this formation can be regarded as permeable to semi-permeable. However, it is not an important water bearing aquifer unit in the area due to its limited thickness and lateral extent, and also according to the shape of the electrical and γ ray logs registered in borehole 1394/1 by Prichonnet et al.(1987).

2.2.4 The Raigon Formation (Pliocene)

The Raigon Formation generally consists of moderate to poorly sorted conglomerate and sand with some clayey interbeds. Lithological description of logs from several boreholes indicate various dimensions of sand grains ranging from fine to medium to coarse grains. Relatively coarse grained sandy units (3 to 4 meters) are observed towards south east of San Jose. Alternating layers of silt and sand with pebbles and gravels are frequently encountered (La Haye, 1988). Along the coast, at the base of the formation, few partially cemented beds (calcite) have been observed (Prichonnet, personal communication)

This formation outcrops at Raigon (east of San Jose) and along the valley slopes, along the San Jose river. La Haye (1988) has pointed out the existence of many sedimentary structures, in outcrops along the slopes, suggesting that the Raigon Formation is thicker than previously believed. The thickness of this formation varies from few to tens of meters. At Libertad, it attains a thickness of about 50 meters. It has a more or less uniform thickness along the cliffs of the coast, ranging from 10 to about 20 meters.

The Raigon Formation is considered as a potential aquifer. The lithologic descriptions so far obtained indicate the possibility of relatively high permeabilities. The existence of considerable thicknesses of sand and gravel contributes to its high permeability, whereas, semi-confining situations may, as well, be expected wherever clayey silty layers persist.

2.2.5 The Libertad Formation (Pleistocene)

The Libertad Formation consists of grayish brown, at times calcareous, fine grained sand, silt and clay. It overlies the Raigon Formation, where altered products obscure a clear contact. This formation merits to have its own litho-stratigraphic unit due to its distinctiveness in appearance (La Haye, 1988).

The top parts of the surface water divide, along "ruta 1", consists of fine and massive facies, which is mapped as the Libertad Formation. In the north, towards the town of San Jose, it grades into a more coarser facies resembling that of the Raigon Formation, where inter-connected vertical channels (root casts) were observed near the surface. Other fractures of micro channels can also be observed, in other parts in this formation, favoring the vertical percolation of rain water. Some calcite concretions were also observed at this place, reflecting pedogenetic activities in a semi - arid environment. Although coarse grains of sand (diameter = 2mm) were observed in the Libertad Formation, the proportion of gravelly materials is not as frequent as in the Raigon Formation (La Haye, 1988).

From the point of view of permeability, this formation can be regarded as semi-permeable to permeable. It may partly confine the aquifer below (Raigon Formation), wherever its permeability is reduced by its fine grained character. However, the vertical permeability being significative, unconfined water table situations are favored.

2.2.6 Dolores Formation (Pleistocene)

The Dolores Formation consists of mudstones and very fine brown argillaceous sandstone. It is a secondary depositional product derived mainly from the previous formations. This formation is encountered in the relatively flat area, towards the mouth of the Santa Lucia river (Tropas Viejas - Delta del Tigre).

The lithological character of the Dolores Formation is very close to that of the Libertad Formation. However, its characteristic may vary from place to place within a small area.

The presence of mudstone lowers the permeability of this formation, wherever it may persist. In general, this formation can be considered as semi permeable to a permeable unit.

2.2.7 Recent Sediments

The recent sediments are divided into fluviatile, and coastal deposits. The fluvial sediments which consist of unconsolidated fine to coarse sand, pebbles and gravels are exposed mostly along the rivers. Sheet wash deposits consisting of fine to medium grained materials including some coarser material (up to gravelly beds) are deposited along valley depressions.

The coastal deposits are well sorted fine to medium grained coast developed sands (mainly eolian, covering few hundred meters in places), which are restricted to the coastal areas.

The grain size distributions within the alluvials are distinguished from the grain size distribution within the rest of the basin by the absence of fine grained matrices (La Haye, 1988). Such characteristics render the alluvials a relatively high permeability. However, due to their limited areal extent and very small thickness (2 to 3 meters), they are not regarded as potential aquifers, but they can still be considered as local zones of groundwater accumulation.

Chapter 3

HYDROGEOMORPHOLOGY

The major landforms are grouped based mainly on topographic aspects: Along the main rivers of San Jose and Santa Lucia the topography (10 - 40 meters) is relatively lower than the rest of the area (see topographic map in Fig. 3.2). It rises along the sides of these rivers, towards the high rising ridges, where the altitude attains 40 to 50 meters. Towards the west of these rivers, a surface water divide separates the Santa Lucia river basin from the Rio de la Plata basin. The topography becomes relatively flat, towards the west of this surface water divide, except along rivers, where it slopes down toward the rivers. The geomorphic situation of the area can be viewed from such broad topographic categorization. In this study, the area has been divided into major geomorphic units reflecting mainly the above mentioned major land forms. Accordingly, a geomorphic map has been prepared (see Fig. 3.1). The purpose of such geomorphic subdivision is to subdivide the area into groundwater zones; the geomorphic units are believed to reflect distinct groundwater situations. In the following, the groundwater characteristics are studied based on five geomorphic units, namely: 1) The interfluvial zone 2) The seepage zone 3) The coastal zone 4) The valley bottom and 5) The fluvio-coastal zone

Figure 3.1

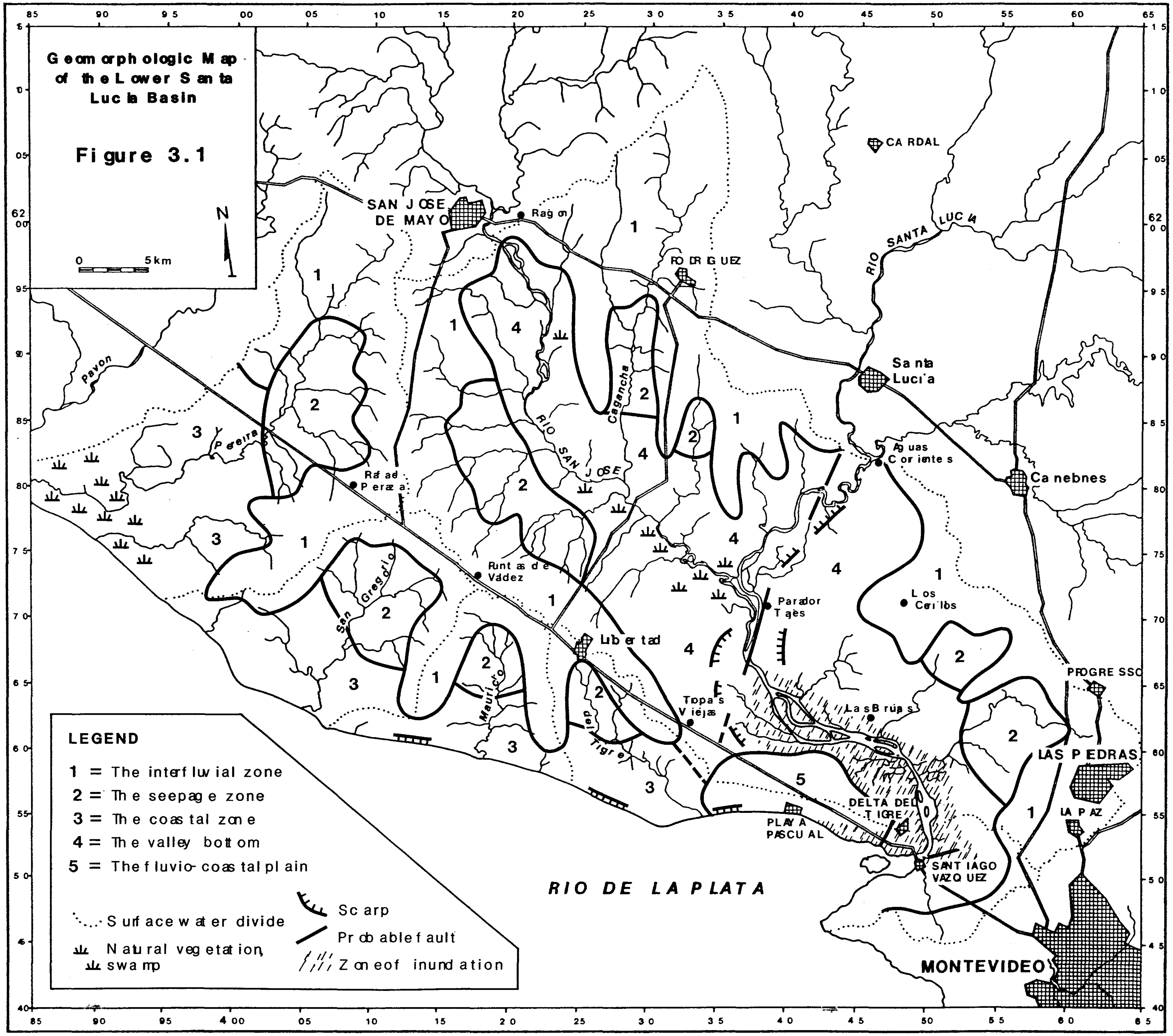
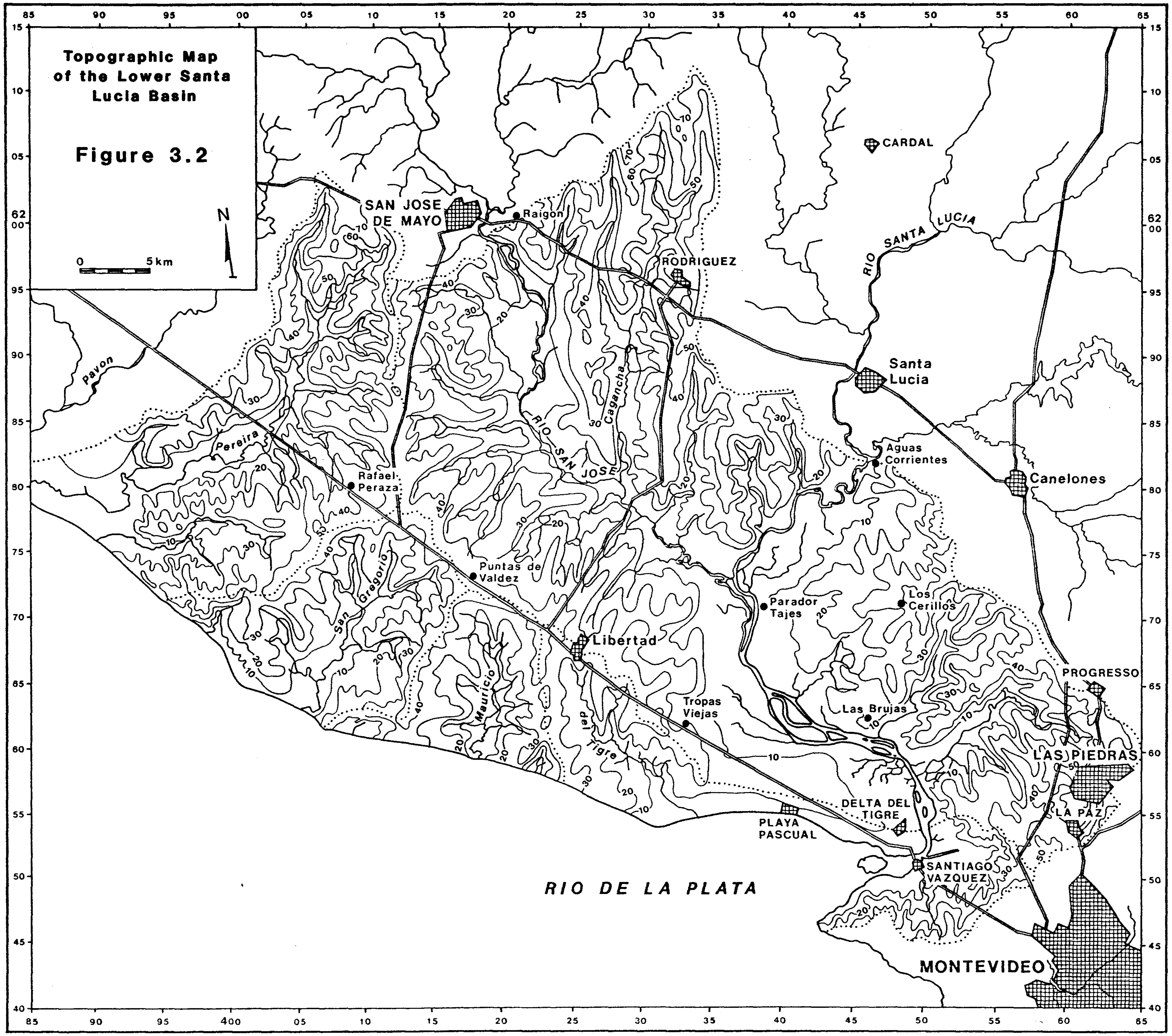

Geomorphologic Map of the Lower Santa Lucia Basin
Figure 3.1
N
0 5km
SAN JOSE DE MAYO
Ragon
RODRIGUEZ
CARDAL
RIO SANTA LUCIA
Santa Lucia
Aguas Corrientes
Canelones
Pavon
Pereira
Rafael Peraza
RIO SAN JOSE
Cagancha
Puntas de Valdez
San Gregorio
Libertad
Mauricio
del Tigre
Parador Tajes
Los Cerrillos
Tropas Viejas
Las Brujas
PROGRESO
LAS PIEDRAS
LA PAZ
DELTA DEL TIGRE
PLAYA PASCUAL
SANTIAGO VAZQUEZ
MONTEVIDEO
RIO DE LA PLATA
62 00
LEGEND
1 = The interfluvial zone
2 = The seepage zone
3 = The coastal zone
4 = The valley bottom
5 = The fluvio-coastal plain
Surface water divide
Natural vegetation, swamp
Scarp
Probable fault
Zone of inundation

Figure 3.2



Topographic Map of the Lower Santa Lucia Basin

Figure 3.2

The geomorphologic units are limited in the east by a relatively elevated area, Las Piedras (see Fig. 3.1), by the Rio de La Plata in the south and by the relatively rugged basement topography in the north and north west.

Other characteristics like swamps and scarps are also included in the geomorphologic map.

3.1 Geomorphic Units and Groundwater Table Conditions

3.1.1 The interfluvial zone

The interfluvial zone is a relatively flat area, with slightly undulating topography. In general, it is inclined towards the south east, where the sediments attain their maximum thicknesses. The average angle of slope is less than 2%.

The average static water level in the interfluvial zones varies from about 50 meters above sea level towards the north west to about 20 meters towards south east.

The existence of groundwater divide is highly correlated with the surface water divide, which separates the coastal zone from the Santa Lucia Basin.

3.1.2 The Seepage Zone

Small valleys formed as a result of the combined effect of groundwater seepage and surface erosion constitute distinct geomorphologic units. These are located along the rivers of Luis Pereyra, San Gregorio, Mauricio and del Tigre. They all have a characteristic feature of relatively narrow gorge in their upper parts with flat and wide marshy region in their lower parts.

Numerous seepages have been observed to emerge from the sides of these valleys. The discharges of the seepages gradually increase downwards along the river valleys.

The local direction of groundwater flow is towards the respective rivers. The seepages emerge from the shallow aquifers.

3.1.3 The Coastal Zone

The coastal zone is a relatively flat region (average slope <1%) adjacent to the Rio de La Plata. Well marked scarps are found along the coast and, leveled ground (due to later erosion) wherever rivers embouch their waters to the Rio de La Plata.

The calcareous incrustations on the wall of a scarp at Kiyu (see Fig. 3.1) indicate seepages of an ancient water level. Lowering of the water table is evidenced by the presence of wetland vegetation, which is presently about 10 meters below the level of the calcareous incrustation.

The average static water level in the coastal zone varies from 5 to 15 meters above sea level and the general groundwater flow direction is north - south (towards Rio de La Plata).

3.1.4 The River Valley Bottom

The valley with its adjacent slopes along the lowermost limits of the rivers of San Jose and Santa Lucia is considered as a single distinct geomorphological unit. The topography slopes gently from the surface divides, along "ruta 1" and "ruta 3" towards the two large rivers, where dense natural vegetation covers the valley bottoms. The groundwater levels, along the slopes, were observed to follow the topography. In general, groundwater flows towards the valley bottom and also along the rivers.

During the wet season, numerous seepages and flowing streams emerge from the soil cover along the slopes of the valley and feed the rivers of San Jose and Santa Lucia. During the dry seasons, the seepages and flowing streams dry out.

3.1.5 The Fluvio - Coastal zone

The area between Santa Lucia river and Rio de La Plata (Delta del Tigre up to Tropas Viejas) is referred to as fluvio - coastal zone (see Fig. 3.1). The topography is flat with average altitude of about 15 meters. It is poorly cultivated. Marshy and inundated regions are found along the borders of the Santa Lucia river and Rio de La Plata.

Marine environment might have reached up to Parador Tajes, or even upstream, up to Aguas Corrientes, where the land unit seems to attain a more or less similar feature. When the ocean started to recede southwards, the fluvial action of the Santa Lucia river became important, thereby flowing directly southwards through Tropas Viejas at first, and following its present "S" shaped course at a later stage (J. Da Silva, 1989, personal communication).

The aquifer unit in the fluvio - coastal zone must have been affected by fluvial deposits mainly from Santa Lucia river (gravels and sand) and probably from buried stream (gravels and sand) due to an abandoned river course. The water level in this region being very close to surface (5 to 15 meters above sea level) could be susceptible to contamination from industrial wastes as well as from the Rio de La Plata, especially at places where pumping can create a significant drawdown.

Chapter 4

THE AQUIFER SYSTEM AND EVALUATION OF AQUIFER PARAMETERS

A formation, group of formations or part of a formation may constitute an aquifer system, depending on the availability of saturated permeable aquifer material yielding an appreciable amount of groundwater.

The individual formations have been described, in section 2.2, from the point of view of their permeabilities. The characteristics of the grain size distributions have also been studied and permeability values estimated towards the end of this chapter.

It is appropriate to clearly establish the aquifer system (the most permeable unit, and its impermeable or semi-permeable boundaries), before entering into groundwater hydrology. It will be demonstrated later (see figures 4.16a to Fig.4.16e) that the permeability of the Raigon Formation is by far superior than the permeabilities of the other formations.

The grain size distributions within the Raigon formation varies from place to place. As can be seen from the logs (Fig. 4.16a to Fig. 4.16e), relatively impermeable units may, at times, be embodied within the permeable units. Although the permeability values of the formations (other than Raigon) are generally low, semi-confined to unconfined situations may prevail depending on the lateral and vertical permeability variations that may exist from place to place. Confining situations are not attributed to formations, but rather to small lenses of clayey or silty layers that are embodied within the formations. According to the informations gathered from the drillers files at DI.NA.MI.GE., the water levels first encountered while drilling wells was in many cases few meters lower than the levels when drilling terminated. Such occurrence of groundwater at relatively shallow levels in relation to the supposed aquifer indicates confined or semi-confined groundwater situation. However, the general response of groundwater to precipitation (see chapter 5) reflects unconfined or semi-unconfined situations.

In conclusion, the Libertad - Raigon Formations can be considered as a complex aquifer system constituted of various layers, some of these layers acting as leaky or semi - confining layers. The underlying Fray Bentos Formation is considered as semi - permeable to impermeable unit.

4.1 The Aquifer Boundaries

The area bounded by the surface water divides around the aquifer system marks the surface boundaries from which surface water inflow starts. The surface water inflows coming from the northern part of the Santa Lucia Basin are attributed to the rivers San Jose and Santa Lucia.

The basement rocks in the north form a flow - controlled boundary, because some quantity of groundwater reaches the aquifer system by underground recharge through the fracture systems and weathered zones within the basement rocks (see section 6.1). On the other hand, the Precambrian basement rocks underlying the sedimentary formations are considered as zero-flow boundaries. The Fray Bentos Formation overlying the basement rocks can also be considered forming a zero-flow boundary, so that the only outlet of surface water and groundwater from the aquifer system would be towards the Rio de La Plata.

All streams crossing the groundwater basin are hydraulically connected to the aquifer system. Therefore, they are considered as head controlled boundaries. Finally, the Rio de la Plata and the lower estuary of the Santa Lucia river form another head controlled boundary.

4.2 The Aquifer Thickness and its Lateral Extent

The thickness of the aquifer system has been extrapolated from existing bore well data. Accordingly a contour map (isopach map) has been constructed (see Fig. 4.1). The potentiality of the aquifer system could be deduced from the isopach map which partly expresses the amount of water that can be stored in the aquifer. As in the figure, the thickness of the aquifer system is around 40 meters towards the south and between 20 to 40 m towards the north. The maximum aquifer thickness is encountered towards the southeast, where a thickness of around 50 meters is attained.

4.3 The Saturated Aquifer Thickness

In unconfined aquifer system, the saturated aquifer thickness is marked by its static water level. The average static water level calculated from the monthly water level records could therefore be used as a measure of its saturated thickness. Since there are not enough well log informations to deduce the actual saturated thickness, it is found by subtracting the average depth to water from the isopach map. A saturated aquifer thickness map is accordingly constructed (see Fig. 4.2). The information from this map is used in the calculation of transmissivity values. It is worth noting that the saturated aquifer thickness also increases towards the south east, where the maximum saturated aquifer thickness of about 35 meters is attained.

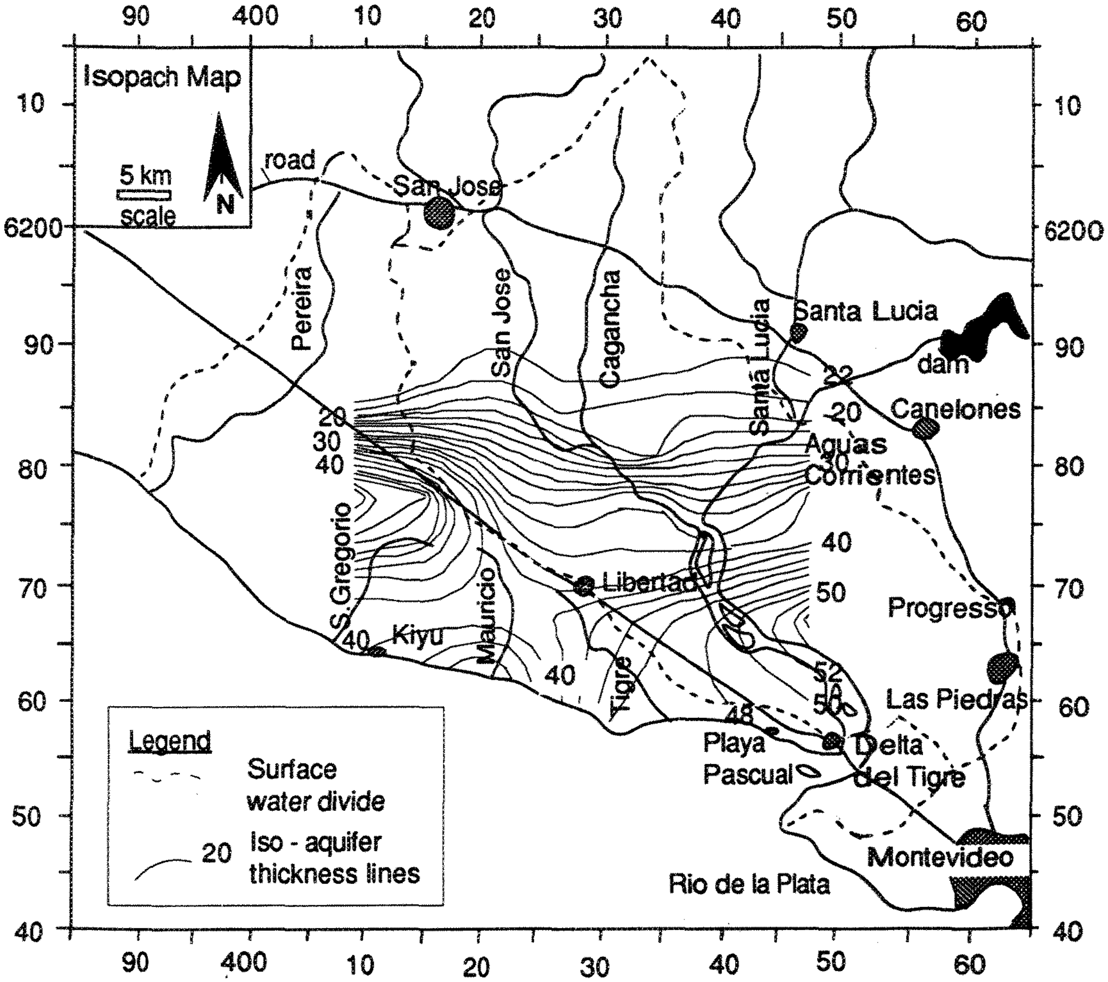


Fig. 4.1 Isopach map of the sedimentary formations in the Lower Santa Lucia Basin

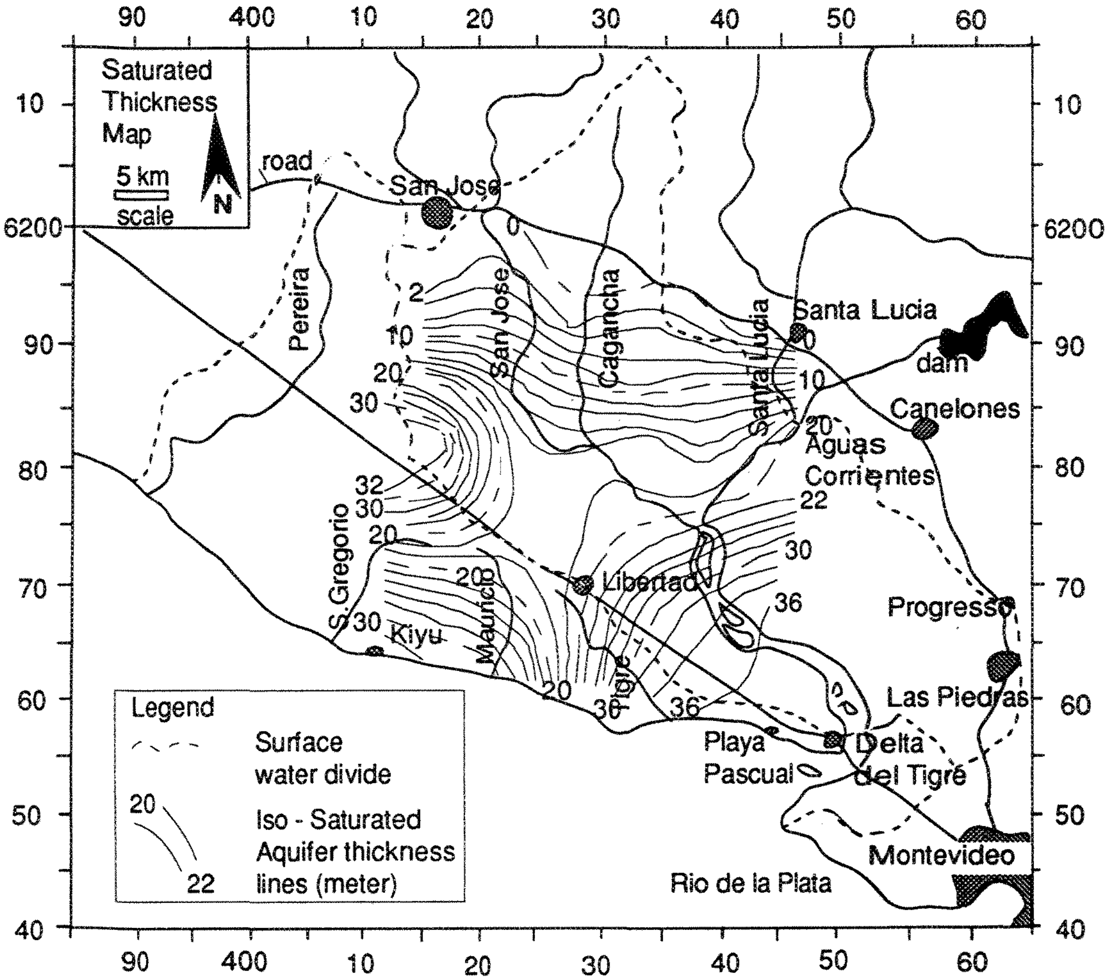


Fig. 4.2 Saturated aquifer thicknesss map of the Santa Lucia Basin

4.4 Analyses and Interpretation of Data from Pumping Tests

One standard pumping test with an observation well, three well tests (without observation wells) and two pumping tests of large diameter wells have been conducted during the month of December 1988. A map showing the location of the tests is prepared (see Fig.4.3). The analyses and interpretations of the data are presented.

4.4.1 Pumping test

A pumping test was conducted on a well Nº 742 (TORYAL S.A. located at 34 km from Montevideo along "Ruta 1"). Measurements were conducted on the well, as well as on the piezometer which is located at 61 meters from the well. Pumping was started at 7:34 on December 16 and was continued at a more or less constant discharge of 578.88 m^3/day for seven hours and forty five minutes. The drawdown was measured both on the well and on the piezometer. Measurements of water level recovery continued for six hours and forty two minutes, until 21:50. The data obtained are presented in Table 3, in the appendix.

Before analyzing the pumping test data, additional informations, like well and piezometer construction and geological log informations were investigated (see also Fig. 4.16a to Fig.4.16e).

- The well is fully (about 37 meters) penetrating the aquifer system; the silty clay layer (Fray Bentos formation) below the bottom of the well is considered as impermeable (see Fig. 4.4).

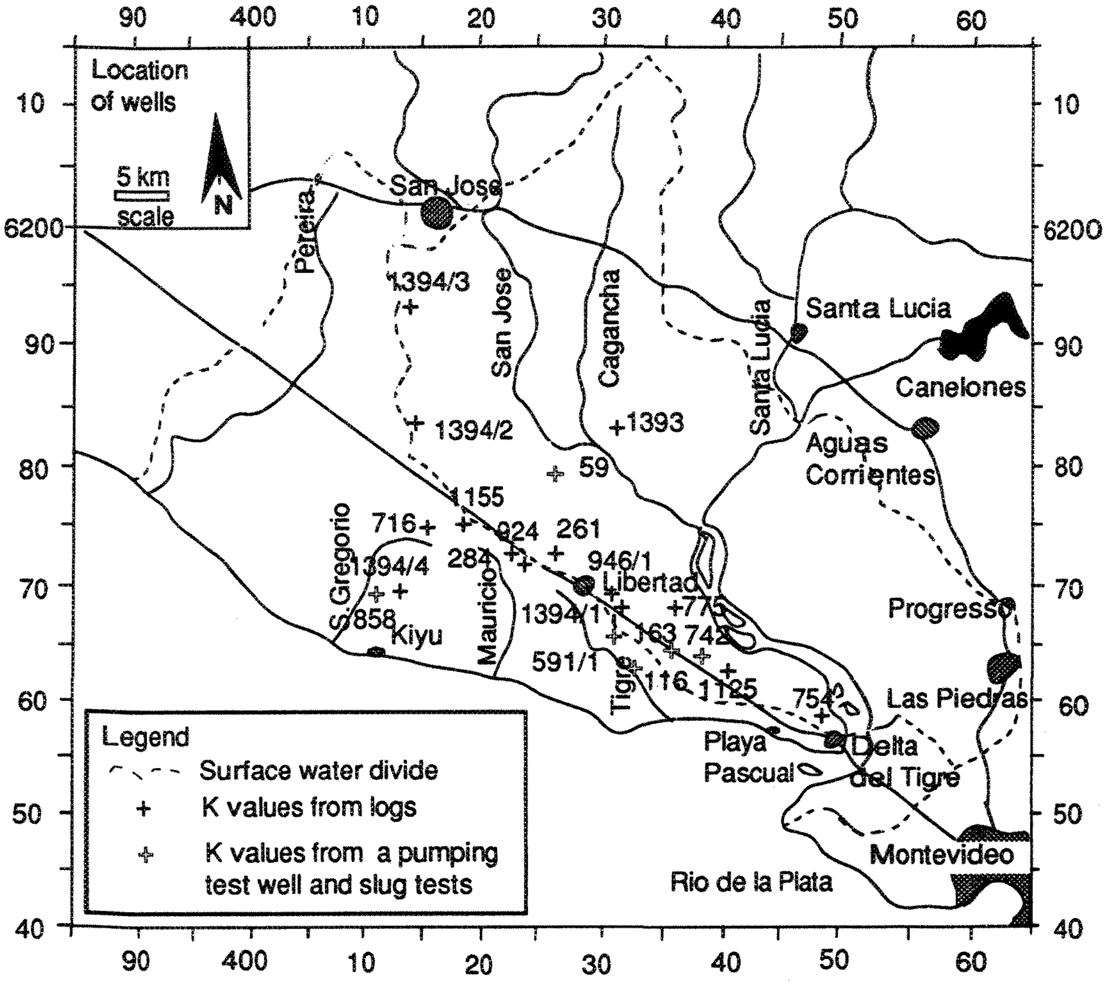


Fig. 4.3 Location map of wells for the evaluation of aquifer parameters

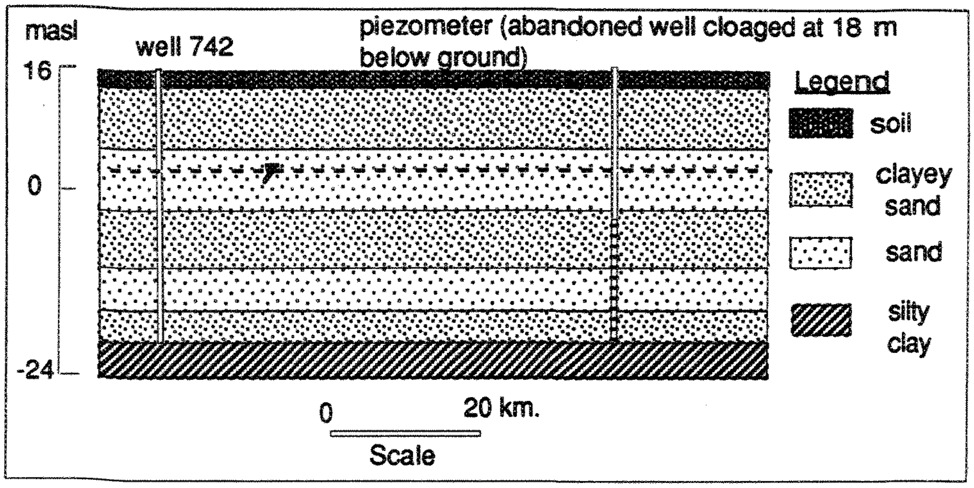


Fig. 4.4 Schematic section of the pumping site area (the data for the well was obtained from the DI.NA.MI.GE. drill-files. The lithology around the piezometer is extrapolated from the lithologic description for the well); masl = meters above sea level.

- An abandoned well which is cloaged at 18 meters below ground has been used as an observation well; it has been considered as partially penetrating. Since the distance of the piezometer from the pumping well is about two times the thickness of the aquifer, the effect of radial flow into the piezometer, in affecting the drawdown, may be considered insignificant.

- The main aquifer is sand occurring at two different horizons; the clayey sand layers can be considered as semi-pervious. Therefore, vertical (upward and downward) leakage is expected. Hence the sand layers can be considered as being semi-confined.

The flow has decreased during the test, but a constant discharge rate can be assumed, since the rate of decrease is negligible.

Like in most methods of interpretations, the following assumptions were made:

- The aquifer has infinite aerial extent.
- The aquifer is homogeneous, isotropic and of uniform thickness.
- The piezometric surface is horizontal before pumping.

The above information is found to be sufficient to choose a suitable method of interpreting the data. Accordingly, the method of Walton (1962) has been used for the interpretation. The procedures of these methods can be found in Kruseman and de Ridder (1979).

Walton's Method

The transmissivity value (KD) was calculated from the following formula:

$$s = Q(W(u,r/L))/4\pi KDt \qquad (4.1)$$

$$\text{where } u = r^2S/4KDt \qquad (4.2)$$

Where, s = drawdown, Q = discharge, W(u, r/L) represents the well function for semi-confined aquifer, L = leakage factor, r = the distance between the well and the piezometer, K = Permeability, D = saturated aquifer thickness, S= storage coefficient and t = time.

- W(u,r/L) versus 1/u was plotted for different values of r/L (see Fig. 4.2)
- s versus t was plotted on another sheet of double logarithmic paper of the same scale (see Fig. 4.6).
- The observed data curve (see Fig. 4.6) was superimposed on the family of type curves
- A match point was selected for which the values of W(u,r/L), 1/u, s and t were read.

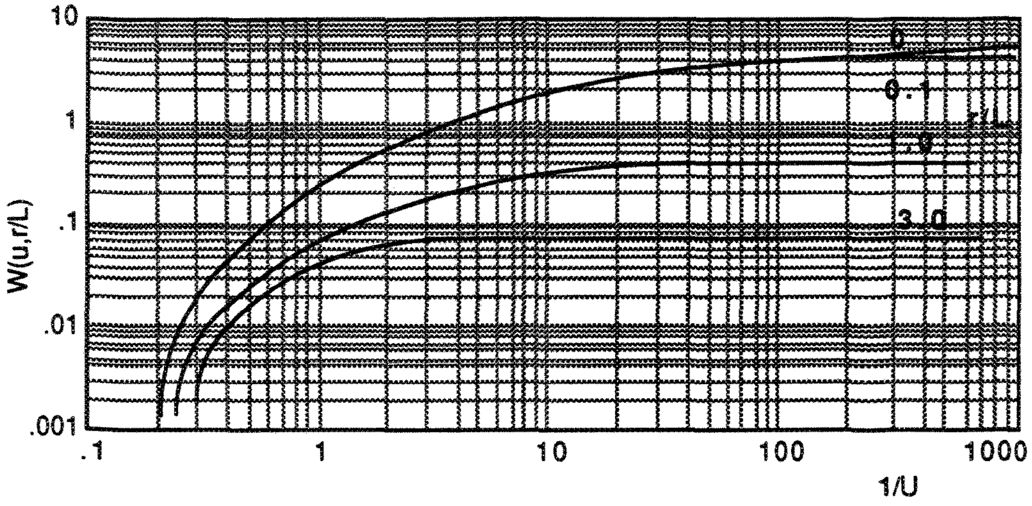


Fig. 4.5 Family of Walton's type curves W(u,r/L) versus 1/u for some values of r/L

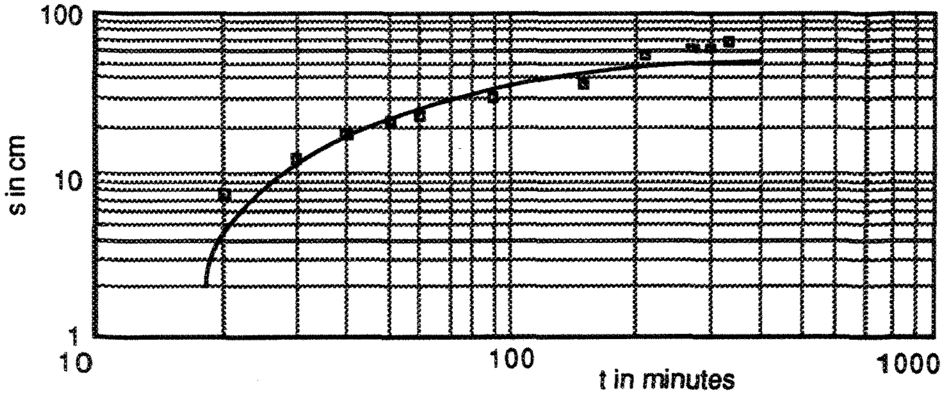


Fig. 4.6 Data curve (t versus s) from the piezometer

The values of $s = 0.35$ m and $t = 0.06944$ days were found after choosing $W(u,r/L) = 1$ and $1/u = 100$ as a match point; the plotted points fall along the curve $r/L = 0.1$. These values are inserted into equations 4.1 and 4.2.

Hence, $KD = Q\ W(u,r/L)/4\pi s = (578.88\ m^3/day \times 1)/4 \times 3.14 \times 0.35 = 132\ m^2/\ day$.

$S = 4KDt\ u\ /r^2 = (4 \times 132 \times 0.06944 \times .01)/\ 61^2 = .0001$

Inspite of our previous assumptions, the storativity value obtained indicates a confining situation. However, such descrepancy could be attributed to having used a cloaged well. We shall therefore keep this data for comparing with other methods.

Since $r/L = 0.1$, $L = 610$ meters.

The hydraulic resistance c, can be calculated from the following equation:

$c = L^2\ /KD = (610)^2\ /132 = 2819$ days

The Hydraulic Conductivity of the Semi-pervious Layers (K')

From the value of hydraulic resistance c, the hydraulic conductivity of the semi-pervious layers (K') can be calculated. The hydraulic resistance c, is expressed as the ratio of the saturated thicknesses of the semi-pervious layers and hydraulic conductivity of the semi-pervious layers; ie., $c=D'/K'$ where D' is the total saturated thickness of the two semi-permeable (clayey sands) layers at the bottom and in between the permeable (sand) aquifers.

By substituting the value of c to the above equation we obtain,

2819 days $=13/K'$, Hence, $K'= 0.0046$ m/day

Recovery Method

Since piezometers are scarce in the study area, we shall take advantage of the data from the pumping test for other methods that are generally used for wells which are not equiped with piezometers, so that the accuracy of the other methods can be compared with the interpretations of the pumping test.

The recovery method has the advantage that the rate of flow of water into the well is constant and is equal to the mean pumping rate. Hence the results of the analysis of the pumping test data can be checked by this method. The recovery method is hereby employed for the pumping well instead of the piezometers. The same procedure has been employed for other wells which are not equiped with piezometers.

The residual drawdown is plotted versus t/t' on semi-logarithmic paper and a straight line is fitted through the points (see Fig. 4.7).

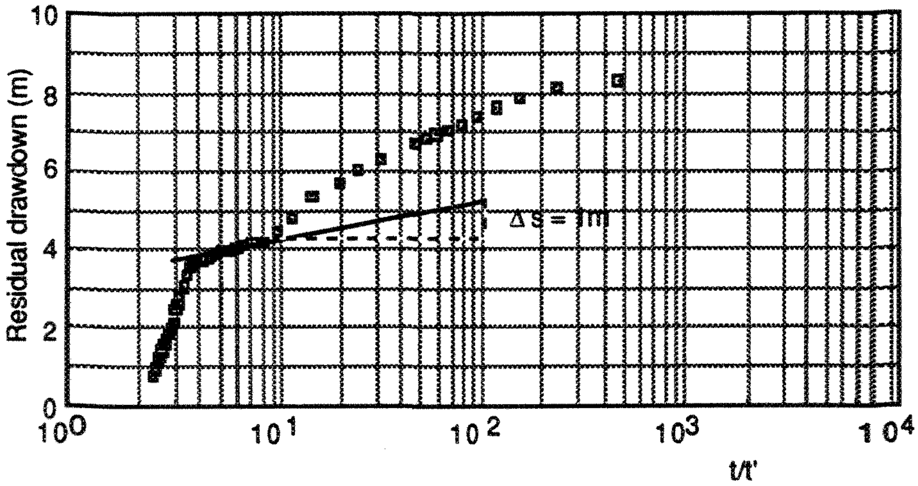


Fig.4.7 . Analysis of recovery data from pumping test (well № 742)

$T = 2.3Q/4\pi\Delta s$; where, Δs = the difference of maximum drawdown per log cycle, T = transmissivity and Q = discharge of the well.

$T = 2.3(578.88)/4\pi = 106\ m^2/day$

Reasonable agreement is observed between the transmissivity values calculated by the above two methods. However, the coefficient of storage cannot be calculated in this method, because well loss is appreciable.

4.4.2 Well Tests

Well tests are pumping tests performed on pumping wells where piezometers are absent. Approximate transmissivity values can be obtained from well tests. The drawdown and recovery of three wells have been observed during well tests performed between 8 to 16 of December 1988.

Before analyzing the well test data, we shall seek for more informations from the existing logs. Although well log informations have not been obtained for all wells, the possible log descriptions can be deduced from the available logs near the wells examined. From the lithologic wells (see Fig. 4.16a to Fig.4.16e), it can be observed that all wells are either semi-confined or semi-unconfined.

The procedures of calculating the transmissivity values are the same as the recovery method previously employed. The plots of the points from the recovery data and the corresponding calculations are hereby presented.

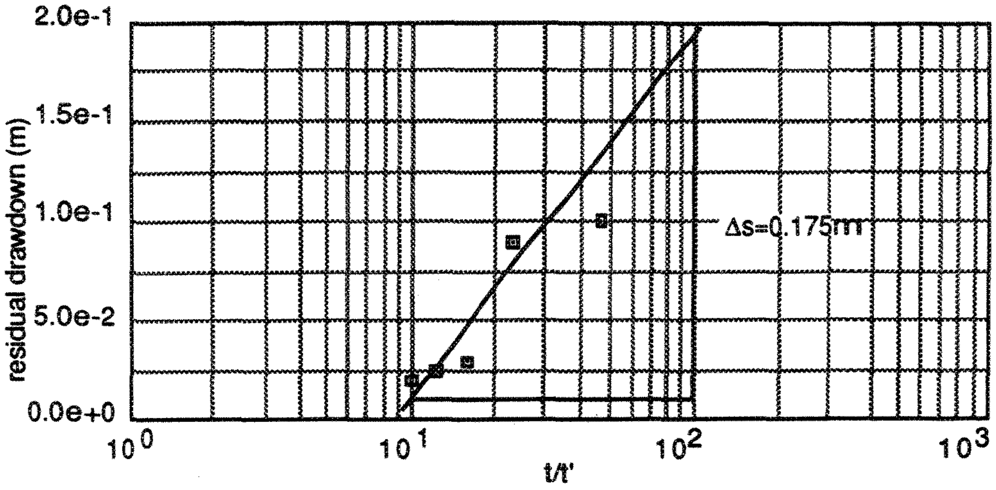


Fig. 4.8. Analysis of recovery data from well 858

$T = 2.3(Q)/4\pi\Delta s$

$T = 2.3(332.31\ m^3/day)/4\pi(0.175\ m)$

$= 348\ m^2/day$

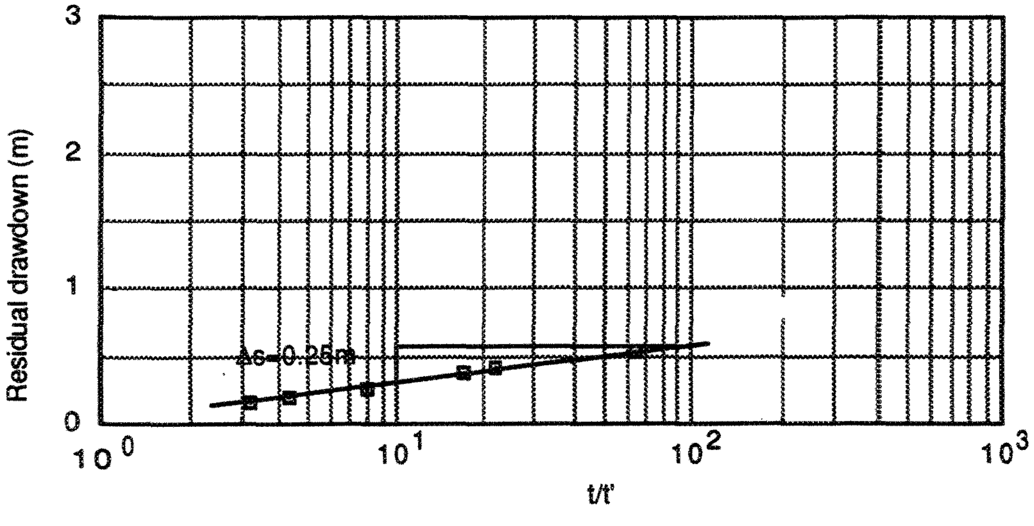


Fig.4.9. Analysis of recovery data from well 163

$T = 2.3(Q)/4\pi\Delta s$

$T = 2.3(316.224\ m^3/day)/4\pi(0.25\ m)$

$= 231.5\ m^2/day$

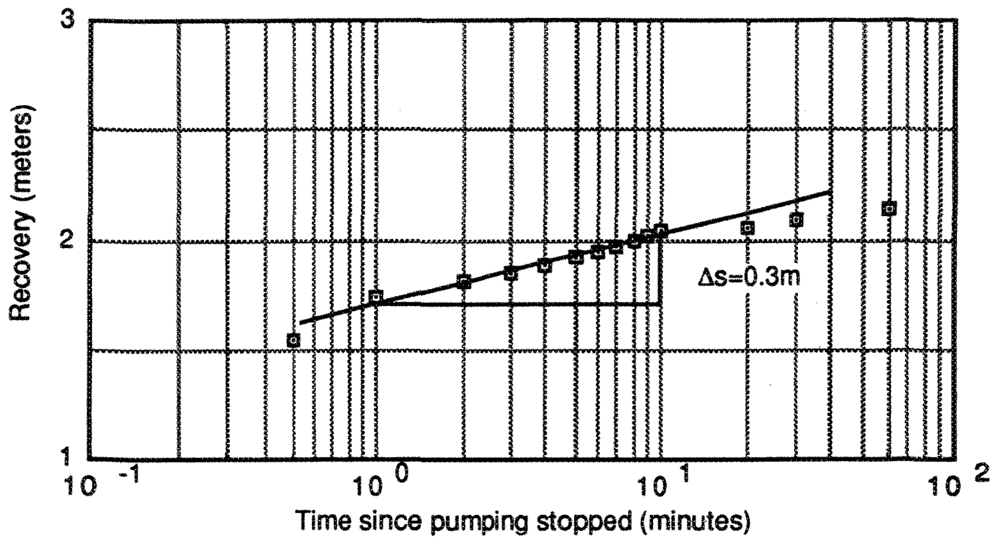


Fig. 4.10. Analysis of recovery data from well 591

$T = 2.3(Q)/4\pi\Delta s$

$T = 2.3(518.4\ m^3/day)/4\pi(0.3\ m)$

$= 316\ m^2/day$

4.4.3 Pumping tests of large diameter wells

Pumping tests have been performed on two large diameter wells which were excavated by hand. Their diameters are around 1.5 m. The interpretation of pumping tests of large diameter wells were based on the following assumptions:

- The aquifers are either confined or semi-confined

- Flow to the wells is unsteady

- Well losses are negligible

- Significant amount of storage is expected in the well due to its large diameter.

The method employed for the interpretation is that of Papadopulos-Cooper's method as given by Kruseman and de Rider (1979).

The family of Papadopulos-Cooper's type curves: $F(u_W,ß)$ versus 1/u were plotted (see Fig.4.11) for different values of ß, from the table of values of the function $F(u_W,ß)$ whose numerical values can be found in hydrogelogical text books. The observed data of s versus t was plotted (see Fig.4.12 & 4.13) on logarithmic paper of the same scale. The values of $F(u_W,ß)$, 1/u, s and t were then obtained by superposition of the data curve on the type curve; the value of ß of the type curve which best matches the data curve is also noted.

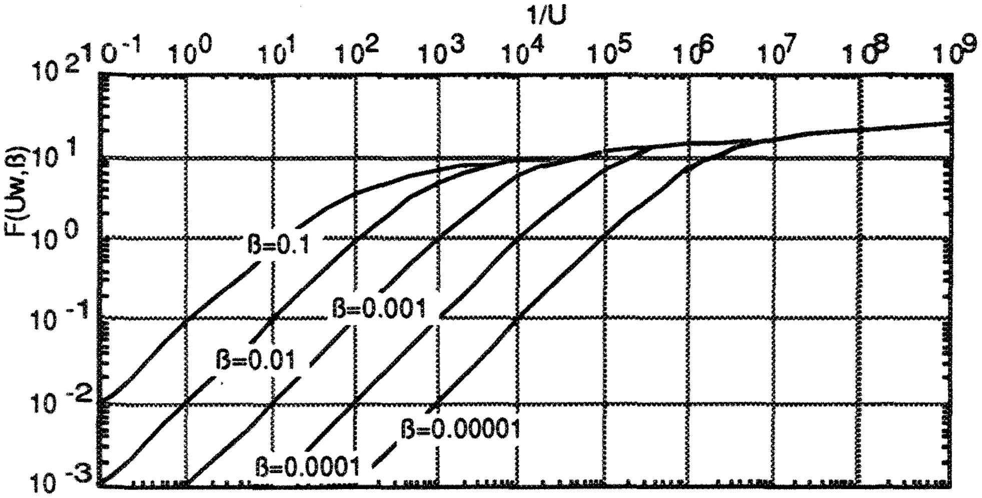


Fig.4.11. Family of Papadopulos-Cooper's type curves: $F(u_W,ß)$ versus 1/u for different values of ß, plotted from table of values of the function $F(u_W,ß)$ given by Kruseman and de Ridder (1979).

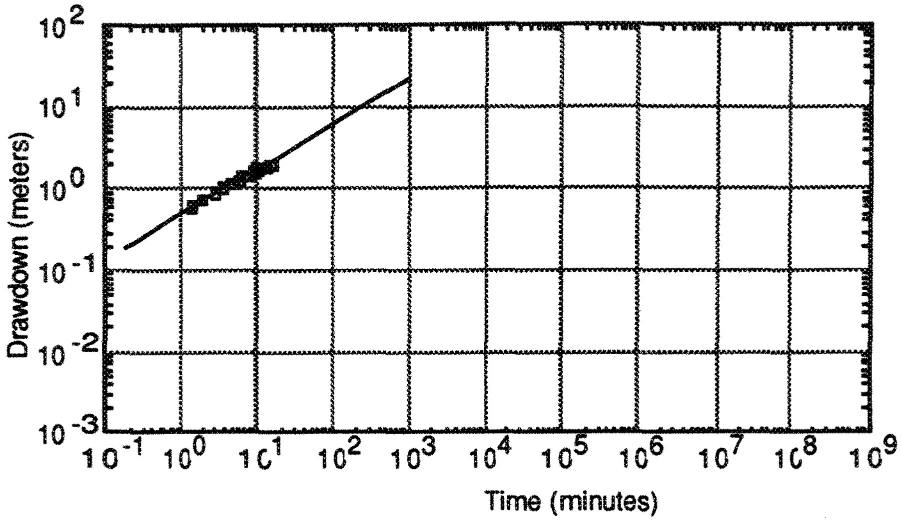


Fig. 4.12 Analysis of pumping test of large diameter wells data from well 59

The transmissivity values calculated by this method are given below:

$\beta = 0.1$, $t = 10$, $s = 1$, $1/u = 300$, $F(u_W,\beta) = 15$

The above values are substituted into the following equation:

$$T = Q(F(u_W,\beta))/4\pi(s) \tag{4.3}$$

$$T = [172.8\ m^3/day(10)]/4\pi(1\ m)$$

$$= 138\ m^2/day$$

Since the well losses are negligible in large diameter wells, the value of storage coefficient may be obtained from equation 4.4.

$$S = [4T(t)(u_W)]\ /r^2{}_W \tag{4.4}$$

$$S = [4(138\ m^2/day)(0.0069444\ days(0.00333)]/(0.4)^2$$

$$= 0.08$$

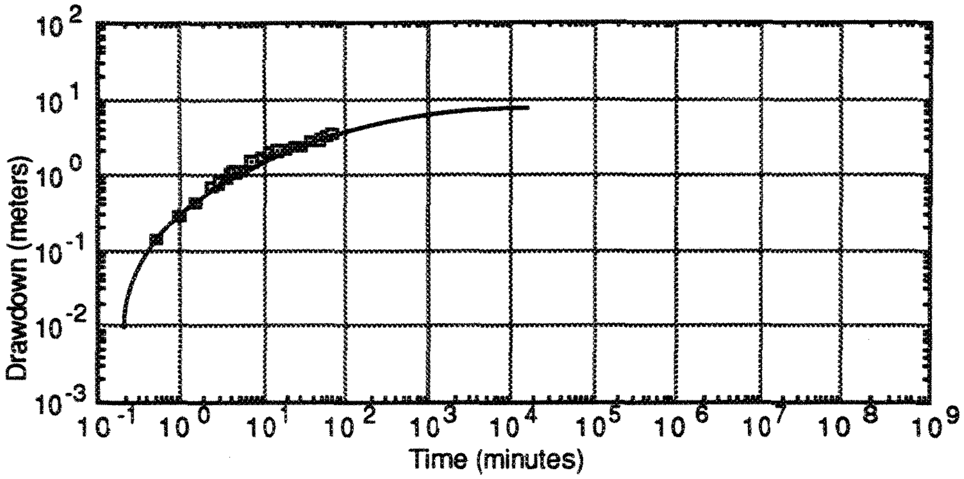


Fig. 4.13. Analysis of pumping test of large diameter wells data from well 116.

The transmissivity values calculated by this method are shown below:

$ß = 0.1$, $t = 10$, $s = 1$, $1/u = 300$, $F(u_W,ß) = 10$

The above values are substituted into equation 4.3

$T = Q(F(u_W,ß))/4\pi(s)$

$= [302.4\ m^3/day(5)]/4\pi(1\ m)$

$= 120\ m^2/day$

The storage coefficient is found in using equation 4.4.

$S = [4T(t)(u_W)]/r^2{}_W$

$= [4(120\ m^2/day)(0.0069444\ days(0.00333)]/(0.465)^2 = 0.05$

The storage coefficient values in both the above cases indicate semi- confined to unconfined or semi unconfined situations (the storage coefficient for unconfined aquifers is between 0.02 to 0.3, whereas, for confined aquifers, it is between 0.00001 to 0.001).

4.5 Specific Capacity and Approximate Transmissivity Values

Specific capacity of wells, defined as Q/S_W, where, Q = discharge and S_W = the maximum observed drawdown, are related to transmissivity values. However, specific capacity is affected by well loss and partial penetration. Since these factors have adverse effects on specific capacities, the actual transmissivity computed from pumping test will be greater than the transmissivity computed from the specific capacity data.

Boonstra and de Ridder (1981) give a simplified formula which can be used to estimate transmissivity values. The formula assumes that after sometimes of pumping from a small diameter well, a steady flow condition is obtained. Based on modification of the Thiem's equation, the order of magnitude of transmissivity can also be calculated by using Logan's method of approximation as given by Kruseman and de Ridder (1979).

$$T = 1.22\ (Q)/S_W \qquad (4.5)$$

Where T= transmissivity, Q = discharge, S_W = and $(Q)/S_W$ = specific capacity

For unconfined aquifers, the corrected value of the drawdown must be used:

$$S'_W = S_W - (S^2_W / 2D) \qquad (4.6)$$

where D is the saturated aquifer thickness

The specific capacity varies with logarithm of $1/ r^2w$ (Walton, 1969). Therefore, large increase in the radius of a well results in comparatively small increase in specific capacities.

In using the above information, the approximate transmissivity values have been computed from the specific capacity of small diameter wells from the old wells. Since the aquifer system represents semi - confined to unconfined situations a factor of 1.2 was chosen instead of 1.22 as in equation 4.5. The validity of the chosen factor was verified from the transmissivity factors so far obtained Hence the specific capacity values of the small diameter wells have been multiplied by 1.2 and the approximate transmissivity values obtained.

In the absence of sufficient data, one should resort to using all the possible means and making the maximum use of the available data, in order to arrive at real values. We have sufficient specific capacity data, and less data on aquifer tests. Therefore, the specific capacity data has been used in order to have a wider coverage of transmissivity values. The approximate transmissivity values obtained are mapped as in Figure 4.14.

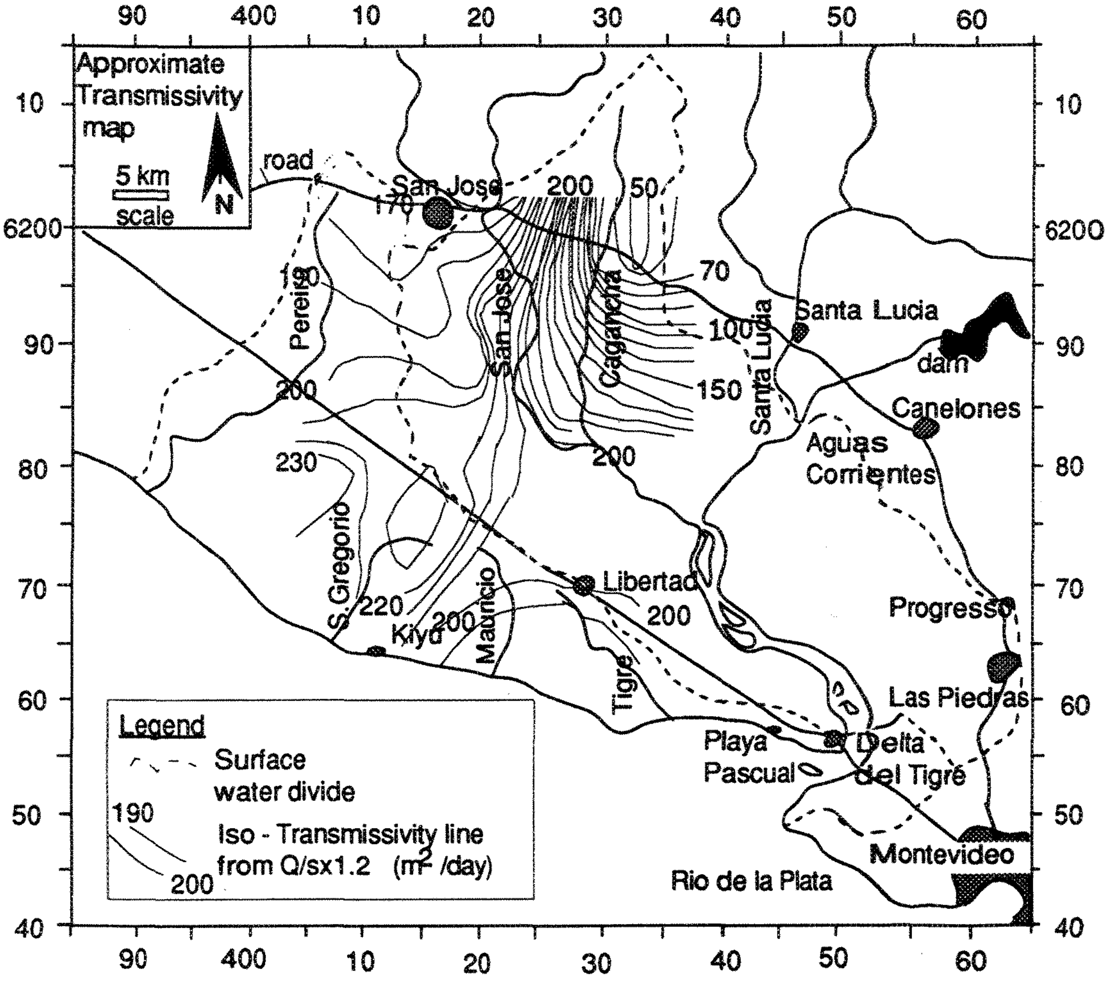


Fig.4.14 Approximate transmissivity map of the aquifer system in the Lower Santa Lucia Basin.

4.6 Determination of Hydraulic Conductivities

The hydraulic conductivities of the sedimentary deposits at the wells were obtained in using the following methods:

a) By dividing transmissivity values obtained from a pumping test, well tests and pumping tests of large diameter wells by the total saturated thickness of the aquifer.

b) By estimation from grain size distributions

c) Flow net method

4.6.1 Grain size Distributions and Quantitative Evaluation of Permeability Values

In chapter 2, the relative permeabilities of the litho-stratigraphic units have been examined. This is a very broad categorization that may only be used as a starting point in identifying the potential aquifer from a non-potential aquifer. Although, permeability values seem to be generally affected by litho-stratigraphy, some variations, in particular grain size distributions, within the stratigraphic units considered, largely dictate the occurrence and movement of groundwater. Therefore, it would be necessary to study in detail the character and grain size distributions of the sediments with particular reference to parameters affecting permeability, like porosity, sorting and content of particles less than 0.016 mm and particles greater than 2mm.

Some granulometric analyses conducted by geologists working in the basin since 1986 is given by Prichonnet et al.(1987). Some permeability values were obtained from granulometric analyses by La Haye (1988). The range of permeability values that were obtained by Jean La Haye and the corresponding standard permeability values of natural soils are given below:-

Kiyu .... 0.06 - 216 m/day (silt to gravel)

South east of Raigon .... 0.000216 - 77.8 m /day (clay to sand)

In the following discussion, the grain size distributions as observed from the lithologic logs will be used to estimate permeability values.

A map showing regional distribution of K values would be a pre-requisite to modeling the ground water of a basin. Unfortunately, it has not been possible to obtain sufficient K values, due to lack of sufficient number of piezometers to conducting pumping tests. However, attempts are made to have reasonable coverage of permeabilities by employing estimation method from grain size. Figures 4.16a to Fig.4.16e (see also Fig. 4.15) show grain size distributions as observed from lithological bore hole descriptions.

Permeability, which depends on the property of the fluid and property of the medium, can be expressed (derivation from the Hagen-Poiseuille equation - Domenico, 1972) as:

$$K = [p_w g N d^2]/\mu \qquad (4.7)$$

Where, p_w is fluid density, g is the acceleration due to gravity, N is a dimensionless-shape factor related to the geometry of the pore space, μ is viscosity and d is the diameter of the particle.

$p_w g/\mu$ characterizes the properties of the fluid. Nd^2 which characterizes the properties of the medium is called intrinsic permeability (k). There are various formulae expressing the intrinsic permeability (k) as a function of parameters like pore diameter and porosity. The most common of these equations is that of Kozeny-Carman (Verruijt, 1970).

$$k = [cd^2 n^3]/(1-n)^2 \qquad (4.8)$$

Where, n is the porosity of the soil and, the coefficient c, which ranges from 0.1 to 0.8, accounts for irregularities in the geometry of the pore space.

It can be seen from the above equations that k depends on the square of the diameter of grains. Taking the specific surface (U-value) which is the inverse of d, as a parameter for the grain size distribution, and $p_w g/\mu$ as being constant, the hydraulic conductivity (K) may be expressed from the Kozeny-Carman's equation as:

$$K = c/[U^2 (n^3/(1-n)^2] \qquad (4.9)$$

It would be reasonable to apply Kozeny-Carman's formula to calculate permeability values, provided that some precautions are made: Since relatively accurate values can only be obtained from field tests (pumping test), the results of K values obtained from the analysis of grain size distributions should be compared with available data on pumping tests.

The formula could then be adjusted, with the purpose of arriving at reasonable estimates of K values.

Three factors largely influence the effective porosity (hence permeability) of sand. These are: the sorting of sand, the presence of small particles less than 16 microns and the presence of gravel. If corrections are made for these factors, then permeability values could best be estimated from the following formula given by Boonstra and de Ridder (1981).

$$K = m\, U^{-2}\ C_{so}\, C_{cl}\, C_{gr} \qquad (4.10)$$

where U = specific surface,

C_{so} = correction factor for the sorting of sand

C_{cl} = correction factor for the presence of particles smaller than 16 microns,

C_{gr} = correction factor for the presence of gravel,

and m is a proportionality factor that can be adopted according to the particular characteristics of the aquifer considered.

For 40% of sand, J. Boonstra and N. A . de Ridder (1981) have shown from various investigations that m varies from 31×10^3 to 71×10^3.

Table 4.1. Permeability values of natural soil in meters per day (Walton, 1962)

Clays	$< 8.64 \times 10^{-5}$
Sandy clays	$8.64 \times 10^{-5} - 8.64 \times 10^{-4}$
Silt	$8.64 \times 10^{-4} - 8.64 \times 10^{-3}$
Very fine sands	$8.64 \times 10^{-2} - 8.64 \times 10^{-1}$
Fine sands	$8.64 \times 10^{-1} - 8.64$
Coarse sands	8.64 - 86.4
Gravels	> 86.4

The permeability values in table 4.1 give indications of the range of permeability values of defined grain sizes. In nature, however, the possible combinations of the above are infinite. Therefore, it becomes very important to give due considerations to the above mentioned factors (sorting of sand, presence of small particles less than 16 microns and the presence of gravel), which would take care of the real situation. An m value of 30 x 10^3 was chosen after several trials (comparison of grain size characteristics with measured values). The particle size limits and their corresponding specific surface (U-values) are classified (see Table 4.2).

Table 4.2. The classification of sandy materials, grain size limits, and corresponding specific surface (U) after Boonstra and de Ridder (1981).

	particle size limits (micron)		
Description	d1	d2	$U=1/2(1/d_1+1/d_2)$
Silt	16	63	390
Very fine sand	63	83	140
Fine sand	83	125	100
Moderately fine sand	125	200	65
Moderately coarse sand	200	333	40
Coarse sand	333	500	25
Very coarse sand	500	1000	15
Extremely coarse sand	1000	2000	7.5

The value of the correction factors needed for the formula have been represented on graphs by Boonstra and de Ridder (1981). The range of values of the correction factors are grouped from the graphs as in Table 4.3.

Table 4.3. Correction factors for equation 4.10, after Boonstra and de Ridder (1981).

Sorting	Correction factor (C_{SO})
High (70-90%	0.99 -1.6
Medium (50-70%)	0.567-0.99
Low (40-50%)	0.44-0.567

Particles < 0.016mm)	Correction factor (C_{cl})
High (5-7%)	0.19-0
Medium (3-5%)	0.433-0.19
Low (0-3%)	0.98-0.433

Gravel >2 mm	Correction factor (C_{gr})
High (40-60%)	1.33-1.97
Medium (20-40%)	1.8-1.33
Low (0-20%)	1-1.8

The U values are obtained from Table 4.3. The estimates of permeability values are then calculated by plugging the correction factors into equation 4.10.

Table 4.4. Permeability values calculated from equation 4.10 and using the lithologic log descriptions (see Fig.4.16a to Fig.4.16e).

N°. on legend	U	C_{so}	(C_{cl})	(C_{gr})	$K=30{,}000U^{-2}\ C_{so}C_{cl}C_{gr}$
1	---	---	---	---	---
2	25	0.4	0.8	1.6	27.65 m/day
3	390	0.4	0.1	1	0.014 m/day
4	390	0.4	0.05	1	0.007 m/day
5	25	0.4	0.1	1	3.46 m/day
6	100	0.8	1.0	1	4.32 m/day
7	390	0.8	1.0	1	0.28 m/day
8	390	0.4	0.1	1	0.014 m/day
9	25	0.8	1.0	1	69.12 m/day
10	40	0.8	1.0	1	27.0 m/day
11	100	0.4	1.0	1	2.16 m/day
12	---	---	---	---	0.00 m/day
13	140	0.4	0.1	1	0.11 m/day
14	65	0.8	1.0	1	10.22 m/day

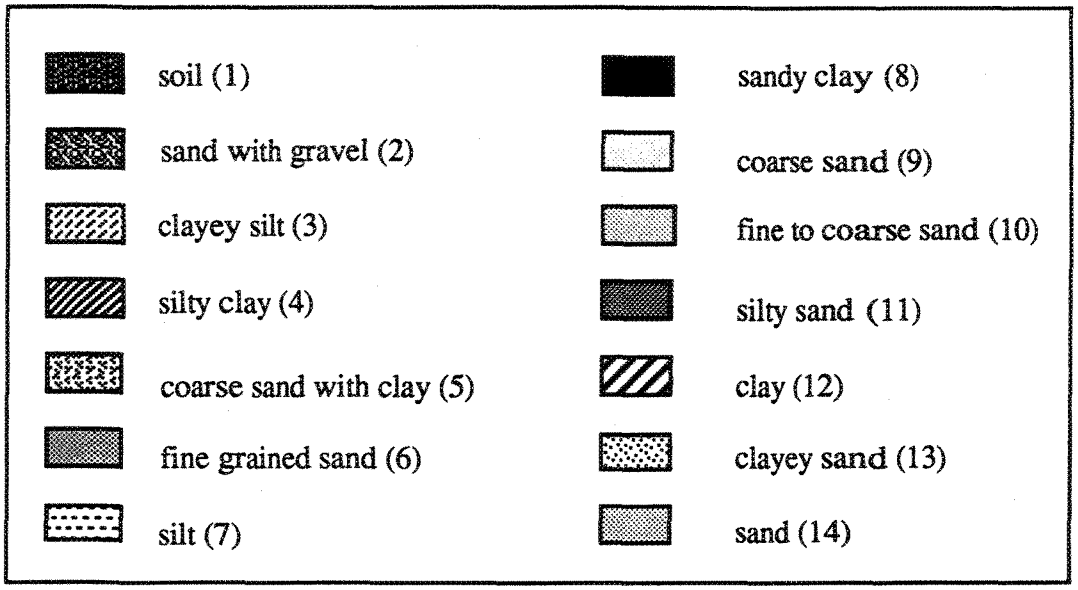


Fig.4.15. Legend used in the lithological borehole descriptions.

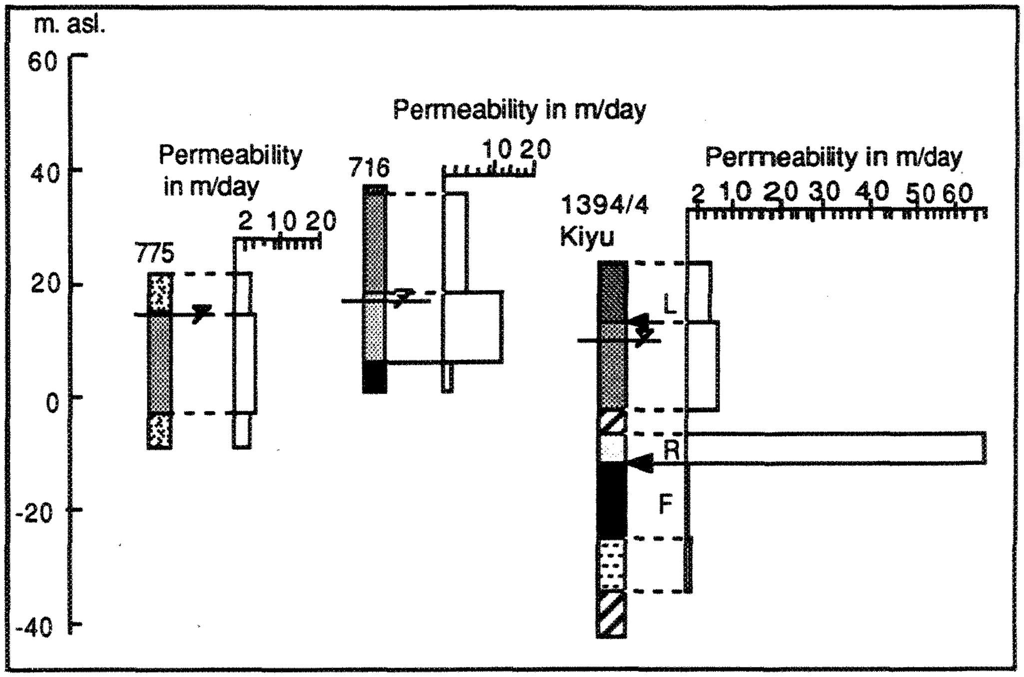


Fig. 4.16a. Lithologic log descriptions compiled from the works of UQAM and DI. NA. MI. GE. (1986 to 1989) and the corresponding permeability values quantitatively evaluated. See Fig. 4.3 for location of boreholes (see also legend in Fig.4.16b).

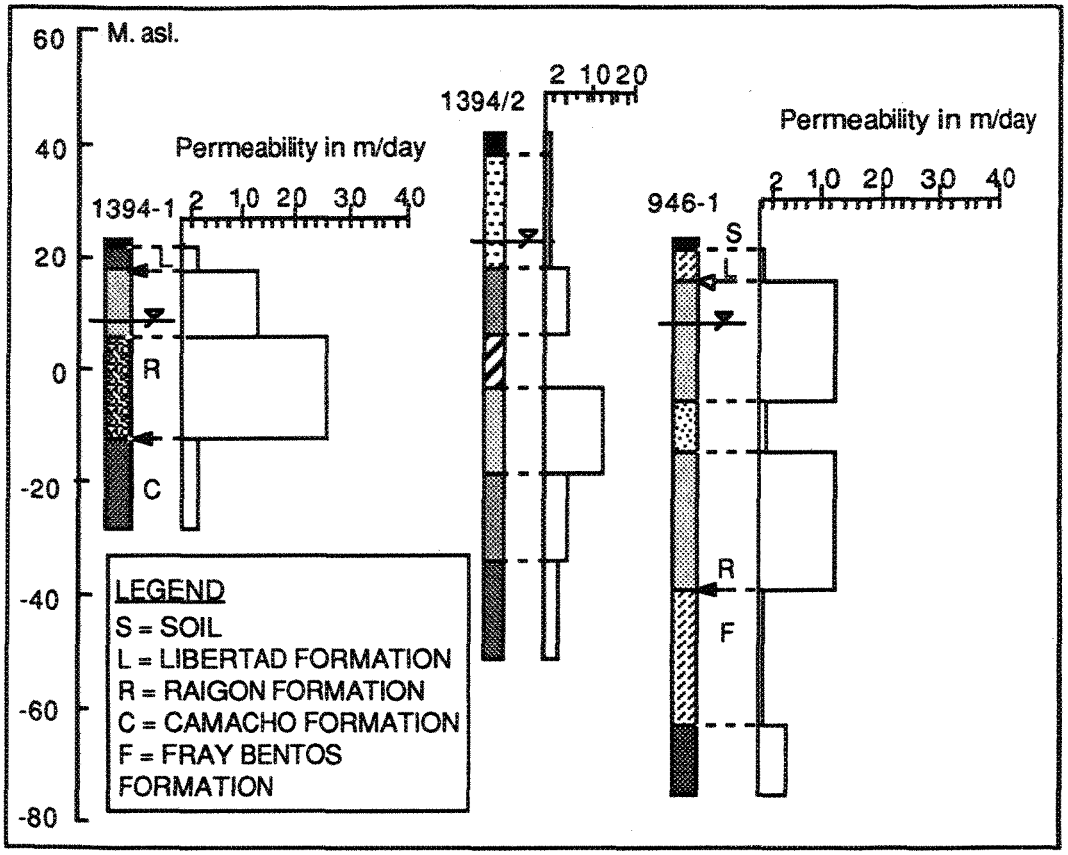


Fig. 4.16b. Lithologic log descriptions compiled from the works of UQAM and DI. NA. MI. GE. (1986 to 1989) and the corresponding permeability values quantitatively evaluated. See Fig. 4.3 for location of boreholes. The stratigraphic formations marked as R, L, etc. are the only ones for which we were sure at the time.

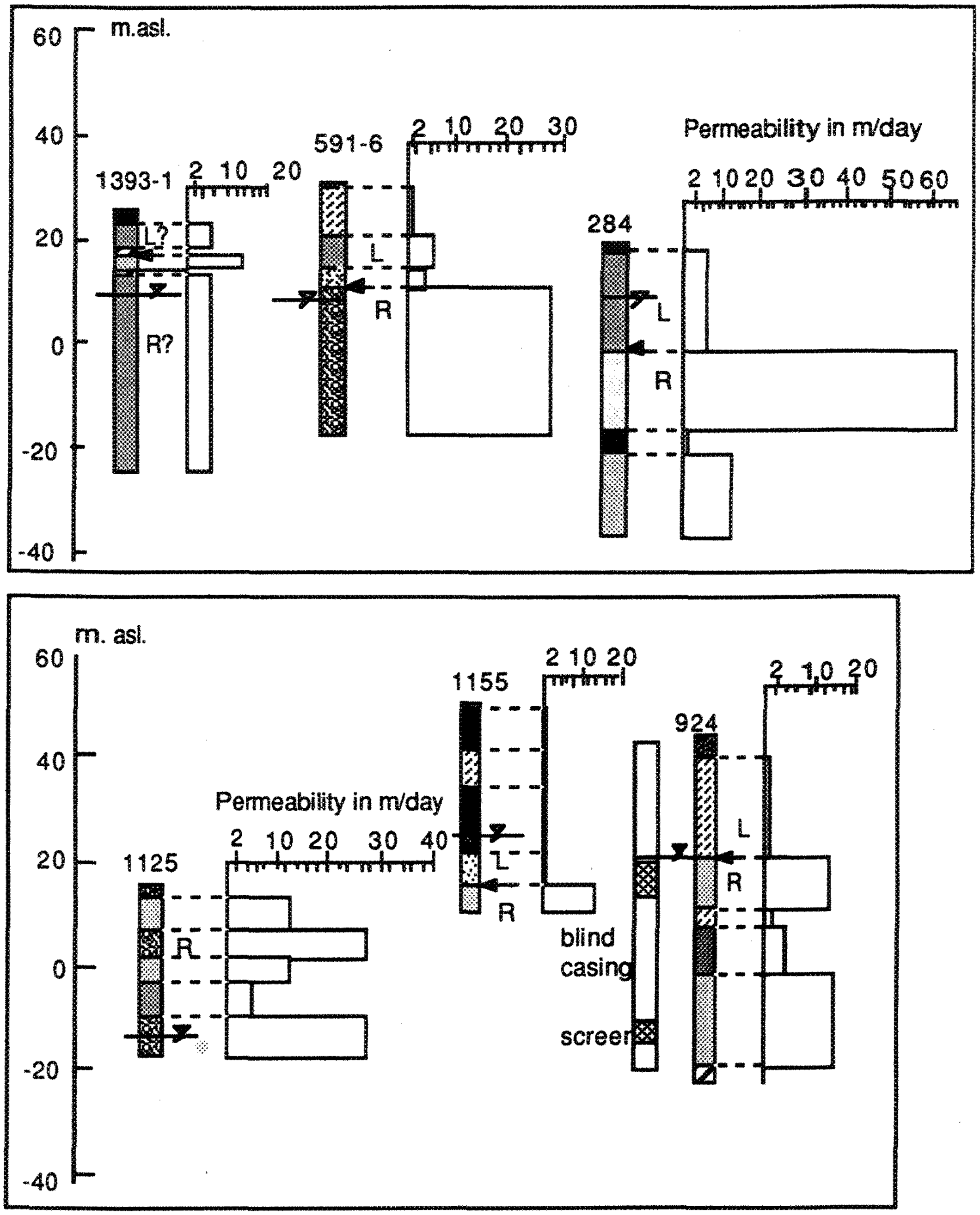


Fig. 4.16c & d. Lithologic log descriptions compiled from the works of UQAM and DI. NA. MI. GE. (1986 to 1989) and the corresponding permeability values quantitatively evaluated. See Fig. 4.3 for location of boreholes (see also legend in Fig. 4.16b).

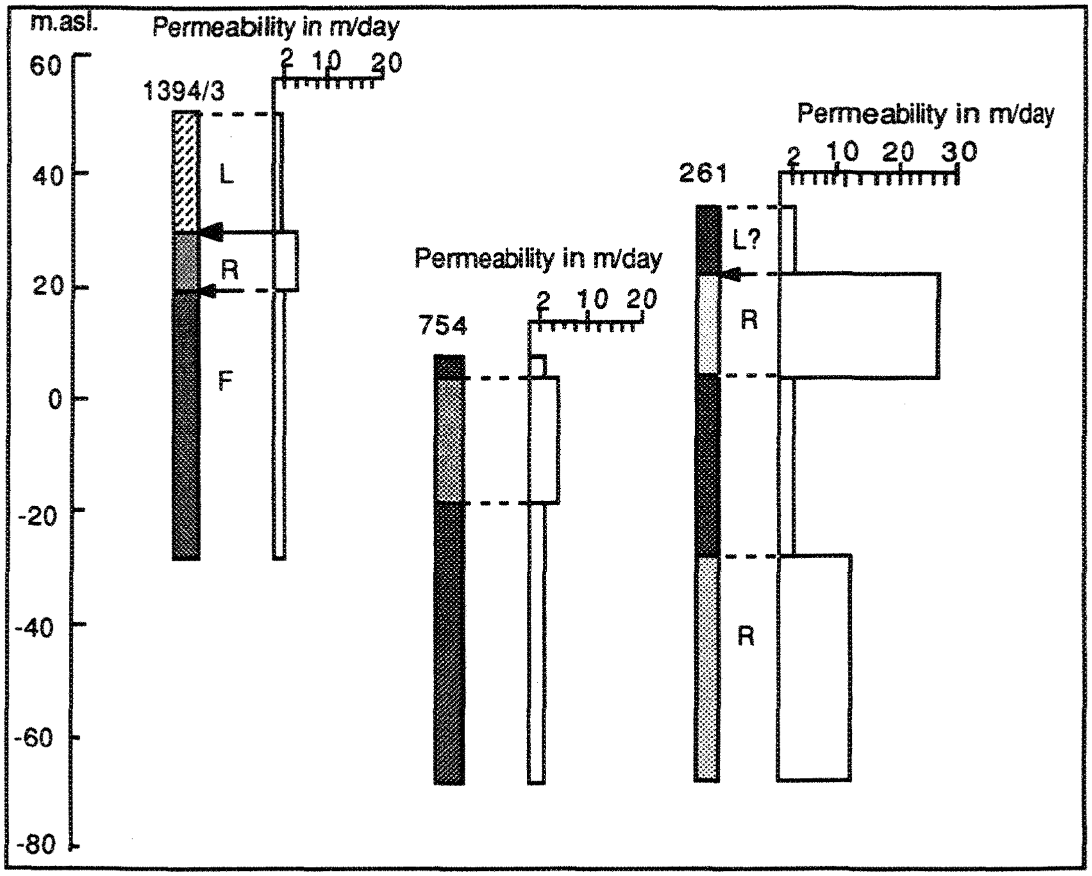


Fig. 4.16e. Lithologic log descriptions compiled from the works of UQAM and DI. NA. MI. GE. (1986 to 1989) and the corresponding permeability values quantitatively evaluated. See Fig. 4.3 for location of boreholes (see also legend in Fig. 4.16b).

The average permeability of each log is obtained by multiplying the permeability values obtained, by the respective thicknesses. Accordingly, the average permeabilities obtained are presented in table 4.5.

Table 4.5. Permeability values calculated from lithological descriptions

Log No.	K values (average)
1394-1	13.40 m/day
1394-2	6.40 m/day
946-1	2.27 m/day
1125-1	2 .00 m/day
1155-1	0.54 m/day
924	2.4 0 m/day
775	3.60 m/day
716	10.00 m/day
1394-4	8.53 m/day
1394-3	1.87 m/day
754	2.80 m/day
261	6.90 m/day
1393-1	6.60 m/day
591	11.00 m/day
284	22.00 m/day

Finally, it can be observed from Table 4.5 that the K values obtained by the estimation method from the grain sizes are fairly close to the permeability values obtained from wells for which field measurements (pumping tests, well tests and pumping tests of large diameter wells) were made.

4.6.2 Determination of Permeability Values From Flow Net Method

So far, some permeability values have been obtained for some parts of the area. Here, the permeability values where data were missing have been calculated from the average water table map.

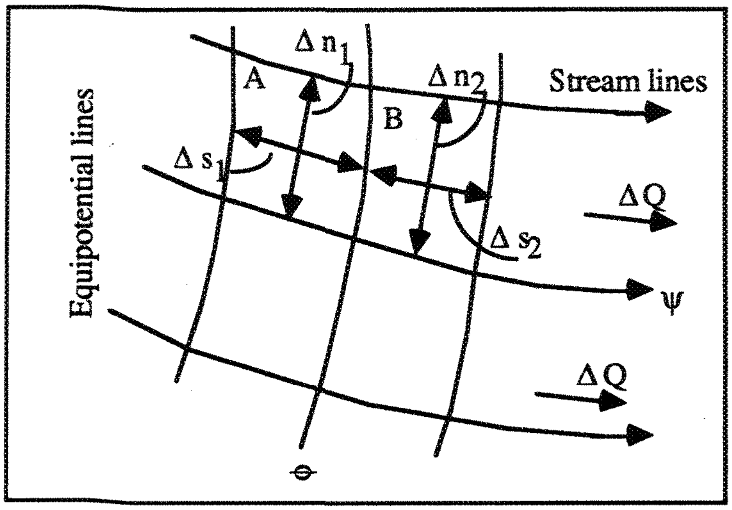


Fig. 4.17. A portion of a flow net, after Bear, 1978

In the absence of recharge and discharge conditions, the amount of water that enters A equals the amount of water that goes out of it and enters B (see Fig. 4.17). Hence considering the discharge Q per unit thickness in an inhomogeneous aquifer, the discharge in area A would be $\Delta QA = KA\ \Delta n_1 \Delta\phi A / \Delta s_1$ and the discharge in area B would be $\Delta QB = KB\ \Delta n_2\ \Delta\phi B / \Delta s_2$.

Where K_A and K_B are permeabilities in the respective segments, Δn_1 and Δn_2 are the average widths of the respective segments, Δs_1 and Δs_2 are the average lengths of the respective segments and $\Delta \phi_A$ and $\Delta \phi_B$ are the potential drops (gradients) of the respective segments.

Hence considering the discharge Q per unit thickness in an inhomogeneous aquifer, the discharge in area A would be equal to discharge in B so that,

$$K_A = K_B \, \Delta n_2/\Delta n_1(\Delta s_1/\Delta s_2) \; (\Delta \phi_B/\Delta \phi_A) \tag{4.11}$$

In using equation 4.11, the permeability values of the area where data are missing have been obtained.

A permeability map has been prepared (see Fig.18). and finally a transmissivity map has been possible from the saturated aquifer thickness map and permeability map (see Fig.4.19).

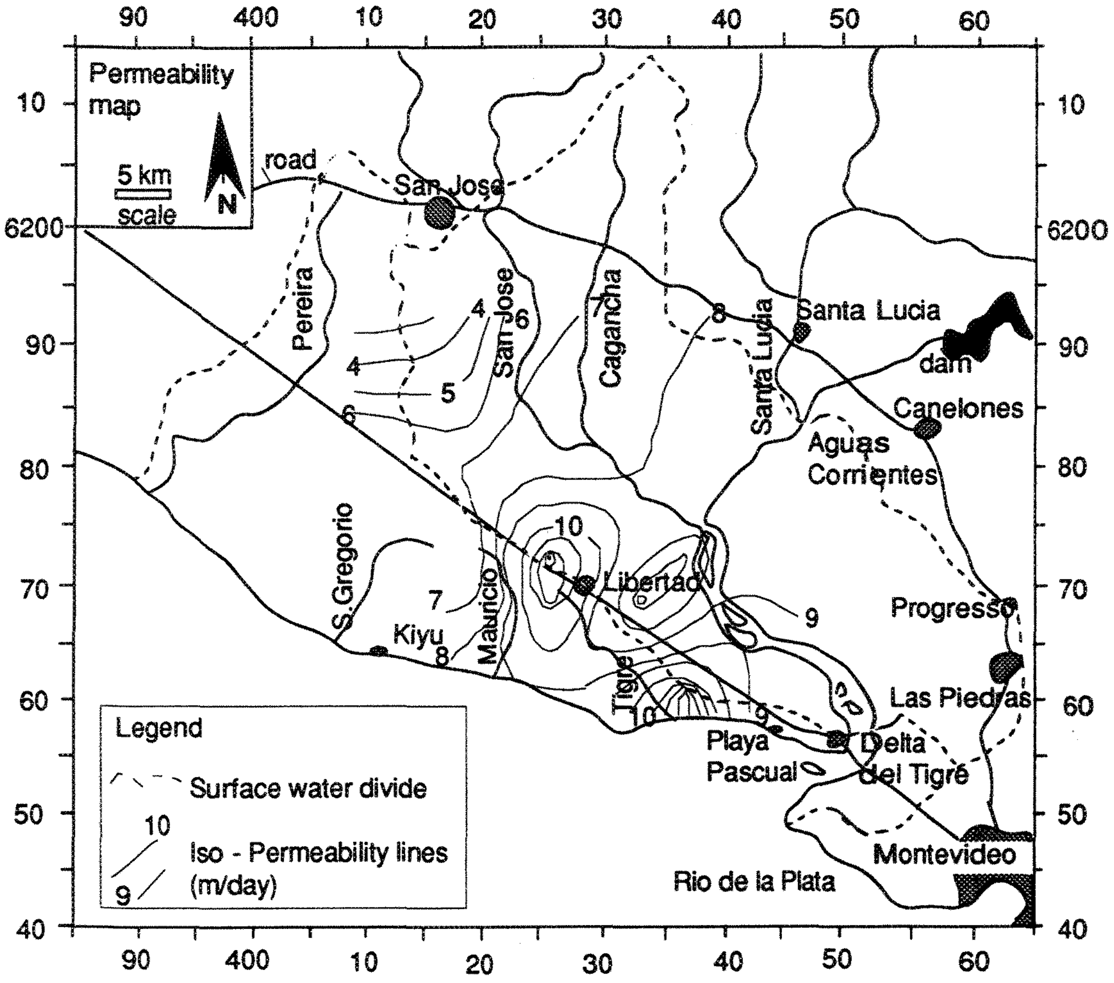


Fig. 4.18 Permeability map of the Lower Santa Lucia Basin

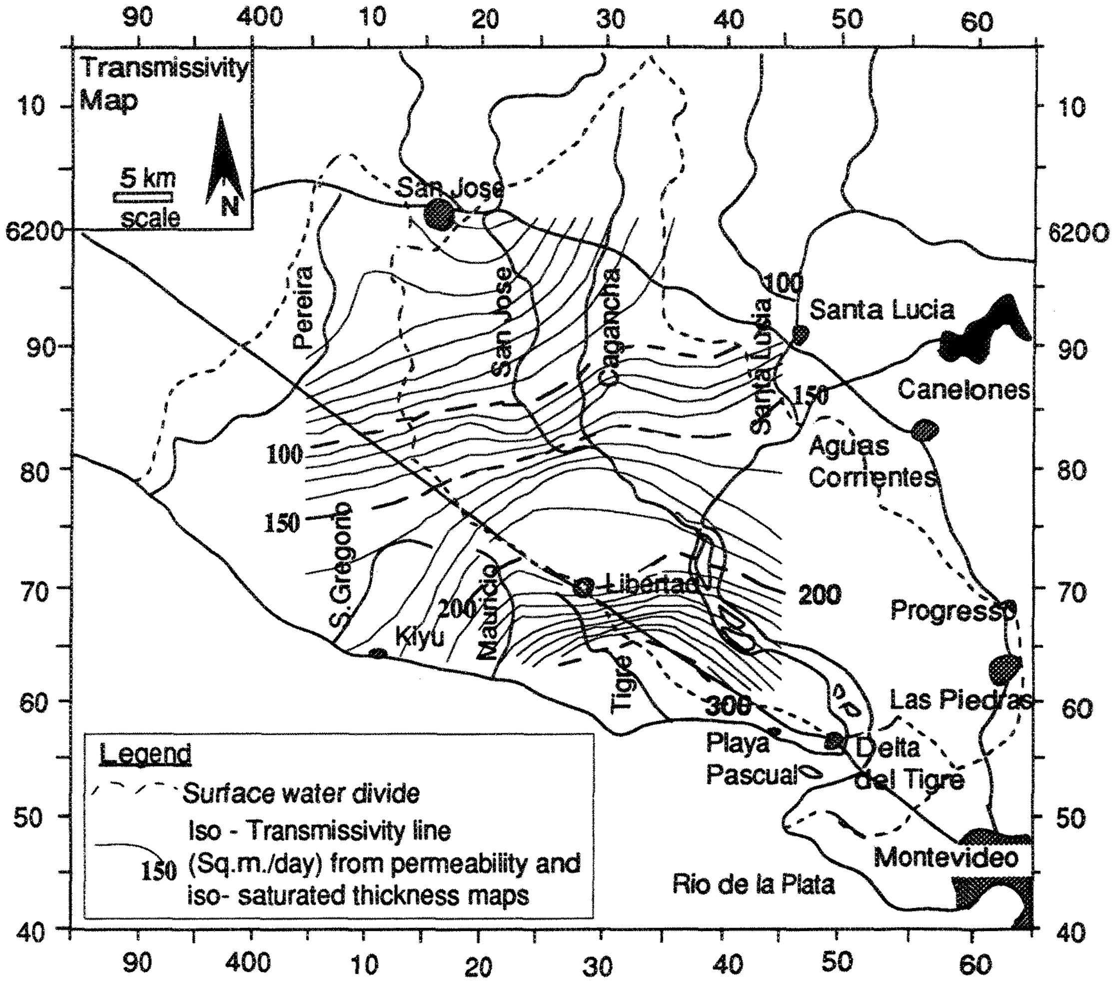


Fig.4.19. Transmissivity map of the Lower Santa Lucia Basin

4.6.3 Comments on Determination of Aquifer Characteristics

All the analytical solutions that describe the response of an aquifer to pumping and, from which various interpretations are made to calculate K, T and S, represent very idealized aquifer configuration. It should be noted, however, that aquifers are, at almost no times, homogeneous and isotropic. Aquifers are seldom perfectly confined or perfectly unconfined. The complex geologic processes in nature usually result in irregular stratigraphy, such as interfingering of aquifers and aquitards. It would therefore be unrealistic to expect accurate values for K,T and S.

Few wells were investigated in this study. The absence of piezometers has been a major handicap to the analysis of aquifer parameters. But other methods have been employed. For example, the approximate method of finding transmissivity values from the specific capacity of the wells gave values close to the values obtained by other methods. Finally, it can be said that the order of magnitude of the values obtained could be reasonable for the study of this basin, while more precise values would be anticipated when more piezometers will be installed in well field areas recommended in chapter 11.

4.7 Porosity and Specific Yield

The property of the aquifer system may be considered as heterogeneous and anisotropic, but we may assume a more or less uniform porosity.

The grain size properties of the aquifer being defined, and permeabilities obtained, it would be possible to extract porosity and specific yield factors from the relationship between known permeability, porosity and specific yield values of clay, silt, sand and gravel. These relationships are plotted on a graph (see Fig.4.20).

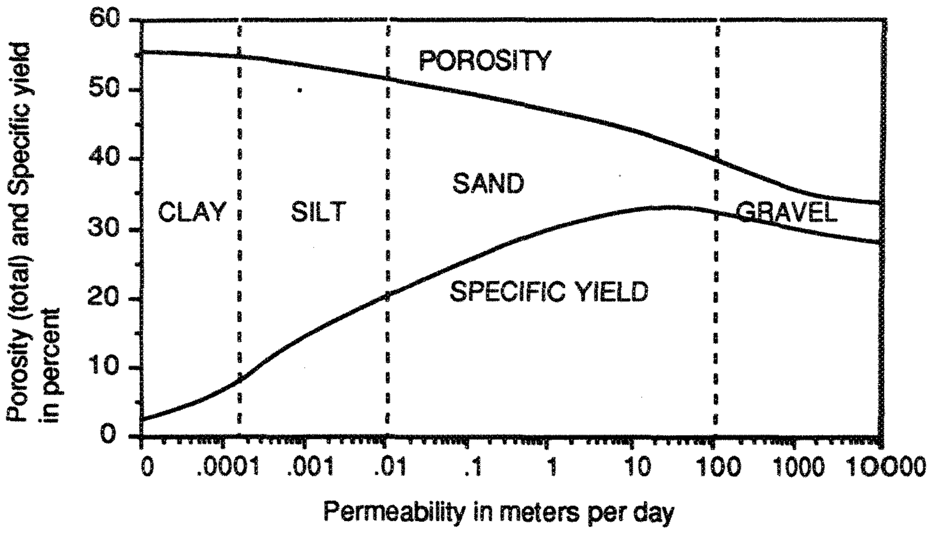


Fig.4.20. Relationship between permeability specific yield and porosity, after Walton 1962.

The porosity and specific yield of the fifteen logs were obtained from the permeability values corresponding to each lithologic unit in Fig. 4.16a to Fig. 4.16e . A weighted mean method is used, whereby the specific yield obtained for the corresponding permeability value is multiplied by the corresponding thicknesses of the units and the weighted average calculated from the total thicknesses.

Table. 4.6. Average Porosity and Specific yield values of the corresponding wells.

Log No	Porosity (%)	Specific yield (%)
1394-1	34	26
1394-2	36	24
946-1	37	22
1125-1	33	23
1155-1	37	18
924	37	22
775	36.8	22.5
716	35	25
1394-4	36	24
1394-3	37	22
754	37	22.3
261	36	24
1393-1	36	24
591	35	25
284	33	23

In confined aquifers, storativity (S) is the volume of water released from storage per unit area and per unit decline. This value is calculated from pumping tests. In unconfined aquifers, storativity is referred to specific yield, which is sometimes called effective porosity. Porosity represents the sum of specific yield and specific retention (the amount of water retained against gravity by hygroscopic and capillary forces). The specific yield of the aquifer system is one of the parameters which will be used in modeling transient groundwater flow. Therefore a contour map (iso - specific yield) is drawn from the table of values in Table 4.6 (see Fig. 4.21).

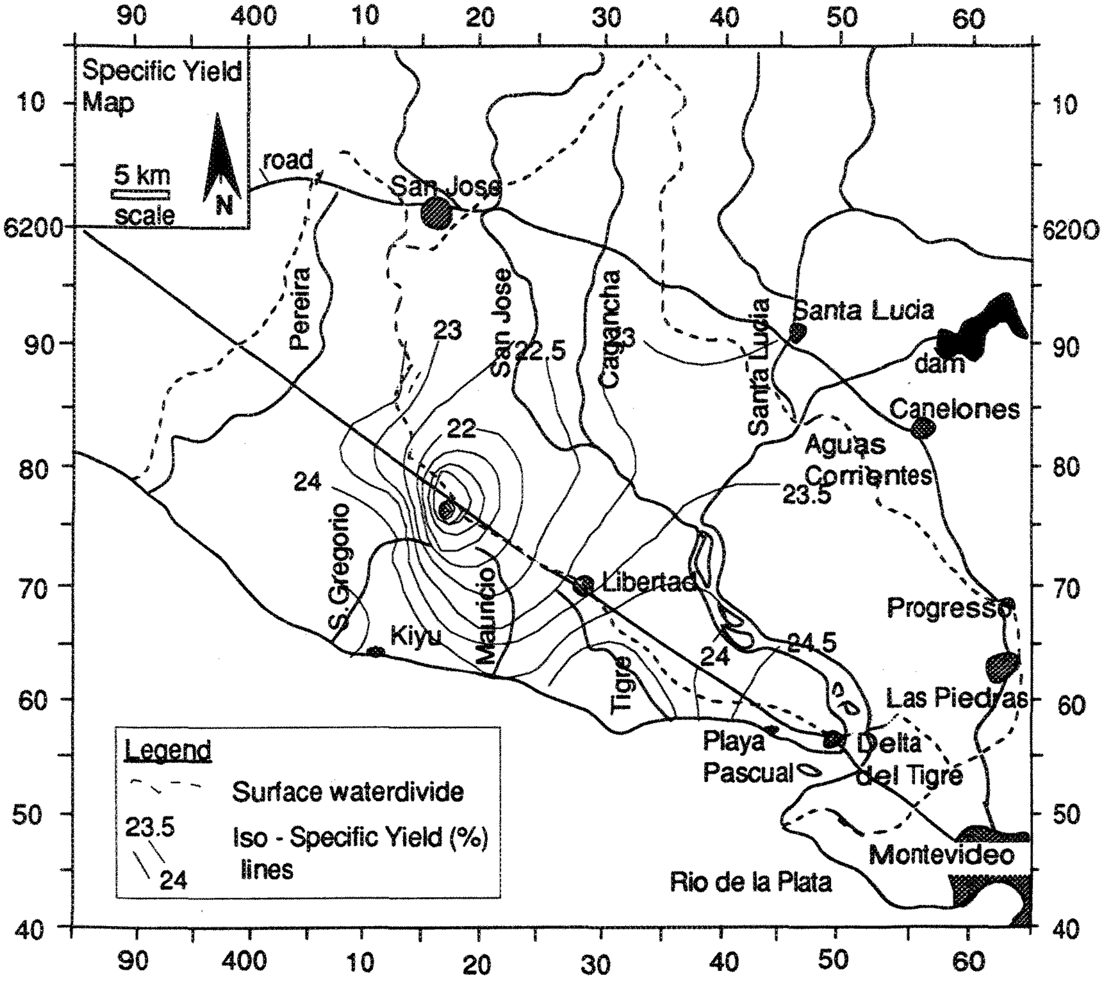


Fig. 4.21 Specific yield map of the Lower Santa Lucia Basin

Chapter 5

FLOWNETS AND OTHER HYDROGEOLOGICAL ASPECTS

5.1 Construction of Flownets

Flownets (hydrologic maps) have been constructed from a monthly water level record of October 1986, and from seven months water level records (December 1987 to November 1988). Contour maps representing equipotential lines are prepared for each month from the water level measurements. The groundwater flow directions are drawn perpendicular to the equipotential lines, reflecting direction of groundwater movement (see Fig. 5.1a to 5.1h). The average water level map is shown on Fig. 5.1i.

In the absence of source or sink, in a steady flow situation and in homogeneous isotropic medium, the equipotentials are everywhere perpendicular to the stream lines. However, these conditions are rarely met in nature. Therefore, assuming the porous medium of the aquifer unit as being homogeneous, but anisotropic, short arrows indicating flow directions are drawn in the water table maps instead of long stream lines.

Figures 5.1a to 5.1h represent the water table maps constructed from the monthly data. From these figures and also from Fig 5.2, it can be confirmed that the monthly variations in the water levels are too small to cause any noticable shrinkage or relaxation in the equipotential lines.

The general directions of the groundwater movements and the position of the groundwater divide do not seem to change from month to month.

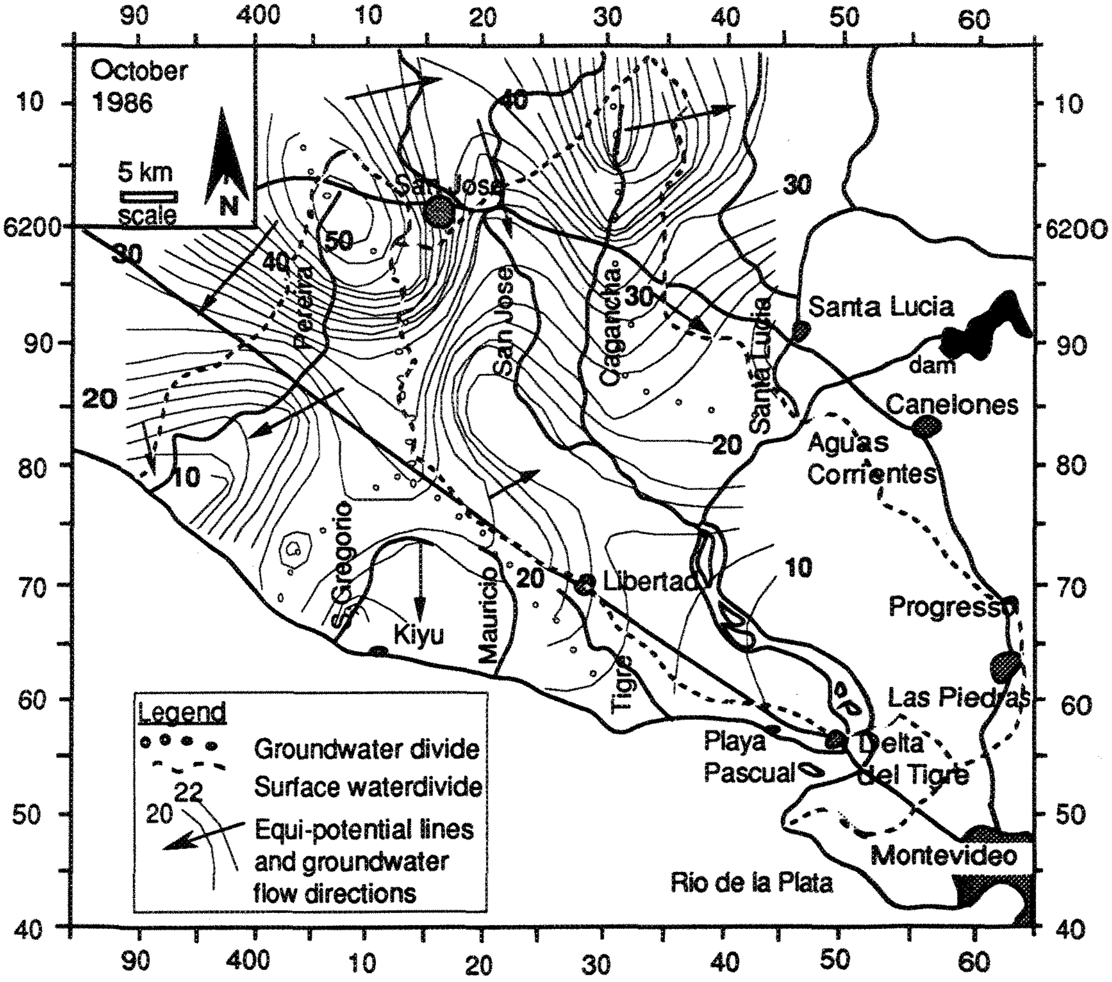


Fig. 5.1a A monthly water level map of the lower Santa Lucia Basin (October 1986)

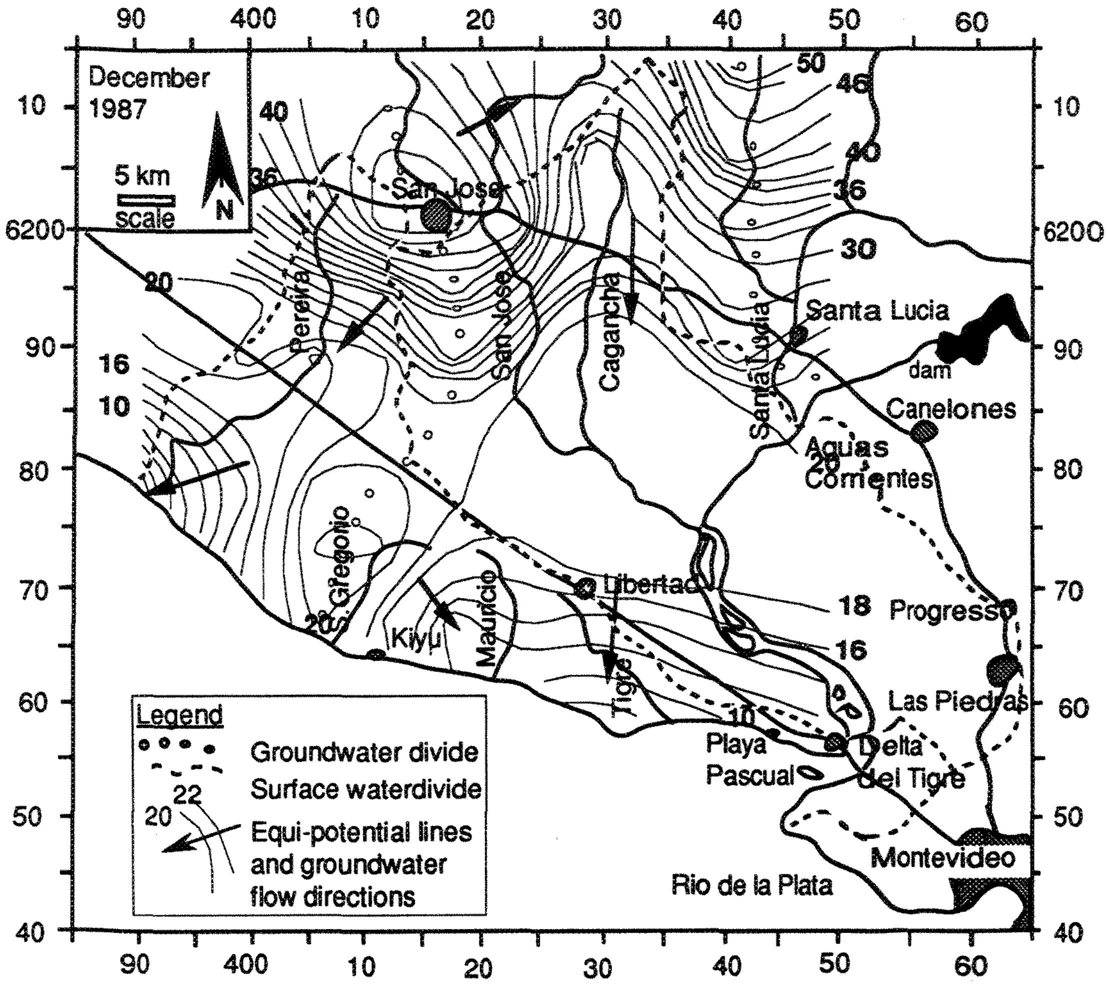


Fig. 5.1b A monthly water level map of the lower Santa Lucia Basin (December 1987)

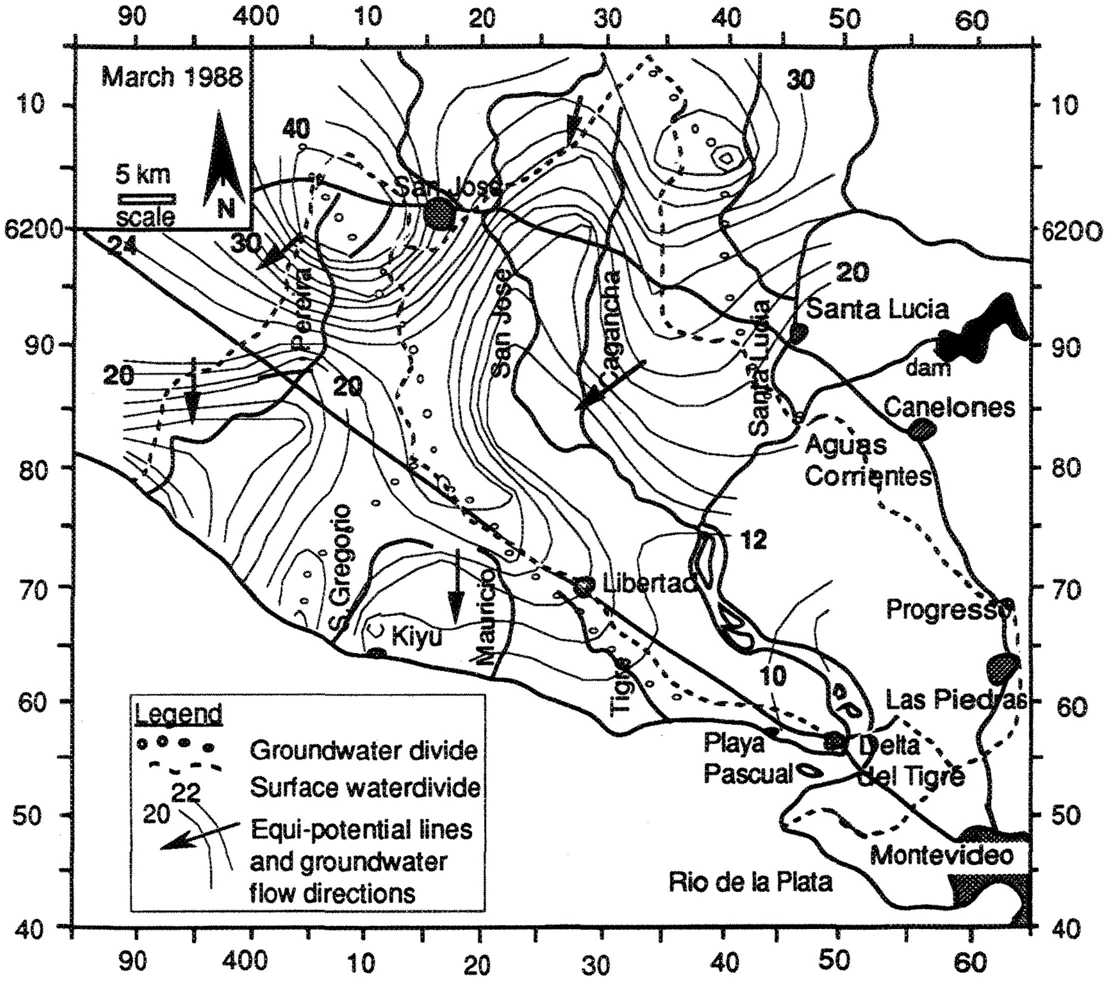


Fig. 5.1c A monthly water level map of the lower Santa Lucia Basin (March 1988)

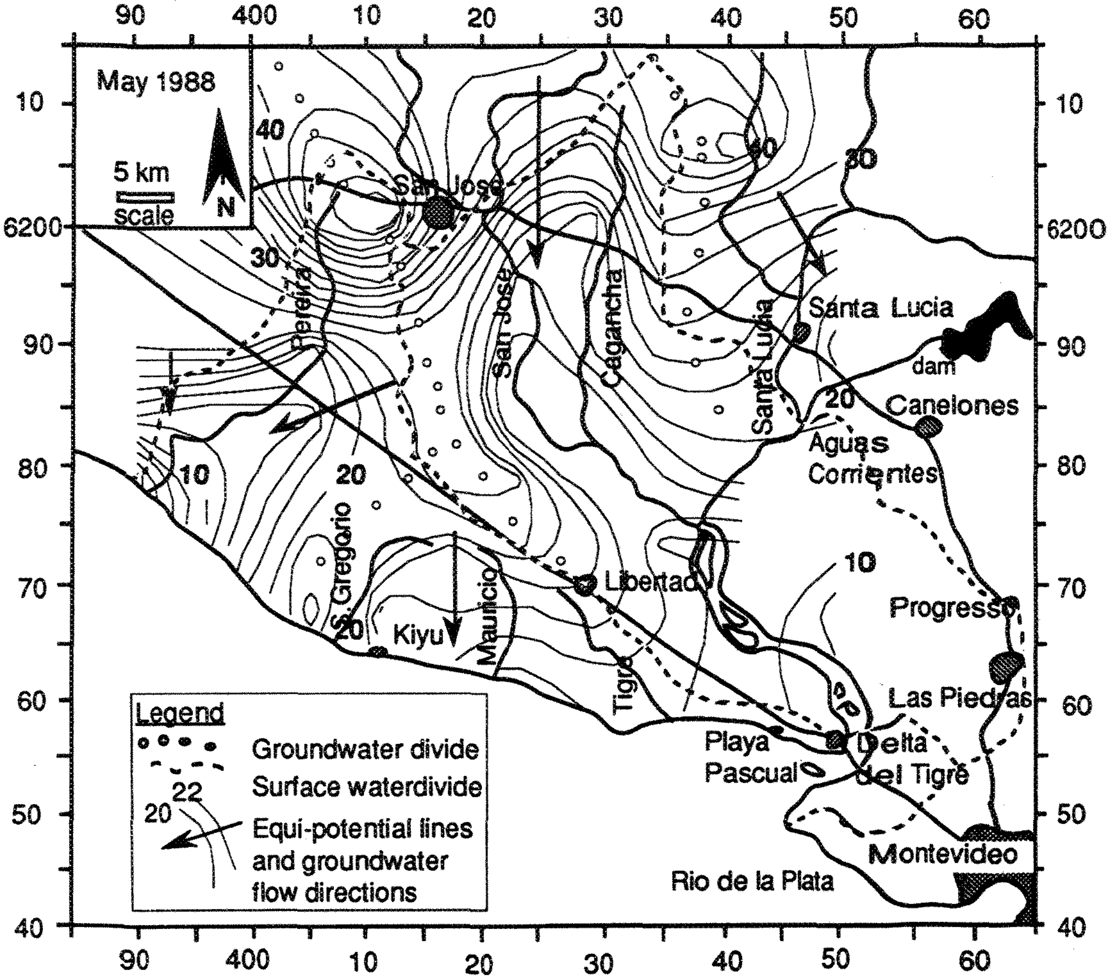


Fig. 5.1d A monthly water level map of the lower Santa Lucia Basin (May 1988)

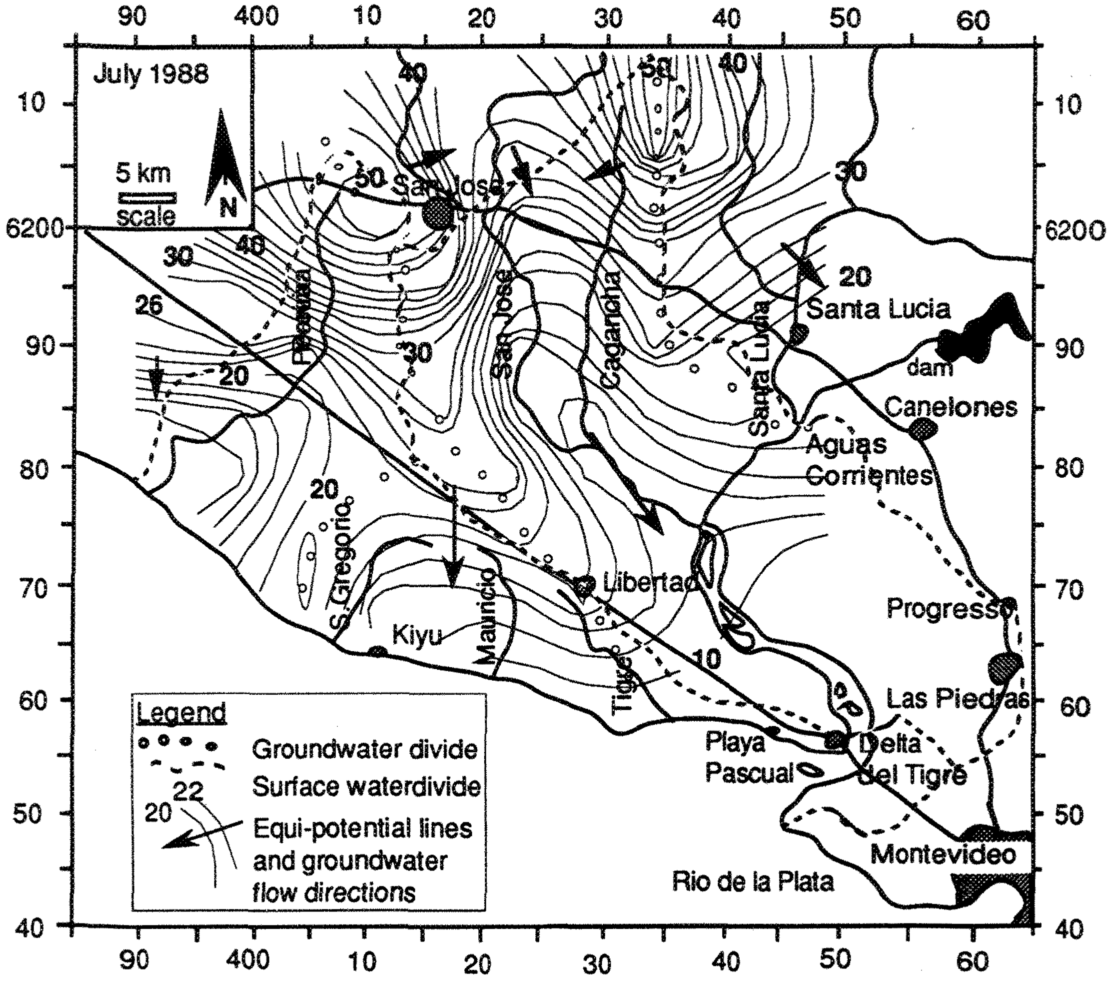


Fig. 5.1e A monthly water level map of the lower Santa Lucia Basin (July 1988)

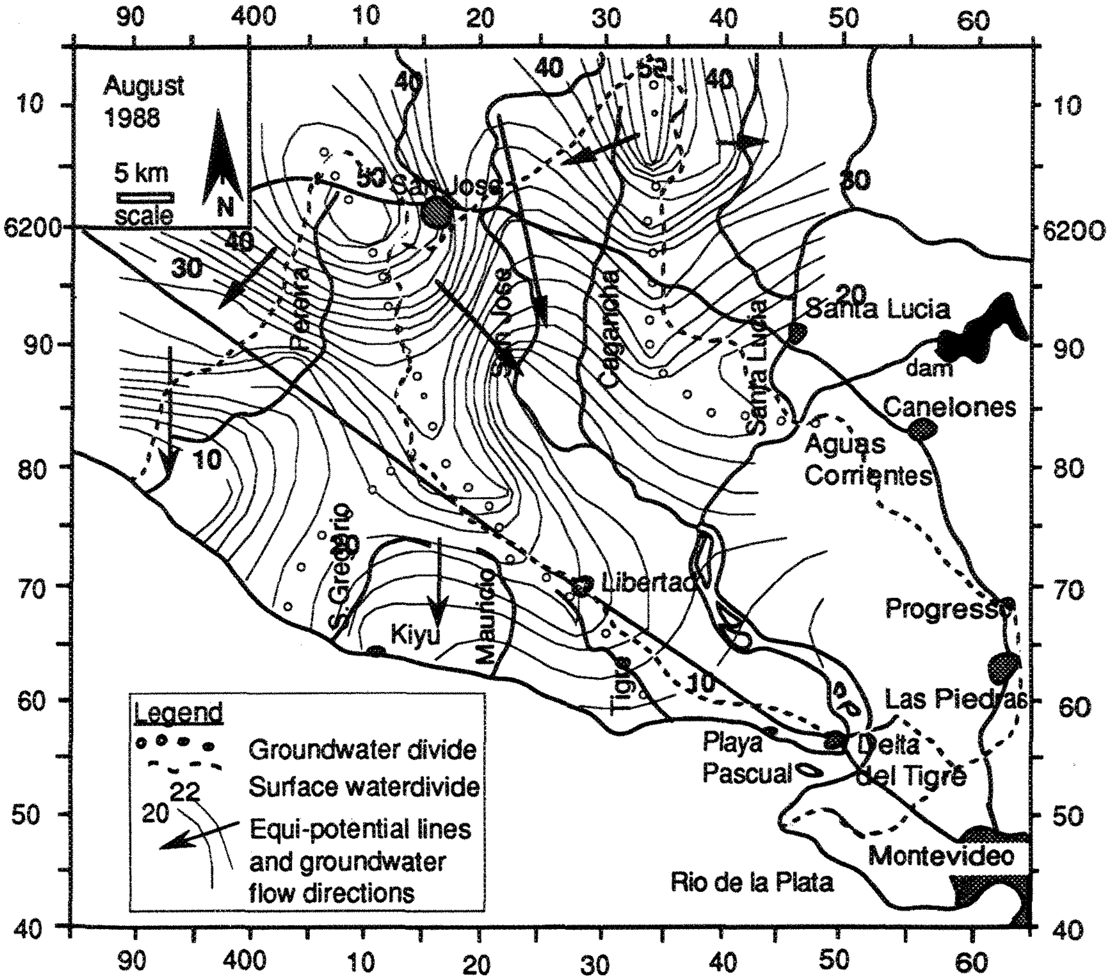


Fig. 5.1f A monthly water level map of the lower Santa Lucia Basin (August 1988)

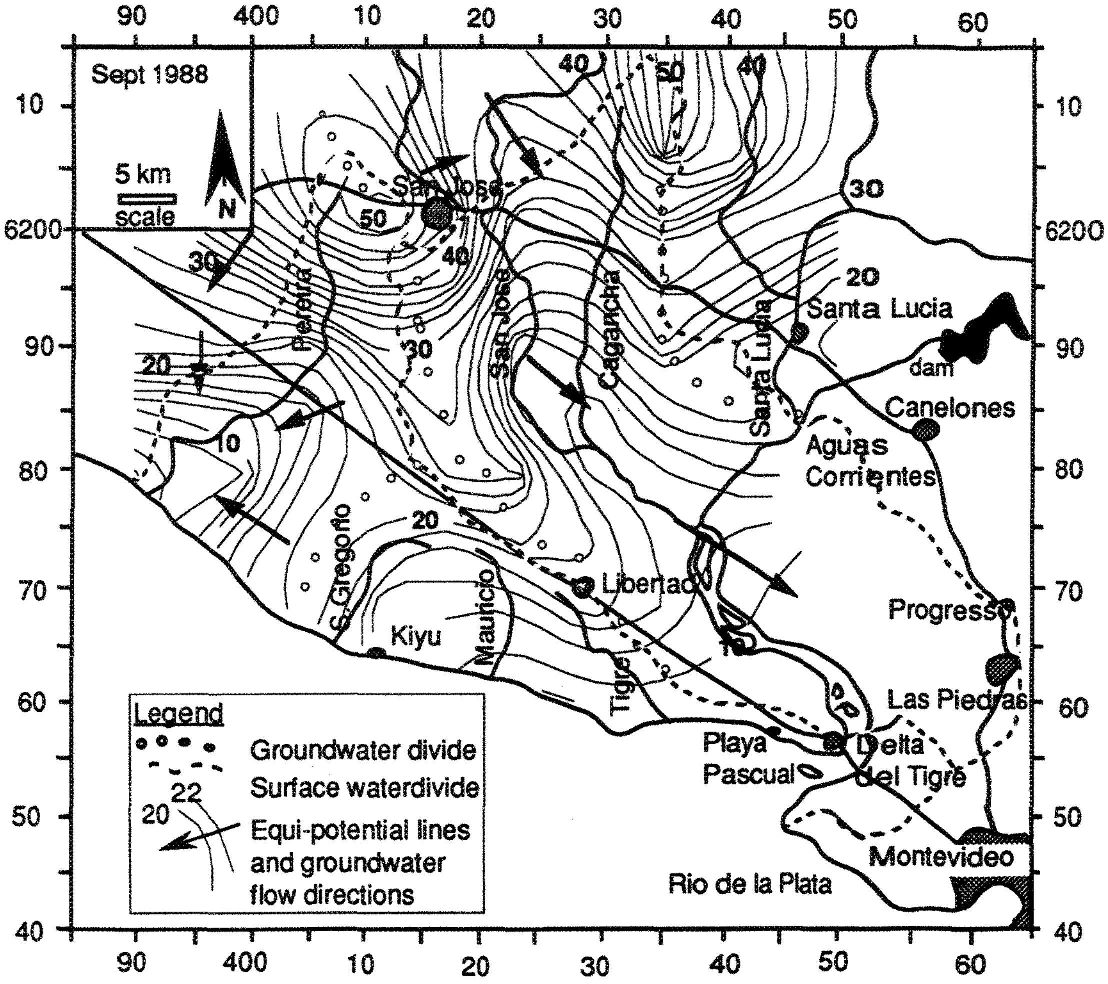


Fig. 5.1g A monthly water level map of the lower Santa Lucia Basin (September 1988)

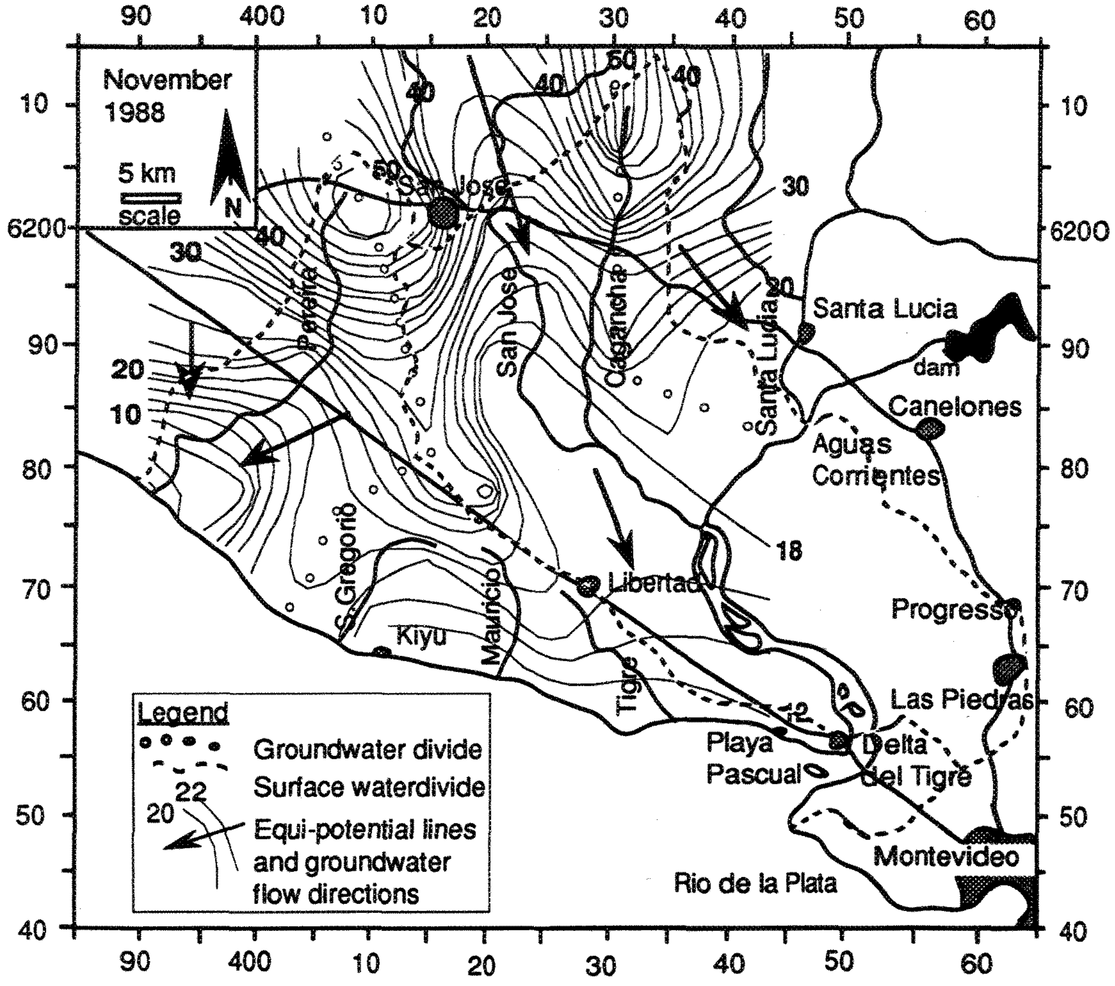
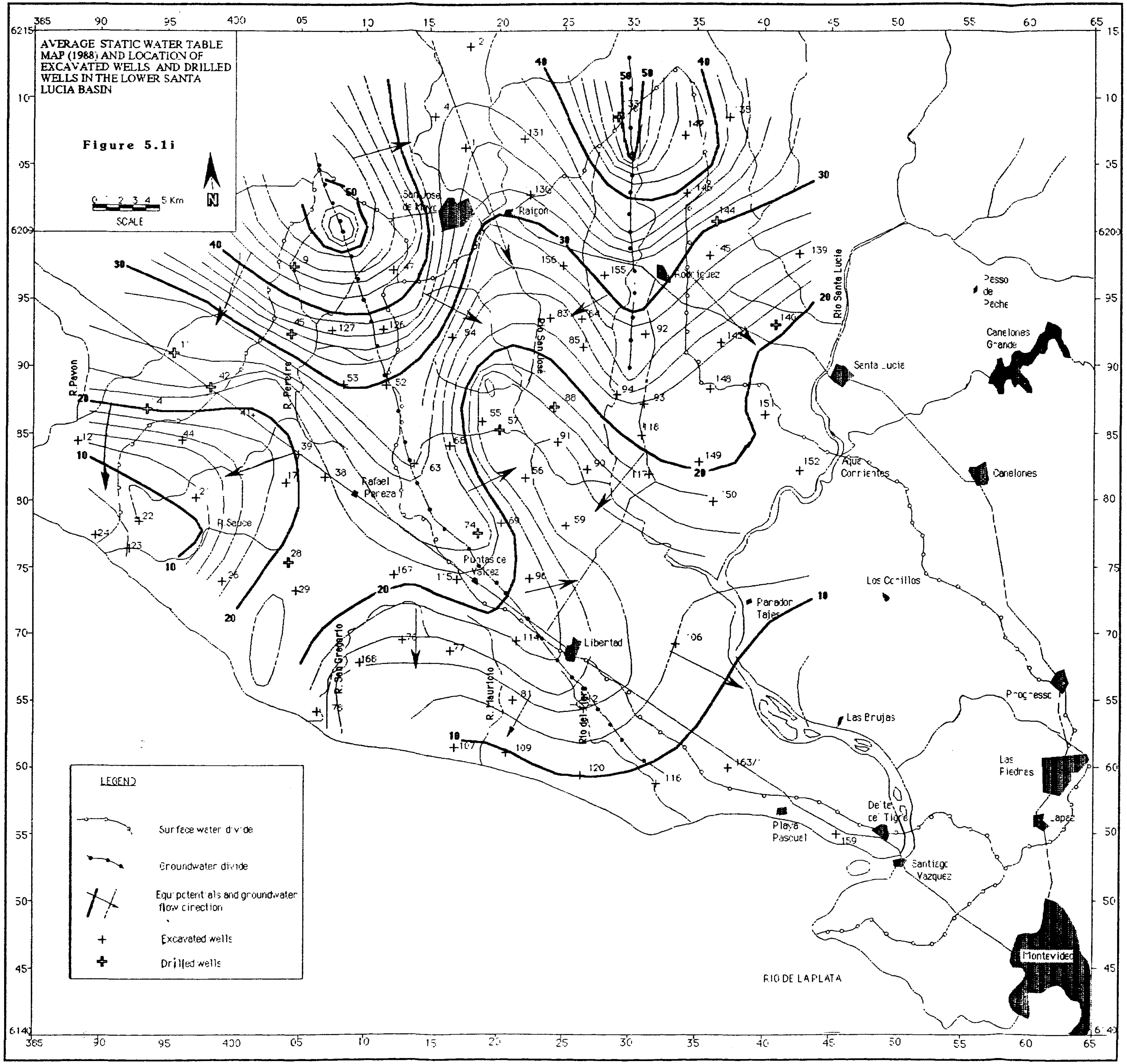


Fig. 5.1h A monthly water level map of the lower Santa Lucia Basin (November 1988)

Figure 5.1i


AVERAGE STATIC WATER TABLE MAP (1988) AND LOCATION OF EXCAVATED WELLS AND DRILLED WELLS IN THE LOWER SANTA LUCIA BASIN
Figure 5.1i
N
0 1 2 3 4 5 Km
SCALE
LEGEND
Surface water divide
Groundwater divide
Equipotentials and groundwater flow direction
Excavated wells
Drilled wells
San José de Mayo
Raigón
Rodríguez
Rio San José
Rio Santa Lucia
Santa Lucia
Canelones Grande
Paso de Pache
Canelones
Aguas Corrientes
Los Cerrillos
Parador Tajes
Libertad
Puntas de Valdez
Rafael Perez
R. Pavon
R. Pereira
R. Sauce
R. San Gregorio
R. Mauricio
Rio del Tigre
Las Brujas
Progreso
Las Piedras
Delta del Tigre
Playa Pascual
Santiago Vazquez
La Paz
Montevideo
RIO DE LA PLATA
10
20
30
40
50
6215
6209
6140
385
390
400
65

5.2 Flownet Data Interpretations and Some Related Hydrogeological Aspects

Careful investigation of the flow regime in the aquifer unit has revealed some useful informations which are indispensable for groundwater studies. In this section, we shall look at some hydrogeological aspects deduced from flownet data interpretations. Groundwater fluctuations principally reflect short and long term effects caused by one or more of the following:

- Dry and wet periods.

- Fluctuations of water levels in rivers which are connected to the aquifer system.

- Extraction of water by pumping or recharge by irrigation water.

- Water losses by evapotranspiration.

In the following discussion, the groundwater measurements are considered as reflecting the average effect of the particular month for which measurements were taken. By doing so, it would be possible to compare the water level measurements with other parameters, like precipitation of the corresponding months. It is assumed from the previous discussion, in chapter 4, that the water level measurements represent a watertable situation which is everywhere the same for the same aquifer (i.e.the Raigon plus the Libertad Formations).

5.2.1 Response of the Aquifer to Effective Precipitation

The aquifer system is replenished from above by water from precipitation and irrigation. Water in the soil zone moves downwards through the unsaturated zone with supply of water at the soil surface. The soil water zone extends from near the ground surface downward through the root zone (50 - 200 cm.). It should be noted that pollutants are also transported down to the groundwater system by such infiltrating waters.

The response of the aquifer to precipitation can be observed from the bar graph showing the monthly precipitation values and the average static water levels for the corresponding months (see Fig. 5.2). Due to the gap in the available water level records (only six months for the year 1988) it may not be possible to affirm the existence of immediate response of the aquifer to precipitation. However, we may not expect significant variations in water levels, since the distribution of rainfall in the area is more or less constant throughout the year; the calculated mean change of water level variations between two consecutive months is about 35 centimeters.

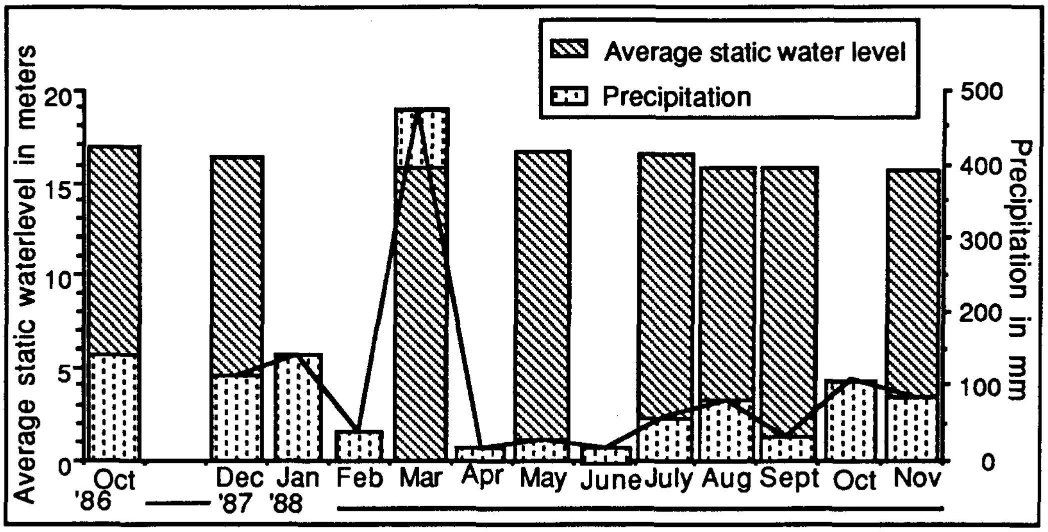


Fig. 5.2 Bar graph showing the monthly precipitation values and the average static water levels for the corresponding months. Note that precipitation was very high (460 mm) in March 1988.

Since precipitation may not be equally distributed over the whole region, all parts of the aquifer may not respond simultaneously and at the same rate. The factors like topography and infiltration capacity of the soil influence the response of the aquifer. Hence, precipitation and water level relationships were examined for two of the environments having different lumped effect on geology, pedology and geomorphology (see Fig. 5.3).

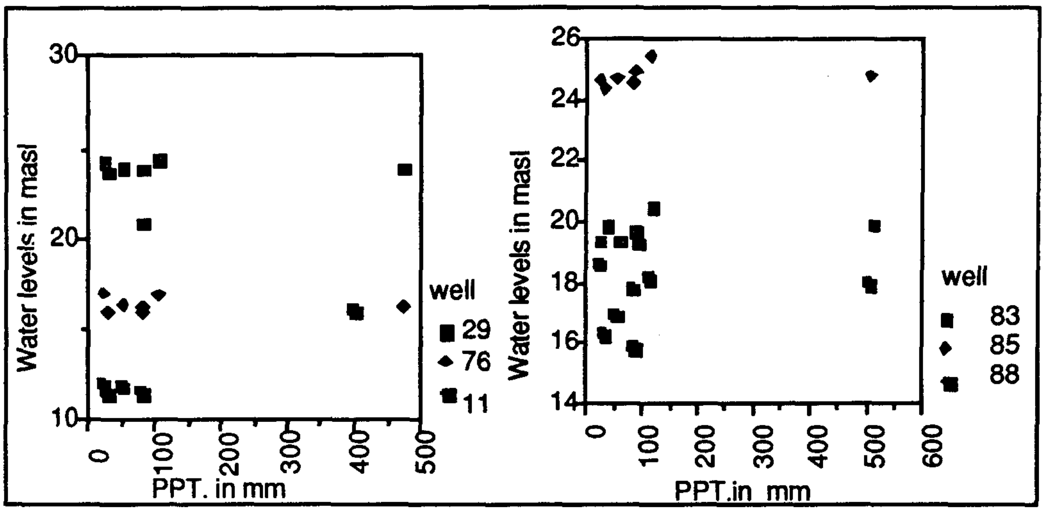


Fig. 5.3. Monthly precipitation (from the data of 1988) versus the corresponding water levels in representative wells from the coastal zone (left figure) and interfluvial zone (right figure).

As in Fig. 5.3, the water levels in wells seem to have some relation with precipitation. The abrupt water level fluctuations on particular wells are not related to natural phenomena. The fact that all the graphs are asymptotic towards the right obviously indicates aquifer saturation limits. Apart from what can be observed from Fig. 5.3, the response of the aquifer to precipitation in the interfluvial zones greatly varies between wells located few meters apart. This could be explained by the heterogeneity of the soil cover affecting the infiltration rates. Better response may be expected in the coastal zones where the pedology is relatively constant.

5.2.2 River Aquifer Relationships

From the hydrologic maps, influent and effluent situations can be distinguished from the shape of the equipotentials. In general, all rivers seem to be recharged by the aquifer. However, it would be hasty to assume such situation as permanent characteristics. The groundwater divide along "ruta 1" seem to be a major recharge zone, while all the rivers are discharge zones except the lower estuaries of the Santa Lucia river which could also be sources of groundwater recharge.

The possibility of interconnection of river water with that of the regional groundwater is an important aspect in groundwater resource evaluations, which can be understood by comparing river drainage map with depth to water map. Figure 5.4 shows the depth to water table map of the area, which is constructed from the average water level depths. The possibility of a two way interconnection (effluent and influent) of the rivers with the aquifer system is higher in areas where surface water is closer to groundwater. It is worth mentioning that this map could be of great help for development plans especially when the need to protecting the groundwater from contamination become crucial.

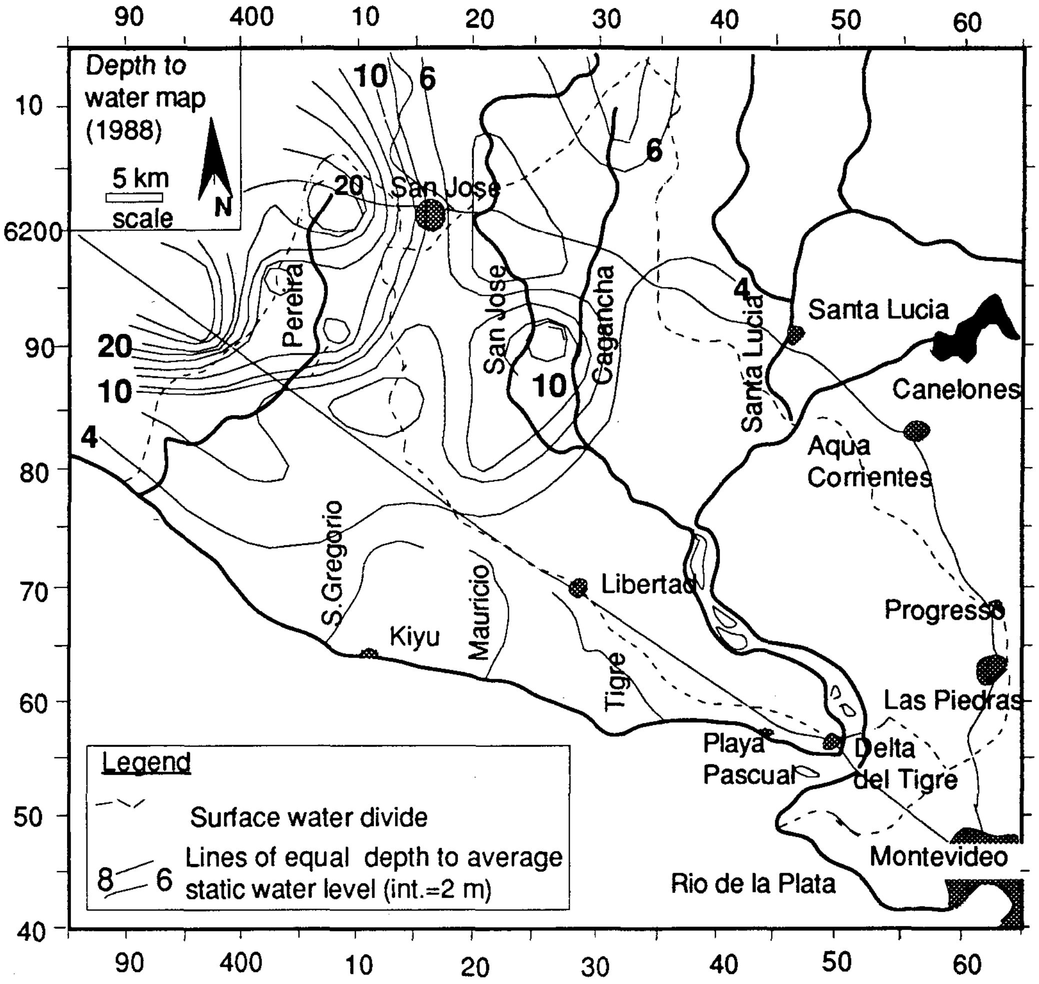


Fig.5.4. Depth to average static water map from the water level measurements of the year 1988.

The possibility of interconnection of rivers with the aquifer system can be understood better if we analyze water level measurements taken at different times. Figures 5.5a and 5.5b show four sections across the main rivers. It can be observed from these sections, representing maximum and minimum water levels, that a drop in water level actually occurs during the driest months. Considering the average water levels of the months, it can be seen from figure 5.2 that the difference between the maximum water level record (May 1988) and minimum water level record (Nov. 1988) is around 1.5 meters. However, the difference between the maximum and minimum water levels in the individual wells vary from place to place (1 to 3 meters) depending largely on the character of the aquifer.

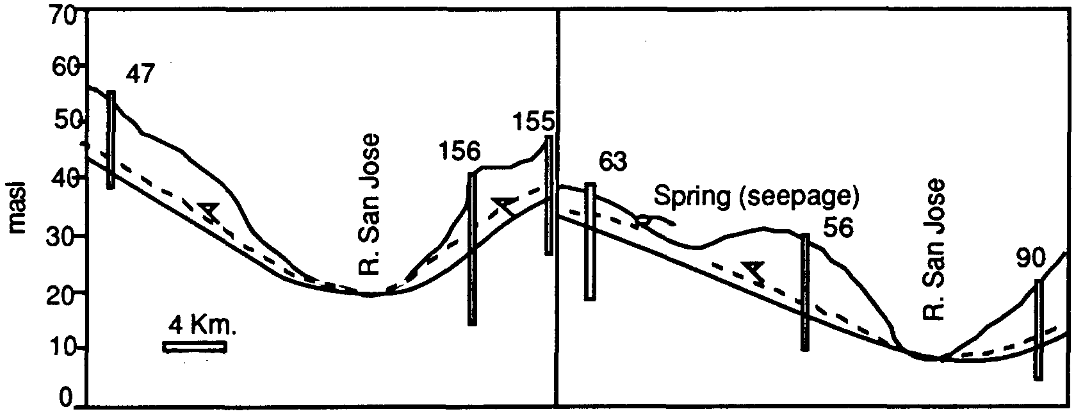


Fig. 5.5a. Two sections south of San Jose town representing maximum and minimum water levels in wells (see Fig.2.3 for locations).

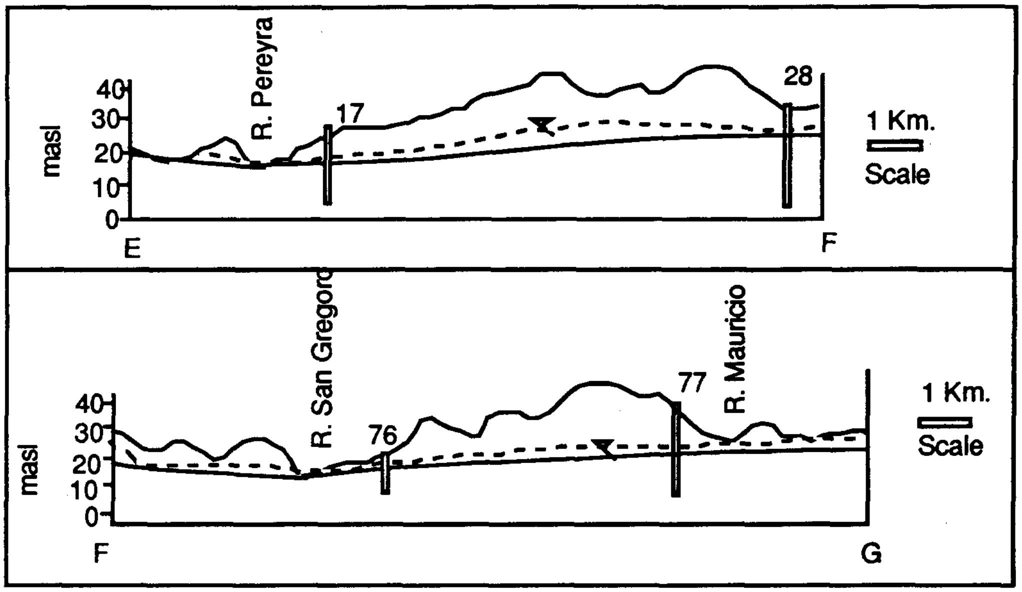


Fig. 5.5b. A section east of river Pereyra (upper) and a section across rivers of San Gregorio and Mauricio (lower) representing maximum and minimum water levels in wells. (see Fig. 2.3 for locations).

Since all the rivers along the coastal zone (Luis Pereyra, San Gregorio, Mauricio and del Tigre) emerge from the aquifer and are all the times contributing to negative storage, they reflect the situation of the aquifer on surface. That is, one may tell if the aquifer suffers from draught periods by observing the water level in these rivers. They could, in a way, facilitate the groundwater movement, thereby receiving some water from the aquifer upstream and giving it back to the aquifer downstream (towards Rio de la Plata).

Quick Flow and Base flow Components

The quantification of aquifer recharge rates by the rivers or discharge rates of rivers requires discharge measurements at different places along its course. Unfortunately, no such data exists. For the present, the available long term discharge measurement of the San Jose river at San Jose town will be given for the sake of comparing the quick flow and base flow components. This relationship is presented as in figure 5.6.

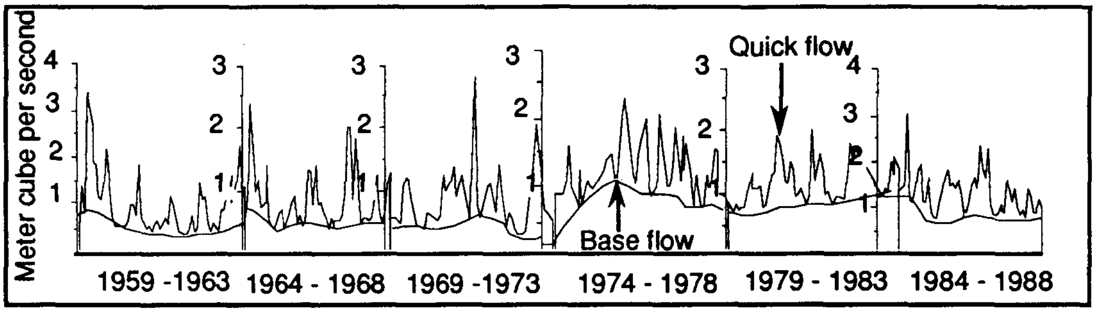


Fig. 5.6. Monthly flows of San Jose river in meter cube per second; base flow components are separated from quick flow components, from the data obtained from "Direccion Nacional de Hidrografia, Division Recursos Hidricos, Departmento de Hidrologia", 1988.

The base flow versus quick runoff relations of the San Jose river reflect the general characteristics (drainage density , relief, soil moisture content, permeability, etc.) of the basin north of San Jose town. Without going into detail, some important points can be obtained from figure 5.6.

- The relatively wet periods are 1975 up to 1977.

- The relatively dry periods are 1985 up to 1988.

- The flow variations between individual months is not great.

- Base flow component (for the years 1959 - 1988) of San Jose river varied between 0.5 to 1.5 meter cube per second which may be regarded as a potential for the groundwater recharge into the lower estuaries of the Santa Lucia river.

5.2.3 Areas of Groundwater Loss

Apart from the previously mentioned rivers, loss of groundwater occurs by evapotranspiration, where groundwater is close to the surface. The fact that the marshy areas are connected to the regional groundwater, hence are contributing to additional groundwater loss due to drainage of water directly from the water table by roots of plants, can be verified by superposing the geomorphological map on the depth to water map.

The presence of certain hydrologic features, like source (a well may be recharged by artificial replenishment from adjacent irrigated field at the time of measurement), or sink (a pumping well may not have been fully stabilized at the time of measurement), have an insignificant effect to the present scale of mapping.

5.2.4 Direction of Groundwater Flow

In the last chapters, the two major sources of groundwater into the aquifer system, namely precipitation and recharge from the upper parts of the basin have been discussed. Local and regional groundwater flow directions can be identified from the water table maps by taking into account all the possible sources of recharge into consideration. The local groundwater flow directions, corresponding mainly to recharge by precipitation, are directed towards valley bottoms: The principal directions of local groundwater flows are east to west and west to east which are reflected mainly on either sides of the banks of San Jose river.

On a regional scale, the principal groundwater direction can be regarded as north - south. This direction corresponds to the general direction of all the rivers (conduits of groundwater gain and/or conduits of groundwater lose). Again on a regional scale, some groundwater enters into the area in the north and leaves the area in the south, corresponding to the regional groundwater flow directions.

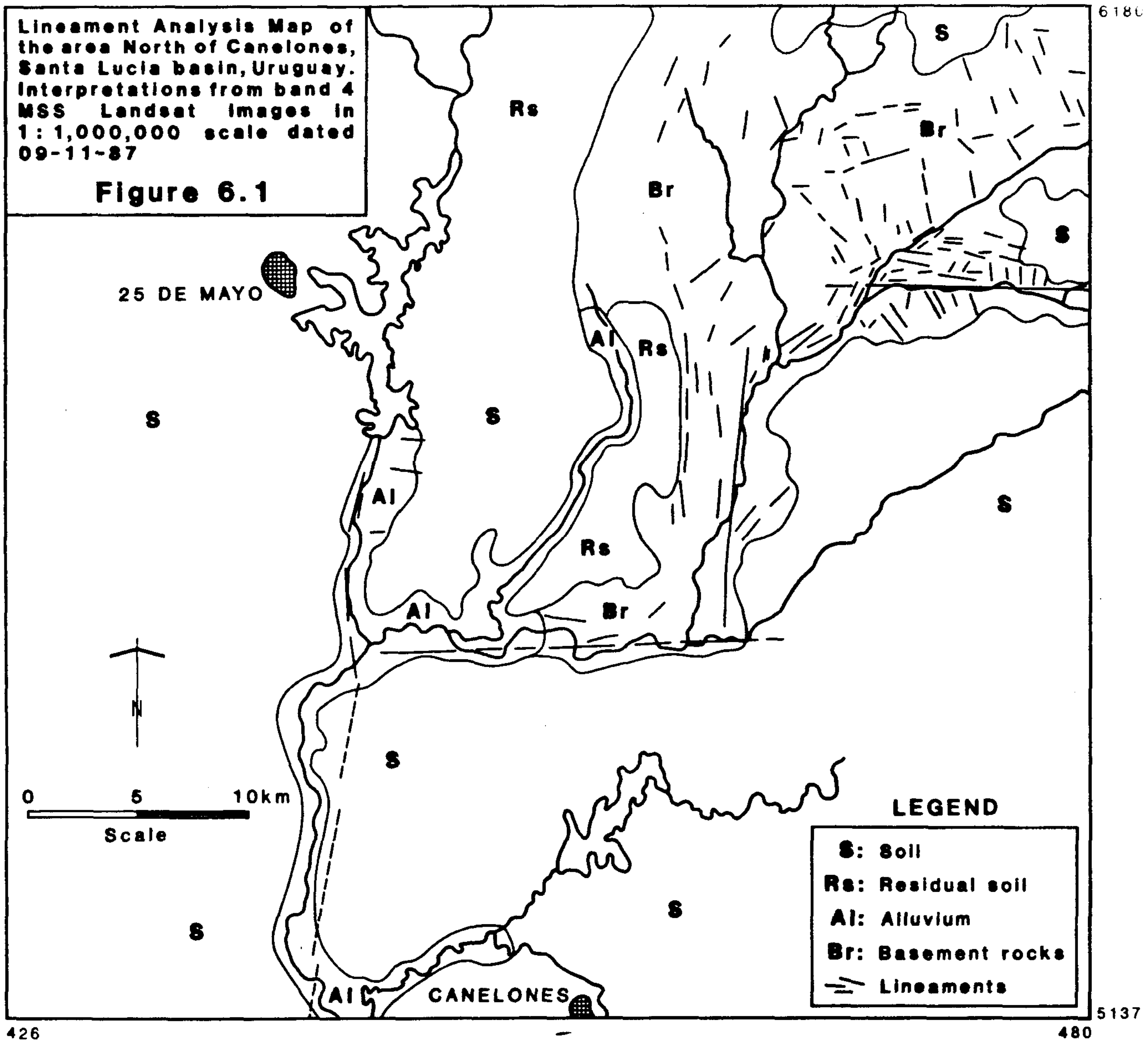
Chapter 6

HYDROLOGIC PARAMETERS AND CLIMATIC FACTORS

6.1 Groundwater Recharge

The possible sources of recharge are analyzed with the aim of quantifying the amount of groundwater inflow into the area. The amount of groundwater outflow is calculated from the average water table map. Three possible sources of recharge into the aquifer system could be identified. These are a) direct recharge by precipitation, b) recharge by rivers and c) groundwater recharge from the upper part of Santa Lucia basin. A part or whole of the aquifer system could, at any time, be recharged by one or the combination of two or three of the above.

In the evaluation of groundwater recharge and discharge, the areas which correspond respectively to groundwater recharge and groundwater discharge zones should first be defined. This is actually a question of scale. Considering the whole of Santa Lucia basin, the study area could be considered as groundwater discharge zone, whereas the rest of the basin would be groundwater recharge zone. In this respect, inflection points (boundary between recharge and discharge) can be marked all along the contact between the basement rocks and the sedimentary formations. On the other hand, considering only the study area, the topographically higher places would, correspond to groundwater recharge zones, whereas the topographically lower areas correspond to groundwater discharge zones.



Lineament Analysis Map of the area North of Canelones, Santa Lucia basin, Uruguay. Interpretations from band 4 MSS Landsat images in 1:1,000,000 scale dated 09-11-87

Figure 6.1

The possibility of recharge from the upper part of the Santa Lucia basin has been analyzed from interpretation of landsat images in 1: 100,000 scale, and some general hydrogeological investigation conducted in the upper part of the Santa Lucia basin. During the interpretation of the landsat images, all linear features related to groundwater flow were marked (see Fig.6.1). Thin residual soil, covering the basement rocks, obscure most of the lineaments. However, some subtle linear features can be observed on the thin soil cover. Taking into account the predominance of humid climatic environment, all linear features, including alignment of thick natural vegetation, may be considered as being related to near surface or deep groundwater movement. The drainage pattern of rivers, probably being closely related to lineaments, may reflect the general trend of groundwater movement. Although the primary trend of the lineaments is east - northeast to west - southwest, some north - south trending lineaments of secondary importance traverse the former. Hence the entrance of groundwater into the area would ultimately be facilitated by the north - south trending lineaments. In fact, this trend is the direction of the regional groundwater movement. Apart from lineaments, intense fracturing and residual weathering of the basement rocks were observed in the northern part of the basin, which could play a role in conducting groundwater to the lower Santa Lucia basin.

So far, the possibility of groundwater recharge from the upper part of the basin has been analyzed. It would be difficult, without studying in detail the upper part of the basin, to quantify groundwater recharge into the area. However, it can be assumed that groundwater recharge equals groundwater discharge. The later is calculated from the average water table map and transmissivity maps (see the following section).

6.2 Groundwater Discharge

The flow through the entire thickness of the aquifer system is calculated in using the following formula :

$$Q = (T \Delta n \Delta \phi) / \Delta s \qquad (6.1)$$

where, Q = total discharge, T = transmissivity, Δn = the average width between the stream lines, $\Delta \phi$ = the potential drop between two equipotential lines, Δs = the average length between the two equipotential lines.

The groundwater discharge (Q) of the study area as calculated from equation 6.1 is given below:

a) Along the valley bottom of San Jose and Santa Lucia rivers $Q = 12000 \text{ m}^3 / \text{day}$. b) Along the rivers of del Tigre, Mauricio and San Gregorio $Q = 2700 \text{ m}^3 / \text{day}$. c) Along river Pereyra $Q = 4500 \text{ m}^3 / \text{day}$.

6.3 Pumpage and Upward Seepage by Plants

The amount of water pumped from the daily use of the people in the area have been estimated. On average, the pumping rate of wells which are operated by wind pumps is about half a liter per second. The pumping rate of wells which are operated by hand pumps is also considered to be in the same order. On average, the pumping rate of wells which are operated by submersible pumps varies from 5 liters per second to 15 liters per second.

The amount of water extracted from the wells (see Table 7.1) was estimated by multiplying the average pumping rate, by the average duration of pumpage (eight hours in most cases) and by the number of wells in each of the hydrogeologic regions considered. The values thus obtained were compared with the possible water usage which was obtained by multiplying the daily consumption of water of people and animals (150 liters per day per person and 25 liters per day per animal) by their respective numbers (Direccion General de Estadistica y Censor Republica del Uruguay, 1985) in each of the hydrogeologic regions considered.

The amount of water continuously extracted by the roots of plants in the marshy areas, where the roots of plants reach the groundwater table, is estimated from the relationship between the amount of groundwater contributed to the roots of plants and depth of water table below the root zones, for different soil types as given by Boonstra and de Ridder (1981). The upward seepage value for the marshy areas considered is found to be around 1.5mm. / day.

6.4. Climatic Factors

6.4.1 Temperature

The only available complete data on temperature is that of Libertad. Therefore, the same data have been employed for the calculation of evapotranspiration in the whole area. The mean monthly temperatures for the years 1980 to 1988 are graphically presented in Fig. 6.2. The relatively cold months are May, June, July, August and September (11°C - 14°C), while the relatively hotter months are January, February, March, November and December (18°C - 23°C).

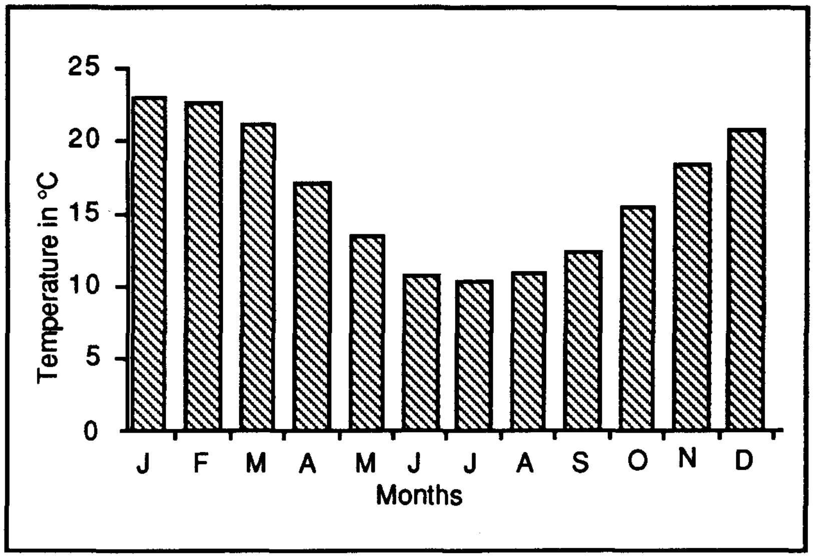


Fig.6.2 Mean monthly temperature at Libertad (for the years 1980 - 1988).

6.4.2 Potential Evapotranspiration

Mean monthly potential evapotranspiration was calculated from the temperature data based on Thornthwaite's formula:

$$PET = (160\,t / I)^a$$

Where PET = potential evapotranspiration in mm.

t = mean monthly air temperature in °C.

I = annual heat index, obtained by adding the twelve monthly heat indices, each of which is defined by:

$$i = (t / 5)^{1.514}$$

a = a factor which is expressed as in the following:

$$a = (6.75\, I^3 \times 10^{-7}) - (7.71\, I^2 \times 10^{-5}) + (1.792\, I \times 10^{-2}) + 0.49239$$

The potential evapotranspiration values obtained by Thornthwaite's method were adjusted for the mean possible duration of sunlight hours in the southern hemisphere at 35° latitude according to the following correction factors expressed in units of 30 days of 12 hours each, Griffiths (1966).

J	F	M	A	M	J	J	A	S	O	N	D
1.23	1.04	1.06	0.94	0.89	0.82	0.87	0.94	1	1.13	1.17	1.25

6.4.3 Precipitation

Complete data on precipitation for the towns of Libertad and Colorado were obtained for the years 1980 - 1988. The missing data for that of San Jose was completed in using 1.07 as a factor of multiplication to the data of Libertad (this factor was obtained by comparison of the general data from the respective stations).

The mean monthly precipitation and evapotranspiration values of Libertad for the years 1980 to 1988 are graphically presented on Fig.6.3. As can be seen from this graph, most of the months have surplus precipitation, while deficit occurs during the months of December and January.

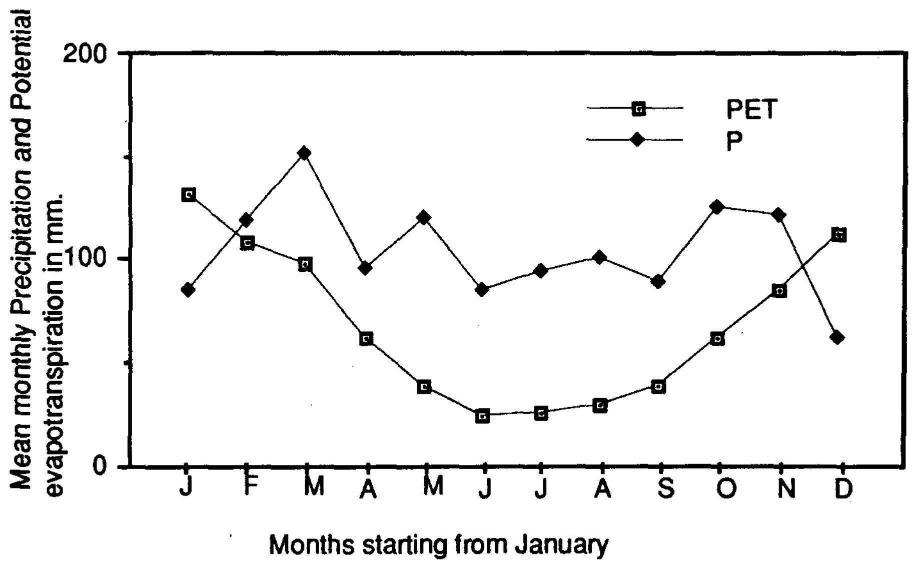


Fig.6.3 Graph showing mean monthly precipitation and mean monthly potential evapotranspiration values of Libertad for the years 1980 - 1988.

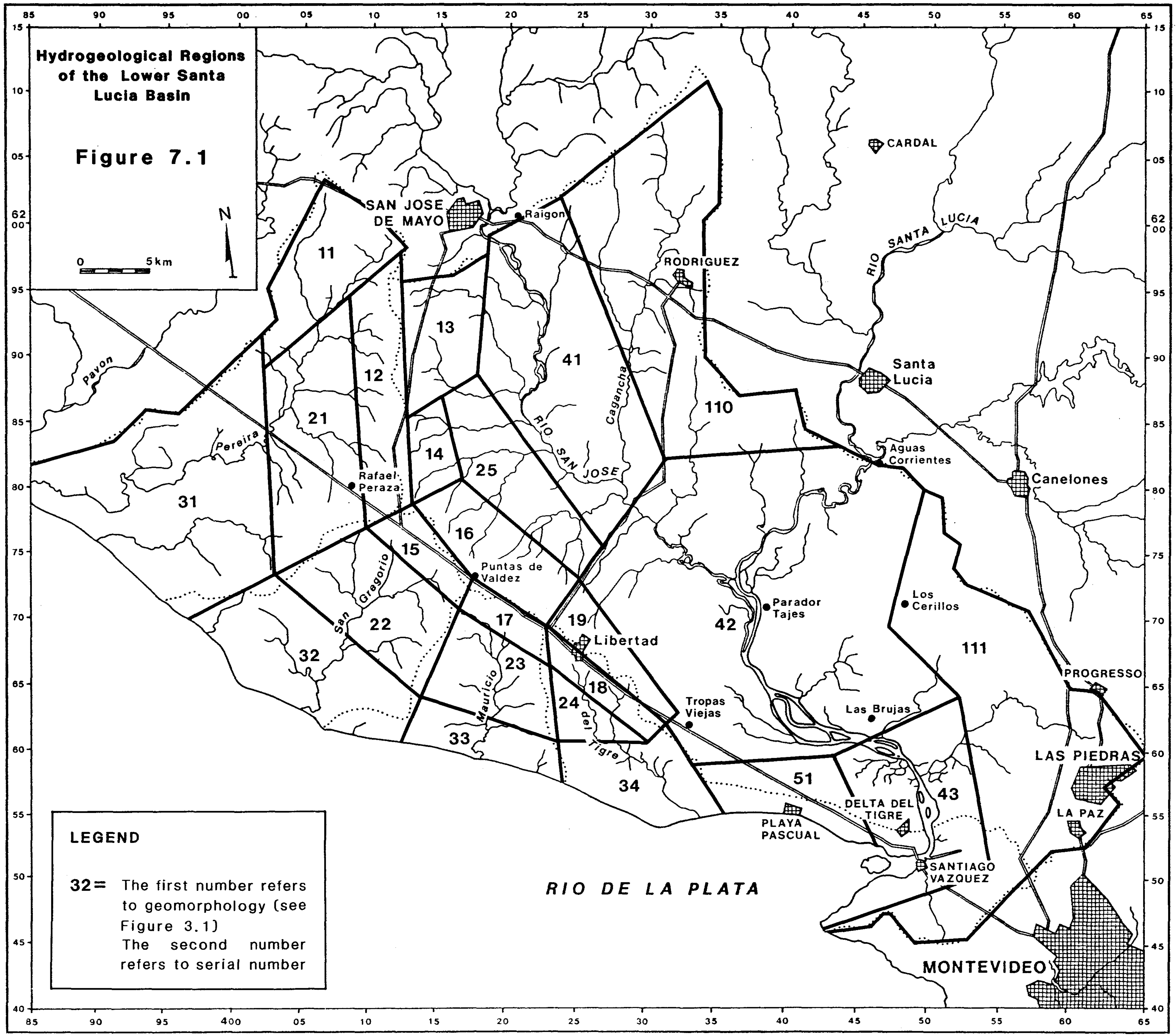
Chapter 7

WATER BALANCE AND AN AQUIFER MODEL

In the previous chapters, the various inflow and outflow components have been discussed. In order to quantitatively evaluate the available water resources of the area, water balance (hydrologic budget) calculations were made, from which the factors affecting water gain and water loss were enumerated. The water balance was done on a yearly basis for the whole region and on a monthly basis for a specific place in the coastal zone (hydrogeologic region number 33, see Fig.7.1). The main purpose of performing the monthly water balance calculations was to estimate the "net infiltration" values, which have been used in groundwater modeling. the monthly water balance was calculated for the year 1988, for which monthly groundwater level measurements were obtained.

The yearly water balance was calculated from the nine years average (1980 - 1988) values of precipitation and evapotranspiration. The area was divided into a number of hydrogeologic regions, so that it would fit into discretization procedure of modeling the basin, in the future. These hydrogeological regions (see Fig.7.1) have been constructed by the superposition of the geomorphological map (Fig. 3.1) with the average water table map (see Fig.5.1i) .

Figure 7.1


Hydrogeological Regions of the Lower Santa Lucia Basin
Figure 7.1
N
0 5km
LEGEND
32= The first number refers to geomorphology (see Figure 3.1) The second number refers to serial number
SAN JOSE DE MAYO
Raigon
RODRIGUEZ
CARDAL
RIO SANTA LUCIA
Santa Lucia
Aguas Corrientes
Canelones
Pavon
Pereira
Rafael Peraza
RIO SAN JOSE
Cagancha
Puntas de Valdez
San Gregorio
Libertad
Mauricio
del Tigre
Tropas Viejas
Parador Tajes
Los Cerillos
Las Brujas
PROGRESSO
LAS PIEDRAS
LA PAZ
DELTA DEL TIGRE
PLAYA PASCUAL
SANTIAGO VAZQUEZ
MONTEVIDEO
RIO DE LA PLATA
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12
13
14
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51
110
111
85
90
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60
65
400
62 00

7.1 Yearly Water Balance

A yearly water balance was performed from the available data (see Table 7.1). The change in storage was obtained from the following hydrologic budget equation:

$$\Delta s = P - (PET + Q + Sup + S.F + O.F) \tag{7.1}$$

Where, Δs = Change in storage in groundwater, P = Precipitation, PET = Potential evapotranspiration, Q = Pumped abstraction, Sup = Upward seepage by roots of plants, S.F = Stream flow (for the rivers of Pereyra, San Gregorio, Mauricio and del Tigre), O.F = Overland flow.

The only stream flow data available, for streams emerging from the aquifer system, is that of San Gregorio, even then, the data is not complete for the years 1980 - 1988. Assuming that stream flow is directly proportional to precipitation, the complete data of Santa Lucia was used in generating data for San Gregorio (the comparative ratios for the respective years were used). Assuming same aquifer properties enclosed by the drainages of the respective rivers and, other factors like topography being constant, the discharge of other rivers with no data was generated by multiplying the ratio of their respective areas with the discharge of San Gregorio.

Apart from the gage stations at San Jose and Aguas Corrientes, no data was obtained at the outlet of Santa Lucia river, therefore, it has not been possible to know the net surface water input by these rivers into the area. For the present, surface water inflow is assumed to be equal to surface water outflow. However, the overland flow within the drainage area of the rivers of San Jose and Santa Lucia may contribute a significant outflow from the area. The overland flow data were estimated from the possible proportionality values of the stream flow data with precipitation, which happens to be within the range of 2%; this value is within the range of possible values for relatively flat areas. The values of the different components in the calculation of the water balance is given in Table 7.1.

Table 7.1 The values of the yearly water balance components (see Fig.7.1 for the hydrogeological regions - H.R).

H.R.	Area	Climatic	P	PET	Pumpage	Seepage	S.F	O.F	ΔS
No.	(km^2)	zone	(------	------	------	mm	------	------	------)
11	68	San Jose	1335.52	815.38	0.27	0	21.67	0.00	498.20
12	60	San Jose	1335.52	815.38	0.37	0	19.14	0.00	500.64
13	56	San Jose	1335.52	815.38	0.26	0	0.00	22.04	497.85
14	24	San Jose	1335.52	815.38	0.30	0	0.00	9.35	510.49
15	25	Libertad	1248.15	815.38	0.29	0	7.98	0.00	424.50
16	60	Libertad	1248.15	815.38	0.49	0	0.00	22.47	409.82
17	16	Libertad	1248.15	815.38	0.91	0	16.40	0.00	415.46
18	21	Libertad	1248.15	815.38	12.17	0	6.69	0.00	413.92
19	32	Libertad	1248.15	815.38	7.98	0	0.00	11.23	413.55
110	229	San Jose	1335.52	815.38	2.55	0	0.00	93.49	424.11
21	113	San Jose	1335.52	815.38	2.58	0	36.05	0.00	481.51
22	84	Libertad	1248.15	815.38	0.87	0	26.80	0.00	405.10
23	56	Libertad	1248.15	815.38	0.65	0	57.60	0.00	374.52
24	16	Libertad	1248.15	815.38	0.68	0	5.10	0.00	426.99
25	65	Libertad	1248.15	815.38	0.28	0	0.00	24.96	407.53
31	200	Libertad	1248.15	815.38	0.37	548	63.80	0.00	-179.39
32	105	Libertad	1248.15	815.38	0.52	0	33.50	0.00	398.75
33	36	Libertad	1248.15	815.38	1.62	0	36.90	0.00	394.25
34	54	Libertad	1248.15	815.38	0.47	0	17.22	0.00	415.08
41	196	San Jose	1335.52	815.38	2.79	548	0.00	80.13	-110.78
42	336	Colorado	1217.37	815.38	1.09	548	0.00	120.52	-267.61
43	108	Colorado	1217.37	815.38	3.38	548	0.00	38.96	-188.34
44	112	Colorado	1217.37	815.38	6.52	548	0.00	40.17	-192.70
51	48	Colorado	1217.37	815.38	3.80	0	0.00	17.04	381.15

The yearly water balance as computed for the different hydrogeologic regions gives us an idea of the order of magnitude of the water gain or loss. As can be seen from Table 7.1, 80 % of the hydrogeologic regions have water gain of 40 to 50 cm. Water losses of around 20 cm, in the rest of the area, are due to the additional losses, as a result of upward seepage by the roots of plants. The present level of near surface groundwater in the marshes of those areas, are maintained by the adjacent recharging rivers and / or seepage from the adjacent aquifers.

7.2 Monthly Water Balance

The monthly water balance for the coastal zone (hydrogeologic region number 33) has been presented in Table 7.2. The procedure in calculating the average monthly water balance is as follows:

The calculation procedure starts from the wet month, whereby the soil moisture of the antecedent dry month is assumed to be zero. If precipitation is less than potential evapotranspiration and, if there is some water in the soil, then the actual evapotranspiration will equal precipitation plus some value evaporating from the soil; actual evapotranspiration can not be greater than potential evapotranspiration. If soil moisture equals zero, or soil moisture deficit occurs, precipitation still being less than the potential rate, then actual evapotranspiration should equal precipitation. If precipitation is greater than potential evapotranspiration, then actual evapotranspiration should equal potential evapotranspiration. Water surplus occurs when the soil is fully saturated (over 150 mm.). The available water capacity of the root zones of 150 mm was chosen according to the procedure of Thornthwhaite and Mather (1954).

For the monthly water balance calculations of the period 1980 to 1988 (see Table 7.2), the calculation starts on February when the soil moisture of the antecedent month is assumed to be zero. For the monthly water balance calculations of the year 1988, the calculation starts on January. The soil is assumed to be fully saturated on December 1987 (the data for this year and month indicate higher value of precipitation compared to evapotranspiration). The monthly water balance gives the change in storage in moisture. The values (indicated in italics in Table 7.2 and 7.3) were obtained by subtracting the actual evapotranspiration from precipitation (a possible situation where soil horizon is absent and no runoff exists). These values have been used, in the following sections, to calculate the change in head in a homogeneous square aquifer, with arbitrary pumping rates.

Table 7.2. Mean monthly water balance for the year 1980 - 1988, wet month starting on February, for a coastal zone (H.R.33) with available water capacity of 150 mm.

mm	J	F	M	A	M	J	J	A	S	O	N	D	Total(Year)
P	85	119	151	96	120	85	94	100	89	125	122	62	1248
PET	132	108	98	62	39	24	26	29	38	62	85	112	815
P-PET	-47	11	53	35	81	60	68	71	51	63	36	-50	432
AcPotWls	-97	0	0	0	0	0	0	0	0	0	0	-50	
Sm	0	11	64	99	150	150	150	150	150	150	150	100	
dSm	0	11	53	35	51	0	0	0	0	0	0	-50	
AET	85	108	98	62	39	24	26	29	38	62	85	112	768
D	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0	0	0	30	60	68	71	51	63	36	0	379
Ip	*0*	*11*	*53*	*35*	*81*	*60*	*68*	*71*	*51*	*63*	*36*	*0*	*529*

Table 7.3. Mean monthly water balance (from the data of 1988), for a coastal zone (H.R.33) with available water capacity of 150 mm, wet month starting on January.

mm	J	F	M	A	M	J	J	A	S	O	N	D	Total(Year)
P	102	57	460	25	30	8	56	78	31	87	86	68	1088
PET	108	122	126	63	26	20	39	30	20	49	79	88	770
P-PET	-6	-65	334	-38	4	-12	17	48	11	38	7	-20	389
AcPotWls	-6	-71	0	-38	-34	-46	-29	0	0	0	0	0	
Sm	144	79	150	112	116	104	121	150	150	150	150	130	
dSm	-6	-65	79	-38	4	-12	17	29	0	0	0	-20	
AET	108	122	126	63	26	20	39	30	20	49	79	88	540
D	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0	184	0	0	0	0	19	11	38	7	0	259
Ip	*0*	*0*	*334*	*0*	*4*	*0*	*17*	*48*	*11*	*38*	*7*	*0*	*459*

Where, P = Precipitation, PET = Potential evapotranspiration, AcPotWls = Accumulated potential water loss, Sm = Soil moisture, dSm = Change in soil moisture, AET = Actual evapotranspiration, D = Soil moisture deficit, S = Soil moisture surplus, *Ip* = Possible infiltration where the soil-water region is connected to the groundwater and no surface runoff occurs.

7.3 An Aquifer Model

In this section, we shall try to integrate the numerical values of the major parameters (ransmissivity "net infiltration" and specific yield) under known scientific laws (equations) that govern the movement of groundwater, and give recommendations as to the quantity of groundwater available (from infiltration alone) for future exploitations. In view of our objectives and present scope of work, it has been appropriate to select an area for a groundwater model consideration. It can be seen from the previous chapters, that the coastal zones have relatively favorable values on aquifer thickness, permeability, specific yield, specific capacity, etc. It would then be reasonable to consider a small area (10000 m^2) from the coastal zone, for which monthly water balance have been calculated, and try to forecast the water level situations over long periods of pumping by applying an aquifer model.

The main purpose of such a model is to examine the behavior of watertable if certain plans for the use of groundwater would be implemented. For example, if a certain amount of groundwater is required from the area considered, the effect of pumping on the water levels could be examined from the model. If the water level may not be allowed to be lower than a certain level (safe yield), then the amount of water to be pumped could be adjusted in such a manner that the safe yield limit will be respected.

The objective behind such simulation technique is to understand and to predict the natural hydrogeological phenomena in a given area. It is an attempt to imitate reality by the use of a mathematical model.

The Finite differencess Method

In this study, a simple transient groundwater flow model has been applied by using the principle of finite differencess method. The change in head with time, with variable pumping rates has been studied by using this model. The position and nature of the boundary conditions, the initial conditions and the inputs into the system have been determined. Following the principle of finite differences method, the region under consideration has been divided into a finite number of square blocks, each having a node at the center, where variables like hydraulic heads representing the entire block are defined (see Fig. 7.2).

Let us consider a steady state situation where the groundwater flow equation is described as:

$$\partial^2 h / \partial x^2 + \partial^2 h / \partial y^2 = 0 \qquad (7.1)$$

The following finite differences algorithm (Bear & Verruijt, 1987) can be used in the approximation of the partial derivatives:

The function F(x,y) is approximated by the central finite differences method as

$$\partial F / \partial x = [F(x + 1/2\,\Delta x, y) - F(x - 1/2\Delta x, y)] / \Delta x \qquad (7.2)$$

Where,

The derivative of the first derivative is given as

$$\partial^2F/\partial x^2 = [F(x+\Delta x, y) - 2F(x, y) + F(x - \Delta x, y)]/(\Delta x)^2$$

$$= [F_{i+1,j} - 2F_{i,j} + F_{i-1,j}]/(\Delta x)^2$$

Taking equal intervals in the x and y directions (i.e.$\Delta x = \Delta y = \Delta$), the steady state groundwater flow equations are thus approximated as in the following:

$$\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2 \approx (h_{i,j-1} + h_{i,j+1} + h_{i-1,j} + h_{i+1,j} - 4h_{i,j})/\Delta^2 \qquad (7.3)$$

The differential equation of 7.1 can then be approximated by

$$h_{i,j} = 1/4\,(h_{i-1,j} + h_{i+1,j} + h_{i,j-1} + h_{i,j+1}) \qquad (7.4)$$

Equation 7.4 is the basis for the finite difference method. It states that the value at the node must equal to the average of the values of the four neighbouring nodes. The correct solution is approximated by iteration procedure (Bear & Verruijt, 1987).

The Transient Groundwater Flow

Transient groundwater flows are defined by a general mathematical model. This is a partial differential equation established for a transient (an unsteady) flow in an aquifer. It is expressed by Bear and Verruijt (1987) as:

$$T(\partial^2h/\partial x^2 + \partial^2h/\partial y^2) = -N \qquad (7.5)$$

Where T = transmissivity and N(x,y,t) = source or sink term at a given time.

For unconfined aquifers , N has been defined by Boonstra & de Ridder (1981) as:

$$-N = R - Pm - S_y \partial h / \partial t \qquad (7.6)$$

Where, R = net rate of recharge, Pm = net rate of pumpage, and S_y = specific yield.

Considering an unconfined aquifer, and using equation 7.6, equation 7.5 becomes,

$$T(\partial^2 h / \partial x^2 + \partial^2 h / \partial y^2) + I = S_y \partial h / \partial t \qquad (7.7)$$

Where, I = Pm -R represents the net infiltration.

An application of Finite Difference Method to Modeling Transient Groundwater Flow in the Coastal Zone (Lower Santa Lucia Basin)

First, a specific area has been chosen from the coastal zones, where all the necessary and relatively more reliable data were obtainable. This area is also considered to be of future interest for groundwater exploitation. For the present, the area around well 109 (see Fig.8.8) has been considered, since the water level measurements at this place are more complete than at other places.

In the foregoing discussion, the problem of homogeneous infiltration in a square aquifer (100 by 100m), where all boundaries are impermeable except where the head is specified at the nodes (see Fig.7.2) will be addressed.

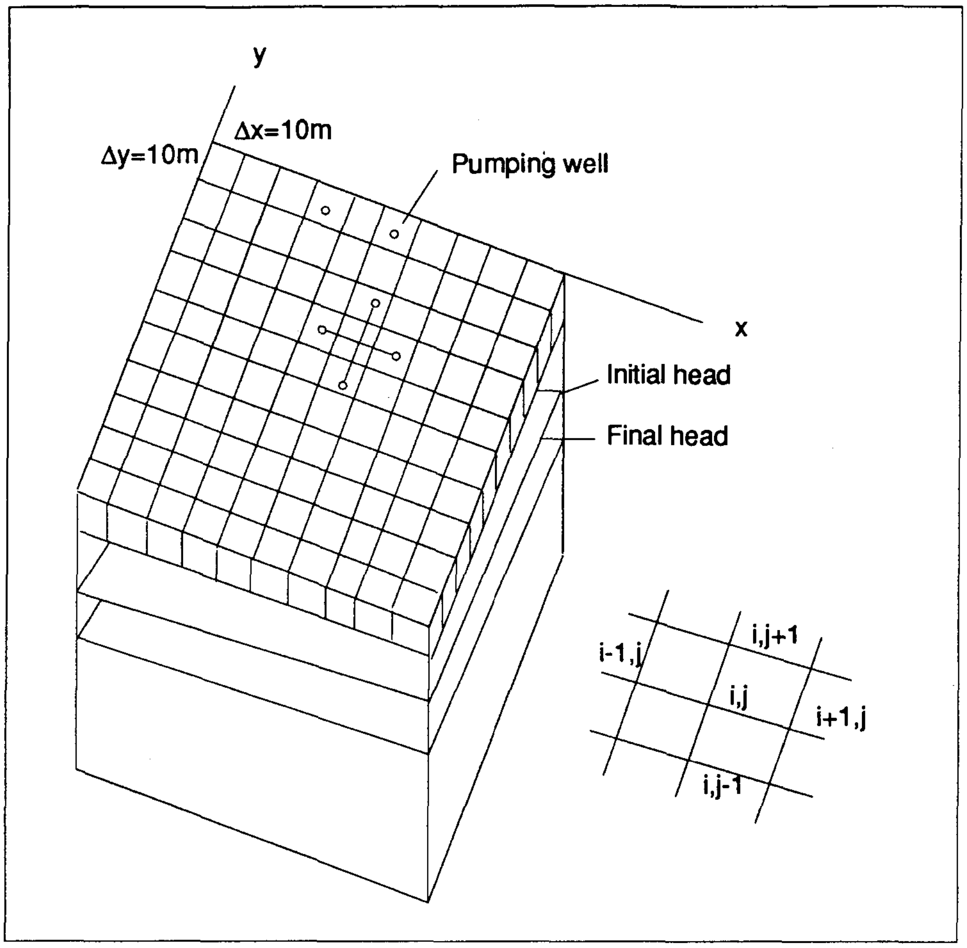


Fig. 7.2 An area of 100 m by 100 m for which the time and head variables are shown in Fig.7.3.

Boundary Conditions and Initial Conditions

In this model the following assumptions are made:

. Only one aquifer (Raigon Formation) is treated;

. The flow in the aquifer is a two dimensional flow system;

. The aquifer has an impermeable bottom (a zero - flow boundary);

. The upper boundary of the aquifer is a free water table (at $t = 0$ $h = h^0$).

In the spatial approximation, there are several possibilities of using the two values of head at node i, j. The procedure followed in our case is the implicit method. Accordingly, the head value at node i, j is expressed in terms of initial node and the four other unknown head values surrounding that node (see Fig.7.2). The unknown values are simultaneously determined (hence the term implicit) from a system of linear equations by a successive iteration Gauss - Seidel (or relaxation) method (Bear and Verruijt, 1987). The new values of $h^1_{i,j}$ are then determined by iteration procedure, on the basis of an initial estimate (see computer Program in the Appendix).

Method of Approach

In this model, the transient groundwater flow equation (eq.7.7) has been utilized, in order to calculate the change of head due to a homogeneous infiltration in a square aquifer. The numerical solution to this equation, which gives the distribution of head in time, has been executed by using a computer program, after Bear and Verruijt, 1987 .

The value of I in equation 7.7 was replaced by the change in storage value (dSm), for a non-pumping situation, and by Ip, for a pumping situation (see Table 7.3). In a homogeneous aquifer, where no pumping is envolved, the water table rise and fall may be related to the soil moisture variations, especially when the water table is relatively shallow. Since the Ip values at the bottom of Table 7.3 assume 100% percolation, the calculated head values would be exaggerated. This has been proved, while calibrating the model (comparing the calculated head with the measured head). This model assumes no groundwater inflow into the aquifer, since all the boundaries are assumed to be impermeable. Therefore, it would be appropriate to use the Ip values, where the reaction of the aquifer to "net infiltration" (recharge minus pumpage) has been considered.

From the previous chapters, the transmissivity and storativity of the aquifer around well 109 has been found to be 225 m^2/day and 0.24 respectively. The monthly dSm values were converted to daily values. The following dSm values have been replaced for I in equation 7.7.

mm	M	A	M	J	J	A	S	O	N	D
dSm (month)	79	-38	4	-12	17	29	0	0	0	-20
dSm (per day)	2.63	- 1.26	.1333	-.4	.567	.97	0	0	0	-.67

Excecution of the Program and Results

The initial head for the area around well number 109 has been supplied from the measured head value of March 1988, which was then 6.7 m. The time period for a single simulation was one month (30 days). In the implicit method of iteration, a time step of 0.1 and number of time steps of 10, will provide the following days: 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6 and 51.2, from which the 30th day can be obtained.

The following input values were used in the computer program (see Computer Program in the Appendix):

Dimension in the x - direction = 100 m, subdivisions = 10 m, dimension in the y direction = 100m, Subdivisions = 10m, initial head = 6.7 m.a.s.l (for march), infiltration rate = 0.00263 m / day (for march), transmissivity = 225 m^2/ day, storativity = 0.24, time step = .1 day, number of time steps = 10, number of iterations = 20, relaxation factor = 1.5

The execution of this program gives head values as indicated on Fig. 7.3.

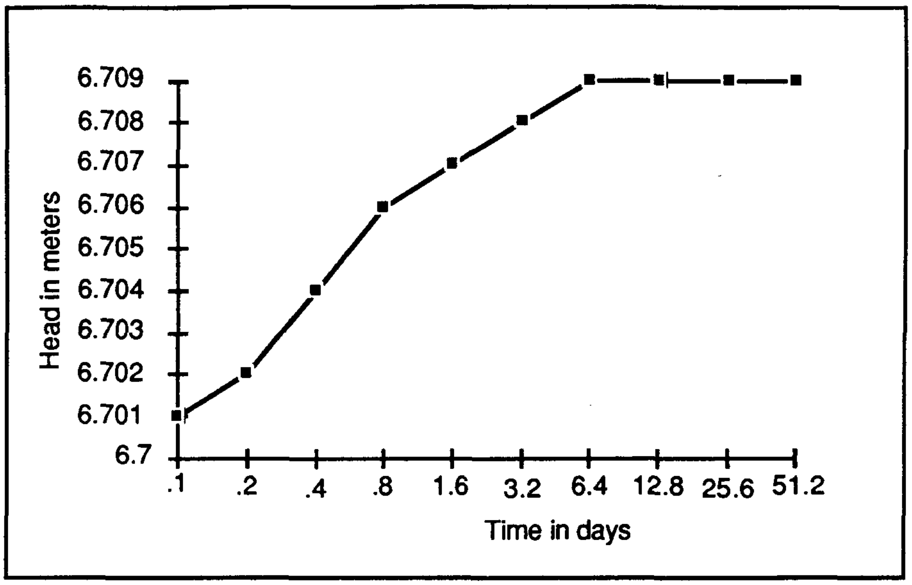


Fig. 7.3 A graph representing the solution of equation 7.7 (the distribution of head in one month); here no groundwater extraction has been considered.

7.4 Calibration of the Transient Groundwater Flow Model

Since the applicability of this model is subject to the accuracy of the values like T, S_y and I, first the model has been calibrated with the available data. In the process of calibration, the outputs of the computer program (the theoretical or calculated values) have been compared with the actual values. The water level measurements have been considered to be the actual values. The relative closeness of the calculated values with the actual values is a measure of the reliability of the model. It should be noted that this closeness depends on the aquifer parameters obtained from field measurements and the water balance calculations, as well as the reliability of the water level measurement itself.

Method of Approach

The measured value at well 109 during March 1988 was used as an initial condition. After the first simulation, the final head at the 30th day of March 1988, was obtained (see Fig.7.3). This value was used as an initial condition for April, and the program was run for the second time. The final head obtained for this month was used as an initial head for the month of May and the program was run for the third time, and so on for the following months. The calculated head values, thus obtained, were compared with the actual measured values. Figure 7.4 shows the result of the combined nine simulations.

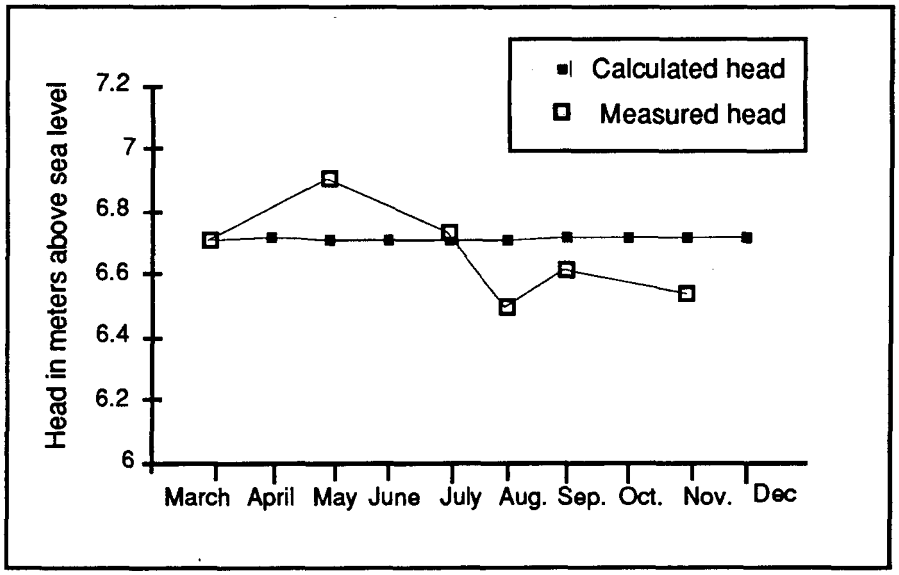


Fig. 7.4 Graphs showing the calculated head values from the model as compared to the measured values at well 109 (from March 1988 to December 1988).

As in figure 7.4, the discrepancy between the measured values and the calculated values is on average 0.1 meter. Since the water levels were measured from wells, instead of from piezometers, they may not represent the real situation; better results could have been obtained if the water levels were measured at smaller intervals (for example 15 days instead of 30 days).

7.5 Prediction of Head With Arbitrary Pumping Rates

As in equation 7.5, the only variable that changes in time, in a confined aquifer, is the head. The aquifer model considered exhibits such changes according to the previously mentioned input parameters.

In using the above "calibrated" model, we shall plug in various possible figures for the values of I and examine the corresponding response of the model.

First, an arbitrary pumping rate of 30 m^3 per day, from an area of 100 by 100 meters has been considered. For an effective porosity of 0.24, the corresponding drop in head as a result of pumpage can be calculated as follows:

Drop in head = Pumpage / [Porosity x Area] = $30 m^3$ /day / [0.24 x 10^4 m] =

-0.0125 m

The drop in head as a result of pumpage has been added to the Ip values, so that the "net infiltration" parameter be obtained in the transient groundwater flow equation.

Assuming that net natural recharge for the future years would be close to the net natural recharge of the nine years (1980 - 1988), for which the mean monthly water balance has been calculated, it would be logical to use the Ip values from Table 7.2 as a basis of prediction. Thus, the net infiltration rates for one artificial year were obtained by subtracting 12.5 mm (discharge rate) from the daily Ip values as in the following:

mm	J	F	M	A	M	J	J	A	S	O	N	D
Ip (month)	0	11	53	35	81	60	68	71	51	63	36	0
Ip(per day)	0	0.3667	1.766	1.66	2.7	2	2.27	2.37	1.7	2.1	1.2	0
I (per day)	-12.5	-12.133	-10.73	-10.84	-10.1	-10.5	-10.23	-10.13	-10.8	-10.4	-11.3	-12.5

Input Values

Dimension in the x - direction = 100 meters, subdivisions = 100 meters, dimension in the y direction = 100m, Subdivisions = 10m, initial head = 6.7 m.a.s.l infiltration rate = -0.0125 m / day, transmissivity = 225 m^2/ day, storativity = 0.24, time step = 0.1 day, number of time steps = 10, number of iterations = 20, relaxation factor = 1.5.

The output values for this particular input have been plotted on a graph (see Fig.7.5.

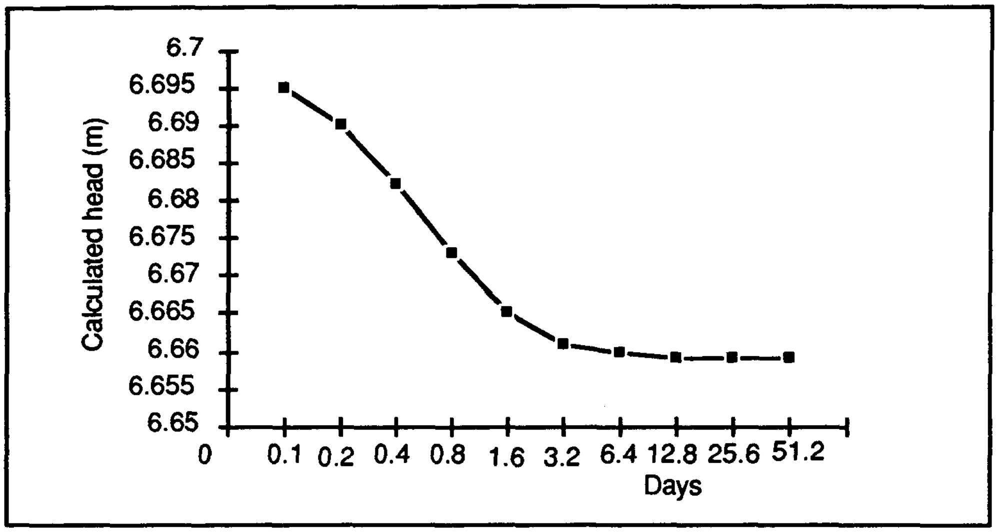


Fig. 7.5 Graph showing the distribution of head in time, where groundwater extraction has been considered.

In order to predict the head in one year, the program was executed twelve times. As mentioned earlier, the final head of the first month has been taken as the initial head for the second month, and so on for the twelve months. The final heads corresponding to each month have been plotted as in Fig.7.6. This model depicts that, precipitation being the only source of groundwater supply, a pumpage of $30m^3$/day from an area of 10000 m^2 would cause a drop of head of 38 centimeters, in one year.

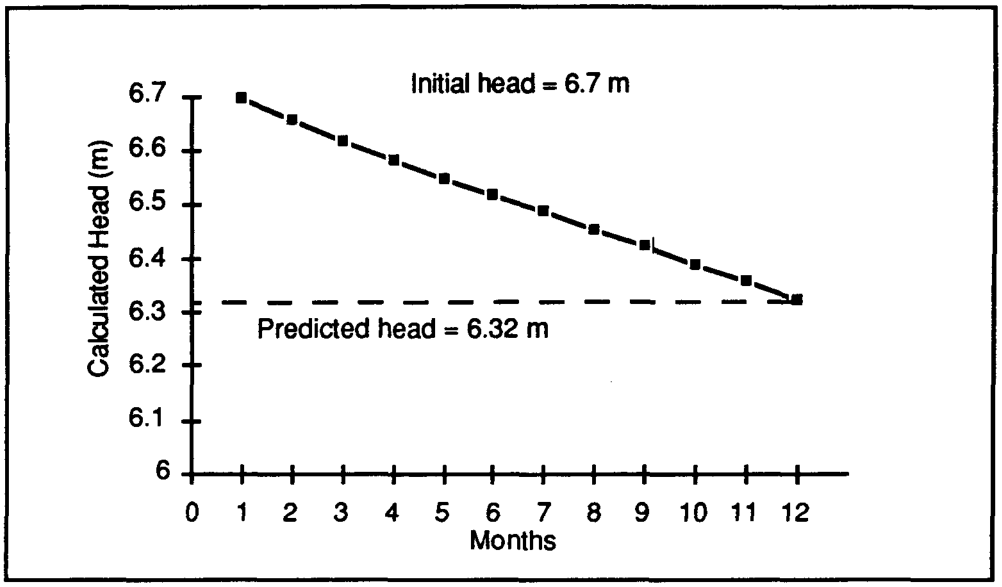


Fig.7.6 Graphs showing the calculated behavior of the water level in one year.

Discussion

The transient groundwater flow equation has been applied, in order to examine the effect of the aquifer properties, the climatic conditions and/ or pumpage on the groundwater fluctuations in the Santa Lucia Basin .

As in Fig.7.3 & 7.4, the "net infiltration" due to the available precipitation would cause a constant rise in groundwater level, whereas a pumpage of $30m^3$ from an area of 10000 m^2 could lower the groundwater level by 38 centimeters in one year time (see Fig.7.5&7.6).

The analysis and evaluation of quantity of groundwater in the Lower Santa Lucia basin encompasses an understanding of the amount of water available for pumping, that is determination of the maximum possible pumping compatible with potentiality of the aquifer and pumping rate.

Todd (1959) defined safe yield as the amount of water which can be withdrawn from a groundwater basin annually without causing undesirable results like sea water intrusion and changes in quality of groundwater. These undesirable results are discussed in the next chapters. It should be noted that the predicted head from the aquifer model assumes a situation whereby groundwater is fully exploited with numerous wells. But this does not happen due to economic reasons. From the model, no significant lowering of the water level has been observed, for few months. But few wells can be used, with greater drawdown than what has been obtained from the model, to attain the required amount of groundwater. Therefore, It should be clear that a detailed analyses of safe yield from the point of view of pumping cost and other management aspects should be considered before exploitation of the groundwater takes place.

Groundwater modeling is a way of simplifying nature, in which the complexity of nature is mathematically treated after a number of assumption and simplifications. During the process of calibration of the model, the various investigatory methods (pumping test, water balance, etc.) have been tested by comparing their results with one another. Therefore, this modeling technique has, in a way, helped to check the work. In our model, the water level measurements were considered to be real, while all the other values (infiltration, transmissivity, etc.) are subject to various types of error.

The small difference (0.1 m) between the theoretical and practical values (see Fig.7.3) reflects the errors in general. However, we should also consider the fact that the water level measurements have not always represented the situation in the aquifer, since the water level measurements were taken from wells instead of from piezometers. Therefore, more data on accurate water level measurements from piezometers and reliable data on aquifer characteristics are indispensable for better results.

Chapter 8

ISOTOPE HYDROLOGY

In this chapter, the isotope data will be analyzed and their application in the present investigation will be discussed. The main reason for the study of the stable isotopes in groundwaters was to identify the possible sources of water entering the aquifer system and to study the processes that may have, since then, affected the isotopic and chemical nature of the water. Such data were also used to monitor the advancement and retreat of saline water of the Rio de la Plata in relation to the adjacent groundwater and surface water (Santa Lucia). Similar analysis of water samples, collected along Santa Lucia river (see Fig. 8.4), were performed in order to find the recharge and discharge conditions between precipitation, river water and groundwater in the basin. Finally, ^{14}C and ^{3}H activities in groundwaters were measured with the objective to assess their "age".

8.1 The Stable Isotope (^{18}O) Composition of Waters From Rivers and Wells in the Lower Santa Lucia Basin

Eighty seven water samples were collected in January - February 1987 from selected wells and along rivers (see Fig.8.8 for the locations).

The isotopic ratios of $^{18}O/^{16}O$ were determined by mass spectrometry. The method followed is that of Epstein & Mayeda (1953):

Isotopic composition is expressed in delta units:

$\partial ^{o}/_{oo}$ = (R sample - R standard) (10^3) /R (standard)

Where, R = isotopic ratio

The standard used in the measurements of the $\partial^{18}O$ of the water samples is V-SMOW (Vienna-SMOW), which is a standard water whose composition is almost identical to that of the standard Mean Ocean Water (SMOW: Faur, 1977)

Some of the reasons to the variations of isotopic compositions in water samples are as follows:

- Water vapor formed by evaporation of liquid water is enriched in ^{16}O and ^{1}H, while the remaining water is enriched in ^{18}O and ^{2}H.

- Rain drops formed by condensation of water vapor are enriched in ^{18}O as opposed to the remaining vapor phase. The isotopic composition of the first rain drop from clouds formed over the ocean is near that of ocean water (around -4 $^{o}/_{oo}$). As condensation continues, the $\partial^{18}O$ in the water vapor progressively becomes more negative and consequently, the ∂ value in the liquid or solid water that precipitates becomes progressively lower.

General theoretical discussions on isotopic variations of waters are given by several authors, for example Epstein & Mayeda (1953), Freidman, Machta & Soller (1962), etc.

The heavy isotope content in precipitation decreases with progressive condensation which is reflected by:

- A global latitudinal zonation with depleted values in areas of higher altitude.

- More depleted values usually occur with increased altitude.

- More depleted values are found during cold months and heavier values in warmer months (seasonality), due to an increase in fractionation with lower temperatures.

In nature continuous segregation of isotopes takes place. Therefore, in light of the above discussion and from the data of the isotopic composition at hand, we could draw valuable hydrogeologic informations.

Figure 8.1 shows the range of $\partial^{18}O$ values for the eighty seven water samples that were collected in January - February, 1987.

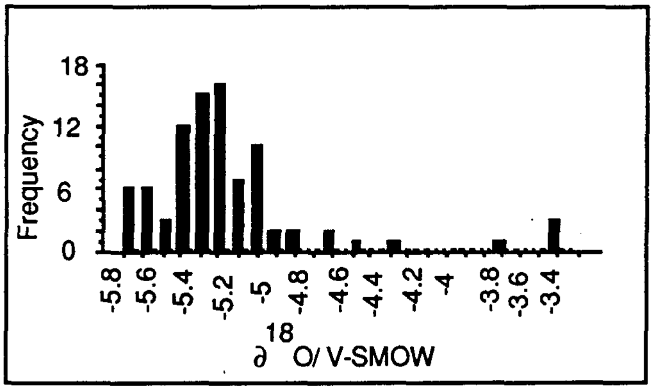


Fig.8.1 Frequency histogram of $\partial^{18}O$/V-SMOW of the samples collected in January - February, 1987.

The mean and standard deviation of the $\partial^{18}O$ values from the data are -5.2 and 0.46 respectively. The minimum and maximum values are -5.7 and -3.4 respectively; the analytical uncertainity is ± 0.1°/ oo

The values of these particular months do not reflect the situation over a period of the year. However, we could still compare these values with the mean monthly isotopic composition of precipitation. The $\partial^{18}O$ data obtained from Buenos Aires (about 100 Km to the south) indicates maximum and minimum values of -2 and -8 °/ oo respectively, for the years 1961-1963 (W. Dansgaard, 1964). According to the International Atomic Energy Agency report (1981), the average value of $\partial^{18}O$ for the years 1965 up to 1978 for Porto Alegre, southeast of Brazil (at the border with Uruguay), was around -5°/ oo. Taking an average value of -5°/ oo as representative of the area, we could possibly say that the $\partial^{18}O$ composition of the waters is closely related to precipitation.

The $\partial^{18}O$ values are around -5.2 along the rivers of San Jose and Santa Lucia. They seem to increase very slightly towards northeast (see Fig. 8.2).

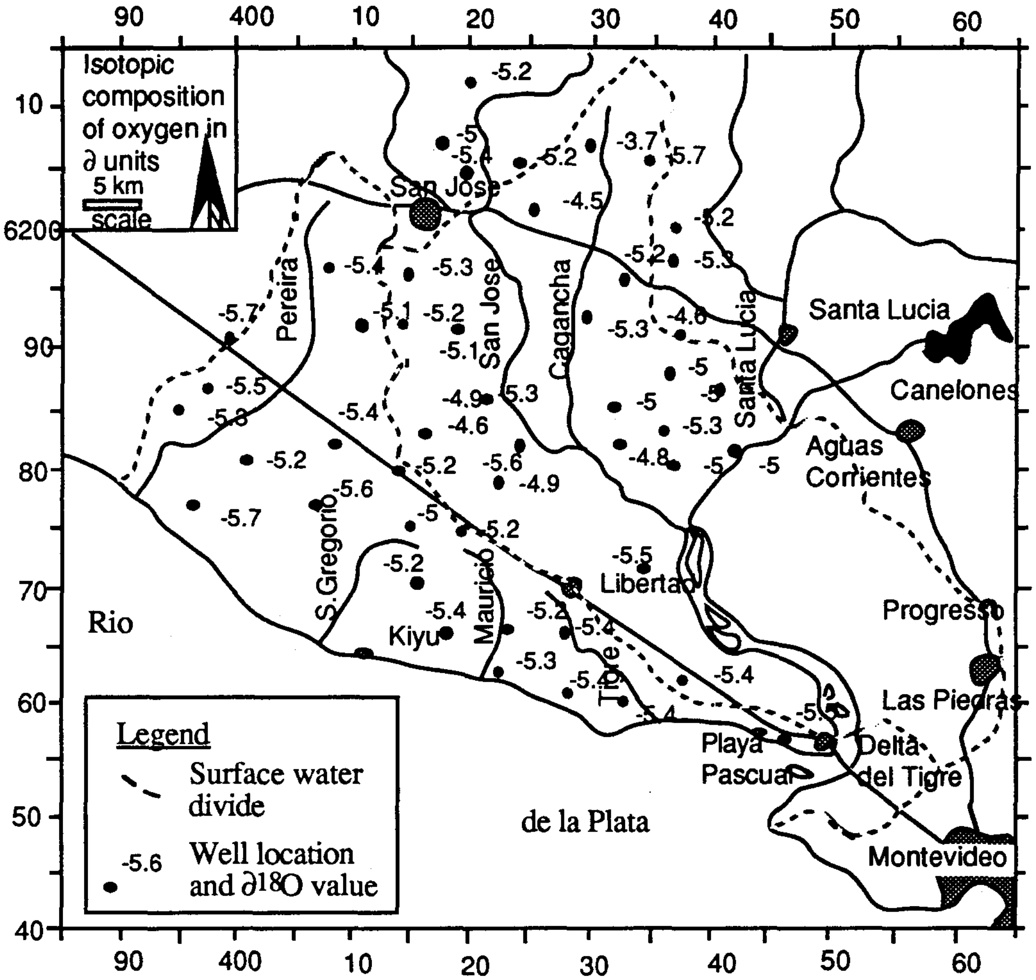


Fig. 8.2 The Geographic locations of the well water samples collected in January - February 1987 and the corresponding ∂^{18}O values.

The relatively low ∂^{18}O values (around -5.4) along the Libertad Plain could be related to a dominant meteoric signal.

Although the waters may all be related to precipitation, the origin of these waters and the isotopic transformations which they underwent are different from one another. The main recharge into the aquifer system being by direct infiltration from precipitation, the predominent isotopic characteristics observed are most probably dominated by the isotopic composition of rain water. Significant temporal variations were observed. However, it should be noted that, apart from a number of geo - hydrologic factors which change in time, the composition of rain water too may change in time and, we can not, under the present level of investigation discuss, further the relationship between precipitation and groundwater recharge.

Separating the samples according to their source, the statistical relations in Table 8.1 were observed:

Table 8.1 Statistical relations of the $\partial^{18}O$ of the waters from different sources.

Source	Mean	Std. Dev	Variance	Minimum	Maximum
Drilled wells	-5.4	0.24	0.08	-5.7	-5.1
Excavated wells	-5.205	0.359	0.129	-5.7	-3.7
Rivers	-3.75	0.7	0.49	-4.8	-3.4

From Table 8.1, we observe that surface waters have relatively higher ∂^{18}O values compared to the groundwater. Drilled wells have more or less the same isotopic composition as excavated wells. However, we observe from the table that the standard deviation for the excavated wells is greater than the standard deviation for the drilled wells. This could, by itself, give a clue to the susceptibility of groundwater to isotopic changes due to evaporation as groundwater becomes shallow (excavated wells are generally shallower than drilled wells). However, no statistically significant relation has been observed between static water level, depth to water and total depth and ∂^{18}O (see Fig.8.3).

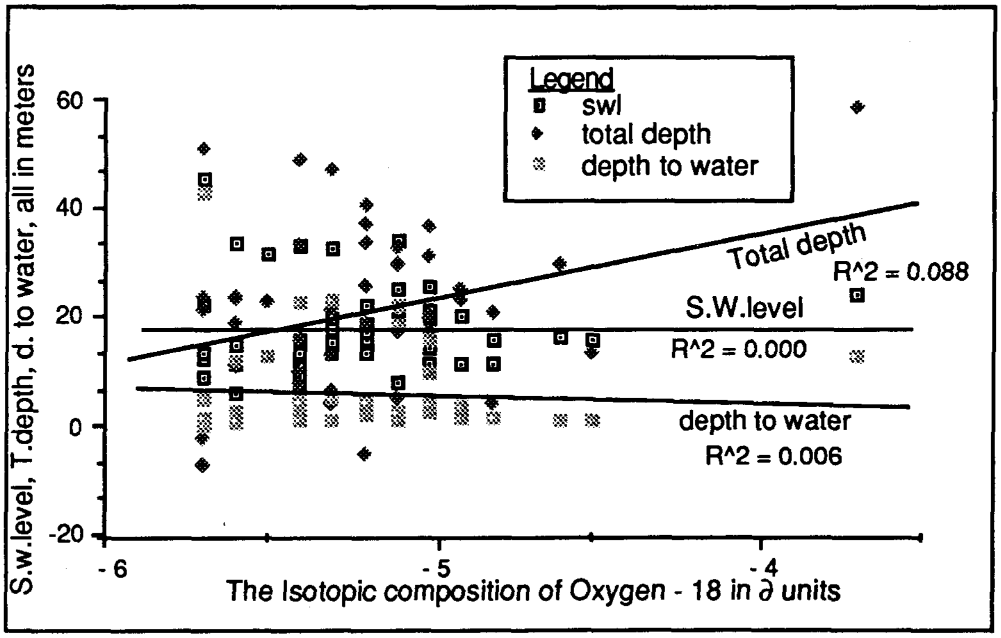


Fig.8.3. The relationship of total depth, static water level and depth to water with the corresponding ∂^{18}O values.

The regression lines representing the static water level and depth to water data are horizontal (constant). The uprising slope of the regression line for the total depth may suggest the sensitivity of the aquifer in shallow wells (mostly the excavated wells) to direct replenishment.

Since water samples were not collected from different depths in wells, it is not possible to know whether or not the aquifer represents a single body of water with a constant isotopic composition along its vertical thickness.

8.2 The Stable Isotope (^{18}O) Composition of Waters From Some Selected Wells in the Lower Santa Lucia Basin, From Santa Lucia River and Rio de La Plata .

The isotopic variations in waters collected in January 1987 have not shown considerable variations. During the later months, limited number of samples were collected over a relatively wider area. Some water samples were collected from the Atlantic ocean, the Rio de la Plata, the Santa Lucia river and and from some wells in the Lower Santa Lucia basin, during May - June, 1988, November - December, 1988 and September 1989. Figure 8.4 shows the location of the sampling points.

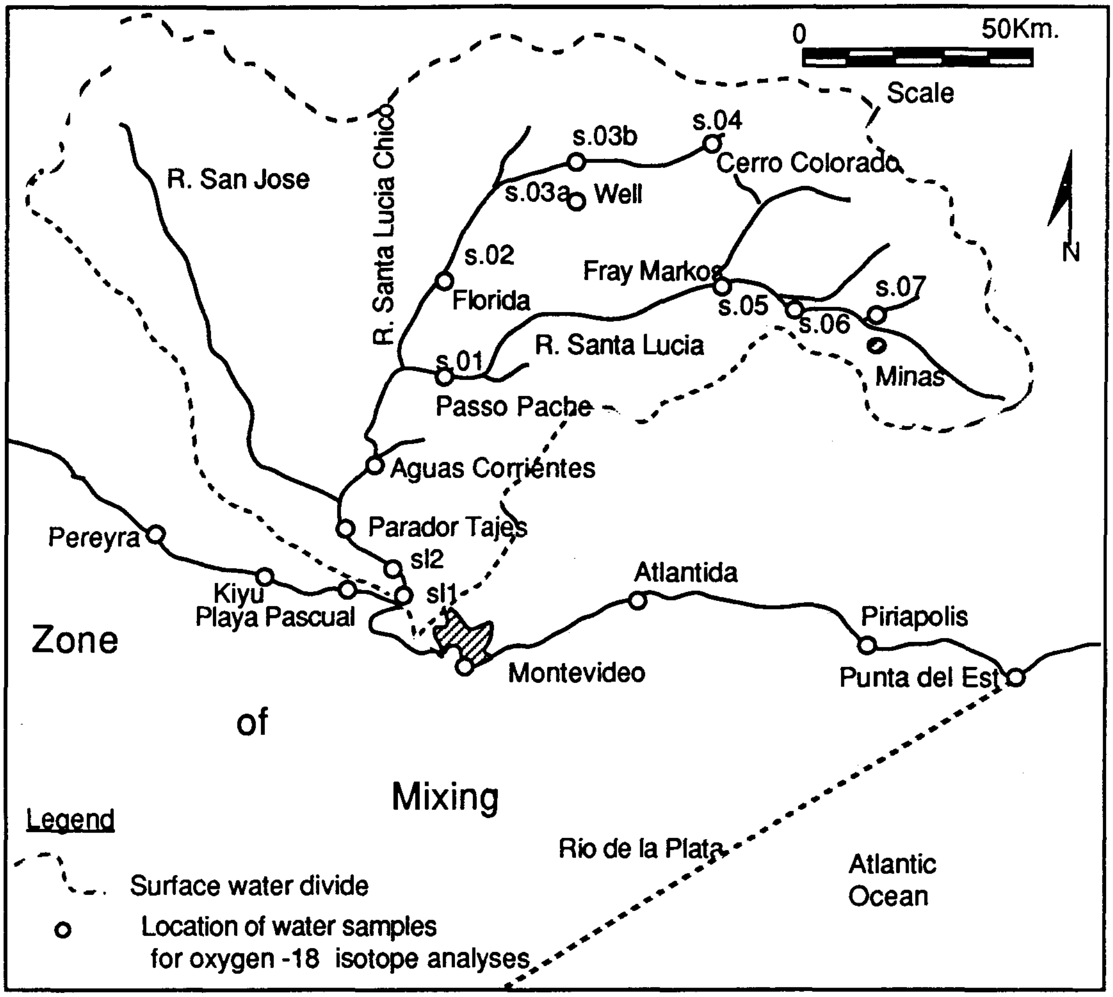


Fig.8.4. Location map showing the points along Rio de la Plata and Santa Lucia river from which water samples were collected for ^{18}O analysis.

The analysis of ^{18}O for the samples collected at the locations given in Fig.8.4. is presented in Table 8.2.

Water Samples From Rio de la Plata Along the Coast

Table 8.2. The ∂^{18}O values along the coast (see location map in Fig.8.4)

Location	∂^{18}O May - June 1988	∂^{18}O Nov. - Dec. 1988	∂^{18}O Sept. 1989
Pereyra	-5.9	-2.1	-5
Kiyu	-5.5	-2.8	-5
Playa Pascual	-5.8	-2.3	-4.9
Montevideo	-5.1	-2.1	-4.7
Atlantida	-4.5	-1.3	-2.9
Piriapolis	-4.1	-0.7	-1.3
Punta del Est	-1.2	1.2	-1.1
Mean	-4.586	-1.443	-3.557
Standard deviation	1.633	1.354	1.772

The ∂^{18}O values (see Table 8.2) clearly indicate that the isotopic composition of Rio de la Plata increases towards the sea, reflecting both evaporative effects and mixing with sea water, as also shown by seasonal variations in isotopic compositon of the waters. The isotopic composition of Rio de la Plata at Pereyra during November - December, 1988 has been higher than the isotopic composition of Rio de la Plata near Piriapolis during the month of May-June, 1988. The consequence of such a big increase has been physically observed, near the coast , at Pereyra, where thousands of fresh water fish were found dead during this period of time.

The direct relations of oxygen isotope with salinity, chlorinity and TDS (see section 8.1.2) would further confirm the possibility of detecting the hazardous consequences which are related to temporal chemical changes in the composition of Rio de la Plata.

Water Samples From Wells

The seasonal changes that occurred in the isotopic composition of some selected wells is given in Table 8.3.

Table 8.3 The $\partial^{18}O$ values for water samples from wells (see location of wells in Fig.8.8)

Well No.	$\partial^{18}O$(May - June) 1988	Well No.	$\partial^{18}O$(Nov- Dec) 1988	$\partial^{18}O$(Sept.) 1989
24	-5.1	90	-5.3	-5.7
23	-5.5	108	-5.1	-5.8
76	-5.4	152	-5.0	-5.3
127	-5.3	159	-5.2	-5.7
86	-5.2	163	-5.2	-5.7
151	-5.1	39		-5.6
		52		-5.5
		115		-5.6
		85		-5.5
		47		-5.6
Mean	-5.267		-5.16	-5.6
Standard deviation	0.163		0.114	0.141

In contrast to the conspicuous seasonal isotopic variations that occurred for the waters along Rio de la Plata, no significant isotopic variations were observed for the water samples from the wells.

Water Samples From Rivers

River waters showed significant seasonal variations (see Table 8.4).

The direct relations of oxygen isotope with distance from Rio de la Plata along Santa Lucia river (Passo Paché, Aguas Corrientes, Parador Tajes, Las Brujas and Delta del Tigre, See Fig.8.4) can be related to the mixing of fresh water with salt water from Rio de la Plata and to evaporation.

Table 8.4. The $\partial^{18}O$ values for water samples from the rivers (see location map in Fig.8.4).

Location	$\partial^{18}O$(may -June 1988	Location	$\partial^{18}O$(Nov-Dec) 1988
San Gregorio	-5.2	Passo Paché (S.L)	-2.5
del Tigre	-4.6	Aqua Corrientes (S.L	-2.5
Pereyra	-5.5	Parador Tajes (S.L)	-2.4
San Jose	-5.3	Las Brujas (S.L)	-3.0
Canelon Grande(Dam)	-7.8	Delta del Tigre (S.L)	-2.8
Santa Lucia (Up Stream	-6.7		
Santa Lucia (D. Stream)	-5.6		
Mean	-5.814		-2.64
Standard deviation	1.079		.251

From Table 8.4, we observe that significant seasonal isotopic variations in ^{18}O composition occurred for water samples from rivers.

For the sake of simplicity, all the mean values previously discussed are summarized as in figure 8.5.

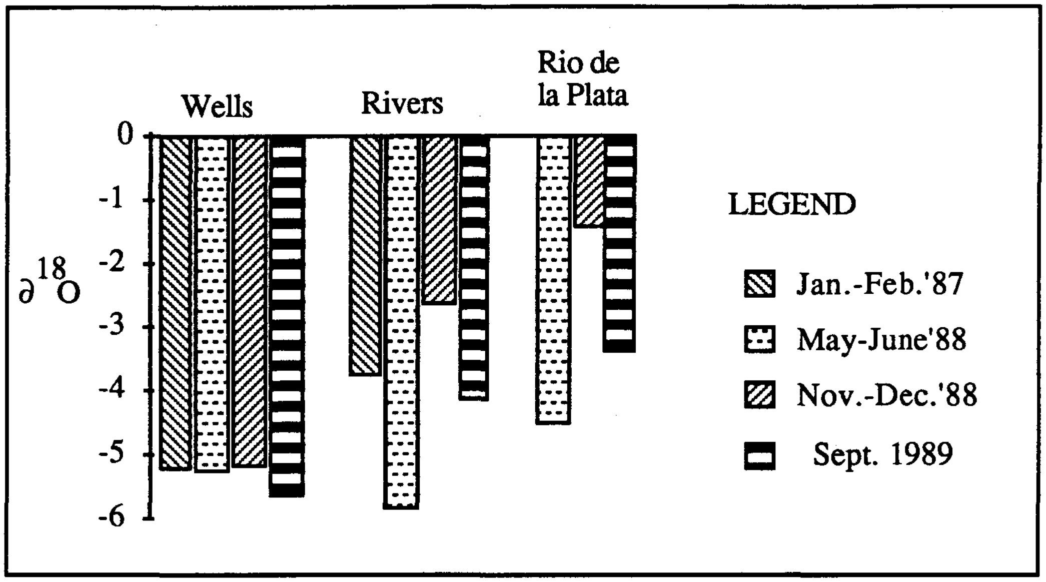


Fig.8.5. Diagram showing the means in $\partial^{18}O$ of all the waters sampled from wells, rivers and Rio de la Plata during the particular months indicated in the figure.

As can be observed in figure 8.5, surface waters are highly affected by seasonal changes, while groundwaters are hardly affected. In general, increasing contents in oxygen - 18 are related to relatively dry months, while decreasing contents in oxygen - 18 are related to relatively wet months. During November-December 1988, the discharge of the surface waters has been observed to decrease as a result of less precipitation.

In conclusion, the reasons to the increase in isotopic composition of oxygen in the rivers are the interrelated parameters of precipitation, evaporation and migration of salt water from the Rio de la Plata upstream along the Santa Lucia river.

The comparatively very slight response to temporal isotopic variations in groundwaters is indicative of a recharge restricted to the period of heavy rains and negligible evaporative or mixing effects.

As seen from Table 8.5 and the geographical location of the sample points given in figure 8.3, no distinct pattern of increase or decrease in $\partial^{18}O$ can be observed in the upper part of Santa Lucia river. The variations seem to be directly related to the intensity of evaporation in relation to the quantity of available water. For example, Santa Lucia Chico river (s.02, s.03, s.04 in Table 8.5) has a comparatively small discharge (hence higher $\partial^{18}O$) compared to Santa Lucia river (s.01, s.05, s.06, s.07 in Table 8.5) which has relatively a greater amount of water (hence lower $\partial^{18}O$). The very high value at Cerro Colorado (s.04) probably corresponds to high evaporation from seepages, whereas lower values at Minas reflect lower evaporation compared to the total volume of the available water. The slight increase of the $\partial^{18}O$ downstream along Santa Lucia, then corresponds to equal quantity of water and comparatively higher rate of evaporation.

Table 8.5. The $\partial^{18}O$ values and the corresponding conductivity and TDS values along river Santa Lucia (upper and lower basin) from water samples collected in September 1989 (see Fig. 8.4 for location).

Sample No.	$\partial^{18}O$	Conductivity (microsiemens)	TDS (mg/l)
sl1	-4.1	5190	1300
sl2	-4.7	1540	740
s.01	-4.3	170	82
s.02	-3.2	370	160
s.03a	-4.3	140	60
s.03b	-3.6	270	130
s.04	-2.1	470	220
s.05	-4.2	270	120
s.06	-3.7	250	120
s.07	-4.1	190	90

No correlation exists except that of TDS with conductivity. Normally, when the total volume of rivers decreases the conductivity and TDS values increase accordingly. If this may be the case, one should expect the corresponding increase in isotopic composition of oxygen. In the Santa Lucia basin, however, the volume of water increases away from the source, due to contributions from the aquifer.

We have observed in the previous sections that the aquifer has lower contents of oxygen - 18 compared to the river waters. Therefore, the lower values encountered, irrespective of high evaporation, are due to effluent discharge from the aquifer adjacent to the rivers. The general tendency of the negative correlation between oxygen - 18 and TDS and conductivity values agrees with the above argument.

The above discussion provides some information as to the possibility of the interconnection of groundwater with surface water. However, more isotopic evidences are needed on seasonal isotopic variations and the corresponding variations in water levels and discharge of surface waters.

The Oxygen - 18 Isotope as Groundwater Quality Indicator

The determination of some critical parameters like TDS, conductivity, Cl and SAR helps in detecting groundwater quality. It should be remembered that it is very difficult to find relations between oxygen - 18 and the water quality indicators, if the type of waters we are dealing with have undergone mixing with waters of different origin having distinct isotopic signals. For example, the $\partial^{18}O$ values of waters from the rivers and waters from Rio de la Plata differ from one another in as much as their chemical compositions are different. Whenever we envisage the above mentioned relationships these distinct waters ("fresh" and "saline") should be handled differently. Otherwise, we would be studying not only the interrelation but the property of mixing these two ("fresh" and "saline") waters.

In the following, relations are envisaged between $\partial^{18}O$ of the waters and certain characteristics like salinity, chlorinity of the mixed (saline and fresh) waters of the Rio de la Plata.

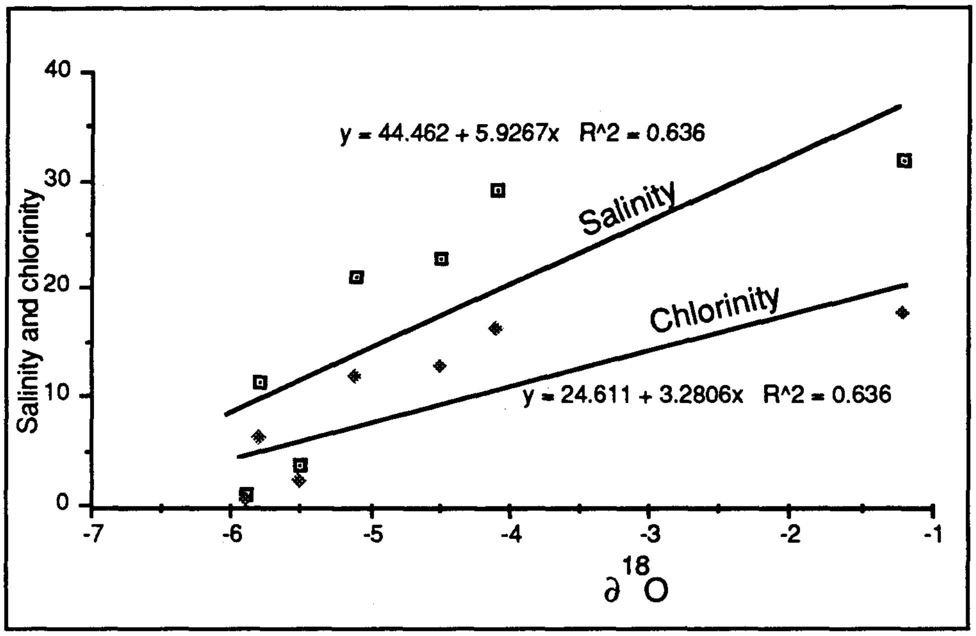


Fig.8.6. Relationship between oxygen - 18, salinity (°/°°) and chlorinity (°/°°) of the waters from Rio de la Plata from the water samples collected in November 1988.

Figure 8.6 shows the relation between oxygen - 18 and salinity and chlorinity of the waters from Rio de la Plata. These waters have a distinct property which is manifested by their increasing salinity and chlorinity values. A correlation coefficient of 0.636 was found in both cases.

Since the above mentioned water quality parameters (TDS, conductivity, SAR, salinity, chlorinity and chloride) are all interrelated chemical parameters which behave conservatively, the determination of one of these parameters could be used to have an idea of the order of magnitude of the other parameters. Previously we have seen the effect of seasonal change on the isotopic composition of Rio de la Plata and Santa Lucia river. These changes are related to the encroachment of the Rio de la Plata upstream along Santa Lucia and probably also affecting the adjacent coastal aquifer.

8.3 The Stable Isotope of Carbon (^{13}C)

Twelve water samples were collected from wells, during the months of January - February, 1987, for the determination of isotopic composition of carbon -13 in dissolved carbon (see Fig.8.8).

The purpose of the analysis was to trace the source of dissolved carbonate species, which would help in deciding whether or not the age determinations made by ^{14}C need any age adjustments.

The variations in isotopic composition between the isotopes of carbon is measurable by mass spectrometry being expressed in delta per thousand compared to the known international standard PDB (Pee Dee Belemnitella).

The $\partial^{13}C$ was analyzed in the GEOTOP laboratory at UQAM. The procedure, in brief, is described in the next page.

The water samples were introduced into vacuum flasks in such a way that no air can enter the flasks. The samples were acidified by phosphoric acid and stirred magnetically, thus allowing only the inorganic CO_2 to be extracted. The inorganic carbon dioxide then passed through various stages of purification (elimination of unwanted gases like N_2, O_2 and of H_2O traces) before the samples were finally taken to the spectrometry for analysis. The results of the analysis are given in Table 8.6.

Table 8.6. Values of different isotopic parameters of the water samples collected at different times between 1987 to1988 (see Fig.8.8).

Well sample Number	∂ C -13 (PDB)	TritiumUnits TU	Carbon -14 (Act. % and age in years BP)
9	-8.2	<8	105±7% (recent)
28	-10.9	<8	94.3±5%(470±130)
53	-11.3	<8	86±5% (1200±100)
54	-14.3	<8	107±7% (recent)
90	-8.3	<8	98.5±9 (recent)
108	-10.4	<8	117.6±6% (recent)
115	-11.2	<8	78.1±7%(2050±15)
140	-10.2	<8	115.7±8% (recent)
152	-10.1	<8	92.5±6%(620±130)
153	-10.1	<8	78.5±7%(1950±10)
159	-15.6	<8	103.3±9% (recent)
163/1	-10.3	<8	103.3±9% (recent)

The Sources of Dissolved Carbonate Species in Groundwater

In the following, the possible sources of dissolved carbonate species will be discussed in relation to the values obtained from the laboratory analysis. The purpose of understanding the source of dissolved carbonate species is to have an idea of the amount and proportion of the different sources of carbonate species that join the groundwater circulation system. By doing so, we will be able to trace the sources of ^{14}C that join the groundwater system and, depending on the type of data obtained, we will be able to make corrections to the ^{14}C measurements, in order to determine the correct relative groundwater ages.

Decomposition of organic material in the soil (humus) or root respiration in the unsaturated zone produces CO_2. The CO_2 produced can dissolve soil carbonates. The atmospheric CO_2 can also cause dissolution of soil carbonates, but is present to a lesser degree. If the soil contains considerable amount of humic acid, the calcium carbonate in the soil can be dissolved by the reaction between the humic acid and the limestone, which produces bicarbonate and carbon dioxide.

Figure 8.9 shows the relative positions in the isotopic compositions of the various reservoirs of the CO_2 cycle, after Duplessy (1972) and Pilot (1970). The relative position in the isotopic composition of the waters analyzed is drawn on the figure so as to visualize the possible ways in which dissolved carbonate species can enter into the groundwater system.

It should be noted that the measured $\partial^{13}C$ is that of the total inorganic carbon content (TIC) in the solution, consisting of dissolved CO_2, HCO_3^- and CO_3^{--} ions.

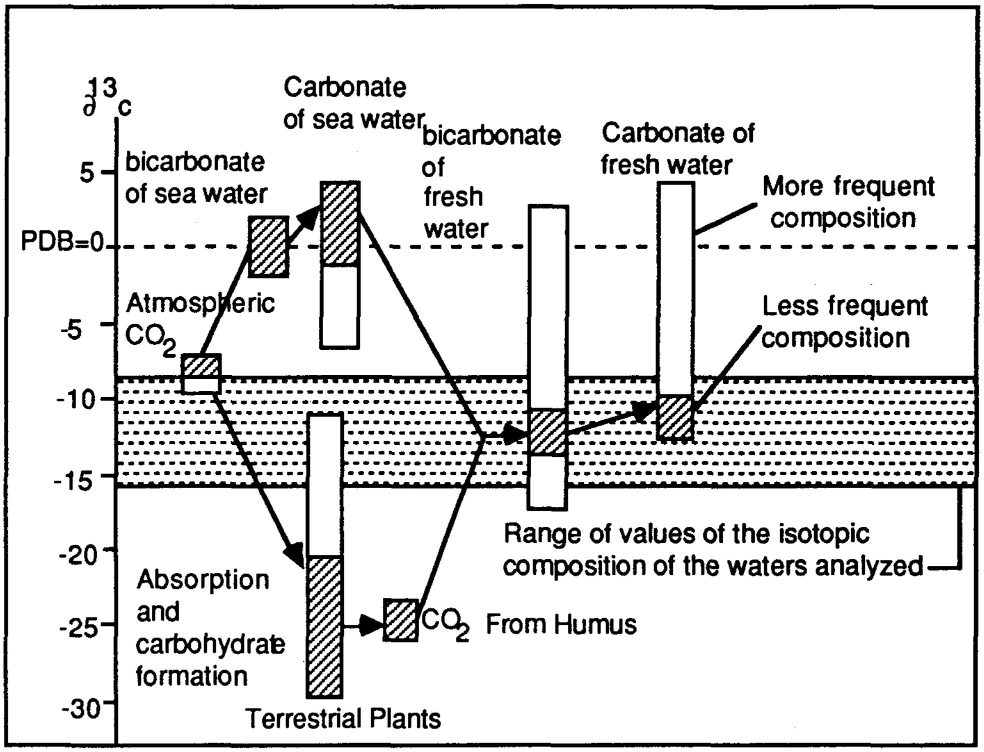


Fig.8.7. A simplified carbon cycle, and the relative position of the isotopic composition of the waters analyzed, after Duplessy (1972) and Pilot (1970).

The $\partial^{13}C$ of atmospheric carbon dioxide is -7.5 °/°° at a partial pressure of about $10^{-3.5}$. During the process of photosynthesis, plants assimilate CO_2. Consequently, the ($\partial^{13}C$) of the plants (particularly those belonging to the Calvin-Benson photosynthetic metabolism) is reduced by 18 °/°° compared to $\partial^{13}C$ of atmospheric carbon dioxide.

The partial pressure of carbon dioxide is much higher in the soil than in the atmosphere, due to the emanations of CO_2 from respiration of plant roots and decay of plant debris. In a well developed soil (non-arid, temperate climate), the soil CO_2 is isotopically equivalent to that of plants with $\partial^{13}C = -25$ °/°° (Pearson and Hanshaw, 1970).

The composition ($\partial^{13}C$) of marine carbonate minerals being 0 °/°° and $\partial^{13}C$ of -25 °/°° for the soil - derived CO_2, a solution with $\partial^{13}C$ of -12 °/°° could be expected (Pearson and Hanshaw, 1970). Because dissolution produces bicarbonates coming in equal proportion from the solid carbonate (0 °/°°) and the gas (-25 °/°°).

In unsaturated horizons, isotopic exchange between HCO_3 (liquid) and CO_2 gas occurs in the soil-air horizon, where, soil, plant roots, dead plants, mineral, air and water coexist.

The reaction between CO_2 containing water with carbonate mineral can be expressed as:

$$CO_2 + H_2O + CaCO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

The carbonate from the aquifer may also establish isotopic exchange with the CO_2.

$$\partial^{13}HCO_3^-\text{liquid} - \partial^{13}CO_2\text{ gas} = 9.5\ °/°°\text{, at } 10°\ C.$$

Finally, the range of ∂13C values of the waters being between -8.2 °/°° and -15.6°/°°, the source of carbonate in the waters analyzed appears to be biological carbon and carbonates (see Fig. 8.7).

The relatively low ∂^{13} value of -15.6 °/°° and -14.3 °/°° for wells 159 and 54 respectively could be due to depletion caused by isotope exchange in the unsaturated zone with an excess of soil CO_2.

The ∂^{13} values of the rest of the waters is relatively stable (around -10°/°°) which fit to the explanations forwarded.

8.4 The Radioactive Isotope of Carbon (^{14}C)

Twelve water samples collected from wells (see Fig.8.8), during August 1987, were analyzed for carbon-14. The main purpose of such analysis is to have an approximate idea of the ages of groundwater in the region.

Initially, several grams of inorganic carbon were recovered in the form of $BaCO_3$ from the water samples (field work by C. Hillaire - Marcel, M. Durand and G. Prichonnet from UQAM and L. Cardozo, S. Marcel and R.Veloso from DI.NA.MI.GE.).

The age of groundwater is the amount of time that groundwater was cut off from the atmospheric carbon dioxide reservoir. In other words, it is the time of groundwater circulation, since its entrance as recharge in the aquifer.

Some $^{14}CO_2$ is produced in the soil zone during root respiration and plant decay and mixed with ^{14}C free inorganic carbon from soil carbonates, then transfered to the groundwater system. This moment is considered in ^{14}C - dating, as the time of recharge (t_0). From this time onwards, it is assumed that the total dissolved carbon isolates itself from the atmosphere, and its ^{14}C starts to decay in closed system.

8.4.1 Dating of Water

The composition of ^{14}C is indirectly measured from ß-particle emissions which accompanies its disintegration. The standard of reference used, as a standard of activity for the laboratory analyses, is that an oxalic acid from NBS which has ^{14}C activity slightly superior to the nineteenth century trees. The amount of ^{14}C is then expressed in terms of percentage of activity of the sample in relation to a reference value of 13.6 dpm/g carbon. Thus, the age of the water samples were obtained (see Table 8.6) from the following equation:

$t = [T_{1/2}/\text{Log } 2] [\text{Log} A_0/A]$ Where, $T_{1/2}$ is taken as 5568 years (the Libby's ^{14}C half life) and A_0/A as the ratio of activities.

8.4.2 Adjustment of Ages

It has been observed, on the previous pages, that some of the carbon dissolved in the bicarbonate could come from gaseous CO_2, while some could come from the calcareous part of the aquifer. The carbon originating from limestone contains no ^{14}C. In other words, the activity in ^{14}C of the calcareous part of the aquifer is 0% (dead carbonate). It is clear, then, that the bicarbonates of the waters could, from the start, be highly affected by the dead carbonate activity. Therefore, the age estimated from the ^{14}C content of the water would be greater than the true age.

The presence of calcareous cement in between sand grains have been observed while acid testing some of the log samples. Therefore, some of the water samples may have been affected by calcareous material.

From the discussion in section 8.3 and also from some evidences gathered from the field, it would be logical to assume the presence of some carbonate minerals affecting the true age of the waters.

8.5 The Radioactive Isotopes of Tritium

Twelve water samples, corresponding to samples analyzed for carbon - 14 and carbon -13, were collected from wells in November - December, 1988 for the analysis of tritium isotopes (see Fig.8.8). The analysis was conducted in the GEOTOP laboratory at UQAM. The results of the analysis is given in Table 8.6.

Tritium levels are usually expressed in tritium units.

$$1\ \mathrm{TU} = \mathrm{T} / \mathrm{H} = 10^{-18}$$

The tritium isotopes are brought to the surface by precipitation after being oxidized. Since the effect of the earth's magnetic field on the particles charged by cosmic rays is higher in areas of higher latitudes, higher tritium units are expected in the northern hemisphere than in the south (Fontes, 1976). Artificial tritium was introduced in the atmosphere during atmospheric tests of thermonuclear devices in 1952. Tritium levels have tremendously increased from 1952 to 1963 and are constantly declining since 1963. Again tritium levels would be relatively higher in the northern hemisphere than in the south, since the tests were carried on in the northern hemisphere. The effect of atmospheric circulations between the northern and southern hemisphere being minimal, tritium levels in the southern hemisphere remain low. Waters which have continental origin have higher tritium compared to those waters of marine origin. This is because the isotopic exchange of oceanic waters lowers the tritium content of the atmosphere above it. The absence of large continental masses in the southern hemisphere, would therefore, attribute to its low tritium level. Low tritium and high deuterium occur in coastal regions. As the moisture moves inland, it picks up more tritium from the atmosphere and is depleted in deuterium by preferential condensation of ^2H_2O (Brown, 1970).

The study area being in the southern hemisphere and at the same time near coast, it would be unlikely to expect high tritium levels. Table 8.7 shows the progressive decrease in tritium levels of precipitation water from 1965 to 1978 at Porto Alegre. Since the study area has, a more or less, similar geographic set up to that of Porto Alegre, similar data could be expected and, following the same trend of decrease till the year 1988, tritium units of less than 10 would be a likely occurrence. However, due to seasonal variations of concentrations, maximum values are expected in late spring and early summer and minimum values in winter (Payne, 1974).

Table 8.7. Isotope values from precipitation water at Porto Alegre, Brazil (Lat. 30.08°S Long. 51.18°W Alt 7 msl.), after International Atomic Energy Agency, Vienna, 1981.

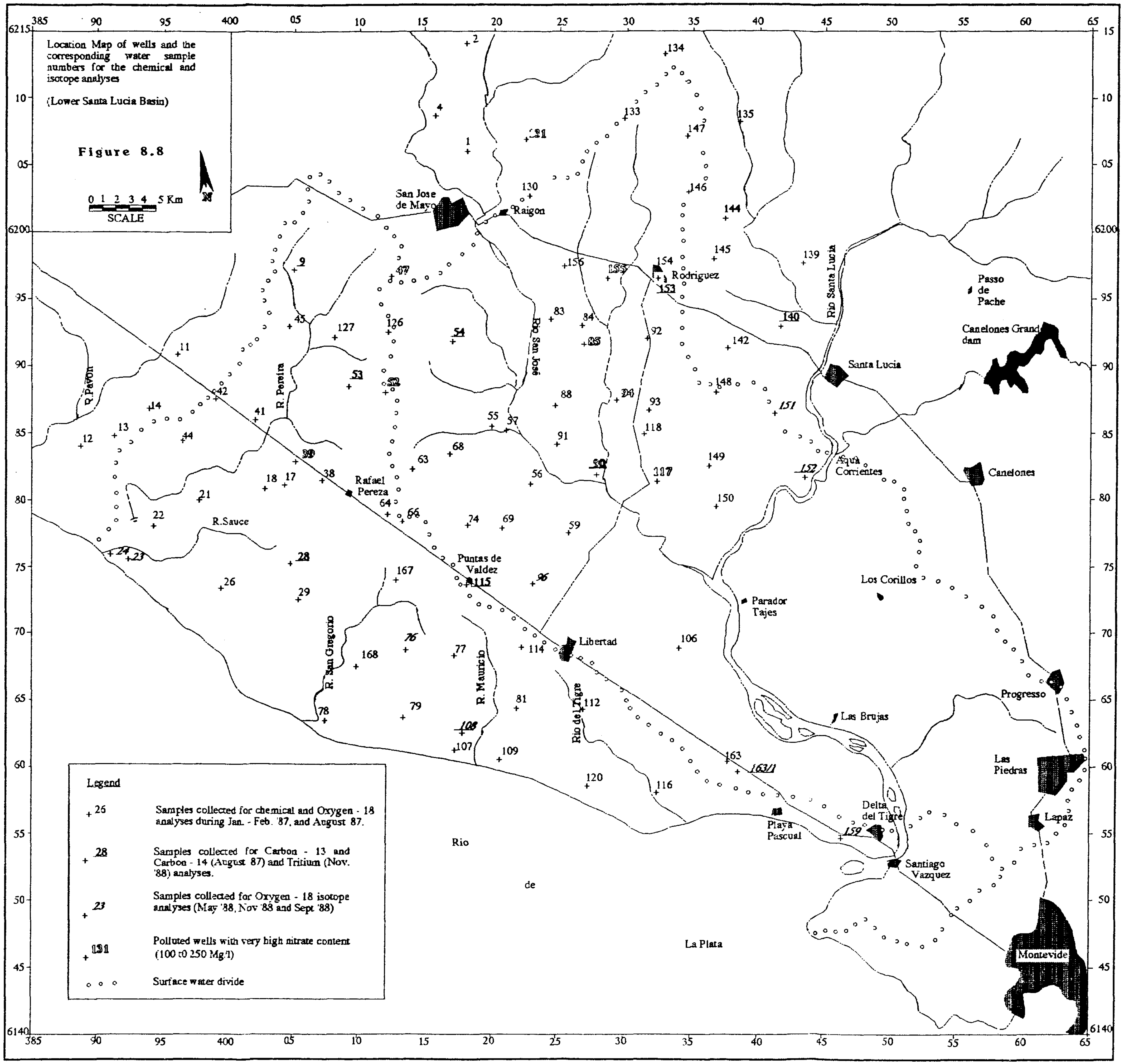
Year	TU	Deuterium	O-18
1965	67	-26.5	-4.9
1966	54.2	-25.9	-4.49
1967	46.5	-18	-3.13
1968	42.1	-28	-5.26
1969	33.2	-26.5	-4.69
1970	38.6	-19.4	-3.7
1971	31	N/A	-5.27
1972	25.1	-84.9	-6.59
1973	20.1	-25.2	-5.14
1974	28.5	-30.9	-5.46
1975	20.9	-29.9	-5.42
1976	16.4	-23.3	-4.91
1977	14	-22.9	-4.31
1978	14.3	-28	-4.27

Tritium levels in groundwater could be higher than the values given in Table 8.7, because tritium concentration could take place during particular season when tritium levels are high, for example in late spring.

In conclusion, ^{14}C activities of total inorganic dissolved carbon (TIDC) indicate recent recharge. Their variability in groundwaters may simply respond to more or less complete $^{14}CO_2$ - TIDC exchange in the unsaturasted zone of the soils.

All the waters analyzed have tritium levels less than 8 TU. Even those from wells 108 and 140 which show ^{14}C activities above 100% indicate very recent recharge, due to the very low ^3H in signal in meteoric waters from the southern atmosphere, this should be seen as contradictory.

Figure 8.8


Location Map of wells and the corresponding water sample numbers for the chemical and isotope analyses
(Lower Santa Lucia Basin)
Figure 8.8
0 1 2 3 4 5 Km
SCALE
N
San Jose de Mayo
Raigon
Rodriguez
Passo de Pache
Canelones Grand dam
Santa Lucia
Rio Santa Lucia
Rio San José
R. Pavon
R. Pereira
R.Sauce
Rafael Pereza
Puntas de Valdez
Aqua Corrientes
Canelones
Los Corillos
Parador Tajes
Libertad
R. San Gregorio
R. Mauricio
Rio de l Tigre
Las Brujas
Progresso
Las Piedras
Lapaz
Delta del Tigre
Playa Pascual
Santiago Vazquez
Montevide
Rio
de
La Plata
Legend
26 Samples collected for chemical and Oxygen - 18 analyses during Jan. - Feb. '87, and August 87.
28 Samples collected for Carbon - 13 and Carbon - 14 (August 87) and Tritium (Nov. '88) analyses.
23 Samples collected for Oxygen - 18 isotope analyses (May '88, Nov '88 and Sept '88)
131 Polluted wells with very high nitrate content (100 t0 250 Mg/l)
Surface water divide
385
90
95
400
05
10
15
20
25
30
35
40
45
50
55
60
65
6215
6200
6140

Chapter 9

HYDROCHEMISTRY

In this chapter, analyses and evaluation of the chemical aspects of the groundwater are considered. Water samples were collected from drilled wells, hand dug wells and surface waters, during different seasons, for chemical analyses. The chemical data which were obtained from the field and laboratory analyses of the water samples are hereby examined with reference to theoretical considerations.

The following chart shows the samples collected during different seasons:

Number	month of sampling	collected by
98	January and February 1987	DI.NA.MI.GE.
48	August 1987	DI.NA.MI.GE.
24	May and June 1988	DI.NA.MI.GE.& author
22	November and December 1989	DI.NA.MI.GE.& author

Some of the parameters like alkalinity, pH, Eh and temperature of air were measured on the site during the sampling process. Laboratory analyses of all the samples were conducted at the UQAM chemical laboratory, where the major cations (Ca, Mg, Na, K) were analyzed by the atomic absorption method and the major anions (SO_4, Cl and NO_3) by the ion chromatographic method. The major cations of the forty eight samples collected during the month of August 1987 were also analyzed by the chemical laboratory at DI.NA.MI.GE.; the results have shown to be reasonably close to those analyzed at the UQAM laboratory (see Tables 4 & 5 in the Appendix).

9.1 Chemical Parameters Measured in the Field

9.1.1 Temperature of the air

The temperature of the air was measured by a simple glass thermometer.

A number of chemical variables in natural waters, like pH and Eh, are greatly affected by fluctuations on temperatures. This is why certain parameters, like pH and Eh, have to be performed at the site during the field investigations. Although the temperature of the groundwater was not measured, the depth to water in most cases is shallow enough to expect a significant relation between temperature of air and temperature of groundwater.

The temperature of the air affects evaporation rates, which in turn will have an impact on a number of parameters, like total dissolved solids, S.A.R (sodium adsorption ratio), electrical conductivities, etc.

9.1.2 Electrical Conductivity

The electrical conductivity or specific conductance (reciprocal of resistivity) of the waters was measured in the field by a conductivity meter. The values are expressed in micro - Siemens/cm.

No significant variations in conductivity values have occurred between measurements performed in January-February 1987, and August 1987. In both cases, the range of values are mostly between 500 and 900 micro - Siemens/cm.

Electrical conductance values are related to the type concentration of ions present in waters. Certain groundwater situations could be understood from conductivity values alone, provided that antecedent comprehensive studies indicating the relationships with other parameters are available.

9.1.3 Alkalinity

The alkalinity values (bicarbonate-carbonate character of waters) were analyzed in the field by slowly adding 0.02 normal (N) sulfuric acid solution to 100 ml of samples of water and reading the resultant changes in pH. Highly alkaline samples were titrated to a pH of 8.3, in which case, the hydrogen ions from the acid combine with the carbonate ions to form bicarbonates; the excess hydrogen ions lower the pH until a pH of 8.3 is reached, where all carbonates are converted to bicarbonates. Titration to this point (where phenolphthalein turns from pink to colorless), represents alkalinity as carbonate. For the waters with initial pH less than 8.3, the samples were titrated to a pH of 4.5 representing alkalinity as bicarbonate.

Alkalinity values reflect the acid neutralizing capacity of aqueous carbonate system, and are directly related to bicarbonate concentrations. The total alkalinity values thus obtained according to the above mentioned procedure of field measurements were used to determine the total carbonate content of the waters.

9.1.4 Hydrogen-Ion Activity (pH)

The hydrogen ion activity (pH) values were measured in the field by a pH-meter equiped with temperature adjustments and calibration devices.

The pH values for the samples collected in August 1987 have been found to show relatively higher values (with mean value of 7.66 and standard deviation of 0.64) compared to the ones collected in January-February, 1987 (with mean value of 7.31 and standard deviation of 0.33). In general, all the waters analyzed have pH values within the range of natural waters.

In an aqueous solution, the hydrogen-ion activity is controlled by interrelated chemical reactions, whereby some ions combine with $[H^+]$ or $[OH^-]$. An example of a common chemical reaction where hydrogen ions are produced is given below (Matthess, 1982):

$$CO_2(g) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$$

$$H_2CO_3(aq) \rightleftharpoons H^+ + HCO_3^-$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{--}$$

In the first step CO_2 is dissolved with water; hydrogen ions are produced in the second and the third steps. An example of hydrogen ion consumption is given below:

$$CaCO_3 + H^+ \rightleftharpoons Ca^{++} + HCO_3^-$$

which may also be expressed as

$$CaCO_3 + H_2O \rightleftharpoons Ca^{++} + HCO_3^- + OH^-$$

The small pH variations between 5 and 8 of the waters in the area, may be explained by a situation whereby the dissolved CO_2 and the hydrogen carbonate ions form a buffered system with the carbon dioxide. However, the variations observed on pH values of water samples could be due to one or to the combination of the following two reasons:- a) Some waters might contain free acids like carbonic acid or organic acids (eg. humic acid). b) The pH values could be raised due to escape of CO_2 from solutions.

The influence of pH values on the chemical characteristics of the waters can be understood from the ongoing discussion.

9.1.5 Eh - Measurements

Measurements of redox potentials were conducted in the field by an Eh-meter. The apparatus consists of a platinum inert electrode and a reference electrode. The inert electrode acts as a donor or acceptor of electrons from the ions in the measured water sample, depending on whether or not the potential of the half-cell* containing the ions, is greater or lesser than that of the reference electrode. The potentials are related to the standard hydrogen electrode (SHE). The potential values obtained from the measurements (Eh values) are electrochemical potentials relative to SHE, which indicate the nature and rates of reaction at electode surfaces. They represent energy gained in the transfer of one mole of electron from an oxidant to H_2. The Eh values read from the Eh - meter are reduction or oxidation potentials measured in volts as compared to that of hydrogen which is arbitrarily set at 0.00 volts. Increasing positive Eh values may then indicate increasing redox potentials. Natural waters with large quantities of oxidizing or reducing agents give measurements of high and low Eh values, respectively (Stumm and Morgan, 1967).

The application of the Eh measurements will be given in the next section.

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* Half-cell is the relative electrode potential of an electrode defined as the electromotive force of a cell where the electrode on the left is a standard hydrogen electrode and that on the right is the electrode in question (Stumm and Morgan,1967).

9.2 The Redox Conditions in the Waters

The relative state of reduction or oxidation in the waters is quantitatively deduced from the measurement of reduction-oxidation (redox) potential, denoted by the symbol Eh. The redox potential can also be expressed by relative electron activity which is defined by pE=-log[e]. Large positive pE values indicate low electron activity which represent oxidizing conditions; smaller values correspond to reducing conditions. pE values are related to Eh values according to the following formula:-

$$pE=Eh(F/2.3RT)$$

Where F= Faraday's constant, R= Universal gas constant,

T= temperature (° Kelvin).

The Eh values obtained from the field measurements were converted to pE values in using the above formula. The values obtained lie between 2 and 3 which indicate a slightly oxidizing situations. In the forgoing discussion, the measured Eh values will be used instead of the calculated pE values.

In using the field measurements of pH and Eh, the nature of the environment in which the waters occurred can be understood. In order to have a clear idea of this environment, we shall first consider the stability of natural waters with respect to all possible pH and Eh values, including the extremes. A stability field diagram has accordingly been constructed (see Fig. 9.1). Then, the pH versus Eh values of the waters have been plotted (see Fig. 9.2) and superimposed on the stability field diagram.

While considering the stability of the measured water samples with respect to the stability field of natural water, we assume that the solutions (water samples considered) have pH and Eh values inside stability field of water under equilibrium.

We shall first consider the two extreme cases of oxidation and reduction of natural water and later represent the pH and Eh values of the measured water samples with respect to these extreme cases of oxidation and reduction.

In the case of reduction , water is decomposed to hydroxyl ions and hydrogen.

$$2H_2O + 2e \rightleftharpoons H_2 + 2OH^-$$

The equation that describes the Eh-pH link (Garrels and Christ,1965) is given by:

$$Eh = -0.059\ pH \qquad (9.1)$$

In the case of oxidation, water is decomposed to give gaseous oxygen and hydrogen ions.

$$2H_2O \rightleftharpoons O_2 + 4H^+ + 4e$$

The equation that describes the Eh - pH link is given by:

$$Eh = 1.23 - 0.059\ pH \qquad (9.2)$$

Equations (9.1 & 9.2) are the two limiting reduction-oxidation equations. The upper and lower limit of water stability are obtained from these equations by substituting pH values of natural environment ranging from 1 to 12. The resulting stability of water and the possible environments are plotted (see Fig.9.1).

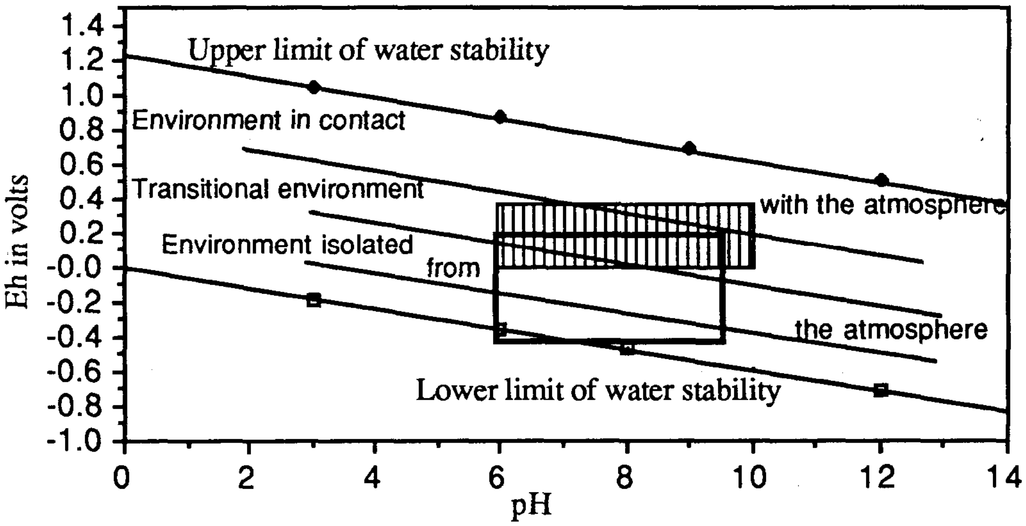

Fig.9.1. Approximate position of some natural environments as characterized by pH and Eh (after Garrels and Christ, 1965). The hatched rectangle inside the diagram represents the pH - Eh limit of the water samples analyzed and the solid rectangle corresponds to the Eh - pH limit of common sedimentary associations referred to in figure 9.4.

As in figure 9.1, oxidation is favored in environments close to the atmosphere having relatively lower pH values, whereas reduction is favored in environments far from the atmosphere having relatively higher pH values. Under natural conditions, there exists no pH value where environments in contact with the atmosphere can be reduced, whereas reduction is possible for all values between 1 and 12, provided that the environments are far enough from the atmosphere.

Having considered the possible occurring natural environments, we shall compare the pH and Eh values of the water samples analyzed with reference to the stability diagram of water.

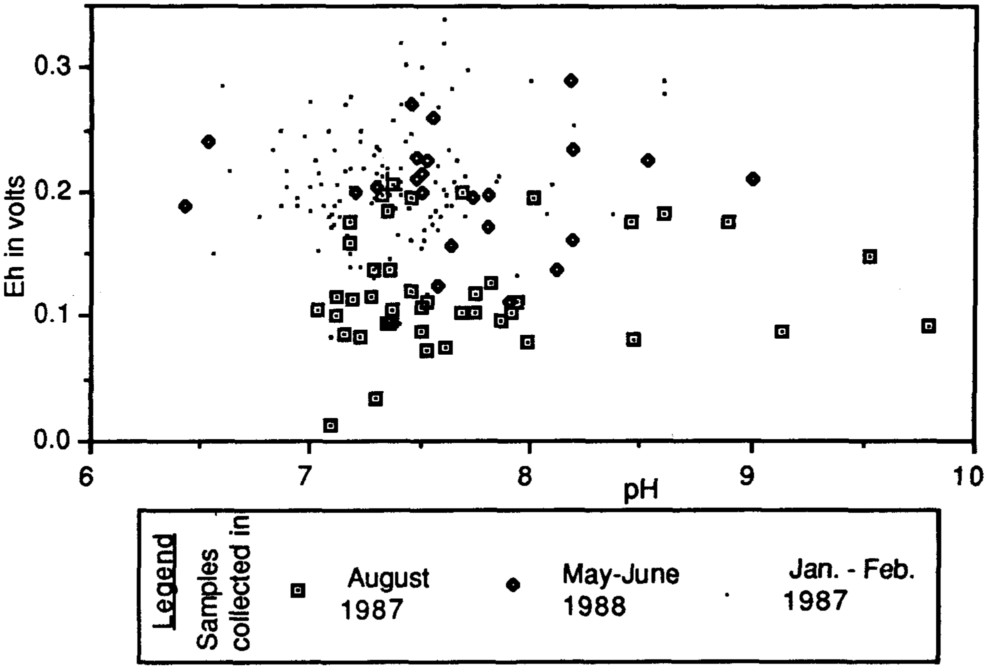

Fig.9.2. Distribution of Eh-pH measurements of the water samples analyzed.

The position of the water samples, with respect to their pH-Eh values is represented as in figure 9.1 (the hatched rectangle), from which we observe that almost all waters lie in between the transitional environment and environment in contact with the atmosphere. Since all the waters have Eh values above 0 volts, it can be said that all waters lie within the zone of oxidation. The variations may be classified as slightly oxidizing (Eh values between 0.00 and 0.2 volts) to moderately oxidizing (Eh values of 0.2 to 0.3 volts) and strongly oxidizing (Eh values greater than 0.3 volts). According to such classification, surface or near surface waters happen to have relatively higher Eh values compared to the groundwaters. Normally Eh values decrease with depth. The Eh values of the wells is mostly between 0.1 and 0.25 volts. Depth versus Eh diagram in figure 9.3 shows a decrease of Eh values with depth for some of the data. This may especially be true for the shallow aquifers.

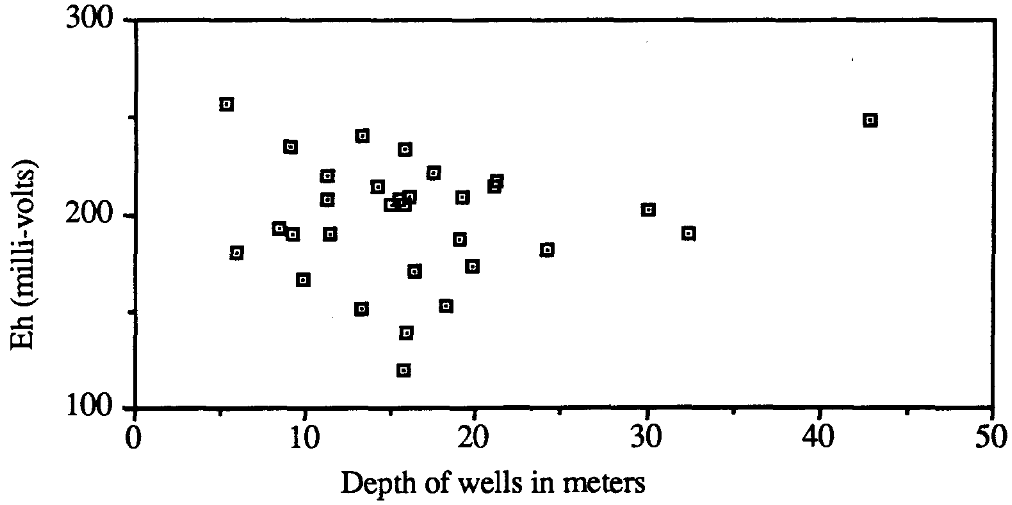

Fig.9.3. Depth versus Eh diagram of water samples collected in January-February, 1987.

One of the major influencing factors for an oxidizing or reducing condition is the presence or the absence of free oxygen in groundwater. The air in the unsaturated zone (ground air) contains higher proportion of carbon dioxide and water vapor. Although the amount of oxygen above the water table is less than normal atmospheric air, oxidizing situations are normally encountered, unless the aquifer is completely isolated from the atmosphere. Reducing situations prevail in confined groundwater situations, or in deep groundwaters where the unsaturated zone lacks oxygen. Moreover, the composition of the ground air and the degree of oxidation depends on geomorphology and climate.

The fact that most of the water samples were collected from relatively shallow aquifers (10-20m) may explain the relative abundance of oxygen for the oxidizing conditions encountered. On the other hand, some parts of the aquifer being semi-confined, dissolved oxygen may have been carried by vertical leakage from the semi-confining layer on top.

The composition of the granular aquifers in the study area being mostly sand, silt and clay, where dispersion and diffusion phenomenon are prevalent, oxygen in the ground air may dissolve at the interface of the water table and be carried to a deeper level.

Figure 9.4 shows the possible sedimentary associations within specific pH and Eh conditions. By superimposing figures 9.4 and 9.1, the possible mineralogical associations in the area can be identified with respect to the measured pH-Eh values.

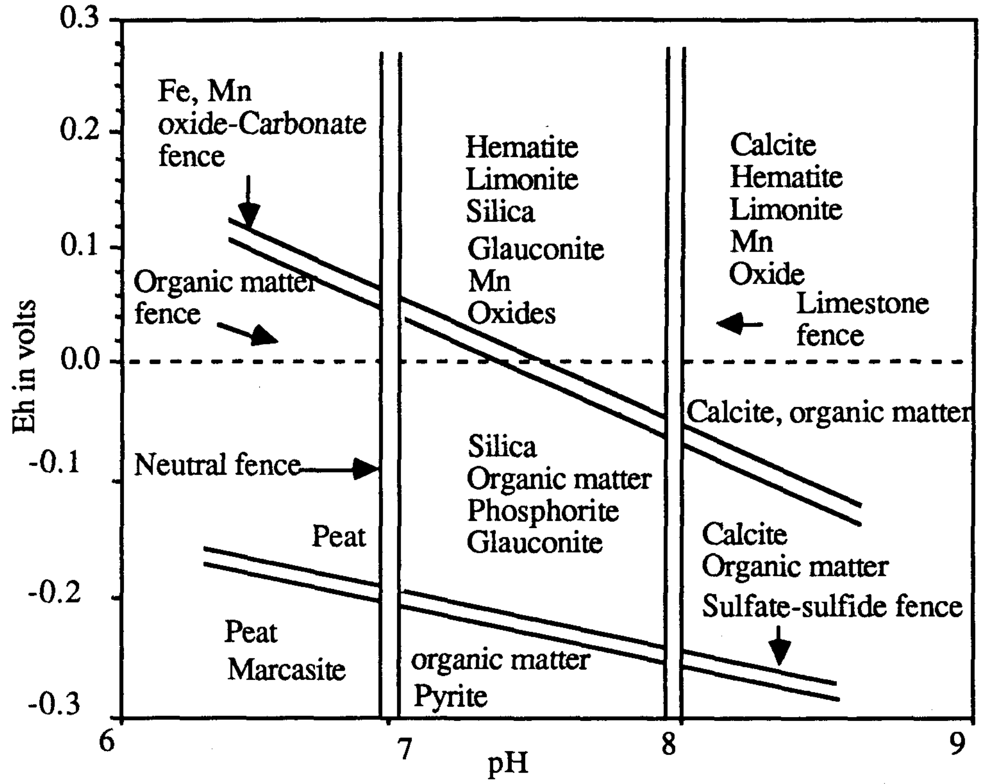

Fig.9.4. Sedimentary associations in relation to environments with specific pH and Eh, after Krumbein and Garrels (1952).

As can be seen from figure 9.4, the possible mineralogical associations in the area are above the organic matter fence. It can be said, from the pH - Eh limit of the waters alone, that the possible source of CO_2 in the area are calcite and organic matter.

Considering the evolution of chemical quality of groundwater, dissolution of soil and sub soil minerals takes place in the upper zone (local groundwater zone). In this zone the water is relatively acidic. This is because CO_2 is constantly being produced in the soil by soil bacteria, by decomposing soil organic matter (Krumbein and Garrels, 1952). The partial pressure of CO_2 is then increased. This results in the production of more hydrogen ions, hence reducing the pH values of the soil and of the shallow groundwater. The acidic water then produced percolates through the unsaturated zone and, on its way, reduces various substances from their less oxidized state. For example, Fe^{+++} may be reduced to Fe^{++}, or NO_3^- to NO_2^-, etc. However, the sedimentary associations as can be deduced from figures 9.1 and 9.4 do not indicate any possibility of reduction.

Contamination of the groundwater in the area due to the fertilizers used will be discussed in the coming chapters; in the meanwhile, let us keep in mind the importance of the interrelationship between depth of groundwater, Eh and pH conditions in relation to oxidation and reduction as discussed above.

9.3. Chemical Equilibrium, Ionic strength and Activity Coefficient

In order to withdraw from the chemical analysis data, valuable informations like salinity, chlorinity and saturation state of waters with respect to calcite and dolomite, some chemical equations have to be used. These equations are based on the general rules governing thermodynamic equilibrium, as discussed in many text books, for example Matthess (1982), and Garrels and Christ (1965).

The driving force of a chemical reaction is related to concentrations of the reacting constituents and concentrations of the products of reaction:

$$aA + bB \rightleftharpoons cC + dD$$

Where, a,b,c,d are the number of moles of the chemical constituents A,B,C and D respectively.

From the law of mass action,

$$K = [C]^c[D]^d/[A]^a[B]^b$$

Where, K is a coefficient known as thermodynamic equilibrium constant or the stability constant. The brackets represent the thermodynamically effective concentrations which are referred to as the activities.

Solute concentrations can be expressed as activities,

$$a_i = m_i\hat{a}$$

Where, a_i is the activity of the solute species i, m_i is the molality, and $\hat{a}$ is the activity coefficient.

The solubility of minerals depends both on the property of the mineral and the property of the water that comes into contact with the mineral. If the solubility of minerals in pure water is compared with the solubility of minerals with high salt content, it can be observed that the solubilities increase in proportion to the salt content in the waters. This is known as ionic strength effect.

The magnitude of solute and solute-solvent interactions are dependent, among other factors, on the ionic concentrations and ion electrical charge. The ionic strength combines the effects of these two major factors, hence it is a measure of the intensity of the electrical field due to ions in solution.

Ionic strength is defined as half the sum of the terms obtained by multiplying the molality of each ion in the solution by the square of its valence.

$$I = 0.5 * \sum_{i=1}^{n} m_i Z_i^2 \qquad (9.3)$$

Were I is the ionic strength, m_i are the respective molalities and Z_i are the respective valences.

The ionic strengths of all the samples collected at different seasons were calculated in using the above formula.

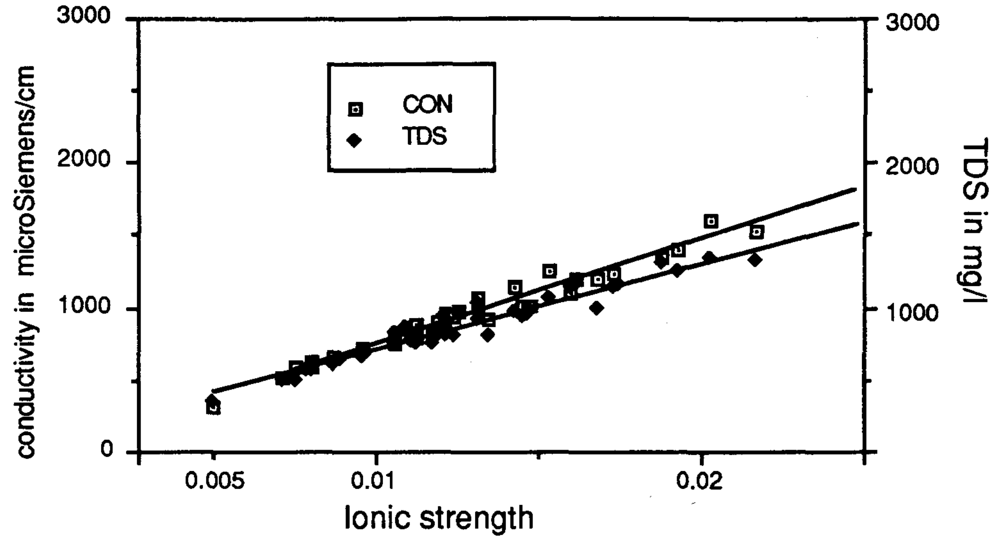

Fig.9.5. Graph showing ionic strength (I) versus conductivity and total dissolved solids (TDS) of the water samples collected in August '87.

As we can see in figure 9.5, The ionic strengths are directly related to conductivity and total dissolved solids.

The activity coefficient â as a function of ionic strength is given as in the following Debye-Hückel (1923) expression:

$$\mathrm{Log}\ \hat{a} = -AZ_i^2\sqrt{I}/1+\grave{a}_iB\sqrt{I}$$

(9.4)

Values of the Ion-Size parameter $\mathring{a}_i$ for the ions are given below:-

$\mathring{a}_i x 10^8$	ions
3.0	K^+, Cl^-, NO_3^-
4.0	SO_4^{2-}
4.25	Na^+, HCO_3^-
6	Ca^{2+}
8	Mg^{2+}

The parameters A and B at 1 bar and for an average temperature of 15°C is given as $A = 0.5042$ and $B= 0.3273 \times 10^{-8}$ · The values of A and B for different temperatures can be found in text books dealing with the subject , for example, Freeze and Cherry (1979). The values corresponding to 15°C have been considered as appropriate for the area.

The above theoretical considerations and calculations will be used in the calculation of saturation states of the waters with respect to calcite and dolomite.

9.4 Saturation State of the Waters With Respect to Calcite and Dolomite

The saturation states of the water samples with respect to calcite and dolomite have been calculated. The procedure followed in the calculation is adopted from Domenico (1972). The analysis results of two samples (N^o.1 and N^o. 2) collected in August 1987 are hereby considered as an example to the procedure followed in calculating the saturation state of the waters. The ionic compositions of the ions in milli-equivalents per liter for the corresponding samples considered are given below:

No	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3
1	1.29	1.13	4.51	0.12	4.56	1.75	0.49	0.58
2	2.22	1.92	6.88	0.07	7.15	2.63	1.80	0.81

The steps to be followed are as in the following:

a) The chemical analyses data are first converted to the concentrations in moles per liter (which is the approximate equivalent of molality).

Molality = ppm x 10^{-3}/formula weight in grams

or, molality = (meq/valence) x 10^{-3}

For the two samples considered, the calculated molalities are as follows:

M(Ca)	M(Mg)	M(Na)	M(K)	M(HCO_3)	M(Cl)	M(SO_4)	M(NO_3)
6.44E-04	5.67E-04	4.51E-03	1.21E-04	4.56E-03	1.75E-03	2.43E-04	5.84E-04
1.11E-03	9.62E-04	6.88E-03	6.70E-05	7.15E-03	2.63E-03	8.98E-04	8.10E-04

b) The second procedure is to calculate ionic strength. By using the formula given for the ionic strength (equation 9.3) the ionic strengths of the two samples were calculated :

Sample No.	I (ionic strength)
1	8.67E-03
2	1.47E-02

c) The third step is to calculate the activity coefficient â as a function of the ionic strength from the Debye-Hückel expression (equation 9.4). The activity coefficients of the ions thus calculated, are given below:

â(Ca)	â(Mg)	â(Na)	â(K)	â(HCO_3)	â(Cl)	â(SO_4)	â(NO_3)
6.96E-01	6.75E-01	6.84E-01	6.75E-01	6.84E-01	6.75E-01	6.82E-01	6.75E-01
6.37E-01	6.07E-01	6.20E-01	6.07E-01	6.20E-01	6.07E-01	6.17E-01	6.07E-01

d) The fourth step is to find the dissociation constants of calcite and dolomite. The carbonate dissolution reactions are:

Calcite : $CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{--}$

Dolomite : $CaMg(CO_3)_2 \rightleftharpoons Ca^{++} + Mg^{++} + 2CO_3^{--}$

In terms of the dissociation constants,

$K_{CaCO3} \rightleftharpoons a(Ca^{++}) \times a(CO_3^{--})$

$K_{CaMg(CO3)2} \rightleftharpoons a(Ca^{++})\ a(Mg^{++})\ a\hat{}^{2}(CO_3^{--})$

The bicarbonate dissolution reactions are:

$HCO_3^- \rightleftharpoons CO_3^{--} + H^+$

Therefore,

$K_{HCO3^-} \rightleftharpoons (a(CO_3^{--})\ aH^+)/aHCO_3^-$

$aCO_3^{--} \rightleftharpoons (K_{HCO3^-}\ aHCO_3^-)/aH^+$

By substituting this last expression for aCO_3^{--}, into the dissociation constants of calcite and dolomite, we obtain the following working equations:

$K_{CaCO3} \rightleftharpoons a(Ca^{++})\ (K_{HCO3^-}\ aHCO_3^-)/aH^+$ (9.5)

$K_{CaMg(CO3)2} \rightleftharpoons (a(Ca^{++})\ a(Mg^{++})\ (K_{HCO3^-}\ aHCO_3^-)/aH^+)\hat{}^{2}$

(9.6)

The right hand side of these equations represent the ionic activity product K_{iap}. The value of aH^+ is taken as 10^{-pH}. From laboratory determinations at 22°C and 1 bar, the equilibrium constants K_{eq} of calcite and dolomite are given as:

$K_{CaCO3} = 0.415.10^{-8}$; $K_{CaMg(CO3)2} = 0.117 \times 10^{-16}$,

$K_{HCO3} = 0.439 \times 10^{-10}$

$K_{iap} < K_{eq}$ represents undersaturation

$K_{iap} = K_{eq}$ represents saturation

$K_{iap} > K_{eq}$ represents oversaturation

The K_{iap} values can be calculated from the above equations. In order to facilitate interpretations, however, percent * saturations can be calculated:

Calcite: $100/K_{CaCO3}\ (a(Ca^{++})(K_{HCO3^-}\ aHCO3^-)/aH^+)$ (9.7)

Dolomite: $100/KCaMg(CO3)_2\ ((a(Ca^{++})\ a(Mg^{++})\ (K_{HCO3^-}\ aHCO3^-)/aH^+)^{\wedge 2})$ (9.8)

The percent saturation values, calculated in using equation 9.7 & 9.8, for the previous two water samples are:

Sample No	calcite	dolomite
1	59.17	29.9
2	79.5	53.8

From the above figures, it can be observed that both the samples are undersaturated with respect to calcite and dolomite, however, sample 2 is closer to equilibrium than sample 1.

The above procedure has been followed in dealing with all the water samples collected at different seasons. The geographical distribution of percent saturation with respect to calcite has been plotted on a map from the calculated values (see Fig.9.6).

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* The saturation index SI, is another standard for comparing the saturation states of waters, (SI=0 represents equilibrium state, as opposed to 100% as in percent saturation)

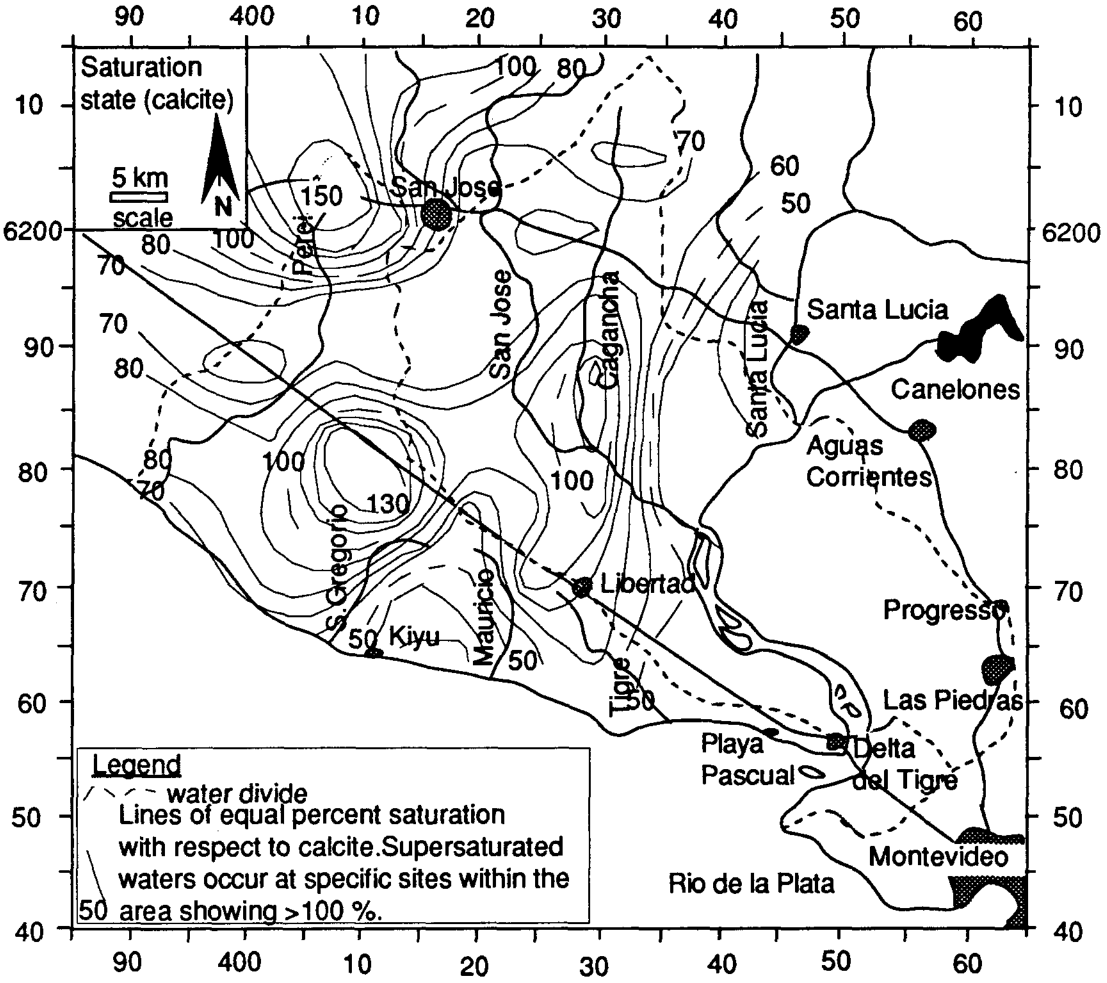

Fig.9.6. Map of percent saturation with respect to calcite calculated from the water analysis data of January - February 1987. (Note, the map shows the general trend and may not reflect the exact situation within the individual wells).

The solubility of the waters indicates that most of the waters are undersaturated with respect to calcite or dolomite. Apart from geology and chemistry such undersaturation of the waters may indicate a short residence time (days or weeks), similar to "conduit type" of springs. Waters which have residence times measured in months may approach saturation.

Undersaturated waters containing excess of CO_2 may corrode pipes and pumps, whereas strongly supersaturated waters may form calcite incrustations. The desired situation where no corrosion or incrustation takes place is slight supersaturation where deposition of calcite protects the pipe from corrosion (Mandel and Shiftan, 1981). The percentage of saturation of the waters with respect to calcite and dolomite have shown to be within the desirable limit.

9.5 Chemical characteristics and origin of the ions

In studying the cause of the present chemical composition of groundwater in the region, the possible sources of groundwater should be traced. Except for the soil water region, relatively deeper aquifers may have solute concentrations originating from the basement rocks in the north. Water flowing from north to south may undergo several stages of chemical changes (dissolution, precipitation), thus reflecting at every stage, antecedent geological conditions. The basin is considered as the only possible initial source of solute concentrations. Towards the south (the coastal zone), the source of solute concentrations may have some relation with Rio de la Plata basin and the Atlantic ocean. All these will be analysed in the foregoing discussion.

Different methods like ionic ratios have been employed to trace the possibility of mixing of groundwater with waters from Rio de la Plata. The sequence of processes through which the water acquired its present composition will be studied with reference to theoretical chemical characteristics of ions. It will be attempted to identify the significant changes in the chemical composition of the groundwater along its flow path.

Considerable variations in chemical compositions were observed for water samples collected during different seasons. However, these variations are uniform; the waters are either diluted or concentrated with proportionate amounts of the ions (the ratios between the ions are the same in all cases). To avoid unnecessary repetition, only the water samples collected during January - February 1987 are used for the ongoing discussion, while comparisons are also made with samples collected during August 1987.

Calcium

The major sources of calcium in waters which originate from the basement rocks are calcium bearing minerals like plagioclase. The calcium ions could be picked up from the decomposition of plagioclase as the groundwater moves along the basement rock fractures. Except the Camacho Formation which is of marine origin, all the rest of the sedimentary formations are of continental origin, among which the Raigon Formation is specially rich in plagioclase (G. Prichonnet, personal communication).

Apart from the above, the amount of calcium in the sedimentary formations depends on the availability of the following:

- Carbonates- calcite ($CaCO_3$), aragonite ($CaCO_3$), dolomite $CaMg(CO_3)_2$, magnesite ($MgCO_3$), nesquehonite ($MgCO_33H2O$), and siderite ($FeCO_3$).

- Limestones (calcite with admixture of magnesium carbonate and other impurities).

- Gypsum ($CaSO_4.2H_2O$), anhydrite ($CaSO_4$) and fluorite (CaF_2).

The presence and the amount of the above minerals in the sedimentary formations depend not only on the original deposition of the sedimentary formation, but also on other factors like paleoclimatic and paleogeomorphic situations. The above mentioned minerals were found in abundance in the Camacho Formation. Therefore, the source of calcium could be the basement rocks and/or the sedimentary formation. The relative importance of the two sources on the concentration of calcium in the water samples will be examined: As can be seen in figure 9.7, no relations exists between total ions and calcium or magnesium ions. Compared to the other ions, calcium precipitates very easily, hence for a long travel distance of water there could be a relatively higher chance of calcium precipitation before the waters become rich in total ions.

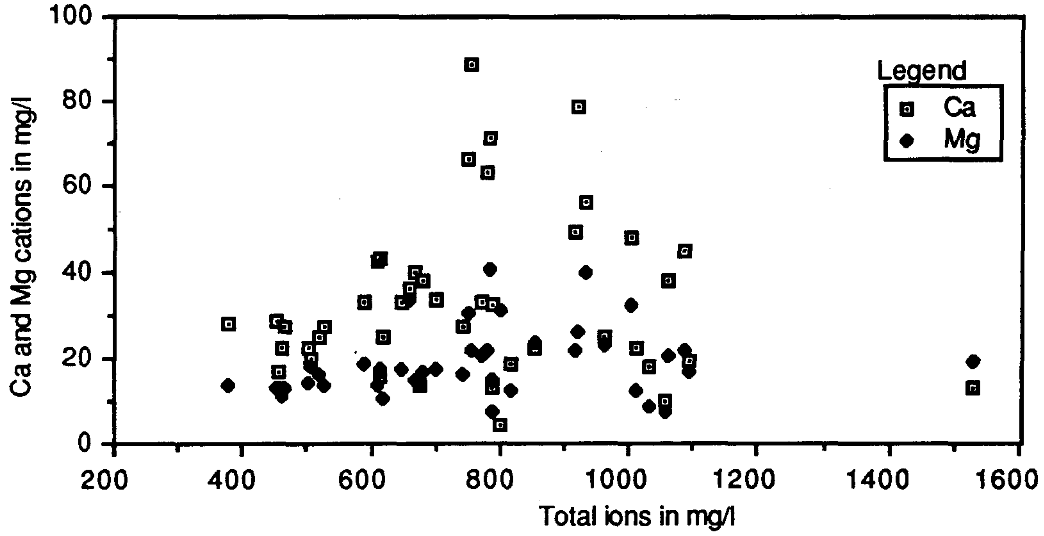

Fig.9.7 Total ions versus Mg and Ca cations for waters collected in Jan.-Feb.,'87

On average, the amount of calcium in the waters ranges from 20 to 60 mg/l (see Fig.9.7). This is relatively small amount suggesting non- existent or relatively small amount of carbonates.

The composition of the sedimentary formations is mostly sand, silt and clay. Some calcite cement have been observed when testing the log samples with HCl acid. In the Raigon Formation which is fluviatile and deltaic in origin, calcite occurs as partial filling of interstices of the sand grains indicating secondary deposition. Some calcite concretions were observed at some localities (Kiyu, near Rio de la Plata and near the town of San Jose) incorporated within the Formation. These concretions were deposited in an arid environment where evapotranspiration had been relatively high. The supersaturation of the waters at the time of deposition of the calcite concretions might have been caused by an environment favoring the growth of algae which increase the pH of waters.

The calcium ions enter into groundwater by the dissolution of calcium bearing solids in waters containing CO_2. Hence, calcium has more chances (usually in shallow groundwaters) to occur in the form of bicarbonates than in other forms.

Calcium ions being susceptible to ion exchange with sodium ions and vice-versa, the exchange of sodium for calcium reduces the quality of the water for agriculture in the irrigated areas. In the coastal areas, the sodium brought by the advancing salt water may be exchanged for calcium (the effect of mixing due to saline water is discussed in chapter 10).

Magnesium

Magnesium is a common alkaline earth metal which is essential in plant and animal nutrition. Magnesium ions enter into groundwater by the dissolution of carbonates, dolomite or ferromagnesian minerals. According to Mandel and Shiftan (1981), the origin of waters may be inferred from the following ionic ratios between magnesium and calcium.

0.5-0.7-----Limestone

0.7-0.9-----Dolomite

> 0.9-------Fresh water from silicate rocks

A water passing through dolomite should dissolve equal amounts of magnesium and calcium before it reaches saturation with respect to either calcite or dolomite. The average range of values of Mg: Ca ratio for the water samples is as represented in figure 9.8.

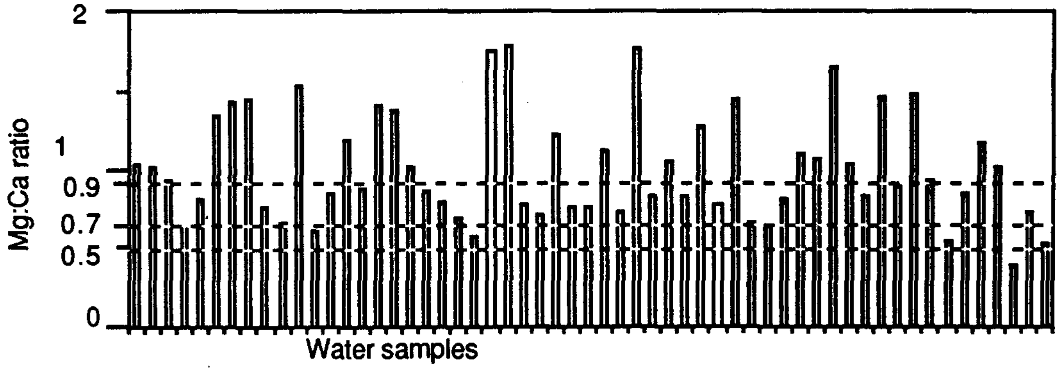

Fig.9.8. Mg:Ca ratios from chemical analysis of waters sampled in January - February, 1987.

No definite source area could be marked as to the origin of the magnesium. However, from the Mg: Ca ratios, it can be said that about half of the waters originate from fresh water silicate rocks, or from environments poor in limestone or dolomite, the source of the other half being limestones or dolomites.

Normally, long residence times of water would also produce [Mg]:[Ca] ratios above 1.0 and high pH, both of which tend to increase along the flow path. Long residence times should then be attributed to waters coming from the basement rocks, in which case the magnesium ions might have originated from altered rocks bearing chlorite and serpentinite. In our case, however the plot of [Mg]:[Ca] ratio as a function of pH and residence time (percent activity of carbon - 14) did not confirm the idea of waters coming from the basement. This agrees with the fact that the waters are relatively young.

Sodium

Sodium is one of the alkali metals which occurs in igneous rocks, in evaporite sediments and in solution in the ocean, in various proportions. The major source of sodium in the waters may be inferred by using the ionic ratios between sodium and potassium. From figure 9.9, we observe that about thirty samples have lower ratios (< 30), about twenty samples present intermediate ratios (between 30 and 55), a significant number of samples (about forty) have relatively high ratios (between 55 and 140) and few (seven) samples present extreme ratios (greater than 140).

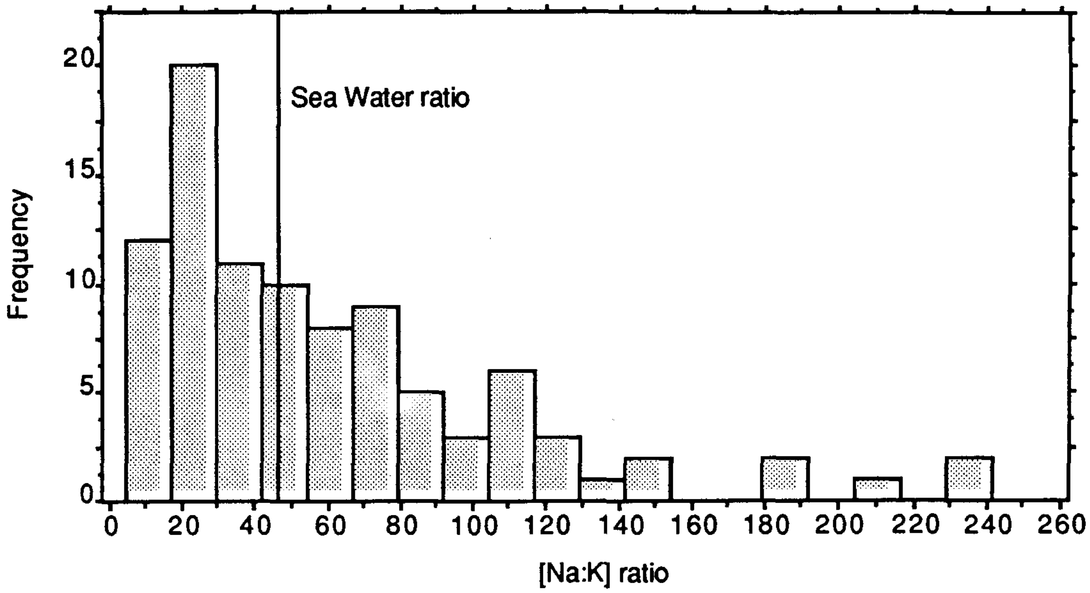

Fig.9.9. Frequency histogram of the [Na:K] ratio of the water samples collected within the months of January and February 1987.

These ratios can be compared with the following ratios, given in text books, like Mandel and Shiftan (1981): - In sea water the Na:K ratio is 47, in rain water it is less than 10 and in most types of aquifers the Na:K ratio is between 15 and 25. According to the ratios obtained from the analysis, and in comparison to the above ratios, most of the water samples exhibit relatively high Na:K ratios. The reasons are explained below.

It can be said that the waters which showed lower values are waters which may have some sort of contact with the surface waters and/or are directly related to shallow groundwater circulations with short lived residence time.

- The negative charges that prevail in crystal lattice of many minerals like clays attract cations. Adsorption and ion exchange proceed until the exchange capacity of the mineral is exhausted (thermodynamic equilibrium is reached between the water and the reacting mineral). In this way, much of the sodium could be retained by adsorption on clayey mineral surfaces that occur within the formations. Hanshaw (1964) showed that clays may preferably adsorb sodium when compacted and may adsorb calcium when dispersed in water.

- The low ratios, less than 15, may also be attributed to advanced stage of sodium calcium exchange, whereby sodium ions are decreased during mixing of waters (sodium ions are decreased from waters due to substitution for calcium).

- When Rio de la Plata gets invaded by sea water, during the relatively dry seasons, the fresh water from the river, rich in calcium, comes in contact with sodium ions, whereby the sea water gains calcium while losing sodium. This mixed water could penetrate into the aquifers of the coastal zone (see chapter 10), where the same process of adding sodium into the aquifer takes place. In the zone of mixing, sodium may be depleted while calcium gets enriched.

Sodium being much less abundant than potassium in sediments, we would expect to have lower Na:K ratio. However, the relatively higher values observed, could be attributed to one or the combination of the following reasons:-

- Adsorption of potassium on clays decreases the K-content of waters hence increasing the ratio.

- Waters which originated from the basement rocks may have higher proportion of Na than K compared to waters from sediments. However, higher proportion of Na could also be caused by irrigation. During cation exchange processes, sodium ions tend to replace calcium or magnesium in fresh water, hence increasing the Na:K ratio.

The above argument can be broadened further and, even distinctions could be made between irrigation waters and waters coming from basement rocks, by using the relationships between total dissolved solids and sodium concentrations.

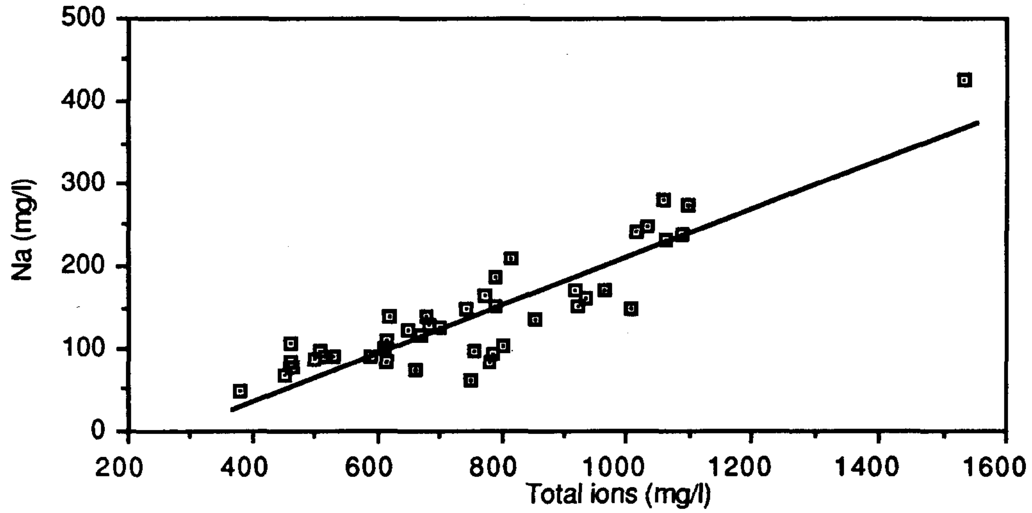

Fig.9.10. Total ions in mg/l versus Na ions in mg/l for waters collected in January - February, 1987.

Direct relation can be observed from figure 9.10, between total dissolved solids (TDS), and sodium ions; correlation coefficient of 0.88 has been obtained.

Since residence times are related to total dissolve solids, it can be said that, in waters with high Na:K ratio, if the total dissolved solids are low (residence time is low), the increase in Na:K ratio could be due to irrigation (increase in sodium adsorption ratio). On the other hand, if both Na:K ratio and total dissolved solids or residence times are high, then the waters must have originated from the basement rocks. It should be noted here that significant amount of sodium is also being induced into the groundwater region due to the use of fertilizers.

Near recharge areas, [Ca+Mg]:[K+Na] ratios usually exceed unity. Further downstream, increase in alkali metals result from ion exchange, hence the ratio is decreased. Figure 9.11 shows the [Ca+Mg:Na+K] ratio of the water samples analyzed during January and February 1987; most of the waters have ratios below unity. Therefore, the recharge area is further away from the point of sampling. This is a supporting evidence to the idea that some waters may have their origin from the basement rocks, unless we attribute the calcium content to the Raigon Formation.

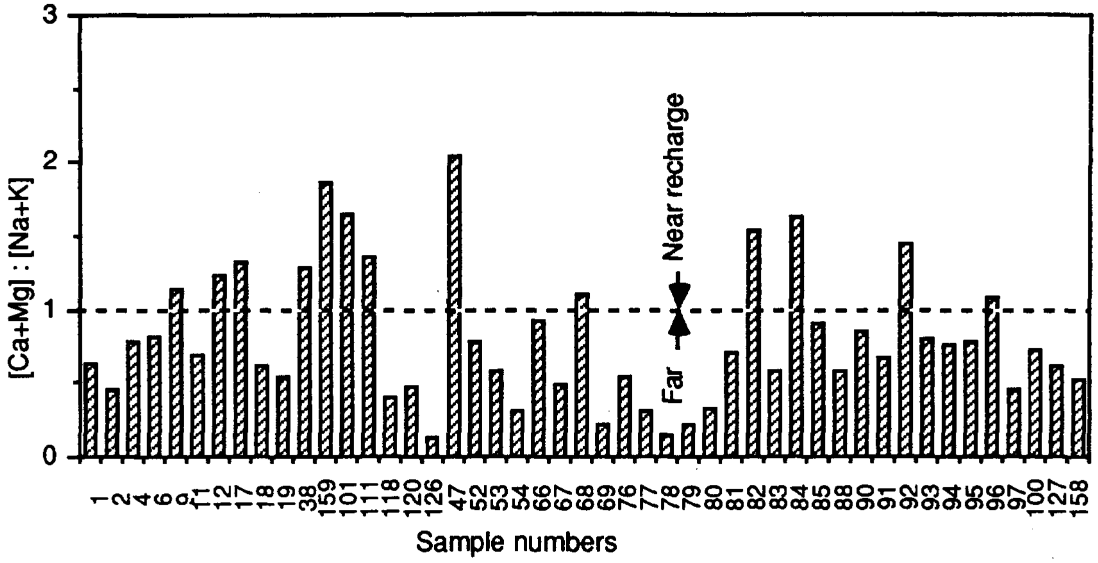

Fig.9.11. Diagram showing the water samples which are relatively near to the recharge areas as opposed to those which are further away in using [Ca+Mg]:[K+Na] ratios of the waters sampled in January February, 1987.

Potassium

In contrast to sodium, potassium is liberated from silicate minerals with greater difficulty and has a strong tendency to be reincorporated into clay minerals (Hem, 1983). Potassium being an essential element for plants, the fertility of soil is retained by adding K onto the soil. These reasons may explain why the concentration of K ions is relatively small compared to other ions.

The average amount of potassium in the water samples collected in January was about 6 mg/l. In August, the average amount was about 8 mg/l. January and February are relatively dry periods of the year. However, these months are the growing seasons of plants. Hence the lesser amount of K ions during these months could be due to extraction of K ions from the soil by the plants. On the contrary, the soil is left barren during August, which may account for the difference of 2 mg/l in excess of K during this month.

Bicarbonate

From the plot of the water types on a Piper's diagram (see Fig.9.18), we observe that most of the waters are of bicarbonate type. The predominance of bicarbonates over the other ions will be explained below:

Although calcite and dolomite are only slightly soluble in water, they form bicarbonates in waters containing CO_2.

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca\,(HCO_3)_2$$

$$Ca\,(HCO_3)_2 \rightleftharpoons Ca+2HCO_3$$

The simultaneous reaction of CO_2 with water yields the following:-

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H+HCO_3 \rightleftharpoons 2H+CO_3$$

Carbonate concentrations may also come from biological activity of plant roots or from oxidation of organic matter. Figure 9.12 shows the relationship of the total ions with the carbonate concentrations; a correlation coefficient of 0.88 has been obtained. The significance of this relationship is that constant increases in carbonate concentrations are observed from rain water to surface streams to groundwaters.

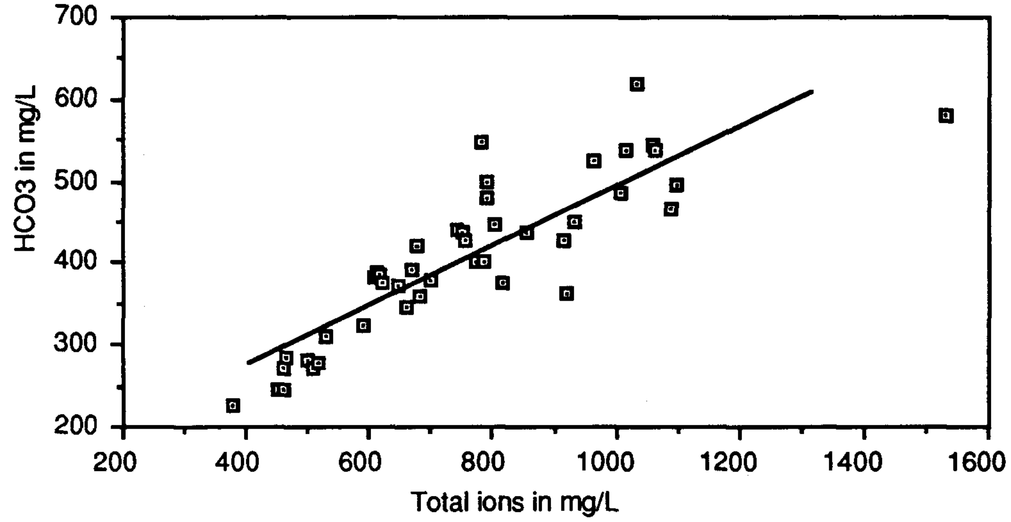

Fig.9.12. Total ions in mg/l versus bicarbonate in mg/l for waters collected on January-February, 1987.

Chloride

The occurrence of chloride in the area can be explained by the whole or part of the above mentioned possible ways, depending on the general geomorphological and geographical situations.

1) Precipitation of chloride takes place when the concentrations exceed that of sea water. When a thin layer of water from the Rio de la Plata or the Atlantic ocean evaporates, the tiny crystals of salt (mainly sodium chloride), which have precipitated from the ocean, get blown up high in the air as spray of dust. These tiny crystals may then dissolve in rain and subsequently be transmitted to groundwater.

2) These tiny crystals of salt may also reach the land by dry fallout.

3) Some local concentrations of chloride in the groundwater (see Fig.9.14) may have resulted from human and industrial wastes.

4) There is be a possibility that halite and other evaporite minerals get incorporated into the aquifers, from which groundwater picks its chloride from solutions.

6) Chloride concentrations may increase by evapotranspiration from the shallow water table.

The iso - chloride map in figure 9.14 gives a general overview of the zones rich in chloride. It has been very difficult to detect general trends of chloride concentrations in the area. However, some localities with exceptionally high chloride concentrations can be observed from the figure, which could be due to deposition of wind blown tiny crystals of salt from the ocean to the adjacent coast.

Chloride concentrations increase with depth, residence time, and total ions which are all interrelated. Figure 9.13 shows the relationship between total ions and chloride concentrations; a correlation coefficient of 0.65 has been obtained.

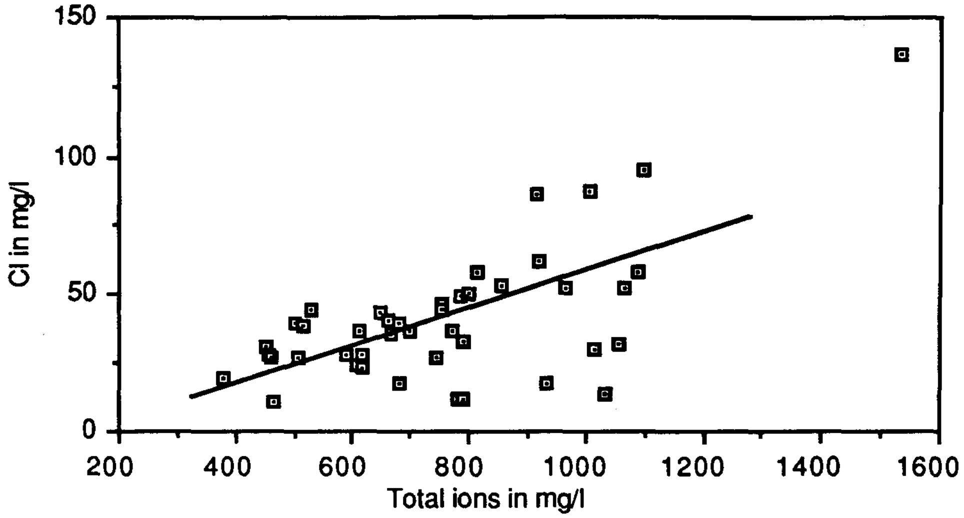

Fig.9.13. Total ions versus Cl in mg/l for waters sampled in Jan. - Feb., 1987.

The increase of chloride concentrations with total ions can be related to groundwater movement, which is generally towards the south. As the groundwater becomes enriched with total ions along its course, chloride ions are progressively picked.

The average chloride content of the waters is about 60 mg/l, which is far below the maximum allowable chloride concentration (250 mg/l). The salt levels may not be detected by tasting, for chloride levels less than 1000 mg/l, if the chloride is present as calcium or magnesium salts.

The iso - chloride map in figure 9.14 shows the development of salt creep. Actually, the danger of salt creep is not acute for the present time, however, some areas like Delta del Tigre are very susceptible to this type of pollution due to different sources of pollution, like agricultural, industrial, domestic pollution and contamination from Rio de la Plata.

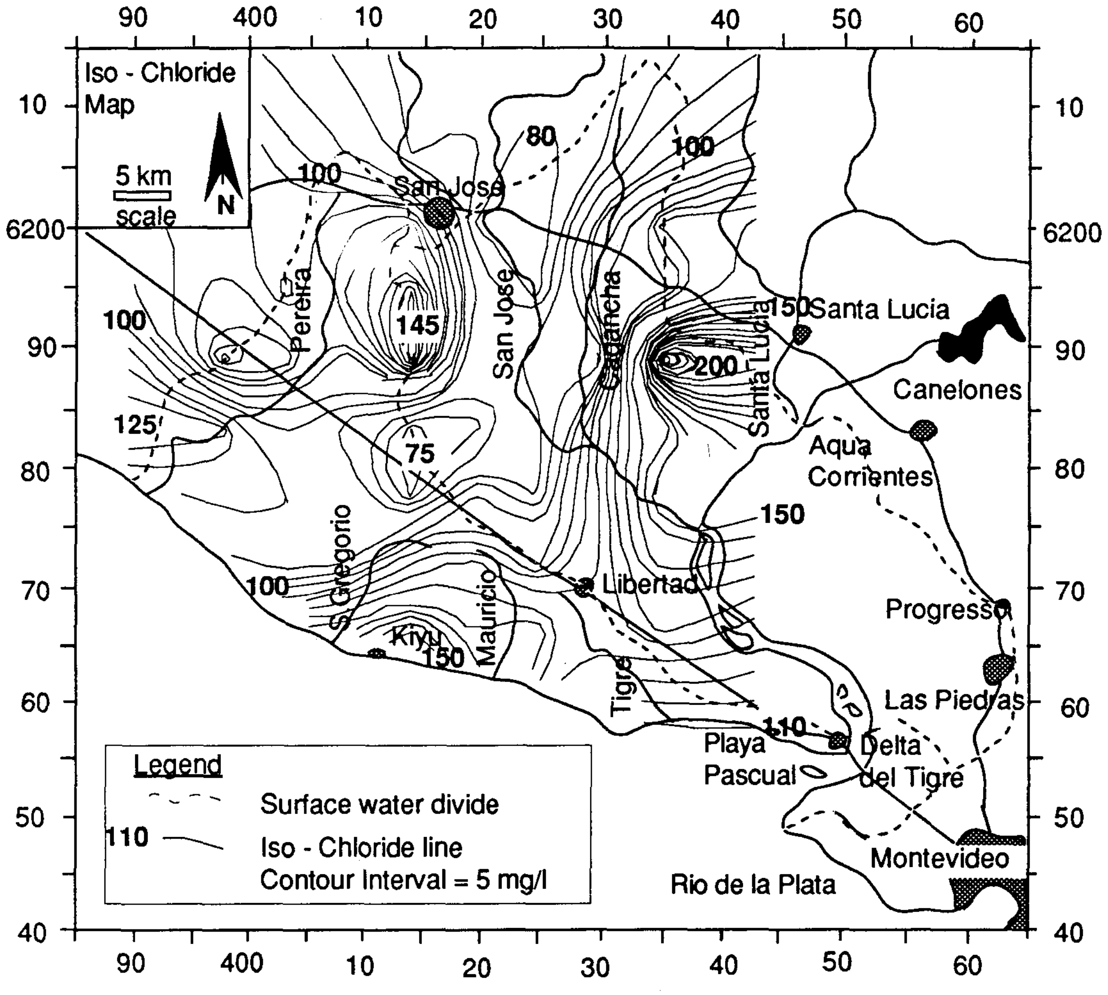

Fig. 9.14 Iso - Chloride map

Temporary Solutions to Anticipated Chloride Problems

An immediate solution to a salt creep could be flushing by fresh water. A mathematical explanation of the effect of flushing phenomenon is given as in the following:

Let the effective porosity of the aquifer in the Delta del Tigre area be equal to 20 % , where development of a salt creep is likely to occur due to industrial and domestic wastes. Considering an area of 1000 m^2 and 20 meters of thickness, the volume of the salty solution (brine) would be 4,000 m^3. Supposing that the brine contains 20,000 kg of dissolved salt, if we flush the aquifer with fresh water at the rate of 20m^3 per minute and the mixture runs out at the same rate, we can calculate how much of salt will be left out at the end of one hour. The assumption of complete mixing is unlikely in porous media, but the figures should give the relative order of magnitude of the effect of mixing.

Let x be the number of kilograms of salt in the aquifer at the end of t minutes. The concentration c would be (x/4,000) kg per m^3

In the time dt, 20 dt m^3 of fresh water comes in and 20 dt m^3 of brine containing 20c dt kg of salt goes out, so that, the amount of salt in the aquifer would be:-

$$dx = -20cdt = -(20x/4{,}000)dt,$$

After dividing by x and integreting, the amount of salt at the end of 1 hour would be:

$$\int_{20{,}000}^{x} dx/x = -(20/4{,}000)\int_{0}^{60} dt$$

$$\text{Therefore, } \ln x/20{,}000 = -(1/200)\int_{0}^{60} dt = -60/200 = -0.3$$

$$\text{Hence, } x = 20{,}000\,(e^{-3}) = 14816.4 \text{ kg}$$

The amount of salt left in the aquifer at the end of one hour would be 14816.4 kg and 14.9 kg at the end of one day, and almost nothing (0.01 kg) at the end of the second day.

The theoretical approach considered helps to realize the importance of flushing. However, the amount of time needed to completely flush out the salt from the aquifer would be much greater than in the above case, since complete mixing does not occur in aquifers.

Sulfate

Sulfur occurs in oxidation states ranging from S^{2-} to S^{6+}. Sulfates are often present in evaporites: Anhydrite ($Ca\ SO_4$), Baryte ($BaSO_4$) and gypsum ($CaSO_42H_2O$). In reducing (low oxygen) environment it occurs in sulfide veins, such as chalcosite (Cu_2S) and pyrite (FeS_2). The chemical behavior of sulfur is therefore related to the redox properties of the aqueous systems (Hem, 1983). S^{2-} ions forming sulfides with metals occur in sedimentary rocks in a reduced state. When these sulfide minerals are weathered, the sulfur is oxidized to yield sulfates; SO_4^{2-} anion is formed in most highly oxidized form. Sulfite is not normally present in natural waters, since it readily oxidizes to sulfates.

From the Eh - pH diagram (see Fig.9.1), it can be observed that most of the waters favor state of oxidation rather than state of reduction. Hence, the Eh - pH conditions of the waters favor the formation of SO_4^{2-} instead of S^{2-} (the fields of dominance of sulfur ions in different states is given in many text books dealing with hydrochemistry).

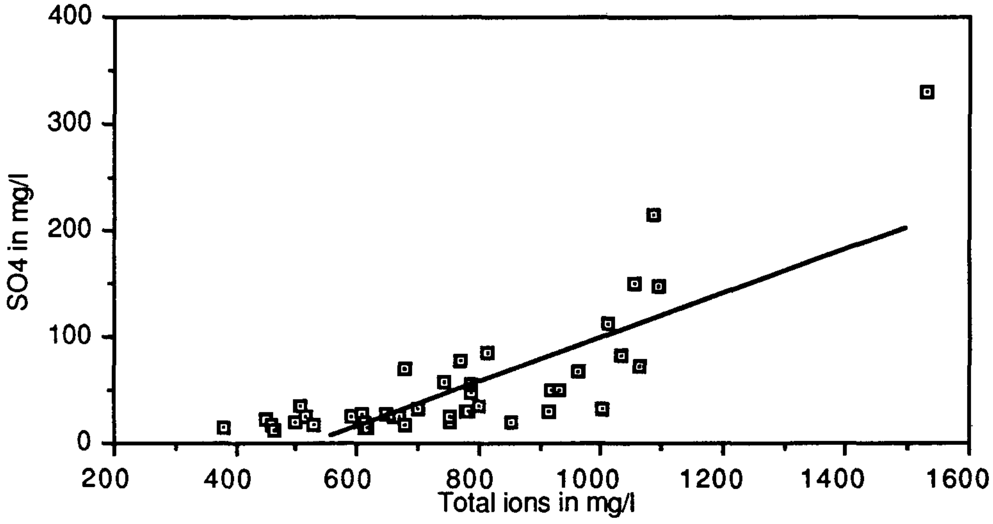

Fig.9.15. Relationship of total dissolved solids with sulfate in mg/l.

Although evaporitic sediments were not observed at the present, they might probably have existed in ancient closed valleys and depressions, where evaporation was favored. The present sulfate content of the waters may be associated with some relics of these evaporites, being incorporated into the sediment. Direct relationship has been observed between the total dissolved solids and the amount of sulfate ions in mg/l (see Fig.9.15). A correlation coefficient of 0.8 has been obtained.

Nitrate

The nitrate content of some waters (see table 4 & 5 in the appendix and location of polluted wells in Map 8) have been found to be beyond the acceptable limit for drinking purposes. Ten samples, collected in January - February 1987, have shown nitrate concentrations between 100 and 200 mg/l. The mean nitrate concentration of the waters is more than 50 mg/l (the internationally accepted upper limit). The map in Fig. 9.17 shows the relative position of the areas where nitrate levels are elevated. It should be noted that all the aquifer indicated by the iso-nitrate lines are not contaminated. A detailed map of such kind could possibly indicate the migration of plumes.

The transport of solutes through the unsaturated zone is generally considered to be slow. However, the unsaturated zone is relatively small, or is absent in some places, hence groundwater could be easily affected by addition of nitrate species. The possible sources of nitrate in the groundwaters of the area are hereby considered.

Nitrate is the most common representative of the nitrogen species in groundwater. Small concentrations of nitrogen compounds are produced in the atmosphere by the oxidation of nitrogen, by electrical discharge and combustion of fuel (Hem, 1970). The four primary forms of nitrogen are nitrogenous organic matter such as protein, ammonia nitrogen, nitrites and nitrates. Some other forms such as cyanide (CN) may occur in water affected by waste disposal (Hem 1970).

The cycle of nitrogen containing organic compounds is controlled by bacterial oxidation and reduction (Garrels et al.1975). Man's interference would further complicate the situation. The cycling of N between organisms and inorganic species is schematically represented as in figure 9.16.

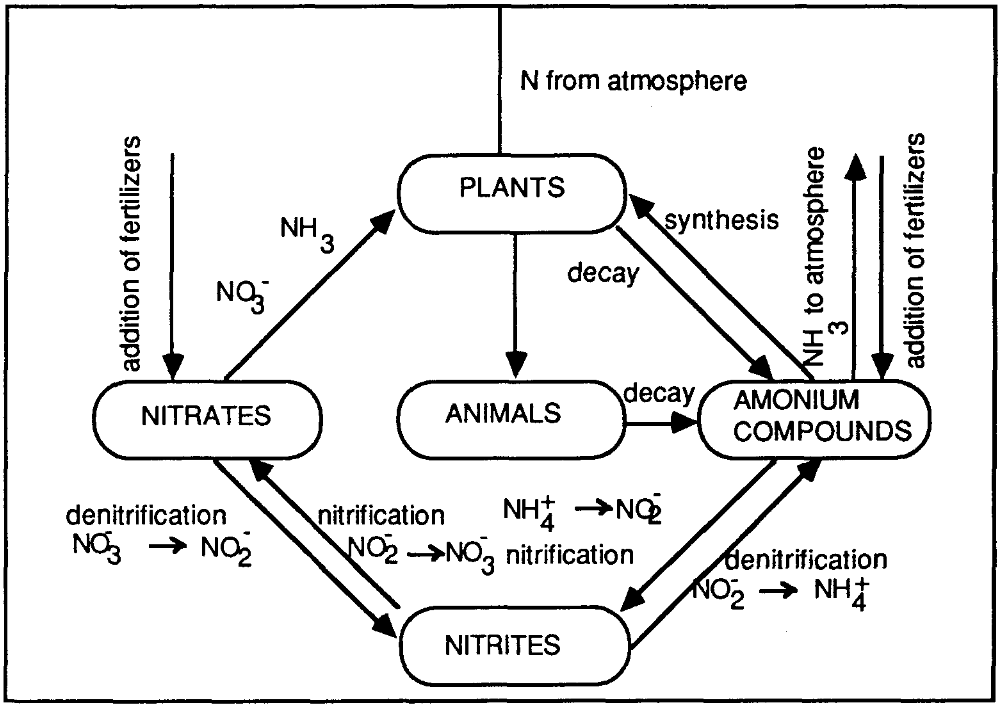

Fig.9.16 Schematic N cycle, after Garrels, Mackenzie and Hunt (1975).

Biological decomposition of organic matter (ammonification) yields ammonium. Nitrates (NO_3^-) can be produced as end products from nitrification of ammonium. Denitrification is another process whereby NO_3^- is reduced to NO_2 or N_2, under high pH and low Eh conditions. Ammonium is transformed into ammonia gas under basic conditions.

The basic chemical reactions involved in bacterially controlled reactions (Garrels et al.,1975) are given below:-

Nitrogen fixing bacteria (Azobacter)

$2N_2 + 6H_2O = 4NH_3$ (organism) $+ 3O_2$

decay

$4NH_3$ (organisms) $= 4NH_3$ gas + other decay products

hydrolysis

$4NH_3$ gas $+ 4H_2O = 4NH_4^+ + 4OH^-$

bacterial nitrification (Nitrosomonas)

$4NH_4^+ + 6O_2 = 4NO_2^- + 8H^+ + 4H_2O$

bacterial nitrification (Nitrobacter)

$4NO_2^- + 2O_2 = 4NO_3^-$

nitrification (Pseudomonas)

$4NO_3^- + 2H_2O = 2N_2 + 5O_2 + 4OH^-$

assimilation

$4NO_3^- + 8H_2O = 4NH_3$ (organisms) $+ 8O_2 + 4OH^-$.

In order to asses the amount of nitrate attributed by fertilizers and animal waste matter, the nitrate content of the fertilizers frequently employed in the area were analyzed for the major ions. The amount of ammonium content of the waters was measured in the field. Among the other ions detected from the fertilizers, nitrate concentrations were found to be the highest (see section 9.7).

The occurrence of nitrate in groundwater of the area is mostly attributed to one or both of the following:- a) Drainage from organic wastes and b) Leaching of fertilizers.

High levels of nitrate can cause infant methemoglobinemia (blue baby disease). In young babies, less than three months old, the consumption of nitrates may deprive them oxygen, which may result in death.

In order to trace the exact source of nitrates in the area, simultaneous field measurements of ammonia and nitrates were conducted in September 1989 from the water samples in wells which showed high nitrate values. TDS and Conductivity measurements were also taken at the same time.

Usually contamination from septic tank effluents are detected by the presence of high levels of NH_4. In our case, all the ammonium measurements have indicated to be minimal. However, this does not exclude the possibility of contamination from septic tanks, because all the NH_4 present in the groundwater could have been oxidized under high Eh conditions. Keeping this in mind, the wells which are located near septic tanks or animal barns were visually inspected. It has been found that fertilizers are used in the vicinity of almost all the wells. If all the wells are located within the agricultural field areas and are at the same time exposed to contamination from septic tanks and or animal wastes, then there is no doubt that nitrate contamination in the area would be caused by both drainage from organic wastes and from leached fertilizers. The relatively high nitrate levels then reflect the intensity of the use of fertilizers and the degree of contamination by organic wastes, which is in accordance with what has been observed in the field. However, the relative importance of each could further be investigated by nitrogen - 15 isotope method. The degree of organic waste contamination could better be assessed with additional data from bacteriological tests.

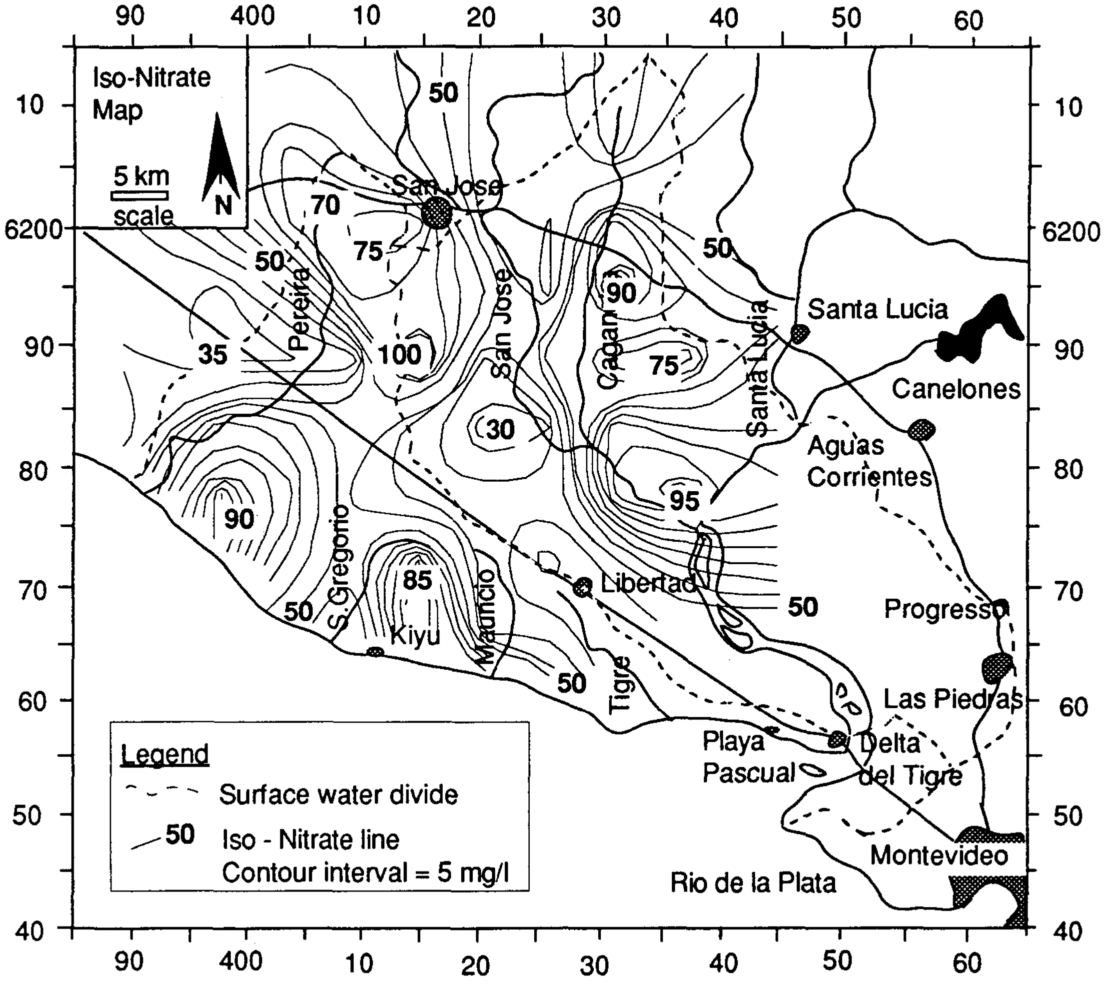

Fig. 9.17 Iso-nitrate map

9.6 Hydrochemical Data Analysis

The data from chemical analysis of the water samples collected in January - February 1987 are hereby interpreted and analyzed. In this section the parameters will be dealt with as groups, while attempting to extract the maximum possible information. The classical hydrochemical data processing methods are employed with careful selection of only the most appropriate. Statistical methods, like cumulative frequency and factor analysis are also included.

9.6.1 Hydrochemical Facies

The general relationships between the chemical characteristics of the groundwater, the lithology and the regional flow pattern could be deduced from the hydrochemical facies. Mapping of these facies could be a good base to study the chemical behavior of waters.

Trilinear diagrams (Piper's diagram) of the water chemistry are constructed (see Fig. 9.18). The concentrations of the cations and anions in meq/l % are separately plotted in two equilateral triangles. In trilinear diagrams, the ionic solutions are treated as though they contained only three cation groups and three anion groups; K is added to Na, and NO_3 is added to Cl. The meq/l% of the ions are extended from the two triangles into the diamond shaped part, thus representing the combined chemical characters of the waters (hydrochemical facies or water types). It is worth noting that waters that fall on the same straight line represent mixing.

Plotting of meq/l % data on trilinear diagrams is one way of grouping data. Such groupings can also be obtained by extracting ratios as shown in Table 9.1.

Table 9.1. Percentage milli equivalent ratios and the corresponding water types.

Na+K/Ca+Mg	$HCO_3/Cl+NO_3+SO_4$	Water Type
<1	>1	$Ca(HCO_3)_2$
<1	<1	$CaSO_4$
>1	<1	NaCl
>1	>1	$NaHCO_3$

If one wishes to know water types, the extraction of the above ratios could be sufficient. The Piper's diagram helps to view the exact position of the meq/l % of each sample with respect to the 100% of the ions, so that their groupings constitute different water types according to their relative positions in the diagram.

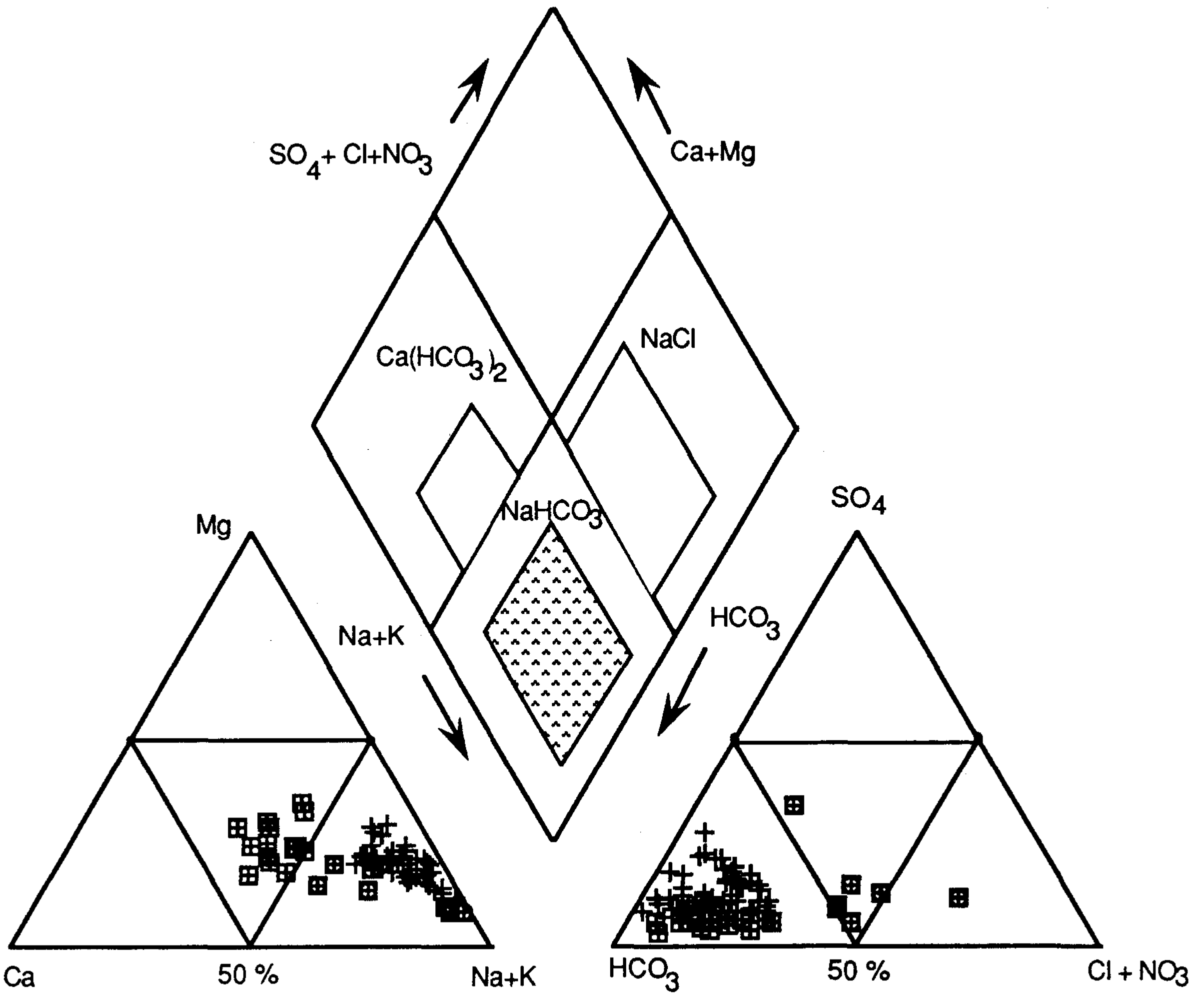

Fig.9.18 Piper's diagram showing the $Ca(HCO_3)_2$, $NaHCO_3$ and NaCl water types

The chemical analysis data as plotted on the Piper's diagram, indicate that most of the waters are of the sodium bicarbonate type. Few waters belong to the calcium bicarbonate type and, even fewer, to the sodium chloride type. No sample has been observed to fall into the calcium sulfate type. The regional distribution of the water types are represented on a map (see Fig.9.22).

Some of the shortcomings (Shœller, 1962) of trilinear diagrams are the following:

1) All the cations must be reduced to only three groups, likewise all the anions must be reduced to only three groups; in consequence to this, the individual effect of the lumped ions cannot be assessed.

2) The percentage values may at times correspond to proportional amounts of cations and anions of more than one sample which plot as a single point.

These shortcomings can be overcomed by adopting the following method:

Cumulative frequency of the meq/l % of the water types

This method is similar to the ion-concentration percentage - frequency relations given by Sen and Al-Dakheel (1983). However, the methodology used here is different from theirs. In this method, first the water types are extracted by using ratios as criteria (see Table 9.1). Once the water types are grouped in this way, the cumulative frequency (instead of just the frequency) of the percent milliequivalents of the individual ions are plotted for each water type. Hence for the three water types already established, the meq % cumulative frequency of the seven ions (including NO_3 as a separate ion) are plotted. Accordingly, twenty one cumulative frequency histograms have been obtained. In order to visualize the importance of each ion in the different water types, three cumulative frequency histograms representing a single ion of the three water types are superimposed to one another (see figures 9.19 and 9.20).

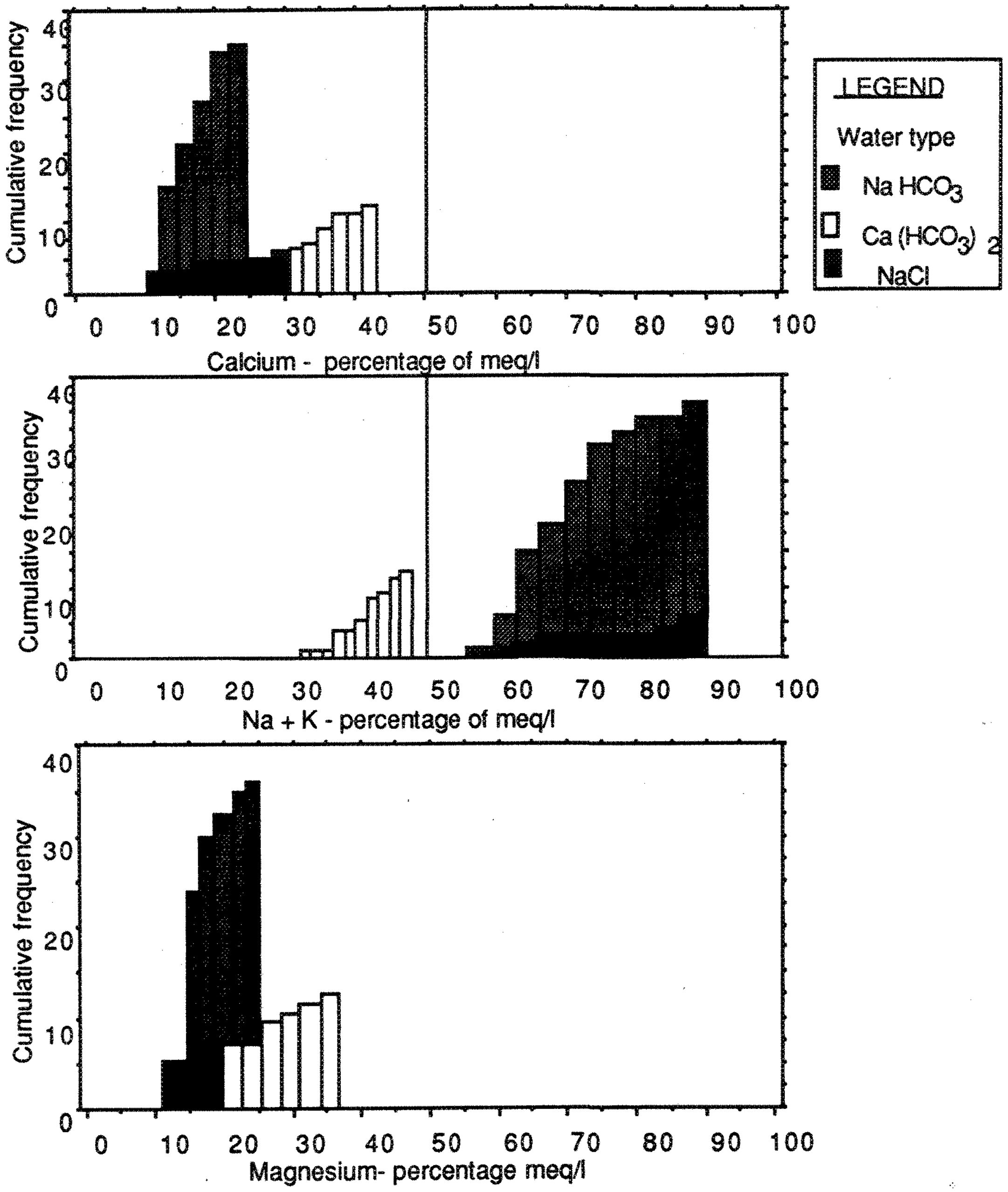

Fig.9.19 Cumulative frequency histograms of the cation percentage values from the water samples collected in January - February, 1987.

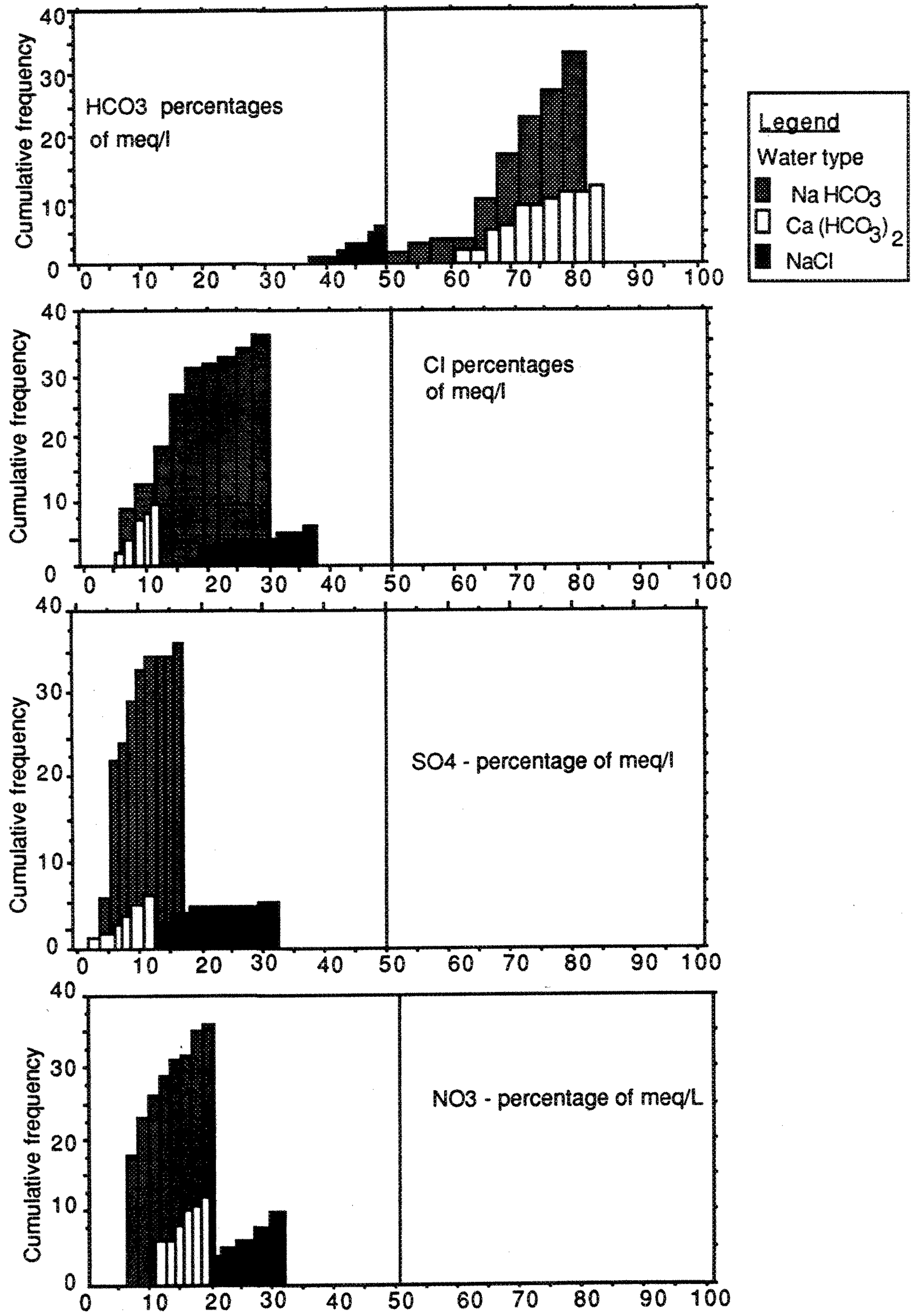

Fig.9.20 Cumulative histograms of the anions

Figures 9.19 and 9.20 include almost all informations that can be obtained from the Piper's diagram. One of the merits of this method is that any number of individual ions can be handled. It is relatively easier to read the percentage values of the individual ions from the figures, compared to the Piper's diagram. The percentage of ions that are particularly dominant in certain type of waters can easily be observed. The figures indicate the cumulative frequency of water samples falling within a certain percentage value from which the number of samples that belong to the water types can be known. One of the interesting features of the figures is that the importance of each ion can easily be compared in each type of water. In conclusion, the use of the above cumulative frequency method is strongly recommended especially when more than six ions are considered.

The following important informations are extracted from the figures:

- The relative magnitude of the type of waters can easily be compared (thirty six samples are of Na HCO_3 water type, twelve samples are of Ca $(HCO_3)_2$ water type, and six samples are of NaCl water type).

- Na+K ions are dominant (more than 50%) over the other ions in the bicarbonate and sodium chloride waters.

- HCO_3 ions are dominant (more than 50%) in the bicarbonate and Ca $(HCO_3)_2$ waters.

- All the other ions occur in smaller proportions (less than 50%) in all types of waters.

- Na + K ions are relatively weak in the Ca $(HCO_3)_2$ waters, whereas magnesium ions are relatively strong in the Ca $(HCO_3)_2$ waters.

- SO_4 ions and NO_3 ions are relatively strong in the NaCl waters. The fact that NO_3 ions are associated with Nacl waters suggests the influence of pollution.

All the above informations are important in the interpretation and analysis of hydrochemical data. Before relating the above hydrochemical informations to hydrogeological data, however, we shall consider similarities of the waters, which are also important in the understanding of hydrological processes. The water types and the similarity groups are both plotted on a map (see map in Fig.22).

9.6.2 Similarities of the waters

In order to group waters that are similar to one another, the data are plotted on the semi - logarithmic diagrams of Schœller (1935,1938). The concentration of the ions (in meq/l) are plotted on a vertical axes in logarithmic scales. The waters which are most similar are grouped together. Usually, plotting of meq/l values on a semi-logarithmic scale is a simple thing, but grouping together of the most similar waters could be long and cumbersome job, especially if the number of graphs are too many. In order to avoid such inconvenience, the following method has been established: First, calculate the ratios of the ions from the data and extract the similarity groups according to the criteria indicated (see Table 9.2); then plot on the same graph the corresponding groupings obtained.

Table 9.2. Table of ionic ratios that are used to facilitate extraction of similarity groups.

Group	Ca/Mg	Na+K/HCO3	SO4/Cl	Cl/NO3
1	<1	<1	<1	<1
2	>1	>1	>1	>1
3	<1	<1	<1	>1
4	>1	<1	<1	>1
5	<1	>1	<1	>1
6	>1	>1	<1	>1
7	>1	<1	>1	<1
8	<1	>1	>1	>1
9	>1	>1	>1	<1

As in the above table, nine groups of similar waters have been arranged (see Fig.21a to 21i). It should be noted that the number of combinations (criteria) to be chosen depend on the possible combinations that may exist.

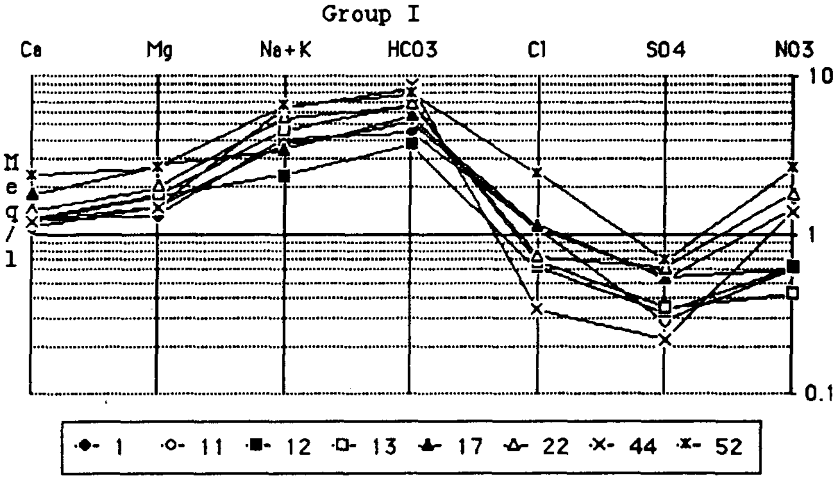

Fig.9.21a Shœller's diagram from analysis of water samples collected in Jan. - Feb. '87. The numbers at the bottom of the figure are sample numbers listed in Table 4 in the appendix.

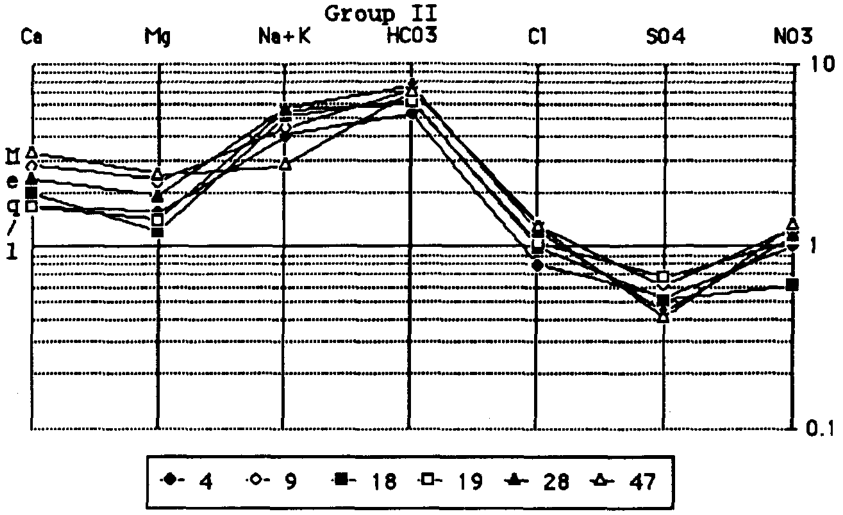

Fig.9.21b Shœller's diagram from analysis of water samples collected in Jan. - Feb. '87.

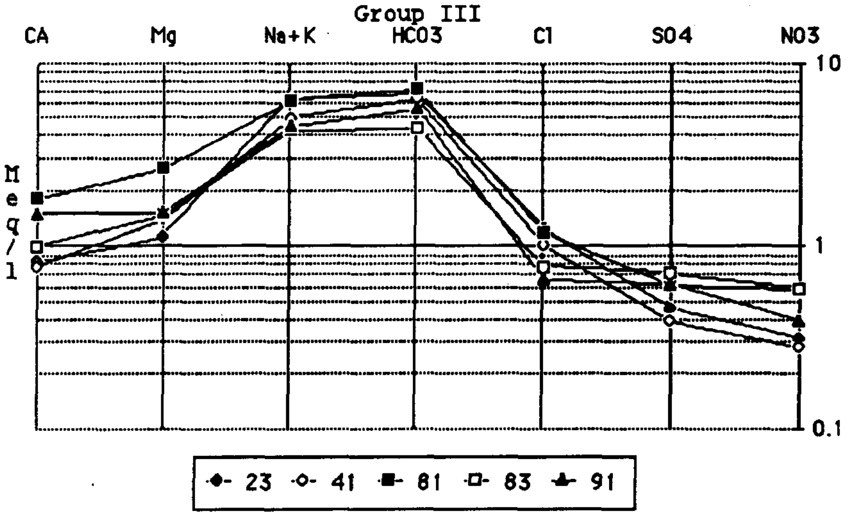

Fig.9.21c Shœller's diagram from analysis of water samples collected in Jan. - Feb. '87.

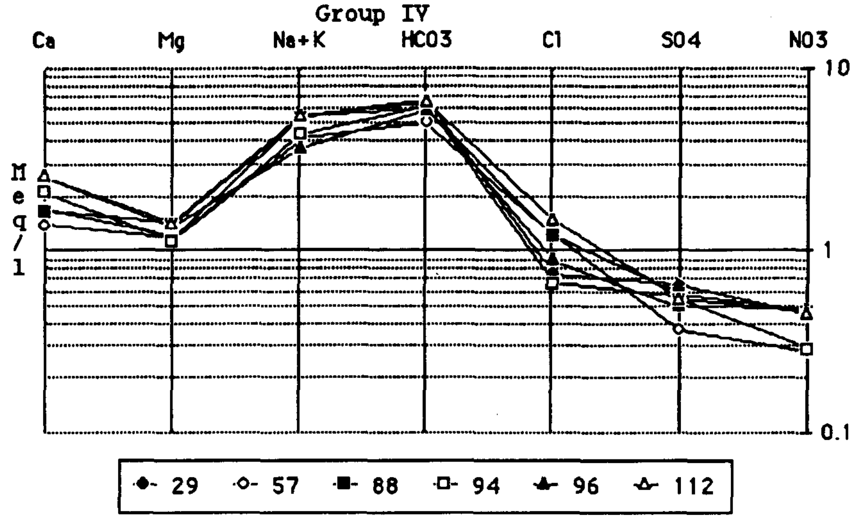

Fig.9.21d Shœller's diagram from analysis of water samples collected in Jan.- Feb. '87.

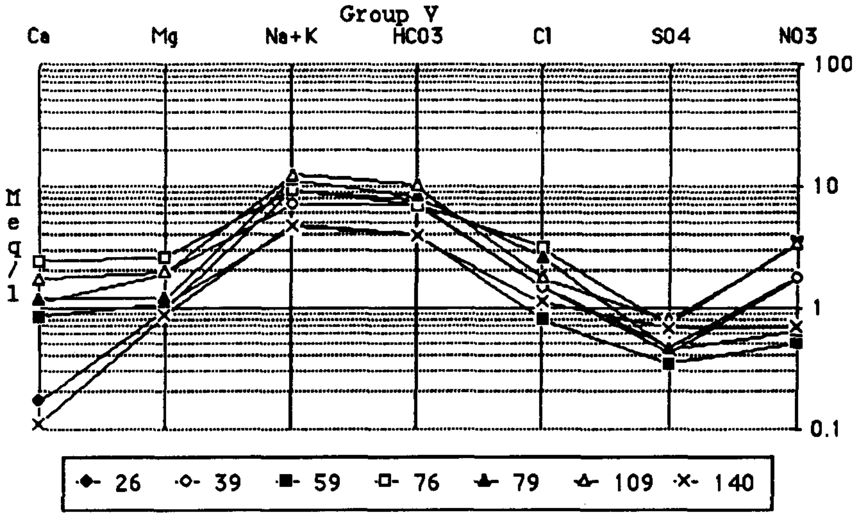

Fig.9.21e Shœller's diagram from analysis of water samples collected in Jan.- Feb. '87.

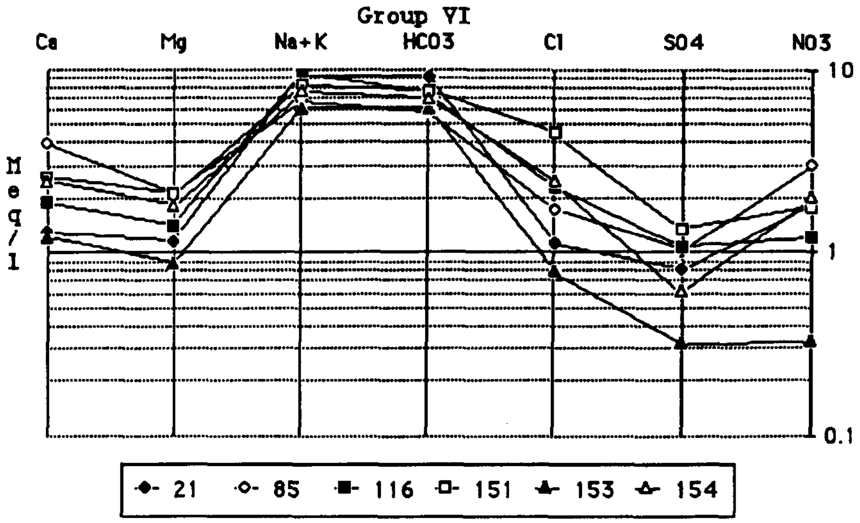

Fig.9.21f Shœller's diagram from analysis of water samples collected in Jan. - Feb. '87.

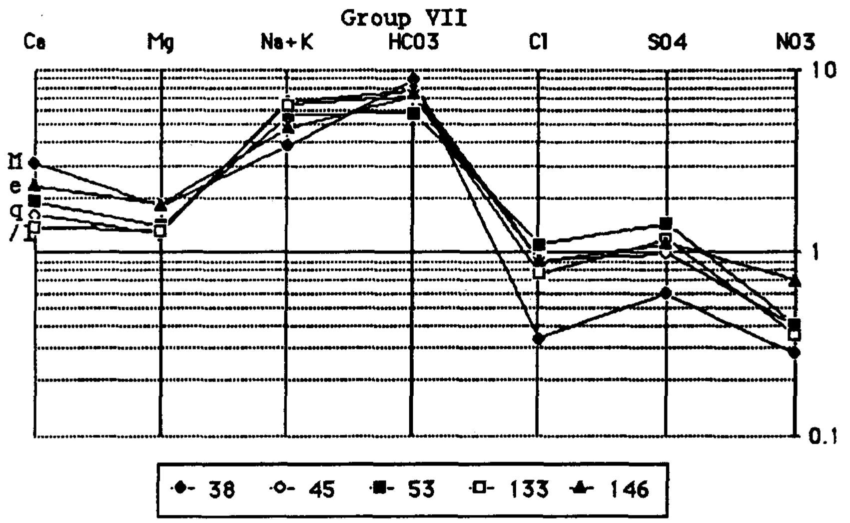

Fig.9.21g Shœller's diagram from analysis of water samples collected in Jan. - Feb. '87.

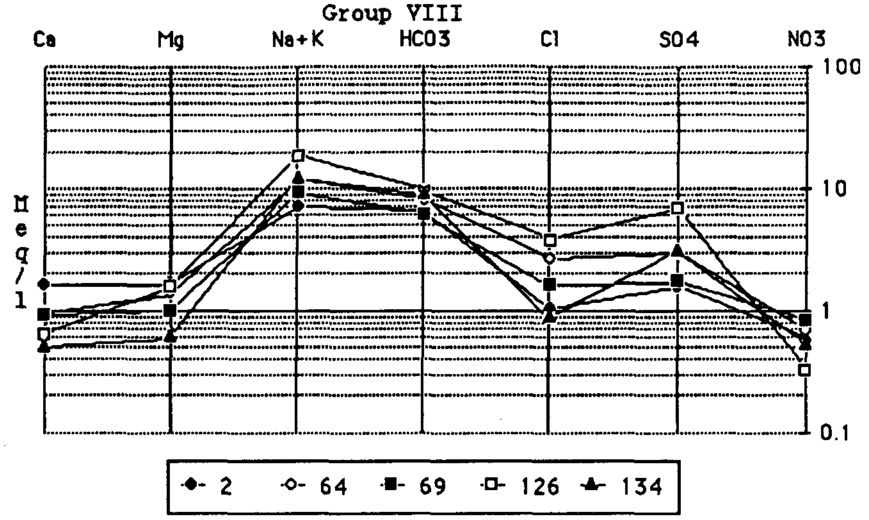

Fig.9.21h Shœller's diagram from analysis of water samples collected in Jan. - Feb. '87.

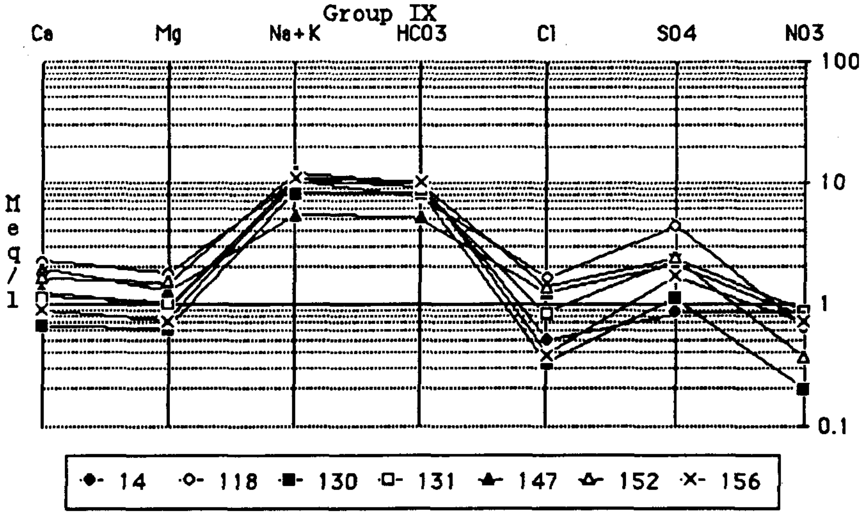

Fig.9.21i Shœller's diagram from analysis of water samples collected in Jan. - Febr. '87.

The list of ratios on Table 9.2 has enabled us to group the waters according to their similarities, from which a map of similar water groups is constructed (see Fig.9.22). The map is constructed according to the following procedure:

The nine groups are again summarized into only three. Hence, group I, VIII and IX particularly having high sodium plus potassium and high chloride contents are regrouped in GROUP 1. Groups I, III and IV having particularly less sodium and potassium are regrouped as GOUP 3. The rest (groups V, VI, VII) are intermediate between the two and are regrouped in GROUP 2 (see map in Fig.9.22).

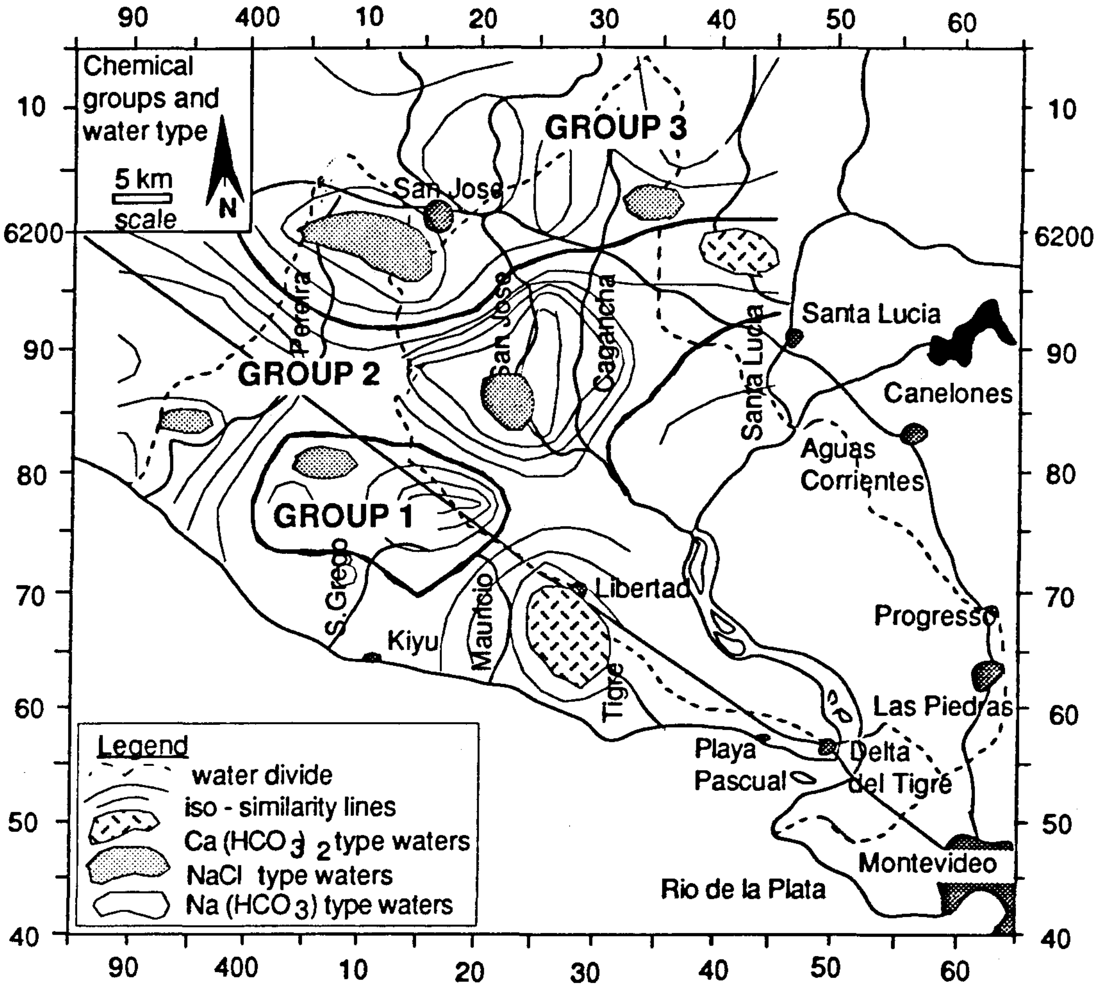

Fig.9.22 Map showing the similarity groups of waters and the water types.

An interesting aspect of the similarity groupings is that the major group divisions are more or less perpendicular to the regional groundwater flow lines. The same type of situation can be observed from the map produced from Q- mode factor analysis (see Fig.9.27).

The application of Shœller's diagram to grouping similar waters is a way of classification system from which the following important informations have been deduced :-

1) The most similar waters have their graphs parallel to each other (equal ratio).

2) Graphs which are parallel and at the same time closer to one another represent waters having the same chemical and recharge conditions.

3) Graphs which are parallel and distant from one another represent waters with the same chemical composition but different recharge conditions.

Dilution of groundwater is possible due to additional recharge by precipitation or seepage from streams. In the case where seepage from streams dilute groundwater, the groundwater closer to the river should be more diluted with respect to the one further away. Based on the above argument, it was attempted from the chemical analysis data, to detect the following conditions:

1) If at a certain point along the course of a stream, both effluent and influent situations occur at different seasons with low and high levels of streams respectively, then the stream water level is connected to the regional groundwater level.

2) If only either one of the two conditions (effluent or influent) are encountered at a certain point along the course of a stream, then the stream water is not connected to the regional groundwater table.

The graphs representing the individual samples from the group were compared in relation to sample locations with respect to the streams. However, no logical conclusions could be reached in regards to the above points, since the available data did not represent seasonal chemical variations which can be compared to seasonal climatic and hydrologic data.

9.6.3 Factor Analysis, the "Alternate" Method

So far, we have classified the waters according to their type and similarity. In factor analysis, other parameters like pH, alkalinity, etc. can also be considered. Factor analysis is a technique of data analysis, whereby a large array of data can be dealt with, creating new variables that are few in number, representing the original data and, at the same time, reflecting its characteristics. Factor analysis can be used to study the relationships between variables (R-mode factor analysis) and the relationship between the objects (Q-mode factor analysis).

In both cases, the purpose of factor analysis is to interprete the structure within the variance-covariance matrix of the multivariate data collection (Davis, 1973). This is done by the extraction of the eigen values and eigen vectors from the variance-covariance matrix. Since the data we are dealing with are not all directly comparable, it would be necessary to convert all of them to a standard form. One way of doing this would be subtracting from each observation the mean of the data set and dividing by the standard deviation. However, the variance-covariance matrix of a standardized data is the same as the correlation matrix. Hence, the correlation matrix is used as a base from which the eigen vectors and eigen values are extracted (see Table 9.3).

Table 9.3. Correlation coeficients of the fourteen variables from the chemical analyses data of January -February, 1987.

	Eh	pH	T	TDS	SAR	Alk	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3
Eh	1													
pH	.045	1												
T	-.333	.06	1											
TDS	.043	.297	-.029	1										
SAR	.145	.407	-.135	.677	1									
Alk	.015	.346	.031	.845	.536	1								
Ca	-.202	-.19	.094	.126	-.494	.088	1							
Mg	.049	-.259	.014	.295	-.355	.155	.608	1						
Na	.103	.391	-.096	.88	.911	.672	-.209	-.08	1					
K	.011	-.123	-.072	-.028	-.151	-.016	.071	.176	-.129	1				
HCO3	.103	.391	-.097	.879	.912	.671	-.209	-.081	1	-.13	1			
Cl	.186	.037	-.135	.642	.426	.297	.061	.336	.602	-.048	.602	1		
SO4	-.074	.294	.035	.667	.649	.424	-.088	-.012	.727	-.195	.727	.366	1	
NO3	-.029	-.115	.014	.399	-.064	.213	.37	.607	.13	.182	.129	.21	-.057	1

Representation of Vectors in N - Dimension

The data we are dealing with contains 89 by 14 = 1246 informations items. In factor analysis, we consider each sample from the data as defining a coordinate axis of geometric space. As an example, let us consider only three samples with only two variables (see Fig.9.23).

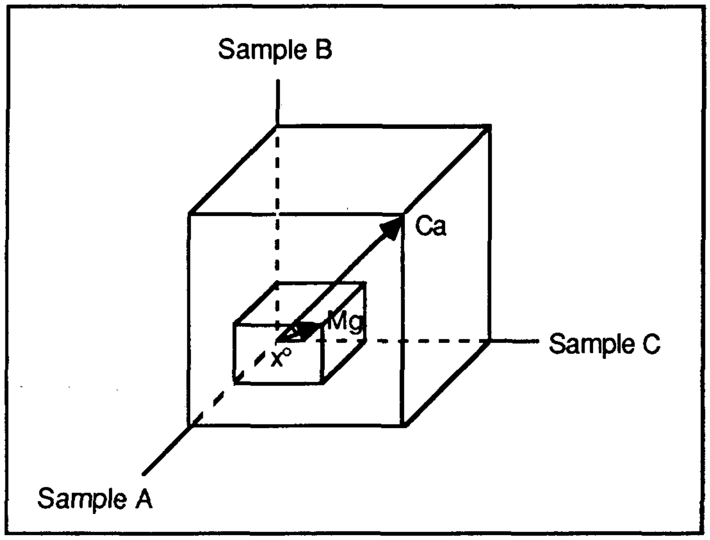

Fig.9.23 Diagram showing the relationship of two variables in space of three dimensions.

The dimension of the space can be analytically extended to N- dimensions, all at right angles to one another, providing representation of all samples. We may then imagine 14 variables plotted as vectors in an imaginary space of 89 samples (dimensions). Or, we may imagine 89 samples plotted as vectors in an imaginary space of 14 variables.

As in Fig.9.23, the angle between the vectors is the measure of the relationship between the characteristics of the samples. In the present case, we have considered the correlation matrix as a matrix of similarity coefficients. These coefficients represent comparison between the variables or between the samples. The values of the coefficients are all between -1 and 1 which may be considered as the expression of cosines of the angles between pairs of vectors of unit lengths. If the vectors are close to one another, then the variables they represent have closer relationships. When the angles between the vectors are perpendicular, then the variables they represent are not correlated. When the angles are greater than 90^0 then the relationship is negative; an inverse relationship is represented by an angle of 180^0. The interrelationship of the variables in the data can then be inspected by looking at their position represented by the vectors in space.

Following the principle of extraction of eigen values and eigen vectors from the data of the 14 by 14 matrix of correlation, 14 vectors can be extracted. However, the relationship among the vectors can be simplified by projecting lines from the vectors onto arbitrarily oriented new axes that are perpendicular to one another (see Fig. 9.24). These axes are called factor axes and the projections onto these factors are referred to as factor loadings. The factor axes are commonly fitted by the principal component method. In this method, the position of the first axis maintains the maximum sum of the squares of the loadings. The next factor axis, which is at right angles to the first, also follows the same principle. The position of the factor axes can be geometrically viewed as axes placed at the center of gravity of the vectors.

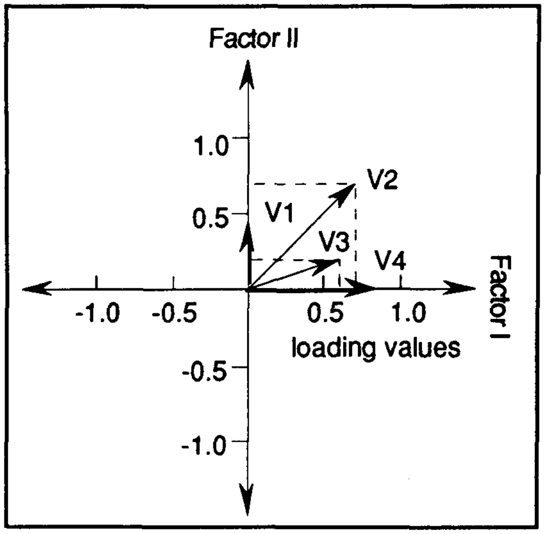

Fig.9.24. Representation of four vectors by only two factors

In figure 9.24, vector one and vector four are made to coincide with the two factor axes, and the other two vectors are represented by the loading values on the two factors. Likewise, it could be possible to represent a large number of vectors by few factor axes.

The sum of the squared factor loadings is called communality (h^2). The communality values indicate if the factor axes are well placed. If $h^2=1.0$, then the factor loadings completely represent the relationship in the matrix. It should be noted here, that if we increase the number of factor axes, then the degree of representations will increase (h^2 will increase).

R- Mode Factor Analysis

In using the above principles of factor analysis, a computer program has been executed for both R - mode and Q - mode factor analysis. The number of factor axes that best represent the data were carefully chosen after several trials (the minimum possible factor axes with the maximum possible communality, h^2, were chosen). For the R - mode factor analysis, it has been observed that all combinations of the four factor axes (the unrotated factor axes of one vs. two, one vs. three, one vs. four, two vs. three, etc.) gave very good results; that is, groupings can clearly be observed. The diagram in figure 9.25 shows one of these combinations. The relationships among the variables can clearly be observed from this diagram.

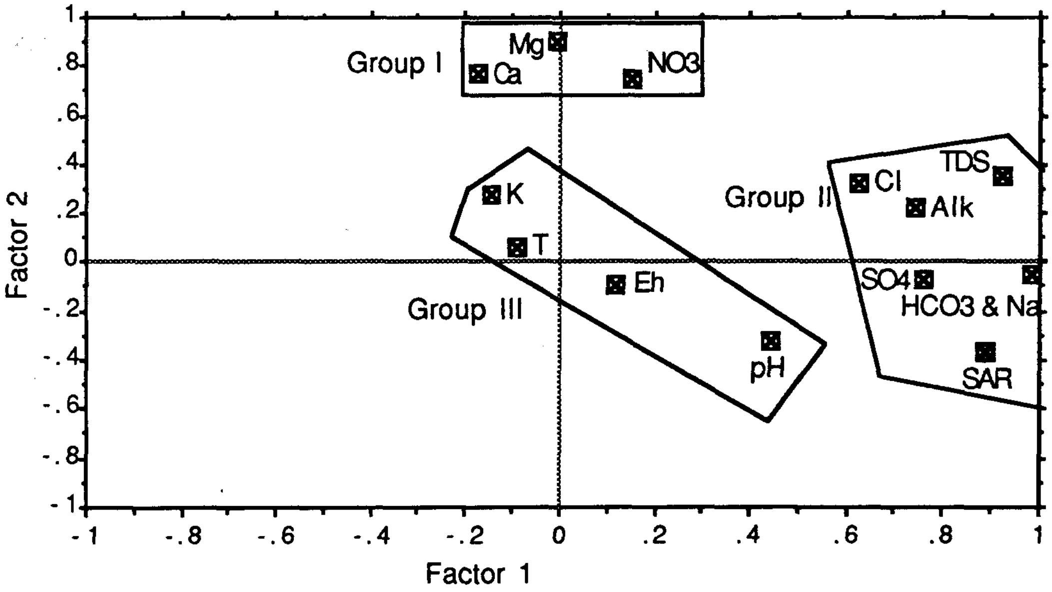

Fig.9.25 Unrotated orthogonal plot : Factor 1 vs. Factor 2

Interpretation of the R - mode factor analysis results

The fourteen variables can be visualized in the vector space of eighty nine samples (dimensions). The interrelations within the vectors (their closeness to one another) are represented by the correlation matrix. In accordance to the previous discussion, the fourteen vectors are represented by only four factor axes. A graphical representation of one of the combinations of the factor axes is given in Fig.9.25. From the table of the communality summary (computer output), we can deduce that the four factor axes would more or less represent the variables, that is the communality values are close to 1 (complete representation).

From figure 9.25, we observe three groups of clusters in relation to two factor axes (factor one and factor two). The other pairs of factor axes are purposely omitted, since we can see clearly three distinct cluster groupings from the two axes:-

- Ca, Mg and nitrate are close to one another in relation to other variables.

- Although temperature, K, Eh and pH are not close enough to one another; they could be considered as having separate grouping when compared to the other variables.

- Na, Cl, HCO_3, SO_4, TDS, alkalinity, and S.A.R are relatively close to one another, hence forming a distinct group.

The fact that some of the variables belong to the same group does not necessarily mean that they are closely related. However, those that are closely related to one another can surely be grouped together. For example, all the variables in group II are closely related; the plots of HCO_3 and Na do overlap. It can be seen from the correlation matrix on Table 9.3, that all the variables within this group have relatively high correlation coefficients among one another.

Let us keep in mind that the result of the execution of the factor analysis program, has nothing more to offer, but a synoptic view of the variables on a plane sheet of paper. To draw conclusions from such a view, without actually doing the proper data interpretations, may give erroneous or far fetched results. In short, factor analysis does not replace classical data interpretations, like Piper's diagram or Shœller's diagram, but it adds to the scope of understanding. However, it could be a "short cut" at times, provided that a prior understanding of the general hydrochemistry exists. It may be wise to compare, or tally the results obtained from factor analysis with the classical interpretation methods. Before doing so, however, we shall consider Q - mode factor analysis.

Q - Mode Factor Analysis

In the Q - mode factor analysis, the relationships between the individual samples are compared. Otherwise, the principle is exactly the same as R - mode factor analysis.

As opposed to a 14 by 14 correlation matrix, in the R - mode factor analysis, eighty nine by eighty nine correlation matrix was extracted from the data matrix while executing the Q - mode factor analysis program. From the correlation matrix, the eigen values and eigen vectors were extracted, then represented by only four factor axes, after several trials of comparing the number of factor axes with the maximum possible communality. No significant differences were observed between the rotated factors and the unrotated factors. However, some combinations of factors, like factor one and two of the unrotated factors did not allow to see distinct groupings. Factor II vs. factor IV was the only combinations that enabled the best groupings (see Fig.9.26).

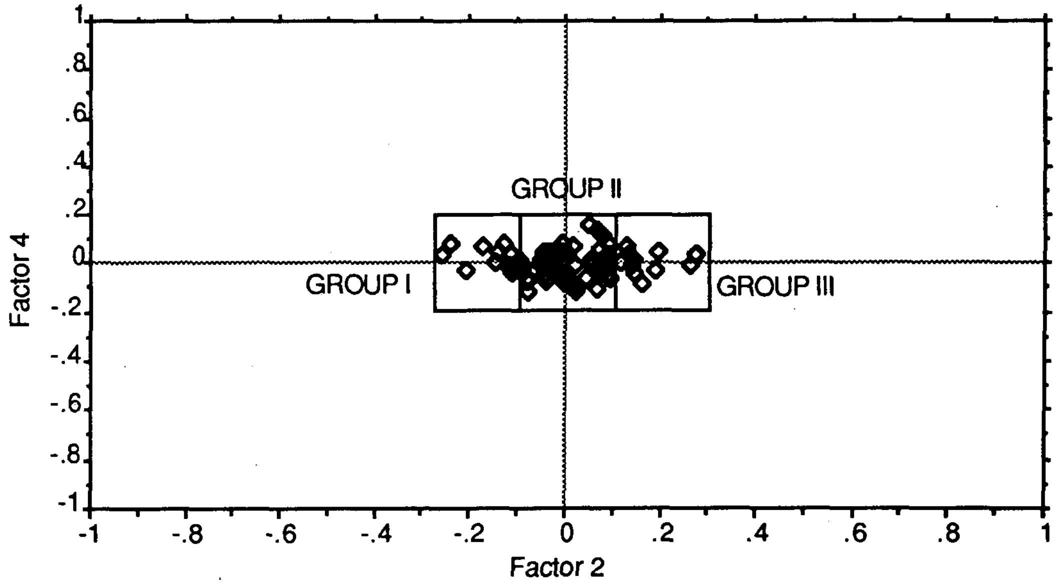

Fig.9.26. Q - Relationship between samples as depicted by Q - mode factor analysis

We observe from figure 9.26 that all the samples are closely related to one another. However, we may arbitrarily group them into three groups. These groupings of the samples are represented on a map (see Fig.9.27).

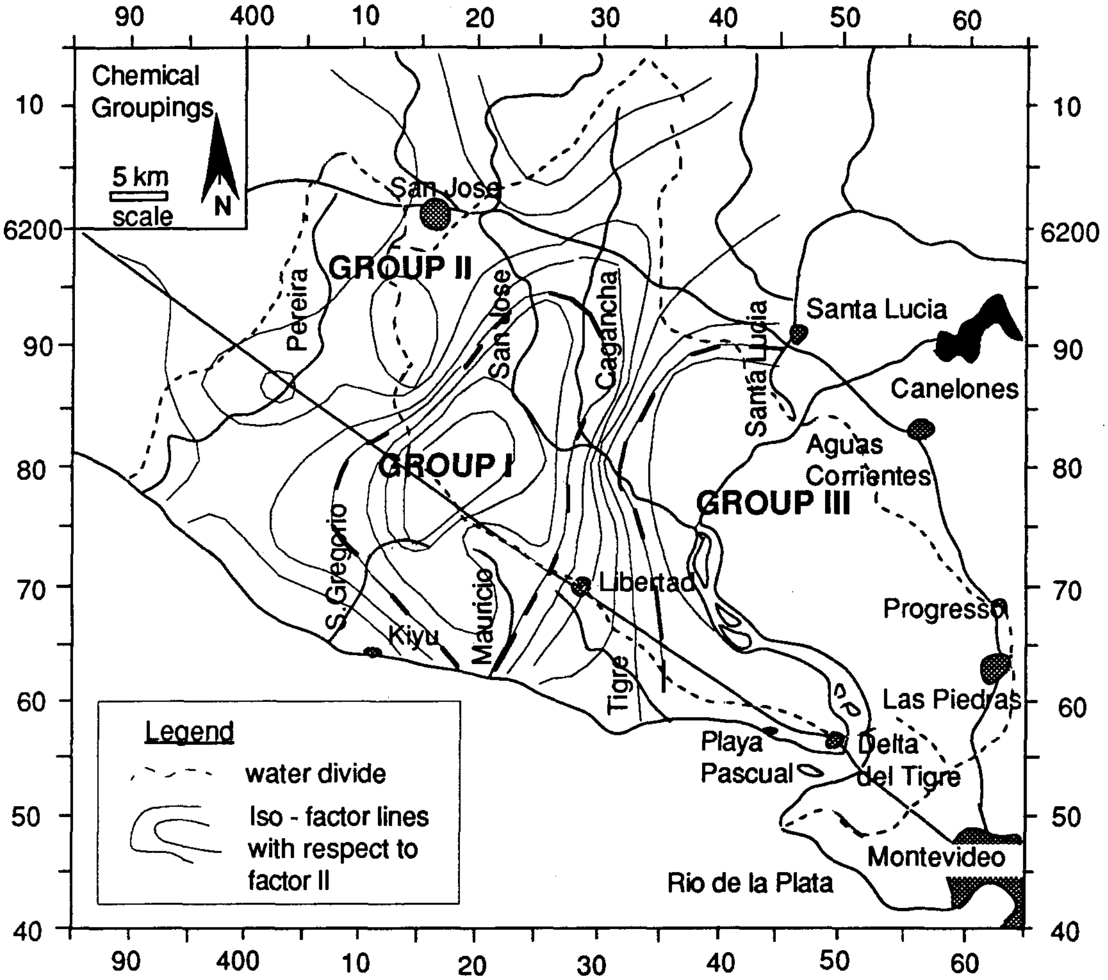

Fig.9.27. Representation of sample groupings on a map from Q - mode factor analysis.

Similar maps representing iso - factor lines with respect to the other factors were plotted. But all the maps showed similar features. Plotting of iso - factor lines with respect to factor axes gives a more or less similar result. It is up to the researcher to choose the ones that best represent the situation.

General hydrogeological informations deduced from the chemical data

So far, different methods of chemical data interpretations have been employed. It can be said, in the final analysis, that the variations within the chemical data are not so significant. That is, in fact, when different interpretation methods will be most needed. No interpretation could ever be complete without being tested by different methods, since no single method is perfect in itself. It would therefore be wise to compare different methods. However, not all methods can be employed under all circumstances. It is therefore up to the hydrogeologist to judge and choose the best methods to employ depending on the type of data, the type of work required and the amount of time and money at his disposal. Once this is accomplished, the next and most important step would be to draw valuable informations from these methods and integrate these informations with other informations from the interrelated disciplines like hydrologic parameters and mineralogy of the environment.

Chemical analyses data could be interpreted and analyzed in various ways and yet, a great deal of valuable information could still remain hidden, due to improper ways and inefficient method of data interpretation. After having considered different methods of data interpretation, it would be appropriate to tackle the most difficult task of extracting relevant hydrogeological informations.

The concept of hydrochemical facies includes zonation controlled by depth of circulation, sedimentological zones and climatic factors (Shœller,1962). Chebotarev (1955) has dealt with vertical zonation in large bassins as influenced by the dynamic aspects of the natural water including velocity movement, recharge- discharge relations, intensity of movement with depth and residence time. For example, salinity increases as the movement deteriorates with depth, with distance from recharge areas, with nearness to the sea and duration of contact.

The well known sequence of Chebotarev states that all waters tend towards the composition of the sea water.ie:

$$HCO^{-}_{3} \rightarrow HCO^{-}_{3} + SO_{4}^{2-} \rightarrow SO_{4}^{2-} + HCO^{-}_{3} \rightarrow Cl+SO_{4}^{2-} \rightarrow SO^{-}_{4}+Cl^{-} \rightarrow Cl^{-}$$

This sequence is applicable to large basins. Although this study has presently concentrated in ther lower part of the Santa Lucia Basin, Chebotarev's sequence could be applied if we consider the whole basin.

Chebotarev's sequence can be viewed as three vertical zones of facies development:

The uppermost zone :- Water in this zone is of the bicarbonate type and low mineralization. It is characterized by high intensity of circulation through well leached rocks.

The intermediate zone:- Water in this zone is of the sulfate type with less intensive circulation and high mineralization.

The lowermost zone:- Water in this zone is of the chloride type in a near stagnant condition, unleached rocks and high mineralization.

The above sequence can be explained by the fact that least soluble salts precipitate first and the most soluble salts precipitate last, at any given time and at any distance from the intake area (Chebotarev,1955).

Following the method of data discrimination, the chemical data of the distinct water types were compared with depth informations. But since most of the wells are shallow, no significant variations in depth actually exists. The relationships observed between depths and chemical characteristics are weak. However, from the different hydrochemical maps so far constructed, and superposing these maps on depth to water map in figure 5.4, the following informations were deduced:-

1) The bicarbonate waters which occur over a larger part of the area correspond to shallow groundwater circulations.

2) Intermediate groundwater circulations are nonexistent, since no sulfate type of waters exit.

3) The presence of sodium chloride type of water is not associated with deep groundwater circulation, but may rather be attributed to other factors like deposition of small salt crystals by the wind, or other source of natural and/or artificial contamination.

The three groups of water as depicted in the map of the Q - mode factor analysis (see Fig.9.24) give a synoptic view of the effect of fourteen parameters on the samples. These groups divide the area into three distinct zones which seem to be more or less perpendicular to the flow lines and at the same time coinciding, more or less, to the distinct geomorphological divisions of the area:- the eastern and northern highs, the rivers and valley bottoms and the central interfluvial zones. Again these divisions coincide, more or less, with the geology of the area. Group I coincides with the Libertad and/or Raigon Formation, Group II coincides with the recent alluvials, whereas Group III coincides with the basement and the Fray Bentos Formation. It is worth to note that the groupings mapped from the Q - mode factor analysis are more or less similar to the groupings mapped from the Shœller's diagram.

From the above circumstantial evidences and, using the Q - mode factor analysis as a basis, we could say that the geology and geomorphology of the area have some influence on the chemical variations of the waters. However, excepting the effect of the basement rocks which are limited towards the north, no distinct mineralogical differences actually prevail in the area. The geomorphology of the area too, is not so significative. The two big rivers of Santa Lucia and San Jose may not play an important role in affecting the quality of the ground water . But it can be observed from the Fig.11.2 that the chemical quality of the waters around these rivers is different than other places. The coastal zone too seems to exhibit a different chemical quality than the rest of the area. How did the groundwater of these three areas become different from one another? The answer to this question will be given in the next section.

9.7 The Geochemical Cycle and Human Activity

In the last section, we have observed three distinct environments (the valley bottoms, the coastal zones and the rest) which are related to three different groups of waters. These groups are not necessarily water types nor waters similar to one another, but simply groups reflecting three distinct chemistry of waters. It would be appropriate, at this stage, to study the environment that may have influenced the present chemical composition of the waters. In doing so, we will be able to know how the chemical quality of groundwater of one area differs from the chemical quality of groundwater of another area. We could, at the same time, clearly distinguish those chemical constituents that are contributing to pollution. The information gathered in this way may also help in the management and control of pollution problems.

We shall look at the possible source and chemical evolution of groundwater. In order to reconstruct the path of the geochemical evolution, the chemico - dynamical situations that exist between circulating water and mineralogy of the environment have to be considered. This is known as the geochemical cycle (Domenico, 1972).

Geochemical cycles are often constructed for large reservoirs, however their applications may not be restricted to size, as long as general understanding, instead of accurate results, is envisaged . With this in mind, a general geochemical cycle which may be applicable to the study area has been constructed.

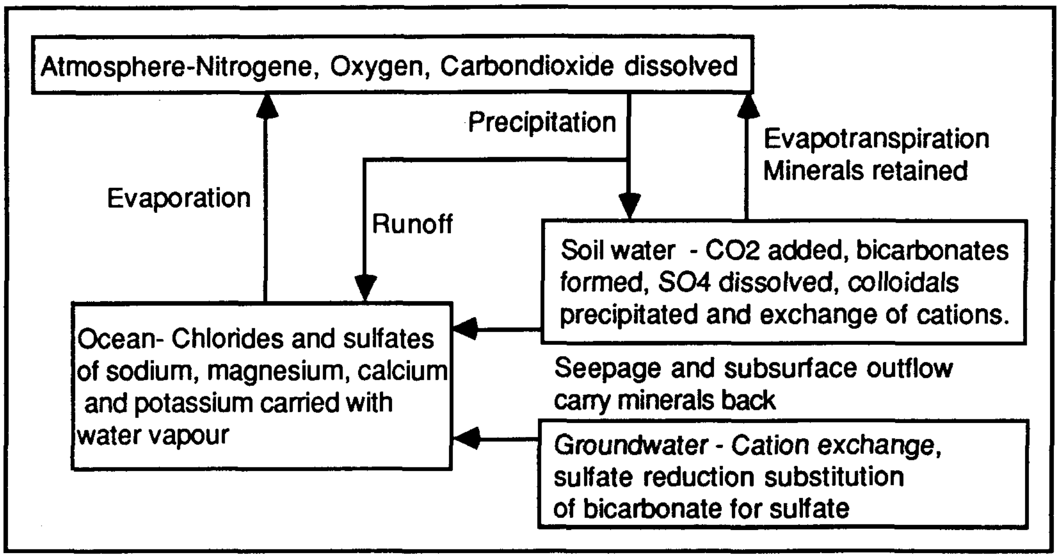

Fig.9.28. An example of the geochemical cycle, after Domenico (1972).

The geochemical cycle represented in figure 9.28 resembles that of the hydrological cycle. It can be used to asses the inputs and the outputs of the chemical components in a basin.

The inputs and the outputs in the geochemical cycle represent quantities and types of chemical constituents. Each component is subject to chemical or physico-chemical process and transformation. Therefore, the inputs will always chemically differ from the outputs during the course of groundwater movement.

The inputs into the basin are chemical components associated with atmospheric deposition, rainfall, groundwater recharge, and chemical deposition by human activities. The outputs from the basin are chemical components associated with direct runoff, effluent seepage from soils, and discharge from groundwater into the ocean.

If input exceeds output, then the change in the deposition of chemical components becomes positive. Positive storage in the chemical composition of groundwater can be considered as an alarm and, if it reaches a certain critical condition, the groundwater may not be of any use.

It is not intended, in this study, to quantify the change in chemical deposition (the balance between inputs and outputs of the chemical components) of the area. We shall, however, examine the chemical input by human beings

The chemical composition of groundwater is affected by the influence of human beings on the environment. A number of factors like diversion of water courses, the replacement of open lands by structures and paved areas in settlement regions affect solute - circulation rates (Hem, 1972). In the study area, solutes are directly added to groundwater in the form of wastes from industries, domestic and agricultural wastes.

It is not intended, in the present study, to deal in detail with all the types of solutes introduced by human beings. Therefore, we shall concentrate only on one of the major agricultural wastes, namely fertilizers, which are introduced in the agricultural areas.

In order to arrive at a reasonable estimate of the amount of solute leached from fertilizers and dissolved in the groundwater, a sample of a fertilizer, frequently utilized in the field (brown in color, usually called triple - 15 , that is, 15% N, 15% P and 15%K) was brought to the UQAM laboratory, in June 1988, for chemical analyses. Synthetic waters were prepared from this sample, on September 21, 1988, by mixing the sample with different quantities of distilled water. First, a standard solution was prepared. Nine grams of the sample was mixed in hundred milliliter of distilled water. This solution was let to stay for few days. It was then diluted with distilled water before analysis.

The proportion of the synthetic water with distilled water in preparing the solutions (from the sample, triple - 15) and the analyses results (in milligrams per liter) are given below:

Solutions	Ca	Mg	Na	K	Cl	SO_4	NO_3	TDS
10 ml in 50 ml	29.28	13.20	45.86	321.06	2083	557	5524	8544.12
10 ml in 100 ml	21.22	6.58	27.12	207.22	982	282	2845	4371.14
10 ml in 200 ml	14.77	3.46	15.54	162.40	450	141	1532	2189.17

In order to obtain the amount of the chemical constituents leached from the fertilizers and dissolved in groundwater as soluble ions, the proportionate amount of these dissolved ions are extrapolated from the linear curve obtained by plotting concentration of ions versus the corresponding proportions. This relation simply reflects the effect of dilution with respect to the accuracy of the laboratory analysis. From the curve, the concentrations corresponding to one gram of fertilizer in one liter of water were extrapolated.

By using the concentrations obtained and assuming linear relations, the proportionate amounts for different weights of fertilizers in different volumes of water were extrapolated.

For the present, we shall refer to the total concentrations of the ions analyzed as the total amount of chemical constituents dissolved in the groundwater. The values obtained for the total concentrations are represented as in figure 9.29.

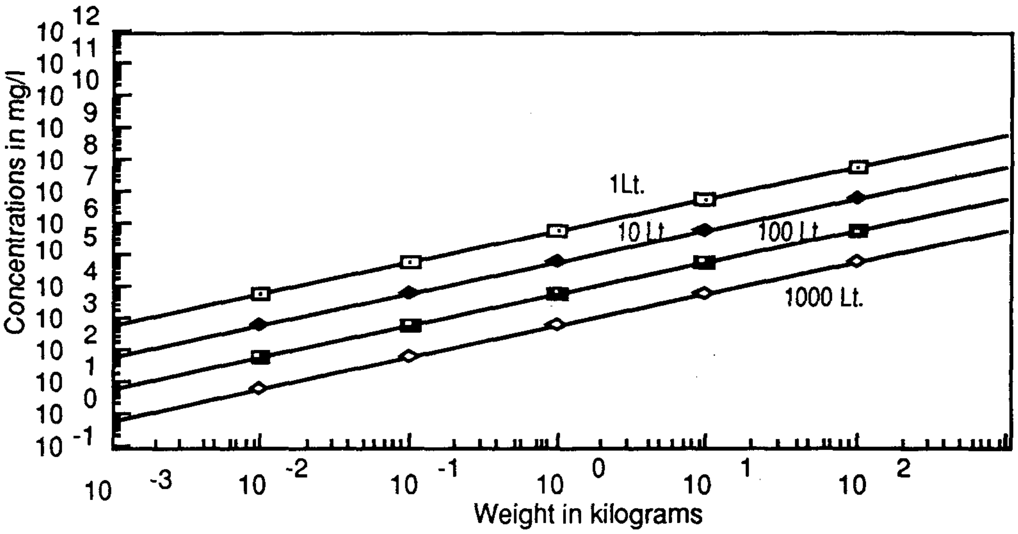

Fig.9.29. Graph of weight of fertilizers in kilograms versus total concentration of ions in mg/l. Note that this figure is more useful to obtain weight of fertilizers than its physical meaning.

The type and amount of fertilizers used in the Santa Lucia basin is given by Censo General Agropecuario (1980). According to this report, different types of fertilizers containing nitrogen (N), phosphorus (P) and potassium (K) are used. The amount of fertilizers used in kilograms per hectare, for the year 1980, as extracted from this report, is as follows:

Superphosphates	Phosphates	Other Phosphates	Urea
197.7	207.6	184.1	113.8

The annual application of fertilizers greatly varies from region to region and from crop to crop. Generally, nitrogen applications (expressed as N) vary from about 100 to 500 kg/ha/year (Freeze and Cherry, 1979). The amount of triple - 15 used in the area is not specifically known. Knowing that the use of fertilizers is increasing year by year, the minimal average annual use of fertilizer could be taken as 200 kg per hectare. If we assume the same figure for triple - 15, the amount of total dissolved solids (TDS) deposited in the area as a result of the use of fertilizer, can be calculated in the following way:

- For the year 1988, the average annual rainfall in the area was 1088 mm. The volume of water corresponding to this rainfall in one hectare would be $108.8*10^4$ liters.

- From the graph in figure 9.27, the amount of total dissolved solids corresponding to 200 kg of fertilizer equals 90kg per hectare.

The amount of TDS that would be available in groundwater after dilution by rain corresponding to 108.8×10^4 liters of rain (distilled water) would be

90kg / 108.8×10^4 liters = 82.721 mg/l

If 82.721 mg/l of total dissolved solids are being added into the Santa Lucia basin every year, then undoubtedly this could cause distinct chemical groupings: so, human activity has changed the natural environment.

The amount of other ions that are brought into the groundwater system due to fertilizers can be calculated in the same manner. It is worth noting that chemical components, other than nitrates, like chlorides and sulphates, which are also introduced into the groundwater system due to application of fertilizers, do accentuate the contamination of groundwater in the lower Santa Lucia basin.

We shall now proceed to calculate the amount of nitrate brought into the groundwater system due to fertilizers.

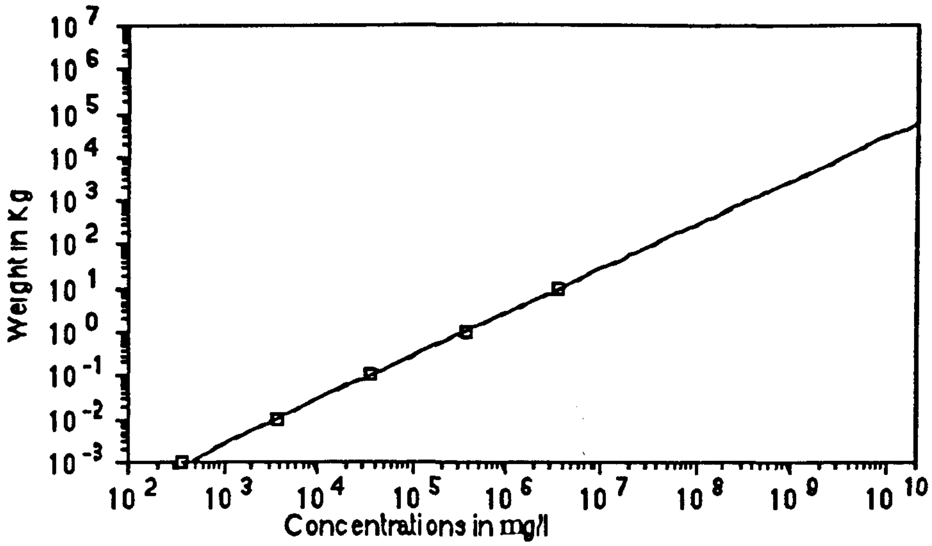

Fig.9.30. Graph of total concentration of nitrate ion in mg/l versus weight of fertilizers in kilograms, for 1 liter of distilled water.

From the graph in figure 9.30, the amount of NO_3 corresponding to 200 kg of fertilizer equals 40kg per hectare. The amount of NO_3 that would be available in groundwater after dilution by rain corresponding to 108.8×10^4 liters of rain (distilled water) would be

40kg / 108.8×10^4 liters = 36.76 mg/l.

If 36.76 mg/l of NO_3 is being added into the Santa Lucia basin every year, then this could explain the historical increase in nitrates, at least since the year 1980. This means that the depositional rate outweighs the leaching rate. What would be the effect of constant addition of nitrate in the area? This question will be answered in chapter 11.

Chapter 10

"SEAWATER" INTRUSION

In this chapter, we shall examine the possibility of environmental pollution caused by "seawater" intrusion along the coast of Rio de la Plata and the lower estuaries of Santa Lucia river.

Under natural undisturbed conditions fresh groundwater is discharged into the ocean from coastal aquifers, whereby a state of equilibrium is maintained with a stationary interface between the freshwater and seawater. However, due to pumping in excess of replenishment, the water table (or the piezometric surface) is lowered to the extent that the interface starts to advance inland until a new equilibrium is reached. This phenomenon is called seawater intrusion. Mixing with small quantities of seawater (about 4%) makes freshwater unfit for consumptive uses (Mandel and Shiftan,1981). When the advancing interface reaches inland (towards pumping well field areas) seawater may contaminate the aquifer, and it might be very difficult to reverse the situation.

We shall first examine the possibility of saline water intrusion in the coastal aquifers of the lower Santa Lucia basin and later provide solutions to realistic examples adopted to existing situations. The numerical data obtained from the study made so far on the quantity and quality of groundwater in the area will be used in conjunction with mathematical equations describing the migration of saline water inlandwards.

10.1 Identification of "Seawater" Intrusion Along the Coastal Areas of Rio de la Plata

In order to control the contamination of saline waters, it would be important to identify, find out the source of salinity in groundwaters, and understand the actual path of its movement. It should be noted that salinity problems in coastal aquifers are not always caused by seawater intrusion. For example, other sources of salinity could be wind born dust of salt, which may be integrated in the aquifer. Irrigation waters may also attribute to salinity problems. It is attempted, in this study, not to have any bias towards neglecting the possibility of seawater intrusion, or exaggerating the likelihood of its occurrence. Rather, the above mentioned possibilities for saline waters are set aside and the relation of saline water from the side of Rio de la Plata examined.

The concept of seawater intrusion in the area should be looked at, as a time and depth dependant mixture of saline water from the Atlantic ocean and freshwater from the rivers. The following table shows the classification of water based upon the total dissolved solids concentrations according to the US Geological Survey, Bowen (1970).

Type	Concentration of total dissolved solids (PPM)
Fresh	0------------1,000
Brackish	1000------10, 000
Salty	10,000--100,000
Brine	More than 100,000

According to the classification given in the previous page, the average total dissolved solids of the water samples collected along the Rio de la Plata during three different seasons indicate freshwater from Pereyra to Kiyu, brackish water from Kiyu to Montevideo and "seawater" from Montevideo up to Punta del Est. As mentioned earlier, this situation is not permanent. Moreover, the water samples were collected only from the top surface of the Rio de la Plata. Even with the presence of wave action, which may affect the upper two meters, freshwater would always float over the dense and salty water from the ocean. Therefore, it is believed that some dense salt water could possibly exist in permanence under the freshwater, all along the Rio de la Plata, up to Colonia. We may possibly conclude from this that there could still arise the problem of sea water intrusion in these coastal aquifers whenever the pumping rate passes beyond the safe limit.

10.1.1. Salinity, Chlorinity and ^{18}O as Indicators of Freshwater - "seawater" Mixing

Since relatively higher chlorinity and salinity is expected for waters mixed with seawater, chlorinity and salinity distributions are indicative of seawater intrusion. In the following, the chlorinity and salinity characteristics of Rio de la Plata will be examined.

Water samples were collected at three different seasons (May - June, 1988, November - December, 1988 and September 1989) from the ocean water at Punta del Est and from the mixed waters (ocean - fresh) at Piriapolis, Atlantida, Playa Rodriguez (Montevideo), Playa Pasqual, Kiyu and Pereyra. The isotopic behavior of these waters has been discussed in chapter 8. In this section the major constituents that normally occur in natural waters were analyzed in the water samples collected from the above mentioned places. The chemical nature of these waters could grossly be viewed from the point of view of certain characters like salinity, chlorinity and ionic strength.

Salinity

Salinity is related, but not exactly to the total salt content (Pytkowicz,1983). Salinity ($S\ {}^{0}/_{00}$) is measured by a salinometer, which actually determines the electrical conductance in relation to a defined electrical conductance value of a solution at 15°C. The conductance values are converted into salinity values according to the salinity scale which is defined as a function of conductivity ratio (conductivity of the sample / conductivity of the solution). The salinity $S\ {}^{0}/_{00}$ value for Standard Seawater, is nearly 35.000 (Pytkowicz, 1983).

Since ionic strengths were calculated from the chemical analyses data, salinity values of the ocean water and the mixed (sea and fresh) waters were obtained by using the following interconvertion equation (Pytkowicz, 1983):

$$I = 0.00147 + 0.019885\ S\ {}^{0}/_{00} + 0.000038\ (S\ {}^{0}/_{00})^2$$

Where, I is ionic strength and S is salinity expressed in parts per thousand. Neglecting the last term, the approximate salinity values are calculated from the following:

$$S\ ^0/_{00} = (I - 0.00147)/0.019885 \qquad (10.1)$$

From Table 10.1, we observe that salinity values have tremendously increased in November compared to that of May. A great deal (thousands) of dead fish were observed at Kiyu, at the time (November 15, 1988) when the water samples were collected. The dead fish were carried in small lenses of fresh waters. They died downstream when they could no longer support the saline water mixture (G. Prichonnet, pers.comm.). The salinity of Rio de la Plata around Kiyu, which caused the death of these fish, at the time of visit, have been determined to be around $S\ ^0/_{00} = 3.7$. As in the above discussion, salinity parameters are considered as good reflectors of ocean waters and are used as indices to localize the intrusion of seawater.

Chlorinity

Jacobsen and Knudsen (1940) defined chlorinity as the weight of silver necessary to precipitate the chloride bromide and iodide in 0.3286707 kg of seawater (Pytkowicz, 1983). Chlorinity, in a way characterizes the electrolyte content of ocean and related waters. It therefore reflects the salt content of the waters. Since ionic strength and salinity are related, chlorinity and salinity are also related by the following formula:

$$Cl\ ^0/_{00} = S\ ^0/_{00}/1.80665 \qquad (10.2)$$

The chlorinity values calculated from the above formula are given in table 10.1. Again, the transitional chemical nature of Rio de la Plata can be observed from chlorinity values which gradually increases from about 0.5 at Pereyra to about 18 at Punta del Est.

Table 10.1. Table of ionic strength, salinity and chlorinity of waters collected in May, 1988 calculated from the corresponding equations (10.1&10.2) The values in italics are for waters collected in November, 1988.

Locality	Ionic Strength	salinity	chlorinity	$\partial^{18}O$
Pereyra	0.005, *0.021*	0.146, *1.007*	0.081, *0.557*	-5.9, *-5*
Kiyu	0.007, *0.077*	0.254, *3.782*	0.141, *2.093*	-5.5, *-5*
Playa Pasqual	0.004, *0.225*	0.127, *11.219*	0.070, *6.210*	-5.8, *-4.9*
Montevideo	0.033, *0.421*	1.549, *21.090*	0.857, *11.674*	-5.1,*4.7*
Atlantida	0.129, *0.456*	6.409, *22.841*	3.547, *12.644*	-4.5, *2.9*
Piriapolis	0.141, *0.581*	6.992, *29.144*	3.870, *16.133*	-4.1,*-1.3*
Punta del Est	0.425, *0.636*	21.276, *31.903*	11.777, *17.659*	-1.2,*1.1*

Oxygen -18 Isotope

Contrasting salinity sources may exhibit isotopic differences which may be observed from differences in isotopic composition of Oxygen-18 in waters of varying salinity (Tan and Pearson, 1975). The relation between salinity and chlorinity with $\partial^{18}O$ has been examined in chapter 8. This relationship can also be observed from table 10.1. It is quite evident that the $\partial^{18}O$ values progressively increase towards the ocean, thus reflecting the degree of mixing of the freshwater with "seawater" from the ocean.

Undoubtedly, the composition of the stable isotope of oxygen - 18 could be used to trace and predict the migration of "seawater" in the aquifer if it exists. However, comparison of the composition of the stable isotope of oxygen-18 from Rio de la Plata with that of the groundwater along the coast has not shown any remarkable evidence of "seawater" contamination. The $\partial^{18}O$ of groundwater shows very little temporal changes in $\partial^{18}O$ corresponding to the isotopic changes of the Rio de la Plata.

10.1.2 The meq/l Values of the Ions as Indicators of Freshwater - "seawater" Mixing

Before dealing with the physical aspects of the intrusion, we shall examine the chemical nature of the Rio de la Plata in relation to the adjacent fresh groundwater. The fundamental aspect of the phenomenon of seawater intrusion is based on the fact that a hydrostatic equilibrium exists between two fluids of different densities. The relative densities of the two fluids, on the other hand, depend on the amount and concentrations of ions in solutions in the fluids.

These two fluids in our case are the relatively light groundwater flowing from north to south and the relatively dense water of the Rio de la Plata. The chemical characteristics of the former have been considered in detail. We shall now consider the chemical characteristics of the Rio de la Plata from its relatively freshwater at Pereyra to the relatively salty water at Punta del est.

Temporal chemical variations of a whole year have not been obtained, however, relatively contrasting variations were obtained from two different seasons (May - June and November - December, 1988).

Shœller's Diagram

Salinity distribution and possible mixing of water from Rio de la Plata with freshwater of the aquifer can be detected by plotting the meq/l values on Shœller's diagram.

Similarity in the major ions of the waters from Rio de la Plata with that of groundwater may indicate the possibility of salt water intrusion. Therefore, the chemical characteristics of the groundwater in the coastal aquifer is compared with the chemical nature of Rio de la Plata.

In the Shœller's diagram (see Fig.10.1) the numbers from 1 to 7 refer to the waters from Rio de la Plata near River Pereyra, Kiyu, Playa Pascal, Playa Rodreguez (Montevideo), Atlantida, Piriapolis and Punta del Est respectively, and wells 108, 159 and 163.

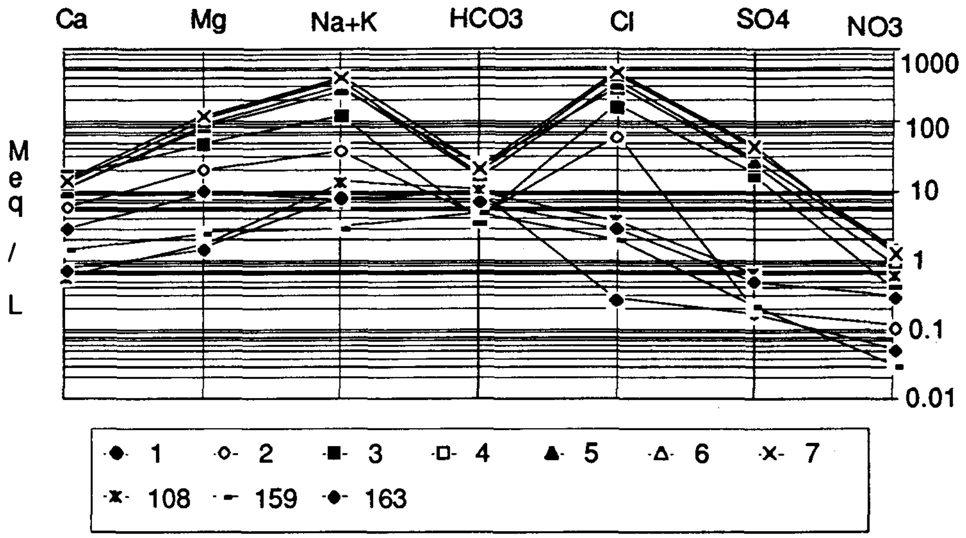

Fig.10.1. Shœller's diagram representing the meq/l values of the waters collected in November, 1988, ranging from relatively salty water (sample N^{o}·7 to relatively freshwater (sample N^{o}· 1) and the mixed groundwaters (108, 159, 163).

The following important informations are observed from the Shœller's diagram: a) The similarity of the graphs is an indication of progressive dilution of seawater by the freshwater from Rio de la Plata (better results could have been obtained if the distances between the sampling stations were kept constant). b) The fresh groundwaters plot parallel (in the lower part of the diagram), indicating similarity to the ocean water (mixing).

It has been observed that the supposedly fresh groundwaters (sample N$^{o.}$ 23 and N$^{o.}$24 from wells near river Pereyra) appear to have higher concentrations than the Rio de la Plata, indicating no contamination from Rio de la Plata during May - June, 1988 . Normally, the intruding seawater should be denser than the floating freshwater, but, the density of groundwater for samples no. 24 and 23 clearly indicates the reverse phenomenon. This can be explained by the fact that the density of groundwater usually remains constant throughout the different seasons, while the density of surface water (Rio de la Plata) changes due to dilution effects of flood and precipitation.

Calcium to Chloride Ratio

The calcium to chloride ratio of seawater, which is normally in the order of 4.8, could be compared with the calcium to chloride ratio of groundwater at various depths (Mucci and Pagé, 1987). The calcium to chloride ratio of groundwater is compared with the "seawater - saltwater mix" from Rio de la Plata (see Fig.10.2). As can be seen from the graph, there is some resemblance of the calcium to chloride ratio of groundwater with the calcium to chloride ratio of Rio de la Plata. The calcium to chloride ratio of the surface waters is also presented in figure 10.2, for the sake of comparison. From the chemical and isotopic data so far considered, nothing definitive could be said about the existence of seawater intrusion.

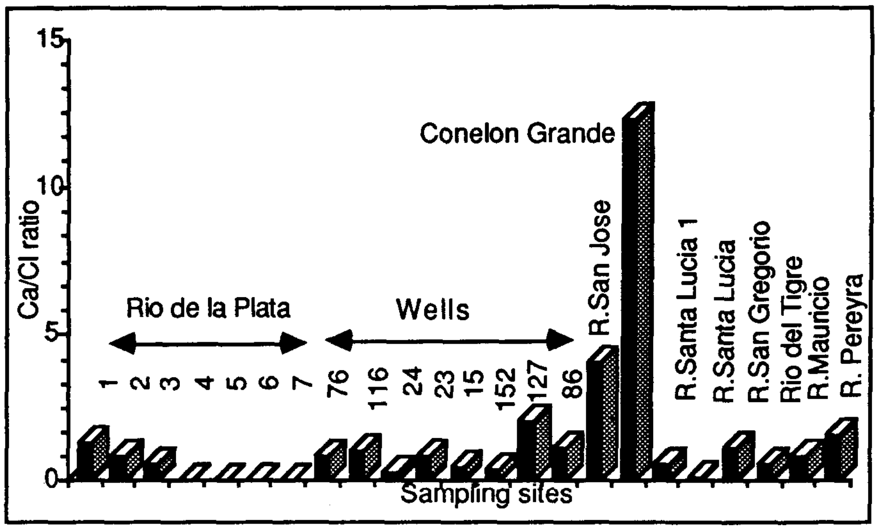

Fig.10.2 Ca / Cl ratios of groundwater, Rio de la Plata and surface waters from chemical analyses data of November, 1988.

10.1.3 Relative Volume of Freshwater and "seawater" Along the Rio de la Plata

Apart from chemical variations in time, chemical variations in depth would play an important role in determining the degree of freshwater - saltwater mixing along Rio de la Plata. It is not intended to deal with the matter intensively, but a general overview of the geometry of Rio de la Plata would help to a better understanding.

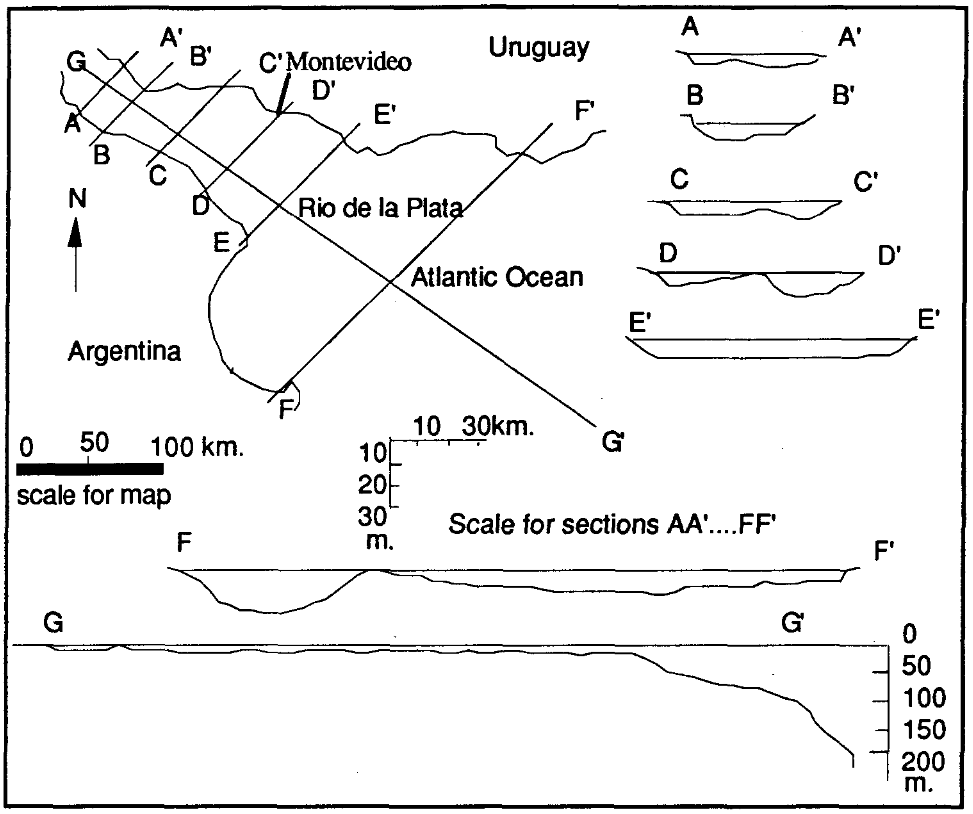

Fig.10.3. Transversal sections (AA' to FF') and a longitudinal (GG') section along the Rio de la Plata (after Servicio de Oceanografia y Hidrografia de la Republica O. del Uruguay y Hidrografia de la Republica Argentina, 1974).

The transversal sections and a longitudinal section along the Rio de la Plata are shown in figure 10.3. As can be observed from the cross sections, the real ocean water begins at Punta del Est (east of section FF'). However, considering the cross sectional area of Rio de la Plata, it would be unrealistic to imagine freshwater all along its depth. In fact, if we compare the sizes of river Uruguay and river Parana (the two main fresh water contributors to Rio de la Plata), it would rather be logical to assume very thin freshwater floating over the ocean water.

It can be seen from figure 10.3 that, on average, the total depth of Rio de la Plata does not exceed 10 meters. However, there could be significant salinity variations within the ten meters of depth. The true picture of "seawater" intrusion can only be understood by incorporating the data of the vertical changes with the horizontal. Unfortunately, no such data have been obtained.

After considering the geometry, the available data on the general chemistry, salinity chlorinity and oxygen - 18 values, it has still become a difficult task to trace a definite line across the Rio de la Plata beyond which the problem of seawater intrusion may prevail.

10.1.4 Effect of Tidal Action on the Rio de la Plata and its influence on Santa Lucia river

It has not been possible to obtain data on fluctuation of water level on the Rio de la Plata. Therefore, the local impacts in the estuaries of Santa Lucia may reach tens of kilometers upstream (from three to five meters above sea level).

A small barrage had been built at Aguas Corrientes to protect the freshwater upstream from surface water contaminations by the envading "seawater" of the Rio de la Plata. We have so far attempted to identify "seawater" intrusion in the coastal aquifers of the Raigon formation and also along the Santa Lucia river. However, the problem of seawater intrusion do not seem to be crucial west of San Gregorio river; it could be a potential problem between the Rio del Tigre and the Santa Lucia river. In the following discussion, the problem of seawater intrusion will be considered within the context of the particular (physical and chemical) nature of Rio de la Plata.

10.2 The Distribution (Shape and Position) of the "Seawater" Intrusion

The Ghyben-Herzberg's model (Todd, 1980) of an interface in a coastal phreatic aquifer is represented as in Fig. 10.4.

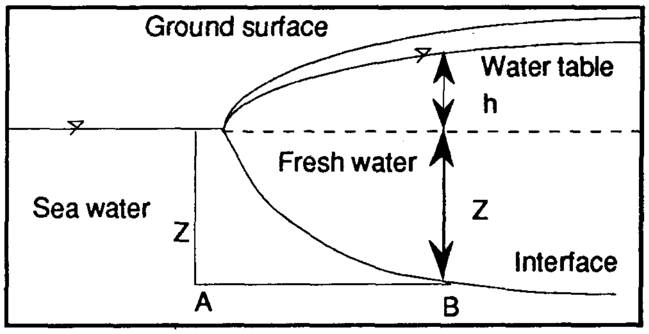

Fig.10.4. The Ghyben - Herzberg interface model in an unconfined coastal aquifer.

In the Coastal cross-section of an unconfined aquifer (see Fig.10.4) , the total hydrostatic pressures at A and at B are as in the following (Todd, 1980):

$$pA = \tilde{A}''gZ$$

$$pB = \tilde{A}'gh + \tilde{A}'gZ$$

where, $\tilde{A}''$ = seawater density, $\tilde{A}'$=freshwater density, g=acceleration of gravity, h = height of the water table from sea level and Z = height of the interface below the sea level.

Since pA=pB,

$$\tilde{A}''gZ = \tilde{A}'gh + \tilde{A}'gZ \qquad (10.3)$$

From equation 10.3, we obtain the Ghyben- Herzberg relation, ie.,

$$Z = (\tilde{A}'h)/(\tilde{A}'' - \tilde{A}') \qquad (10.4)$$

If we substitute 1.025 g/cm^3 for the density of seawater , we obtain Z = 40h. This implies that if the water in the unconfined aquifer is lowered by one metre, then the seawater interface will rise by forty metres.

For variable densities we can deduce from equation 10.4,

$$Z = h\,\Omega \qquad (10.5)$$

where Ω = density contrast ($\tilde{A}' / \tilde{A}'' - \tilde{A}'$) between freshwater and salty water.

In order to be able to apply the above formula for the problem of "seawater" intrusion in the coastal aquifer of the lower Santa Lucia basin, the density of the mixed saltwater - freshwater of the Rio de la Plata and the density of the relatively fresh groundwater should be determined and the density contrast (Ω) evaluated.

The difficulty of tracing a definite line across the Rio de la Plata, beyond which the problem of seawater intrusion may prevail, has been mentioned earlier. However, it is obvious that the Ω value for the area considered should be between 1 and 1.025 g/cm^3. Although significant chemical variations occur on the concentrations of dissolved solids, during different seasons and years, a choice should be made in using the available chemical analyses data.

The relationship of Ichiye (1966) states that the increase of density with salinity is approximately 8×10^{-4} g/cm^3 for each 1‰ increase (Stewart and Plaford, 1986). Taking a salinity of 32 for the seawater its density would be 1.0256 g/cm^3.

The salinity of Rio de la Plata varies from 1.007 at Pereyra to 31.903 at Punta del Est (see Table 10.1). Taking half way in between, salinity of 16 would correspond (according to Ichiye's relationship) to density 1.0128.

Using equation 10.5 and substituting 1.0128 g/cm^3 for the density of mixed fresh - ocean water, we obtain, $Z = 79$ h. This implies that if the water in the unconfined aquifer is lowered by one metre, then the "seawater" interface will rise by 79 metres.

Nature of the "Seawater" - Freshwater Interface

The interface between freshwater and seawater being parallel to the flowlines, theoretically no flow should occur across it. However, relatively small thickness (a few meters or more) of mixing zone prevails at the interface. The fact that this mixing zone is small relative to that of the fresh and "seawater" bodies is the basis for the "sharp" interface approximation of flow in coastal aquifers (Jackson, 1983). Nonetheless, the reasons for mixing at the interface are given below:

a) The flow of freshwater is a way of returning the solutes back to the sea which disperse in porous media flow.

b) Fluctuations in the interface are produced by tides. Flushing of "seawater" by freshwater creates small movements of seawater called Nomitsu current (Jackson, 1983). The magnitude of these currents determine the thickness of the mixing zone.

c) Seasonal water table fluctuations affect the thickness of the mixing zone.

d) Molecular diffusion plays a lesser important factor, because the velocity component is dominant over molecular diffusion towards the interface.

e) Aquifer exploitation, or freshwater injection increases the thickness of the mixing zone.

The Shape and Position of the Interface

The toe of the interface is situated at the point where the height from the sea level to the interface, in unconfined aquifers (or the aquifer thickness in confined aquifers) equals to the depth of the impermeable base (see Fig.10.5). In the landward direction, away from the toe, the aquifer contains only freshwater. The seaward freshwater flow (Q_L) at this point is the difference between the total replenishment (R) of the aquifer and the withdrawal.

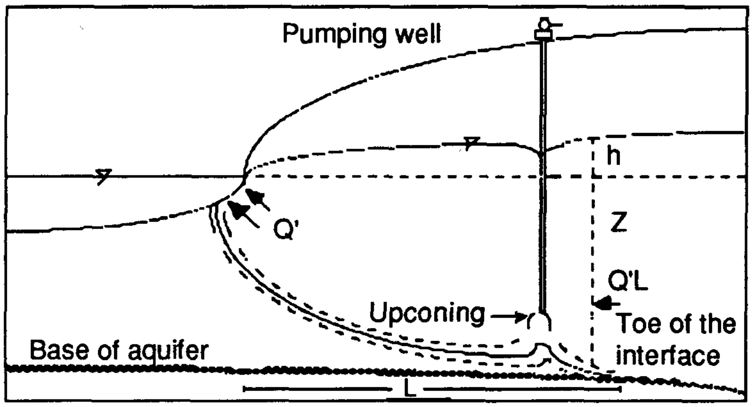

Fig.10.5. An example of a coastal cross section with pumping well at the seaward part of the interface.

The relationship among the length (L) of the seawater intrusion, the discharge (Q) to the sea and the piezometric head (h) above the toe is expressed by the following relation (Bear, 1979).

$$QL=Kh^2/2\Omega \qquad (10.6)$$

or, $F=Kh^2/2\Omega Q$

(10.7)

From equations 10.6 and 10.7, the following can be deduced: a) as the difference between the total replenishment (R) of the aquifer and the withdrawal (in other words, inflow of groundwater (Q) into the ocean) increases, the extent of seawater intrusion expressed by L decreases; b) when Q decreases (due to groundwater extraction), the interface moves towards the inland position. Therefore the management of the coastal aquifers requires a knowledge of the behavior of L with different Q.

Verruijt (1968) gives the following two equations which express the position of the interface :

$$h =\surd[2\Omega Q' /K(1+\Omega)x] \qquad (10.8)$$

$$Z =-\surd[Q'^2/(\Omega^2K^2)(1-\Omega/1+\Omega)+2Q'x/\Omega K(1+\Omega)]$$

(10.9)

Where Q' is the flow of freshwater into the sea per unit length of aquifer, Z is positive upwards, x is the distance with the origin at the seashore, being negative away from the shoreline, K is permeability and Ω is the density contrast.

The Position of the Interface With Constant Discharge as Obtained from Field Values of Transmissivity

Let us consider an aquifer at the coastal plain, for example at Colonia Wilson. Let us assume that no groundwater is extracted from this area.

- The average aquifer thickness at this place is about 30m .
- The hydraulic gradient , $i = 0.001$
- Transmissivity $= 300\ \mathrm{m^2/day}$

Since $Q' = i \times T$, where, i = gradient, T = transmissivity, the values of T can be substituted in equations 10.8 and 10.9 to obtain the specific discharge (Q') from the aquifer into Rio de la Plata. From the previous discussion the difference between density of Rio de la Plata and the density of freshwater could be taken as $\Omega = 0.0128$.

The average discharge (Q') flowing into Rio de la Plata is

$Q' = T \times i = (300\ \mathrm{m^2/day})(0.001) = 0.3\ \mathrm{m^2/day}$

$K = T/\text{aquifer thickness} = (300\ \mathrm{m^2/day})/30\mathrm{m} = 10\ \mathrm{m/day}$

For different values of x (distance from the shore) the different values of h and Z were generated by programming Verruijt's equations (10.8 & 10.9).

Graphs of x versus h, and x versus z have been plotted from the calculated values of h and Z for the fixed values of the different parameters given above, with respect to x values which were made to vary (see Fig.10.6a &10.6b). From these figures, we can deduce not only the parabolic shapes, as indicated by Verruij A. (1968) , but also the various distances and depths which vary in accordance with the parameters considered in the formula.

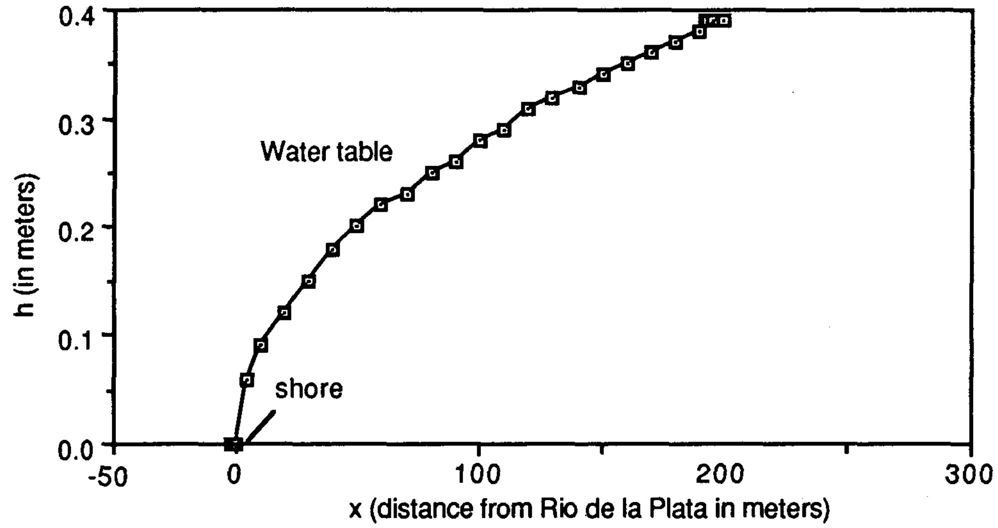

Fig.10.6 a) A water table curve of the fresh groundwater from the coastal aquifer

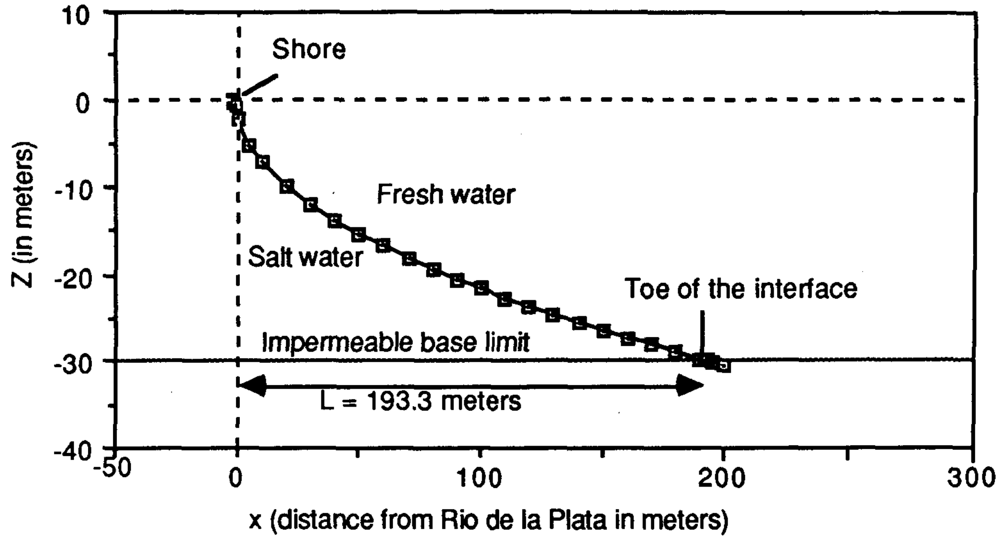

Fig. 10.6b) A curve of the interface between fresh groundwater and the "seawater" of the Rio de la Plata.

We can observe from figures 10.6 a & 10.6 b the relations between the distance up to the toe of the interface (L) and specific discharge Q'. We have previously mentioned that the two are inversely related. We note from Fig.10.6b, that for Q' = 0.3 m^2/day, the contact (toe) of the impermeable bed with the interface (since the aquifer thickness considered is 30 metres) is at x = 193.3 metres. The outlet of the interface goes up to -1.16 metres in the "seaward" (Rio de la Plata) direction. These figures indicate no danger of seawater intrusion to coastal aquifers.

Let us now examine the possible situation for a different Q'. Since K,T, Ω and b are constants, the only way we can change Q' would be by adding or subtracting a certain quantity of water into the aquifer.

The Position of the Interface With Q' Ten Times Less Than the Original Q'

Let us suppose that a number of wells will be drilled, along the coastal aquifer, thus reducing the inflow of freshwater into the sea. Let us assume a ten times reduction of the original Q' considered. By using the same formula and by choosing x, for all values of h greater than zero and for all values of Z between 0 and -30, we obtain different values of h an Z. Let us suppose that the value of Q' has become 0.03 m^2/day, due to pumping.

Obviously, the water table must lower. In the previous case, the water table was at h = 0.39m for x = 193.3 m.. But in this case, the water table is at h = 0.116 for x = 193.3m. Due to such lowering (0.284m) of the water table, seawater has penetrated a considerable distance into the aquifer (see Fig.10.7a and 10.7b).

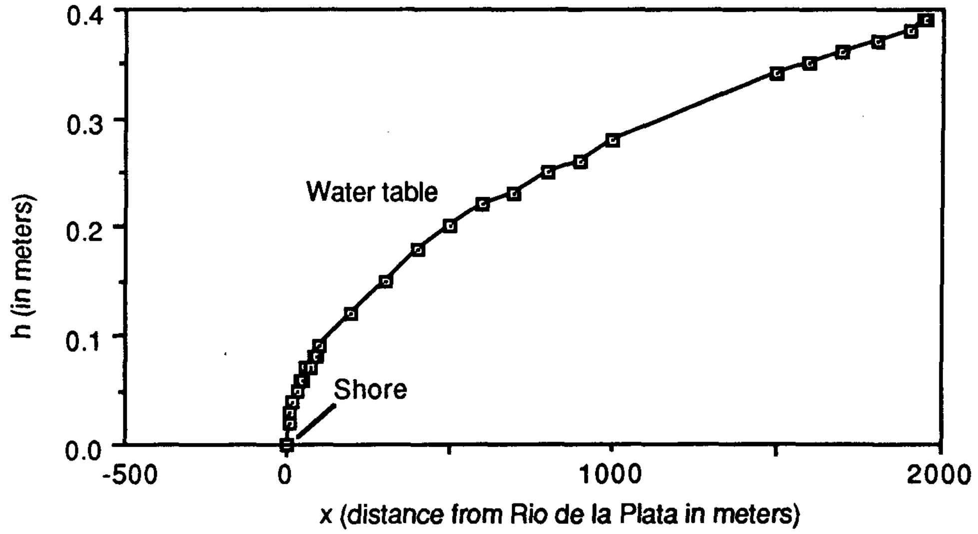

Fig. 10.7a. A water table curve for groundwater discharge ten times less than the previous.

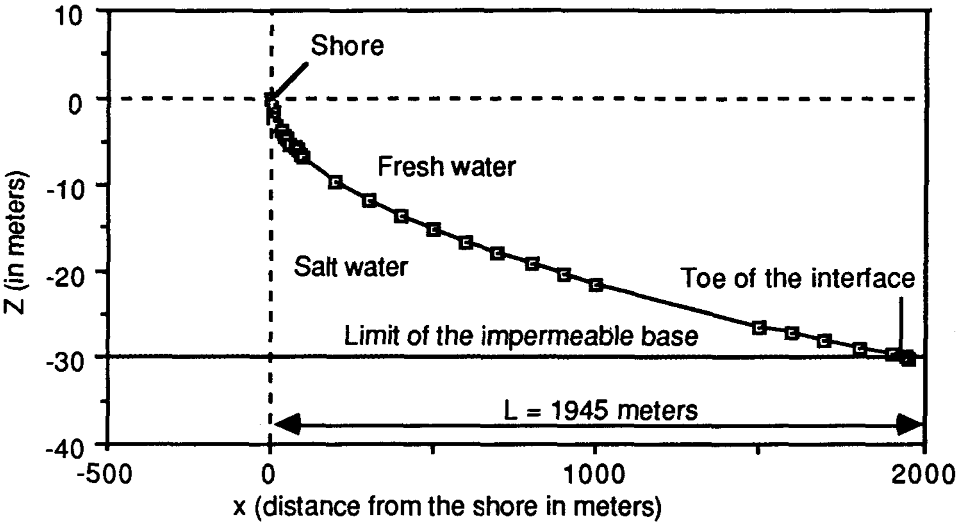

Fig. 10.7b. A curve of the interface for groundwater discharge ten times less than the previous.

At the shore, the interface boundary starts at -0.12m, while in the previous case, it started at x = -1.16 metres. On the other hand, the intersection of the impermeable bed with the interface is at x = 1945 metres, which means that the interface has moved a considerable distance into the aquifer (about ten times the first distance).

The above examples indicate the possible consequences related to extraction of groundwater from coastal aquifers. However the real situation may be better understood by a model study.

10.3 Effect of Wells on the "Seawater" Intrusion

Let us now examine what actually happens when we extract groundwater from coastal aquifers; the possibility of fixing L (toe of the interface) by controlling Q' will be discussed in this section.

If groundwater exploitation takes place at the landward of the toe, the interface will move inland depending on the intensity of exploitation of the aquifer. In order to illustrate the situation, let us consider a single pumping well (see Fig. 10.8) with a constant discharge (Q_W), located in a homogeneous aquifer with a uniform flow at a constant specific discharge rate Q'. The flow net for this situation is shown in figure 10.8b.

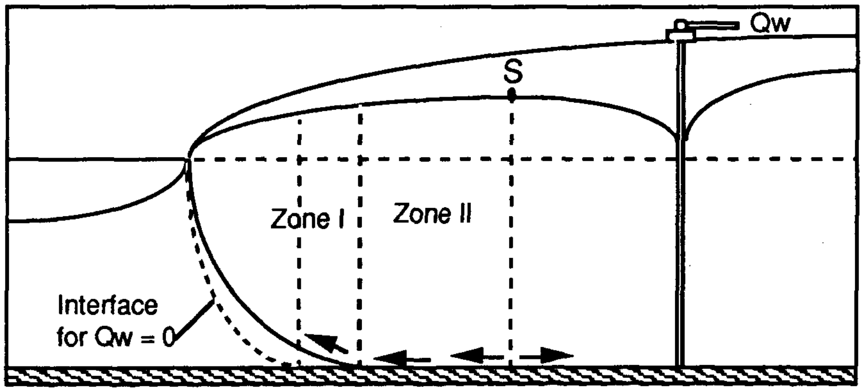

Fig.10.8a. Location of the interface for a well near the coast, Bear (1979).

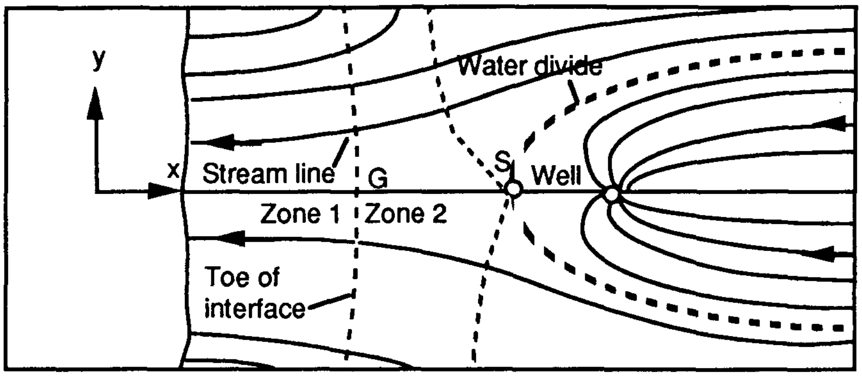

Fig.10.8b. Location of the interface in the x-y plane for a well near the coast, Bear (1979).

The two main features of this flow net are groundwater divide and stagnation point. The groundwater divide marks the limit of the influence of the discharging well. The stagnation point (S) is the point (along the water divide and, in the x-direction) where the resultant velocity, produced both by the pumping well and the natural flow in the aquifer vanishes (Bear, 1979).

In figure 10.8b, Point G represents the toe of the interface, zone I in figure 10.8a represents the area under the influence of the sea, and zone II represents a free zone which is neither influenced by the sea nor by the well. As discharge from the well (Q_W) increases, the influence of the well widens (the water divide defined by S moves towards the sea) and the interface moves towards the inland. Zone II narrows and finally disappears. Point S and point G will approach one another until they finally merge to a single point (stagnation point), with toe of the interface directly below the divide, creating unstable critical situation. Once this critical situation is reached any further increase in pumping rate will produce further drawdown of the water table with the consequent inland migration of the interface which may result in upconing (see Fig. 10.12).

Actually the critical discharge occurs when the toe of the interface coincides with the stagnation point (point G and point S respectively). We can obtain x_S (the location of the interface in the x-y plane, the dashed line in figure 10.8b) by applying Strack's (1976) formula (Bear 1979):

For the stagnation point :

$$x_S = x_W\{ 1- Q_W/\pi Q x_W \}^{1/2} \qquad (10.10)$$

Where, x_W refers to the location of the interface with respect to the well

10.4 Prediction of the Influence of a Well

If we have a line of fully penetrating wells, say at a distance 500 metres from the coast, it would be necessary to know the following points.

- the maximum distance of the toe of the interface at which the wells can be pumped without any danger of "seawater" intrusion,

- how much water can be pumped from the wells without "seawater" passing this maximum distance and contaminating the aquifer.

From the previous discussion, this maximum tolerable distance is the location of the stagnation point x_s with respect to the coast, and the critical discharge (Q_c) is the discharge of wells at the stagnation point. If we assume that the critical distance (stagnation point) is located at 300 meters from the shore, in order to protect the wells, the bottom of the interface should be kept at 300 meters, so that z = -30 m, for x = 300m. What would be the critical discharge of wells in this situation?

The critical discharge (Q_c) can be obtained from equation 10.9.

Taking the same parameter values as in the previous example, then

$Q'_c{}^2(1-\Omega)/\Omega K + 2xQ'_c - Z^2\Omega K(1+\Omega) = 0$

$= 7.7125Q'_c{}^2 + 600Q_c - 116.675 = 0$

$Q'_c = 0.193952\ m^2/day$

In the case with no pumping, Q' was 0.3 m^2/day, the present Q' is 64.65 % of the first Q', which means that we could extract 35.34 % of the initial aquifer flow to Rio de la Plata before we reach the critical situation.

The aquifer specific discharge for this critical situation is then,

$0.3534(0.3)\text{m}^2/\text{day} = 0.10602 \text{ m}^2/\text{day}$

If we want to keep a distance of 300 meters between each well then each well can yield less than ($0.10602 \text{ m}^2/\text{day} \times 300\text{m}) = 31.806 \text{ m}^3/\text{day}$. The critical discharge of wells in this situation would be about 0.4l/s for 300m of interval.

The above example indicates the possibility of extracting groundwater from the coastal aquifer, even at a distance of 500 meters from the shore, without having the problem of intrusion of saline water. However, water must not be pumped from the seaward part of the coastal aquifer between the toe of the interface and the shore, otherwise the problem of upconing may arise.

Problem of Upconing

If the pumped well is situated on top of the interface, then the cone of depression around the well will cause a corresponding upconing of the interface. If upconing continues beyond a certain critical rise, then the seawater will be drawn into the well (see Fig.10.9). This is a dangerous situation, whereby the well could be ruined due to very high salt content. The problem could arise even before the actual "cone" reaches the bottom of the well, due to widening of the zone of transition by hydrodynamic dispersion (Mandel and Shiftan, 1981).

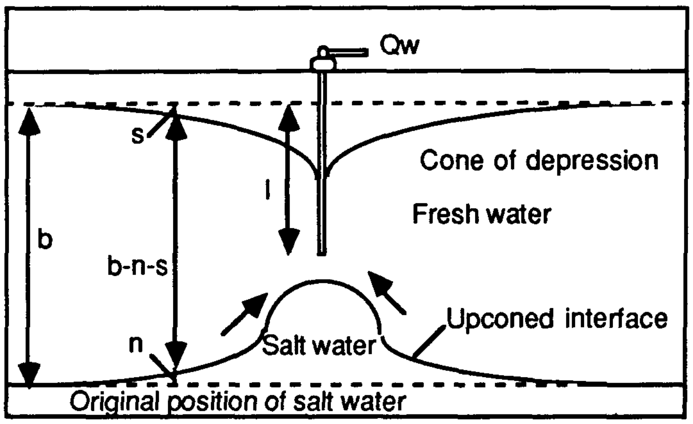

Fig. 10.9. Upconing of the freshwater - saltwater interface beneath a pumping well, after Mc Whorter and Sunada (1977).

According to the Dupuit-Forchheimer approximation, the piezometric head on a vertical line is constant (Mc Whorter and Sunada, 1977). Therefore,

$$\Delta n = - \tilde{A}'/\Omega(\Delta h) \qquad (10.11)$$

Where Δn represents the change in the distance to freshwater - seawater interface, and Δh is the change in piezometric surface elevation in confined aquifers or change of elevation of the water table in unconfined aquifer.

The above equation shows the inter-relationships between the interface and piezometric surface or water table; a rise of the interface corresponds to a drawdown in a pumping well.

Theoretical considerations and field evidences have shown (Mc Whorter and Sunada, 1977) that the critical rise equals, approximately, one half of the distance between the interface and well bottom. In order to be on a safer situation, therefore, the position of the well screens have to be kept as much as possible high up, above the interface and drawdowns have to be kept relatively small.

The steady discharge for a well is given by Mc Whorter and Sunada (1977):

$$Q = -2\pi K(b-s-n)r\,ds/dr \tag{10.12}$$

Where, b is the undisturbed fresh water thickness, s is the drawdown n is the interface elevation above the original level and r is the radial distance

In the case where the length of the screened portion of the well is small in relation to the depth, the steady state interface beneath the well would be (Mc Whorter and Sunada, 1977):

$$n_w = Q\tilde{A}'/2\pi\ (b-l)\Omega K \tag{10.13}$$

Where, l is the distance between the top of the aquifer and the well screen. Using the condition that the interface should be kept at one third of the distance between the bottom of the well and the original interface elevation, the maximum safe discharge is obtained from the following equation :

$$Q_m = 2\pi/[3(b-l)^2(\Omega/\tilde{A}')K] \tag{10.14}$$

If we consider a well 16m in length having 1m of screen at the bottom, where the original (undisturbed) interface is at 32m below the water table, and if K is 10 m/day, the maximum discharge by which we could pump without causing the "seawater" to intrude into the well can be calculated by using equation 10.14:

$$Qm = [2\pi(32-16)^2 (0.0128)(10)] /3 = 205.887 \text{ m}^3/\text{day} = 2.4 \text{l/s}$$

10.5 Prevention and Control of the "Seawater" Intrusion

Before concluding this chapter, some points will be given regarding prevention and control. No serious problem of saline water intrusion have so far been detected in the coastal aquifers of the studied area, but problems may arise in the future, when the need to intensive exploitation of groundwater in the coastal aquifers become inevitable. The following points may then serve for future use.

Reduction or Modification of Pumping Pattern

Intrusion of seawater can be controlled by reducing the amount of groundwater extracted. This should be done in accordance with the water need and availability of other sources of water supply.

Rearrangement of the pumping pattern may also be an alternative solution: If pumping is concentrated towards the inland areas, the free zone area between the toe and the well widens. As a consequence, the time of reaching the stagnation point will increase significantly.

Artificial Recharge

If additional source of water become available, for example flood during rainy seasons, an artificial recharge by spreading can be employed. In this case, the fresh waters of San Gregorio, Mauricio or del Tigre can be used for spreading purposes. With such procedure, fresh groundwater discharge into Rio de la Plata could be augmented, which will push the salt water away from the aquifer, thus preventing any undesireable effect of salt water encroachment.

Temporary salinity problems can be reduced by a line of wells parallel and near the coast pumping the "seawater", at a rate which will prevent the encroachment of the saline water landwards.

Chapter 11

DEVELOPMENT OF GROUNDWATER RESOURCES

Having considered all the major aspects related to the quantity and quality of groundwater, the next step would be to extract only those informations which are relevant to development aspect. Since a great deal of informations have been represented in the form of maps, a good way of extracting the informations needed would be to superimpose these maps and trace the salient features from each. Accordingly, a water resource map has been prepared which can be used for development of groundwater resources (see Fig.11.8).

This study has revealed that there is not a free zone where groundwater could be developed safely, without having to care about the groundwater quality of the adjacent land. Therefore, analysis of the water quality becomes a necessary prerequisite for groundwater resources development.

11.1 Groundwater Quality Evaluations

11.1.1 Quality of Groundwater for Drinking Purposes

In this section, we shall examine, only the critical chemical parameters which indicate the deterioration of the quality of groundwater. The chemical quality of the groundwater for drinking purposes are compared with the internationally accepted quality standard, as given by the World Health Organization, and quality standards for drinking purposes in Uruguay, as given by OSE (Administracion de las Obras Sanitarias, 1986).

Table 11.1. Drinking Water Standards in Uruguay, after OSE (1986). The values in parenthesis are for European standard, after the World Health Organization (Freeze and Cherry , 1979).

pH	6 to 9
Total Hardness	500 mg/l as $CaCO_3$
Chloride	300 (250) mg/l
Sodium	200 mg/l
Sulfate	400 (250) mg/l
Nitrate	45 (50) mg/l
Total dissolved solids	1000 (500)mg/l

The mean and standard deviation of the ions in the water samples analyzed are represented on a diagram (see Fig.11.1). From the average data of January - February 1987, only nitrates were found to have concentrations beyond the drinking standard (50 ppm). The mean and standard deviation of the ions give a general idea of the water quality. But they do not reflect the situation over the area.

High concentration (beyond objectionable limit) of some ions are known to exist at some places. The geographical locations of the areas affected by some of the most important water quality parameters like nitrate and chloride are represented on contour maps (see Fig. 9.14 and Fig. 9.17). It is, therefore, essential to consult these maps in order to identify areas with particular ion concentration.

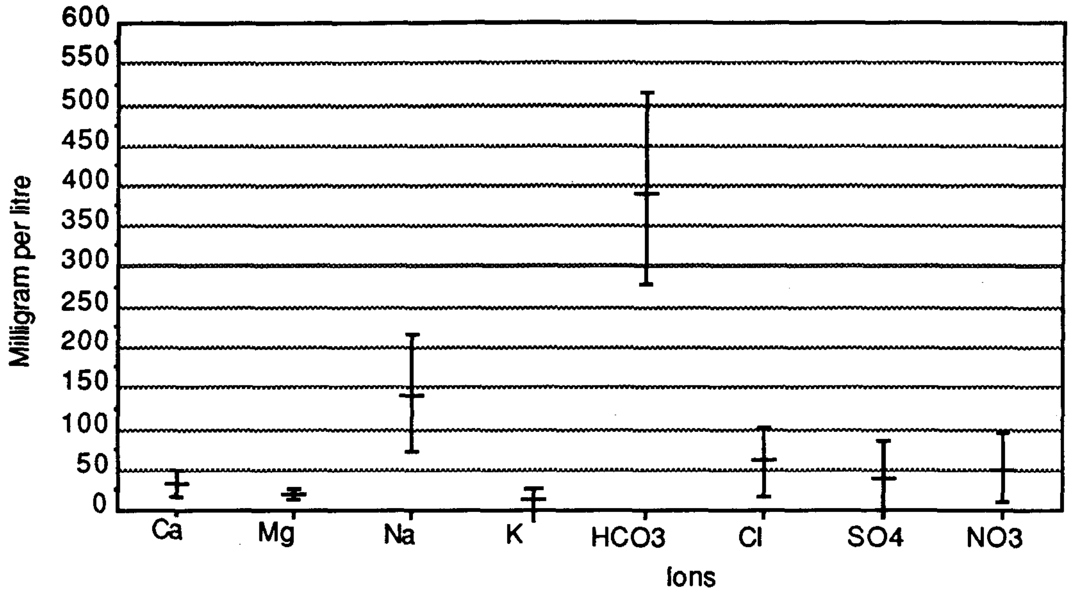

Fig.11.1. Mean and standard deviation of the major cations and anions from the water analysis data (98 samples) of January - February, 1987.

The total dissolved solids pass beyond the desirable limit (1000 ppm) in most places. A water quality map has been prepared by the superposition of the most important water quality parameters in the area, namely TDS and nitrate (see Fig. 11.2).

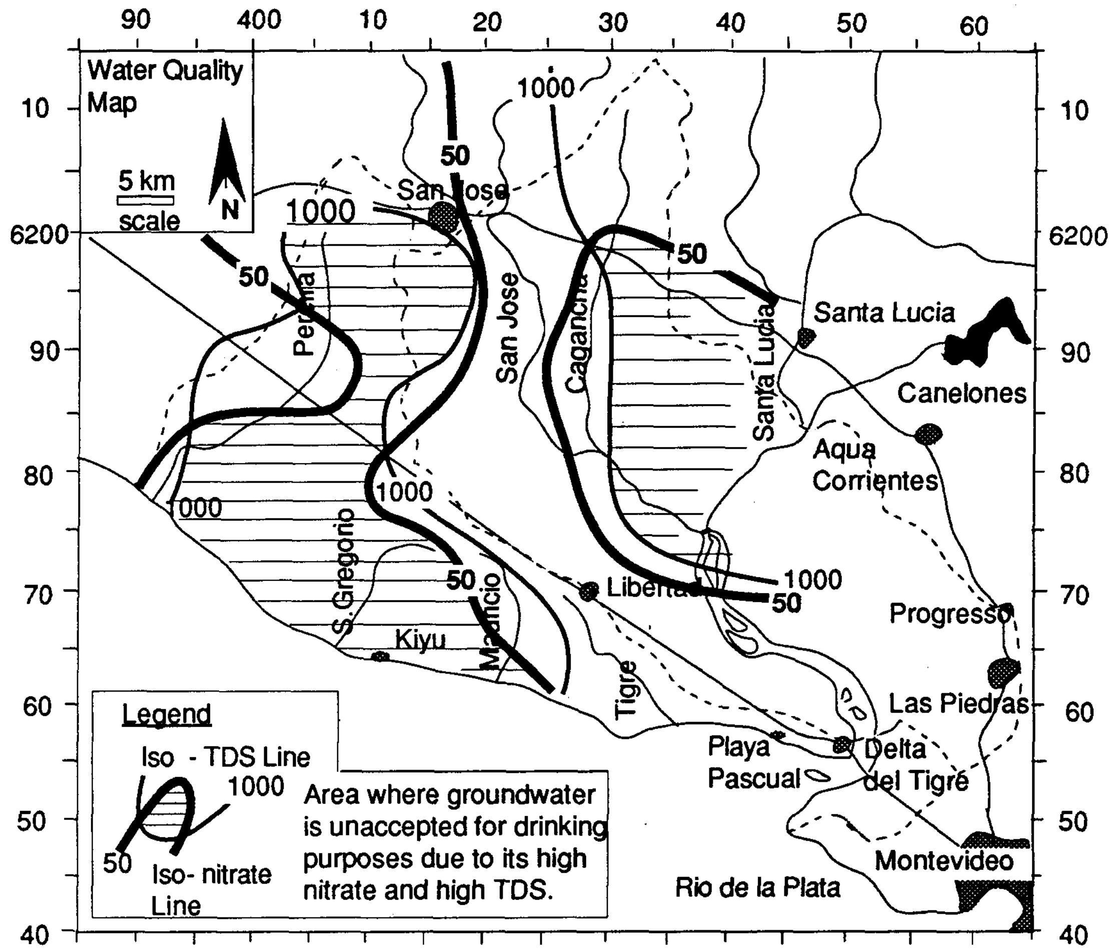

Fig. 11.2 Map showing a general overview the groundwater quality of the Lower Santa Lucia basin based mainly on TDS and nitrate data of January - February 1987.

We can see from Figure 11.2 that a large part of the groundwater in the aquifer are within the objectionable limit for drinking purposes. When the concentration of the contaminant attain objectionable level, the groundwater is said to be polluted. It should be noted that not all of the aquifer indicated on the map in Figure 11.2 is contaminated. Repeated analysis have indicated the presence of polluted groundwater from some of the wells examined. These wells are marked on a map (see Fig.8.8).

11.1.2 Quality of Groundwater for Agricultural Purposes

Normally fresh waters contain less sodium than calcium and magnesium. But in most of the waters analyzed, the sodium cations represent the highest percentages among the cations. This may be due to the precipitation of calcium and magnesium cations by evaporation from irrigation waters that have high bicarbonates, thus allowing proportionate amount of sodium to remain in the water. The waters in the irrigated areas may have been used and reused. As a consequence, the content of sodium becomes elevated. This raises the problem of sodium hazard.

As plants withdraw water from the ground by osmosis, favorable balance must be maintained between salts within plants and salts within solution. The structure of soil particles is affected by high concentration of sodium in soil solutions relative to the concentration of calcium and magnesium. Flocculation of soil particles occurs due to relatively high concentration of calcium and magnesium, compared to the concentration of sodium, whereas defloculation of soil particles occurs due to relatively higher concentration of sodium compared to the concentration of calcium and magnesium. Flocculation provides good circulation of air and water, while defloculation prevents free movement of water and air. The sodium adsorption ratio (SAR) is an index which is used to predict the sodium hazard of water (degree of flocculation produced by sodium). It is defined by the following relation (Walton, 1970):-

$$SAR = Na/0.5(Ca + Mg)$$

Where, the ion concentrations are expressed in equivalents per million (epm).

High SAR values indicate the possibility of sodium in the water which can replace the calcium and magnesium in the soil. SAR values smaller than 10 are considered as low, intermediate between 10 and 18, and high exceeding 18.

Generally, it can be said that most of the waters are within the safe SAR limit. However, at some localities and in particular months, when irrigation practices are at their peak, the sodium hazard could possibly create problems to the growth of plants.

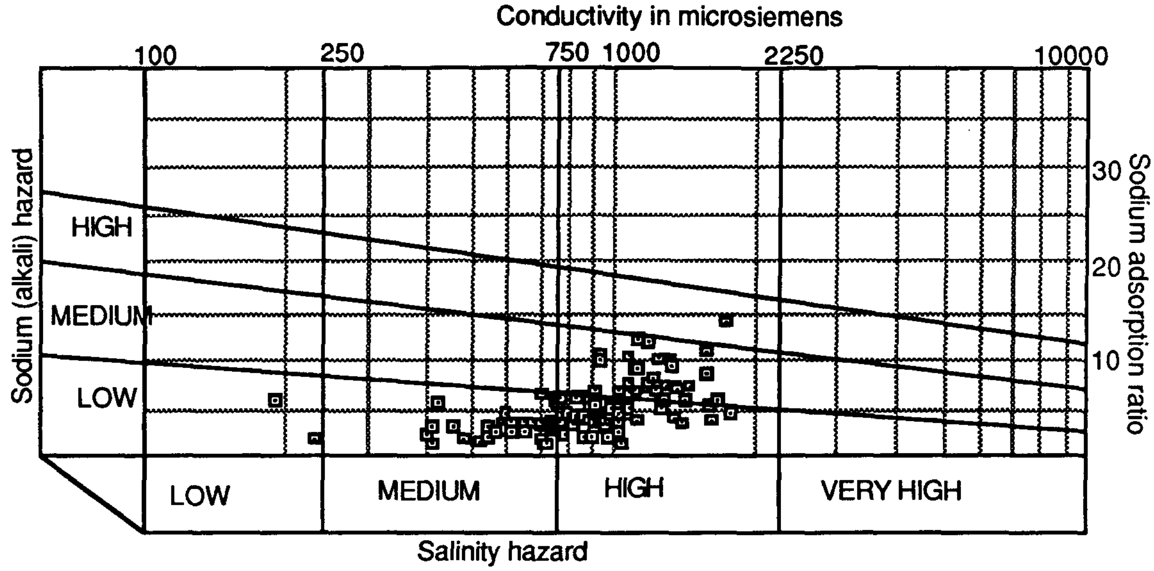

Fig.11.3 Suitability of the groundwater for irrigation in the Lower Santa Lucia basin (data from the January - February, 1987), cf.Walton (1970).

Figure 11.3 shows the position of the groundwaters in relation to sodium adsorption ratio and conductivity. As some plants are specifically sensitive to salinity, the quality of the groundwater will depend on the type of plants grown. The use of Figure 11.3 then depends on the salt tolerance of the type of crops planted. The iso - SAR map (see Fig. 11.4) indirectly reflects the quality of the land for agricultural purposes .

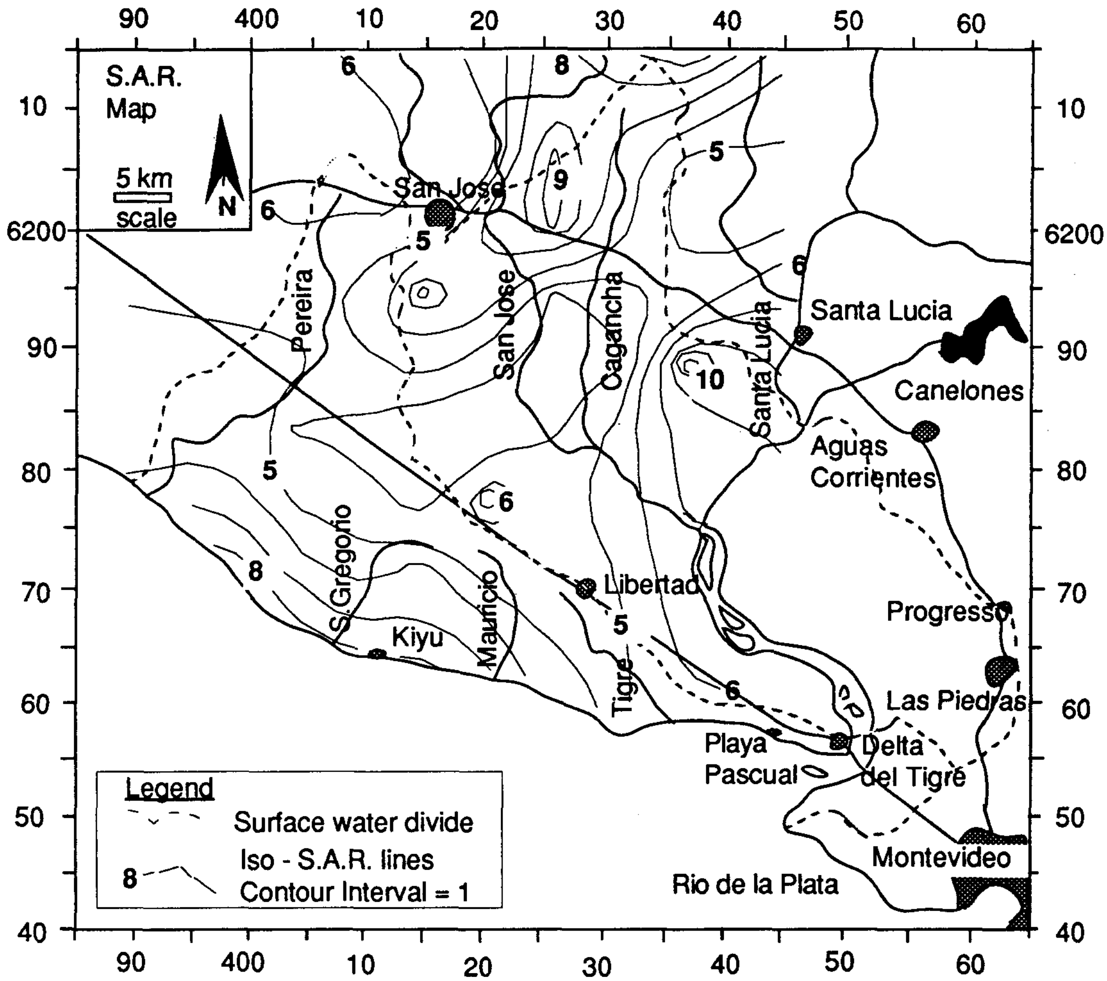

Fig.11.4 Iso - S.A.R. map

11.1.3 Quality of Groundwater for Industrial Use

Each industry may have its own water quality specifications depending on the type of industrial product it manufactures. But , in general, the quality of groundwater from the point of view of its hardness seem to be a universal characteristic affecting any industry.

Hardness of water is caused mainly by the presence of calcium and magnesium. The two types of hardness are carbonate or temporary hardness (Ca and Mg carbonates and bicarbonates) and non carbonate or permanent hardness (Ca and Mg sulfates, chlorides and nitrates).

The total hardness values are usually used as a measure of the hardness property of waters. Total hardness which is the total concentration of calcium and magnesium expressed in milliequivalent per liter is given by Freeze and Cherry (1979):

$$\text{Total hardness} = 2.5\,(Ca^{2+}) + 4.1(Mg^{2+})$$

The total hardness of the waters was calculated from the above formula and represented on a table (see Table 6 in the Appendix). There are a number of hardness scales and various hardness quality standards. Generally, hardness of less than 100 mg/l is considered to be suitable. Hardness between 100 and 150 is considered to be hard, while hardness greater than 150 is very hard. In this respect, few waters were very hard, most waters were found to be hard, some waters were intermediate and few waters soft.

11.2 Groundwater Pollution

We have observed in the previous sections, that most parts of the area are affected by groundwater contamination. In fact, groundwater quality has passed beyond the acceptable limit and groundwater pollution has become a threat. The major sources of pollution in the area are agricultural pollution, industrial pollution and domestic pollution.

The areas affected by point source pollution are marked on a map (see Fig.11.6). It is not intended to deal with all these sources of pollution. However, some aspects will be given from the point of view of groundwater development.

11.2.1 Nonpoint Pollution Conceptual Model

The source of pollution caused by human beings can be classified as point or nonpoint source of pollution.

Point sources are discrete, have identifiable locations and can usually be measured or quantified (Nostony and Chesters, 1981).

Nonpoint sources, such as application of fertilizers do not have distinct point sources where measurements can be conducted (see land use map in Figure 11.6). Unlike point sources, they are derived from non - continuous applications and, apart from the intensity of the applications, they depend on other factors like climatic events and geological conditions. Therefore, they enter into groundwater at intermittent intervals.

A proper understanding of the quality of groundwater and pollution problems, requires an understanding of the path of the geochemical evolution through which the waters may have undergone before attaining their present composition.

The composition of water is a result of a large number of factors and processes that are interrelated. The hydrochemistry of groundwater reflects the source of water, the lithology of the aquifer and the local chemical conditions like temperature, pressure, redox, etc.(Matthess, 1982). Consequently, the occurrences of dissolved chemical species in groundwaters are due to chemical reactions in the atmosphere and the combination of physical and chemical processes in geological formations (Domenico, 1979).

Modeling the nonpoint pollution caused by fertilizers would actually mean modeling the whole or part of the watershed. In any case, a detailed study should be done in analyzing all the factors which affect the transport of contaminants.

The two basic approaches to modeling nonpoint pollution are lumped parameter models and distributed parameter concept (Novotony and Chesters, 1981). In lumped parameter models, the watershed is treated as one unit, while in the distributed parameters approach the watershed is divided into preferred units, depending on a number of factors like soil, topography etc., whereby each unit is modeled separately.

The principal source of nonpoint pollution in the Santa Lucia basin is agricultural pollution. Fertilizers are employed over the entire area of the lower Santa Lucia basin, excepting the marshy areas along the major rivers. Rain water and irrigation water dissolve and carry fertilizers, herbicides and pesticides down through the unsaturated zone and replenish the aquifer with contaminants (see Fig. 11.5).

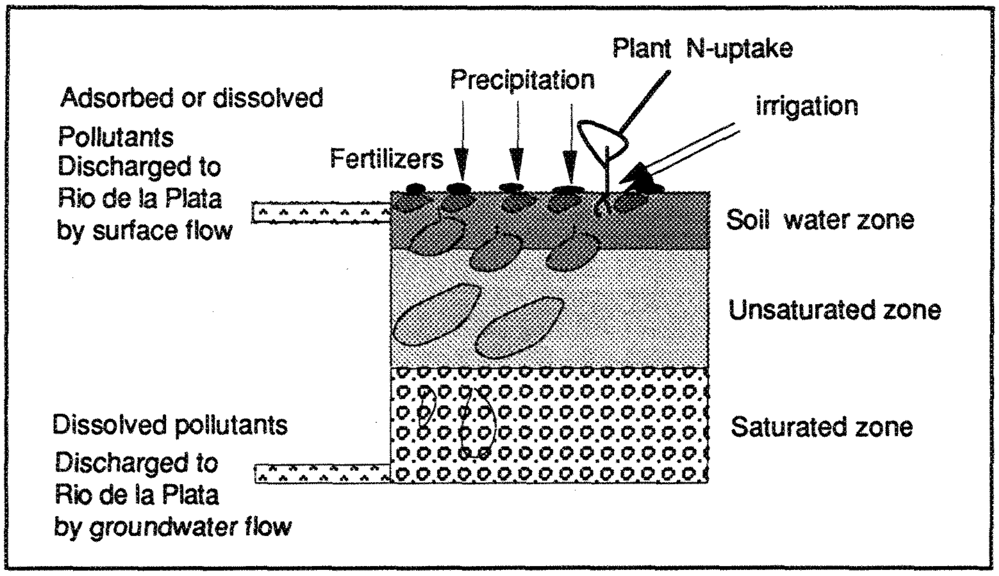

Fig. 11.5 A simplified model of nonpoint pollution applicable to the study area.

In chapter 9.7, we have calculated that about 36.79 mg/l of nitrate is being dissolved into the groundwater system every year. This is the amount of nitrate that have originated from fertilizers. However some nitrates could also have been caused by domestic pollution, whereby some quantity of nitrate is introduced into the groundwater system by percolation of organic waste from septic tanks and / or animal dung. Apart from this, some nitrate could come from background (natural) groundwater quality caused by a leachate from the upper soil layer, or originating from minerals. Some of the nitrate values detected in the groundwaters are brought about by plants which fix the atmospheric nitrogen in their roots.

In the soil water zone, some nitrogen is taken by plants, while some nitrogen dissolves as nitrate to reach the groundwater system passing through the unsaturated zone. In the process, some nitrogen is being lost due to denitrification processes. From the point of view of transport of contaminants, the behavior of dissolved nitrate in the saturated zone will follow the behavior of the water itself. Therefore, in the soil zone molecular diffusion becomes important , whereas in the groundwater zone advection becomes important.

The contaminants are discharged in various ways depending on the hydrogeomorphological situation. In chapter nine, the different ways in which groundwater is being discharged out of the basin have been discussed. It would be enough to mention that contaminants also follow the same path. However, we should note that, as there is no groundwater inflow of contaminant from the northern part of the basin, contaminant outflow exceeds contaminant inflow from the lower Santa Lucia basin.

In short, a proper understanding of the path and amount of nitrate in the groundwater would require a detailed study of the various parameters including the property of soil (texture, composition, erodibility), crop and vegetation cover, crop yield, type of crop, growth stage of crops, etc. The distributed parameters approach would be most appropriate to modeling nonpoint pollution, whereby the watershed is divided into preferred units, depending on the factors mentioned above.

In spite of the above procedure, a rough estimate of the total amount of nitrate leached from the land surface to join the groundwater system can be obtained:

If we consider an agricultural area of one hectare producing a type of crop with nitrogen uptake of 20 kg/tonne of nitrogen, the amount of nitrogen uptake can be calculated from the amount of total crop production. According to "Censo General Agropecuario", the amount of crop production for the year 1980 varies from 3 to 6 tonnes per hectare.

Let us assume an average crop production of 4 tonnes per hectare for the year 1989. According to Novotny & Chester (1981) the amount of nitrogen uptake is

$$UP_N = (\text{crop yield} \times \text{nitrogen content}) / \text{growing period}$$

If we assume a growing period of 120 days, the total nitrogen uptake of the crops would be

$$UP_N = 4(\text{tonnes / hectare}) \times 20 \ (\text{Kg / tonnes}) / 120 \text{ days}$$

= 0.67 kg / day per hectare

If we assume that the area was irrigated every day for 2 hours, the rate of infiltration (for a sandy loam the rate of infiltration is about 30 mm per hour) of the irrigated water would be 60 mm per day. If the water contained 10 mg / liter of nitrogen, then the plants would obtain

$$0.06(\text{m/day}) \times 10{,}000\ (\text{m}^2 / \text{hectare}) \times 10\ \text{g} / \text{m}^3 = 6\ \text{kg} / \text{day}$$

On top of the 6 kg / day obtained from irrigation water, the plants also get some nitrogen from fertilizers. The amount of nitrate leached from fertilizers is 40 kg per year per hectare which is equivalent to 9.1 kg of nitrogen per year per hectare (see section 9.7). It is probable that all the 9.1 kg of nitrogen from the fertilizers become consumed during the growing season of plants (during the 120 days). The amount of nitrogen that the plants receive from fertilizers would then be 0.08 kg per day.

The amount of nitrogen leached can be obtained by subtracting the nitrogen uptake by plants from the sum of nitrogen added by irrigation water and fertilizers.

Nitrogen leached = (6.08 - 0.67) = 5.41 kg per day per hectare.

The nitrogen concentration in the leachate is equal to the nitrogen leached divided by the total volume of water. Here, we have to take the amount of evapotranspiration into consideration. The average amount of evapotranspiration during the growing seasons for the year 1989 was about 3 mm / day. Therefore, the nitrogen concentration in the leachate is:

$$C_N = (5.41\ \text{kg per day}) / (\,(0.06 - .003) \times 10{,}000) = 9.5\ \text{mg/l}\ \text{ per hectare}$$

The above figures give an idea of the amount of nitrate that could possibly dissolve in the groundwater system of the Lower Santa Lucia basin. However, other parameters like biological nitrogen (from organic wastes) and nitrogen from the atmosphere, fixed by certain plants, have not been considered.

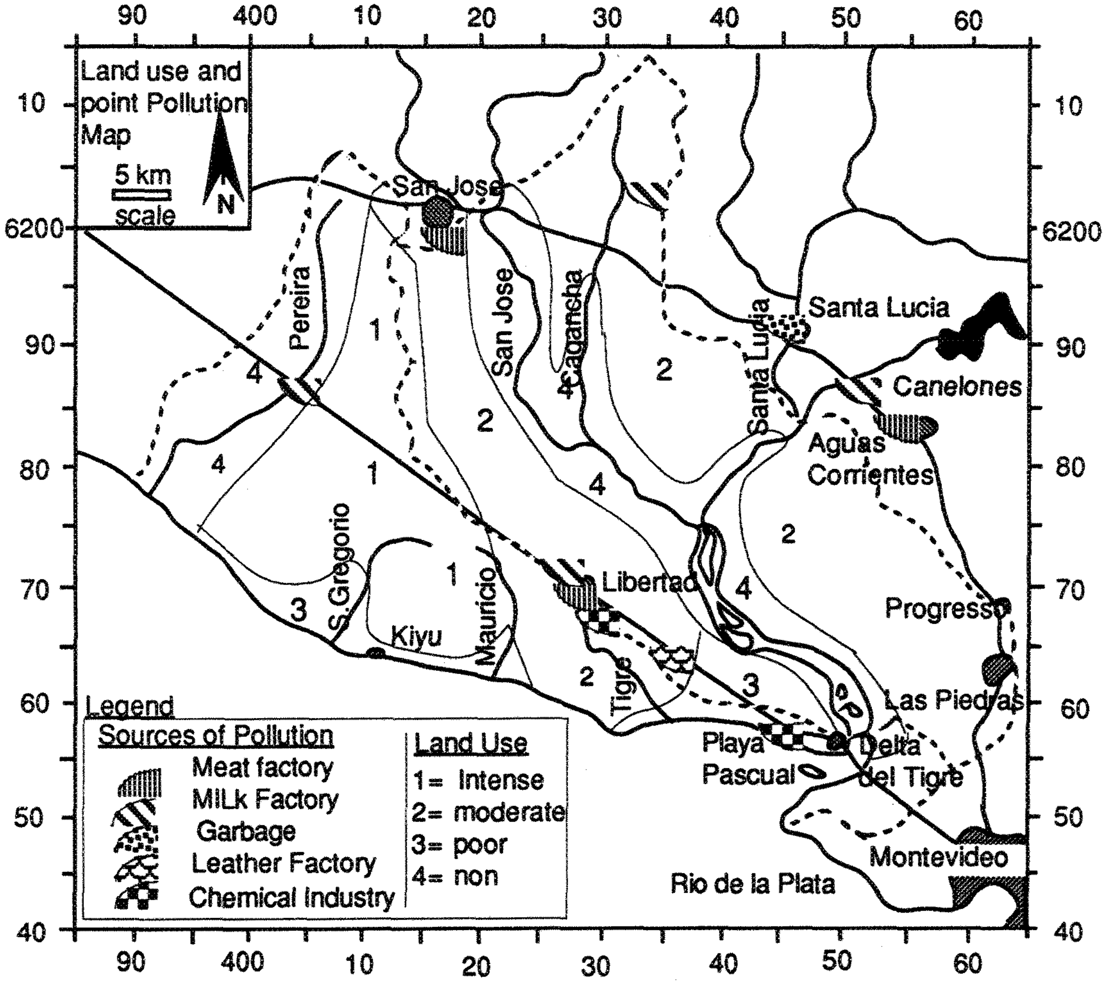

Fig. 11.6 Map showing land use and major sources of the industrial and domestic pollution in the Lower Santa Lucia Basin.

11.3 Groundwater Quality Protection and Improvement

An aquifer can be considered as protected if no vertical infiltration occurs to contaminate the water. The aquifer (Raigon Formation) is naturally unprotected. In this type of situation, the most effective means of preventing the undesirable consequence of contamination would be the control of pollutant emission:

- The extensive use of fertilizers should be restricted by law.

- Settlement areas should be equiped with underground pipe or drain (sewer system) for carrying of waste matter. Proper treatment and storage facilities should be constructed for individual detached homes.

- The dumping of other sources of pollution (industrial, domestic) should be done in accordance to laws protecting natural environment. Most rules and regulations require that landfill areas be located in low permeability soils and in socially acceptable sites. Novotny et al. (1981) give several methods of leachate control. However the application of each depends on their effectiveness and cost. A method of preventing leachate from contaminating the aquifer is shown on Fig. 11.6.

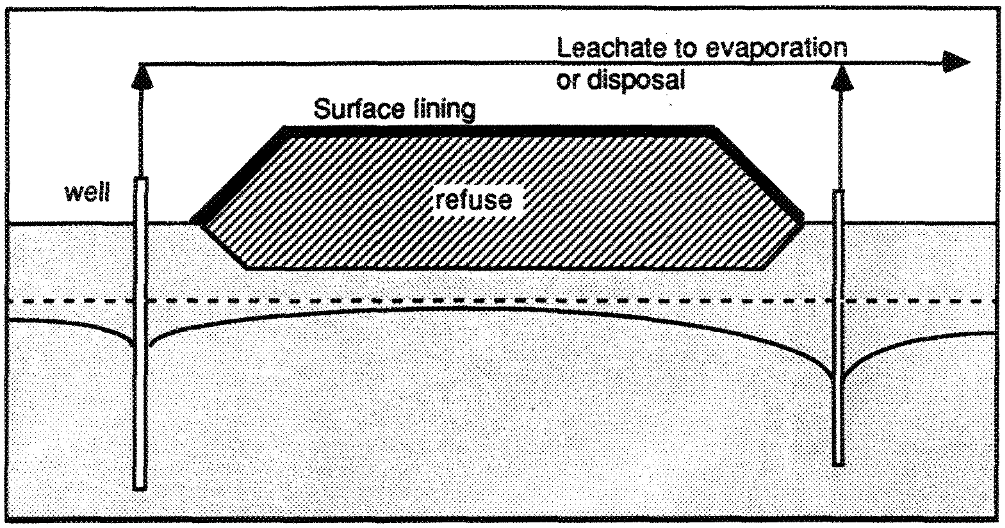

Fig. 11.7. Control of groundwater pollution by creation of landfills, after Vladimir Novotny et al. (1981).

As in Fig. 11.7, infiltrating water could be restricted by placement of an impermeable layer over the landfill. If the aquifer becomes highly contaminated, wells may have to be drilled by the sides of the landfills from which the leachate could be pumped out from the aquifer. This is an expensive procedure and the only way to avoid it would be to operate a landfill site properly, where municipal, industrial or private waste could be disposed compacted and clay capped in an appropriate manner.

The chances of nitrate contamination could be reduced by replacing the hand dug wells with deep bore wells. Direct infiltration from the surface around the well casing could be avoided by cementing the upper part (up to few meters below the soil water region).

The portion of the aquifer that is contaminated should be restricted. A method of improving the contaminated water would be drilling a line of wells or constructing drainage ditch (for shallow aquifers) at some distance from the recharge area and taking out the contaminated water from the aquifer. Such an application may not be required for the present problem in the Santa Lucia basin. However, it may be an important aspect to consider if the worst situations may arise.

It may be a difficult task to restrict the use of fertilizers. Solbe (1986) suggests the use of cover plants as alternative methods to reducing nitrate concentration from groundwater. Cover plants with high capacity of nitrogen uptake (green manure crops or catch crops) can be introduced between crops. The cover plants must be sown at the time of harvesting the main crop or at the time of ploughing. These cover plants could also be applied around perennial crops, fruit trees and vineyards. This method could easily be applied in the Lower Santa Lucia basin.

Biological treatments of nitrates by denitrification process is another method of reducing nitrate content in groundwaters. The rate and degree of denitrification are influenced by four factors Solbe (1986): oxygen content, moisture content, pH, and carbon content. In general, denitrification is activated by lack of oxygen, increase of moisture content, high pH and adequate carbon. The introduction of carbon by discing or ploughing has proved to be very effective method of in situ denitrification Solbe (1986). Such method could also be applied in the Lower Santa Lucia basin.

11.4 Recommendations on Development of Groundwater Resources

One of the main objectives of this work being provision of recommendations for future development of groundwater resources, a water resource map has been prepared so that the most relevant informations for practical applications come into focus (see Fig.11.8). The water resources map is prepared by the superposition of water quality map with other maps, like geological map transmissivity map and specific yield map. This map helps to geographically locate areas of interest; it expresses the overall assessments made on the general groundwater quantity and quality of the area.

The most favorable areas for the development of groundwater are the coastal plains. Well field areas (111** in Fig.11.8) have been chosen for future development of groundwater. Obviously, legal and administrative matters should be settled as to sharing of groundwater with the local farmers before commencing large scale groundwater exploitation. Although the groundwater quality of some part of the coastal plain (312! in Fig.11.8) is poor, it could be a potential groundwater resource area if some provision be made to improve the groundwater quality. The second well field areas chosen for future groundwater development are located between the surface water divide along "ruta 1" and San Jose river. Local groundwater productions could continue in the rest part of the area with precautions taken to avoid contaminated regions. Exploitation of groundwater is not recommended in the areas susceptible to saltwater contamination (122+ in Fig.11.8).

More detailed hydrogeological work is recommended in the chosen well field areas; systematic, continuous monitoring of the resource should be conducted. Exploration boreholes (piezometers) should be drilled in the well field areas equiped with small diameter casing and screen. These boreholes should be spaced uniformly with an average spacing of two kilometers. Some of these boreholes could even be used as observation wells while pumping tests are conducted. Monthly water level records are sufficient for the present. However, automatic water level recorders may be installed, if continuous monitoring of water levels may be desired.

The water quality could be monitored from water samples taken from exploited wells. Measurement of electrical conductivity could be taken more frequently while full chemical analysis could be done once or twice a year. The information withdrawn from the chemical characteristics of the waters alone is not sufficient to state the potability of groundwater. It would therefore be an essential task to undergo bacteriological analysis especially on some of the shallow excavated wells with high nitrate content.

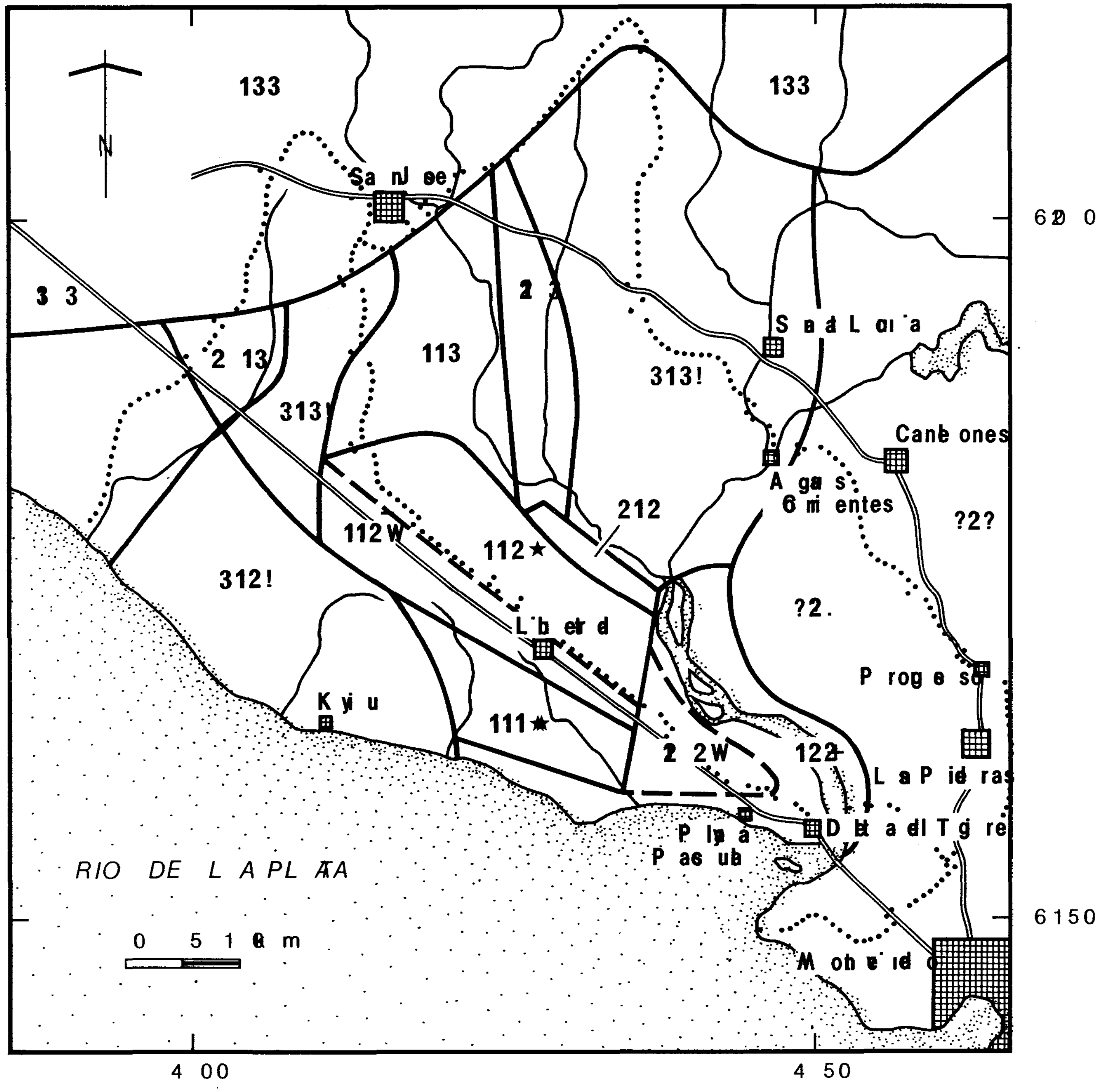

Figure 118

Water Resources Map of the Lower Santa Lucia Basin

LEGEND FOR THE WATER RESOURCES MAP

231
- FIRST NUMBER REFERS TO WATER QUALITY
- SECOND NUMBER REFERS TO GEOLOGY (PERMEABILITY SPECIFIC YIELD)
- THIRD NUMBER REFERS TO TRANSMISSIVITY

\+ Area affected with saltwater contamination from Rio de la Plata

★ ★ Strongly and less strongly recommended

★ Wellfield areas for GW development

! Very high nitrate content, the contaminated wells should be abandonned as soon as possible

W High density of wells

LEGEND FOR WATER QUALITY

EXPLANATIONS FOR THE NUMBERS ON THE MAP	COMMENTS
1 = TDS < 1000 mg/l and NO_3 < 50 mg/l	Good
2 = TDS < 1000 mg/l and NO_3 > 50 mg/l or TDS > 1000 mg/l and NO_3 < 50 mg/l	Fair to poor
3 = TDS > 1000 mg/l and NO_3 > 50 mg/l	Poor

LEGEND FOR GEOLOGY (PERMEABILITY, SPECIFIC YIELD)

EXPLANATIONS FOR THE NUMBERS ON THE MAP	COMMENTS
1 = Raigon and Libertad Formation (K > 5 m/day, S > 20%)	Very good
2 = Dolores and Raigon or Fray Bentos (K < 5 m/day, S < 20%	Fair to poor
3 = Basement Complex (K << 5 m/day, S << 20%)	Poor

LEGEND FOR TRANSMISSIVITY

EXPLANATIONS FOR THE NUMBERS ON THE MAP	COMMENTS
1 = T > 200 m^2/day	Very good
2 = 100 m^2/day < T < 200 m^2/day	Fair to poor
3 = T < 100 m^2/day	Poor

GENERAL CONCLUSIONS

This study has revealed some important hydrogeological aspects that are indispensable for groundwater resources development:

The Lower Santa Lucia basin is part of a large graben which embodies minor grabens and horsts, which are filled with Oligocene to Holocene sediments. The aquifer system consists generally of a sandy unit (Raigon Formation) whose permeability ranges from about 5 to 30 m/ day. Some small lenses of clay and silt are embodied within this formation, thus creating confined to semi-confined situations. The aquifer unit is covered, at places, by a relatively less permeable unit (Libertad Formation with an average permeability of 2 to 5m/day). In general, the response of the aquifer to precipitation shows free water table situations. The "potentiality" (permeability and thickness) increases towards the south. The transmissivity values range between 200 to 300 m^2 per day towards the coastal areas. Some groundwater is being discharged from the aquifer along rivers whose seepages commence near the main surface water divide (along "ruta 1" and "ruta 3"). The groundwater discharge along these river courses produces a considerable loss of groundwater from the basin. Potential loss of groundwater also occurs by evapotranspiration from the swampy areas along the lower courses of the rivers. On the other hand, some evidences like north - south fracture systems on the basement rocks indicate replenishment of the sedimentary formation by groundwater inflow from the upper part of the basin.

The water balance calculations (see chapter 7) based on nine years (1980 to 1988) climatic data showed negative change in storage in the hydrogeologic regions which are dominated by marsh. The present level of near surface groundwater in these regions is accounted by the inflow of groundwater from the adjacent rivers as well as from high level groundwater in the adjacent aquifer. In general, the change in storage in most regions is positive (around 400mm/year).

It has been attempted to forecast the water level situations over long periods of pumping in the coastal areas. An area of 10000m^2 in the coastal zone has been considered as an example for which monthly water balance was calculated. The application of transient groundwater flow model for this area showed a drop of head of 38 centimeters in one year, corresponding to transmissivity value of 225 m^2 /day, pumping rate of 30 m^3 /day and "net infiltration" as obtained from the average monthly water balance of nine years (1980 to 1988). The exact rate of present pumpage within the area considered is not known. However, with discharge of 30 m^3 /day from a 10000m^2 area the sustained yield by replenishment will keep the water level to a "safe" level (not more than 38 centimeters in one year.

The analyses of the stable isotope of ^{18}O have revealed the importance of precipitation as being a major source of groundwater supply to the aquifer. The isotope analyses of saltwater from Rio de la Plata showed clear relationship between ∂^{18}O and TDS, conductivity salinity and chlorinity. The ∂^{18}O values have not indicated possibility of mixing of surface water from Rio de la Plata with the groundwater of the coastal aquifers. However, the clear relations of the ∂^{18}O with the above mentioned characteristic parameters of saltwater proves the importance of $\partial^{18}O$ to monitoring saltwater intrusion.

The Eh and pH relationships of the water samples reflects the transitional environments from which the water samples were collected. The common sedimentary association corresponding to this environments reflect oxidizing situation.

The ion content of the waters (from the chemical analysis of the water samples collected in January to February, 1987) indicate that most of the waters are undersaturated with respect to calcite and dolomite. However, most of the waters were found to be moderate to hard.

It has also been attempted to trace the origin of the waters from the chemical analyses. Several methods, like magnesium to calcium ratio, sodium to potassium ratio, and calcium plus magnesium to potassium plus sodium ratio were employed. It has been possible to conclude from these methods that relatively small amount of water could possibly enter into the aquifer system from the basement rocks. In general, the concentration of calcium in the waters (on average less than 50 mg/l) and the hardness properties (between 100 and 150 mg/l) do not suggest carbonate origin of the waters.

The possible origin of the waters have been more precisely understood from the different hydrochemical data interpretation methods employed. The grouping of the water samples according to their hydrochemical facies shows that most of the waters are of $NaHCO_3$ type, some waters $Ca(HCO_3)_2$ type, and few waters NaCl type.

The geographical distribution of the water samples from the point of view of their general chemical characteristics have been analyzed by Q - mode factor analysis.

The similarity of the waters too have been plotted on a map. The conclusion drawn from these methods are:

Basically, the chemical quality of the waters has resulted from the composite effect of the basement and sedimentary deposits. The chemical qualities of the fresh waters from the upper courses of Santa Lucia and San Jose rivers may have some influence on the groundwater towards the lower parts of the basin. The iso - nitrate contour map and iso - TDS contour maps show that the areas around these rivers are free from high nitrates and high TDS. Although the lower part of the basin could be affected by recharge coming from the upper part, the influence of man's activity, in adding fertilizers onto the alluvial plain will also contribute to the groupings observed; the effect of point source pollution, like domestic and industrial pollution would intensify the situation. In the coastal areas, the chemical quality of the groundwater may have been influenced by saltwater from Rio de la Plata; the presence of sodium chloride type of waters suggests deposition of wind-born salt crystals from the saltwater in the south.

This study has not shown any clear evidence of aquifer contamination due to saltwater intrusion associated with pumping in the coastal areas. However, the areas around Delta del Tigre do not escape from such fate, because the surface water of Santa Lucia is also affected by the salinity of the Rio de la Plata whose effect reaches up to Aguas Corrientes during high tide. Lowering of the groundwater level by few centimeters may then cause saltwater movement towards the aquifer from the saltwater body (Santa Lucia and Rio de la Plata which surrounds Delta del Tigre).

Although the chemical quality of most of the groundwater in the lower Santa Lucia basin has been within the limit of acceptable standard for agricultural and industrial purposes, it is vulnerable to contamination, due to the general unconfined situation. The very high nitrate content (100 to 200 mg/l in a number of hand dug wells) renders groundwater unsuitable for drinking purposes.

The major findings in this study have been summarized in the form of a water resources map. Practical applications to groundwater resources development could be implemented based on this map. However, monitoring of water levels and groundwater quality control are essential to check any possible danger of hazard (seawater intrusion, aquifer damage, etc.).

This study has shown that quality of groundwater, in the Lower Santa Lucia basin is at a critical stage. Therefore development of groundwater resources would require improving the quality. The different ways of improving water quality are given in section 11.3. In the practical life, it may not be desired to wait until the groundwater in the area gets improved; the need to exploiting groundwater of a reasonable quantity and quality may become crucial at a given time. This study affirms that the desired amount of groundwater (for drinking, agricultural and industrial purposes) can be obtained from the Santa Lucia Basin, provided that a great deal of care is given to the protection of its quality. People must be aware of the possible hazard that the deterioration of groundwater may cause to the health of human beings. A major effort should be taken to protect and improve the groundwater quality in the Lower Santa Lucia Basin.

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APPENDICES

Abreviations utilized in the Appendices

x, y = Geographical co-ordinates

z = Elevation above sea level

D = Diameter of well

Date = Date of drilling, water level measurement and sampling

T.D. = Total depth

SWL = Static water level

DWL = Dynamic water level

Q = Discharge

Q/s = Specific discharge

S. No. = Sample number

e = Excavated wells

p = Drilled wells

meq/l = Milliequivalent per litre

mg/l = Milligram per litre

mS/cm = Micro Siemens per centimetre

TDS = Total dissolved solids

SAR = Sodium adsorption ratio

Table 1 List of drilled wells

W. No.	X	Y	Z	Date	Drilled by	T.D.	D
946/1	431.8	6162	22 m	25-sept-44	DINAMIGE	93.0 m	—
946/2	431.8	6162	22 m	25-octo-44	DINAMIGE	19.0 m	155mm
1322	432.2	6162	18 m	20-sept-61	DINAMIGE	22.0 m	184mm
1163	427.7	6166	35 m	26-octo-54	DINAMIGE	23.5 m	152mm
1177/2	427.7	6166	35 m	21-sept-55	DINAMIGE	38.4 m	216mm
1177/1	427.7	6166	35 m	10-déce-55	DINAMIGE	21.0 m	216mm
748	434.5	6163	14 m	2-déce-31	DINAMIGE	30.0 m	172mm
591/1	430.1	6161	34 m	19-avri-33	DINAMIGE	42.1 m	150mm
591/2	430.1	6161	34 m	9-mars-33	DINAMIGE	29.2 m	115mm
591/3	430.1	6161	34 m	23-janv-38	DINAMIGE	40.2 m	150mm
591/4	430.1	6161	34 m	10-août-33	DINAMIGE	23.8 m	150mm
591/5	430.1	6161	34 m	4-nove-33	DINAMIGE	44.0 m	200mm
591/6	430.1	6161	34 m	15-déce-33	DINAMIGE	48.0 m	295mm
284	425.2	6168	32 m	10-mai-21	DINAMIGE	51.1 m	245mm
840	425.2	6168	32 m	15-avri-41	DINAMIGE	35.9 m	285mm
149/3	424.5	6168	35 m	21-janv-10	DINAMIGE	14.5 m	184mm
1284	426.2	6166	30 m	10-avri-60	DINAMIGE	28.6 m	194mm
1130/1	420.5	6166	26 m	8-juin-58	DINAMIGE	33.3 m	152mm
1130/2	420.5	6166	26 m	27-août-53	DINAMIGE	36.5 m	152mm
1138	420.5	6166	26 m	29-août-54	DINAMIGE	35.5 m	152mm
1170/1	420.5	6166	26 m	26-janv-55	DINAMIGE	40.6 m	153mm
1202	420.5	6166	26 m	31-mai-58	DINAMIGE	47.8 m	156mm
1331/1	420.5	6166	26 m	4-mai-62	DINAMIGE	29.0 m	194mm
1331/2	420.5	6166	26 m	17-août-60	DINAMIGE	31.8 m	194mm
794/1	420.5	6168	26 m	26-mars-39	DINAMIGE	27.8 m	172mm
794/2	420.5	6168	26 m	10-sept-39	DINAMIGE	45.9 m	146mm
924	420.5	6168	26 m	26-janv-40	DINAMIGE	56.0 m	167mm
1109/2	420.5	6168	26 m	16-avri-52	DINAMIGE	37.0 m	170mm
1109/2	420.5	6168	26 m	25-juin-52	DINAMIGE	41.0 m	209mm
1117	420.5	6168	26 m	15-sept-52	DINAMIGE	31.0 m	152mm
1371	420.5	6168	26 m	16-déce-65	DINAMIGE	34.6 m	194mm
777	417.5	6161	9 m	14-sept-48	DINAMIGE	38.9 m	232mm
858	409.6	6166	10 m	26-mai-41	DINAMIGE	11.9 m	146mm
716	414	6170	28 m	4-mars-31	DINAMIGE	35.7 m	152mm
149/4	420.2	6172	45 m	25-mars-10	DINAMIGE	41.0 m	184mm
1016	403.5	6180	18 m	25-nove-47	DINAMIGE	25.2 m	210mm
1155	416.8	6173	16 m	—	DINAMIGE	37.0 m	—
149/5	405.6	6176	42 m	17-juin-10	DINAMIGE	27.0 m	184mm
C 90	405.6	6176	42 m	—	COPERPOA	31.0 m	—
C487	405	6182	30 m	—	COPERPOA	18.4 m	—
C489	405	6182	30 m	—	COPERPOA	22.5 m	—
C496	405	6182	30 m	—	COPERPOA	20.5 m	—
C 502	405	6182	30 m	—	COPERPOA	19.0 m	—
C497	426.5	6166	37 m	—	COPERPOA	38.0 m	—

Continued....

Table 1 List of drilled wells

Well No.	SWL	DWL	(Q)	Q/s
946/1	—	—	—	—
946/2	12.3 m	6.9 m	8.3m3/h	1.5 m2/h
1322	8.9 m	1.5 m	6.3m3/h	0.9 m2/h
1163	17.3 m	14.8 m	4.4m3/h	1.8 m2/h
1177/2	24.6 m	18.9 m	22.7m3/h	4.0 m2/h
1177/1	20.0 m	18.0 m	10.5m3/h	5.4 m2/h
748	-8.3 m	-14.6 m	30.0m3/h	4.8 m2/h
591/1	10.8 m	-4.5 m	50.0m3/h	3.3 m2/h
591/2	20.0 m	10.1 m	31.2m3/h	3.2 m2/h
591/3	13.5 m	-5.1 m	36.0m3/h	1.9 m2/h
591/4	22.8 m	13.2 m	28.0m3/h	2.9 m2/h
591/5	26.4 m	16.3 m	90.0m3/h	8.9 m2/h
591/6	11.5 m	0.8 m	88.0m3/h	8.2 m2/h
284	13.1 m	-9.9 m	14.4m3/h	0.6 m2/h
840	11.9 m	7.6 m	16.0m3/h	3.7 m2/h
149/3	24.7 m	—	4.0m3/h	—
1284	21.9 m	18.2 m	19.3m3/h	5.3 m2/h
1130/1	-0.2 m	-1.6 m	22.0m3/h	15.7 m2/h
1130/2	0.8 m	-2.8 m	13.0m3/h	3.6 m2/h
1138	-0.7 m	-3.7 m	14.3m3/h	4.8 m2/h
1170/1	0.8 m	-2.5 m	8.0m3/h	2.4 m2/h
1202	5.8 m	-13.4 m	6.6m3/h	0.3 m2/h
1331/1	8.0 m	5.2 m	16.5m3/h	5.9 m2/h
1331/2	10.4 m	7.1 m	20.3m3/h	6.2 m2/h
794/1	12.0 m	4.0 m	26.4m3/h	3.3 m2/h
794/2	—	-12.0 m	15.8m3/h	—
924	5.7 m	2.9 m	16.1m3/h	5.8 m2/h
1109/2	-1.3 m	-4.3 m	17.8m3/h	5.9 m2/h
1109/2	1.0 m	-6.8 m	15.8m3/h	2.0 m2/h
1117	7.4 m	5.0 m	13.8m3/h	5.8 m2/h
1371	-0.7 m	-1.2 m	9.3m3/h	18.6 m2/h
777	-14.0 m	-26.5 m	22.4m3/h	1.8 m2/h
858	4.3 m	-4.7 m	19.8m3/h	2.2 m2/h
716	9.8 m	0.8 m	14.3m3/h	1.6 m2/h
149/4	13.0 m	—	7.0m3/h	—
1016	11.3 m	7.8 m	19.8m3/h	5.7 m2/h
1155	-11.0 m	-16.5 m	6.6m3/h	1.2 m2/h
149/5	26.0 m	—	7.0m3/h	—
C 90	—	—	4.4m3/h	—
C487	—	—	22.0m3/h	—
C489	—	—	22.8m3/h	—
C496	—	—	20.3m3/h	—
C 502	—	—	17.3m3/h	—
C497	—	—	16.5m3/h	—

Continued......

Table 1 List of drilled wells

W.No.	X	Y	Z	Date	Drilled by	T.d.	D
C 454	430.8	6162	31 m	—	COPERPOA	31.8 m	—
B788	411	6178	48 m	—	Hidrotecnica S	33.5 m	—
B211	410.3	6178	50 m	—	Hidrotecnica S	25.0 m	—
B789	410.3	6178	50 m	—	Hidrotecnica S	31.0 m	—
B112	408.8	6180	37 m	—	Hidrotecnica S	37.5 m	—
B306	412	6163	25 m	—	Hidrotecnica S	36.7 m	—
B30	412	6163	32 m	—	Hidrotecnica S	34.7 m	—
B944	432	6156	4 m	—	Hidrotecnica S	12.8 m	—
B996	432	6156	4 m	—	Hidrotecnica S	14.4 m	—
B1181	432	6156	4 m	—	Hidrotecnica S	25.5 m	—
E366	430.1	6161	34 m	—	Pike YCIA.S.A	31.0 m	—
E364	425.4	6166	35 m	—	Pike YCIA.S.A	28.5 m	—
E352	425.2	6168	32 m	—	Pike YCIA.S.A	66.3 m	—
E350	423.5	6169	48 m	—	Pike YCIA.S.A	34.5 m	—
E355	404.2	6174	42 m	—	Pike YCIA.S.A	35.3 m	—
E360/1	401	6174	38 m	—	Pike YCIA.S.A	48.5 m	—
E360/2	401	6174	38 m	—	Pike YCIA.S.A	36.8 m	—
E360.3	401	6174	38 m	—	Pike YCIA.S.A	32.8 m	—
A149/6	392.9	6192	—	1-sept-06	Dinamige	22.5 m	184mm
C134	396.4	6189	—	—	Coperpoa	36.7 m	—
A751	423.1	6169	52 m	—	Dinamige	45.0 m	—
C90	420.5	6172	40 m	—	Dinamige	31.0 m	—
H 283	413	6161	42 m	—	Dinamige	53.0 m	—
H286	413	6161	42 m	—	Dinamige	68.3 m	—
H41	420.5	6168	26 m	—	Dinamige	31.0 m	—
H42	420.5	6168	27 m	—	Dinamige	42.7 m	—
H88	420.5	6168	27 m	—	Dinamige	56.0 m	—
17	406.7	6171	27 m	—	Dinamige	23.0 m	—
K15/1	408.8	6179	28 m	—	Dinamige	41.8 m	—
K15/2	408.8	6179	28 m	—	Dinamige	39.8 m	—
K112	421.3	6170	41 m	—	Dinamige	51.1 m	—
N4/1	411.6	6166	30 m	—	Dinamige	34.0 m	—
N4/2	411.6	6166	30 m	—	Dinamige	40.0 m	—
N4/3	411.6	6166	30 m	—	Dinamige	45.0 m	—
P35	404.7	6176	35 m	—	Dinamige	31.0 m	—
R16	428	6165	42 m	—	Dinamige	60.0 m	—
R18	413	6161	42 m	—	Dinamige	10.0 m	—
R42	428	6165	42 m	—	Dinamige	55.0 m	—
N7	420.9	6170	35 m	—	Dinamige	44.0 m	—
N5	419.6	6171	47 m	—	Dinamige	53.0 m	—
B62	412.7	6192	45 m	—	Dinamige	16.8 m	—
C250	433.5	6181	15 m	—	Dinamige	45.0 m	—
AB62/1	403.7	6183	16 m	14-nove-60	Dinamige	55.5 m	—
A1362/2	403.7	6183	16 m	14-nove-60	Dinamige	56.5 m	—

Continued......

Table 1 List of drilled wells

W.No.	SWL	DWL	(Q)	Q/s
C 454	----	----	15.8m3/h	----
B788	----	----	5.2m3/h	----
B211	----	----	3.5m3/h	----
B789	----	----	19.6m3/h	----
B112	----	----	----	----
B306	----	----	1.8m3/h	----
B30	----	----	2.7m3/h	----
B944	----	----	1.8m3/h	----
B996	----	----	2.0m3/h	----
B1181	----	----	2.2m3/h	----
E366	----	----	6.0m3/h	----
E364	----	----	5.4m3/h	----
E352	----	----	5.0m3/h	----
E350	----	----	1.2m3/h	----
E355	----	----	3.8m3/h	----
E360/1	----	----	9.0m3/h	----
E360/2	----	----	7.5m3/h	----
E360.3	----	----	8.0m3/h	----
A149/6	-7.4 m	----	2.5m3/h	----
C134	----	----	3.7m3/h	----
A751	----	----	18.0m3/h	----
C90	----	----	12.0m3/h	----
H 283	----	----	5.0m3/h	----
H286	----	----	1.6m3/h	----
H41	----	----	7.0m3/h	----
H42	----	----	9.0m3/h	----
H88	----	----	6.0m3/h	----
? 17	----	----	3.0m3/h	----
K15/1	----	----	----	----
K15/2	----	----	----	----
K112	----	----	5.5m3/h	----
N4/1	----	----	3.0m3/h	----
N4/2	----	----	5.0m3/h	----
N4/3	----	----	10.0m3/h	----
P35	----	----	3.5m3/h	----
R16	----	----	16.0m3/h	----
R18	----	----	6.0m3/h	----
R42	----	----	24.0m3/h	----
N7	----	----	15.0m3/h	----
N5	----	----	5.5m3/h	----
B62	----	----	4.0m3/h	----
C250	----	----	5.0m3/h	----
AB62/1	9.2 m	2.2 m	10.0m3/h	1.4 m2/h
A1362/2	10.8 m	-2.6 m	9.3m3/h	0.7 m2/h

Continued......

Table 1 List of drilled wells

W.No.	X	Y	Z	Date	Drilled by	Tot.dep.	D
A971/1	437	6195	45 m	11-avri-42	Dinamige	62.0 m	—
Ac 43	445.2	6206	55 m	—	Dinamige	44.5 m	—
A942	445.2	6206	55 m	—	Dinamige	31.5 m	—
H325	448.1	6200	31 m	—	Dinamige	54.0 m	—
K96	435	6215	65 m	—	Dinamige	27.2 m	—
K 98	434.6	6217	55 m	—	Dinamige	22.0 m	—
A 747	418.1	6200	25 m	21-janv-44	Dinamige	34.1 m	—
A990	418.8	6201	23 m	24-sept-42	Dinamige	53.3 m	—
Ac 52	419.9	6200	35 m	5-nove-16	Dinamige	25.3 m	—
5	420.4	6202	28 m	—	Cados Froritto	—	—
12	414.9	6201	35 m	—	Cados Froritto	18.0 m	—
11	420	6201	30 m	—	Cados Froritto	63.0 m	—
18	415.1	6199	35 m	—	Cados Froritto	29.0 m	—
20	425.7	6199	42 m	—	Cados Froritto	29.5 m	—
21	420	6199	25 m	—	Cados Froritto	42.5 m	—
E 362	416	6199	38 m	—	Pike 1 CIA	35.7 m	—
E351	432	6197	42 m	—	Pike 1 CIA	49.3 m	—
A971/1	428.9	6197	35 m	11-avri-42	Dinamige	52.0 m	—
A971/2	428.9	6197	35 m	9-avri-42	Dinamige	21.5 m	162mm
A 971/3	428.9	6197	35 m	16-juin-42	Dinamige	20.5 m	152mm
X Po8	425.1	6199	35 m	—	Dinamige	—	—
A 476	445.8	6167	21 m	—	Dinamige	100.0 m	—
A538	448.9	6166	26 m	—	Dinamige	80.0 m	—
A816	447.5	6165	35 m	—	Dinamige	30.0 m	—
A490	440.6	6173	11 m	—	Dinamige	116.2 m	—
A 1196	439.7	6170	8 m	—	Dinamige	116.0 m	—
A 756	441.4	6181	20 m	25-janv-34	Dinamige	53.0 m	—
H 192	450.6	6185	9 m	—	Stella S.A	38.7 m	—
H194	450.6	6185	9 m	—	Stella S.A	37.9 m	—
H121	443.4	6190	15 m	—	Stella S.A	19.7 m	—
H127	443.4	6190	15 m	—	Stella S.A	57.0 m	—
H116	446.3	6182	16 m	—	Stella S.A	32.0 m	—
K208	448.4	6166	18 m	—	Luis Girino	51.0 m	—
K337	442.5	6165	7 m	—	Luis Girino	20.2 m	—
E353/1	443.4	6190	15 m	—	Pike y CIA	99.0 m	—
E353/2	443.1	6190	17 m	—	Pike y CIA	—	—
E358	441.4	6181	20 m	—	Pike y CIA	70.6 m	—
B1179	440.1	6184	22 m	—	Hidrtecnica	26.8 m	—
K327	443.4	6190	15 m	—	Luis Girino	16.5 m	—
C Po 1	439.6	6157	15 m	—	Coperoa	—	—

Continued......

Table 1 List of drilled wells

Well No.	SWL	DWL	(Q)	Q/s
A971/1	39.6 m	—	—	—
Ac 43	—	—	5.7m3/h	—
A942	—	—	4.8m3/h	—
H325	—	—	1.0m3/h	—
K96	—	—	—	—
K 98	—	—	8.0m3/h	—
A 747	20.7 m	1.3 m	6.0 m	0.3 m2/h
A990	11.8 m	-25.8 m	3.5 m	0.1 m2/h
Ac 52	20.5 m	10.7 m	2.5 m	0.3 m2/h
5	—	—	10.0m3/h	—
12	—	—	1.5m3/h	—
11	—	—	3.0m3/h	—
18	—	—	1.0m3/h	—
20	—	—	2.0m3/h	—
21	—	—	1.0m3/h	—
E 362	—	—	5.7m3/h	—
E351	—	—	4.0m3/h	—
A971/1	29.6 m	—	4.0m3/h	—
A971/2	30.0 m	28.0 m	22.0m3/h	11.0 m2/h
A 971/3	30.9 m	27.9 m	23.0m3/h	7.7 m2/h
X Po8	—	—	12.0m3/h	—
A 476	—	—	0.8m3/h	—
A538	—	—	5.5m3/h	—
A816	—	—	2.0m3/h	—
A490	—	—	8.0m3/h	—
A 1196	—	—	6.0m3/h	—
A 756	—	—	—	—
H 192	—	—	2.3m3/h	—
H194	—	—	2.3m3/h	—
H121	—	—	2.6m3/h	—
H127	—	—	4.2m3/h	—
H116	—	—	17.0m3/h	—
K208	—	—	1.5m3/h	—
K337	—	—	15.0m3/h	—
E353/1	—	—	5.3m3/h	—
E353/2	—	—	—	—
E358	—	—	4.8m3/h	—
B1179	—	—	3.0m3/h	—
K327	—	—	4.0m3/h	—
C Po1	—	—	—	—

Table 2 Monthly water level records

S.N.	Topo-Map	Propriator	Ty.	X	Y	Alt.	T.d.
1	San Jose	EchemeNDi,F	e	417.50	6206.10	46.00	15.70
2	San Jose	Cabrera	e	417.90	6214.40	55.00	18.30
4	San Jose	Maidana,R	e	415.30	6208.70	46.00	19.80
5	San Jose	Barbe	p	407.80	6200.80	74.00	43.50
7	San Jose	Fabre,R	p	406.60	6197.60	61.00	20.90
9	San Jose	Acosta,E	p	404.80	6197.20	59.00	33.00
10	San Jose	Perez,E	p	402.20	6195.20	53.00	23.60
11	Arazati	Vega,J	p	395.90	6190.70	24.00	45.30
12	Arazati	Fabre,S	e	388.70	6183.50	12.00	8.10
14	Arazati	Artagabeitia	p	393.80	6186.20	41.00	31.35
15	Arazati	Fabre,J.A.	p	394.60	6189.00	44.00	33.80
17	Cagancha	Rapetti,P	e	404.10	6180.60	27.00	13.30
19	Cagancha	Maccio,A	e	402.10	6179.90	29.00	14.10
21	Arazati	Perez,L	e	397.50	6179.40	12.00	22.00
22	Arazati	Berriel,L	e	393.30	6177.50	33.00	17.00
23	Pta.Jesus Ma.	Regusi,B	e	392.50	6175.10	5.00	8.80
24	Pta.Jesus Ma.	Aserradero	e	389.90	6176.10	5.00	12.40
25	Pta.Jesus Ma.	Rodriguez,S	e	395.30	6173.90	22.00	10.10
26	Pta.Jesus Ma.	Sellanes,D	e	399.20	6172.50	37.00	23.20
27	Pta.Jesus Ma.	Calleros Hno	p	401.00	6174.10	40.00	22.00
28	Sangregorio	Maccio,F	p	404.40	6174.40	45.00	33.30
29	Sangregorio	Travieso	e	405.10	6171.80	33.00	12.20
38	Cagancha	Calleros,A	e	407.00	6180.70	28.00	5.90
39	Cagancha	Guerra	e	404.90	6182.40	31.00	15.00
41	Cagancha	Chacon,V	e	401.80	6185.50	12.00	5.37
42	Arazati	Rapetti,C	p	398.50	6187.20	40.00	40.00
43	Arazati	Fabre,J	p	398.10	6187.10	44.00	40.20
44	Arazati	Escuela 91	e	396.30	6183.80	29.00	21.00
45	Cagancha	Fabre,J	p	404.50	6192.50	42.00	30.00
47	San Jose	Machi,J	e	412.20	6196.70	55.00	13.30
52	Cagancha	Diaz,W	e	411.90	6187.70	46.00	15.73
53	Cagancha	Fernandez,L	e	408.70	6188.20	36.00	21.00
54	Cagancha	Bentancour,N	e	416.70	6191.50	36.00	21.20
55	Cagancha	Lema,A	e	419.40	6185.10	18.00	15.40
56	Cagancha	Perez,N	e	422.50	6180.80	21.00	11.30
57	Cagancha	Perez,N	p	420.50	6184.60	22.00	32.37
59	Cagancha	Perez,C	e	425.50	6176.80	18.00	9.00
63	Cagancha	Esteche,M	e	413.85	6181.85	45.00	16.38
68	Cagancha	Viera,W	e	416.70	6182.85	33.00	11.20
69	Cagancha	Acuna,R	e	420.50	6177.30	42.00	20.20
74	Cagancha	Moro Tambo	p	418.00	6177.3	36.00	25.00
76	Ccgancha	Cabrera,N	e	413.20	6168.00	30.00	15.40
77	San Gregorio	Britos,N	e	416.90	6167.30	35.00	20.85
78	San Gregorio	Rodriguez	e	406.80	6162.60	28.00	7.90
79	San Gregorio	Cabrera,A	e	413.30	6162.80	46.00	38.00
82	San Gregorio	Garcia,N	e	423.40	6166.00	33.00	16.00

Continued..........

Table 2 Monthly water level records

S.N.	Date	SWL	Date	S.W.L	Date	S.W.L.	Date	S.W.L.
1	octo-86	33.73	déce-87	ND	mars-88	32.83	mai-88	33.42
2	octo-86	41.70	déce-87	ND	mars-88	41.13	mai-88	41.15
4	octo-86	37.39	déce-87	36.54	mars-88	35.20	mai-88	35.20
5	octo-86	60.55	déce-87	ND	mars-88	57.45	mai-88	58.67
7	octo-86	56.60	déce-87	51.84	mars-88	ND	mai-88	51.67
9	octo-86	50.48	déce-87	49.00	mars-88	ND	mai-88	48.48
10	octo-86	39.40	déce-87	38.20	mars-88	ND	mai-88	37.85
11	octo-86	20.40	déce-87	18.56	mars-88	ND	mai-88	21.87
12	octo-86	7.18	déce-87	5.55	mars-88	5.04	mai-88	5.97
14	octo-86	23.05	déce-87	22.25	mars-88	21.65	mai-88	23.05
15	octo-86	33.85	déce-87	ND	mars-88	32.83	mai-88	32.76
17	octo-86	19.47	déce-87	ND	mars-88	17.14	mai-88	17.65
19	octo-86	20.26	déce-87	20.21	mars-88	18.45	mai-88	17.89
21	octo-86	8.80	déce-87	ND	mars-88	ND	mai-88	2.25
22	octo-86	20.55	déce-87	19.00	mars-88	ND	mai-88	19.10
23	octo-86	0.00	déce-87	-2.00	mars-88	-2.87	mai-88	1.66
24	octo-86	-6.70	déce-87	-6.00	mars-88	-6.43	mai-88	5.58
25	octo-86	15.60	déce-87	ND	mars-88	13.70	mai-88	13.85
26	octo-86	22.40	déce-87	25.33	mars-88	17.48	mai-88	18.20
27	octo-86	28.75	déce-87	24.60	mars-88	23.82	mai-88	25.20
28	octo-86	29.00	déce-87	25.08	mars-88	24.02	mai-88	ND
29	octo-86	25.56	déce-87	24.33	mars-88	23.80	mai-88	ND
38	octo-86	25.33	déce-87	ND	mars-88	23.10	mai-88	ND
39	octo-86	19.30	déce-87	ND	mars-88	18.50	mai-88	19.35
41	octo-86	10.45	déce-87	8.88	mars-88	9.59	mai-88	9.10
42	octo-86	23.00	déce-87	24.63	mars-88	ND	mai-88	ND
43	octo-86	26.45	déce-87	24.28	mars-88	24.60	mai-88	25.17
44	octo-86	13.70	déce-87	12.68	mars-88	12.03	mai-88	12.75
45	octo-86	23.85	déce-87	24.72	mars-88	ND	mai-88	24.45
47	octo-86	52.00	déce-87	48.69	mars-88	ND	mai-88	ND
52	octo-86	34.00	déce-87	33.00	mars-88	32.72	mai-88	33.15
53	octo-86	31.44	déce-87	ND	mars-88	ND	mai-88	31.00
54	octo-86	18.55	déce-87	ND	mars-88	16.30	mai-88	ND
55	octo-86	4.95	déce-87	4.50	mars-88	3.50	mai-88	3.90
56	octo-86	ND	déce-87	ND	mars-88	8.66	mai-88	11.10
57	octo-86	13.35	déce-87	ND	mars-88	12.52	mai-88	12.57
59	octo-86	14.55	déce-87	ND	mars-88	13.30	mai-88	13.70
63	octo-86	32.45	déce-87	ND	mars-88	30.48	mai-88	30.31
68	octo-86	25.60	déce-87	ND	mars-88	22.80	mai-88	27.61
69	octo-86	24.84	déce-87	24.00	mars-88	23.62	mai-88	23.59
74	octo-86	ND	déce-87	ND	mars-88	29.8	mai-88	30.35
76	octo-86	19.62	déce-87	16.85	mars-88	16.27	mai-88	17.05
77	octo-86	18.02	déce-87	15.40	mars-88	14.90	mai-88	15.80
78	octo-86	22.30	déce-87	21.23	mars-88	21.35	mai-88	21.25
79	octo-86	12.05	déce-87	11.75	mars-88	11.25	mai-88	11.60
82	octo-86	19.85	déce-87	ND	mars-88	18.71	mai-88	19.98

Continued..........

Table 2 Monthly water level records

S.N.	Date	S.W.L.	Date	S.W.L.	Date	S.W.L.	Date	S.W.L.
1	juil-88	32.99	août-88	32.84	sept-88	32.93	nove-88	32.77
2	juil-88	41.02	août-88	40.30	sept-88	41.05	nove-88	40.6
4	juil-88	35.86	août-88	36.90	sept-88	36.02	nove-88	36.2
5	juil-88	58.54	août-88	58.50	sept-88	58.98	nove-88	58.78
7	juil-88	52.4	août-88	54.34	sept-88	53.88	nove-88	53.75
9	juil-88	48.51	août-88	48.80	sept-88	48.86	nove-88	48.77
10	juil-88	37.87	août-88	37.72	sept-88	37.8	nove-88	37.7
11	juil-88	21.67	août-88	21.45	sept-88	21.32	nove-88	21.38
12	juil-88	5.25	août-88	5.19	sept-88	5.08	nove-88	4.95
14	juil-88	23.01	août-88	22.56	sept-88	22.72	nove-88	22.61
15	juil-88	32.77	août-88	32.85	sept-88	32.98	nove-88	32.59
17	juil-88	17.58	août-88	17.04	sept-88	16.09	nove-88	16.02
19	juil-88	18.04	août-88	18.62	sept-88	18.48	nove-88	18.38
21	juil-88	2.12	août-88	-2.04	sept-88	-4.47	nove-88	-5.38
22	juil-88	19.02	août-88	18.39	sept-88	18.35	nove-88	18.3
23	juil-88	2.13	août-88	-2.52	sept-88	-2.38	nove-88	-2.38
24	juil-88	6.14	août-88	-6.52	sept-88	-6.6	nove-88	-7.2
25	juil-88	13.54	août-88	13.40	sept-88	13.38	nove-88	13.24
26	juil-88	18.2	août-88	17.49	sept-88	17.97	nove-88	17.87
27	juil-88	25.2	août-88	20.09	sept-88	23.8	nove-88	23.5
28	juil-88	24.43	août-88	24.30	sept-88	24.38	nove-88	23.46
29	juil-88	ND	août-88	ND	sept-88	ND	nove-88	ND
38	juil-88	23.5	août-88	23.17	sept-88	23.09	nove-88	22.95
39	juil-88	18.93	août-88	18.89	sept-88	18.86	nove-88	18.68
41	juil-88	9.16	août-88	10.24	sept-88	10.2	nove-88	10.2
42	juil-88	30.73	août-88	30.04	sept-88	ND	nove-88	30.1
43	juil-88	24.93	août-88	24.39	sept-88	24.35	nove-88	24.09
44	juil-88	12.68	août-88	12.20	sept-88	11.98	nove-88	11.97
45	juil-88	23.87	août-88	23.83	sept-88	23.88	nove-88	23.72
47	juil-88	49.36	août-88	47.47	sept-88	46.95	nove-88	46.82
52	juil-88	33.1	août-88	33.18	sept-88	33.34	nove-88	33.4
53	juil-88	30.88	août-88	30.88	sept-88	30.75	nove-88	30.8
54	juil-88	17.21	août-88	16.85	sept-88	15.2	nove-88	17.27
55	juil-88	3.96	août-88	3.90	sept-88	3.82	nove-88	3.85
56	juil-88	10.9	août-88	10.87	sept-88	10.98	nove-88	11.04
57	juil-88	11.75	août-88	9.33	sept-88	12,2	nove-88	12.73
59	juil-88	13.72	août-88	13.70	sept-88	13.62	nove-88	13.7
63	juil-88	29.26	août-88	29.79	sept-88	29.72	nove-88	29.65
68	juil-88	26.88	août-88	26.69	sept-88	26.88	nove-88	25.17
69	juil-88	23.45	août-88	23.50	sept-88	23.72	nove-88	23.39
74	juil-88	30.23	août-88	30.12	ND	29.76	nove-88	29.75
76	juil-88	16.35	août-88	16.26	sept-88	15.98	nove-88	15.92
77	juil-88	16.13	août-88	15.96	sept-88	14.67	nove-88	15.16
78	juil-88	21.76	août-88	21.91	sept-88	20.94	nove-88	20.88
79	juil-88	11.6	août-88	11.35	sept-88	11.4	nove-88	10.3
82	juil-88	18.63	août-88	18.55	sept-88	18.48	nove-88	18.42

Continued..........

Table 2 Monthly water level record

S.N.	Topo-Map	Propriator	Ty.	X	Y	Alt.	T.D.
83	Cagancha	Paez,J	e	424.10	6193.30	28.00	11.20
85	Cagancha	Valvarde,H	e	426.90	6190.90	36.00	14.60
88	Cagancha	Devida	p	424.60	6186.50	26.00	42.80
90	Cagancha	Dominguez,O	e	427.20	6181.40	20.00	15.70
92	Cagancha	Masoleni,L	e	431.50	6191.70	36.00	9.80
93	Cagancha	Acosta,M	e	431.50	6186.20	32.00	9.24
94	Cagancha	Perdomo,O	e	429.10	6187.00	35.00	8.36
96	San Gregorio	Bravo,A	e	423.00	6172.90	31.00	10.70
97	San Gregorio	Vilaro,E	e	431.75	6172.15	18.00	11.90
100	San Gregorio	Cervetto,R	e	428.75	6171.10	30.00	13.28
101	San Gregorio	Bidegain	e	428.55	6172.50	16.00	7.55
106	San Gregorio	Supervielle	e	443.95	6168.05	21.00	17.30
107	San Gregorio	Velazquez,L	e	416.90	6160.00	14.00	11.30
108	San Gregorio	Rivara,M	e	417.60	6161.30	11.00	11.10
109	San Gregorio	Mackrey,S	e	420.50	6159.60	25.00	19.57
116	San Gregorio	Goldaraz,N	e	432.10	6156.90	12.00	9.10
117	Cagancha	Echeverri,L	e	431.70	6180.90	35.00	15.95
130	San Jose	La Ilusion	e	422.50	6202.50	28.00	16.00
131	San Jose	Casana,G	e	422.30	6207.00	50.00	17.40
132	San Jose	Almacen	e	428.00	6203.00	60.00	14.82
133	San Jose	Carrau	p	429.50	6208.50	70.00	24.20
135	Cardal	Ceretta	e	438.00	6208.40	39.00	16.92
136	Cardal	Fallabrino	e	441.80	6206.00	40.00	12.59
138	Cardal	Cravea	e	443.60	6203.50	45.00	16.50
139	Cardal	Cladera,H	e	442.60	6197.50	33.00	14.90
140	Santa Lucia	F.San Jose	p	441.20	6192.70	29.00	16.00
141	Santa Lucia	Gonzarri	e	443.90	6190.90	20.00	19.36
142	Santa Lucia	Falero,E	e	437.20	6191.00	35.00	8.00
144	Cardal	Campo y casa	p	436.80	6201.00	40.00	19.00
145	Cardal	Perez,A	e	436.40	6197.90	38.00	12.87
146	Cardal	Caraballo	e	434.40	6202.70	48.00	10.83
147	Cardal	Stabile,J	e	434.30	6207.10	59.00	13.50
148	Santa Lucia	Irazoqui,M	e	436.30	6187.50	39.00	25.74
149	Santa Lucia	Britos Hnos.	e	435.80	6182.10	34.00	17.64
151	Santa Lucia	Bertiz Hnos.	e	440.90	6186.00	32.00	14.37
155	San Jose	Echeverry	e	428.40	6196.30	50.00	19.15
156	San Jose	Escuela34	e	425.20	6197.10	48.00	18.95
166	SanGregorio	Bonino,J	e	401.70	6168.60	46.00	23.00
167	SanGregorio	Bosso,L	e	412.50	6173.20	35.00	18.00
168	SanGregorio	Triay,R	e	409.50	6166.50	17.00	9.50

Continued..........

Table 2 Monthly water level record

S.N.	Date	S.W.L.	Date	S.W.L	Date	S.W.L.	Date	S.W.L.
83	octo-86	20.36	déce-87	20.41	mars-88	19.92	mai-88	19.30
85	octo-86	25.52	déce-87	25.40	mars-88	24.75	mai-88	24.60
88	octo-86	18.52	déce-87	18.07	mars-88	17.88	mai-88	18.50
90	octo-86	5.00	déce-87	7.40	mars-88	7.15	mai-88	7.17
92	octo-86	30.77	déce-87	29.88	mars-88	29.86	mai-88	29.79
93	octo-86	25.94	déce-87	25.20	mars-88	25.10	mai-88	25.13
94	octo-86	28.40	déce-87	27.95	mars-88	ND	mai-88	27.86
96	octo-86	25.95	déce-87	23.54	mars-88	22.77	mai-88	ND
97	octo-86	10.00	déce-87	ND	mars-88	7.30	mai-88	9.00
100	octo-86	19.35	déce-87	ND	mars-88	19.55	mai-88	ND
101	octo-86	10.55	déce-87	ND	mars-88	9.48	mai-88	10.06
106	octo-86	5.85	déce-87	ND	mars-88	5.40	mai-88	5.70
107	octo-86	4.80	déce-87	4.40	mars-88	4.25	mai-88	4.67
108	octo-86	4.90	déce-87	4.10	mars-88	4.26	mai-88	4.41
109	octo-86	7.00	déce-87	6.65	mars-88	6.70	mai-88	6.90
116	octo-86	ND	déce-87	ND	mars-88	ND	mai-88	ND
117	octo-86	21.70	déce-87	20.87	mars-88	21.83	mai-88	21.55
130	octo-86	15.18	déce-87	14.20	mars-88	14.15	mai-88	14.50
131	octo-86	36.66	déce-87	36.53	mars-88	ND	mai-88	36.95
132	octo-86	52.46	déce-87	51.33	mars-88	ND	mai-88	50.20
133	octo-86	61.35	déce-87	60.15	mars-88	ND	mai-88	59.57
135	octo-86	24.15	déce-87	ND	mars-88	24.00	mai-88	ND
136	octo-86	32.00	déce-87	ND	mars-88	30.52	mai-88	ND
138	octo-86	30.65	déce-87	ND	mars-88	29.67	mai-88	ND
139	octo-86	22.00	déce-87	ND	mars-88	22.39	mai-88	ND
140	octo-86	17.45	déce-87	ND	mars-88	19.15	mai-88	ND
141	octo-86	4.55	déce-87	ND	mars-88	5.90	mai-88	ND
142	octo-86	29.40	déce-87	29.32	mars-88	29.34	mai-88	29.63
144	octo-86	25.88	déce-87	ND	mars-88	25.48	mai-88	ND
145	octo-86	28.65	déce-87	ND	mars-88	27.87	mai-88	ND
146	octo-86	42.10	déce-87	ND	mars-88	40.44	mai-88	ND
147	octo-86	51.93	déce-87	ND	mars-88	51.72	mai-88	ND
148	octo-86	15.42	déce-87	17.66	mars-88	17.40	mai-88	17.42
149	octo-86	20.26	déce-87	21.40	mars-88	21.45	mai-88	21.45
151	octo-86	22.85	déce-87	ND	mars-88	20.90	mai-88	ND
155	octo-86	36.00	déce-87	35.90	mars-88	ND	mai-88	36.10
156	octo-86	ND	déce-87	ND	mars-88	ND	mai-88	ND
166	octo-86	ND	déce-87	ND	mars-88	26.40	mai-88	ND
167	octo-86	18.00	déce-87	17.78	mars-88	17.53	mai-88	ND
168	octo-86	8.50	déce-87	8.35	mars-88	8.07	mai-88	8.20

Continued..........

Table 2 Monthly water level record

S.N.	Date	S.W.L.	Date	S.W.L.	Date	S.W.L.	Date	S.W.L.
83	juil-88	19.29	août-88	19.26	sept-88	19.83	nove-88	19.68
85	juil-88	24.66	août-88	24.90	sept-88	24,34	nove-88	24.46
88	juil-88	16.86	août-88	15.77	sept-88	16.2	nove-88	17.77
90	juil-88	7.09	août-88	7.07	sept-88	7.18	nove-88	4.95
92	juil-88	29.63	août-88	29.61	sept-88	29.69	nove-88	29.6
93	juil-88	25.09	août-88	25.03	sept-88	25.15	nove-88	25.1
94	juil-88	27.78	août-88	27.81	sept-88	27.75	nove-88	27.68
96	juil-88	22.79	août-88	22.58	sept-88	22.3	nove-88	22.18
97	juil-88	6.75	août-88	7.53	sept-88	7.09	nove-88	ND
100	juil-88	19.02	août-88	18.75	sept-88	18.7	nove-88	18.58
101	juil-88	9.8	août-88	10.11	sept-88	9.88	nove-88	9.7
106	juil-88	5.62	août-88	5.53	sept-88	5.98	nove-88	ND
107	juil-88	4.32	août-88	4.29	sept-88	4.2	nove-88	4.22
108	juil-88	4.66	août-88	4.55	sept-88	4.57	nove-88	4.5
109	juil-88	6.73	août-88	6.49	sept-88	6.61	nove-88	6.53
116	juil-88	ND	août-88	7.39	sept-88	7.4	nove-88	7.35
117	juil-88	20.81	août-88	20.74	sept-88	20.92	nove-88	20.82
130	juil-88	14.48	août-88	14.10	sept-88	12.88	nove-88	13.2
131	juil-88	36.86	août-88	36.50	sept-88	37.46	nove-88	36.9
132	juil-88	50.08	août-88	49.50	sept-88	49.35	nove-88	49.4
133	juil-88	59.87	août-88	60.02	sept-88	57.96	nove-88	58.75
135	juil-88	24.08	août-88	23.99	sept-88	25.79	nove-88	24.1
136	juil-88	31.31	août-88	32.13	sept-88	31.5	nove-88	31.65
138	juil-88	30.18	août-88	30.51	sept-88	30.58	nove-88	30.45
139	juil-88	22.38	août-88	22.33	sept-88	ND	nove-88	ND
140	juil-88	19.87	août-88	20.24	sept-88	20.08	nove-88	15.97
141	juil-88	4.77	août-88	4.22	sept-88	7.21	nove-88	ND
142	juil-88	29.65	août-88	29.65	sept-88	ND	nove-88	ND
144	juil-88	25.5	août-88	25.55	sept-88	25.74	nove-88	25.56
145	juil-88	28.28	août-88	28.42	sept-88	ND	nove-88	ND
146	juil-88	41.02	août-88	41.53	sept-88	41.44	nove-88	41.48
147	juil-88	50.77	août-88	49.96	sept-88	51.49	nove-88	50.77
148	juil-88	16.86	août-88	15.82	sept-88	17.2	nove-88	17.12
149	juil-88	21.47	août-88	21.44	sept-88	21.45	nove-88	21.42
151	juil-88	20.92	août-88	21.00	sept-88	20.58	nove-88	20.42
155	juil-88	36.03	août-88	35.76	sept-88	35.25	nove-88	ND
156	juil-88	ND	août-88	34.50	sept-88	34.22	nove-88	34.1
166	juil-88	25.86	août-88	25.47	sept-88	24.9	nove-88	ND
167	juil-88	17.69	août-88	ND	sept-88	ND	nove-88	ND
168	juil-88	7.85	août-88	7.77	sept-88	7.8	nove-88	7.71

Table 3a. Pumping test data from well 742 (TORYAL S.A. - Ruta uno - Km. 34)

Pumping well Time (minute)	Drawdown (m.)	piezometer time (minute)	Drawdown (cm.)
0	0	10	1.6
1	11.86	20	7.6
6	12.55	30	12.8
7	12.58	40	17.7
8	12.6	51	21.8
9	12.62	60	24
10	12.64	90	30.8
20	12.68	150	37.3
30	12.69	210	57.6
60	12.74	270	61
120	12.79	300	62
150	12.81	330	66.6
180	12.8		
240	12.84		
310	12.81		
360	12.8		
420	12.85		
465	12.86		

Table 3b Table of recovery data (well)

t (time since pumping started)	t' (time since pumping stopped)	t/t'	s' (residual drawdown)
466	1	466	8.32
467	2	233.5	8.16
468	3	156	7.85
469	4	117	7.64
470	5	94	7.38
471	6	78	7.18
472	7	67	7.07
473	8	59	6.97
474	9	52.7	6.85
475	10	47.5	6.75
480	15	32	6.33
485	20	24	6
490	25	19	5.69
500	35	14	5.38
510	45	11	4.81
520	55	9	4.47
530	65	8	4.23
540	75	7	4.17
560	85	6.5	4.12
570	95	6	4.04
580	105	5.5	3.99
590	115	5	3.95
600	125	4.8	3.89
610	135	4.5	3.83
620	145	4.3	3.78
630	155	4.1	3.74
640	165	3.8	3.69
650	175	3.7	3.65
660	185	3.6	3.56
670	195	3.4	3.36
680	205	3.3	3.07
690	215	3.2	2.84
700	225	3.1	2.63
710	235	3	2.45
720	245	2.9	2.17
730	255	2.8	1.99
740	265	2.8	1.86
750	275	2.7	1.72
760	285	2.6	1.6
770	295	2.6	1.49
780	305	2.5	1.36
790	315	2.5	1.24
800	325	2.4	1.13
810	335	2.4	1.01
820	345	2.37	0.92
830	355	2.34	0.8

Table 3c Table of recovery data (Piezometer)

t (time since pumping started)	t' (time since pumping stopped)	t/t'	s' (residual drawdown)
6.50E+02	175	3.71	6.81
6.80E+02	205	3.32	6.2
7.10E+02	235	3.02	5.27
7.40E+02	265	2.79	4.51
7.70E+02	295	2.61	4.1
8.00E+02	325	2.46	3.65
8.30E+02	355	2.34	3.45

Computer program - Transient flow by implicite finite difference method after Bear and Verruijt, 1987.

```
100 REM DEFINT :I-N:KEY OFF:GOSUB 460
110 PRINT"--- Bear & Verruijt - Groundwater Modeling"
120 PRINT"--- Non-steady Groundwater Flow"
130 PRINT"--- Implicit Finite Differences":PRINT"--- Program 9.3"
140 PRINT"--- Homogeneous infiltration in rectangular aquifer"
150 PRINT:PRINT:DIM F(50,50),FA(50,50):TT=0
160 INPUT"Dimension in x-direction : ";XT
170 INPUT"   Subdivisions ........ : ";NX:DX=XT/NX:A=1/(DX*DX)
180 INPUT"Dimension in y-direction : ";YT
190 INPUT"   Subdivisions ........ : ";NY:DY=YT/NY:B=1/(DY*DY)
200 INPUT"Initial head ........... : ";H
210 INPUT"Infiltration rate ...... : ";P
220 INPUT"Transmissivity ......... : ";T
230 INPUT"Storativity ............ : ";S:DT=S/(2*T*(A+B))
240 PRINT"Suggestion for time step : ";DT
250 INPUT"Time step .............. : ";DT
260 INPUT"Number of time steps ... : ";NS
270 INPUT"Number of iterations ... : ";NI
280 INPUT"Relaxation factor ...... : ";RX:GOSUB 460
290 FOR I=0 TO NX:FOR J=0 TO NY:F(I,J)=H:FA(I,J)=H:NEXT J,I
300 A=T*A:B=T*B:FF=2*A+2*B+S/DT:II=INT(NX/2+.1):JJ=INT(NY/2+.1)
```

continued..........

Computer program - Transient flow by implicite finite difference method after Bear and Verruijt, 1987.

==

```
310 FOR IS=1 TO NS:TT=TT+DT
320 FOR IT=1 TO NI:FOR I=1 TO NX-1:FOR J=1 TO NY-1
330 C=A*(FA(I-1,J)-2*FA(I,J)+FA(I+1,J))
340 D=B*(FA(I,J-1)-2*FA(I,J)+FA(I,J+1))
350 AA=P+C+D-S*(FA(I,J)-F(I,J))/DT:FA(I,J)=FA(I,J)+RX*AA/FF
360 NEXT J,I:FOR J=1 TO NY-1:FOR I=1 TO NX-1
370 C=A*(FA(I-1,J)-2*FA(I,J)+FA(I+1,J))
380 D=B*(FA(I,J-1)-2*FA(I,J)+FA(I,J+1))
390 AA=P+C+D-S*(FA(I,J)-F(I,J))/DT:FA(I,J)=FA(I,J)+RX*AA/FF
400 NEXT I,J,IT
410 FOR I=1 TO NX-1:FOR J=1 TO NY-1:F(I,J)=FA(I,J):NEXT J,I
420 PRINT"Time : ";:PRINT USING "#######.###";TT;
430 PRINT"  ---  Head in the center : ";
440 PRINT USING "###.###";F(II,JJ):IF IS>1 THEN DT=2*DT
450 NEXT IS:END
460 PRINT" Finite Differences - 3 ";
470 PRINT:PRINT:RETURN
```

Table 4 Chemical analysis data (January - February 1987)

Sample No.	X	Y	Date of Sampling	Conduct. MS/cm.	Alkalini Total	Ph Units	Eh Mic.volt	pE Units
1	417.5	6206.1	10-Feb.-87	700.00	227.00	7.53	119.00	2.02
2	417.9	6214.4	10-Feb.-87	990.00	330.00	7.03	152.00	2.59
4	415.3	6208.7	10-Feb.-87	770.00	266.00	7.1	173.00	2.94
9	404.8	6197.2	9-Feb.-87	1020.00	361.00	7.39	207.00	3.54
11	395.9	6190.7	27-Jan.-87	750.00	267.00	7.58	170.00	2.88
12	388.7	6183.5	27-Jan.-87	520.00	189.00	6.88	216.00	3.66
13	391.2	6184.2	27-Jan.-87	700.00	344.60	7.34	195.00	3.29
14	393.8	6186.2	27-Jan.-87	1140.00	489.20	7.61	190.00	3.18
15	394.6	6189	27-Jan.-87	650.00	235.90	7.57	269.00	4.54
17	404.1	6180.6	29-Jan.-87	870.00	285.00	7.23	240.00	4.05
18	402.2	6180.2	29-Jan.-87	860.00	321.00	7.54	180.00	3.06
19	402.1	6179.9	29-Jan.-87	870.00	310.00	7.03	215.00	3.66
21	397.5	6179.4	29-Jan.-87	1230.00	461.00	7.56	184.00	3.11
22	393.3	6177.5	29-Jan.-87	940.00	336.00	7.32	213.00	3.60
23	392.5	6175.1	23-Jan.-87	890.00	343.50	7.40	218.00	3.73
24	389.9	6176.1	23-Jan.-87	1080.00	407.20	7.43	240.00	4.10
25	395.3	6173.9	23-Jan.-87	830.00	327.70	7.31	234.00	4.02
26	399.2	6172.5	23-Jan.-87	1140.00	372.70	7.65	209.00	3.60
27	401	6174	31-Jan.-87	740.00	298.00	7.18	140.00	2.38
28	404.4	6174.4	29-Jan.-87	1010.00	380.00	7.64	283.00	4.78
29	405.1	6171.8	31-Jan.-87	840.00	340.00	7.94	134.00	2.24
38	407.0	6180.7	31-Jan.-87	780.00	449.00	7.13	180.00	3.05
39	404.9	6182.4	29-Jan.-87	1080.00	358.00	7.00	205.00	3.46
41	401.8	6185.5	27-Jan.-87	800.00	319.30	7.37	257.00	4.36
42	398.5	6187.2	27-Jan.-87	1120.00	543.30	7.86	212.00	3.59
43	398.1	6187.1	27-Jan.-87	1020.00	332.40	7.70	180.00	3.04
44	396.3	6183.8	27-Jan.-87	1060.00	439.10	7.34	220.00	3.72
45	404.5	6192.5	9-Feb.-87	960.00	394.00	7.6	202.00	3.45
47	412.2	6196.7	9-Feb.-87	1040.00	358.00	7.18	151.00	2.58
52	411.9	6187.7	20-Jan.-87	1350.00	398.80	7.10	234.00	4.00
53	408.7	6188.2	20-Jan.-87	940.00	294.30	7.30	214.00	3.67
54	416.7	6191.5	4-Feb.-87	840.00	345.00	7.15	217.00	3.66
55	419.4	6185.1	4-Feb.-87	580.00	222.00	7.04	207.00	3.47
56	422.5	6180.8	4-Feb.-87	680.00	230.00	7.06	190.00	3.19
57	420.5	6184.6	4-Feb.-87	730.00	254.00	7.1	190.00	3.21
59	425.5	6176.8	4-Feb.-87	590.00	200.00	6.83	235.00	3.98
63	413.85	6181.9	4-Feb.-87	590.00	232.00	7.09	171.00	2.90
64	411.4	6178.4	18-Jan.-87	1590.00	407.00	7.50	280.00	4.78
66	412.9	6177.9	4-Feb.-87	780.00	315.00	7.38	204.00	3.47
68	416.7	6182.9	4-Feb.-87	480.00	185.00	8.1	207.00	3.49
69	420.5	6177.3	20-Jan.-87	1110.00	308.70	7.30	236.00	4.03
76	413.2	6168	21-Jan.-87	1670.00	353.90	7.43	302.00	5.18
77	416.9	6167.3	21-Jan.-87	760.00	339.70	7.60	320.00	5.49
78	406.8	6162.6	21-Jan.-87	1750.00	432.10	7.60	340.00	5.81
79	413.3	6162.8	21-Jan.-87	1320.00	419.80	7.71	298.00	5.14
81	421.5	6163.5	1-Feb.-87	950.00	362.00	7.45	246.00	4.21
83	424.1	6193.3	6-Feb.-87	650.00	222.00	7.17	220.00	3.76

Continued.........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	T.(AIR) °C	18O ∂ units	Ca mg/l	Ca meq/l	Ca meq/l	Mg mg/l	Mg meq/l	Mg meq%	Na mg/l
1	23.0	-5.40	25.31	1.26	18.96	16.00	1.32	19.75	90.40
2	24.8	-5.20	32.98	1.65	15.63	20.60	1.69	16.10	163.40
4	23.0	-5.00	32.98	1.65	22.61	18.80	1.55	21.24	91.00
9	22.0	-5.40	56.37	2.81	29.33	28.00	2.30	24.01	100.80
11	31.00	-5.70	22.28	1.11	17.41	18.20	1.50	23.43	85.40
12	35.00	-5.10	24.20	1.21	22.67	21.00	1.73	32.42	51.00
13	34.20	-5.30	25.00	1.25	16.22	22.00	1.81	23.53	102.00
14	33.50	-5.50	25.20	1.26	10.40	11.80	0.97	8.02	224.00
15	30.50	-5.10	32.14	1.60	26.42	13.00	1.07	17.61	74.00
17	37.00	-5.40	36.56	1.82	22.48	34.00	2.80	34.46	75.80
18	30.00	-5.60	40.10	2.00	23.66	14.80	1.22	14.39	117.00
19	30.80	ND	33.46	1.67	19.11	17.40	1.43	16.38	126.60
21	33.20	-5.20	26.30	1.31	11.17	14.20	1.17	9.94	210.60
22	38.00	ND	28.80	1.44	16.02	24.60	2.02	22.55	117.80
23	23.00	-5.70	16.60	0.83	9.95	13.80	1.13	13.64	141.80
24	22.00	-5.70	3.38	0.17	1.72	13.20	1.09	11.09	190.00
25	23.00	ND	35.53	1.77	20.84	22.00	1.81	21.26	106.60
26	22.00	ND	3.36	0.17	1.60	12.00	0.99	9.41	212.40
27	25.5	-5.70	32.98	1.65	20.20	17.40	1.43	17.57	112.80
28	33.00	-5.60	47.85	2.39	23.78	23.40	1.92	19.17	126.60
29	25.5	ND	34.19	1.71	20.40	14.40	1.18	14.16	123.00
38	26.7	-5.60	62.82	3.13	35.82	21.60	1.78	20.30	84.80
39	36.00	-5.60	22.45	1.12	10.92	23.80	1.96	19.08	135.60
41	35.00	ND	15.70	0.78	10.89	17.00	1.40	19.44	111.20
42	35.00	ND	30.87	1.54	13.92	14.80	1.22	11.00	188.20
43	37.00	ND	37.87	1.89	18.87	16.60	1.37	13.63	150.20
44	35.80	ND	24.40	1.22	13.40	18.20	1.50	16.47	144.80
45	22.0	ND	32.26	1.61	16.75	15.20	1.25	13.01	152.60
47	21.0	-5.30	66.09	3.30	38.09	30.60	2.52	29.06	60.60
52	29.00	-5.20	47.98	2.39	20.58	32.60	2.68	23.05	149.60
53	33.00	-5.00	38.24	1.91	21.24	17.00	1.40	15.56	128.40
54	34.7	-5.10	13.53	0.68	8.49	14.60	1.20	15.10	139.00
55	34.7	-5.30	22.34	1.11	19.08	11.20	0.92	15.77	84.00
56	34.7	-5.60	22.58	1.13	18.08	14.40	1.18	19.01	88.00
57	34.7	-5.30	27.79	1.39	20.77	14.00	1.15	17.24	91.40
59	32.3	ND	17.05	0.85	12.91	13.20	1.09	16.48	106.00
63	32.0	-4.60	27.29	1.36	23.49	13.00	1.07	18.44	76.40
64	29.50	-5.20	19.41	0.97	6.73	17.00	1.40	9.71	273.80
66	30.5	-5.20	42.94	2.14	28.85	17.53	1.44	19.41	85.20
68	32.0	-4.90	28.03	1.40	29.10	13.80	1.13	23.61	49.40
69	28.00	-4.90	18.52	0.92	8.26	12.40	1.02	9.11	210.60
76	22.00	-5.20	49.18	2.45	16.94	32.00	2.63	18.16	211.80
77	24.00	-5.30	6.28	0.31	4.61	15.20	1.25	18.40	116.40
78	25.00	ND	14.00	0.70	4.52	14.00	1.15	7.44	310.00
79	24.00	-5.40	23.59	1.18	8.56	14.80	1.22	8.85	258.20
81	25.5	-5.20	36.26	1.81	16.84	32.40	2.66	24.81	139.00
83	30.5	-5.00	20.00	1.00	14.78	18.00	1.48	21.93	96.00

Continued.........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	Na meq/l	Na meq%	K mg/l	K meq/l	K meq%	Na+K meq/l	na+k meq%)	HCO3 mg/l)	HCO3 meq/l
1	3.93	59.02	5.91	0.15	2.27	4.08	61.29	276.94	4.54
2	7.11	67.53	3.05	0.08	0.74	7.19	68.27	402.60	6.60
4	3.96	54.39	5.01	0.13	1.76	4.09	56.15	324.52	5.32
9	4.38	45.71	3.57	0.09	0.95	4.48	46.67	440.42	7.22
11	3.71	58.16	2.51	0.06	1.01	3.78	59.16	325.74	5.34
12	2.22	41.64	6.81	0.17	3.27	2.39	44.91	230.58	3.78
13	4.44	57.71	7.63	0.20	2.54	4.63	60.24	420.41	6.89
14	9.74	80.56	4.84	0.12	1.02	9.87	81.58	596.82	9.78
15	3.22	53.03	6.99	0.18	2.95	3.40	55.97	287.80	4.72
17	3.30	40.63	7.70	0.20	2.43	3.49	43.06	347.70	5.70
18	5.09	60.17	5.91	0.15	1.79	5.24	61.96	391.62	6.42
19	5.51	63.04	5.01	0.13	1.47	5.64	64.51	378.20	6.20
21	9.16	77.99	4.12	0.11	0.90	9.27	78.89	562.42	9.22
22	5.12	57.12	15.10	0.39	4.31	5.51	61.43	409.92	6.72
23	6.17	74.12	7.43	0.19	2.28	6.36	76.41	419.07	6.87
24	8.27	84.42	10.58	0.27	2.76	8.54	87.19	496.78	8.14
25	4.64	54.50	11.30	0.29	3.40	4.93	57.90	399.79	6.55
26	9.24	88.10	3.67	0.09	0.90	9.33	88.99	454.69	7.45
27	4.91	60.23	6.36	0.16	2.00	5.07	62.23	363.56	5.96
28	5.51	54.86	8.60	0.22	2.19	5.73	57.05	463.60	7.60
29	5.35	63.97	4.84	0.12	1.48	5.47	65.45	414.80	6.80
38	3.69	42.15	5.91	0.15	1.73	3.84	43.88	547.78	8.98
39	5.90	57.50	50.10	1.28	12.49	7.18	70.00	436.76	7.16
41	4.84	67.25	6.81	0.17	2.42	5.01	69.67	389.55	6.38
42	8.19	73.98	4.75	0.12	1.10	8.31	75.08	662.83	10.86
43	6.53	65.25	8.78	0.22	2.24	6.76	67.49	405.53	6.65
44	6.30	69.32	2.87	0.07	0.81	6.37	70.13	535.70	8.78
45	6.64	69.07	4.39	0.11	1.17	6.75	70.24	480.68	7.88
47	2.64	30.44	8.15	0.21	2.41	2.84	32.85	436.76	7.16
52	6.51	55.94	1.98	0.05	0.44	6.56	56.37	486.54	7.97
53	5.59	62.16	3.67	0.09	1.04	5.68	63.20	359.05	5.88
54	6.05	76.05	1.12	0.03	0.36	6.08	76.41	420.90	6.90
55	3.65	62.55	5.95	0.15	2.61	3.81	65.15	270.84	4.44
56	3.83	61.44	3.57	0.09	1.47	3.92	62.91	280.60	4.60
57	3.98	59.54	6.38	0.16	2.44	4.14	61.99	309.88	5.08
59	4.61	69.98	1.62	0.04	0.63	4.65	70.61	244.00	4.00
63	3.32	57.32	1.71	0.04	0.75	3.37	58.07	283.04	4.64
64	11.91	82.73	4.66	0.12	0.83	12.03	83.56	496.54	8.14
66	3.71	49.91	5.30	0.14	1.83	3.84	51.73	384.30	6.30
68	2.15	44.70	4.87	0.12	2.59	2.27	47.29	225.70	3.70
69	9.16	81.87	3.32	0.08	0.76	9.25	82.63	376.61	6.17
76	9.21	63.59	7.43	0.19	1.31	9.40	64.90	431.76	7.08
77	5.06	74.53	6.54	0.17	2.46	5.23	76.99	414.43	6.79
78	13.49	87.17	5.28	0.14	0.87	13.62	88.04	527.16	8.64
79	11.23	81.69	4.84	0.12	0.90	11.36	82.59	512.16	8.39
81	6.05	56.29	8.66	0.22	2.06	6.27	58.35	441.64	7.24
83	4.18	61.86	3.79	0.10	1.44	4.27	63.29	270.84	4.44

Continued..........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	Na meq/l	Na meq%	K mg/l	K meq/l	K meq%	Na+K meq/l	na+k meq%	HCO3 mg/l	HCO3 meq/l
1	3.93	59.02	5.91	0.15	2.27	4.08	61.29	276.94	4.54
2	7.11	67.53	3.05	0.08	0.74	7.19	68.27	402.60	6.60
4	3.96	54.39	5.01	0.13	1.76	4.09	56.15	324.52	5.32
9	4.38	45.71	3.57	0.09	0.95	4.48	46.67	440.42	7.22
11	3.71	58.16	2.51	0.06	1.01	3.78	59.16	325.74	5.34
12	2.22	41.64	6.81	0.17	3.27	2.39	44.91	230.58	3.78
13	4.44	57.71	7.63	0.20	2.54	4.63	60.24	420.41	6.89
14	9.74	80.56	4.84	0.12	1.02	9.87	81.58	596.82	9.78
15	3.22	53.03	6.99	0.18	2.95	3.40	55.97	287.80	4.72
17	3.30	40.63	7.70	0.20	2.43	3.49	43.06	347.70	5.70
18	5.09	60.17	5.91	0.15	1.79	5.24	61.96	391.62	6.42
19	5.51	63.04	5.01	0.13	1.47	5.64	64.51	378.20	6.20
21	9.16	77.99	4.12	0.11	0.90	9.27	78.89	562.42	9.22
22	5.12	57.12	15.10	0.39	4.31	5.51	61.43	409.92	6.72
23	6.17	74.12	7.43	0.19	2.28	6.36	76.41	419.07	6.87
24	8.27	84.42	10.58	0.27	2.76	8.54	87.19	496.78	8.14
25	4.64	54.50	11.30	0.29	3.40	4.93	57.90	399.79	6.55
26	9.24	88.10	3.67	0.09	0.90	9.33	88.99	454.69	7.45
27	4.91	60.23	6.36	0.16	2.00	5.07	62.23	363.56	5.96
28	5.51	54.86	8.60	0.22	2.19	5.73	57.05	463.60	7.60
29	5.35	63.97	4.84	0.12	1.48	5.47	65.45	414.80	6.80
38	3.69	42.15	5.91	0.15	1.73	3.84	43.88	547.78	8.98
39	5.90	57.50	50.10	1.28	12.49	7.18	70.00	436.76	7.16
41	4.84	67.25	6.81	0.17	2.42	5.01	69.67	389.55	6.38
42	8.19	73.98	4.75	0.12	1.10	8.31	75.08	662.83	10.86
43	6.53	65.25	8.78	0.22	2.24	6.76	67.49	405.53	6.65
44	6.30	69.32	2.87	0.07	0.81	6.37	70.13	535.70	8.78
45	6.64	69.07	4.39	0.11	1.17	6.75	70.24	480.68	7.88
47	2.64	30.44	8.15	0.21	2.41	2.84	32.85	436.76	7.16
52	6.51	55.94	1.98	0.05	0.44	6.56	56.37	486.54	7.97
53	5.59	62.16	3.67	0.09	1.04	5.68	63.20	359.05	5.88
54	6.05	76.05	1.12	0.03	0.36	6.08	76.41	420.90	6.90
55	3.65	62.55	5.95	0.15	2.61	3.81	65.15	270.84	4.44
56	3.83	61.44	3.57	0.09	1.47	3.92	62.91	280.60	4.60
57	3.98	59.54	6.38	0.16	2.44	4.14	61.99	309.88	5.08
59	4.61	69.98	1.62	0.04	0.63	4.65	70.61	244.00	4.00
63	3.32	57.32	1.71	0.04	0.75	3.37	58.07	283.04	4.64
64	11.91	82.73	4.66	0.12	0.83	12.03	83.56	496.54	8.14
66	3.71	49.91	5.30	0.14	1.83	3.84	51.73	384.30	6.30
68	2.15	44.70	4.87	0.12	2.59	2.27	47.29	225.70	3.70
69	9.16	81.87	3.32	0.08	0.76	9.25	82.63	376.61	6.17
76	9.21	63.59	7.43	0.19	1.31	9.40	64.90	431.76	7.08
77	5.06	74.53	6.54	0.17	2.46	5.23	76.99	414.43	6.79
78	13.49	87.17	5.28	0.14	0.87	13.62	88.04	527.16	8.64
79	11.23	81.69	4.84	0.12	0.90	11.36	82.59	512.16	8.39
81	6.05	56.29	8.66	0.22	2.06	6.27	58.35	441.64	7.24
83	4.18	61.86	3.79	0.10	1.44	4.27	63.29	270.84	4.44

Continued.........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	HCO3 meq%	Cl mg/l	Cl meq/l	Cl meq%	SO4 mg/l	SO4 meq/l	SO4 meq%	NO3 mg/ l	NO3 meq/l
1	66.80	38.67	1.09	16.05	26.16	0.54	8.02	38.47	0.62
2	67.18	36.99	1.04	10.62	77.04	1.60	16.33	35.78	0.58
4	69.32	28.31	0.80	10.40	25.50	0.53	6.92	63.53	1.02
9	69.02	47.37	1.34	12.77	29.47	0.61	5.87	79.99	1.29
11	65.35	74.14	2.09	25.59	13.19	0.27	3.36	28.87	0.47
12	70.23	22.42	0.63	11.75	15.79	0.33	6.11	39.75	0.64
13	82.60	23.96	0.68	8.10	16.81	0.35	4.20	26.38	0.43
14	81.66	17.95	0.51	4.23	41.19	0.86	7.16	51.65	0.83
15	74.15	32.21	0.91	14.28	20.33	0.42	6.65	19.42	0.31
17	64.28	40.64	1.15	12.93	25.69	0.53	6.03	92.13	1.49
18	75.10	35.53	1.00	11.72	24.45	0.51	5.96	38.29	0.62
19	68.53	37.07	1.05	11.56	32.89	0.68	7.57	69.24	1.12
21	70.72	39.85	1.12	8.62	38.97	0.81	6.22	116.63	1.88
22	67.76	25.82	0.73	7.34	29.98	0.62	6.29	114.38	1.84
23	77.33	44.21	1.25	14.04	21.88	0.46	5.13	19.33	0.31
24	76.03	61.36	1.73	16.16	32.76	0.68	6.37	9.55	0.15
25	77.37	23.21	0.65	7.73	23.05	0.48	5.67	48.46	0.78
26	66.21	53.50	1.51	13.40	22.59	0.47	4.18	113.15	1.83
27	77.50	18.36	0.52	6.73	19.56	0.41	5.30	49.92	0.81
28	72.99	43.14	1.22	11.69	21.02	0.44	4.20	71.79	1.16
29	78.65	26.76	0.75	8.73	31.05	0.65	7.48	27.57	0.44
38	86.24	19.31	0.54	5.23	29.55	0.62	5.91	16.89	0.27
39	65.83	53.14	1.50	13.78	20.00	0.42	3.83	111.69	1.80
41	70.27	71.89	2.03	22.31	19.85	0.41	4.55	16.19	0.26
42	67.30	127.92	3.61	22.35	63.17	1.32	8.15	22.01	0.36
43	65.61	65.64	1.85	18.27	50.67	1.05	10.41	35.83	0.58
44	82.09	18.92	0.53	4.99	10.83	0.23	2.11	71.69	1.16
45	77.38	32.55	0.92	9.02	47.95	1.00	9.81	23.99	0.39
47	61.91	82.04	2.31	20.01	18.57	0.39	3.34	105.59	1.70
52	57.03	117.28	3.31	23.65	32.32	0.67	4.81	125.70	2.03
53	66.52	39.21	1.11	12.50	70.17	1.46	16.51	24.49	0.40
54	79.89	17.44	0.49	5.70	18.59	0.39	4.48	53.16	0.86
55	74.98	27.33	0.77	13.02	17.06	0.36	6.00	22.05	0.36
56	69.22	39.36	1.11	16.71	20.65	0.43	6.47	31.33	0.51
57	72.81	44.35	1.25	17.93	17.75	0.37	5.30	17.16	0.28
59	70.75	28.38	0.80	14.16	16.52	0.34	6.09	31.54	0.51
63	79.79	10.22	0.29	4.96	11.75	0.24	4.21	39.82	0.64
64	55.91	94.93	2.68	18.39	146.55	3.05	20.96	42.81	0.69
66	79.46	23.45	0.66	8.34	15.13	0.32	3.97	40.40	0.65
68	75.19	18.90	0.53	10.83	15.13	0.32	6.40	23.09	0.37
69	59.37	58.14	1.64	15.77	84.48	1.76	16.92	51.24	0.83
76	48.84	110.64	3.12	21.53	35.34	0.74	5.08	220.56	3.56
77	84.80	23.31	0.66	8.21	10.14	0.21	2.64	21.66	0.35
78	59.77	164.57	4.64	32.10	51.21	1.07	7.38	6.74	0.11
79	62.65	142.00	4.00	29.89	23.83	0.50	3.70	31.27	0.50
81	67.80	81.62	2.30	21.56	28.90	0.60	5.64	33.14	0.53
83	68.10	27.49	0.78	11.89	34.17	0.71	10.91	36.76	0.59

Continued.........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	NO3 meq%	T.anio meq/l	T.cation meq/l	T.D.S. mg/l	S.A.R.
1	9.13	6.66	6.79	517.86	3.46
2	5.88	10.53	9.82	772.44	5.50
4	13.36	7.28	7.67	589.65	3.13
9	12.34	9.59	10.46	785.99	2.74
11	5.70	6.39	8.17	570.33	3.25
12	11.91	5.33	5.38	411.55	1.83
13	5.10	7.69	8.34	644.19	3.59
14	6.95	12.10	11.98	973.45	9.23
15	4.92	6.07	6.36	485.89	2.78
17	16.76	8.11	8.87	660.22	2.17
18	7.23	8.46	8.55	667.70	4.01
19	12.35	8.74	9.05	699.87	4.42
21	14.43	11.75	13.03	1013.9	8.23
22	18.61	8.97	9.92	766.40	3.90
23	3.51	8.32	8.88	684.12	6.23
24	1.44	9.79	10.71	817.61	10.44
25	9.23	8.51	8.47	669.94	3.46
26	16.21	10.49	11.26	875.36	12.16
27	10.47	8.15	7.69	620.94	3.96
28	11.12	10.04	10.41	806.00	3.75
29	5.14	8.36	8.64	676.61	4.45
38	2.62	8.75	10.41	788.66	2.35
39	16.57	10.26	10.88	853.54	4.76
41	2.87	7.19	9.09	648.19	4.63
42	2.20	11.07	16.14	1114.5	6.97
43	5.70	10.01	10.13	771.12	5.12
44	10.81	9.09	10.70	827.41	5.41
45	3.80	9.61	10.18	789.62	5.55
47	14.73	8.66	11.56	808.40	1.55
52	14.50	11.63	13.98	994.00	4.09
53	4.47	8.99	8.85	680.23	4.34
54	9.93	7.95	8.63	678.34	6.24
55	6.01	5.84	5.92	460.77	3.62
56	7.61	6.23	6.64	500.49	3.56
57	3.97	6.68	6.98	528.71	3.53
59	9.00	6.59	5.65	458.31	4.69
63	11.05	5.80	5.81	463.23	3.01
64	4.74	14.40	14.56	1095.0	10.95
66	8.22	7.43	7.93	614.25	2.77
68	7.57	4.81	4.92	378.92	1.91
69	7.95	11.19	10.40	815.31	9.29
76	24.55	14.49	14.49	1098.1	5.78
77	4.36	6.79	8.01	613.96	5.73
78	0.75	15.47	14.46	1092.6	14.02
79	3.76	13.75	13.40	1010.9	10.27
81	5.01	10.74	10.68	801.62	4.04
83	9.10	6.75	6.52	507.05	3.75

Continued..........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	X	Y	Date of sampling	Conduct. mS/cm	Total Alkalin.	Ph units	Eh m.volts	pE units
84	426.5	6192.7	6-Feb.-87	980.00	328.00	6.89	205.00	3.48
85	426.9	6190.9	6-Feb.-87	1410.00	296.00	6.93	195.00	3.29
88	424.6	6186.5	6-Feb.-87	820.00	304.00	7.22	249.00	4.18
90	427.2	6181.4	6-Feb.-87	1630.00	370.00	7.17	205.00	3.46
91	424.7	6183.7	6-Feb.-87	750.00	284.00	7.11	206.00	3.49
92	431.5	6191.7	6-Feb.-87	970.00	351.00	7.16	166.00	2.78
93	431.5	6186.2	6-Feb.-87	610.00	200.00	6.86	190.00	3.23
94	429.1	6187.0	6-Feb.-87	760.00	314.00	7.13	193.00	3.23
96	423.0	6172.9	3-Feb.-87	790.00	300.00	7.3	140.00	2.38
97	431.75	6172.2	4-Feb.-87	990.00	353.00	7.09	84.00	1.42
101	428.55	6172.5	2-Feb.-87	720.00	286.00	6.86	250.00	4.28
106	433.9	6168.0	1-Feb.-87	910.00	280.00	7.0	184.00	3.14
107	416.9	6160.0	1-Feb.-87	300.00	110.00	6.56	150.00	2.59
108	417.6	6161.3	1-Feb.-87	940.00	274.00	7.39	165.00	2.82
109	420.5	6159.6	1-Feb.-87	1600.00	500.00	7.52	170.00	2.89
112	426.7	6163.3	1-Feb.-87	920.00	330.00	7.08	180.00	3.09
114	422.0	6168.1	1-Feb.-87	1420.00	332.00	7.55	175.00	2.95
115	417.1	6172.8	22-Jan.-87	910.00	288.00	7.41	320.00	5.49
116	432.1	6156.9	1-Feb.-87	1240.00	370.00	7.36	145.00	2.49
117	431.7	6180.9	6-Feb.-87	1350.00	442.00	7.23	139.00	2.36
118	431.2	6184.3	6-Feb.-87	1460.00	382.00	7.5	155.00	2.64
120	426.9	6157.6	1-Feb.-87	610.00	235.00	7.08	180.00	3.09
126	411.75	6192.2	24-Jan.-87	2250.00	475.30	7.70	212.00	3.62
127	407.9	6191.9	24-Jan.-87	1130.00	365.80	7.34	214.00	3.64
130	422.5	6202.5	10-Feb.-87	940.00	410.00	7.84	209.00	3.53
131	422.3	6207.0	10-Feb.-87	1250.00	441.00	7.57	222.00	3.75
133	429.5	6208.5	10-Feb.-87	910.00	ND	8.38	182.00	3.06
134	432.7	6213.5	10-Feb.-87	1310.00	446.00	8.07	183.00	3.08
135	438.0	6208.4	10-Feb.-87	990.00	394.00	7.4	209.00	3.54
139	442.6	6197.5	11-Feb.-87	190.00	279.00	7.38	203.00	3.40
140	441.2	6192.7	11-Feb.-87	700.00	197.00	7.09	183.00	3.06
142	437.2	6191.0	11-Feb.-87	1200.00	408.00	7.28	195.00	3.26
144	436.8	6201.0	10-Feb.-87	1080.00	351.00	7.44	187.00	3.17
145	436.4	6197.9	10-Feb.-87	1030.00	354.00	7.36	198.00	3.37
146	434.4	6202.7	10-Feb.-87	540.00	371.00	7.28	229.00	3.89
147	434.3	6207.1	10-Feb.-87	940.00	255.00	7.02	226.00	3.82
148	436.3	6187.5	11-Feb.-87	2500.00	449.00	7.48	200.00	3.39
149	435.8	6182.1	11-Feb.-87	1370.00	423.00	7.24	220.00	3.73
150	436.7	6178.9	11-Feb.-87	1300.00	390.00	7.66	225.00	3.81
151	440.9	6186.0	11-Feb.-87	1620.00	385.00	7.32	221.00	3.74
152	442.9	6181.2	11-Feb.-87	1330.00	494.00	7.56	208.00	3.52
153	432.2	6196.1	7-Feb.-87	750.00	308.00	7.61	198.00	3.37
154	432.2	6196.1	7-Feb.-87	1270.00	349.00	7.27	192.00	3.28
155	428.4	6196.3	10-Feb.-87	1290.00	429.00	7.31	209.00	3.53
156	425.2	6197.1	10-Feb.-87	1200.00	507.00	7.38	187.00	3.19
159	446	6153.2	13-Feb.-87	710.00	234.00	7.63	233.00	3.91
163	437.6	6158.8	23-Jan.-87	420.00	134.20	6.60	285.00	4.94

Continued..........

Table 4 Chemical analysis data (January - February 1987)

Sample	T.(AIR)	18O	Ca	Ca	Ca	Mg	Mg	Mg	Na
No.	°C	∂ Units	mg/l	meq/l	meq%	mg/l	meq/l	meq%	mg/l
84	30.5	-5.30	71.39	3.56	31.95	40.60	3.34	29.95	92.40
85	30.0	ND	79.00	3.94	30.81	26.00	2.14	16.71	151.00
88	30.0	ND	33.09	1.65	19.51	17.20	1.41	16.72	121.60
90	32.0	ND	55.94	2.79	21.09	40.00	3.29	24.86	161.00
91	32.0	ND	30.07	1.50	19.91	18.60	1.53	20.29	100.80
92	30.4	ND	88.90	4.44	42.18	21.80	1.79	17.05	95.20
93	27.0	ND	28.99	1.45	25.63	13.00	1.07	18.94	67.20
94	30.4	ND	42.44	2.12	27.81	13.80	1.13	14.90	98.60
96	32.0	ND	51.87	2.59	33.93	16.60	1.37	17.89	80.60
97	30.5	ND	28.22	1.41	16.94	14.80	1.22	14.64	125.40
101	29.5	-5.40	50.03	2.50	37.85	19.60	1.61	24.44	51.20
106	30.0	-5.50	24.16	1.21	12.42	13.20	1.09	11.19	167.20
107	22.3	-4.80	0.51	0.03	0.75	0.64	0.05	1.54	73.40
108	22.3	-5.40	14.35	0.72	5.85	13.60	1.12	9.14	238.20
109	25.5	-5.30	34.42	1.72	10.67	24.00	1.97	12.26	279.20
112	23.0	-5.40	51.83	2.59	27.26	17.40	1.43	15.09	117.00
114	29.0	ND	38.72	1.93	15.34	24.80	2.04	16.20	194.40
115	27.00	-5.20	45.23	2.26	25.35	22.60	1.86	20.88	107.20
116	22.0	-5.40	38.35	1.91	15.01	17.40	1.43	11.23	207.40
117	27.0	-4.80	37.87	1.89	13.69	20.80	1.71	12.40	232.80
118	27.0	-5.00	45.21	2.26	15.51	21.80	1.79	12.33	239.40
120	23.0	-5.40	19.19	0.96	16.93	10.40	0.86	15.12	83.00
126	26.00	-5.20	13.05	0.65	3.12	19.20	1.58	7.56	426.80
127	29.00	-5.10	4.16	0.21	2.82	31.20	2.57	34.89	103.60
130	26.7	-4.50	13.30	0.66	6.97	7.60	0.63	6.56	187.60
131	27.0	-5.20	22.81	1.14	8.91	12.20	1.00	7.85	243.20
133	27.0	-3.70	27.43	1.37	14.89	16.20	1.33	14.49	146.80
134	26.5	ND	10.23	0.51	3.84	7.40	0.61	4.57	279.20
135	26.5	ND	26.40	1.32	14.18	20.40	1.68	18.05	143.60
139	24.0	ND	26.36	1.32	13.15	18.40	1.51	15.13	163.80
140	24.5	ND	2.19	0.11	1.90	10.60	0.87	15.12	108.40
142	24.0	-4.60	17.00	0.85	8.37	18.00	1.48	14.60	177.00
144	21.6	-5.20	30.35	1.51	16.01	19.00	1.56	16.52	144.40
145	21.6	-5.30	36.00	1.80	19.97	26.00	2.14	23.77	115.00
146	26.5	ND	46.80	2.34	25.95	22.20	1.83	20.29	106.60
147	26.5	-5.70	39.12	1.95	22.55	15.60	1.28	14.82	123.60
148	25.0	-5.00	24.74	1.23	5.50	20.80	1.71	7.62	446.40
149	26.0	-5.30	39.12	1.95	14.71	21.00	1.73	13.01	219.00
150	26.0	-5.00	44.20	2.21	14.79	24.00	1.97	13.24	244.40
151	24.8	-5.00	52.14	2.60	20.12	25.60	2.11	16.28	186.40
152	24.5	-5.00	32.74	1.63	10.66	18.40	1.51	9.88	277.40
153	24.3	-5.10	24.74	1.23	14.89	10.60	0.87	10.52	140.00
154	24.3	-5.00	49.44	2.47	20.77	22.00	1.81	15.23	170.20
155	26.7	-5.20	24.74	1.23	11.49	23.40	1.92	17.91	172.00
156	24.8	-5.00	17.97	0.90	7.23	8.80	0.72	5.84	246.80
159	28.5	-5.50	40.37	2.01	31.32	26.40	2.17	33.75	46.60
163	19.00	-5.40	3.79	0.19	4.30	7.20	0.59	13.46	79.40

Continued.........

Table 4 Chemical analysis data (January - February 1987)

Sample	Na	Na	K	K	K	Na+K	na+k	HCO3	HCO3
No.	meq	meq%	mg/l	meq/l	meq%	meq /l	meq%	mg/l	meq/l
84	4.02	36.05	8.95	0.23	2.05	4.25	38.10	400.16	6.56
85	6.57	51.33	5.73	0.15	1.15	6.72	52.48	361.12	5.92
88	5.29	62.51	4.15	0.11	1.25	5.40	63.77	370.88	6.08
90	7.00	52.92	5.87	0.15	1.13	7.15	54.05	451.40	7.40
91	4.38	58.17	4.80	0.12	1.63	4.51	59.80	346.48	5.68
92	4.14	39.38	5.73	0.15	1.39	4.29	40.77	428.22	7.02
93	2.92	51.79	8.02	0.21	3.63	3.13	55.43	244.00	4.00
94	4.29	56.33	2.85	0.07	0.96	4.36	57.28	383.08	6.28
96	3.51	45.96	6.63	0.17	2.22	3.68	48.18	366.00	6.00
97	5.45	65.63	9.05	0.23	2.79	5.69	68.41	430.66	7.06
101	2.23	33.77	10.16	0.26	3.94	2.49	37.71	348.92	5.72
106	7.27	74.95	5.46	0.14	1.44	7.41	76.39	341.60	5.60
107	3.19	93.68	5.37	0.14	4.03	3.33	97.71	134.20	2.20
108	10.36	84.66	1.70	0.04	0.36	10.41	85.01	334.28	5.48
109	12.15	75.44	10.23	0.26	1.63	12.41	77.07	610.00	10.00
112	5.09	53.65	14.82	0.38	4.00	5.47	57.65	402.60	6.60
114	8.46	67.16	6.38	0.16	1.30	8.62	68.46	405.04	6.64
115	4.66	52.38	4.84	0.12	1.39	4.79	53.77	351.36	5.76
116	9.02	70.78	14.82	0.38	2.97	9.40	73.76	451.40	7.40
117	10.13	73.38	2.87	0.07	0.53	10.20	73.91	539.24	8.84
118	10.41	71.60	3.21	0.08	0.56	10.50	72.16	466.04	7.64
120	3.61	63.82	9.16	0.23	4.14	3.84	67.96	286.70	4.70
126	18.57	88.86	3.85	0.10	0.47	18.66	89.33	579.87	9.50
127	4.51	61.29	2.87	0.07	1.00	4.58	62.28	446.28	7.31
130	8.16	85.70	2.85	0.07	0.77	8.23	86.47	500.20	8.20
131	10.58	82.80	2.20	0.06	0.44	10.64	83.24	ND	ND
133	6.39	69.46	4.15	0.11	1.15	6.49	70.62	441.64	7.24
134	12.15	91.29	1.55	0.04	0.30	12.18	91.59	544.12	8.92
135	6.25	67.22	2.00	0.05	0.55	6.30	67.77	480.68	7.88
139	7.13	71.23	1.91	0.05	0.49	7.17	71.72	340.38	5.58
140	4.72	81.79	2.69	0.07	1.19	4.78	82.98	240.34	3.94
142	7.70	75.95	4.30	0.11	1.08	7.81	77.03	497.76	8.16
144	6.28	66.42	3.85	0.10	1.04	6.38	67.46	428.22	7.02
145	5.00	55.60	2.33	0.06	0.66	5.06	56.27	431.88	7.08
146	4.64	51.52	7.88	0.20	2.24	4.84	53.76	452.62	7.42
147	5.38	62.10	1.80	0.05	0.53	5.42	62.63	311.10	5.10
148	19.42	86.56	2.78	0.07	0.32	19.49	86.87	547.78	8.98
149	9.53	71.78	2.60	0.07	0.50	9.59	72.28	516.06	8.46
150	10.63	71.30	3.94	0.10	0.68	10.73	71.97	475.80	7.80
151	8.11	62.70	4.57	0.12	0.90	8.23	63.60	469.70	7.70
152	12.07	78.77	4.12	0.11	0.69	12.17	79.46	602.68	9.88
153	6.09	73.46	3.67	0.09	1.13	6.18	74.59	375.76	6.16
154	7.40	62.34	7.70	0.20	1.66	7.60	63.99	425.78	6.98
155	7.48	69.62	4.12	0.11	0.98	7.59	70.60	523.38	8.58
156	10.74	86.56	1.80	0.05	0.37	10.78	86.93	618.54	10.14
159	2.03	31.51	8.60	0.22	3.42	2.25	34.93	285.48	4.68
163	3.45	78.54	6.36	0.16	3.70	3.62	82.24	163.72	2.68

Continued.........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	HCO3 meq%	Cl mg/l	Cl meq/l	Cl meq%	SO4 mg/l	SO4 meq/l	SO4 meq%	NO3 mg/l	NO3 meq/l
84	65.13	49.29	1.39	13.80	30.27	0.63	6.26	92.46	1.49
85	50.63	61.80	1.74	14.91	49.29	1.03	8.78	186.21	3.00
88	72.72	43.58	1.23	14.70	27.77	0.58	6.92	29.31	0.47
90	48.25	148.17	4.18	27.25	53.26	1.11	7.23	164.25	2.65
91	77.33	23.24	0.66	8.92	29.97	0.62	8.50	23.89	0.39
92	73.65	44.55	1.26	13.18	24.47	0.51	5.35	46.24	0.75
93	67.24	30.63	0.86	14.52	23.14	0.48	8.10	37.36	0.60
94	80.58	23.72	0.67	8.58	26.53	0.55	7.09	18.08	0.29
96	76.16	31.79	0.90	11.38	24.23	0.50	6.40	29.58	0.48
97	64.53	101.71	2.87	26.22	26.30	0.55	5.01	28.78	0.46
101	79.32	17.59	0.50	6.88	16.12	0.34	4.66	40.85	0.66
106	55.99	97.07	2.74	27.37	44.17	0.92	9.20	46.11	0.74
107	ND	9.73	0.27	ND	7.63	0.16	ND	ND	ND
108	49.69	145.29	4.10	37.16	40.42	0.84	7.63	37.66	0.61
109	62.59	63.28	1.78	11.17	38.50	0.80	5.02	210.19	3.39
112	72.39	53.34	1.50	16.50	26.42	0.55	6.03	28.71	0.46
114	51.51	145.19	4.09	31.77	77.67	1.62	12.55	33.32	0.54
115	66.92	72.86	2.05	23.87	14.31	0.30	3.46	30.67	0.49
116	61.69	81.78	2.31	19.23	51.88	1.08	9.01	74.92	1.21
117	65.37	52.53	1.48	10.96	73.36	1.53	11.30	103.68	1.67
118	53.10	57.82	1.63	11.33	214.92	4.47	31.10	39.82	0.64
120	79.16	19.50	0.55	9.26	13.48	0.28	4.73	25.19	0.41
126	46.24	136.31	3.84	18.70	330.17	6.87	33.44	20.56	0.33
127	59.93	84.49	2.38	19.52	34.66	0.72	5.91	110.74	1.79
130	83.18	11.63	0.33	3.33	54.05	1.13	11.42	12.66	0.20
131	68.62	29.75	0.84	6.53	111.79	2.33	18.11	53.69	0.87
133	75.74	27.24	0.77	8.04	57.87	1.20	12.61	21.42	0.35
134	66.32	31.47	0.89	6.60	149.19	3.11	23.10	33.21	0.54
135	73.88	41.34	1.17	10.93	37.60	0.78	7.34	51.90	0.84
139	54.15	83.09	2.34	22.75	62.72	1.31	12.68	66.58	1.07
140	53.31	72.27	2.04	27.58	33.99	0.71	9.58	43.63	0.70
142	60.98	93.11	2.63	19.62	83.40	1.74	12.98	53.26	0.86
144	58.53	102.93	2.90	24.21	78.07	1.63	13.55	27.60	0.45
145	61.02	94.75	2.67	23.03	45.78	0.95	8.22	55.61	0.90
146	66.72	63.71	1.80	16.16	57.52	1.20	10.77	43.78	0.71
147	55.32	43.75	1.23	13.38	101.36	2.11	22.89	48.03	0.77
148	43.95	281.82	7.95	38.91	140.12	2.92	14.28	36.18	0.58
149	62.71	86.36	2.44	18.06	71.27	1.48	11.00	68.86	1.11
150	50.98	149.48	4.22	27.56	74.53	1.55	10.14	107.28	1.73
151	50.51	154.05	4.34	28.50	67.52	1.41	9.22	111.17	1.79
152	70.60	48.60	1.37	9.80	114.06	2.37	16.97	22.80	0.37
153	81.09	28.04	0.79	10.41	15.20	0.32	4.17	20.42	0.33
154	57.93	86.61	2.44	20.28	29.30	0.61	5.06	124.93	2.02
155	60.60	88.03	2.48	17.54	70.74	1.47	10.40	100.54	1.62
156	78.43	13.45	0.38	2.93	81.48	1.70	13.12	44.18	0.71
159	ND	50.82	1.43	ND	11.51	0.24	ND	ND	ND
163	67.57	18.85	0.53	13.38	22.09	0.46	11.58	18.38	0.30

Continued..........

Table 4 Chemical analysis data (January - February 1987)

Sample No.	NO3 meq%	T anion meq/l	T cation meq/l	T.D.S. mg/L	s.A.R.
84	14.81	11.15	10.07	785.52	2.16
85	25.69	12.80	11.69	920.15	3.77
88	5.66	8.46	8.36	647.58	4.27
90	17.28	13.23	15.34	1079.9	4.02
91	5.25	7.54	7.34	577.85	3.56
92	7.83	10.52	9.53	755.11	2.35
93	10.13	5.64	5.95	452.34	2.61
94	3.74	7.61	7.79	609.10	3.36
96	6.06	7.63	7.88	607.30	2.49
97	4.24	8.31	10.94	764.92	4.76
101	9.14	6.60	7.21	554.47	1.55
106	7.44	9.70	10.00	738.97	6.80
107	ND	3.41	ND	ND	16.16
108	5.51	12.24	11.03	825.50	10.82
109	21.22	16.10	15.97	1269.2	8.94
112	5.08	9.49	9.12	712.12	3.59
114	4.17	12.59	12.89	925.52	6.00
115	5.75	8.90	8.61	649.07	3.25
116	10.08	12.75	11.99	937.95	6.98
117	12.37	13.80	13.52	1063.5	7.55
118	4.46	14.54	14.39	1088.2	7.32
120	6.85	5.66	5.94	466.62	3.79
126	1.61	20.89	20.55	1529.1	17.58
127	14.64	7.35	12.20	818.00	3.83
130	2.07	9.52	9.86	789.89	10.17
131	6.74	12.78	12.85	1013.6	10.22
133	3.62	9.19	9.56	742.75	5.49
134	3.98	13.30	13.45	1056.7	16.24
135	7.85	9.29	10.66	803.92	5.10
139	10.42	10.00	10.30	763.24	5.99
140	9.52	5.77	7.39	514.11	6.73
142	6.42	10.14	13.38	943.83	7.14
144	3.71	9.46	11.99	834.42	5.06
145	7.73	9.00	11.60	807.35	3.57
146	6.35	9.00	11.12	801.11	3.21
147	8.40	8.66	9.22	684.36	4.23
148	2.86	22.43	20.43	1500.2	16.00
149	8.23	13.27	13.49	1024.7	7.02
150	11.31	14.91	15.30	1123.3	7.35
151	11.77	12.93	15.24	1071.5	5.29
152	2.63	15.32	13.99	1120.0	9.62
153	4.34	8.29	7.60	618.43	5.93
154	16.73	11.88	12.05	915.96	5.06
155	11.46	10.75	14.16	1006.5	5.95
156	5.51	12.40	12.93	1033.2	11.93
159	ND	6.43	ND	ND	1.40
163	7.47	4.40	3.97	319.79	5.53

Table 5 Chemical analysis data (August 1987)

Sample Number	X	Y	Date of sampling	Cond mS/cm	Total Alkalin.	T(AIR) °C	Ph units	Eh m.volts
1	417.5	6206.1	21-Aug.87	670	228.25	15	7.3	35
2	417.9	6214.4	21-Aug.87	1010	357.50	15	7.87	97
4	415.3	6208.7	21-Aug.87	710	271.56	16	7.15	85
17	404.1	6180.6	18-Aug.87	940	313.50	10	7.36	94
18	402.2	6180.2	18-Aug.87	890	333.44	12	7.61	76
19	402.1	6179.9	18-Aug.87	860	309.38	11	7.03	105
38	407	6180.7	16-Aug.87	790	384.31	7	7.82	127
39	404.9	6182.4	16-Aug.87	1140	385.00	7	7.5	87
41	401.8	6185.5	8-Aug.-87	840	347.19	11	7.37	97
45	404.45	6192.5	24-Aug.87	960	374.69	16	7.5	107
47	412.15	6196.7	22-Aug.87	1200	364.38	18	7.11	101
52	411.9	6187.7	21-Aug.-7	1400	446.19	13	7.12	100
53	408.7	6188.2	21-Aug.87	930	323.13	12	7.37	106
54	416.7	6191.5	13-Aug.87	ND	407.00	18.5	7.32	198
55	419.4	6185.1	13-Aug.87	ND	240.63	18.5	7.17	177
56	422.5	6180.8	13-Aug.87	ND	242.00	17	7.17	158
57	420.5	6184.6	13-Aug.87	ND	268.81	18.5	7.45	195
59	425.5	6176.8	14-Aug.87	590	ND	11	8.9	177
62	412.2	6182.5	18-Aug.87	840	ND	10	8.47	82
63	413.85	6181.9	18-Aug.87	590	285.31	10	7.36	95
64	411.4	6178.4	16-Aug.87	1600	455.13	6	7.75	102
66	412.85	6177.9	16-Aug.87	320	166.38	6	7.94	112
68	416.7	6182.9	13-Aug.87	520	191.81	15	8.01	196
69	420.5	6177.3	19-Aug.87	1070	303.19	10.5	7.34	95
74	418	6177.3	19-Aug.87	500	220.00	9	7.27	116
83	424.1	6193.3	23-Aug.87	630	220.00	16	7.36	137
84	426.5	6192.7	23-Aug.87	920	291.50	13	7.12	115
85	426.85	6191	23-Aug.87	126	325.88	18	7.09	13
88	424.6	6186.5	23-Aug.87	800	303.88	19	7.22	84
90	427.2	6181.4	23-Aug.87	1530	380.19	22	7.53	111
91	424.7	6183.7	23-Aug.87	690	301.81	20	7.19	114
92	431.5	6191.7	12-Aug.87	1005	384.31	18	7.35	185
93	431.5	6186.2	12-Aug.87	830	ND	17	8.6	183
94	429.1	6187	24-Aug.87	1720	349.94	22	7.28	138
117	431.65	6180.9	12-Aug.87	1350	ND	13	8.46	177
118	431.2	6184.3	13-Aug.87	970	ND	15	9.53	148
126	411.75	6192.2	21-Aug.87	ND	508.75	14	7.69	104
127	407.9	6191.9	19-Aug.87	1020	405.63	9	7.53	73
130	422.5	6202.5	20-Aug.87	850	ND	11	9.79	92
131	422.3	6207	22-Aug.87	1110	422.81	20	7.75	118
133	429.5	6208.5	22-Aug.87	900	359.56	17	7.46	120
134	432.7	6213.5	24-Aug.87	1200	458.56	17	7.91	103
153	432.2	6196.1	12-Aug.87	760	386.38	18	7.68	200
154	432.2	6196.1	12-Aug.87	1250	367.81	18	7.37	207
155	428.4	6196.3	20-Aug.87	1230	434.50	11	7.99	79
156	425.2	6197.1	20-Aug.87	1020	ND	11	9.14	88

Continued..........

Table 5 Chemical analysis data (August 1987)

Sample Number	Ca mg/l	Ca meq/l	Ca meq%	Mg mg/l	Mg meq/l	Mg meq%	Na mg/l	Na meq/l
1	25.80	1.29	18.26	13.80	1.13	16.09	103.65	4.51
2	44.44	2.22	19.99	23.40	1.92	17.35	158.2	6.88
4	33.28	1.66	21.83	18.00	1.48	19.46	100	4.35
17	57.99	2.89	32.52	27.20	2.24	25.14	82.2	3.58
18	36.08	1.80	19.66	16.80	1.38	15.09	133.8	5.82
19	31.72	1.58	17.12	17.40	1.43	15.48	140.4	6.11
38	51.85	2.59	30.57	22.00	1.81	21.38	90	3.92
39	51.23	2.56	23.70	26.60	2.19	20.28	135.8	5.91
41	42.59	2.13	24.91	19.00	1.56	18.32	107.2	4.66
45	30.48	1.52	15.18	13.80	1.13	11.33	166.8	7.26
47	116.77	5.83	52.27	34.80	2.86	25.67	52.4	2.28
52	84.76	4.23	28.69	33.20	2.73	18.52	177.4	7.72
53	38.25	1.91	20.22	15.60	1.28	13.59	141	6.13
54	25.17	1.26	13.73	12.80	1.05	11.51	156.2	6.79
55	24.86	1.24	19.69	12.20	1.00	15.92	90	3.92
56	24.86	1.24	15.99	11.80	0.97	12.51	125.2	5.45
57	29.86	1.49	18.63	15.20	1.25	15.63	117	5.09
59	36.70	1.83	31.17	12.60	1.04	17.64	65	2.83
62	32.35	1.61	17.48	15.60	1.28	13.90	141.6	6.16
63	27.98	1.40	21.83	14.00	1.15	18.00	87.4	3.80
64	36.08	1.80	11.20	18.60	1.53	9.51	290.2	12.62
66	20.16	1.01	24.19	8.60	0.71	17.00	50.4	2.19
68	28.61	1.43	24.76	13.80	1.13	19.69	70.2	3.05
69	19.22	0.96	8.39	11.20	0.92	8.06	217.2	9.45
74	30.79	1.54	27.76	15.20	1.25	22.58	59	2.57
83	27.36	1.37	22.33	11.80	0.97	15.87	84.8	3.69
84	78.11	3.90	40.58	29.60	2.43	25.34	70.2	3.05
85	70.52	3.52	26.64	27.20	2.24	16.94	168.2	7.32
88	33.28	1.66	19.84	15.80	1.30	15.53	121.8	5.30
90	90.79	4.53	27.54	44.80	3.68	22.40	185.4	8.06
91	32.35	1.61	20.82	17.40	1.43	18.46	105.2	4.58
92	88.98	4.44	42.85	17.60	1.45	13.97	99.4	4.32
93	48.46	2.42	27.64	19.00	1.56	17.86	104	4.52
94	51.23	2.56	28.00	15.20	1.25	13.69	118.6	5.16
117	50.31	2.51	16.57	18.20	1.50	9.88	254.4	11.07
118	8.20	0.41	3.84	5.80	0.48	4.48	223.2	9.71
126	37.63	1.88	8.11	21.00	1.73	7.46	447.2	19.45
127	59.83	2.99	27.46	30.80	2.53	23.30	120.6	5.25
130	19.54	0.98	9.49	8.20	0.67	6.56	196	8.53
131	23.30	1.16	8.58	14.00	1.15	8.50	255.8	11.13
133	32.97	1.65	17.19	17.00	1.40	14.61	148.4	6.46
134	11.36	0.57	3.97	6.80	0.56	3.92	300.8	13.08
153	20.16	1.01	10.63	10.40	0.86	9.04	172.2	7.49
154	53.08	2.65	21.90	21.60	1.78	14.69	172.2	7.49
155	59.83	2.99	21.88	27.20	2.24	16.39	190.8	8.30
156	24.86	1.24	10.87	12.80	1.05	9.23	208	9.05

Continued...........

Table 5 Chemical analysis data (August 1987)

Sample	Na	K	K	K	Na+K	na+k	HCO3	HCO3
No.	meq%	mg/l	meq/l	meq%	meq/l	meq%	mg/l	meq/l
1	63.93	4.74	0.12	1.72	4.63	65.65	278.47	4.56
2	62.05	2.62	0.07	0.60	6.95	62.65	436.15	7.15
4	57.19	4.50	0.12	1.51	4.47	58.70	331.31	5.43
17	40.19	7.46	0.19	2.14	3.77	42.33	382.47	6.27
18	63.56	6.06	0.16	1.69	5.98	65.25	406.79	6.67
19	66.06	4.83	0.12	1.34	6.23	67.40	377.44	6.19
38	46.26	5.90	0.15	1.78	4.07	48.05	468.86	7.68
39	54.77	5.24	0.13	1.24	6.04	56.01	469.70	7.70
41	54.66	7.05	0.18	2.11	4.84	56.77	423.57	6.94
45	72.42	4.18	0.11	1.07	7.36	73.49	457.12	7.49
47	20.45	7.05	0.18	1.62	2.46	22.06	444.54	7.29
52	52.35	2.53	0.06	0.44	7.78	52.79	544.35	8.92
53	64.97	4.50	0.12	1.22	6.25	66.19	394.21	6.46
54	74.26	1.80	0.05	0.50	6.84	74.77	496.54	8.14
55	62.13	5.57	0.14	2.26	4.06	64.39	293.56	4.81
56	70.19	4.01	0.10	1.32	5.55	71.51	295.24	4.84
57	63.64	6.56	0.17	2.10	5.26	65.74	327.95	5.38
59	48.12	7.05	0.18	3.07	3.01	51.19	239.04	3.92
62	66.71	6.88	0.18	1.91	6.34	68.62	429.44	7.04
63	59.45	1.80	0.05	0.72	3.85	60.17	348.08	5.71
64	78.50	5.00	0.13	0.80	12.75	79.29	555.25	9.10
66	52.71	9.92	0.25	6.10	2.45	58.81	202.98	3.33
68	52.97	5.82	0.15	2.58	3.20	55.55	234.01	3.84
69	82.68	3.85	0.10	0.86	9.55	83.55	369.89	6.06
74	46.37	7.13	0.18	3.29	2.75	49.66	268.40	4.40
83	60.33	3.52	0.09	1.47	3.78	61.80	268.40	4.40
84	31.79	8.61	0.22	2.29	3.27	34.08	355.63	5.83
85	55.39	5.32	0.14	1.03	7.45	56.42	397.57	6.52
88	63.31	4.34	0.11	1.33	5.41	64.63	370.73	6.08
90	49.02	6.72	0.17	1.04	8.24	50.07	463.83	7.60
91	59.02	5.16	0.13	1.70	4.71	60.72	368.21	6.03
92	41.73	5.90	0.15	1.46	4.47	43.18	468.86	7.68
93	51.71	9.51	0.24	2.78	4.77	54.50	296.08	4.85
94	56.51	6.39	0.16	1.79	5.32	58.30	426.92	7.00
117	73.06	2.86	0.07	0.48	11.14	73.54	619.00	10.15
118	91.13	2.29	0.06	0.55	9.77	91.68	472.22	7.74
126	83.98	4.18	0.11	0.46	19.56	84.44	620.68	10.17
127	48.26	4.18	0.11	0.98	5.35	49.24	494.86	8.11
130	82.95	4.01	0.10	1.00	8.63	83.95	547.70	8.98
131	82.12	4.26	0.11	0.80	11.24	82.92	515.83	8.45
133	67.46	2.78	0.07	0.74	6.53	68.20	438.67	7.19
134	91.66	2.53	0.06	0.45	13.15	92.11	559.45	9.17
153	79.14	4.42	0.11	1.19	7.60	80.34	471.38	7.73
154	61.93	7.05	0.18	1.49	7.67	63.42	448.73	7.35
155	60.82	4.83	0.12	0.91	8.42	61.73	530.09	8.69
156	79.30	2.70	0.07	0.61	9.12	79.90	648.35	10.63

Continued...........

Table 5 Chemical analysis data (August 1987)

Sample No.	NO3 meq/l	NO3 meq%	Total cation	Total anion	T.D.S. mg/L	S.A.R.	SiO2 mg/L
1	0.58	7.92	7.05	7.38	612.18	4.10	64.20
2	0.81	6.54	11.09	12.38	952.33	4.78	57.80
4	0.98	12.21	7.61	7.99	667.14	3.47	57.80
17	1.43	14.08	8.90	10.19	811.62	2.23	70.60
18	0.59	6.24	9.16	9.53	789.53	4.61	66.30
19	0.89	9.41	9.24	9.41	786.44	4.98	68.50
38	0.22	2.40	8.46	8.96	756.67	2.64	59.90
39	1.63	12.94	10.79	12.60	983.62	3.84	72.70
41	0.26	2.79	8.53	9.45	770.91	3.43	70.60
45	0.36	3.37	10.02	10.60	869.23	6.30	64.20
47	2.54	19.06	11.15	13.35	1002.8	1.09	59.90
52	2.89	17.83	14.74	16.21	1256.7	4.14	70.60
53	0.35	3.42	9.44	10.14	813.13	4.86	62.00
54	0.81	8.03	9.15	10.05	857.02	6.32	70.60
55	0.32	4.66	6.30	6.84	575.12	3.70	64.20
56	0.47	6.24	7.76	7.58	648.62	5.18	72.70
57	0.21	2.51	8.00	8.19	676.79	4.35	70.60
59	0.49	8.14	5.88	6.04	502	2.36	49.20
62	0.78	7.63	9.23	10.23	819.54	5.12	55.60
63	0.64	9.28	6.40	6.88	611.67	3.37	70.60
64	0.71	4.01	16.08	17.78	1341.7	9.78	68.50
66	0.24	5.98	4.16	3.99	356.14	2.37	32.10
68	0.52	9.23	5.77	5.62	489.2	2.70	55.60
69	0.70	6.17	11.43	11.39	916.85	9.74	68.50
74	0.51	9.11	5.54	5.55	497.76	2.17	59.90
83	0.58	8.29	6.11	6.97	568.92	3.41	57.80
84	1.66	15.90	9.61	10.42	807.43	1.72	51.30
85	4.34	28.99	13.21	14.99	1164.5	4.31	68.50
88	0.41	4.39	8.37	9.27	745.51	4.36	68.50
90	3.39	19.27	16.45	17.61	1322.1	3.98	72.70
91	0.35	4.25	7.75	8.35	700.21	3.71	72.70
92	0.69	5.73	10.36	12.12	933.07	2.52	68.50
93	1.42	14.34	8.75	9.89	756.61	3.21	53.50
94	0.25	2.53	9.13	9.94	805.08	3.74	66.30
117	1.75	10.46	15.15	16.69	1308.2	7.82	64.20
118	0.30	2.57	10.65	11.77	956.29	14.59	70.60
126	0.33	1.34	23.16	24.46	1816.2	14.49	66.30
127	1.48	12.00	10.87	12.36	975.84	3.16	66.30
130	0.20	1.85	10.28	10.95	940.74	9.39	74.90
131	0.91	6.74	13.55	13.55	1134	10.34	83.40
133	0.34	3.42	9.57	10.00	825.61	5.23	62.00
134	0.43	3.06	14.28	13.88	1153.7	17.44	55.60
153	0.31	3.27	9.47	9.62	836.46	7.76	79.20
154	1.94	14.23	12.10	13.63	1061	5.04	77.00
155	1.61	11.25	13.65	14.28	1140.8	5.14	68.50
156	0.30	2.50	11.41	11.79	1025.5	8.45	70.60

Table 6 Hardness values from the chemical analysis of waters collected in Jan. - Feb.'87.

S. No.	Hard.	S.No.	Hard.	S .No.	Hard.
1	128.85	64	128.85	127	128.85
2	166.91	66	166.91	130	166.91
4	159.53	67	159.53	131	159.53
6	374.25	68	374.25	133	374.25
9	255.75	69	255.75	134	255.75
11	130.32	76	130.32	135	130.32
12	146.6	77	146.6	137	146.6
13	152.7	78	152.7	139	152.7
14	111.38	79	111.38	140	111.38
15	133.65	80	133.65	142	133.65
17	230.8	81	230.8	144	230.8
18	160.93	82	160.93	145	160.93
19	154.99	83	154.99	146	154.99
20	111.68	84	111.68	147	111.68
21	123.97	85	123.97	148	123.97
22	172.86	88	172.86	149	172.86
23	98.08	90	98.08	150	98.08
24	62.57	91	62.57	151	62.57
25	179.05	92	179.05	152	179.05
26	57.6	93	57.6	153	57.6
27	153.79	94	153.79	154	153.79
28	215.55	95	215.55	155	215.55
29	144.55	96	144.55	156	144.55
38	245.61	97	245.61	157	245.61
39	153.75	100	153.75	158	153.75
41	108.95	101	108.95	159	108.95
42	137.85	106	137.85	163	137.85
43	162.75	107	162.75	163/1	162.75
44	135.62	108	135.62	166	135.62
45	142.97	109	142.97	167	142.97
47	290.65	110	290.65	168	290.65
52	253.61	111	253.61	169	253.61
53	165.3	112	165.3	170	165.3
54	93.685	114	93.685	118	93.685
55	101.77	115	101.77	120	101.77
56	115.49	116	115.49	126	115.49
57	126.85	117	126.85		
63	96.745	59	96.745		