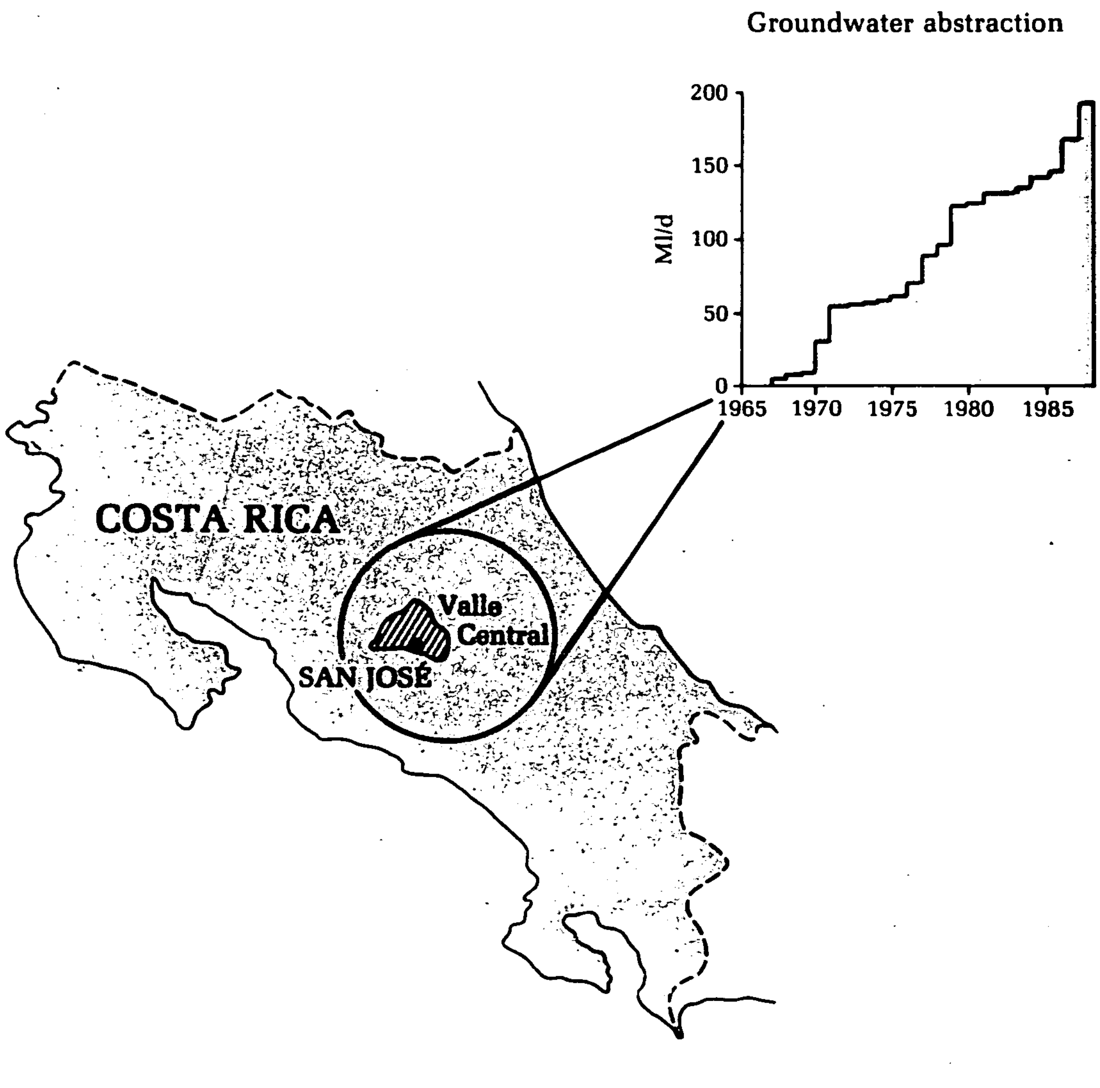
SENARA

The continuation of hydrogeological investigations in the north and east of the Valle Central, Costa Rica

Final Report 1984-87

BGS Technical Report WD/88/13R



For
Instituto Costarricense de Acueductos y Alcantarillados
San José, Costa Rica

BRITISH GEOLOGICAL SURVEY

TECHNICAL REPORT WD/88/13R

Hydrogeological Series

The continuation of hydrogeological investigations in the north and east of the Valle Central, Costa Rica

Final Report 1984-87

The work described in this report was carried out jointly by the British Geological Survey (BGS. Wallingford, UK) and the Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento (SENARA, San José, Costa Rica) on behalf of the Instituto Costarricense de Acueductos, y Alcantarillados (ICAYA, San José, Costa Rica). A Spanish translation of the report has been produced in Costa Rica by SENARA.

Bibliographic reference

British Geological Survey. 1988. The continuation of hydrogeological investigations in the north and east of the Valle Central, Costa Rica: Final Report 1984-88. *British Geological Survey Technical Report* WD/88/13R.

Keyworth, Nottingham British Geological Survey 1988

BRITISH GEOLOGICAL SURVEY

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PREFACE

This report is the conclusion of a three year investigation of the groundwater resources of the Valle Central in Costa Rica carried out jointly by BGS (British Geological Survey) and SENARA (Servicio Nacional de Aguas, Riego y Avenamiento) on behalf of ICAyA (Instituto Costarricence de Acueductos y Alcantarrillados) under the terms of their loan agreement with the World Bank. The objective of the investigation is to obtain a better understanding of the complex groundwater regime, principally of the Colima aquifers, and on this basis to make recommendations for a rational policy of further groundwater exploitation and the prevention of groundwater pollution.

The study has been based on new hydrogeological information gained from the drilling of cored investigation boreholes and trial production boreholes and re-evaluation of existing data. A variety of hydrogeological techniques have been employed, including borehole flow logging and laboratory testing of rock hydraulic properties, and numerous water samples have been analysed for a wide range of chemical parameters. The laboratory tests of rock properties have been particularly important in providing new scientific data about the movement and storage of water in the lavas and pyroclastics.

It is concluded that development of an additional 1000-1500 l/s of groundwater from the Colima aquifers is possible. The most effective strategy for development is the construction of new wellfields. Recommended areas for new groundwater abstraction include an extension of the Valencia Wellfield, a new wellfield within the area between Pitahaya and Barreal and a possible wellfield south of the Aeropuerto Juan Santamaria. The groundwater quality is generally excellent but there are indications of deterioration and, in some areas, aquifers are at risk of becoming seriously contaminated in the future. As groundwater development expands it will be increasingly important to monitor both groundwater levels and groundwater quality in order to maintain borehole yields and the potability of groundwater supplies.

ACKNOWLEDGEMENTS

This project was funded by the World Bank (BIRF) and the British Commonwealth Development Corporation (CDC) under a loan agreement with the Instituto de Costarricense de Acueductos y Alcantarillados (ICAyA). BGS and SENARA are grateful for having been given the opportunity to study the complex and interesting aquifer system of the Valle Central in more detail than has previously been possible.

Particular thanks are due to Ing Herbert Farrer (ICAyA-Gerente Tecnico) and his colleagues for their support and for administration of the project finances. The British Embassy Commercial Section are also thanked for their role in liaison and implementation of the project.

We would like to acknowledge the earlier groundwater investigations carried out by Howard Humphreys & Sons which provided an excellent basis for the current project. Thanks are also due to Cimco SA, Perforadora Latina and ICAyA who were responsible for drilling the numerous boreholes for the project. Dr Flora Perez and her staff, especially Quim Azucena Urbina are thanked for the analysis of water samples. We acknowledge also the data and assistance provided by the Ministerio de Salud (Division de Saneamiento Ambiental), the Instituto de Cafe and ESPH and the help given to us by many of the ICAyA staff especially Ing Manuel Ruiz, Ing Vinicio Urbina, Ing Eugenio Azofeifa, Ing Ronaldo Calvo, Ing Antonio Salas and Ing Irving Perera.

Finally we wish to thank Mike Allsop and Lic Fernando Duarte for looking after the project accounts and Carole and Keyna who typed all the reports.

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APPENDICES

An appendix containing the details of all boreholes drilled and tested during the project is being prepared independently by SENARA. A summary of all relevant data is, however, included in this report which may be read without reference to the appendix.

PROJECT PROGRESS REPORTS

The following interim progress reports were produced during the project.

Rodriguez, H. and Vasquez, C. 1984. Estudio Hidrogeologico para desarrollo de los acuiferos Colima. Aplicacion del modelo matematico IGS-SENARA. SENAS Informe Technico, 153.

Perkins, M. 1985. Borehole flow logging in the Valle Central : Costa Rica visit, July 1985. BGS Report WD/OS/85/33.

BGS-SENARA 1985. Further groundwater evaluation and development in the Valle Central, Costa Rica. Year 1 Technical Report. BGS Report WD/OS/85/32.

BGS-SENARA 1987. Further groundwater evaluation and development in the Valle Central, Costa Rica. Year 2 Technical Report. BGS Report WD/OS/87/2.

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1. INTRODUCTION

1.1 Background to Project.

(a) The current loan agreement of the Instituto Costarricense de Acueductos y Alcantarillados (ICAyA) with the World Bank (BIRF) and the British Commonwealth Development Corporation (CDC), for the implementation of the Orosi Project, includes an item on the further investigation of groundwater in the Valle Central. The groundwater resources of this region constitute a major source of water-supply for the San Jose Metropolitan area and for other towns in the vicinity. Bearing in mind the proven high potential of the aquifers of the region, there was a need to determine groundwater recharge and discharge mechanisms, to define an aquifer protection policy and to strengthen ICAyA's capacity in this field through technical collaboration.

(b) A project was thus defined to be carried out, during 1984-87, by an interinstitutional collaboration agreement between ICAyA, the British Geological Survey (BGS, formerly IGS) and the Servicio Nacional de Aguas Subterraneas, Riego y Avenamiento (SENARA, formerly SENAS). SENAS and IGS had already co-operated on groundwater research in the region, under British technical collaboration arrangements, and SENAS have been involved since the outset of scientifically-based groundwater investigations in Costa Rica.

(c) The discovery of abundant groundwater in the volcanic geological formations on the northern side of the Virilla river in the Valle Central (Fig 1.1) was first made in 1968 by the UNDP-promoted AQUASUB Project for 'Investigation of Groundwater in Selected Areas of Costa Rica', and soon after the springs of Puente Mulas and La Libertad were captured for public water-supply. This marked the beginning of a rapid expansion in groundwater abstraction within the Valle Central (Fig 1.2).

(d) AQUASUB was implemented by means of a joint agreement between the UNDP, ICAyA, the Ministerio de Agricultura y Ganaderia (MAG), the Instituto Costarricense de Electridad (ICE) and the Ministerio de Economia, Industria y Comercio-Direccion de Geologia, Mineria y Petrolio. This project culminated in the formation of a national organisation to specialise in the field, SENAS.

(e) The programme developed by AQUASUB consisted of a hydrogeological reconnaissance of the region, directed towards an estimate of the total recharge rate in the catchment area, an inventory of all groundwater springs, determination of the groundwater regime and hydraulic parameters, such as aquifer transmissivity and storativity, and a survey of the superficial geology and infiltration potential.

(f) Using the limited results of this investigation, Howard Humphreys & Sons, consultants to ICAyA in 1972 for a 'Study of Water-Supply in the San Jose Metropolitan Area', examined eight possible alternative schemes for groundwater abstraction from the aquifers in the River Virilla catchment. Following a technical and economic evaluation, they recommended groundwater abstraction by way of a wellfield with a capacity of 1000 l/s in the neighbourhood of La Valencia, Santo Domingo de Heredia (Fig 1.1), initially to be equipped to yield 500 l/s. This recommendation began to be implemented, when drilling commenced in 1975.

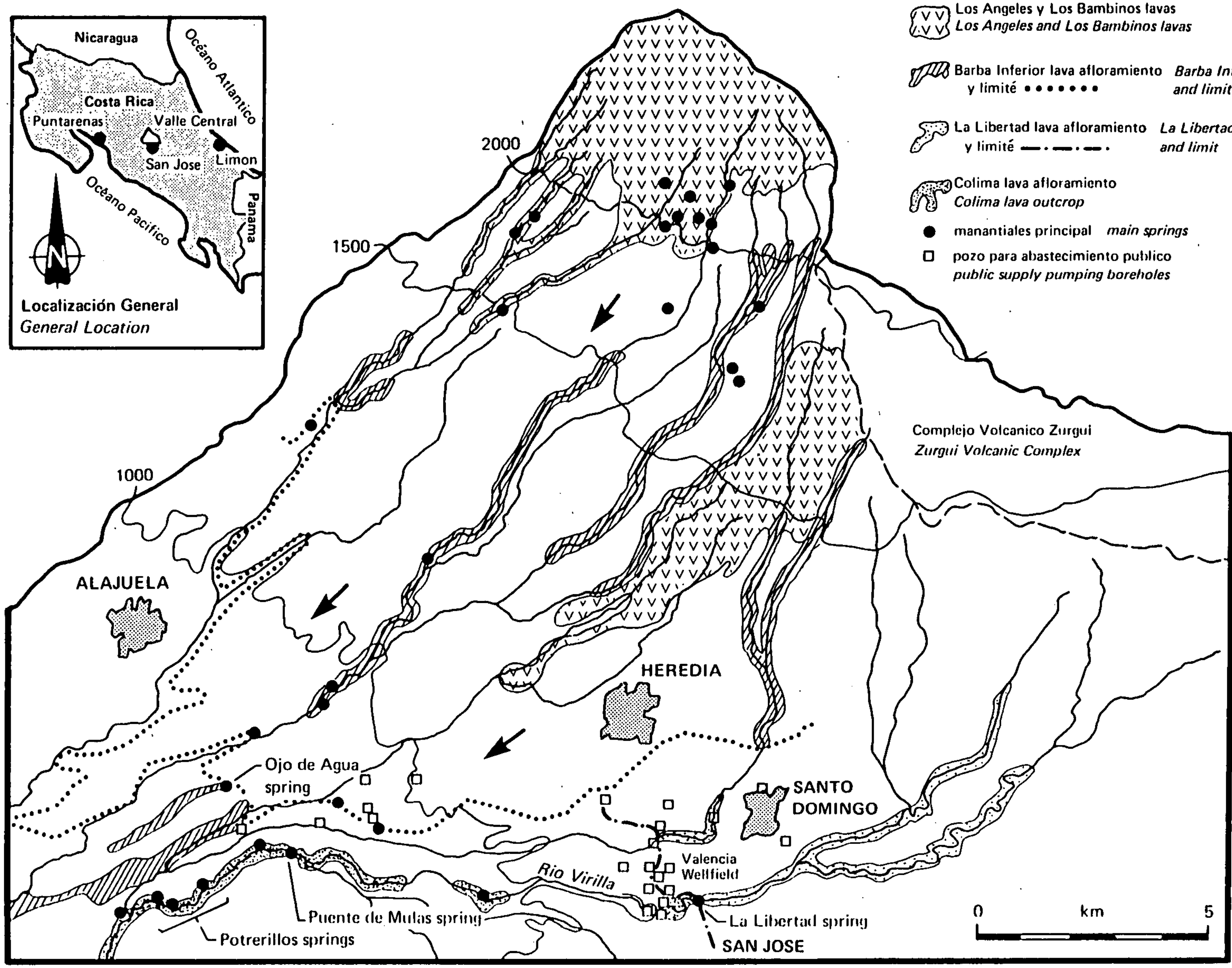

Fig 1.1 Simplified hydrogeological map of the Valle Central.

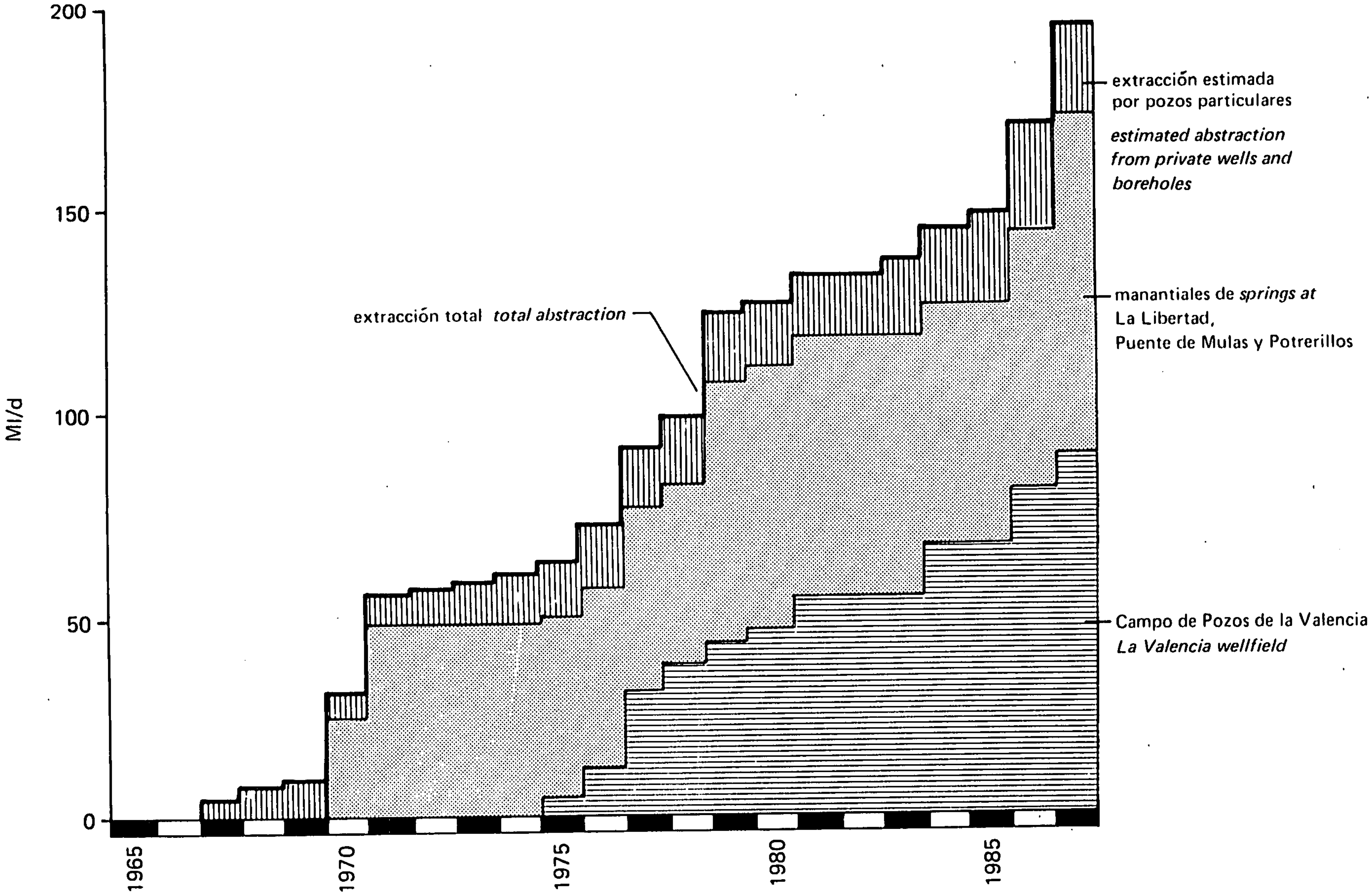

Fig 1.2 Historic growth of groundwater abstraction from the Colima aquifers.

(g) However, in 1977 SENAS sounded a possible alarm; with increasing abstraction from the wellfield under construction, and below-average rainfall in the preceding years, groundwater levels were falling. If this trend were to continue, it could lead to a design failure of the La Valencia wellfield. With a view to examining this problem, in 1978 SENAS and IGS (who had already collaboratd spasmodically since 1975) drew up a programme for the re-evaluation of groundwater resources in the Colima aquifers in the Valle Central. This programme reviewed previous evaluations and then attempted to construct a computerised mathematical aquifer model. The model, if capable of calibration with historic hydrological data, would serve to define the most suitable scheme for further development and the necessary controls to prevent interference with existing exploitation. While the model was being constructed, ICAyA was advised to halt well construction and restrict further groundwater abstraction in the immediate area of La Valencia Wellfield to considerably below the intended capacity of 1000 l/s until the additional effects of pumping from proposed new wells had been simulated.

(h) Consequently, ICAyA restricted wellfield exploitation to 690 l/s from 10 wells, including one well (La Peregrina) drilled to provide a water-supply to that urbanisation in the vicinity of the wellfield. In addition to this and utilising the same aquifers, the springs of La Libertad yielded 80 l/s and the springs, galleries and tunnels at Puente Mulas added a further 660 l/s, making a total groundwater use of about 1400 l/s (Fig 1.2).

(i) In the 'Study of the San Jose Metropolitan Aqueducts for Inegration in the Orosi Project', it was established that (if no further action were taken) the water deficit prior to commissioning of the Orosi Project would reach the catastrophic figure of 660 l/s with respect to maximum daily demand and 400 l/s with respect to average demand, in the next few summers. Faced with this situation, the possibility of abstracting an additional 300 l/s from La Valencia Wellfield was explored. This was the first practical use of the new aquifer numerical simulation model, which aided definition of the drilling sites for new wells and prediction of the aquifer response to additional future abstraction.

(j) The British technical collaboration programme to construct a numerical simulation model of the Colima aquifers required the recompilation and integration of all available hydrogeological data and a natural extension of this project was the production of a hydrogeological map of the Valle Central. This was published by BGS-SENARA in 1984 and first addressed, at reconnaissance level, the issue of pollution vulnerability of the aquifers in the area.

(k) Despite the high potential attributed to the Colima Aquifers northwest of San Jose, studies were also begun in other areas to identify aquifers suitable for supplying water to the San Jose Metropolitan Area. To explore the possibility of using groundwater in the sector east of San Jose to supply the metropolitan area, a study was carried out by ICAyA and SENARA in 1980. This established that the geological unit with the highest groundwater potential is the Reventado Formation, which underlies the mudflows east of San Jose and in the Zapote Curridabat area, and outcrops further east.

(l) Following one of the recommendations made in this study, a series of differential flow measurements along the rivers of this latter area was made in summer 1981. These measurements support the existence of important groundwater recharge in the area. The application of the aquifer mathematical model to La Valencia Wellfield was instrumental in suggesting important riverbed infiltration in the area northeast of San Jose, since it required the existence of substantial groundwater recharge to the Colima aquifer in this area.

(m) All the previous work pointed towards the need for a new and broader study to clarify the groundwater panorama in the Valle Central, since definitive information on the location and quantity of exploitable groundwater is needed for the rational planning of future water-supply both for the San Jose Metropolitan Area and other large towns in the Valle Central, before resorting to the import of resources from other catchments.

1.2 Objectives of Project.

(a) The investigations to take place by way of the interinstitutional agreement between ICAyA, BGS and SENARA were designed to allow ICAyA to exploit more rationally the groundwater of the Valle Central. The investigations would continue the series begun by ICAyA in collaboration with SENAS, and, more recently, with IGS.

(b) Since the existing main pipelines and pumping stations from La Valencia Wellfield and Puente Mulas Springs were not being used to full capacity, it was necessary in the short term to take action to obtain additional yield. It was proposed that full use be made of the total pipeline capacity to convey water to the San Jose Metropolitan Area, since a water-supply deficit was anticipated here until the Orosi Project is operational.

(c) The most important objective of the investigations in the longer term is to broaden the knowledge of the recharge and discharge of both deep and superficial aquifers in the Valle Central, in order to ascertain the available flows and suitable locations for future exploitation. Moreover, this knowledge will serve as the basis for an improved policy for the control of groundwater exploitation and the prevention of contamination of these aquifers, which are located in an area subject to rapid urban development.

(d) The longer term investigations were, for the most part, to be centred in the area to the northwest of San Jose. A hydrogeological evaluation of the area east and northeast of San Jose would also be undertaken. Although the expected groundwater potential here is volumetrically less concentrated than in lower-lying catchment area, its location and altitude favour the supply of water to the San Jose Metropolitan Area by gravity and/or low-head pumps.

1.3 Institutional Organisation of Project.

(a) In a telex to ICAyA dated 22 November 1982, BIRF advised that it had no objection to the contracting of IGS for the groundwater study programme in the Valle Central, bearing in mind that IGS already knew the area well, having worked there under British technical cooperation programmes. In turn IGS, in a telex of 24 December 1982 and letter of 5 January 1983, declared that they saw no difficulty in formalising a contract with ICAyA to continue the hydrogeological investigations.

(b) Thus, ICAyA began discussions with representatives of IGS and SENAS to outline the organisation and procedure to be used for the studies. It was concluded that the following scheme would be the most suitable: IGS should act as project directors and be responsible for the progress and development of the studies, acting in both a consulting and advisory capacity: SENAS should be responsible for the execution of the work and should choose part- and full-time project staff from its personnel. SENAS should respect whatever is put forward by IGS concerning the study methods and investigation procedures.

(c) ICAyA would contribute by ensuring that the programme developed in the way specified in the work schedule, making necessary suggestions and comments to ensure compliance with the schedule, since it is of the utmost importance to ICAyA that the studies should be concluded within the period defined in the aforementioned loan agreement.

1.3.1 ICAyA: Tasks and Responsibilities

(a) ICAyA, as the body directly interested in the promotion of these studies, were to ensure that the programme activities were completed within the specified timetable, and that the studies were carried out in logical sequence, so that the investigation objectives could be achieved. ICAyA were also responsible for organising, as required, the contracts needed for the execution of specialised construction works, such as borehole drilling, necessary for the studies.

(b) ICAyA took charge of all the financial transactions, including accounts submitted both by BGS and SENARA, as a result of the project activities. Thus, ICAyA were in control of all costs incurred, and checked items on each account before presentation for payment to BIRF.

1.3.2 BGS (IGS): Tasks and Responsibilities

(a) BGS were to be the general consultant, whose responsibilities were to define the investigation aims, to propose the investigation activities, to recommend the procedure for their execution, to offer specialised technical assistance, to provide technical support to the SENARA activities, and to put forward three-monthly progress reports and comprehensive annual reports to ICAyA on the state of the investigation.

1.3.3 SENARA (SENAS): Tasks and Responsibilities

(a) SENARA were responsible for the completion of all field activities, and participated in the coordination of these activities, with BGS and ICAyA and in the interpretation of investigation results. SENARA were also to submit to ICAyA three-monthly progress reports and reports of the costs incurred for the project and on the activities in their charge.

1.4 Organisation of Technical Activities.

(a) Within the Valle Central study area, several smaller areas were designated for more specific and detailed investigation. These areas, illustrated in Fig 1.3 are known as:

(i) The Valencia Wellfield (Campo de Pozos)
(ii) Puente de Mulas
(iii) Zona Barba
(iv) Zona Este (divided into North and South)

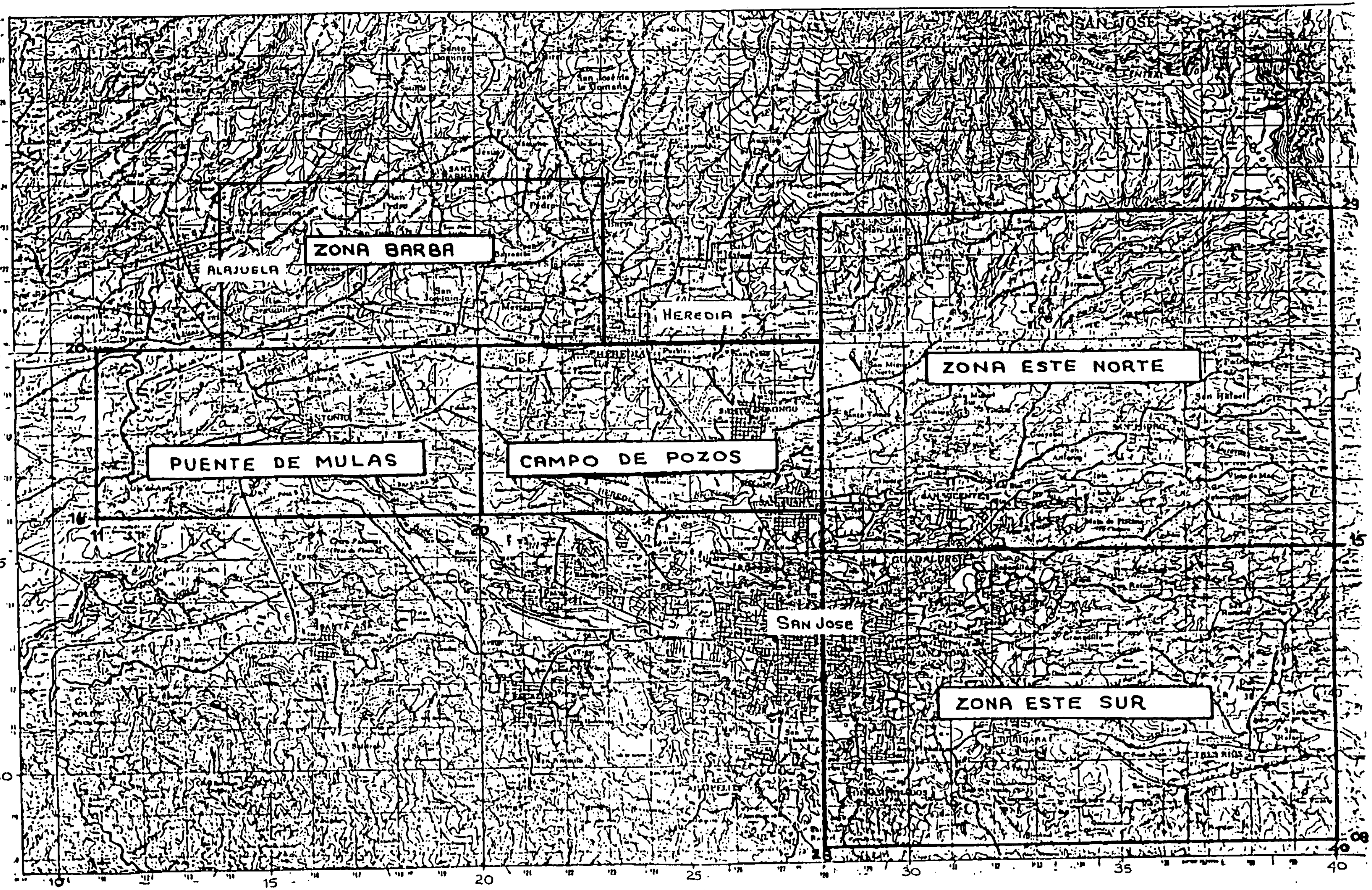

Fig 1.3 Location of detailed project study areas.

(b) The investigations in (i) and (ii) were aimed towards locating the most appropriate areas to increase the abstraction of groundwater for potable water-supply to the San Jose Metropolitan Area both in the short-term to make use of excess capacity in the existing distributions and for the development of new wellfields in the longer term. A third area, (iii) Zona Barba, was defined at a later stage in the project to encompass the need for more detailed study of the relationship between the Barba and Colima Superior aquifers. The investigations in (iv), the Zona Este, were at more of a reconnaissance level with the practical aim of identifying and developing new groundwater potential for local supply to communities in the higher elevations in the east of the San Jose Metropolitan Area.

(c) The project terms of reference identified a series of tasks to be carried out in the various project areas. Each of the major technical activities and their implementation is discussed below. The division of responsibility between ICAyA, BGS and SENARA for each of these technical activities is given in Table 1.1.

1.4.1 Field Studies

(a) Groundwater level monitoring: This activity was common to the investigation in all the detailed study areas and continued throughout the project. A network of monitoring boreholes was defined (Fig 1.4) and groundwater levels measured regularly (monthly) by SENARA. As new investigation boreholes were drilled during the project, piezometers were installed in the various aquifers and added to the monitoring network. The information is fundamental to the establishment of a hydrogeological database for the Valle Central against which to gauge fluctuations and long-term trends in groundwater levels and to assess the impact of new abstractions. The data has been used to update and calibrate the mathematical model.

(b) Spring inventory and monitoring: Spring discharges throughout the main study areas (excluding the Zona Este) were measureo during the course of the project. It was intended that this activity should provide basic hydrgeological information for future reference and identify springs with potential for development for local potable water supplies. This information is summarised in Fig 3.1.

(c) River and spring gauging: Differential gauging of the Virilla river was undertaken mainly at the end of the dry season to aid evaluation of the spring discharge to the river.

(d) Surface geological and geophysical exploration: Surface geological mapping was undertaken in key areas and those with inadequate existing coverage. In other instances, standard surface resistivity geophysical techniques were employed to aid subsurface interpretation and drilling site selection. The results of this work are not specifically reported but have been incorporated as appropriate into the hydrogeological interpretation.

(e) Geophysical well logging: Geophysical well logging was carried out by BGS in several production boreholes in area (i) to investigate the groundwater flow in the lavas. A package of equipment was assembled by BGS for project use in Costa Rica and staff from SENARA trained in its operation.

Table 1.1 Responsibility for technical activities.

Activity	ICAyA	BGS	SENARA
FIELD STUDIES			
Groundwater level monitoring		I	P,E,I
Spring inventory and monitoring	P,E		E
River gauging		P	P,E,I
Surface geology and geophysics			P,E,I
Geophysical well logging		P,E,I	E
BOREHOLE DRILLING			
Investigation boreholes	P	P,I	P,S,I
Large diameter trial boreholes	E,S	P,I	P,S,I
Production boreholes	E,S	P,I	P,S,I
LABORATORY AND COMPUTER STUDIES			
Groundwater quality investigations	E	P,E,S,I	E
Isotope analysis		P,E,I	E
Rock physical properties		P,E,I	
Mathematical modelling		P,E,I	E
Landsat image analysis		P,E,I	

P Planning
E Execution
S Supervision (where appropriate)
I Interpretation

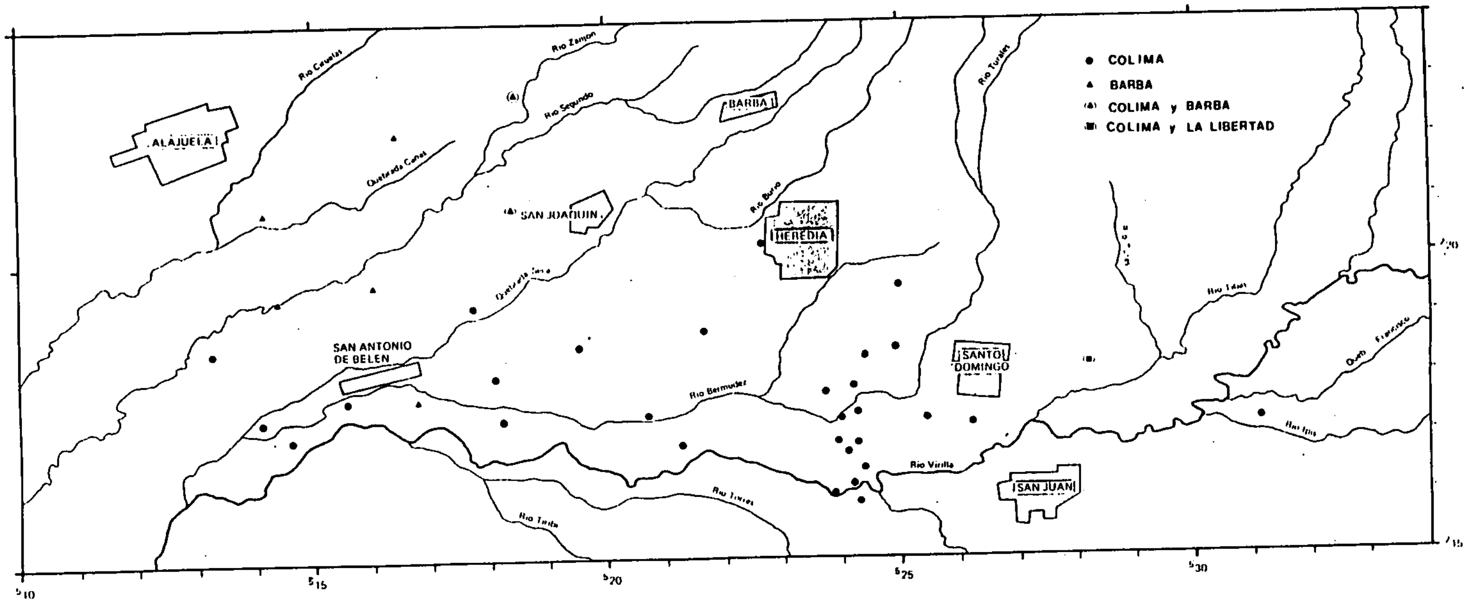

Fig 1.4 Groundwater level observation boreholes.

1.4.2 Borehole Drilling

(a) Investigation boreholes: Small diameter (1"-2.5") cored investigation boreholes were drilled in all the special study areas to improve geological correlation and to obtain vital information about groundwater levels in the volcanic sequence. The boreholes were drilled with a rotary rig using water as a drilling fluid. The details of this activity are discussed in section 1.5.

(b) Large diameter trial boreholes: Within areas (ii), (iii) and (iv) trial production boreholes were drilled for carrying out pumping tests in areas of groundwater development potential. A combined pneumatic hammer/rotary rig was used with air or water as a circulating fluid.

(c) Production boreholes: Several boreholes were located, drilled, tested and brought into production by ICAyA in area (i) to increase abstraction from the existing Valencia Wellfield. A rotary hammer rig was employed.

1.4.3 Laboratory and Computer Studies

(a) Groundwater quality investigation: A range of chemical and biological analyses were carried out on samples collected from a wide variety of locations throughout the Valle Central but particularly in study areas (i) and (ii). The results provide baseline information on current groundwater quality in the different aquifers, detect existing pollutants and highlight potential pollution problems. The data might also be useful in corroborating the recharge mechanisms of the different aquifers.

Inorganic constituents - the programme commenced with quarterly sampling from a network of 15 river and groundwater locations. Both the frequency of sampling and the sampling points were modified in the light of interim results, and a much wider range of borehole locations were sampled at least once, usually in association with other sampling programmes.

Trace elements - a survey of trace elements in groundwater was carried out to determine both naturally occurring elements associated with the volcanic rocks and certain elements that may be derived from pollution. The main Colima groundwater sources and many of the springs issuing from shallow aquifers were sampled.

Organic constituents - a range of groundwater and river samples were analysed for total organic carbon. In those areas considered to be potentially vulnerable to industrial pollution, selected groundwater samples were analysed for the presence of synthetic and potentially toxic organic compounds.

(b) Isotope analysis: Groundwater samples from different aquifers and at different altitude have been analysed by BGS for the stable isotopes ^{2}H and ^{18}O as an aid to the interpretation of the aquifer recharge mechanism. Several tritium analyses were also carried out to determine the age of various groundwaters as an indication of the residence time in the aquifer system.

(c) Rock physical properties: Lithological samples obtained from the cored investigation boreholes were analysed by BGS to determine their laboratory physicohydraulic properties with the objective of improving understanding of the flow, storage and recharge mechanisms in the aquifer system.

(d) Development of a mathematical model: The existing mathematical model was based on a single layer aquifer simulation of the Colima aquifers in the Valle Central. A more sophisticated two layer model of these aquifers was developed by BGS during the project, incorporating revised hydrogeological interpretation and calibrated against the most recent data. The model was designed and tested in the UK and on completion installed on an IBM microcomputer at SENARA where staff were trained in its use. A range of simulations were run to determine the impact of various scenarios for increasing groundwater abstraction from the Colima aquifers.

(e) Landsat image analysis: Satellite imagery was studied as a possible means of deriving additional information about surface geology and aquifer recharge. A computer tape of a LANDSAT multispectral image of the Valle Central was purchased and analysed by BGS using a full range of computer image enhancement techniques. The method was not found to be appropriate to the investigation.

1.5 Scope of Drilling Programme.

(a) Table 1.2 summarises the number of boreholes of different types that were originally planned and those actually drilling during the course of the project. The location of the small diameter cored boreholes (investigation boreholes) and the large diameter trial holes are shown on Fig 1.5. The details of the small diameter cored boreholes are summarised in Table 1.3. These and other boreholes are the basis of the many geological cross sections illustrated in this report, the locations of which are shown on Figure 1.6. Details of other boreholes are included in Chapter 5.

(b) The drilling programme was always conceived as being flexible within the financial limits. Amendments to the originally planned programme include the drilling of 8 boreholes in the Zona Este Sur not originally envisaged but implemented at the specific request of ICAyA in relation to the emergency plan. Another addition to the original programme was the inclusion of 5 boreholes in the Zona Barba but as a consequence fewer investigation boreholes were required in the Puente de Mulas area.

(c) The actual meterage of drilling and depths of all boreholes were within the ranges originally estimated but the numbers of investigation and trial boreholes drilled in the main study areas were slightly fewer than planned.

(d) The most important outstanding item in the drilling programme is the recommended borehole WO in the Valencia Wellfield. This borehole was intended for use as an observation borehole equipped with a continuous water level recorder to monitor long-term changes in groundwater level in the wellfield.

Table 1.2 Summary of Drilling Programme.

Investigation Area	Large diameter production boreholes		Large diameter trial boreholes		Small diameter cored boreholes	
	Planned	Actual	Planned	Actual	Planned	Actual
(a) Campo de Pozos	5	5	1*	1	1	2
(b) Puente de Mulas	0	0	2	2**	7	4
(c) Zona Barba	0	0	0	1	0	4
(d) Zona Este Norte	0	0	2	0	7	3
(e) Zona Este Sur	0	1	0	7	0	0
TOTAL	5	6	5	11	15	13

* outstanding borehole WO in Valencia Wellfield for installation of continuous water level recording apparatus.

** includes one borehole drilled and financed by ESPH in 3rd year of project at a site in Pitahaya selected as result of project investigations.

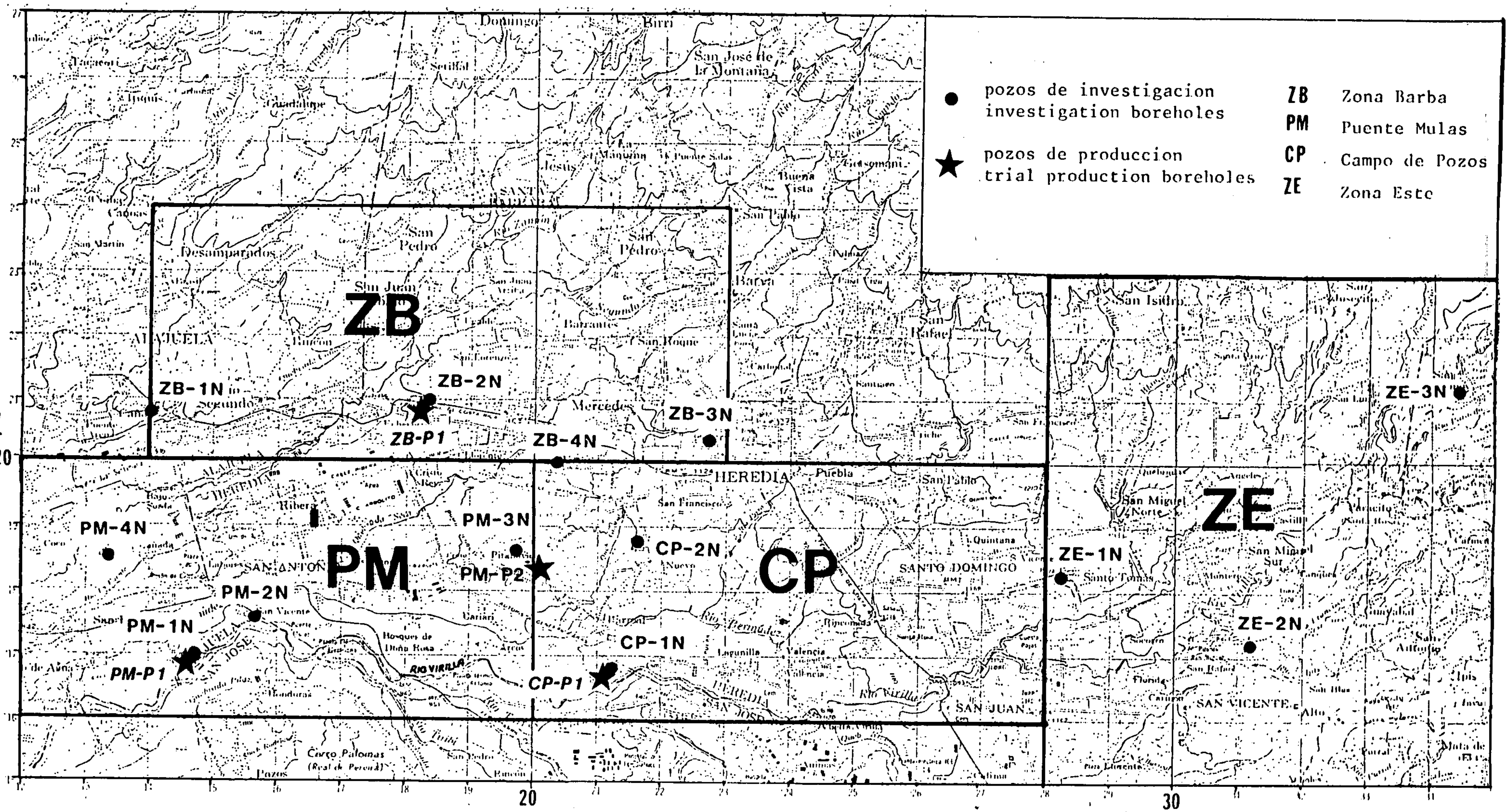
pozos de investigacion
investigation boreholes
pozos de produccion
trial production boreholes
ZB Zona Barba
PM Puente Mulas
CP Campo de Pozos
ZE Zona Este
ZB
PM
CP
ZE
ZB-1N
ZB-2N
ZB-3N
ZB-4N
ZB-P1
PM-1N
PM-2N
PM-3N
PM-4N
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Table 1.3. Summary of investigation boreholes drilled during project.

DETAILS	PEUNTE DE MULAS				CAMPO DE POZOS		ZONA BARBA				ZONA ESTE		
	PM-1N AB-909 Calle Potrerillos	PM-2N AB-908 Puente Mulas	PM-3N AB-951 SERTRA	PM-4N AB-965 Canada	CP-1N AB-1026 Animas	CP-2N AB-1034 Pueblo Nuevo	ZB-1N BA-206 Rio Segundo	ZB-2N BA-207 San Joaquin	ZB-3N BA-216 Heredia	ZB-4N AB-1025 Calle Chucos	ZE-1N AB-910 Santo Tomas	ZE-2N AB-950 La Isla	ZE-3N BA-215 San Jeronimo
Grid Ref	5147-2170	5156-2176	5197-2186	5133-2185	5212-2168	5216-2188	5140-2209	5183-2210	5227-2203	5203-2200	5282-2182	5311-2172	5344-2211
Depth (m)	100.00	126.30	206.50	15.000	185.00	200.00	80.00	218.00	186.25	160.38	132.00	191.00	200.45
Altitude (m)	872	902	1015	870	1010	1100	920	1020	1120	1058	1190	1240	1375
No. piezos	2	2	2	2	2	2	2	2	2	3	2	1	2
PIEZOMETER 1													
Depth (m)	100.00	126.30	164.70	150.00	185.00	197.00	80.00	135.00	186.25	160.00	132.00	191.20	200.45
Diameter (in)	3/4	3/4	1/2	3/4	3/4	3/4	3/4	1	3/4	3/4	3/4	3/4	1
Aquifer	CI	CI	CI	CI	CI	CI	CI	CS	CI	CI	CS	CS	CS
Water (mbd)	74.37	83.64	88.95	63.00	64.75	133.35	68.80	37.40	158.00	95.00	122.00	144.00	158.00
K (m/d)	15.00	2.56	0.842										
Depth seal (m)								135				155	
PIEZOMETER 2													
Depth (m)	47.25	64.00	98.00	77.00	128.00	136.00	43.80	74.00	80.00	112.00	106.00		130.00
Diameter (in)	3/4	3/4	1/2	1	3/4	3/4	1	3/4	1/2	3/4	3/4		3/4
Aquifer	CS	CS	CS	CS	CS	CS	CS	B	CS	CS	LL		?
Water (mbd)	seca	52.40	86.32	54.00	67.25	120.30	27.38	37.50	96.20	99.00	90.80		60.00
KP (m/d)		134.45	2.20				6.00						
Depth seal (m)		70	143	77	128	154	43.80	80	116	112	106		130
PIEZOMETER 3													
Depth (m)										76.00			
Diameter (in)										3/4			
Aquifer										B			
Water (mbd)										53.00			
KP (m/d)													
Depth seal (m)										76.00			

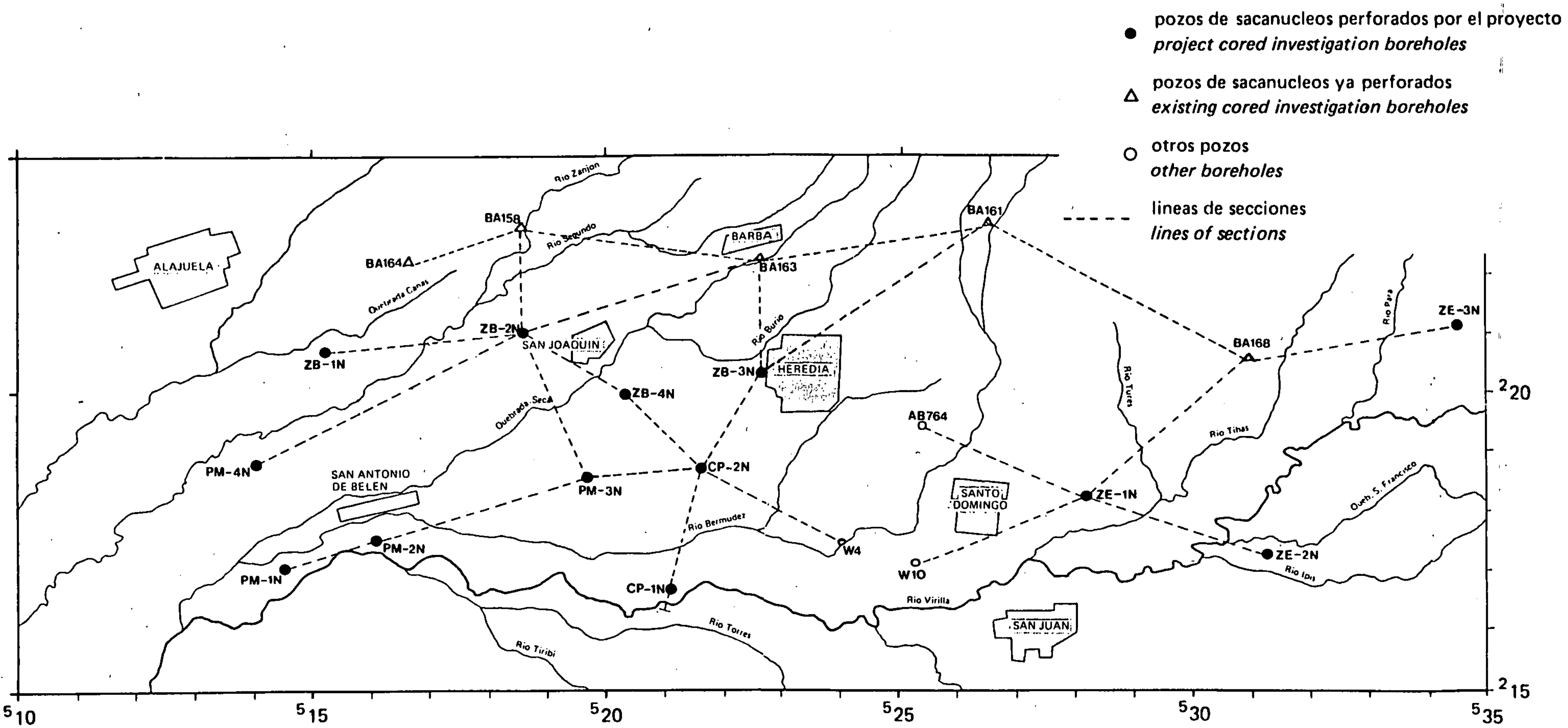


Fig 1.6 Map showing lines of geological cross-sections and boreholes used for geological correlation.

2. GEOLOGY OF AQUIFER SYSTEM

2.1 Background.

(a) The northern and central parts of the Valle Central are primarily formed of Quaternary volcanic rocks derived from the Barba, and to a lesser extent the Poas and Irazu volcanoes. The volcanic sequence comprises andesitic lava flows interbedded with extensive pyroclastic layers, principally tuffs and ignimbrites. These volcanic rocks butt up against older Tertiary volcanic sedimentary and intrusive rocks which form the southern flank of the valley. A series of thick lahars, ash and alluvial deposits are present in the eastern area and will be described separately in section 5.3.2.

(b) There are considerable problems of geological correlation because most lava flows and tuffs are similar in composition but exhibit abrupt changes in thickness. A simplified geological sequence is illustrated in Fig 2.1. The lavas form the principal aquifers and the pyroclastics (tuff and ignimbrites) behave as aquitards and occasionally as aquicludes. The outcrop and boundaries of the main lava formations are shown in Fig 1.1 and Figs 2.2 and 2.3 illustrate typical geological cross sections west-east and north-south.

(c) The Barba formation comprises several lavas that crop out on the upper slopes of the Barba volcanoe and form local aquifers. Underlying these most recent lavas is the Barba Inferior, commonly referred to as the Barba aquifer. It is an extensive flow, widely covered by the Carbonal tuff but exposed along river valleys. The lava dips in a south-easterly direction and varies considerably in thickness up to a maximum of 95 m.

(d) The most important aquifers in the Valle Central are developed in the deeper Colima formation of lavas which are limited in outcrop to the river canyons in the lower part of the valley (Fig 1.1). The upper group is defined as comprising the La Libertad lava separated from the underlying Colima Superior by a tuff layer. The exact source and extent of the La Libertad lava is uncertain. It is a thick lava unit (up to 110 m) terminating in the region of the Valencia Wellfield having apparently flowed from the east or north-east. Its importance as an aquifer is minor compared to the Colima Superior lava. This flow extends from north-east to south-west across the slopes of the Barba volcano from which it probably originated. Its maximum thickness is only 55 m but the brecciated nature of the flow produces the high permeability that makes it a good aquifer where there is sufficient saturated thickness.

(e) A tuff and ignimbrite sequence (Puente de Mulas formation) that is recorded in boreholes throughout the Valle Central separates the Colima Superior from the older Colima Inferior group of interbedded lavas and tuffs. These lavas occur over a wide area; a fact that has led to the belief that they originated as fissure eruptions. They constitute the major aquifer in the Valle Central.

(f) The geological succession as described is well established and the classification has not been modified during the course of the project. The areal geological mapping on which the study is based is essentially that presented on the published hydrogeological map of the Valle Central. Some new geological information has been derived as a result of certain project activities described below.

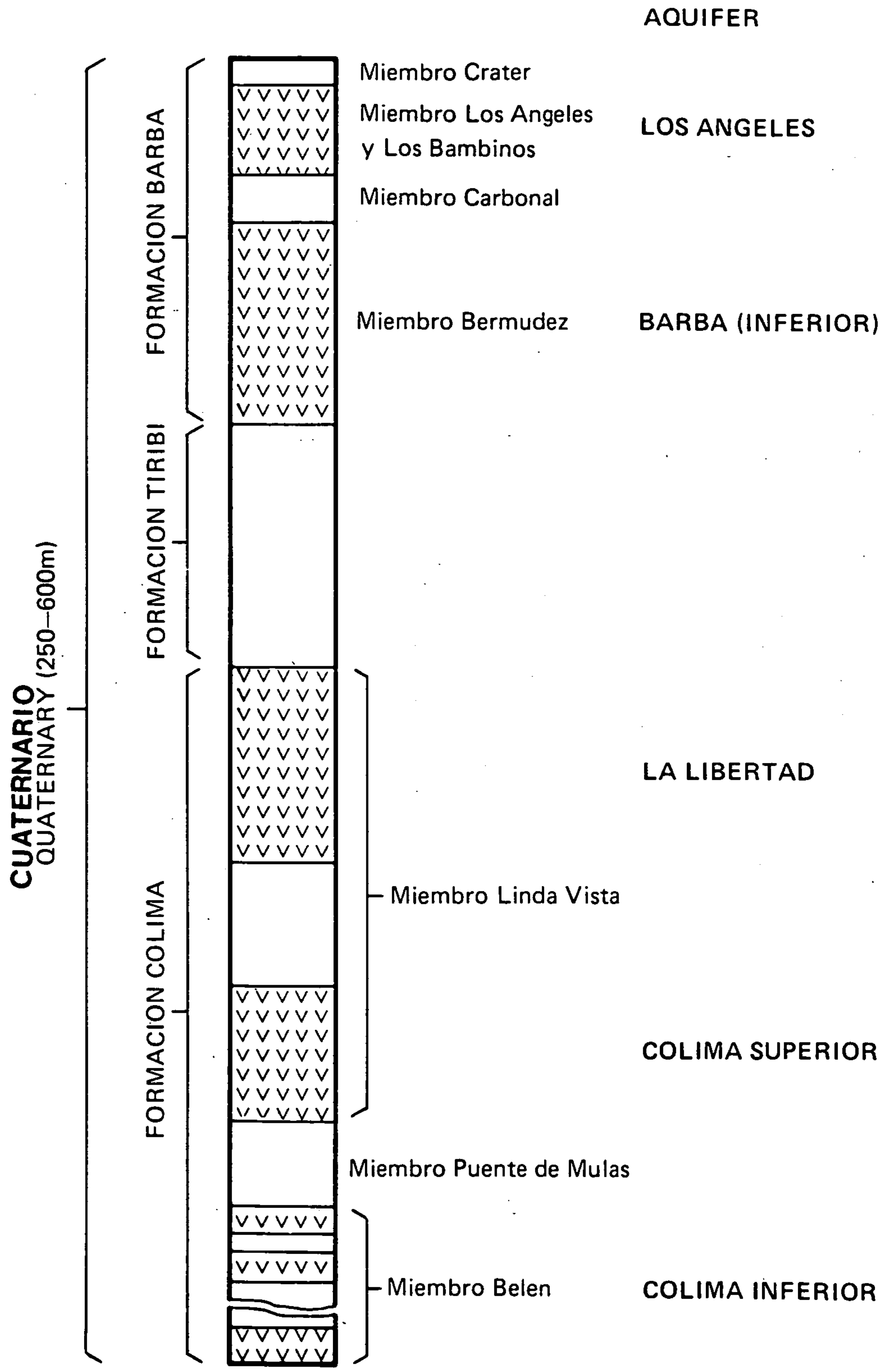


Fig 2.1 Generalised geological sequence for the Valle Central.

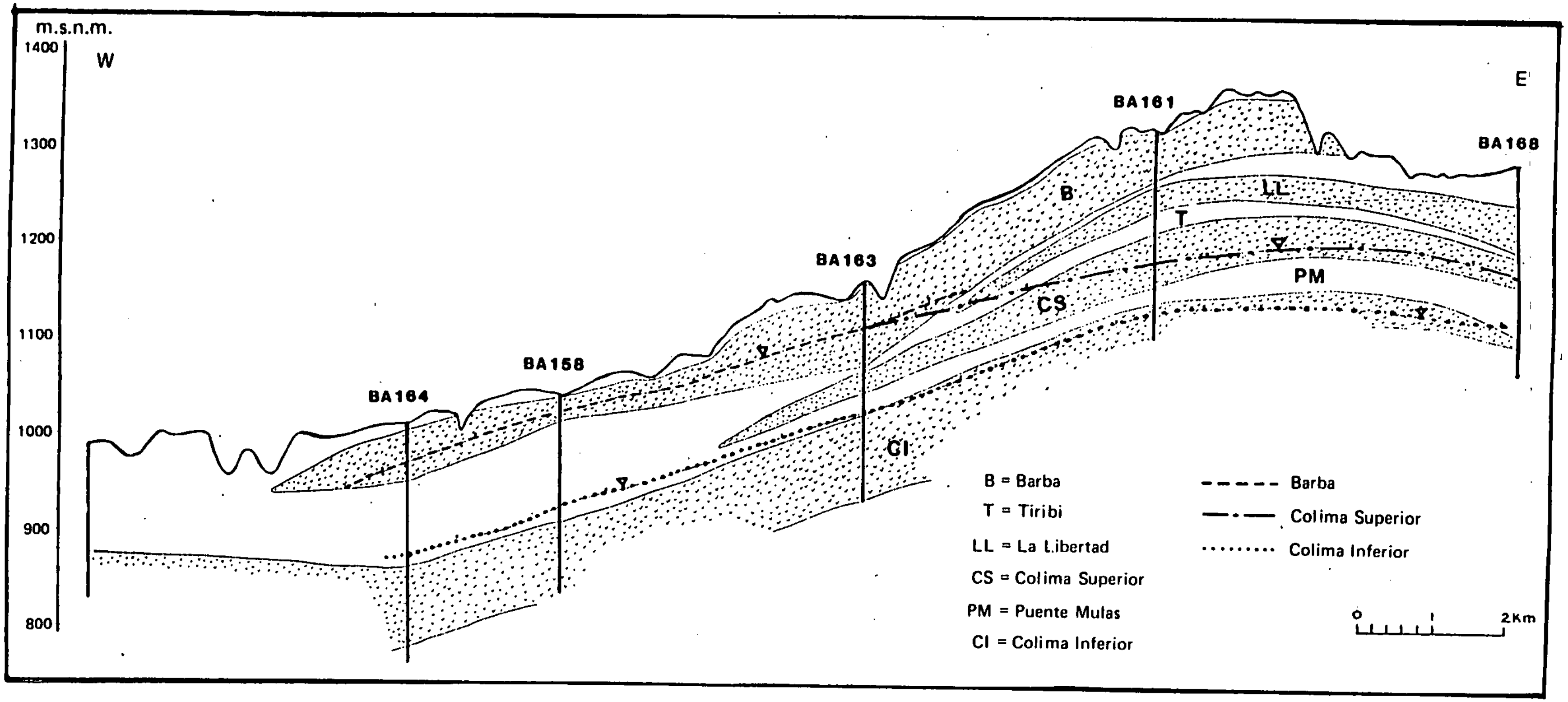


Fig 2.2 Typical geological cross-section from west to east across the Valle Central.

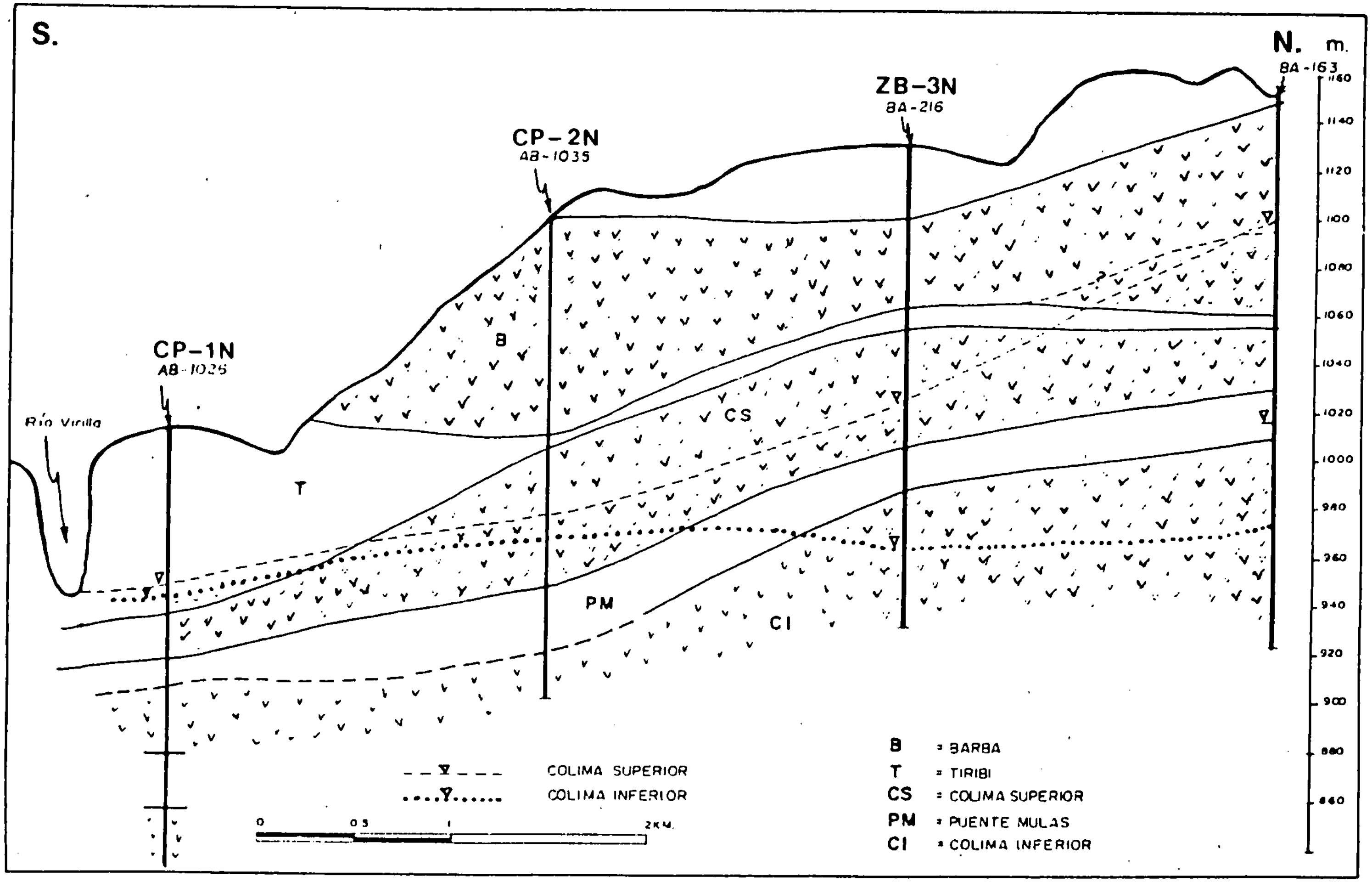


Fig 2.3 Typical geological cross-section from north to south across the Valle Central.

2.2 Geological Mapping.

(a) Some basic geological mapping was carried out in the Zona Este Norte and Puente de Mulas study areas. The results are not illustrated but were used to improve the regional hydrogeological interpretation of those areas and aid the siting and design of boreholes. Geological surveying of parts of the Virilla canyon produced a more detailed record of lava outcrops along key sections of the river bed and valley sides which helped to clarify the groundwater discharge regime in the Puente de Mulas area.

(b) Interpretation of LANDSAT satellite imagery to corroborate and enhance surface geological mapping did not prove to be an effective technique under the conditions present in the project area. A computer compatible tape of a multi-spectral image was acquired and subjected to a wide range of computer image enhancement procedures. The very strong spectral reflectance of the vegetation, however, masked virtually all detail related to either geology or soil condition and no useful information could be extracted.

2.3 Cored Investigation Boreholes.

(a) The cored investigation boreholes, unlike the large diameter rotary drilled holes, have provided excellent lithological records. Some new geological information has been derived from interpretation of these borehole data.

(i) Considerable undulations in the base of the Barba lava are evident and a channel structure can be recognised in the San Joaquin area (see Fig 3.3).

(ii) The Colima Superior appears to become thinner to the north and west (Fig 2.4) and a boundary to this lava flow is implied running NE-SW between San Pedro de Barba and the Rio Segundo (see Fig 3.4). A tongue of the lava flow can be shown to extend west, beyond the Guachipelin spring.

(iii) In the Zona Este Norte a new interpretation suggests that there could be a similar wedging out of the Colima Superior towards a southern boundary somewhere in the region of the Rio Tibas. Geological correlation in this area is particularly difficult and open to question. There are also major problems in correlating the geology between the northern and southern parts of the Zona Este. The whole area is discussed more fully in section 5.3.

(iv) The occurrence of the La Libertad and Barba aquifers in the area north of the Valencia Wellfield and their relationship is uncertain. The La Libertad lava is thought to be a separate flow which possibly originated from a different volcanic system to that from which the Barba and Colima Superior derive. The lava could be almost contemporaneous with the main Barba flow although it is probably older.

2.4 Geophysical Logging.

(a) Natural gamma radiation logs were made during the geophysical logging of several boreholes in the Valencia Wellfield. The method showed potential for lithological correlation. The Puente de Mulas formation could

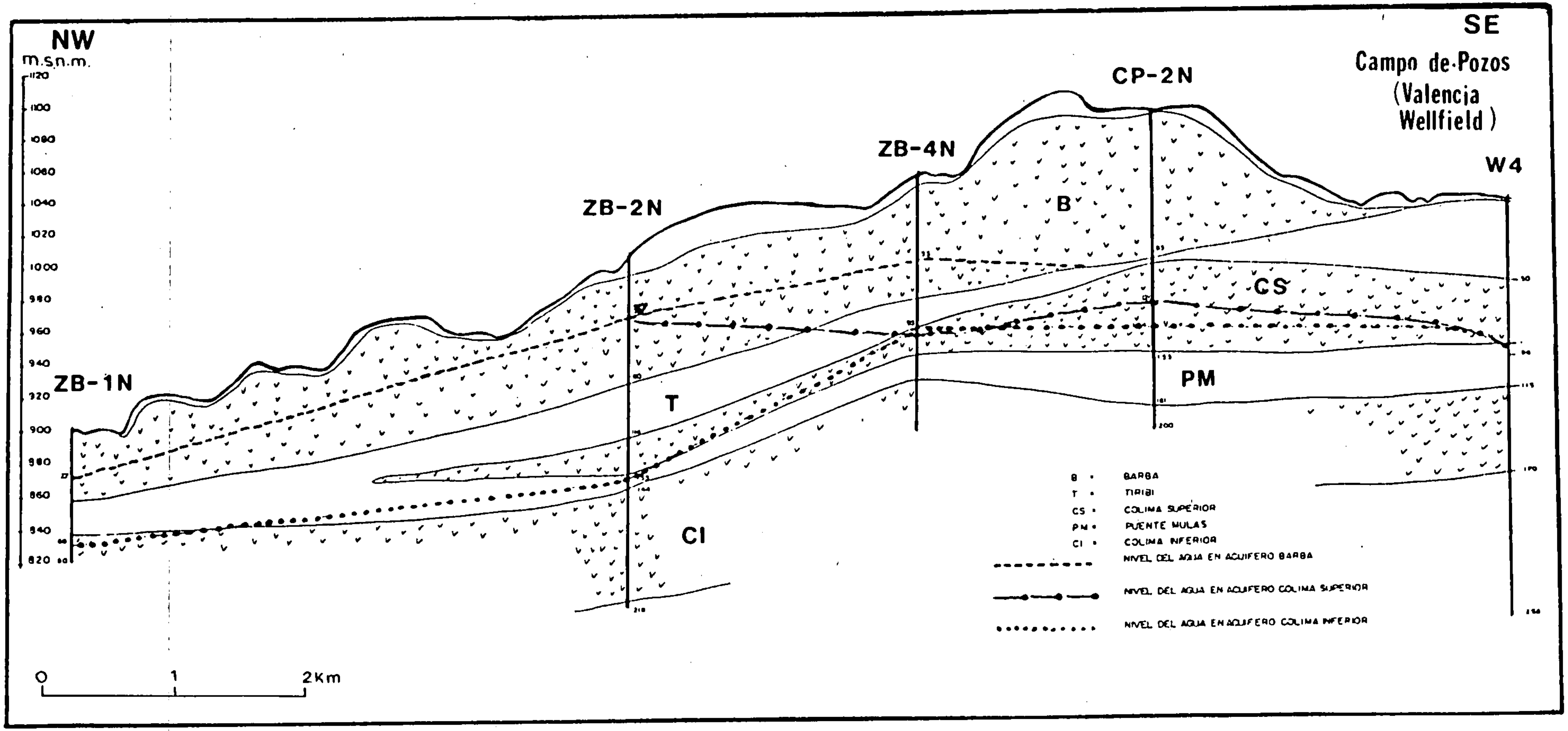


Fig 2.4 Geological section from Alajuela to the Valencia Wellfield illustrating the structure of the aquifers.

possibility of correlation between boreholes without adequate sampling (Fig 2.5).

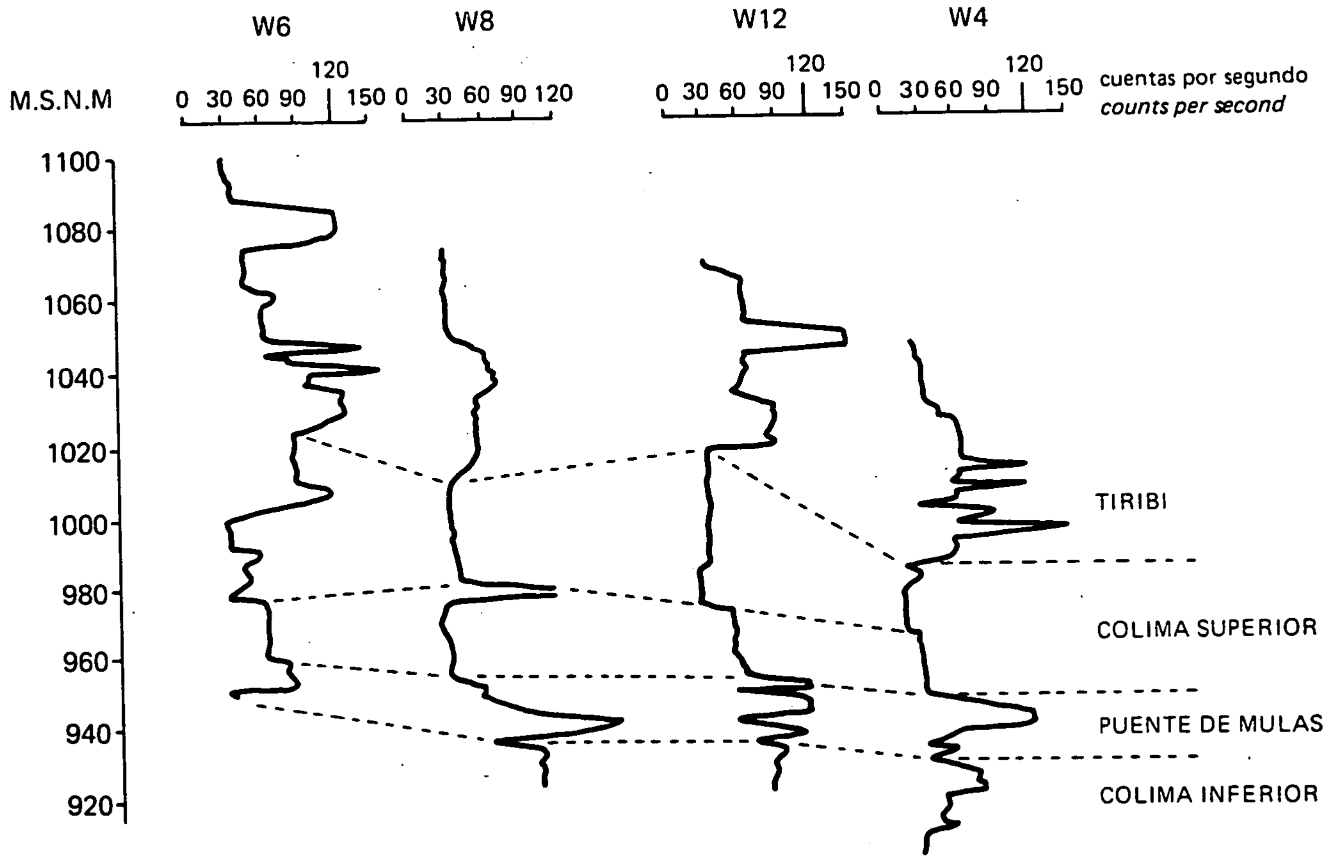


Fig 2.5 Tentative correlation of natural gamma formation logs for some production boreholes.

3. GROUNDWATER REGIME

3.1 Introduction.

(a) The main Valle Central aquifers, the Colima Superior and Colima Inferior, are the focus of the current investigation. In the past, these two aquifers have sometimes been regarded as a single groundwater system because their groundwater levels were believed to be more or less the same through most of the area, implying hydraulic continuity between them. The present study considers each aquifer system and its groundwater resources independently where appropriate. The aquifers of the Zona Este Sur are regarded as a different groundwater system and are discussed separately in section 5.3.

(b) The Colima aquifers form part of a complex multi-aquifer system. Quantifying groundwater recharge and discharge for the various component aquifers presents many problems.

(c) Recharge to the Colima lavas occurs primarily by downward leakage from overlying lavas and tuffs of groundwater derived both from surface infiltration of rainfall and seepage from rivers. The factors controlling the downward transfer of groundwater between the lavas are not well understood. Several project activities have therefore been aimed at achieving a better knowledge of the recharge regime of the Colima Superior and Inferior but the topic remains a complex one and is the last aspect of the hydrogeology to be considered.

(d) Groundwater discharge from the Colima aquifers is by springs and direct riverbed seepage along the Virilla canyon. Previous groundwater resource assessments have used baseflow separation of low flow at the San Miguel gauging station on the Rio Virilla to quantify the total Colima discharge. A value of 8700 l/s derived in this way was employed for calibration of the mathematical model used in the last resource study. This value has been critically reviewed and attempts made to determine a realistic minimum estimate of the available Colima groundwater resources. This being the most readily quantifiable component of the groundwater regime, it is a logical starting point to the new resource assessment.

3.2 Aquifer Discharge.

(a) Only the discharge of the Colima aquifers was investigated; no attempt was made to quantify the discharge of the Barba aquifer which is subordinate to the main study. Because their discharge is confined to the Virilla canyon, the minimum discharge from the Colima lavas can be determined from differential river gauging and spring flow measurements along this river valley.

(b) A series of such measurements were made during the dry season. Flow guaging of this river system presents formidable problems because of:-

(i) finding adequate and accessible sections for measurement,

(ii) the difficulty of taking measurements in a large river in a deep canyon, and

(iii) the number of man-made diversions for irrigation etc. which pose problems of deducting many small inflows from tributary flows.

(c) From these measurements a figure of 5500 l/s was calculated to be the minimum discharge of Colima groundwater (Fig 3.1) after taking into account the 1200 l/s already being abstracted from boreholes, notably in the Valencia Wellfield. This figure is significantly below previous estimates and is regarded as a pessimistic value representing the long-term minimum available groundwater resources of the Colima aquifers. Measurements at the end of the dry season reflect the lowest groundwater flows but in the previous study it was noted that the hydraulic gradient in the Colima aquifers showed very little fluctuation implying only small seasonal variation in groundwater discharge in either of the Colima aquifers which implies only small seasonal variation in the groundwater throughflow.

(d) The value of 5500 l/s might, however, be an underestimate because it does not take account of discharge from the Colima Inferior to the Rio Virilla downstream of the Potrerillos springs or the possible transfer of water from this aquifer to the adjoining catchment of the Rio Poas to the west. These components are not thought to be large but have not been quantified and are effectively ignored in the mathematical model which uses the discharge distribution shown in Fig 3.1.

(e) Although discharge from the Colima aquifers is the main interest, information about other aquifers is included on Fig 3.1.

3.3 Groundwater Levels.

(a) Groundwater levels in the multi-aquifer system are complex. Despite the presence of tuffs and ignimbrites that form intermittent aquicludes supporting perched water tables, there is large scale transfer of water between the lava layers. Where several water levels exist in the volcanic sequence, the most accurate data is obtained through the correlation of the water level with geology and depth during the drilling of the small diameter cored boreholes.

(b) Interpretation is made more difficult by the frequent occurrence of two or more water levels associated with one aquifer. This may arise from local perching of groundwater above a layer of massive lava within a flow or because an equilibrium level forms when aquifers with different piezometric levels are open in the borehole at the same time. Unfortunately the project did not have sufficient resources to install lined and screened observation boreholes in the different aquifers. In an attempt to augment the existing observation network, small diameter piezometers were installed at key depths in the cored investigation boreholes and subsequently monitored. A difficulty with this type of installation at the depths necessary in this aquifer system is that some piezometers become blocked.

(c) Groundwater level contours for the Barba aquifer (Fig 3.2) were constructed to determine its saturated thickness which is a factor affecting recharge to the underlying Colima Superior aquifer. New data from the cored boreholes has enabled definition of the area where the

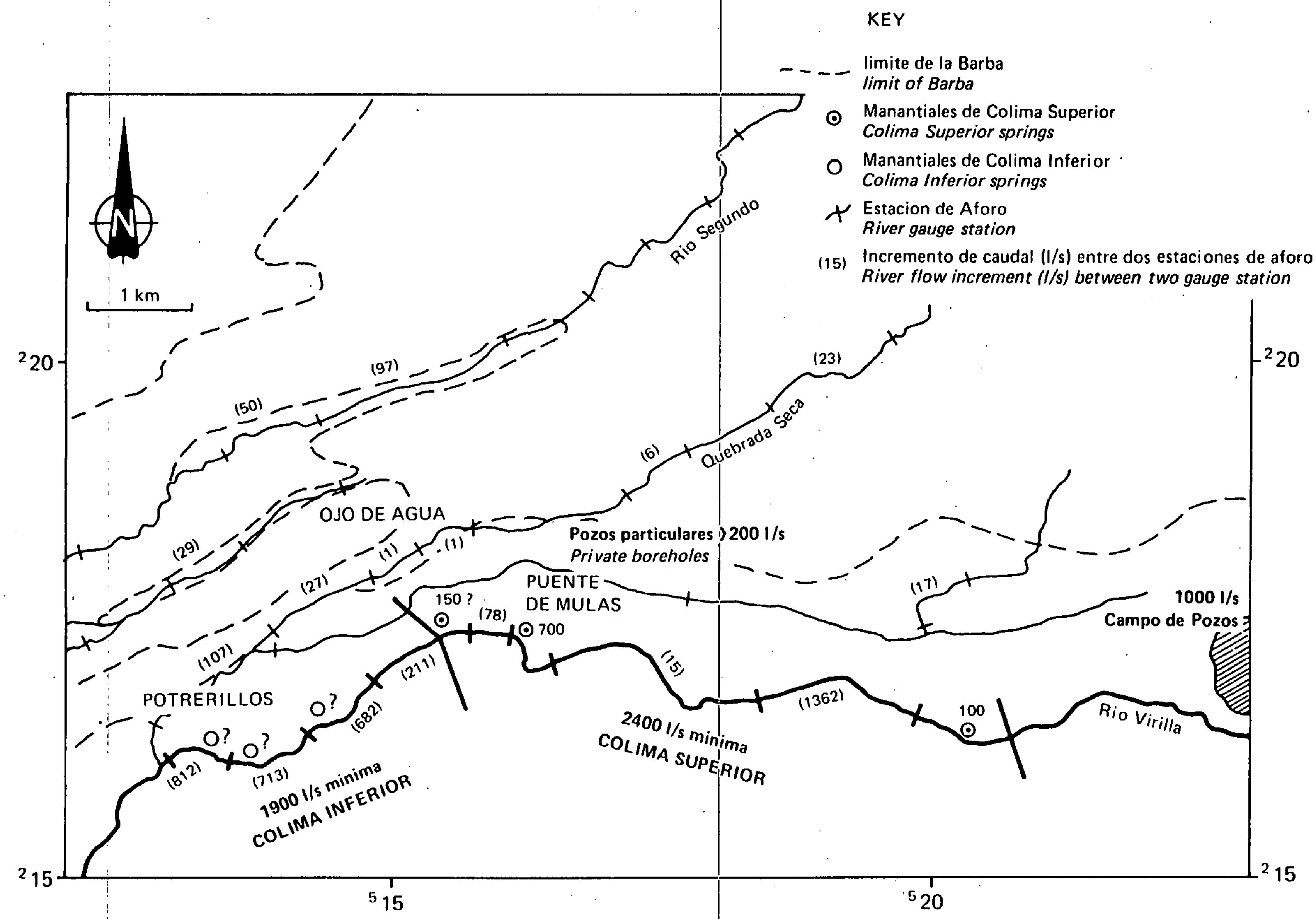


Fig 3.1 Summary of Colima aquifer discharge derived from river and spring flows.

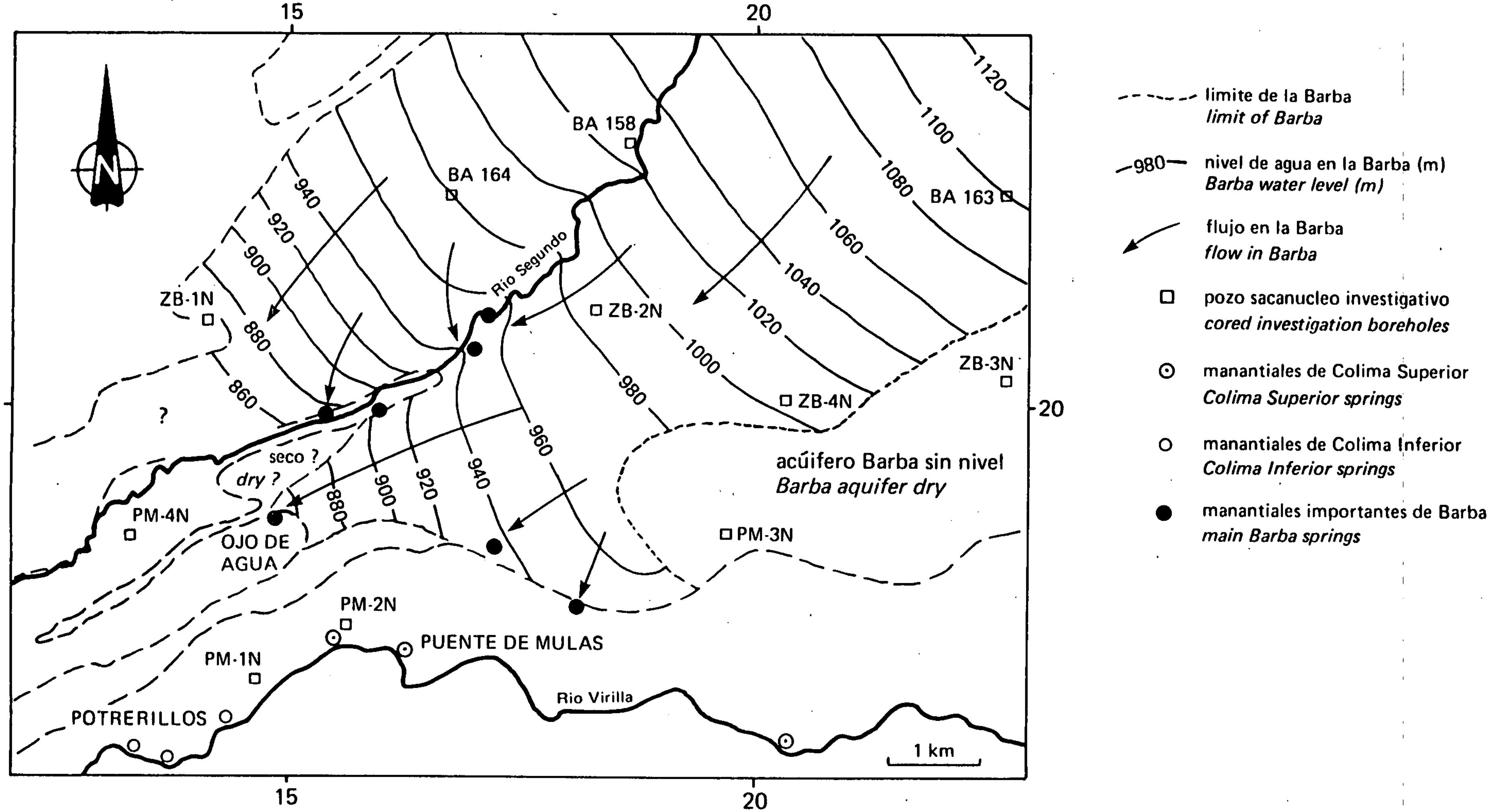


Fig 3.2 Groundwater levels in the Barba aquifer.

Barba aquifer is permanently dry. The presence of a channel structure in which the saturated thickness is up to 40 m (Fig 3.3) has been identified as an important subsurface influence on the groundwater flow.

(d) A reappraisal of the geology and water level information from existing, as well as new, boreholes demonstrated previously unknown differences in the piezometric surfaces of the Colima Superior and Inferior aquifers (see Figs 2.2, 3.4 and 3.5). In the lower parts of the valley in proximity to the Rio Virilla, the groundwater level in the two aquifers is similar or equal but the levels progressively diverge (Figs 2.3, 3.4 and 3.5) producing significant head differences between the two at higher altitudes. The Colima Superior which is unconfined throughout much of the area appears to become confined where the lava thins in the region north-west of Heredia, and its water level is similar to that of the perched Barba aquifer (Fig 2.4). This interpretation is, however, based on relatively few reliable data points and requires confirmation.

(e) In the eastern zone the situation is less clear. The tuff layer that separates the Colima Superior and La Libertad lavas is not always present and even where the La Libertad is recognised, it does not always have a perched water table. The area over which the La Libertad is dry cannot yet be accurately defined. The Colima Superior aquifer itself is unconfined in the Zona Este Norte and has generally limited saturated thickness.

(f) The Colima Inferior comprises several layers separated by tuffs. Very little information exists for any but the uppermost lava for which two separate groundwater levels have been recorded in some boreholes. According to this upper level, which may be perched above a massive lava, the aquifer is generally confined but it could be unconfined in higher parts of the catcment where the piezometric level is considerably below that of the Colima Superior (Fig 3.5).

3.4 Aquifer Hydraulic Characteristics.

(a) The hydraulic regime of the Valle Central aquifers is dominated by generally steep hydraulic gradients in sloping-based lava aquifers. Most of the lavas possess considerable transmissivity and groundwater flow velocities are likely to be high. During the course of the project, work has been carried out to establish the origin of the high transmissivity in the lavas and clarify the hydraulic behaviour of the pyroclastics.

3.4.1 Rock Physical Properties

(a) Laboratory tests of hydraulic conductivity and porosity were carried out on core from two of the investigation boreholes (PM-2N and PM-3N), sampling at regular depth intervals of 8 m in the lava and 2 m in the pyroclastics. A total of 70 core samples were analysed. The results compare well with the limited data of this kind previously available for the Valle Central volcanics but provide additional information because complete vertical sequences were sampled and also examined visually for fractures and other structures. Fig 3.6, which includes existing as well as new data, demonstrates the relationship between porosity and hydraulic conductivity of the various lithologies. The full information on the two cored holes is illustrated in Figs 3.7 and 3.8.

(b) The rock within a lava sequence can vary from highly brecciated to massive lava with very few and narrow fractures. The intrinsic hydraulic conductivity of the breccias could not be measured because specimens were

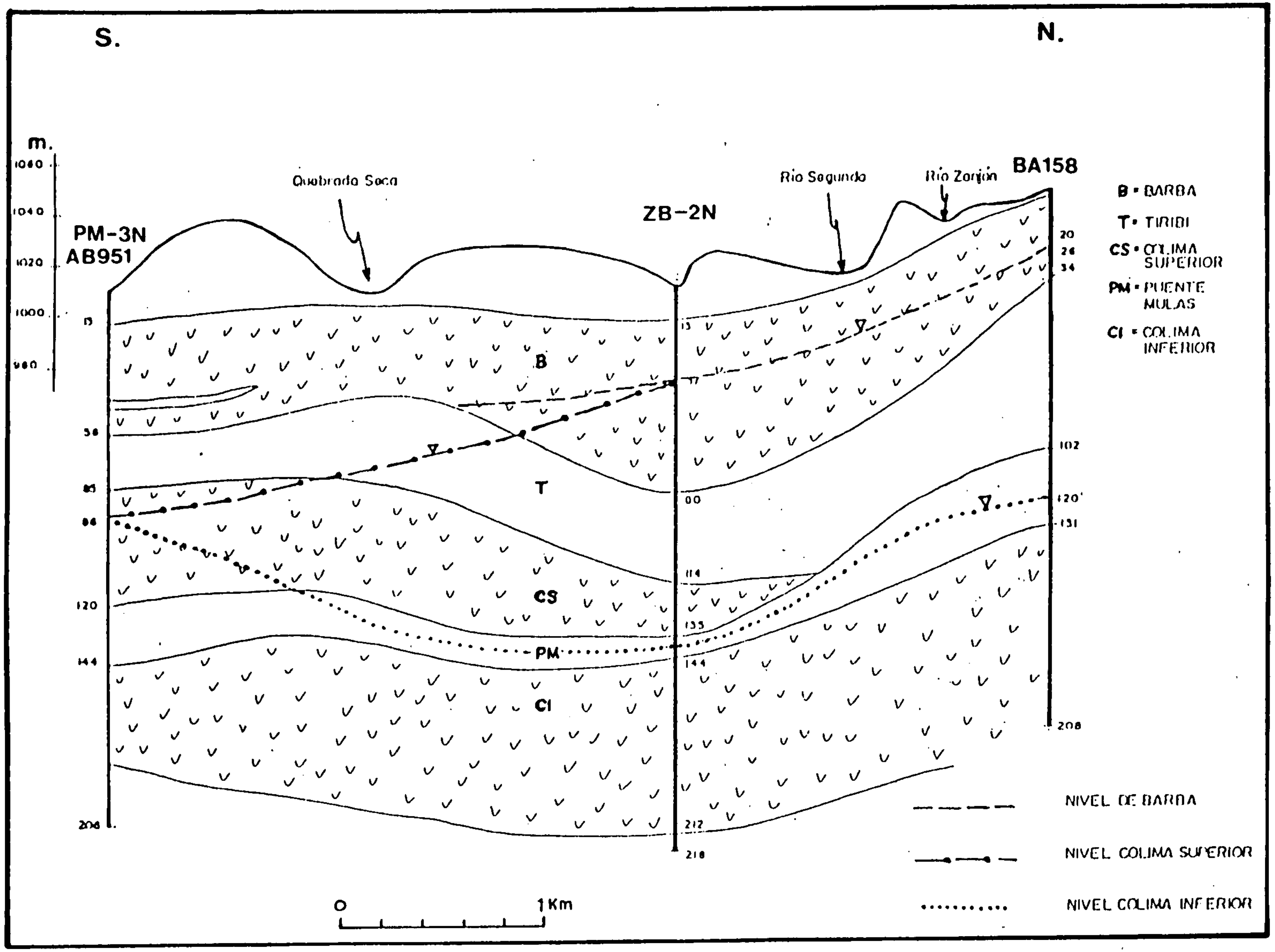


Fig.3.3 Hydrogeological cross-section through San Joaquin showing variable saturated thickness of the Barba aquifer.

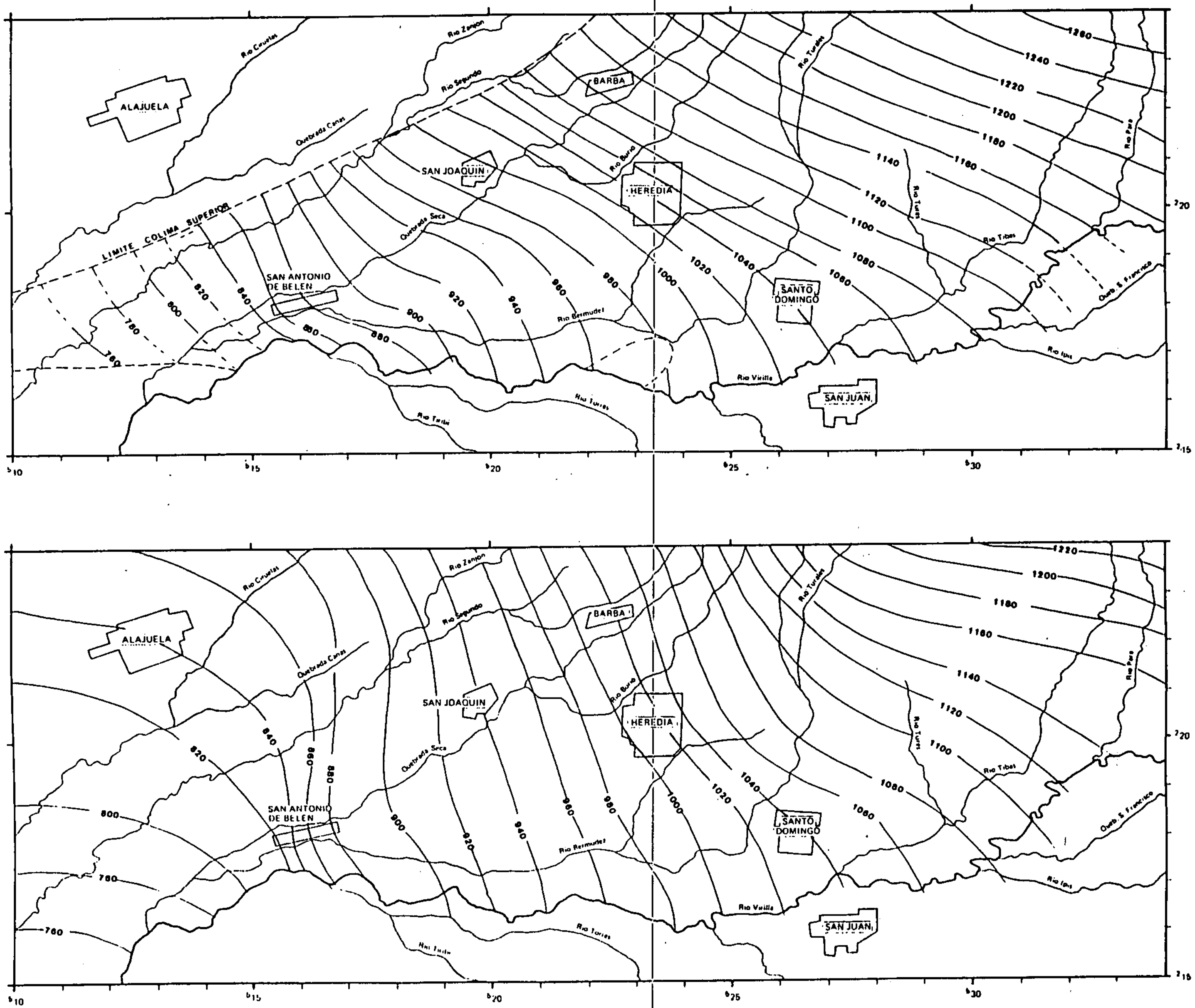


Fig 3.4 Groundwater level contours for the (a) Colima Superior and (b) Colima Inferior aquifers.

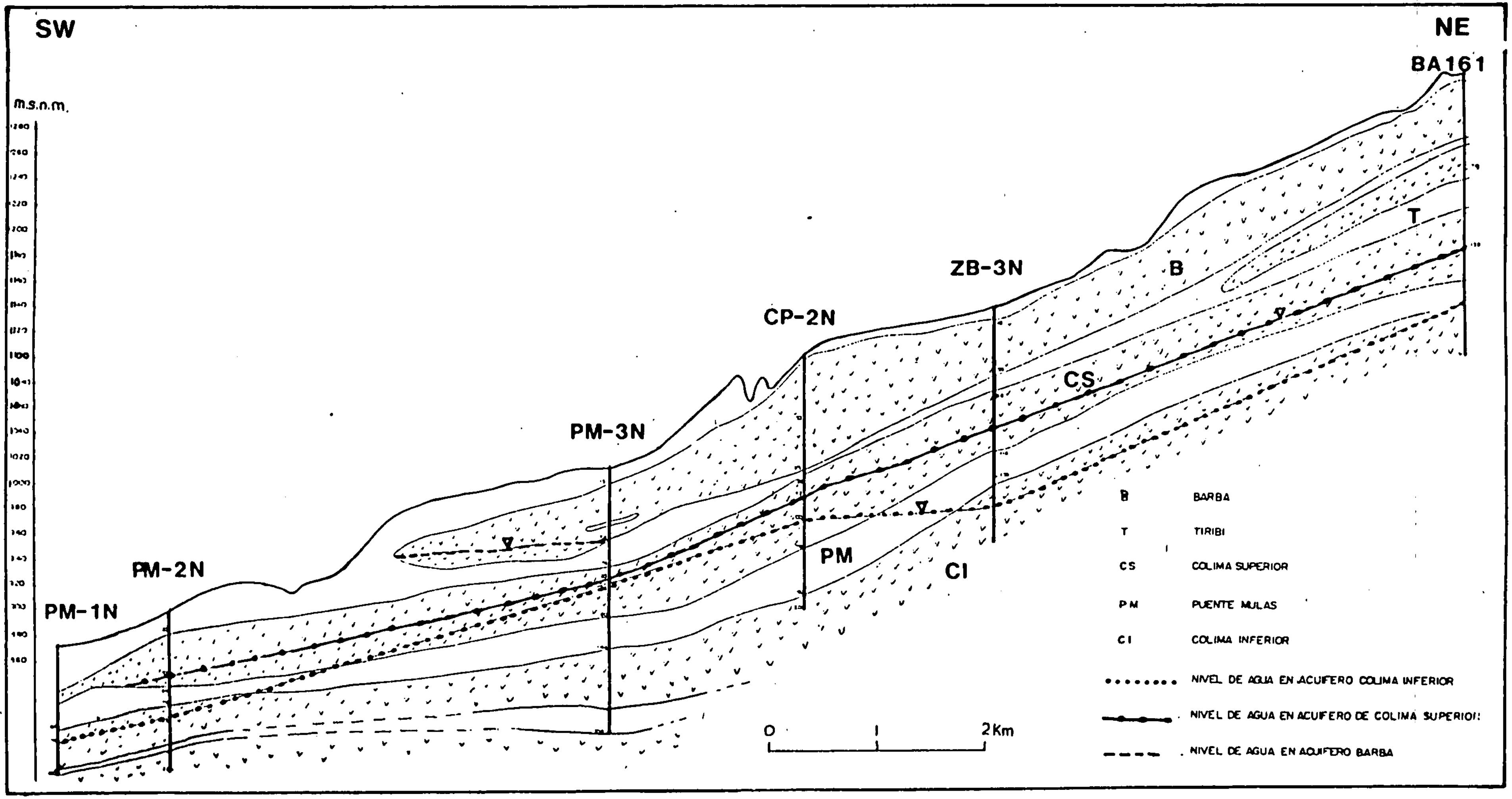


Fig 3.5 Geological cross-section illustrating variation in the piezometric levels of the Colima aquifers.

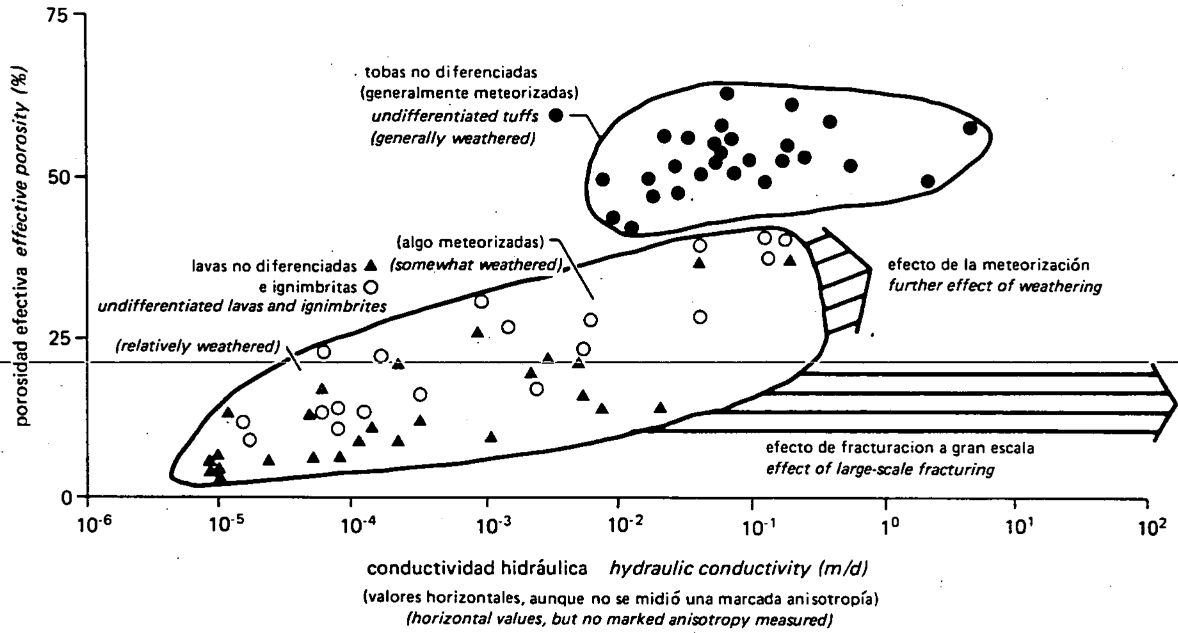


Fig 3.6 Laboratory hydraulic properties of volcanic rocks from the Valle Central.

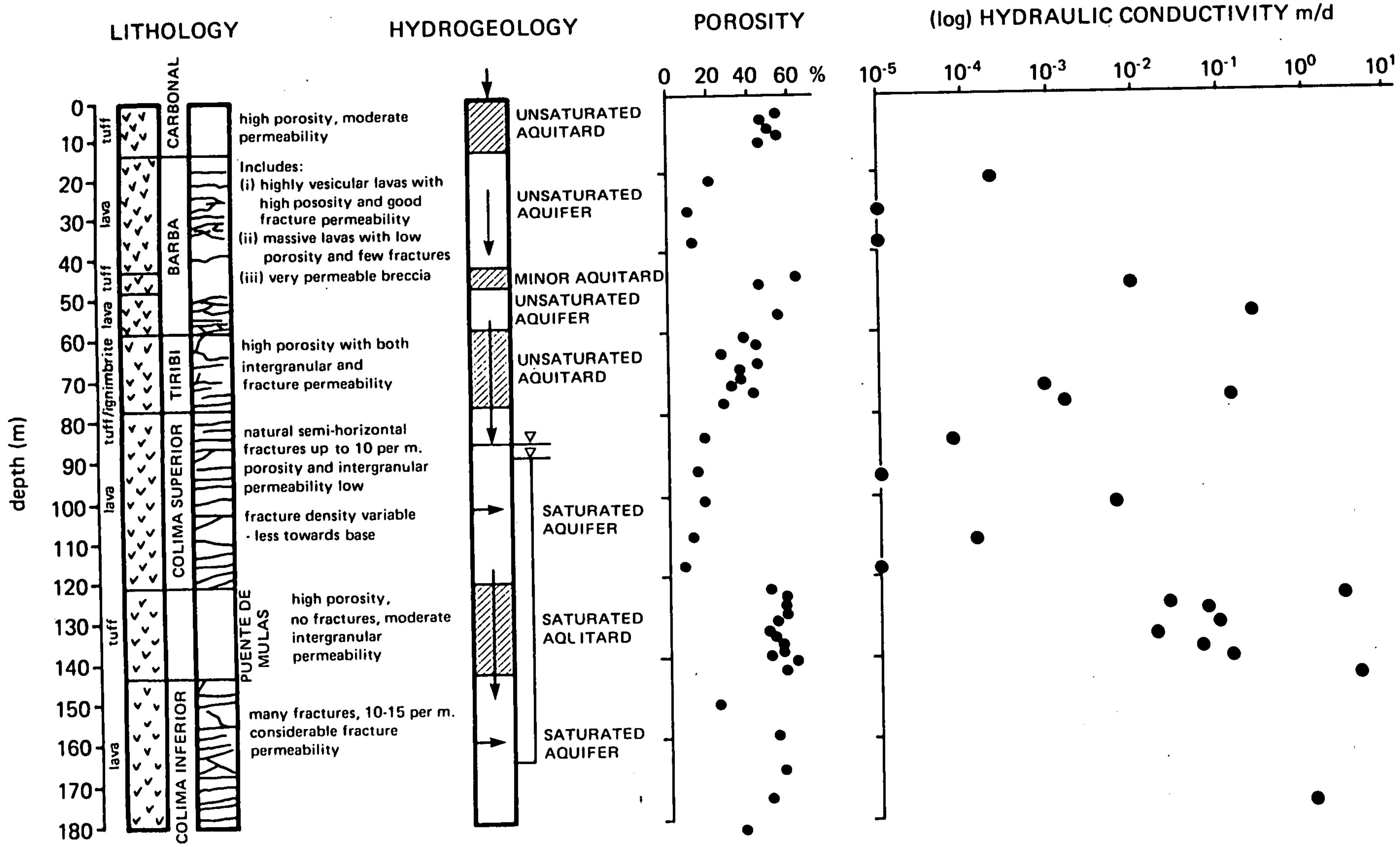


Fig 3.7 Lithological fracture log and hydraulic properties profile for borehole PM-3N.

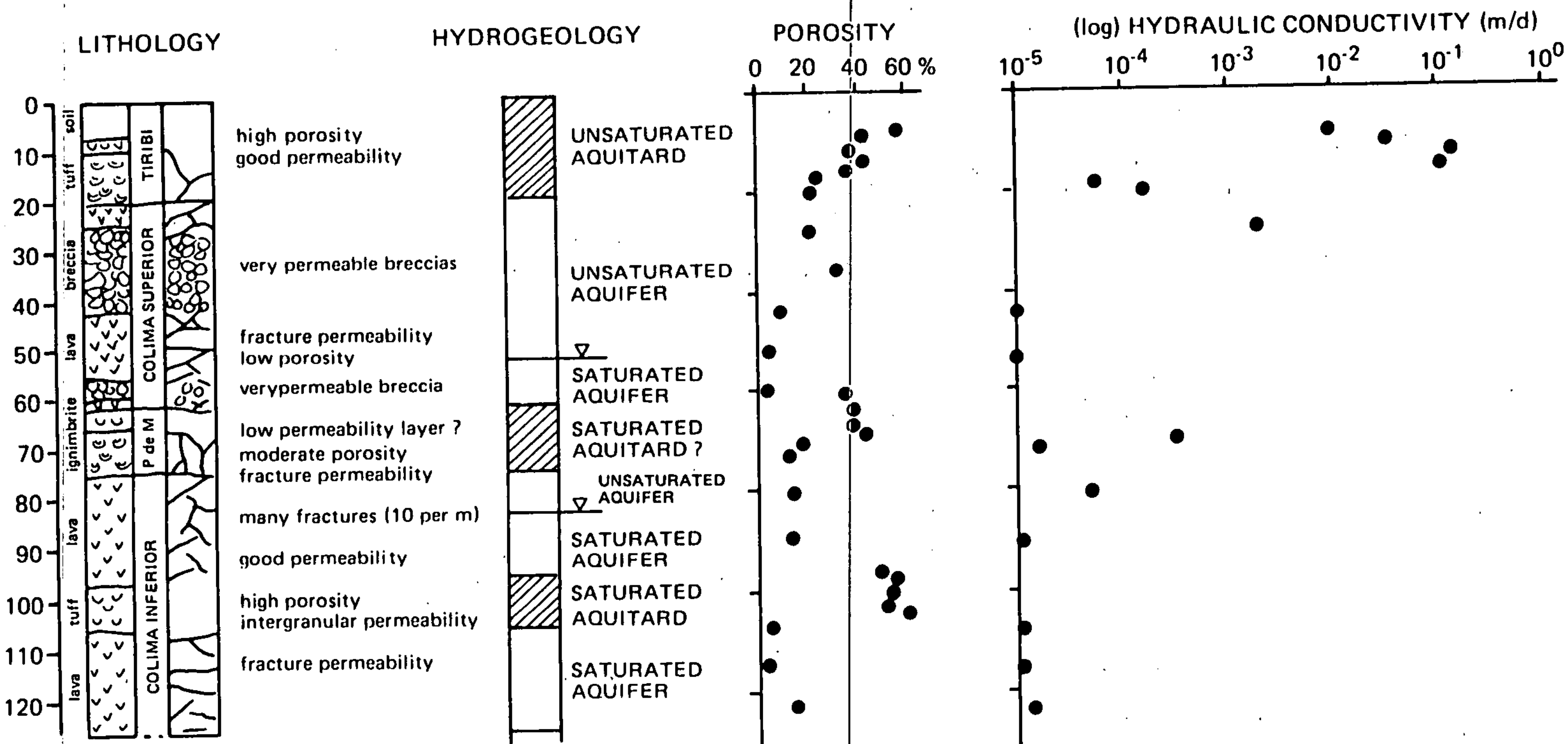


Fig 3.8 Lithological fracture log and hydraulic properties profile for borehole PM-2N.

not large enough for cores to be cut but porosities are high, up to 55%. The massive lavas have less porosity, <20% and usually <10%, and very low intrinsic hydraulic conductivity. The permeability of the lavas is therefore afforded almost exclusively by fractures and fissures. Breccias form highly permeable layers permitting both vertical and horizontal movement of water and where present they will contribute the bulk of the aquifer transmissivity. The massive lavas examined in the cores showed signs of alteration on the fracture surfaces, implying some groundwater flow through them. Generally these layers will retard but not prevent downward movement of water but may cause locally perched water levels.

(c) The tuffs of the Carbonal and Tiribi have sufficient hydraulic conductivity to allow almost unrestricted infiltration of surface rainfall and subsequent downward leakage between lava units. Their large porosity (50%-60%) provides considerable groundwater storage capacity and their wide range of pore sizes will enable gravity drainage to occur. Where the piezometric level of a lava aquifer is within an overlying tuff, the unit storage of the aquifer is significantly increased and the behaviour of pumping boreholes will be affected accordingly.

(d) The primary objective of the laboratory testing of rock properties was to identify the characteristics of the major aquitards that cause the widely observed perching of groundwater levels. It is the Puente de Mulas formation that comprises the most important aquitard in the sequence since it separates the two Colima aquifers. The characteristics of this layer vary between the two boreholes examined. In borehole PM-2N the Puente de Mulas formation is an ignimbrite which, although of relatively low porosity and very low intergranular permeability, is traversed by a moderate number of fissures through which water could move. There is, however, a very low porosity tuffaceous layer at the top of the ignimbrite which probably allows the Colima Superior water level to remain perched above that of the Colima Inferior in this locality. The situation differs in borehole PM-3N where the Puente de Mulas formation is a relatively uniform tuff which has high porosity and moderate hydraulic conductivity. The absence of fissuring in this formation may retard the downward movement of water but is unlikely to cause a perched water level in the overlying lava.

3.4.2 Borehole Flow Logging

(a) To obtain detailed information about the nature of groundwater flow in the lavas, a trial programme of geophysical borehole logging was undertaken by BGS using lightweight portable logging equipment. The technique involves logging at high resolution the variations in electrical conductivity, temperature and hydraulic flow within a borehole column under both static (non-pumping) and dynamic (pumping) conditions. Interpretation of the results can identify the depths and relative amounts of inflow to the borehole together with information about natural head differences which generate flow in the borehole column. The successful application of the technique prompted the purchase by the project of a package of borehole logging equipment for use in Costa Rica.

(b) Several boreholes in the Valencia Wellfield were logged. In boreholes already in operation (W4, W6 and W12) the large diameter production pump had to be removed and replaced by a smaller electric pump bypassed by a tube to enable access for equipment below the pump. The interpretation of flow logs in these boreholes was constrained by the complex configuration of lining tubes and varying drilled diameter which combine to distort the natural flow into and within the borehole column. Boreholes W8 and W11 were logged during construction.

(c) It is not possible to draw too broad conclusions from the limited work in the Valencia Wellfield. Interpretation of the flow in individual boreholes is complex (Fig 3.9) but several important observations give insight into the groundwater flow regime of the Colima aquifers:

(i) Groundwater flow in both the Colima aquifers is limited to a relatively small number of horizons, probably brecciated or well-fractured zones.

(ii) Vertical groundwater head differences exist between and within the aquifers. The precise nature of these head differences takes a different form in each of the boreholes logged (Fig 3.9). In W4 there is a natural upward flow from the Colima Inferior to the Colima Superior. In W11 the upward flow occurs within the Colima Inferior and in W6 there is downward flow from the Colima Superior. Both W8 and W12 exhibit little evidence of vertical flow under static conditions. These results, for boreholes in one small area, merely demonstrate the complexity of the hydraulic relationship between the Colima aquifers.

(iii) The contribution to the flow from the Colima Inferior is larger than expected, being more than 50% in most of the boreholes studied.

(d) It is recommended that new boreholes are logged prior to completion in order to determine the major inflow levels. One of the likely reasons for poor yield-drawdown characteristics in some of the existing boreholes in the Valencia Wellfield is that important flow horizons may have been lined out. A knowledge of the borehole inflow can also be used to prevent dewatering of important flow zones as a result of increasing pump drawdowns.

3.4.3 Pumping Tests

(a) Pumping tests are usually a powerful tool to elucidate aquifer characteristics but they are not easily implemented in the Valle Central because of the multi-layer aquifers and steeply sloping groundwater table.

(b) To date very few pumping tests have been successfully carried out with adequately sited observation boreholes or piezometers. Only rarely have interference effects been recorded even where an observation borehole has been available.

(c) In the absence of observation borehole drawdown data, recourse has to be made to estimates of transmissivity derived from time/drawdown data under steady state pumping in individual boreholes and the additional information from step-drawdown tests and yield-drawdown characteristics. Both types of data are subject to substantial errors because it is difficult to separate the influence of the borehole construction from the real aquifer response. Storage coefficients cannot be obtained from observations in the pumping borehole.

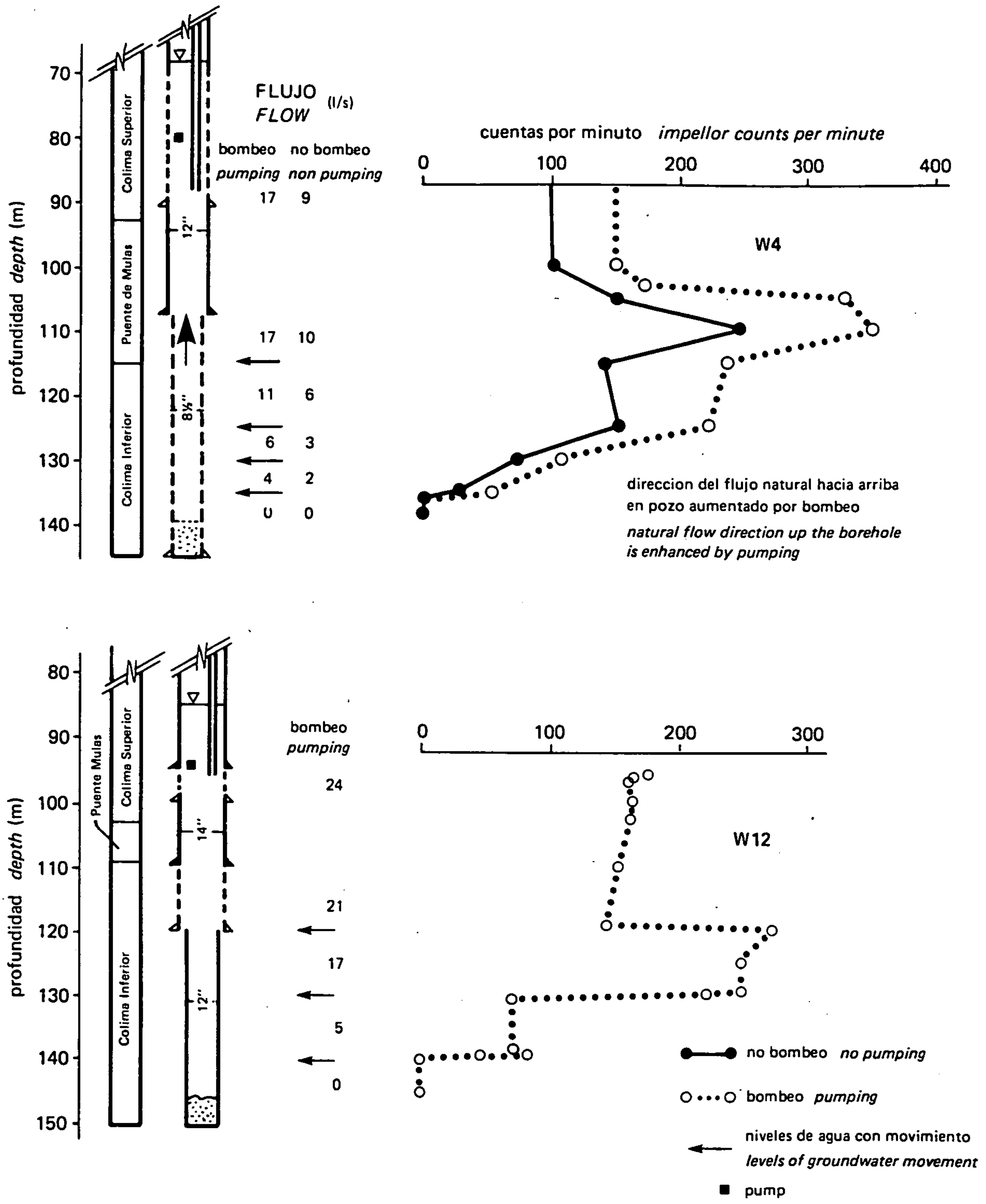


Fig 3.9 Summary of borehole flow logging in boreholes W4 and W12.

(d) When the yield-drawdown characteristics are excellent, as in many of the boreholes in the Valencia Wellfield (Fig 5.4), very high transmissivity (>5000 m^2/d) is implied but such values have not often been corroborated by actual pumping test data. Several of the project pumping tests did have observation boreholes but were inadequate in many respects and there are problems of interpreting aquifer transmissivity from them. Nevertheless, high transmissivities are required to permit the considerable volumetric throughflow of the aquifer which has been estimated by independent techniques (see 3.2). Consequently, the transmissivity values employed in the numerical model are generally higher than the values normally derived from pumping tests.

(e) Pumping tests on the Colima aquifers were carried out in the course of the project in the new production boreholes in the Valencia Wellfield and in the trial production boreholes. In every case the interpretation of the results in terms of the aquifer transmissivity is difficult. The data are not therefore presented here but relevant results are discussed in Chapter 5 and details of the tests are included in Appendix 1.

(f) Further inadequately controlled pumping tests are unlikely to improve the current knowledge of the aquifer characteristics. There is, however, a clear requirement for a few carefully controlled pumping tests with suitably constructed observation boreholes at critical locations. Such tests could clarify the magnitude of the storativity of the unconfined Colima Superior aquifer which is very uncertain (see 3.5) and might also be used to determine the relative contribution to groundwater flow of the Colima Superior and Inferior aquifers.

3.4.4 In-situ Permeability Tests

(a) In an attempt to obtain more information about the permeability and hence the relative transmissivities of the different lava layers, in-situ permeability tests were carried out during the drilling of several of the cored investigation borholes.

(b) These tests involve the injection of water into the borehole at a constant rate such as to maintain a constant head. A permeability value can then be calculated from the relationship between the rate of water injection and the head for the aquifer interval being tested.

(c) The tests should be carried out over the full saturated thickness of the aquifers, preferably by testing long sections during each test, if the results are to be interpolated into transmissivity values. This proved to be impractical due to problems of selecting and isolating the appropriate test intervals while drilling was in progress.

(d) Several permeability values were derived but they are mainly very low (<15 m/d) and give unrealistically low transmissivity values when multiplied by the aquifer saturated thickness. This is attributed to the fact that the tests only applied to a small section of the aquifer in each case, since permeability is very irregularly distributed within the lavas, the permeability value derived cannot be assumed to be representative of the whole lava. The few results obtained are therefore of little value.

3.5 Estimation of Aquifer Storativity.

(a) The storativity values of the aquifers are necessary for understanding the drawdown behaviour in individual boreholes and the spread of interference. Because the transmissivity in the aquifers is high and the hydraulic gradients are steep, there is rapid throughflow in the aquifers which is a major factor determining aquifer response. However, the possible range of storativity values in the types of aquifer and hydrogeological conditions in the Valle Central is very large and is therefore relevant to a discussion of aquifer response and also an important variable in the aquifer model.

(b) The normal method of determining storativity is from the observation borehole response during a pumping test, but such data has not yet been successfully obtained in the Valle Central. Estimates are therefore based solely on a knowledge of the aquifer materials and their properties and the degree of confinement of the groundwater.

(c) The piezometric surface of the Colima Superior aquifer is usually located within the formation in a water-table condition (unconfined) but the aquifer is locally confined by the overlying Tiribi tuff. For the unconfined condition, the storativity of the Colima Superior is unlikely to be less than 1% but significant thicknesses of the aquifer are highly brecciated lavas with high porosity. Here the storativity is probably significantly greater and values as high as 15% have been used in the calibration of the model. In reality, there may be considerable spatial variability in the storativity of the unconfined Colima Superior and it is difficult to estimate an average figure for the dewatering of a given thickness of rock.

(d) Where the Colima Superior is confined or semi-confined by the Tiribi tuffs the storativity may not necessarily be a low value typical of a confined aquifer (5×10^{-3} to 5×10^{-1}). Higher values may occur, at least in some areas, because of the large drainable porosity of the tuffs (Fig 3.6).

(e) The Colima Inferior is generally confined by the Puente de Mulas layer and only very locally unconfined. The storage coefficient of this aquifer is probably normal for a confined aquifer, perhaps between 5×10^{-4} and 5×10^{-3}. As in the case of the Colima Superior, in those limited areas where the Colima Inferior is confined by the Tiribi, the storativity will be greater.

3.6 Aquifer Recharge.

3.6.1 Recharge Mechanism

(a) The groundwater recharge regime is complex and controlled by many factors. Field infiltration tests, together with laboratory measurement of rock permeabilities have demonstrated that the infiltration capacity of the ground throughout the Valle Central is substantial. Weathered brecciated lavas have the greatest infiltration capacity but the tuffs are sufficiently permeable (Fig. 3.6) to allow infiltration of at least 50 mm/d so that only the most intense rainfall will be rejected directly as surface runoff or rapidly discharged as throughflow to generate surface runoff.

(b) The very high spatial and temporal variability of the rainfall and its intensity make estimation of the average infiltration rate for a given surface formation subject to large error. Rainfall data is sparce and it is generally only possible to estimate a very approximate value of surface infiltration. From limited work previously carried out in the catchments of the Rio Mancarron and Rio Bermudez and surface infiltration values in the range 10^{-1} to 10^{-3} cm/min were derived from short soil infiltration tests.

(c) Over most of the Valle Central the rainfall infiltrating the surface layers will recharge one of the shallow aquifers but some of it will be discharged from these as baseflow to the numerous small rivers. Although recharge can occur in any month, especially at high altitude, the overall distribution is markedly seasonal, as reflected in the widely fluctuating water table in the Barba and other shallow aquifers. Furthermore, although most rivers are receiving water from these aquifers they may also become influent and recharge the aquifers along some parts of their courses or when groundwater levels are low. This component of recharge is extremely difficult to quantify.

(d) Understanding the recharge to the Colima aquifers requires some understanding of the groundwater regime of the overlying aquifers. Except for those areas where either of the Colima aquifers is overlain only by tuff and must receive some recharge by direct infiltration through the tuff (Fig 3.10), recharge to the Colima aquifers is via an overlying (and usually perched) aquifer.

(e) Figure 3.10 illustrates the relative amounts and broad zones of recharge to the Colima aquifers. The factors controlling the rate of groundwater recharge to the Colima Superior by vertical seepage from the Barba or La Libertad are

(i) the thickness and hydraulic conductivity of the intervening Tiribi aquitard, and

(ii) the difference between the groundwater level in the perched aquifer and the level of the base of the Tiribi (where the Colima Superior is unconfined) or the difference between the groundwater level of the perched aquifer and the Colima Superior where the latter is confined.

(f) If it could be assumed that the variations of thickness and vertical hydraulic conductivity of the Tiribi were insignificant, then the highest rates of groundwater recharge to the Colima Superior would be in the areas where it is unconfined. It is, however, suspected that this may not be the case because towards the northern limit of the Colima Superior the steep hydraulic gradient in the aquifer suggests that there could be a much reduced resistance to vertical seepage

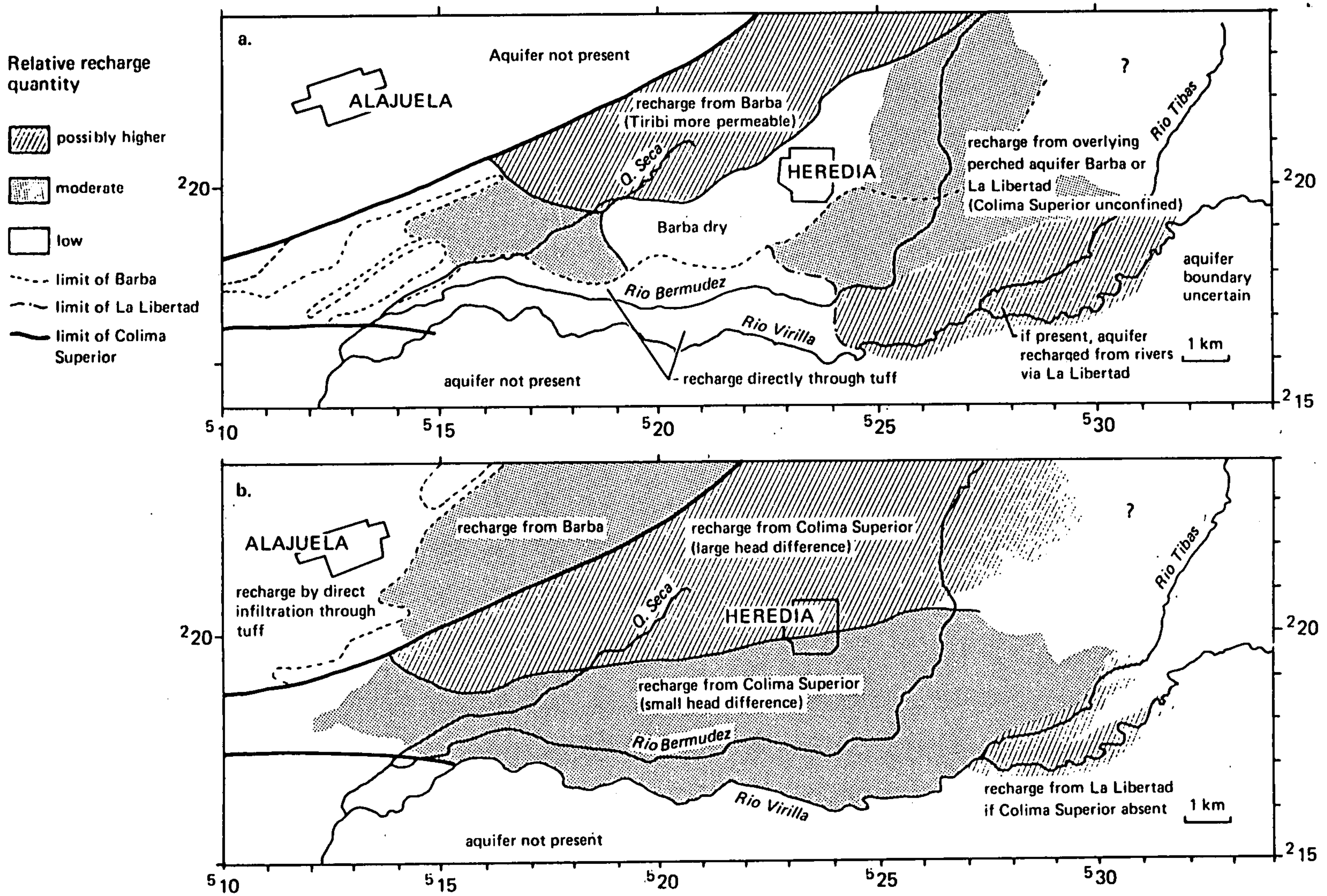


Fig 3.10 Diagram illustrating relative groundwater recharge zones for (a) Colima Superior and (b) Colima Inferior aquifers.

through the Tiribi in this area. It is probably a zone of significant recharge to the Colima Superior fom the Barba (Fig. 3.10a).

(g) If the Colima Superior aquifer is present between the Rios Tibas and Virilla to the east of San Jose (see section 5.3) then this too will be an area of significant recharge. The overlying La Libertad aquifer in this area is receiving a large amount of recharge from the rivers and much of this water is probably transferred by downward leakage to the underlying Colima aquifer (whether Superior or Inferior).

(h) Comparable factors will control the transfer of water from the Colima Superior to the Colima Inferior (Fig. 3.10b). Except in limited areas close to discharge points, the Colima Inferior never becomes unconfined. If it is assumed that the hydraulic resistance of the Puente de Mulas aquitard is uniform, then the predominant factor controlling the seepage will be the water level difference between the two aquifers but there is insufficient evidence to justify this assumption. Nevertheless the water level difference is the only known criteria on which the relative recharge to the Colima Inferior from the Colima Superior (Fig 3.10b) can at present be estimated.

(i) Where the Colima Superior is absent, the Colima Inferior will be recharged by direct infiltration through the Tiribi or from the Barba via the Tiribi. Also, recharge to the Colima Inferior may be relatively higher in the area east of San Jose as an indirect effect of leakage to the La Libertad from the Rios Tibas and Virilla.

3.6.2 Isotope analysis

(a) Tritium determinations were made on several borehole and spring source to obtain an indication of the age of the water. The results (Table 3.1) fall mainly within the range 5-15TR (tritium units). Since there is no historical record of tritium fallout in the Valle Central, interpretation has been made with reference to data from the IAEA stations at El Salvador and Panama. These suggest that the water could have originated as recently as 10-15 years ago, implying very rapid groundwater throughflow rates but this interpretation is not unique. The water could equally be a mixture of older water although undoubtedly it must contain a large component of post-1953 origin. The highest result of 72TR for one of the Potrerillos springs, if reliable, is a clear indication of a groundwater component that originated in the peak tritium fallout of the mid 1960's, giving a transit time through the aquifer system of 20 years. Such rapid throughflow is consistent with the steep hydraulic gradients and high transmissivities of the lava aquifers.

(b) Stable isotope results for groundwaters are presented in Table 3.2. Many of the sites have been sampled more than once and during different seasons but in virtually all cases the results have been consistent enough to take an average figure. The stable isotopes in groundwater are determined by the composition of the rainfall and the amount of evaporation that preceded infiltration. The relationship of the two isotopes in precipitation is linear and is expressed as the "meteoric water line". The stable isotope content of rainfall varies with the temperature at which precipitation occurs and hence there is normally a marked altitude effect reflected in variations up and down the meteoric line. The Valle Central groundwaters conform well to the meteoric line

Table 3.1 Tritium analyses for Valle Central groundwaters.

SAMPLE SITE	AQUIFER	SAMPLING DATE	TRITIUM (TR)
Ojo de Agua Spring	Barba	June 1984	7.7
La Libertad Spring	La Libertad	June 1984	11.7
Well AB471	Colima Superior	Nov. 1983	21.0
Well AB446	Colima Superior	June 1984	10.2
Puente de Mulas	Colima Superior	Nov. 1983 June 1984	14.0 6.1
Valencia Well 3	Colima Superior and Inferior	June 1984	5.6
Valencia Well 13	Colima Superior and Inferior	June 1984	6.0
Valencia Well 9	Colima Inferior	Nov. 1983	9.3
Well AB877	Colima Inferior	June 1984	4.7
Potrerillos Springs	Colima Inferior	Nov. 1983 June 1984	72.8 9.5

Table 3.2 Summary of averaged stable isotope values for Valle Central aquifers.

AQUIFER	SITE	SPRING (S) OR BOREHOLE (B)	NUMBER OF SAMPLES	δ^2H	$\delta^{18}O$
Los Angeles & Los Bambinos (high-level springs)	La Hoja	S	2	-50	- 8.0
	Marin Canas	S	1	-57	- 8.3
	Fuente de Perez	S	2	-54	- 7.8
	Porrosati	S	2	-59	- 8.4
	Alajuela	S	2	-68	-10.2
	Roble	S	1	-73	-10.6
	Sacramento	S	1	-69	- 9.8
	Los Angeles	S	1	-45	- 7.2
Barba	Ojo de Agua	S	3	-63	- 9.0
	Santa Barbara	S	1	-65	- 9.4
	Cerveceria	S	1	-64	- 9.1
	San Antonio de Belen	S	1	-65	- 8.9
	BA169	S	1	-64	- 9.1
	BA173	S	1	-57	- 8.4
La Libertad	La Libertad	S	4	-65	- 9.0
Colima Superior	AB 308	B	2	-60	- 7.8
	AB 446	B	2	-59	- 8.8
	AB 336	B	1	-55	- 8.0
	AB 471	B	5	-57	- 8.4
	Puente de Mulas	S	7	-57	- 8.5
	Guachipelin	S	1	-59	- 8.6
Colima Superior and Colima Inferior mixed	AB 328	B	1	-61	- 8.6
	W1	B	1	-59	- 8.6
	W2	B	3	-52	- 8.0
	W3*	B	3	-61	- 9.0
	W4	B	2	-53	- 7.8
	W5	B	1	-46	- 7.1
	W7	B	1	-55	- 8.3
	W12*	B	1	-60	- 9.1
	W13	B	3	-54	- 8.4
	W14	B	3	-54	- 8.0
	W15*	B	1	-60	- 9.0
Colima Inferior (Valencia wellfield)	W9	B	4	-65	- 9.0
Colima Inferior (Potrerillos area)	AB 877	B	2	-51	- 8.2
	Potrerillos Group	S	10	-52	- 8.0
	Freddy	S	1	-50	- 8.2
	Penal	S	1	-49	- 7.6

* major flow from Colima Inferior

(Fig 3.11) and there is little deviation from the line to suggest processes of isotopic modification after rainfall.

(c) The results can be divided into five groups which are distinguished on the plot (Fig 3.11).

(i) High level springs, sampled as representative of higher altitude rainfall, which have widely differing isotopic contents that span the range of all other samples.

(ii) Groundwaters from the Barba and La Libertad which form the most depleted (lightest) isotopic group.

(iii) Colima Superior groundwaters that form a relatively broad intermediate group.

(iv) Colima Inferior groundwater from the downstream Potrerillos area which is relatively enriched (heavy), and

(v) Colima Inferior sources from the Valencia Wellfield which are by comparison with other Colima Inferior groundwater, isotopically light.

(d) In the early stages of the project some rivers were sampled for isotope analysis. The results, plotted in Figure 3.12 in relation to the groundwater groups of Figure 3.11 show extreme seasonal variation in rivers like the Tibas and Virilla, indicative of a large surface runoff contribution during the wet season. Smaller streams like the Quebrada Seca exhibit less seasonal variation which suggests a dominantly baseflow origin all year.

(e) Ideally an altitude effect should be determined through long term monitoring of rainfall at different altitude. The use of high level springs to establish an isotope-altitude effect has produced ambiguous results that cannot be satisfactorily explained. A plot of the spring altitude against oxygen-18 content reveals no clear relationship. This may be due to the fact that some of these springs derive their supply from altitudes much higher than their outlet and/or it may reflect a complex weather pattern with rainfall contributions from the Pacific and Atlantic sides of the Cordillera Central. Despite this conflicting evidence of the isotope-altitude effect, there is no doubt that the groundwaters become isotopically enriched (heavier) with depth in the aquifer system. Considering all the known inputs to the catchment, it must be assumed that lower altitude infiltration is the source of this enriched water.

(f) The isotope characteristics of springs at the downstream end of the Barba aquifer suggest a high altitude origin which is consistent with recharge to this aquifer by leakage from rivers fed by high altitude rainfall runoff. A similar recharge regime is implied by the isotopically depleted nature of the La Libertad spring which gives credence to the theory that this aquifer has a large input directly from the rivers in the eastern area which also are fed by relatively high altitude runoff.

(g) The underlying Colima Superior theoretically receives its recharge by leakage from the Barba and La Libertad. The fact that it contains isotopically heavier groundwater than either of these aquifers implies an additional source of recharge must be contributing in sufficient quantity to modify the isotope content. This source is presumed to be direct

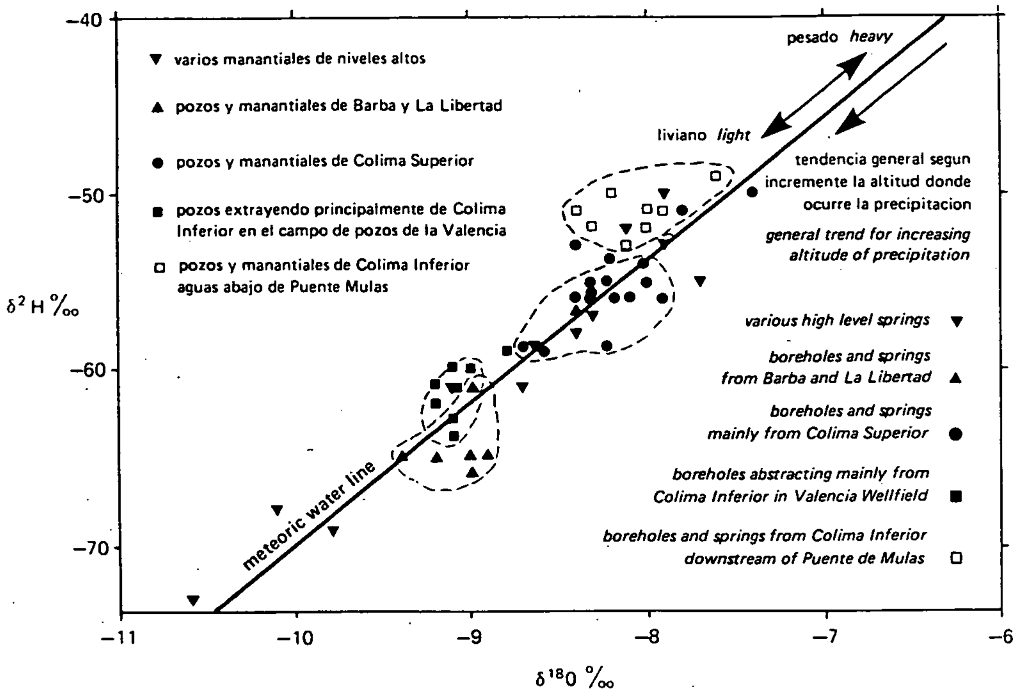


Fig 3.11 Environmental stable isotope data for groundwaters in the Valle Central.

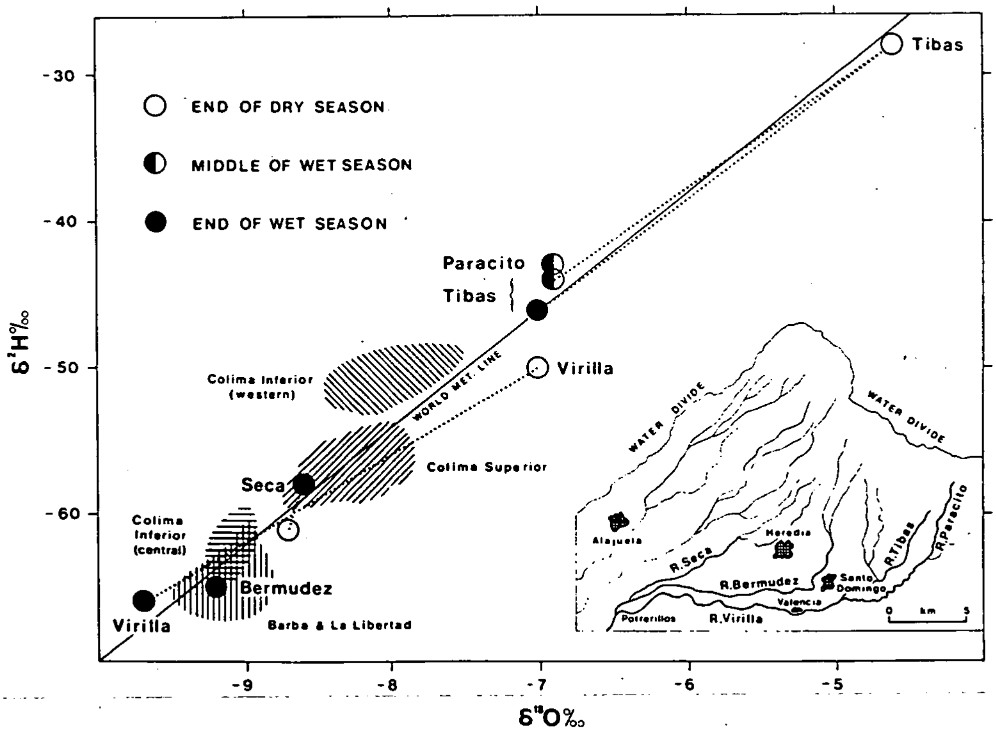


Fig 3.12 Environmental stable isotope data for rivers in the Valle Central.

infiltration through the overlying tuffs where there is no perched aquifer above the Colima Superior; a source previously thought to be negligible.

(h) The deepest aquifer, the Colima Inferior, has different isotopic content depending on where it is sampled which implies different sources of recharge. In the area downstream of Potrerillos where the groundwater is isotopically heavy, it is supposed that most of the recharge has come from the Colima Superior and that isotopic enrichment has occurred as a result of some direct infiltration of low level rainfall although the area over which this could occur is small. In the Valencia Wellfield the isotopic relationship between the various aquifers can only logically be explained if the La Libertad is directly recharging the Colima Inferior without transit through the Colima Superior. This has led to speculation that the Colima Superior may be absent over part of the eastern area. This hypothesis is discussed in section 5.3.

4. GROUNDWATER QUALITY

4.1 Natural Characteristics

(a) Groundwater samples from selected springs and boreholes throughout the Valle Central have been collected for major ion analyses at intervals during the course of the project, with the most comprehensive sampling in November 1985. Historical data are limited, but the results obtained are generally consistent with those of the previous groundwater quality monitoring. A most satisfactory agreement was obtained between split samples analysed independently in the ICAyA-Tres Rios and BGS-Wallingford laboratories.

(b) All groundwaters are remarkably low in dissolved constituents, with the exception of high silica and moderate bicarbonate (Table 4.1), and exhibit surprising spatial uniformity and only minor temporal change.

(c) The only significant variation is that groundwater sources in the Los Angeles formation, high on the slopes of the Barba volcano, have much lower concentrations of some constituents, and several boreholes in the Valencia Wellfield have higher concentrations of Na, Cl and HCO_3. It is probable that these latter boreholes obtain a larger proportion of their supply from the Colima Inferior and that their chemical analyses reflect a larger contribution from this aquifer.

(d) The reason for the low concentration of dissolved salts appears to be the absence of soluble chloride and sulphate minerals in the volcanic rocks of the area.

(e) A reconnaissance study of the chemistry of some river waters was undertaken early in the project to assess the possible role of rivers in aquifer recharge. While seasonally more variable in composition, the river waters are of similar ionic composition to groundwater, although more dilute. Chemistry cannot thus be used to diagnose whether rivers are influent to aquifers. In consequence, no further analyses of river waters were recommended for the purposes of groundwater investigation.

(f) In some volcanic terrains, certain trace elements can be present naturally in groundwater at elevated and troublesome concentrations in relation to public health. These include fluoride, arsenic, boron and selenium. During 1986, various springs of the shallow aquifers in the Valle Central, together with the principal Colima groundwater sources, were made the focus of a groundwater trace element survey. Many trace elements are unstable in solution and precautions have to be taken to preserve samples at the time of collection. The necessary field equipment and reagents were supplied by BGS and the samples were sent by air cargo to Britain for analysis.

(g) A wide range of trace elements were determined (Table 4.2), and many occur at concentrations below the current detection limit. Others were found to be present in very small concentrations, in most cases below the WHO and/or EEC recommendations for potable water-supply, with the exception of one sample in respect of aluminium (Al) and two for barium (Ba).

(h) On the higher slopes of the volcanic cones, groundwaters have been reported occasionally to experience abrupt falls in pH, with the

Table 4.1 Summary of inorganic chemistry of Valle Central Groundwaters.

Site	Name	Aquifer	Number of Samples	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^- (mg/l)	SO_4^{2-}	Cl^-	NO_3^-	SiO_2
Typical Range				12-20	6-12	6-10	4-10	80-120	1-10	2-15	1-15	60-85
W-1		CS-CI	1	18	11			121		21		
W-2		CS-CI	4	15-20	9-12			98-124	3.1-8	7-19	2-3	65-79
W-3		CS-CI	2	15-18	11-12			129-130	6-7	16-17		
W-4		CS-CI	4	12-17	3-8	3-6	3-10	69-89	4-6	3-8	4-16	30-85
W-5		CS-CI	1	12	6			83	2	6		
W-7		CS-CI	1	17	10			115		21		71
W-9		CI	4	16-18	11-13	20-22	6-7	137-143	6-10	20-25	1-4	81-85
W-12		CS-CI	1	15	10			119	7	11		
W-13		CS-CI	3	12-13	8			97-102	1-5	4-8		75-81
W-14		CS-CI	4	8-16	8.5-10	8-9	3-4	94-102	2-11	7-10	3-6	65-85
W-15		CS-CI	1	16	11			127	3	14		79
AB-308	Ande	B(?)	3	18-20	7-8			93-98	1-2	5-10		73-87
Scott Paper		CS	1	17	8			95	0		10	81
BA-173		A	1	9	5			69		2		10
AB-471	La Peregrina	CS	5	14-17	8-10	7	4	97-110	1-3	2-10	2	73-85
AB-877	Potrerillos	CI	3	14-17	7-9			88-98	0-9	4-12	3	77-85
AB-336			1	18	9			107	1	8		81
BA-169	Cicafe	B	1	15	7			83	4	7		
AB-328	Tajo Zamora	CS-CI	3	18-20	8-9			97-99	1-2	7-12		79-87
Fuente Perez		A	1	7	5			34	10	7		59
La Hoja		A	1	10	6			71		6		57
Puente Mulas		CS	6	19-20	8-9	8	4	101-106	1-8	7-12	4	75-85
Potrerillos		CI	5	14-16	8-16			96-100	0-7	10-12	13	75-81
La Libertad		LL	4	18-20	8-9	7	4-7	90-93		5-9	23	85-87
Penal		CI	1	13	8			94	8	14	2	68
Guachipelin		CS	1	17	3			95	3	8	9	78
Sta Barbara		B	1	13	6			73	5			
Echeverria		B	1	16	8			84	9			
Belen		B	1	26	8			95	12			
Los Angeles		A	1	2	1			15	4	3		
Ojo de Agua		B	4	15-22	7-8			84-90	1-3	7-12	9	69-78

A = Angeles aquifer
B = Barba aquifer
LL = La Libertad aquifer
CS = Colima Superior aquifer
CI = Colima Inferior aquifer

Table 4.2 Trace element analyses for selected water-supply boreholes and springs.

(all in μg/l)

LOCATION	TYPE	AQUIFER	Hg	Se	Ba	B	Al	Ni	F
La Libertad	S	LL	DL	0.3	72	DL	DL	DL	290
Los Angeles	S	LA	ND	DL	5	DL	130	DL	100
BA 169	B	BA	DL	0.8	8	DL	DL	DL	130
Echeverria	S	BA	DL	0.6	9	DL	DL	DL	130
Santa Barbara	S	BA	DL	0.4	14	DL	120	DL	120
Ojo de Agua	S	BA	DL	0.4	9	DL	DL	DL	170
San Antonio	S	BA	DL	0.3	16	DL	DL	DL	180
Puente de Mulas	S	CS	DL	0.4	250	DL	220	DL	210
AB 328	B	CS/CI	DL	0.3	16	DL	DL	DL	210
AB 471	B	CS	0.13	0.3	20	DL	DL	DL	260
CP-W4	B	CS/CI	ND	0.4	140	DL	DL	DL	190
CP-W3	B	CS/CI	DL	0.3	26	110	DL	DL	370
CP-W9	B	CI	DL	0.4	20	80	DL	DL	430
Potrerillos	S	CI	DL	0.5	12	40	DL	ND	220
LIMIT OF DETECTION			0.1	-	2	35	100	50	-
MAX. CONCENTRATION		OMS	1	10	-	-	200	-	1500
LIMIT FOR POTABLE WATER		EEC (GL)MAC	1	10	(100)	(1000)	200	50	700+

B = Borehole
S = Spring

LA = Los Angeles
BA = Barba
LL = La Libertad
CS = Colima Superior
CI = Colima Inferior

Pb (5 μg/l)
Cd (0.5 μg/l)
Be (1 μg/l)
Cr (3 μg/l)
Cu (10 μg/l)
V (20 μg/l)
As (50 μg/l)*

less than the limit of detection indicated in parenthesis

DL = below detection limit

ND = not determined

* method of analysis does not permit lower detection limit; this is also the maximum permissible concentration

dissolution of metallic elements, and the enforced abandonment of the supply. It is not clear whether this phenomenon is due to the presence of volcanic discharge of hydrogen sulphide and/or carbon dioxide gas, or to the local burial of organic wastes from the coffee industry.

4.2 Groundwater Pollution Risk

(a) An evaluation of the groundwater pollution risk for the main aquifers of the Valle Central has been undertaken in the course of the present project. It was, however, restricted to the preliminary reconnaissance level, because more human resources would have been necessary to permit a comprehensive survey.

(b) In general terms, it is helpful to view groundwater pollution risk as the interaction between (a) the imposed subsurface contaminant load generated by human activity at the land surface, and (b) the natural aquifer pollution vulnerability, consequent upon a set of intrinsic formation properties. In addition, the probability of a significant subsurface contaminant load actually occurring, should be aggregated when considering activities which present the possibility of environmental accidents causing a significant discharge to the subsurface.

(c) The principal sources of subsurface contaminant load to the principal aquifers of the Valle Central (mainly located to the north of the Rio Virilla) are considered to be:

(i) Effluent discharge to the soil and to influent rivers, especially in the main industrial development area situated in the Cantons of Heredia and Belen, which is without main sewerage.

(ii) Soil discharge from on-site sanitation in almost all urban areas north of the Virilla, since only limited parts of Heredia and Alajuela have main sewerage.

(iii) Influent rivers, which although of excellent quality in their upper sections, become heavily-contaminated within and below the San Jose Metropolitan Area (that is, downstream of a line through Heredia - Santo Domingo - San Juan de Tibas - Guadelupe - Curridabat).

(iv) Leaching of fertilisers and pesticides from intensively cultivated agricultural soils north of the Rio Virilla.

Each of these potential pollution sources is discussed in more detail in subsequent sections.

(d) The vulnerability of the principal volcanic aquifers themselves is a relatively complex subject. A preliminary classification was attempted for the Hydrogeological Map of the Valle Central prepared by BGS and SENARA and published in 1985. Areas where highly-permeable lavas outcrop at the surface, and especially where they form the beds of rivers, must be regarded as of very high pollution vulnerability. Such conditions exist locally in some parts of the Valle Central but more generally the lavas are covered by volcanic tuff deposits.

(e) These tuff deposits, together with the thick soil sections developed on some lava outcrops, afford considerable protection to groundwater since they greatly delay infiltration providing increased possibility of degradation and/or sorption of potential pollutants. Thus where a significant thickness of tuff overlies an aquifer concern about groundwater pollution will be restricted to the more mobile and persistent pollutants, especially where they are discharged continuously and extensively.

(f) The presence of considerable thickness of tuff deposits above the Colima aquifers in most areas will also considerably delay the arrival of such pollutants to these aquifers. Where exposed at the surface, The Tiribi formation is likely to have natural infiltration rates of less than 1 m/a, introducing a time lag of about 10 years in recharge to the Colima Superior.

(g) Most of the significant industries in the Cantons of Heredia and Belen, other than food processing factories, are located in Figure 4.1. Tentative estimates of the volume and chemistry of their effluents are given in Table 4.3, which is based on available data on water use and on the nature of the industrial enterprise alone. No chemical analyses of effluents are available.

(h) Most of these effluents are discharged, in some cases after limited treatment, to the Rio Bermudez or Quebrada Seca (Figure 4.1), which are influent to the underlying Barba aquifer (Figure 4.2), or, in a few cases, directly to the ground. It is thus considered that there is high risk of serious pollution affecting the San Antonio de Belen spring source, located immediately down hydraulic gradient in the Barba aquifer, and some risk that this contamination could be transmitted through the Tiribi formation to affect the Puente Mulas springs.

(i) The presence of unsewered sanitation in most urban areas north of Rio Virilla is considered to present a significant local risk of groundwater contamination by nitrate and/or fecal pathogens in the shallow La Libertad and Barba aquifers.

(j) Throughout the lower parts of the Valle Central, the fact that many smaller watercourses are both influent and heavily contaminated presents further risk of deterioration of groundwater quality. For the most part, however, the Rio Virilla itself is so deeply incised as to constitute a focus of aquifer discharge and its poor quality does not affect groundwater. However, an important riverbed recharge area for the Colima aquifers has been identified upstream of San Juan de Tibas along a length of some 5 to 6 kms of the beds of the Rio Virilla and Rio Tibas (Figure 4.3). At present, those sections of these rivers are of excellent quality, and no immediate risk is apparent.

(k) Coffee plantations occupy a large proportion of the land north of the Rio Virilla between 900-1500 m ASL. In the Valle Central they constitute the most intensive cultivation of agricultural soils and represent 30-40% of the non-urban land use. Traditional cultivation methods did not employ significant quantities of fertilisers and pesticides, but they are rapidly being displaced by higher technology methods. These involve split application of 200-300 kgN/ha/a on two or three occasions, together with 80-120 kgK/ha/a, 40-60 kgP/ha/a and some Mg, Ca, B and Zn salts. As regards pesticides, there is rapidly increasing use of herbicides (up to 10 kg/ha/a of active ingredients such as 2.4D, paraquat, glycophosphate and oxyfluorophenol) and major use of both preventative and curative fungicides (normally copper salts involving applications of

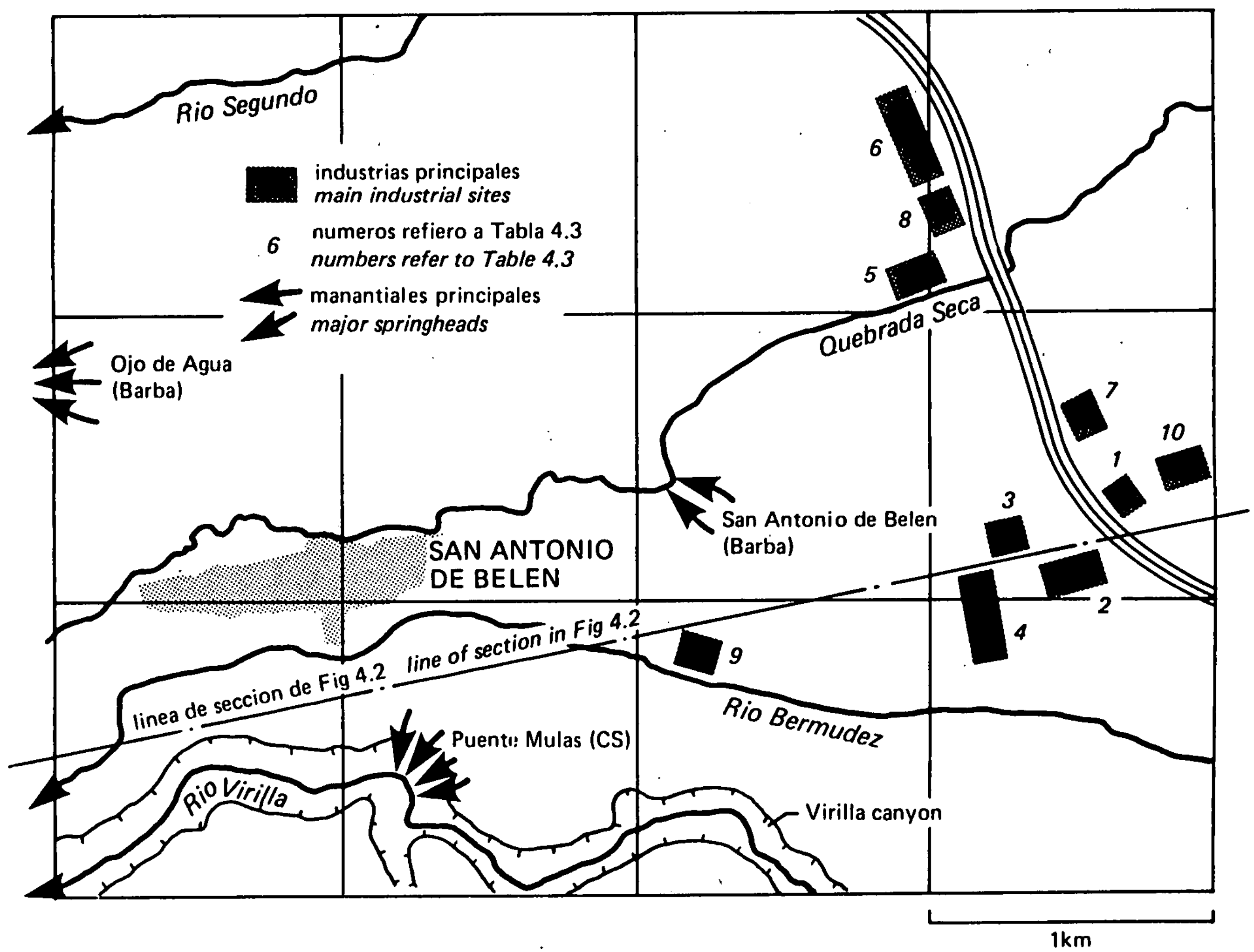


Fig 4.1 Distribution of the principal industries and water supply springs in the industrial park of Belen and Heredia Cantons.

Table 4.3 <u>Provisional characterisation of effluents from the industrial area of Heredia and Belen Catons.</u>

INDUSTRY			PROBABLE TYPE OF EFFLUENTS			
NAME	TYPE	PRODUCT	WATER USE (l/s)	CHLORINATED ORGANICS	HEAVY METALS	BOD
Proplas	chemical	plastics	?	**		*
Conducen	metal	cables	5-10	*	*	
Trimpot	metal	electronic	5-10	*	*	
Tica Tex	textile	cables	10-20	**	*	**
Red Point	textile	leather	<5	*		*
Firestone	chemical	tyres	10-20	**		**
Metalin	metal	metals	?	*	*	
Olympic Fibres	textile	leather	?	**	*	**
~~Scott Paper~~	~~chemical~~	~~paper~~	~~50~~	~~*~~		~~***~~
Bticino	metal	electronic	?	*	*	
Mennen	chemical	cosmetics	?	*		*

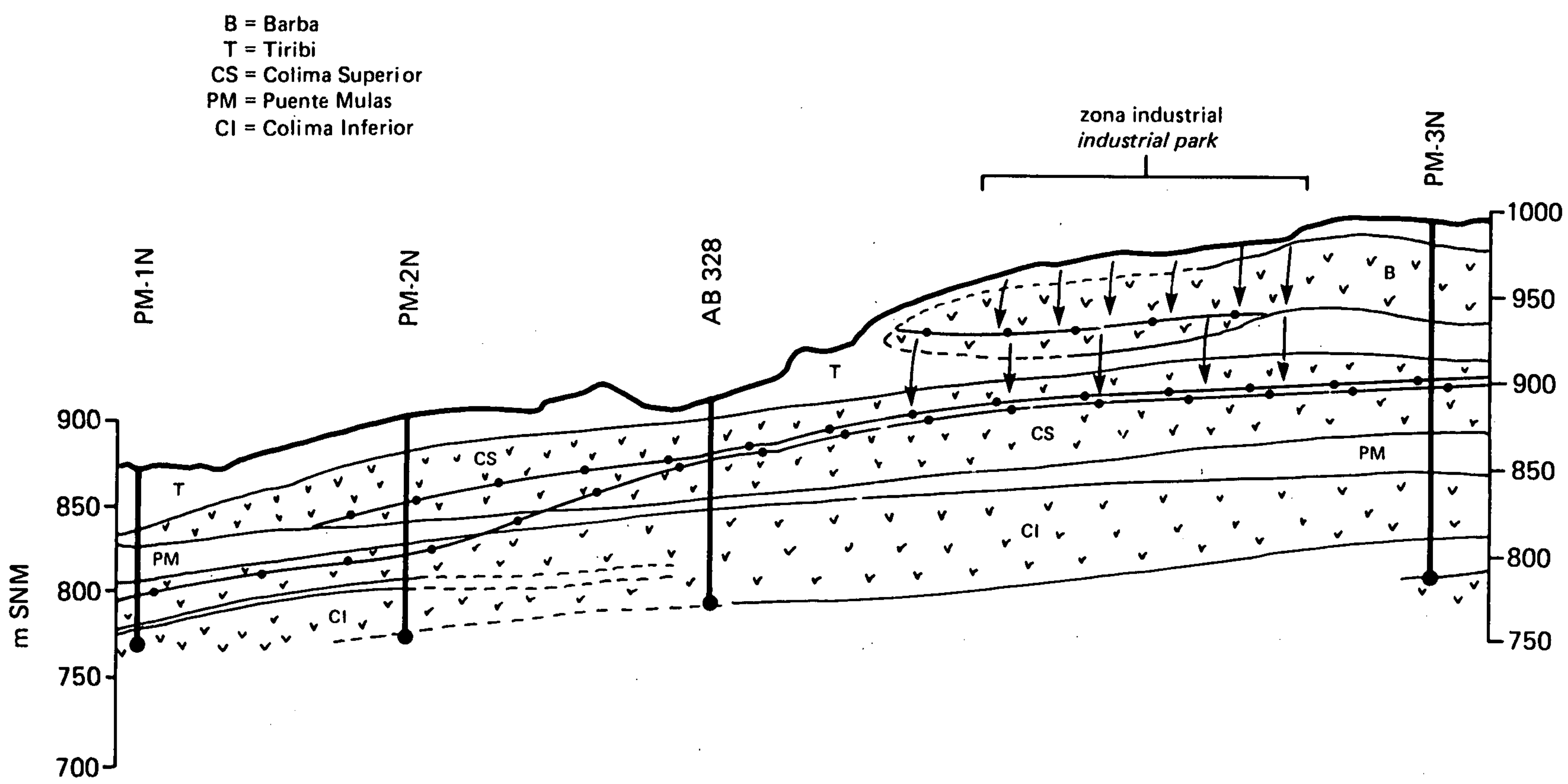


Fig 4.2 Geological cross-section from Puente de Mulas through the industrial park of Belen and Heredia Cantons.

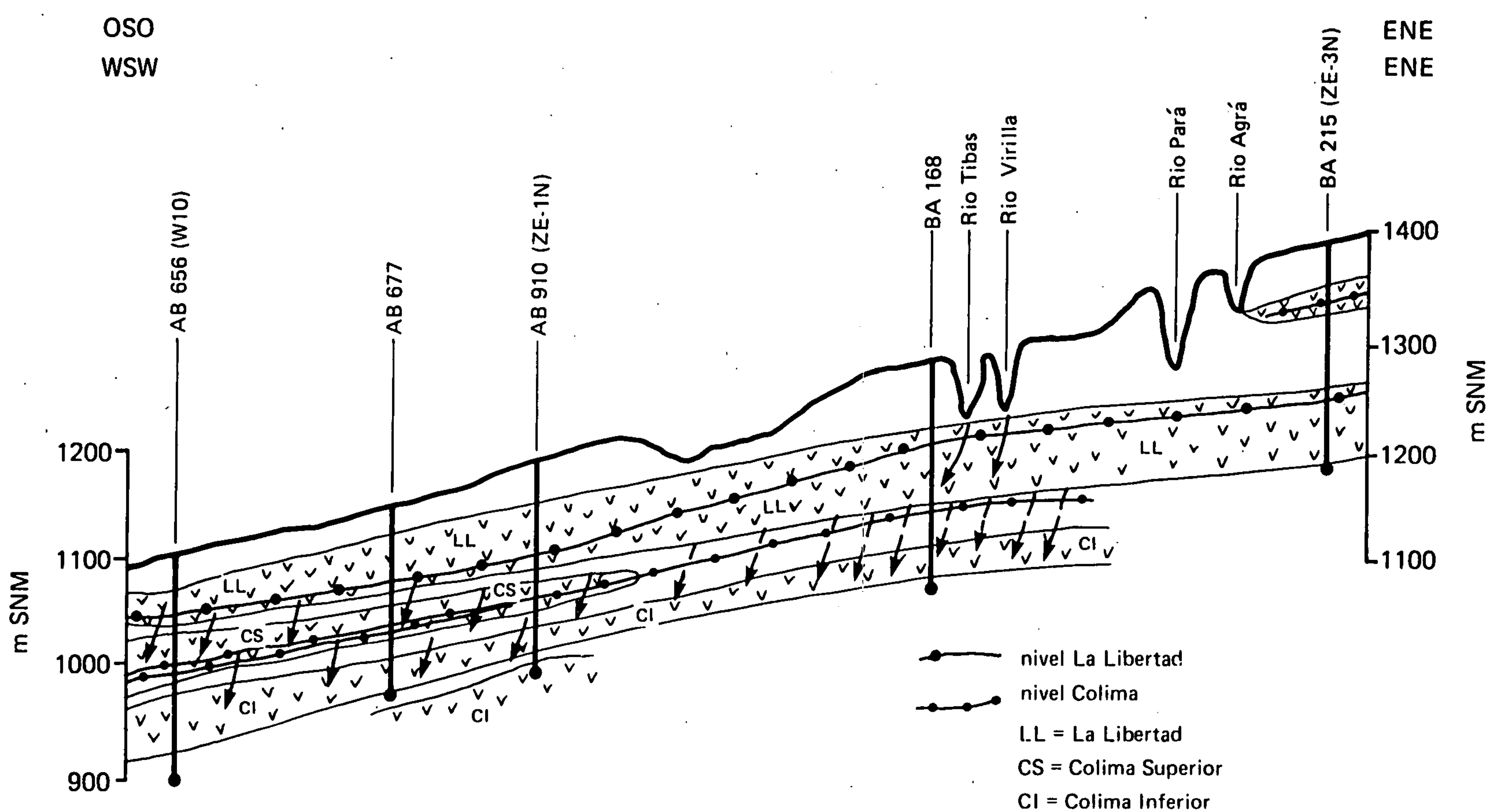


Fig 4.3 Schematic geological cross-section to show surface water-groundwater relations upstream of San Juan de Tibas.

5-15 kgCu/ha/a, with some Pb and As compounds). Other compounds, including the nematocidic pesticides, aldicarb and carbofuran, are applied in small quantities when sewing new bushes.

(1) Despite this trend in the use of fertilisers and pesticides, the potential for serious diffuse groundwater pollution appears to be limited, although some problems occur in the immediate vicinity of shallow water sources. The reason is that infiltration rates are very high (often exceeding 1000 mm/a) and even with proportionally high leaching losses, the resultant contaminant concentrations in groundwater should remain generally tolerable as a result of soil retention and/or dilution (Table 4.4).

4.3 Indicators of Quality Deterioration

(a) In view of the significant risk of groundwater pollution in the lower parts of the Valle Central, a program of groundwater sampling and analyses for pollution indicators and selected organic compounds was initiated in mid-1986. This included the following:

(i) Monitoring of nitrate (NO_3) concentrations in the principal groundwater sources by ICAyA from July 1986 onwards.

(ii) Reconnaissance sampling of 30 sites throughout the Valle Central with analysis for pH, Cl, NO_3, NH_4 by ICAyA, ABS by UCA and DOC in Britain in May-Jun 1987, with follow-up work in Aug-Sep 1987.

(iii) Screening for organic compounds in a limited number of sources sampled in Jan-Feb 1987 and Aug-Sep 1987, samples being transported by air to Britain for analysis.

The results corresponding to the May-June 1987 sampling are summarised in Figures 4.4 and 4.5.

(b) Although the levels of NO_3 and Cl are relatively low, the broad correlation between nitrate and chloride concentrations in all sources, other than those in the Colima Inferior aquifer (which is known to have a higher natural chloride background), together with the tendency for increasing concentrations down hydraulic gradient and occurrence of highest levels in the lowest spring discharges from the respective aquifers, suggests that groundwater quality is being affected (directly or indirectly) by discharge of urban effluents. The correlation may, however, be affected to some degree by the presence of agriculturally derived nitrates. None of the other indicators showed a diagnostic variation. The pH varied mainly between 6.5-7.5, ABS was invariably less than 0.2 mg/l and NH_4 only exceeded 0.1 mg/l in a single borehole in the industrial area.

(c) The principal groundwater sources, and especially the springs at La Libertad and Puente Mulas, have been shown to exhibit marked seasonal variation in NO_3 concentrations (Figure 4.6), with maxima soon after the commencement of the wet season. This suggests leaching of nitrogeneous material accumulated in the subsoil as an important pollution mechanism. Such accumulation could be from agricultural practices, but is more likely to derive from unsewered sanitation.

(d) The implication of groundwater contamination from effluent discharge is compounded when reference is made to Figure 4.5, in which a broad

Table 4.4 Estimation of probable maximum concentration of agricultural chemicals leached from coffee plantations into groundwater recharge.

COMPOUND	MAX APPLICATION (kg/ha/a)	PROPORTION OF AREA	RELATIVE MOBILITY	MAX. % LEACHED	MAX CONCENTRATION IN RECHARGE (μg/l)*	WHO LIMIT (AD) (μg/l)
NO_3-N	300	35%	high	40%	4200 (18mgNO_3/l)	10,000
Cu	15	35%	v. low	1%	5	1,000
2.4D	10	25%	moderate	5%	13	100
Paraquat	1	25%	v. low	1/2%	0.1	(0.5)

* presuming 1000 mm/a infiltration

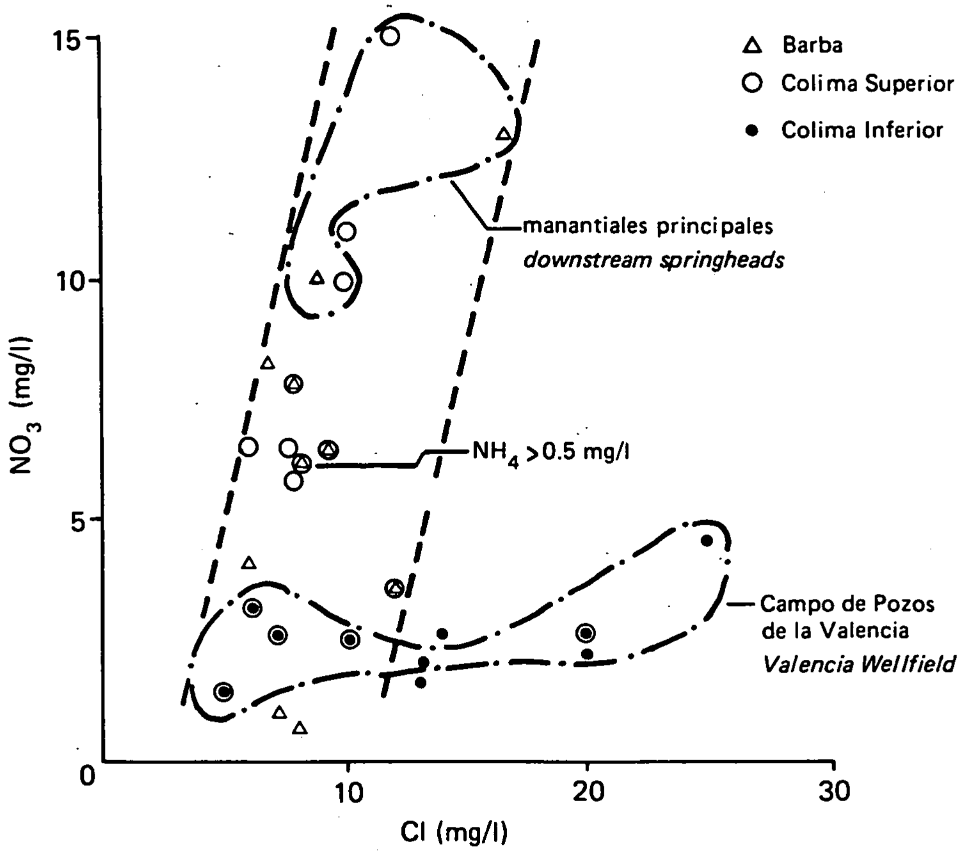


Fig 4.4 Correlation between nitrate (NO_3) and chloride (Cl) concentrations for the Valle Central groundwaters (May-June 1987).

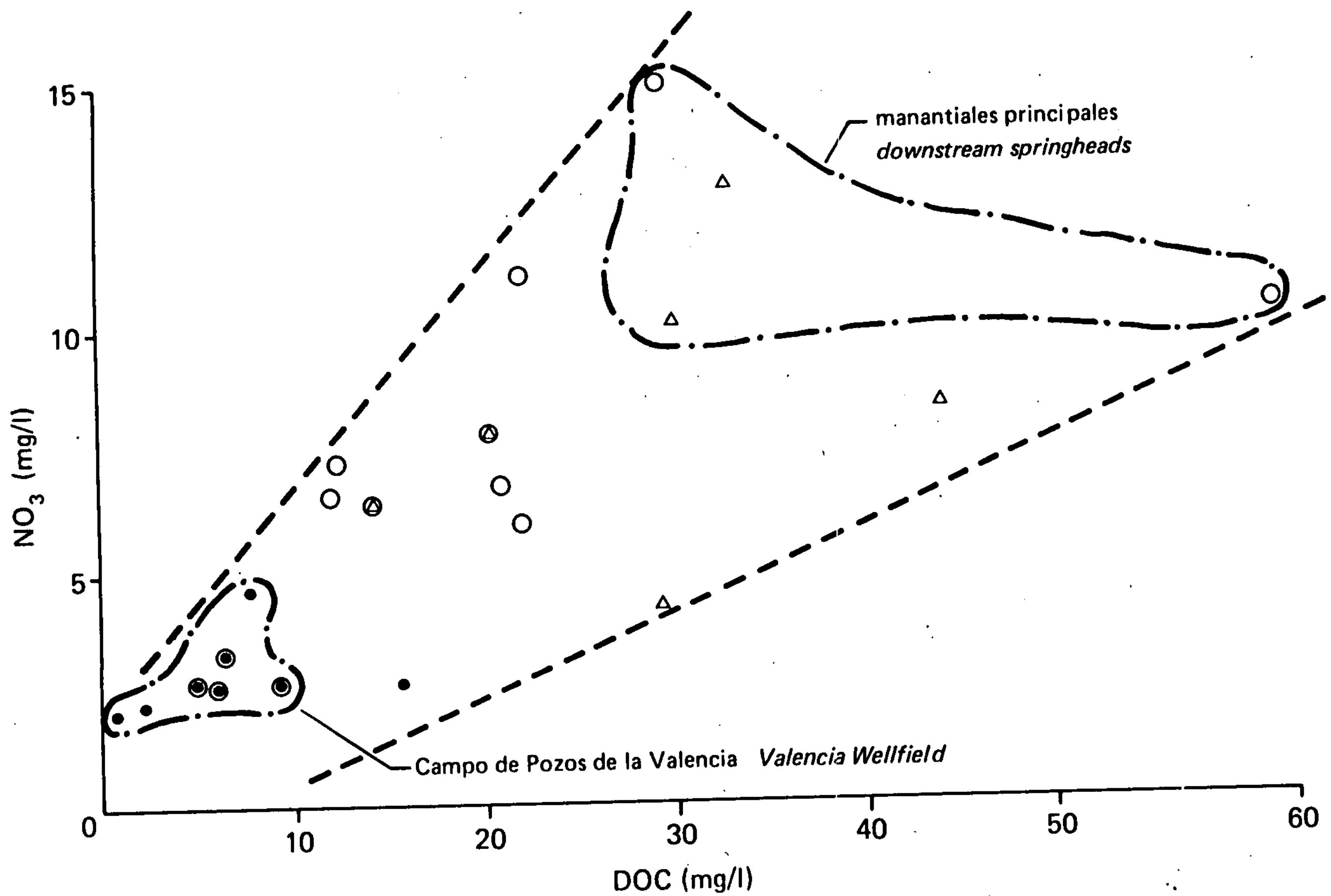


Fig 4.5 Correlation between nitrate (NO_3) and dissolved organic carbon (DOC) concentrations in the Valle Central.

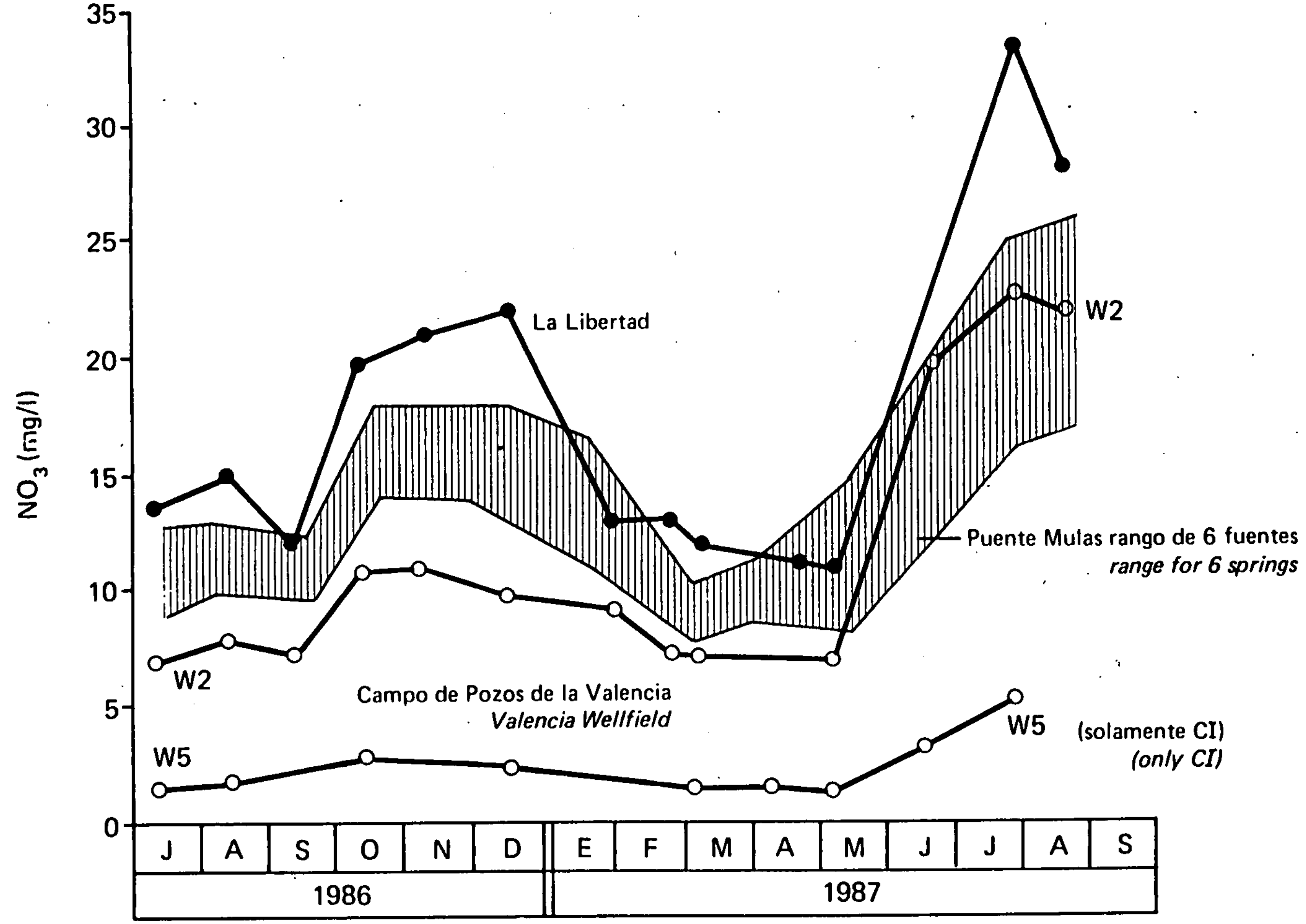


Fig 4.6 Temporal variations in nitrate (NO_3) concentrations of selected Valle Central groundwater sources (July 1986 - Sept 1987).

correlation between NO_3 and DOC is evident, with increasing DOC concentrations down hydraulic gradient and at the downstream springheads.

(e) There is still limited international experience in the use of DOC as an index of groundwater contamination, and very few published data on background concentrations in humid tropic regions. Numerous compounds may comprise DOC. These include oils and greases, humic and fulvic acids, synthetic detergents, organic acids, etc. DOC concentrations in excess of 10 mg/l must, in any event, be regarded as high and probably indicative of groundwater pollution. They may indicate the presence of synthetic organic compounds which could constitute a health hazard in drinking water, and/or the potential for formation of halogenated compounds (such as the trihalomethanes) with the presence of a chlorine residual in water distribution systems.

(f) Problems are known to occur with poor analytical replicability for TOC, and to lesser degree for NO_3. For this reason follow-up work was undertaken in an attempt to confirm and extend the aforementioned correlation. Problems arise in the analysis of DOC because of the frequent presence of very mich higher concentrations of inorganic carbon (as bicarbonate) in most groundwaters. The analytical procedure involves three steps: first, acidification and purging of inorganic carbon species; second, wet chemical or photo oxidation of the organic carbon; third, quantification of the CO_2 produced, usually by infrared absorption spectrometry. These steps introduce the possibility of serious variation in DOC measurements due to such causes as incomplete purging of inorganic carbon and/or loss of volatile organic fractions. NO_3 determinations are also prone to significant variation between analytical methods, due to incomplete conversion or to interference of other ions, and losses may occur if samples are not transported adequately and analysed rapidly.

(g) Unfortunately, the results of the limited follow-up work, using two British laboratories for DOC determination and a revised method for NO_3 measurement in the ICAyA laboratory, generated inconsistent results (Table 4.5). This must, to some degree, call into question the validity of the earlier results, and unfortunately no further project resources were available to evaluate the situation. Nevertheless, the occurrence of elevated DOC, and increasing NO_3, concentrations in some downstream groundwaters of the Valle Central is irrefutable and gives rise to considerable concern. This subject should be investigated further at the earliest opportunity.

(h) None of the common industrial solvents were found to be present above detection level in the 15 samples transported to Britain for analysis by the GC-EC and GC-MS methods (Table 4.6). However, should the recommended follow-up work in relation to DOC corroborate the systematic occurrence of elevated concentrations, further analyses for certain common, and potentially toxic, synthetic organic compounds will also be required.

4.4 Groundwater Protection Strategy

(a) General guidelines on groundwater protection measures in relation to common polluting activities was given by hydrogeological formation in the Hydrogeological Map of the Valle Central prepared by BGS and SENARA, and published in 1986. These guidelines are generally still applicable but

Table 4.5 Summary of follow-up analytical work on DOC and NO_3.

(1987)

SOURCE		DOC			NO_3 (ICAyA)	
NAME	TYPE	LAB A* Aug-Sep	LAB B Aug-Sep	LAB A* May-Jun	Aug-Sep SIE*	May-Jun SWM*
San Antonio de Belen	S	25	1	33	40	13
Puente Mulas	S	1	2	29	22	15
La Esperanza	B	11	8	21	10	6
CP-W4	B	10	1	5	16	3
Club Ande	B	1	nd	nd	30	nd
Tica Tex 1	B	22	nd	nd	28	6
Tica Tex 3	B	1	1	nd	24	nd
Conducen	B	1	2	21	18	8
Pieles CR	B	1	2	nd	15	nd
Firestone	B	22	3	nd	34	4

S = Spring
B = Borehole
SIE = specific ion electrode
SWM = standard method

* there is natural seasonal variation between these dates in the year 1987

Table 4.6 Summary of results of analytical screening for synthetic organic compounds.

SOURCE		ANALYTICAL RESULTS		
NAME	TYPE	DATE Jan-Feb 87	Aug-Sep 87	NOTES
La Peregrina	B	*		all <LD
CP-W4	B	*		all <LD
Ojo de Agua	S	*		all <LD
Puente Mulas	S	*	*	all <LD
San Antonio de Belen	S	*	*	all <LD
La Esperanza	B		*	all <LD
Conducen	B		*	all <LD
Firestone	B		*	TCE = 5 µg/l all <LD
Ticatex 3	B		*	all <LD

(phthalate detected in most sources at up to 10 µg/l)

COMPOUND	LIMIT OF DETECTION (µg/l) Jan-Feb 87	Aug-Sep 87
Phenol	50	nd
Benzene	40	nd
Toluene	20	nd
Xilene	20	nd
Freon 113	10	1
111 Tricloroetane	2	1
Tricloroethylene (TCE)	1	1
Tetracloroetylene (PCE)	2	1
Cloroform	20	2
Carbon tetracloride	nd	1
Diclorobenzene	nd	10
Dibromometane	nd	1
Bromoform	nd	2
Pyrene		0.1
Polychlorobiphenol		0.1
Phtalate isomers		0.1

B = borehole
S = spring
nd = not determined
LD = limit of detection

the actual boundaries of some formations may require revision in the light of the more detailed investigations undertaken during the present project.

(b) One exception relates to the use of unsewered sanitation in the more extensive urban areas upstream of important groundwater sources. In the case of Santo Domingo this appears to be the most probable source of increasing NO_3, and probably DOC, concentrations in La Libertad springs. Similar influences probably affect the spring sources at San Antonio de Belen and Puente Mulas. If further local investigation confirms this observation, such areas will require installation of main sewerage to protect groundwater quality.

(c) Measures to improve the quality of the Rio Bermudez and Quebrada Seca are also required to reduce the risk of serious groundwater pollution downstream. The industrial area in the Cantons of Belen and Heredia must be considered high priority for main sewerage, and for this to be effective, as far as groundwater interests are concerned, the outfall would need to be in the Rio Virilla downstream of Puente Mulas.

(d) As regards the Valencia Wellfield, an active policy of quality conservation in the Rio Tibas and upper reaches of the Rio Virilla are required to avoid direct and rapid deterioration in the quality of groundwater recharge to the Colima aquifer upstream.

(e) The production boreholes of the Valencia Wellfield have an enclosed (10-15 m radius) sanitary protection area. Bearing in mind that the Colima Superior aquifer is semiconfined and/or covered by tuffs of the Tiribi formation, this is considered generally adequate. However, in the cases of boreholes W1 and W7 human settlement, including small workshops, has encroached right up to the perimeter fence. The discharge into surface drainage of human excreta, spent oils and solvents from these settlements could infiltrate to shallow perched water tables during heavy rainfall, with the associated risk of direct entry to the boreholes down the annulus behind the solid lining tubes. An improvement in sanitary conditions in the vicinity of these production boreholes is required. An example of optimal wellhead protection may be found in the municipal production borehole of Santo Domingo some 500 m SE of this town.

5. APPRAISAL OF GROUNDWATER RESOURCES

5.1 Colima Aquifers.

(a) The hydrogeological criteria outlined in previous chapters are the fundamental basis of the groundwater resource appraisal but in recommending the location of new abstractions, it is necessary also to consider the location of predicted demand areas and possible interference with existing sources.

(b) The annual throughflow of the combined Colima Superior and Inferior aquifers is estimated to be no less than 5500 l/s. Currently developed abstraction capacity from these aquifers amounts to about 2200 l/s made up of 1000 l/s from the Valencia Wellfield, 650 l/s from the Puente de Mulas springs, 250 l/s from the Potrerillos springs and approximately 300 l/s from various private sources.

(c) The fact that more than one third of the available resources have already been captured for supply will obviously make it more difficult to obtain further significant quantities of water without interference with existing abstractions. The problem is made worse by the fact that the terminal springs of the Colima aquifers, at Puente de Mulas and Potrerillos, have been captured. These spring flows are more susceptible to interference from new abstractions than are most borehole sources. In considering the impact of new wellfield abstractions, a major significance has therefore been attached to the likely interference effect at these springs and, to a lesser extent those at Ojo de Agua and La Libertad.

(d) Interference with the boreholes of the Valencia Wellfield is also of major importance but interference with isolated individual borehole sources has not been considered. It would be unwise to reject the possibility of a major development of the groundwater resource in an area of good potential, solely to avoid interference with minor existing sources. The policy should be to compensate individual users whose private supply is jeapordised, for instance by providing them with water from the new wellfield.

(e) During the course of the project some significant general observations have been made about the Colima aquifers which bear directly upon their potential for further large scale development:-

(i) the water levels in the various Colima lavas separate close to discharge points making abstraction of large yields from boreholes more difficult,

(ii) the Colima Superior contains a considerable amount of water but the often small saturated thickness of the aquifer and high transmissivity concentrated in relatively few horizons in the lava mean that it is often difficult to capture the water in boreholes,

(iii) the Colima Inferior is a good aquifer but the fact that it often comprises more than one lava means that boreholes have to be deep to achieve good yields and over much of the higher ground its water level is deeper than 150 m,

(iv) yield-drawdown characteristics of Colima aquifer boreholes are very variable and strongly influenced by the borehole construction; excellent yield drawdowns such as those found in some Valencia Wellfield boreholes will only be achieved where there are favourable conditions in both Colima aquifers at a single location,

(v) the Valencia Wellfield vicinity has particularly favourable hydrogeological conditions which are unlikely to be repeated throughout much of the Valle Central such that there is limited scope for another wellfield with equally large borehole yields.

(f) The evaluation of the Colima groundwater resources has been concentrated in:-

(i) the Valencia Wellfield with a view to increasing abstraction,

(ii) several areas which have potential as possible sites for new wellfields.

The latter were selected after consideration of the aquifer occurrence, transmissivity, depth to water, groundwater flow and recharge together with consideration of possible interference effects and location of potential demand areas. Figure 5.1 shows the broad areas that have been subject to detailed resource appraisal and model simulations and illustrates some of the more important criteria that influenced their location, notably the proximity to existing major abstractions and depth to water. Each of the areas with potential for further groundwater development is considered separately. Large diameter trial production boreholes were drilled in several of the areas and details are summarised in Table 5.1.

5.1.1 Campo de Pozos : Valencia Wellfield

(a) The initial development of the Valencia Wellfield during 1975-78, involved a total of 10 boreholes and at this stage of development the wellfield was capable of producing about 650 l/s. Although the original design specification for the wellfield was for a total production of 1000 l/s, in 1978 further development was halted due to alarm over falling water levels (Fig 5.2). The results of further investigations and aquifer modelling by SENARA and BGS reaffirmed the wellfield potential. Water levels began to recover during the early 1980's and plans to increase the wellfield production were reinstated.

(b) Five new production boreholes (W6, W8, W10, W11, W12) have been drilled in the Valencia wellfield during the course of the current project. The details are summarised in Table 5.2 and their locations are shown on Figure 5.3. In common with the boreholes previously drilled in this area, most of the new wells exhibit good yield-drawdown characteristics (Fig 5.4), but pumping tests did not provide sufficient information for accurate assessments of aquifer transmissivity. The yield-drawdown characteristics of these and other boreholes in the wellfield, however, imply transmissivities ranging from about 500 m^2/d where there is poor yield-drawdown to greater than 5000 m^2/d where the borehole performance is excellent.

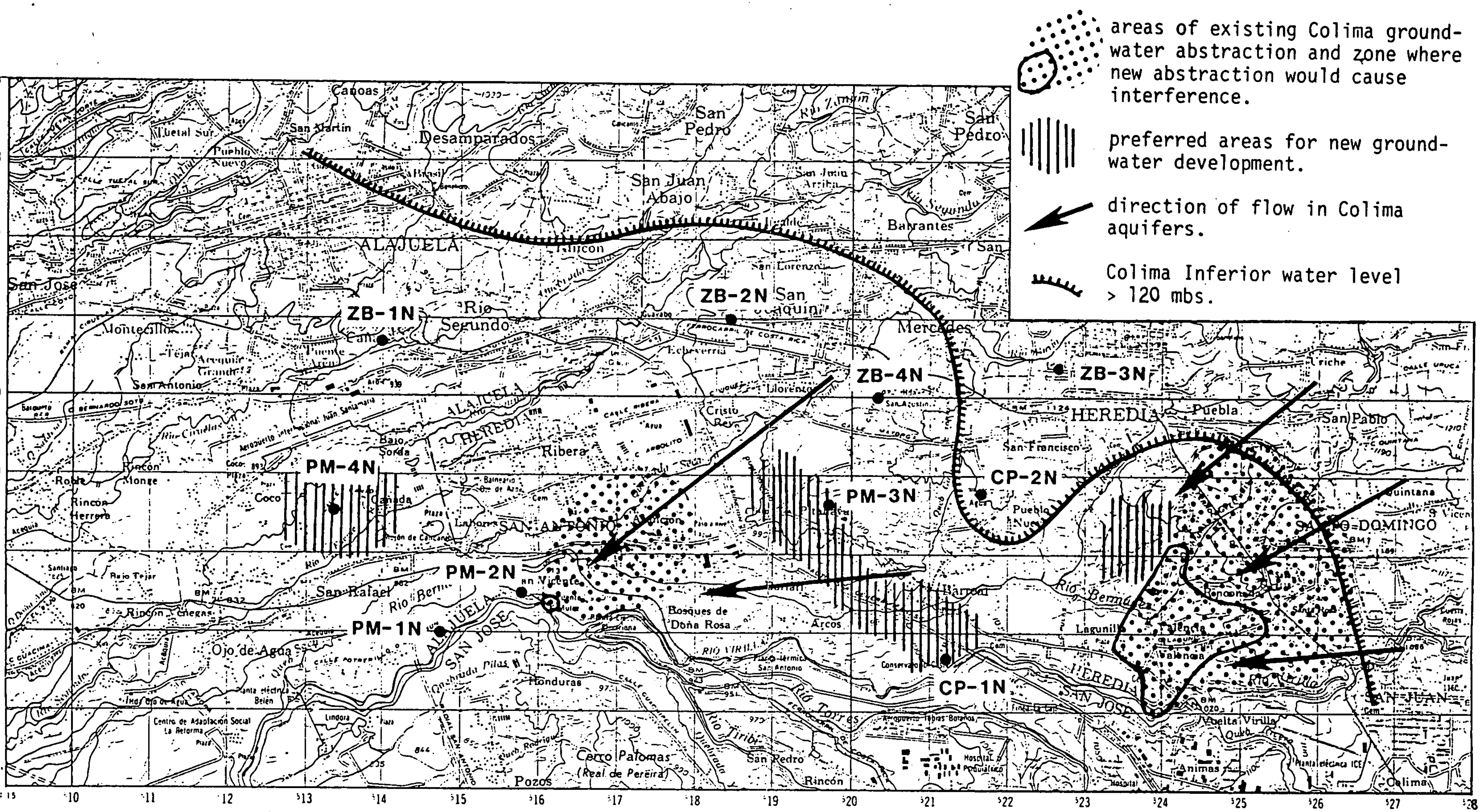


Fig 5.1 Map showing areas with potential for further development of Colima aquifers.

Table 5.1 Summary of large diameter trial production boreholes.

WELL NUMBER SITE NAME PROJECT NUMBER	AB-1153 POTRERILLOS PM-P1	AB-1089 CENADA PM-P2	BA-268 SAN JOAQUIN ZB-P1	AB-1152 CASTELLA CP-P1	
				I	II
Grid Ref.	514.55-217.05	520.10-218.30	518.33-221.00	521.15-216.70	
Elevation (m)	865	1002	1025	1005	
Depth (m)	110	162	83	130	180
Depth of pump (m)	92	112	63	119	119
Original water level (m)	75	73	34.4	88	68
Screen type	JOHNSON	VERTICAL BRIDGE	JOHNSON	OPEN	OPEN
Diameter (inches)	10	14	10	8	8
Position (m)	87-94	100-162	64.5-77	120-130	?
Pumping rate (l/s)	10	72	8-10	12-20	20
Drawdown (m)	6	2.4	35.5-35.9?	9.5	18
Aquifer	C.I.	C.S.-C.I.	BARBA	C.S.	C.S.-C.I.
Available drawdown	5	9		22	25
Recommended abstraction (l/s)		75	10		
Specific capacity (l/s/m)	1.66	3	0.22-0.27	1.39-1.08	1.11

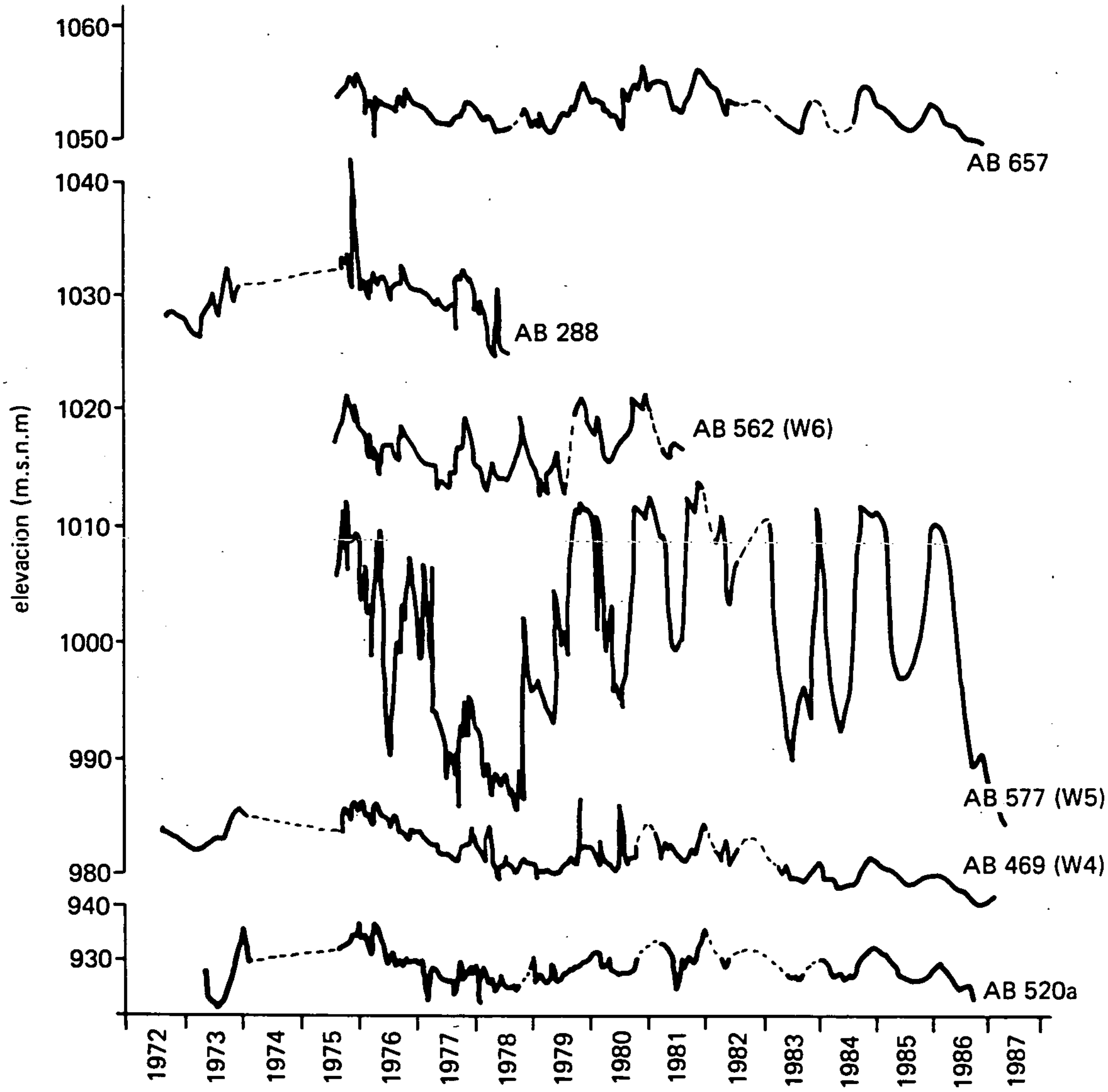


Fig 5.2 Groundwater levels in selected boreholes in the Colima aquifers, 1972-87.

Table 5.2 Summary of production boreholes drilled in the Valencia Wellfield

CHARACTERISTICS	W-6 AB-562	W-8 AB-902	W-10 AB-1002	W-11 AB-993	W-12 AB-881
Grid reference	218.40-524.40	524.27-217.40	525.46-217.30	523.75-217.75	524.20-216.82
Altitude (m)	1100.0	1074.0	1105.0	1056.0	
Total depth (m)	168.0	170.0	170.0	175.0	160.0
Depth of pump (m)	108.0	115.0	140.0?	120.0	120.0
Original water strike (m)	107.0	92-96	121.0	84.0	83.2
Screen: Type	bridge	bridge	slotted	Johnson	slotted
Diameter (inches)	10.0	6.0	8.0	10.0	14.0
Depth range (m)	130-168	135-170	135-150	109-179	93-99, 111-120.5
Pump discharge (l/s)	58.0	80-85	40.0	80-85	78.0
Drawdown (m)	9.5	6.5	18.0	3.8	4.5
Aquifer(s)	CS-CI	CS-CI	CS-CI	CS-CI	CS-CI
Available drawdown (m)	13.0	32.0	4.0	41.0	26.0
Recommended pumping rate (l/s)	65.0	95.0	35.0	100.0	65.0
Specific capacity (l/s/m)	7.0	14.0	2.1	22.5	17.3

CS = Colima Superior
CI = Colima Inferior

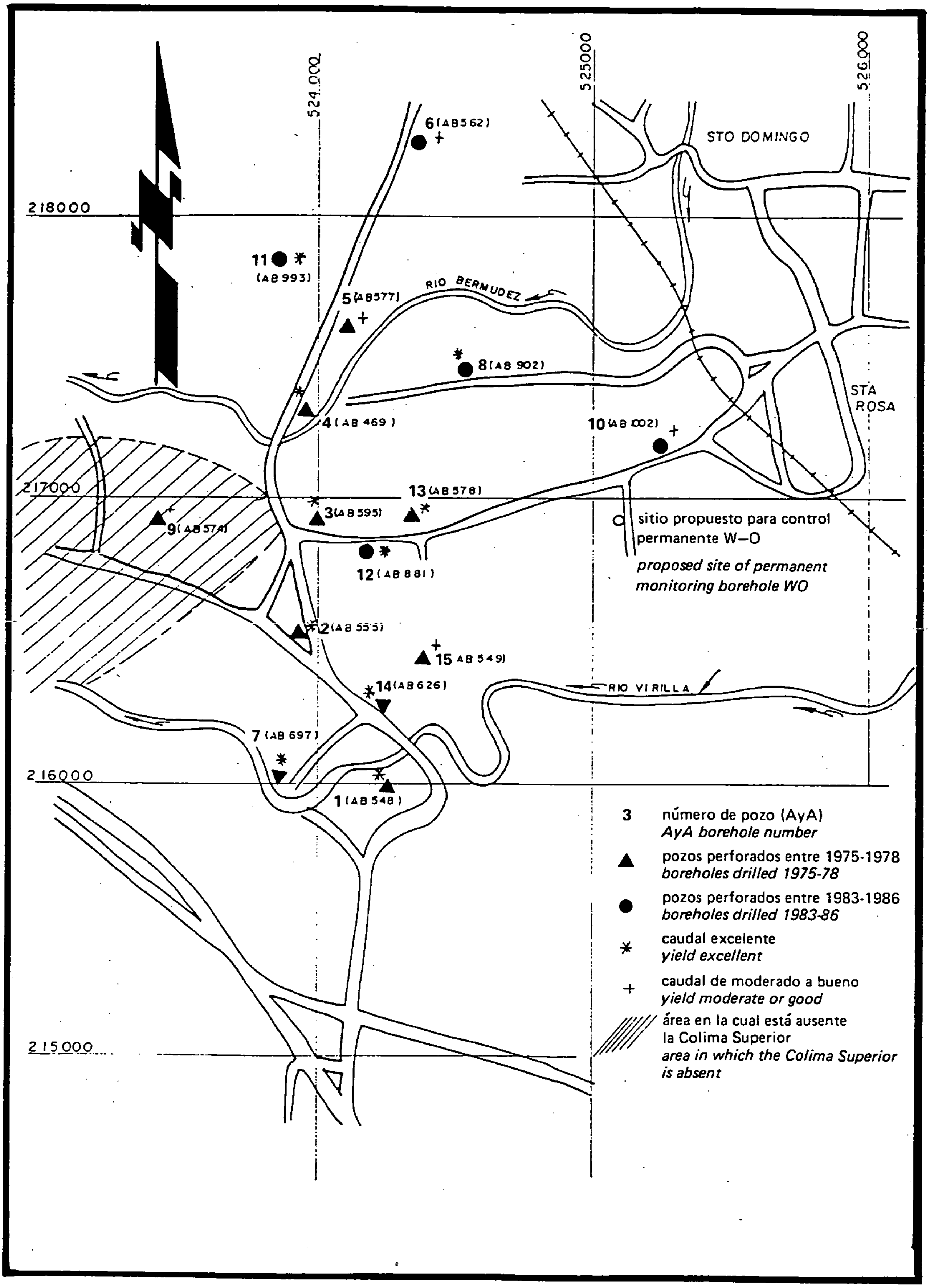


Fig 5.3 Location of boreholes in the Valencia Wellfield.

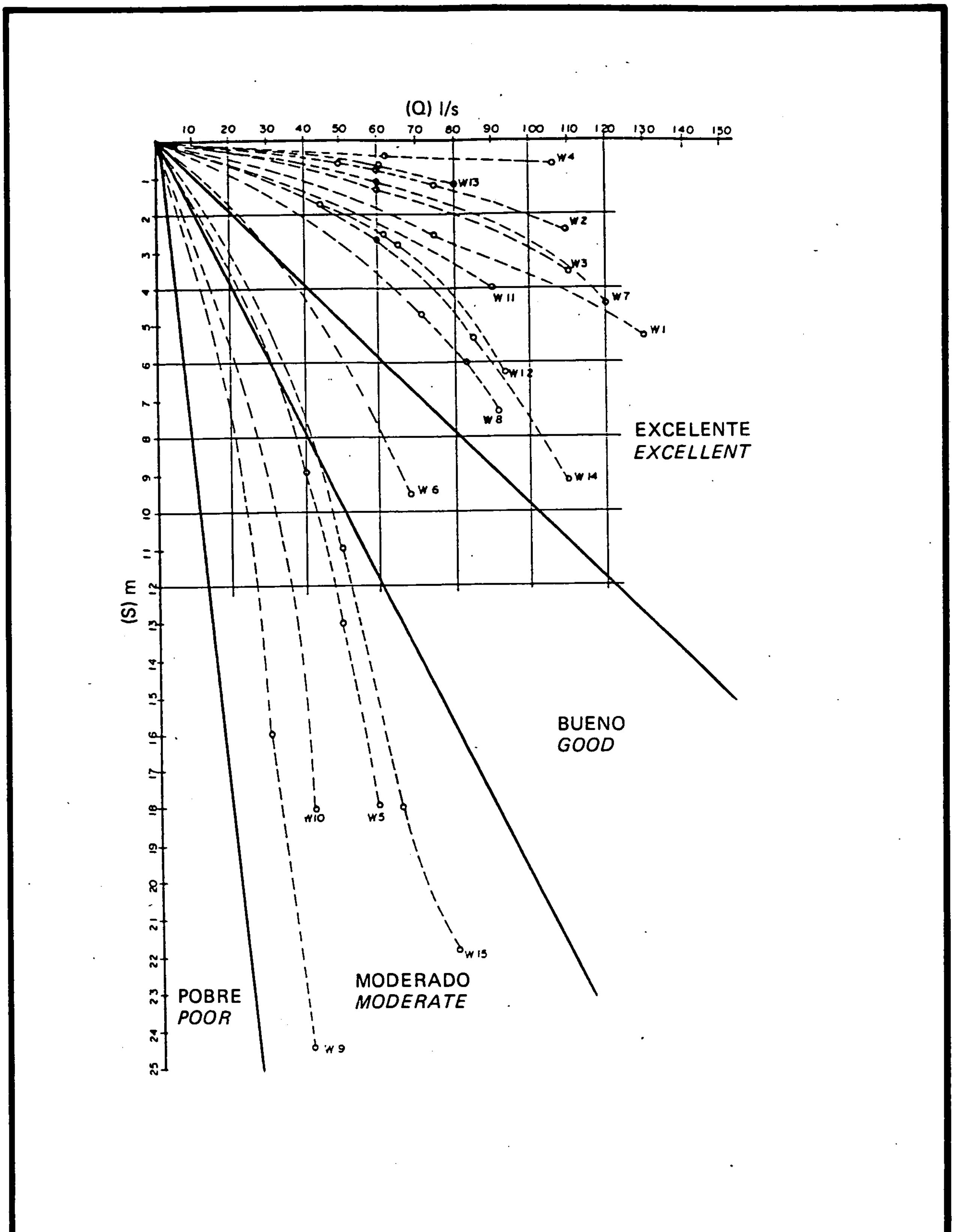


Fig 5.4 Yield-drawdown characteristics of boreholes in the Valencia Wellfield.

The poor yields of some boreholes almost certainly reflect poor well construction and the the higher values of transmissivity are more likely to represent the true aquifer characteristics. The combined additional abstraction from the new boreholes has increased the total wellfield production to the target value of 1000 l/s.

(c) Significant problems were experienced during the drilling of the new production boreholes with the result that, in most cases, only a poor lithological record was obtained. Figure 5.5 summarises the lithology of all the production boreholes in the Valencia Wellfield. It demonstrates very clearly the considerable spatial variability characteristic of volcanic geology.

(d) It is not possible to establish a clear relationship between aquifer lithology and borehole yield, particularly since variable borehole design and construction also affects yield - drawdown characteristics. The borehole flow logging (see section 3.4.2) illustrated that the hydraulic regime of the aquifers is also very complicated. The available data suggests that a significant proportion of the borehole yield in the wellfield, probably greater that 50%, is from the Colima Inferior.

(e) Groundwater levels in the wellfield have once again been generally falling since 1983 and the rate of decline increased in 1986/7. Part of this trend reflects low rainfall in 1985 and 1986 and may also reflect the increased abstraction in the northern part of the wellfield where most of the observation boreholes are located. Since the saturated thickness of the Colima Superior is only small (<20 m) in many of the boreholes (Fig 5.5) there is the possibility that this aquifer will become seriously dewatered if groundwater levels continue to fall. The inevitable consequence would be a major reduction in well yields. It is thus extremely important that the water level in the wellfield is closely monitored. An independent measurement in an observation borehole not directly influenced by the pumping regime of an individual borehole is therefore strongly recommended. Such an independent monitoring borehole (W0 on Fig 5.3) should be drilled in the wellfield and equipped with a continuous water level recorder.

(f) The current fall in groundwater levels in the vicinity of the Valencia Wellfield suggests that there is limited scope for expansion. The area to the north-west of the wellfield is considered to be the only possible location for additional boreholes. In most other directions, expansion is not possible. To avoid reduction of flow to the existing boreholes, new boreholes should not be located immediately to the north-east of the wellfield which is the direction from which the groundwater is flowing (Fig 5.1). Expansion of the wellfield to the south or south-east is restricted by the Virilla Canyon and the risk of dewatering the La Libertad springs, and expansion to the south-west is unlikely to produce good yields since it is downstream of the present abstractions and the Colima Superior is locally absent.

(g) The yield-drawdown characteristics of the production borehole W11 (Figs 5.3 & 5.4) are very good. This might indicate good groundwater flows to the north-west of the wellfield in the area between the Rio

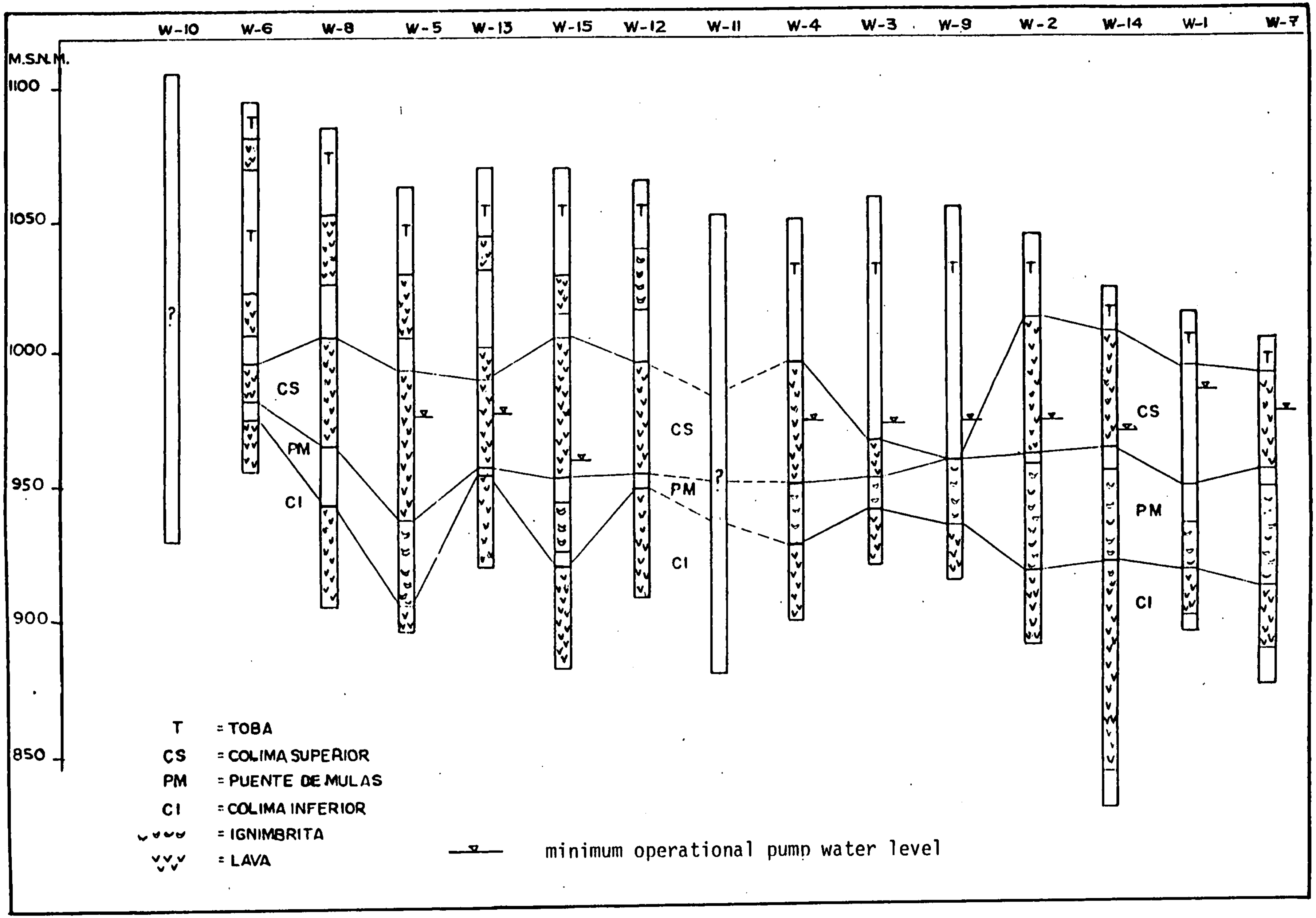


Fig 5.5 Geological correlation and minimum operational water level of boreholes in the Valencia Wellfield.

Pirro and the Quebrada Gertrudis. The hydrogeological conditions in this area are illustrated by the segment between CP-2N and W4 on the geological section in Figure 2.4. The water levels of the Colima Superior and Inferior aquifers are very similar (70-80 mbs). The depth to water increases greatly where the Barba lava is overlying, as in borehole CP-2N, and this creates drilling difficulties as well as high pumping costs. The possible expansion of the wellfield is therefore restricted to the area south of the Barba limit.

(h) A wellfield of six boreholes pumping at 50 l/s in this area was simulated using the mathematical model (see 6.7.1).

5.1.2. Campo de Pozos : Animas Area

(a) Hydrogeological interpretation of the Campo de Pozos study area revealed another area, outside the Valencia Wellfield, with potential for further groundwater abstraction. The area is that lying between Barreal and the Rio Virilla (Fig 5.1). Along this stretch of the Rio Virilla, south of Collegio Castella, natural springs, known as the Las Animas springs, discharge to the river at a rate of approximately 100 l/s. There is also a substantial quantity of discharge directly to the river bed (Fig 3.1). A resource evaluation of the Colima aquifers in this locality was undertaken to establish the origin of the springflow (thought to be from the Colima Superior) and to investigate the feasibility of a small wellfield to tap the groundwater flow to the natural discharge points of the Colima Superior and possibly also the deeper Colima Inferior water.

(b) An investigation borehole CP-1N was drilled close to the Animas spring (Fig 1.5). The geological cross section, Figure 2.3, shows that the area has the advantages that:-

(i) it is south of the Barba limit,

(ii) the water levels of the Colima Superior and Colima Inferior are similar and only 70-80 m below surface,

(iii) it is close to a point of natural unutilised groundwater discharge, and

(iv) it is not near to any other major abstraction.

(c) On the basis of this preliminary assessment of the area, a trial production borehole, CP-P1 was drilled close to the investigation borehole (Fig 1.5). The borehole was pump tested when the base of the Colima Superior was reached at 90 m (water level 76 m), with very poor results suggesting that in this location, the transmissivity of the aquifer is low or the distribution of permeability is unfavourable which produces a small available drawdown.

(d) A second test when the borehole was at a depth of 130 m having penetrated 20 m of the Colima Inferior aquifer, produced more favorable results. Drawdown was experienced in the first minute of the test and was thereafter minimal and no effect measured in the observation borehole at 140 m distance. A reliable calculation of a transmissivity value is therefore not possible but a value of

400 m^2/d was derived from the drawdown in the pumped borehole. Unfortunately the maximum pumping rate in this test did not exceed 20 l/s due to operational limitations.

(e) An assessment of these results does, however, suggest that better yields could probably be obtained from the Colima Inferior in this area without excessive drawdown, particulary if boreholes were drilled deeper to penetrate a greater depth of the aquifer. It is anticipated that the yield-drawdown of the wells would be comparable with the moderate case in the Valencia Wellfield (Fig 5.4) and better yields would be obtained if the Colima Superior was productive in some of the boreholes.

(f) The model was used to simulate a wellfield of 500 l/s in the area (see 6.7.2).

5.1.3 Puente de Mulas : Pitahaya area

(a) A cored investigation borehole, PM-3N, was located in this area because only very limited information existed about lithology and ground water levels. The new information gained from this borehole (Figs 3.3 & 3.5) shows that the Colima Superior is unconfined with a saturated thickness of more than 30 m and the Colima Inferior is confined with a similar water level. This water level is less than 100 m below the surface whilst the overlying Barba aquifer is dry.

(b) This combination of hydrogeological conditions is potentially favorable for groundwater development but such conditions probably do not extend over a large area. Further north and east of borehole PM-3N, the Colima Inferior water level becomes deeper. To the south and west the likelihood of interference with the Puente de Mulas springs and numerous small existing groundwater abstractions increases.

(c) One of the project's trial production boreholes was scheduled for the Pitahaya area to prove the Colima resources but ESPH subsequently decided to drill in the same area. Arrangements were made for the data from this latter borehole to be made available to the project to economise on the project drilling programme. The borehole is referred to as PM-P2 in Table 5.1.

(d) A step drawdown and constant discharge test were carried out in borehole PM-P2 using the investigation borehole (PM-3N) for observation. The data are difficult to interpret but the transmissivity derived from the drawdown in the Colima Inferior piezometer in the observation borehole (which is downstream of the pumping borehole) is less than 1000 m^2/d. This value is considered to be an underestimate because the borehole construction is such that part of the Colima Superior is lined out and the remainder completed with a screen of limited open area. This probably explains why no response was registered in the Colima Superior piezometer in the observation borehole.

(e) The yield-drawdown characteristics of the borehole are encouraging, comparable with the moderate/good boreholes in the Valencia Wellfield (Fig 5.4). Improved yields could probably be achieved with better borehole construction and perhaps also deeper boreholes that penetrate a greater depth of aquifer.

(f) A wellfield of ten boreholes pumping at 50 l/s in this area was simulated using the mathematical model (see 6.7.2).

5.1.4 Puente de Mulas : Potrerillos Area

(a) Investigation boreholes PM-1N, PM-2N and PM-4N (Figs 1.5 & 3.5) drilled in this area have helped to clarify the relationship between the two Colima aquifers. This relationship is a key factor affecting the efficient development of additional groundwater supplies from the Puente de Mulas region but is very complex.

(b) From the interpretation of the available data, it appears that the Colima Superior lava thins out to the west of the Puente de Mulas and Guachipelin springs which represent the terminal discharge of the aquifer. Some water by-passes these springs (Fig 3.4a) but is presumed to be lost by leakage to the Colima Inferior. The Colima Inferior, which is present throughout the area, consists of one or more lavas (Figure 3.5)

(c) In proximity to the Virilla River, groundwater discharge from the different aquifers causes considerable separation of the piezometric levels. This effect is seen in the difference in water level between the Colima Superior and Inferior in borehole PM-2N. The same effect is likely to produce a difference in piezometric level between the individual lavas of the Colima Inferior as each lava discharges progressively further downstream in the Virilla Canyon.

(d) To avoid the risk of rapid and major depletion of the Puente de Mulas springflow, no additional abstraction from the Colima Superior should be permitted for a distance of at least 2 km upstream of the springs (Fig 5.1). In theory, abstraction from the Colima Inferior in this zone should not cause interference at the Puente de Mulas springs but very careful borehole construction to seal off the Colima Superior would be reqiured. This would be difficult to achieve in practice and also there is the possibility that abstraction from the Colima Inferior would lower water levels in this aquifer sufficiently to induce additional downward leakage from the Colima Superior, thereby indirectly reducing flow to the springs.

(e) A safer option for increased groundwater development in this part of the Valle Central is therefore to exploit the Colima Inferior downstream of Puente de Mulas. The decision to capture some of the Potrerillos springs for emergency supply before completion of these investigations has, however, imposed a constraint on this alternative because of the risk of interfering with this newly developed supply.

(f) The considerable flow from the so-called Potrerillos group of springs and direct discharge from the Colima Inferior to the river bed implied from river gauging (Fig 3.1), amounts to about 2000 l/s outflow between Puente de Mulas and the Plant Electrica Belen. This flow almost certainly derives from more than one lava flow within the Colima Inferior. Only 10-15% of this flow has been captured by the recent engineering at Potrerillos.

(g) A trial production borehole was sunk in proximity to the investigation borehole PM-1N but drilling had to be terminated before the borehole had reached the desired depth such that it penetrated only 12 m of saturated Colima Inferior aquifer. The pumping test carried out in the borehole was inadequate and no useful data were obtained. It is recommended that the borehole is deepened by 20 m and properly tested. A favorable result is not, however, anticipated because it is now thought likely that, at this proximity to the river, the water levels of the individual lavas will be separated making groundwater capture by boreholes inefficient.

(h) In theory, greater success might be achieved by locating boreholes away from the discharge area where there is less likelihood of multiple water levels in the Colima Inferior and where the risk of depleting the Potrerillos springflow is reduced. To test this hypothesis, the model was used to simulate the behaviour of a wellfield abstracting from the Colima Inferior in the area immediately south of the Juan Santamaria airport (see 6.7.3).

5.1.5 Zona Barba : San Joaquin

(a) A cored investigation borehole ZB-2N, was drilled in this location (Figs 1.5, 2.4 & 5.6) to determine the relationship between the Barba and Colima aquifers. The results reveal some potential for development of the Barba aquifer but also suggest the possibility of developing Colima groundwater in the area.

(b) The Colima Superior is apparently confined at this location and the Colima Inferior water level is substantially deeper, at 138 mbs. The difference between this relationship and that present in borehole PM-3N is illustrated on the section in Fig 3.3. Although the potential for obtaining water from the Colima Superior obviously diminishes as the aquifer thins to the north, the Colima Inferior water level does not deepen northwards as rapidly as it does further east (Fig 5.1).

(c) Boreholes of 200 m depth could theoretically produce useful groundwater supplies from the Colima Inferior in this area between San Joaquin and San Juan Arriba, if the drawdown was not excessive. The absence of the Colima Superior would reduce borehole yield to at least half that of boreholes in the Valencia Wellfield and a total wellfield design of no more than 300 l/s should be contemplated. The area is not, however, a good prospect for a new wellfield if compared to the other options discussed above. A trial production borehole would be required to prove the aquifer potential if development of the Colima Inferior was considered for local supply.

5.2 Barba Aquifer

(a) To evaluate the groundwater resources of the Barba aquifer was not part of the original terms of reference but the Zona Barba was defined during the course of the project when it became apparent that the relationship between the Barba and Colima Superior aquifers could be important. Investigation boreholes drilled to provide information about this relationship have also provided some information relevant to understanding the Barba groundwater resource potential.

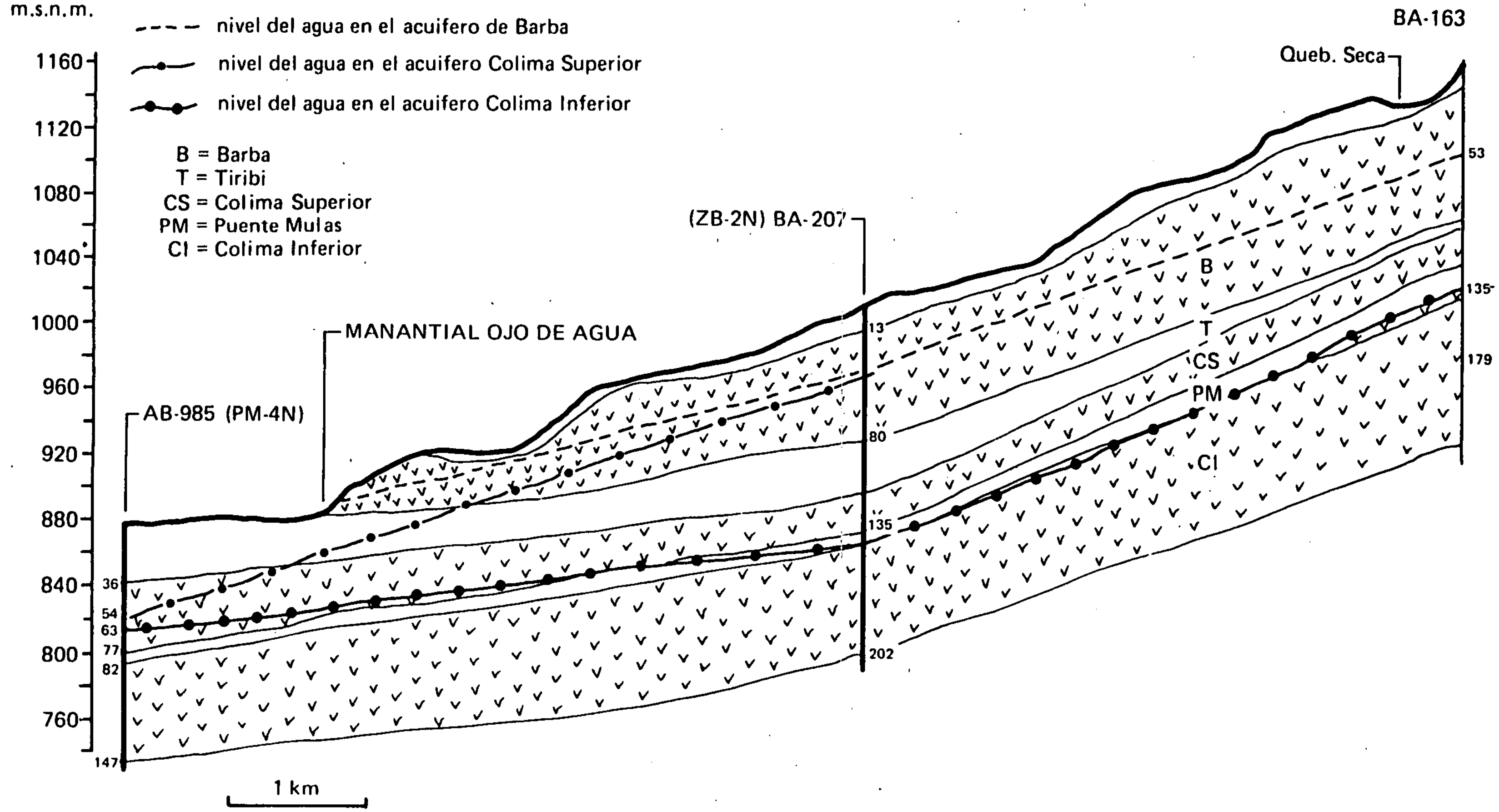


Fig 5.6 Geological section illustrating the relationship between water levels in the Barba and Colima aquifers.

(b) The groundwater level contours for the Barba aquifer have been revised using the new information (Fig. 3.2). They define with greater accuracy than before, the extent of the area in which the Barba aquifer is permanently dry. It has also shown that, in most parts of the aquifer, the seasonal fluctuations are large and that the available drawdowns are very limited. The presence of a channel structure running north-west to south-east in the area of San Joaquin, revealed in borehole ZB-2N (Fig 3.3) is an important feature since it is associated with an above average saturated thickness (about 40 m) in the Barba aquifer. The greater the saturated thickness, the greater the prospect for obtaining respectable borehole yields from this aquifer.

(c) The possibility of obtaining small scale groundwater supplies from boreholes in the Barba in this area (Fig. 5.1) was sufficiently attractive to warrant siting one of the trial production boreholes here (Table 5.1). Test pumping of this 80 m borehole, located close to the investigation borehole ZB-2N, produced moderate drawdown indicative of a high transmissivity aquifer, followed by a sudden rapid fall in water levels. The reasons for the sudden increase in drawdown are not known but it is likely to be due to dewatering of a high permeability layer within the lava. This result, although not conclusive, suggests that the aquifer is unlikely to sustain significant abstraction in this area. It might, however, be usefully exploited for small scale supply of perhaps 100 l/s produced from several shallow wells.

(d) Any development of the Barba aquifer would need to be viewed very carefully in relation to the existing captured spring sources, notably at Ojo de Agua. To some extent also, it may be necessary to consider the possible effect on the Colima Superior which receives an important component of its recharge from the Barba. In theory the effect of modest exploitation of the Barba at higher altitudes should be minimal in both respects. The aquifer would probably respond to increased abstraction by drawing more recharge from and/or reducing flow to the rivers.

5.3 Zona Este Aquifers.

(a) In the project terms of reference, a little investigated area of almost 100 km^2 (12 km x 8 km) to the north-east of San Jose between the Barba and Irazu cones was included for hydrogeological reconnaissance (Zona Este Norte).

(b) The aim was to establish whether the excellent Colima aquifers of the Valencia Wellfield (i) extended eastwards, (ii) were receiving an important component of their total recharge in this area and (iii) could be exploited to supply new urbanisations within the area, much of which was outside the command of the Tres Rios treatment plant even when its intake would be supplemented by the Orosi Project.

(c) Investigation was to be carried out primarily by the drilling of cored small-diameter boreholes, supported by surface geological and geophysical surveys and other techniques as necessary. If the results justified, the potential would be further evaluated by the drilling of a few trial production boreholes.

(d) Early in the first year of the project, an urgent need for supplementary water-supplies in the eastern and south-eastern suburbs of San Jose arose, as a consequence of exceptionally low dry-season riverflows at Tres Rios.

(e) It was decided to expand the project terms of reference to include evaluation of the groundwater potential in a further area of about 100 km^2, to be designated as Eastern Zone-South (Zona Este Sud) (Fig 1.3). In view of the urgency to generate additional supplies close to existing trunk mains and storage tanks of the distribution, it was further decided to proceed directly with a speculative programme of production borehole drilling without prior hydrogeological investigation, but to use this programme for the systematic collection of hydrogeological data so as to allow subsequently an evaluation of the groundwater resources of the area.

(f) The results of these two essentially independent investigations will be presented and analysed separately, but the relation between the two areas will be discussed subsequently.

5.3.1 Zona Este Norte

(a) Three cored boreholes (ZE-1N, ZE-2N and ZE-3N in Fig 5.7 and Table 1.3) were drilled during the second and third years of the project in this zone. The boreholes confirm broad hydraulic continuity with the Valencia Wellfield area. Although the detailed interpretation is open to some question the most likely correlation has (i) the La Libertad aquifer extending eastwards over most of the area (Fig 5.8), (ii) the Colima Superior wedging out with the Colima Inferior coming to underlie directly the La Libertad aquifer. Such explanation is consistent with the available facts and greatly aids the interpretation of the isotopic composition of the Colima Inferior in the Valencia Wellfield.

(b) Hydrogeological correlation between the new boreholes (Fig 5.9) suggest that: (i) the shallower La Libertad aquifer is likely to receive major recharge directly from the beds of the Tibas and Upper Virilla rivers, each over lengths of 6-8 km, (ii) this aquifer is in relatively free hydraulic communication with the underlying Colima Inferior by downward leakage through intervening tuffaceous deposits.

(c) Thus the hypothesis of major groundwater recharge in this area formulated during the previous modelling of the Colima aquifers, and corroborated by subsequent differential riverflow gauging, is strongly corroborated by the results of the present investigations. It remains very difficult to quantify this recharge by direct measurement or by calculation, but it is likely to be considerably in excess of 1000 l/s.

(d) These tracts of the Tibas and Upper Virilla rivers also become areas in which the La Libertad and Colima Inferior aquifers are relatively vulnerable to pollution. It is thus important to water-supply interests that the current high quality of these rivers in this area is conserved.

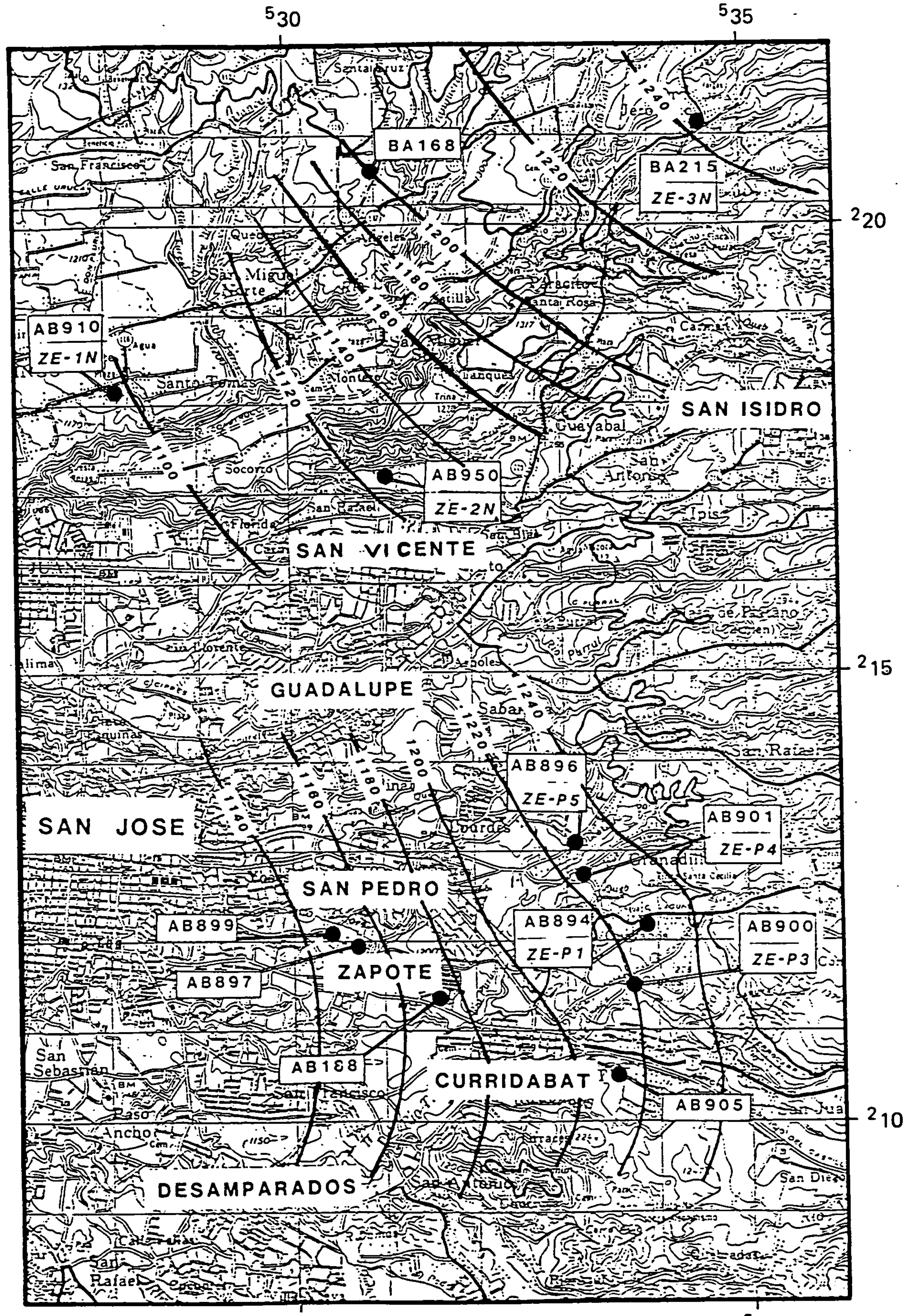


Fig 5.7 Location of boreholes and groundwater level contours in the Zona Este of the Valle Central.

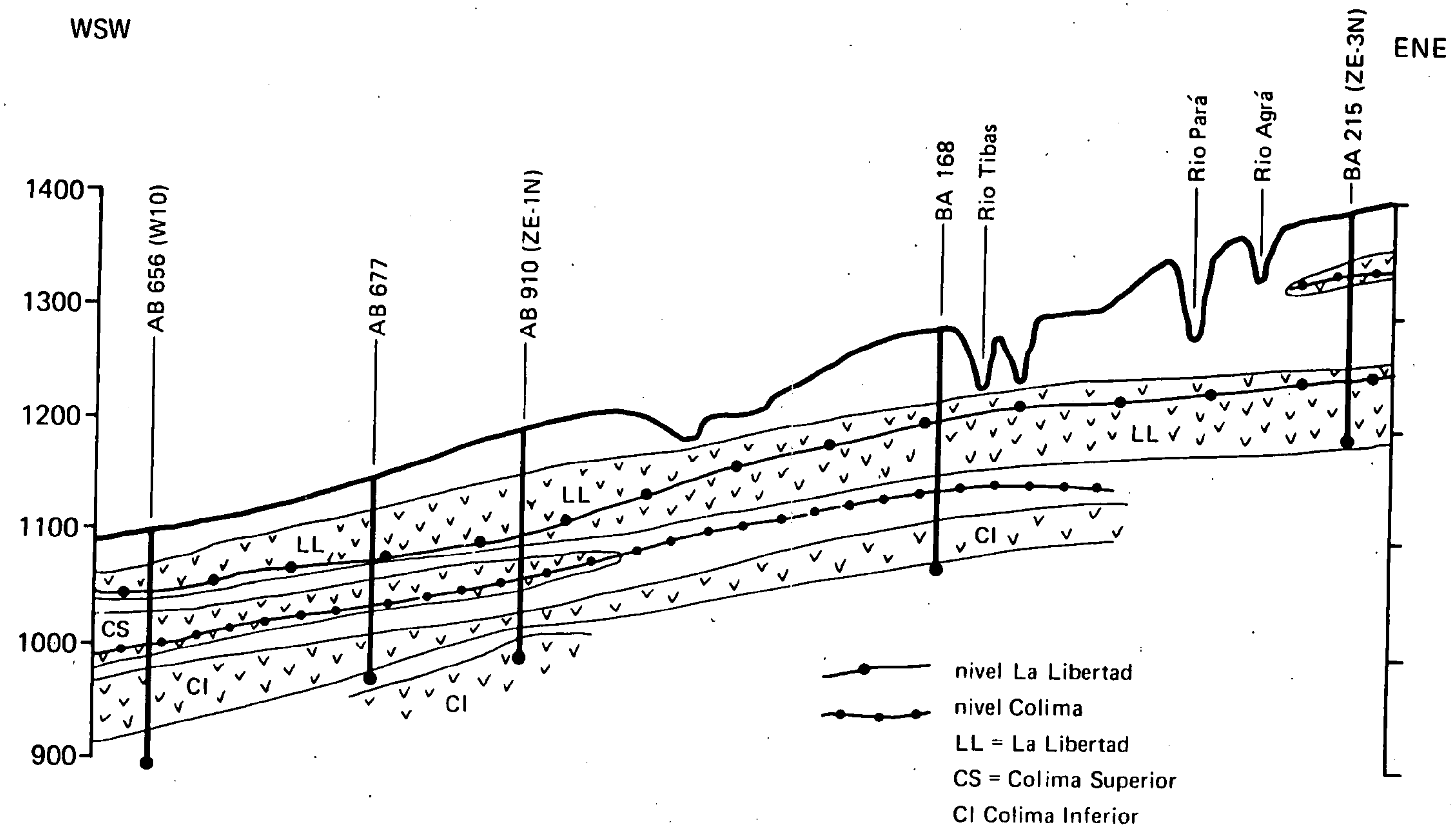


Fig 5.8 Geological section illustrating the Colima aquifers east of the Valencia Wellfield.

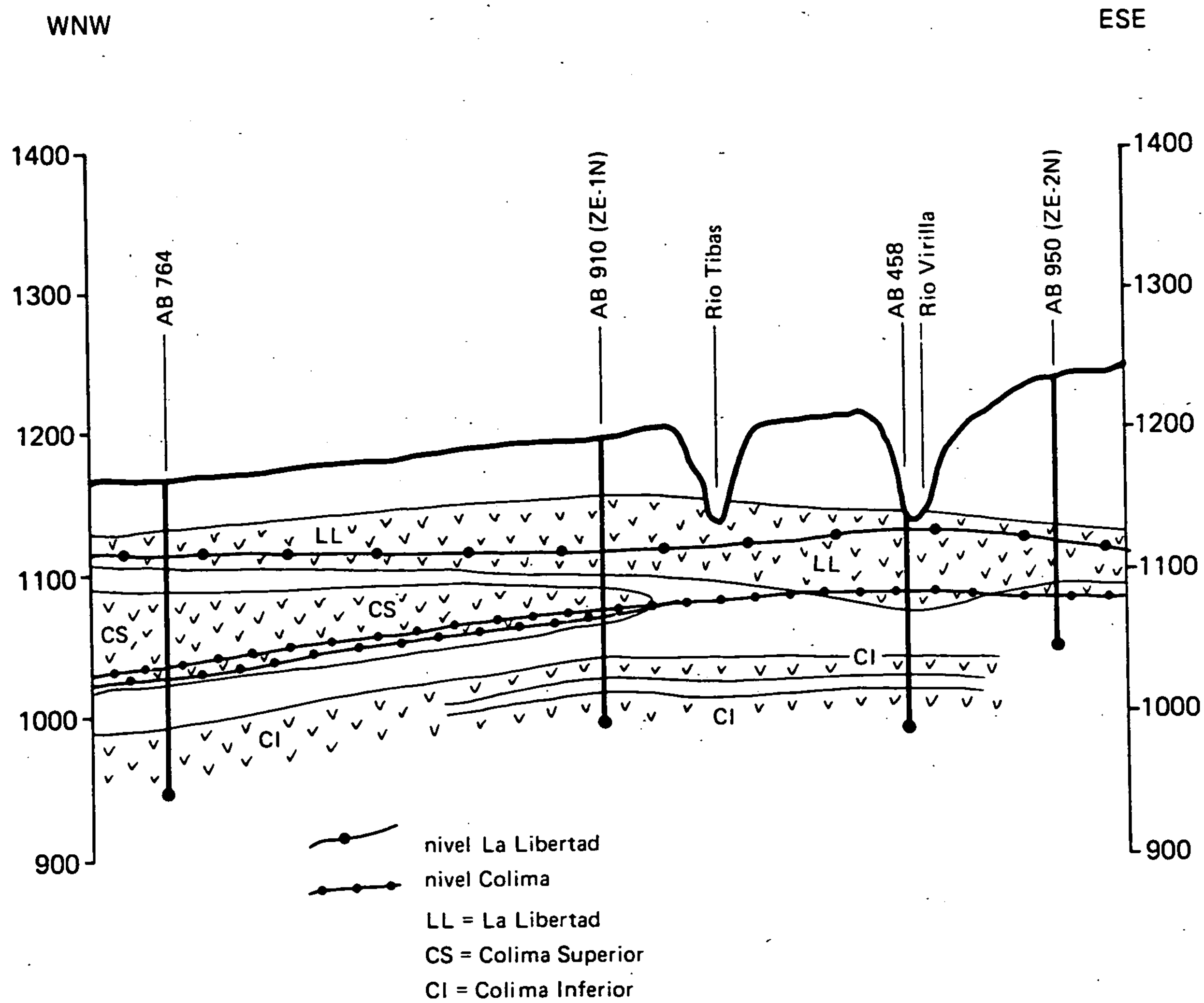


Fig 5.9 Geological section across the Zona Este Norte illustrating the relationship between rivers and aquifers.

(e) The zone remains, however, relatively unfavourable for large-scale groundwater development for delivery to external demand centres. This is a consequence of the excessive depth to the groundwater table (100-150 m) and the fact that production boreholes would need to be drilled to 180-250 m depth to intersect both the La Libertad and Colima Inferior aquifers. Nevertheless, the La Libertad aquifer should be capable of yielding useful on-site supplies for small-scale urban and industrial developments in the area, given drilling depths of up to 200 m and pumping lifts of up to 150 m.

5.3.2 Zona Este Sud

(a) During the first and second years of the project, a total of seven speculative production boreholes were drilled and tested in this zone under the emergency plan, and an eighth existing borehole was rehabilitated (Table 5.3).

(b) Six of these boreholes were sufficiently successful to merit commissioning, given the short-term, dry-season, water-supply deficit of the area. They have been empirically estimated to have a combined 100-day yield in excess of 100 l/s with individual yields in the range 10-35 l/s for drawdowns of 10-40 m with static groundwater levels of up to 25 m depth.

(c) The most successful boreholes are those that appear to penetrate alluvial sediments (mainly gravels) derived from the underlying volcanic lavas and beneath the ubiquitous lahar (mudflow) cover in the Zapote-Curridabat basin (Figs 5.10 & 5.11).

(d) However, the alluvio-volcanic history of the area results in very complex and generally unfavourable hydrogeological conditions, as borne out by the results of the pumping tests on the eight project boreholes (Fig 5.10). This graph should be read in conjunction with the corresponding data for the Valencia Wellfield (Fig 5.4), where the same yield categories are used although the scale of presentation is different. Only one borehole (AB 188) is superior in short-term characteristic to the most inferior of the production boreholes drilled in the latter area (W9), and even then its performance is only moderate.

(e) Moreover transmissivities of the alluvio-volcanic aquifer are mainly in the low range of 20-60 m^2/d (Table 5.3), and the hydrogeological conditions are prone to abrupt lateral variation which presents problems in the siting, design and construction of production boreholes.

(f) It is thus recommended that the groundwater resources of this area should continue to be developed on a speculative piecemeal basis to supply the needs of local industry and small urbanisations beyond the command of the ICAyA distribution system or possibly, as an alternative retained by ICAyA as a small (developed) standby resource in the event of failure of the surface water-supply system due to severe drought or other emergency.

(g) In any event, the groundwater resourcs of the area are relatively limited, even in the most favourable sector, the Zapote-Curridabat basin. They are made up of two components:

Table 5.3 Summary of boreholes drilled in the Zona Este.

BOREHOLE NO.	AB894[a] Guayabos (ZE-P1)	AB896 Cedros (ZE-P5)	AB897 Don Bosco —.—	AB899[a] Zapote —.—	AB900 Galera (ZE-P3)	AB901 Dianä (ZE-P4)	AB905 Lomas de Ayarco —.—	AB188[b] McGregor —.—
GROUND LEVEL (mASL)	1270	1260	1170	1170	1230	1230	1220	1190
DEPTH (m)	123	73	129	116	90	114	104	?
DIAMETER COMPLETED (m)	14-8	8	8	8	8	8	8	?
RANGE SCREENED (m) (generally discontinuous)	75-118	45-73	105-126	42-45+ 63-81	75-87	37-76	56-61 68-101	?
LAHAR THICKNESS (m)	56	22	72	102	30	29	17	?
AQUIFER LITHOLOGY	lavas	lavas	gravels over lavas	lavas	gravels over lavas	lavas	gravels over lavas	gravels over lavas
GROUNDWATER STRIKE (m)	27	6	72	?	?	10	40	?
GW LEVELS PERCHED (m)	27	6	-	-	-	-	-	?
TEST GW LEVEL (m)	42	21	23	25	2	6	13	26
PUMPING TEST RATE (1/s)	6	15	30	5	10	12	20	50
DRAWDOWN 1-DAY (m)	27	45	31	25	24	42	38	22
TRANSMISSIVITY (m^2/d)	20	20	80	<20	20	40	60	110
AQUIFER BOUNDARIES	-	S+ at 45 m	lateral barrier	-	S+ at 30 m	S+ at 36 m	S+ at 50 m	-
RECOMMENDED PUMPING RATE 100-DAYS (1/s)	-	10	20	-	10	10	20	35
WELL EFFICIENCY (%)	50	90	90+	?	70	?	20	?

a production borehole recommended not commissioned

b rehabilitated pre-existing production borehole

S+ major increase in drawdown below stated water level

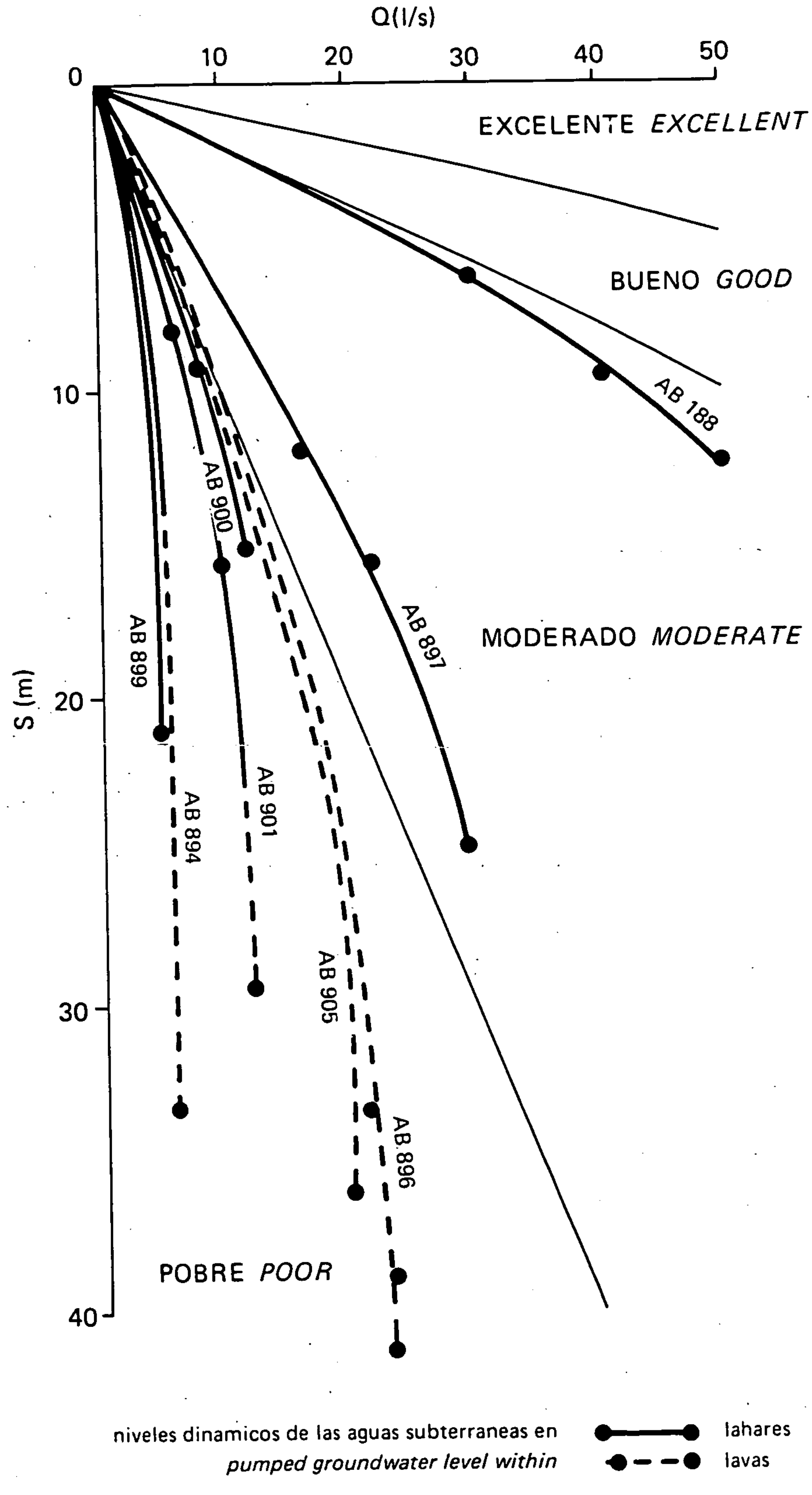


Fig 5.10 Yield-drawdown characteristics of production boreholes in the Zona Este of the Valle Central.

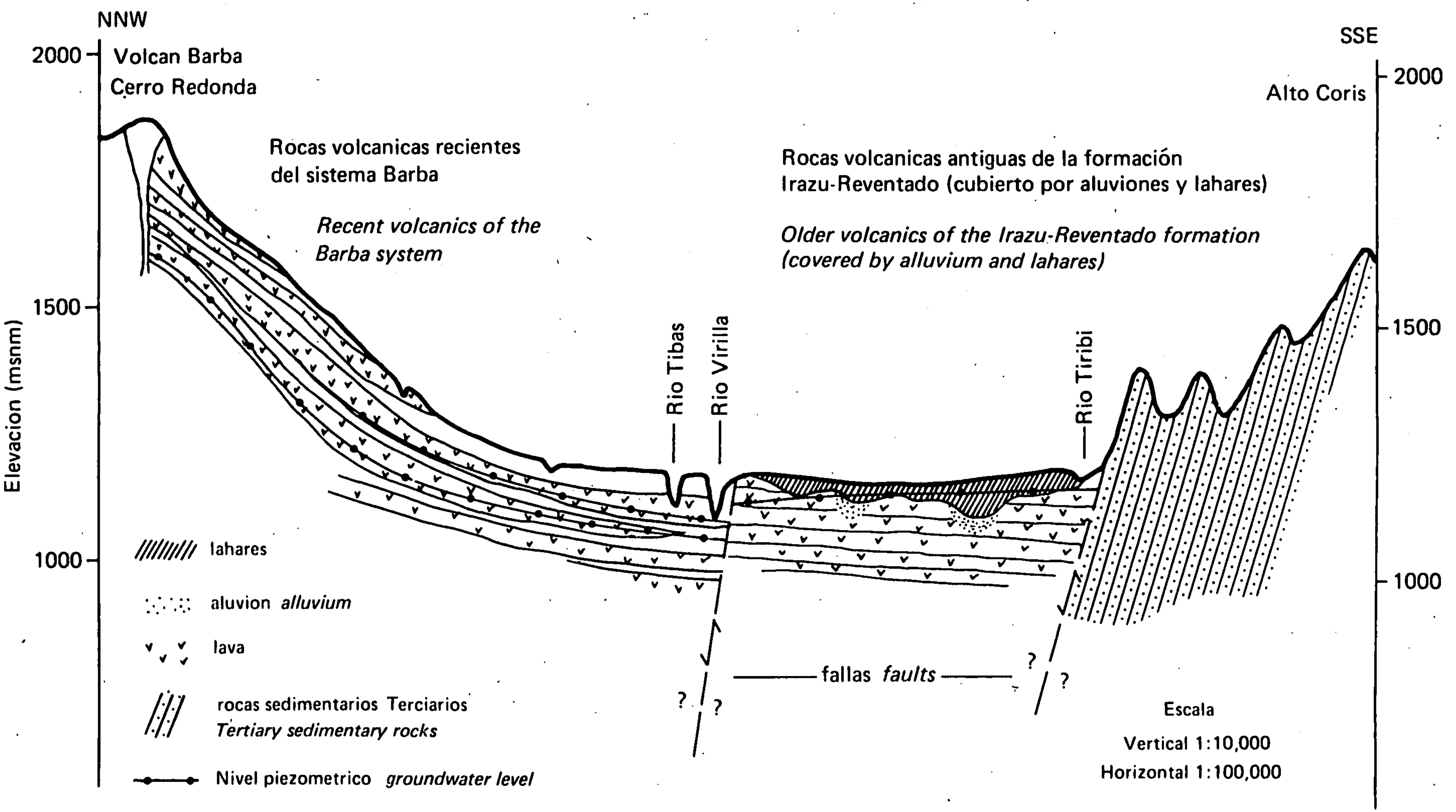


Fig 5.11 Schematic section across the Zona Este of the Valle Central.

(i) The regional inflow from the east through the alluvio-volcanic system, which is estimated, on the basis of the regional hydraulic gradient (Fig 5.7) and transmissivity values (Table 5.3), to be probably in the range 3000-5000 m^3/d (35-55 l/s).

(ii) The recharge induced from the overlying strata as a consequence of pumping, which will ultimately be derived from excess rainfall infiltrating the lahar deposits. This latter component is much more difficult to estimate and is likely to exhibit considerable spatial variation. Given the high rainfall of the area, and the heterogeneous nature of the lahar, it is considered that there is good prospect of this recharge on average exceeding 1000 $m^3/d/km^2$ (12 $l/s/km^2$), and perhaps being considerably higher than this figure.

(h) In view of the relatively limited resources, however, it would be prudent to install at least one regional observation borehole, if significant long-term groundwater abstraction with respect to the above estimates is contemplated. Analysis of the evolution of groundwater levels with increasing abstraction will be the most cost-effective way of refining the estimate of replenishable resources, given the complex hydrogeological conditions.

5.3.3 Regional Hydrogeological Setting

(a) It is of considerable interest in relation to the long-term resource evaluation and management in the Valle Central, to deliberate upon the difference between the northern and southern sectors of the Eastern Zone.

(b) The lavas of the southern sector are very inferior in hydraulic characteristics (Fig 5.10) to the north of the Virilla river. This suggests that they (if not the overlying alluvial and lahar deposits) are older, more compacted and/or of different origin and deposition, presumably part of the Reventado Formation of the Irazu volcanic suite.

(c) It is also of relevance to note the marked difference in groundwater levels in the two sectors, despite similar groundwater flow directions, there being more than 60 m difference in level between the Reventado Formation in the south and the La Libertad aquifers in the north (Fig 5.7).

(d) A possible explanation of these various independent observations is that the two sectors are separated by a major west-east geological fault zone running generally just south of the Virilla river. A possible regional structure is illustrated in schematic cross-sectional form (Fig 5.11).

(e) Various geological studies of the region have speculated upon a tectonic origin for the Valle Central. The existence of such a major fault system would explain not only the marked contrast in the hydrogeology between the northern and southern sectors of the Eastern Zone, but could also be the source of the Colima Inferior lavas, which are believed to be the product of fissure eruptions, in view of their areal extension.

6. MATHEMATICAL MODEL

6.1 Background.

(a) During a previous collaborative project between SENARA and BGS, a single layer mathematical model was developed to simulate the Colima aquifers in the Valle Central. It was planned to use an updated and extended version of this model for the present project and in addition to develop a two layer model for a smaller area around Puente de Mulas where the groundwater levels in the two Colima aquifers were known to differ significantly. As the project progressed, it became apparent that water level differences between the Colima Superior and Colima Inferior were much more widespread and the decision was therefore made to extend the two layer model to cover a much larger area of the Valle Central, similar to that of the previous single layer model.

6.2 Introduction.

(a) The model covers an area of 360 km^2 (Fig 6.1) defined geometrically by IGN co-ordinates N224, N212, E534 and E504. These boundaries were chosen so that the area included the most significant zone for groundwater flow and possible development. Additionally the boundaries were chosen so that flow across them was likely to be insignificant or could be estimated with reasonable precision from hydrological data. Within this modelled area, the model is only active where an aquifer exists.

(b) The model uses a finite difference method to formulate the water balance equation based upon a rectangular grid of cells (nodes). The dimensions of the cells vary from 250 m to 1000 m according to the location in the model. In the central region where there is most interest in the detail of the hydrogeology, the cells are square with dimensions 250 m x 250 m. In the outer regions, where there is less data available, the size of cells can be up to 1000 m x 1000 m. The total number of cells is 4712 (2356 in each of the two layers).

(c) The fact that the model has two layers and consequently more variables means that the computer program is large and requires a lot of processing time. The method of variable sized cells is used to restrict the amount of computer storage and the running time of the model, while at the same time simulating the aquifer in detail over the most important part of the area. The restriction in cell numbers enables the model to be run on an IBM PCAT computer as well as a mainframe although the running time on the PC is considerable.

(d) The model solution is based on the USGS computer program "A modular three-dimensional finite-difference groundwater flow model" by M.G. McDonald and A.W. Harbough. The program has been adapted for this particular problem and additional subroutines have been developed and incorporated. Two similar forms of the model are supplied for use with steady state and transient (non-steady state) conditions.

(e) Data may be input to the program so that for each cell there is information on the position of the aquifer layers, groundwater levels and aquifer hydraulic properties. The model calculates the water balance between adjacent cells to define groundwater flow to and from the cell in each direction. Horizontal flow is determined according to the transmissivity and the difference between the head (groundwater level) in

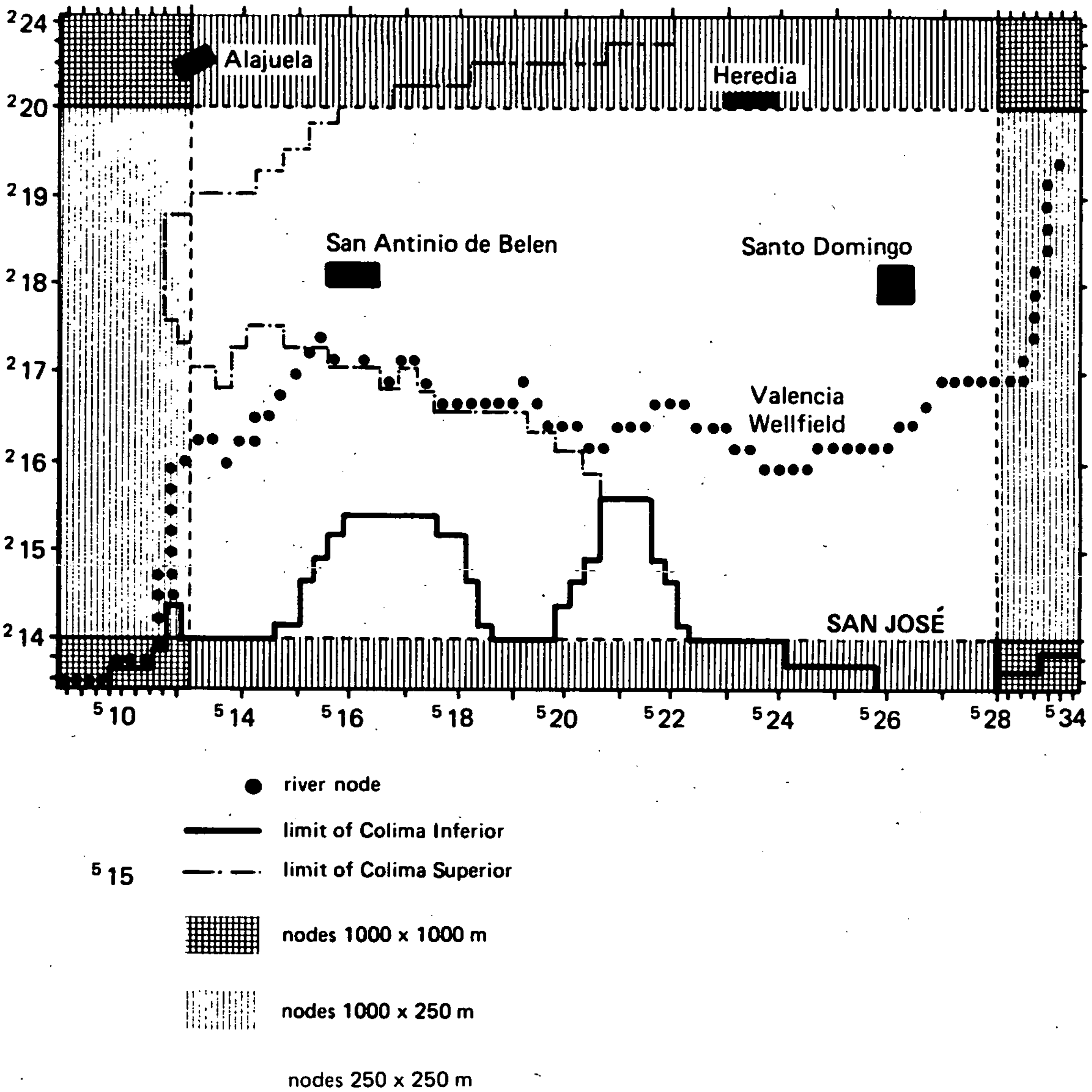


Fig 6.1 Basic structure of the mathematical model.

the cells. Vertical flow through the Puente de Mulas layer between the Colima aquifers is determined by the thickness and hydraulic conductivity of the layer and the vertical head difference across it. Movement of water to and from the river (Rio Virilla) is calculated according to the relative head in the aquifer and the level of the river and the hydraulic resistance of the river bed. Because of the complexity of the interaction between cells, it is necessary for the calculation to be undertaken many times (iteratively) until the error is very small.

6.3 **Model Parameters.**

6.3.1 Aquifer Layers

(a) The layers are defined by a value for the top and the base of the two Colima lavas expressed as altitude above sea level. The values were derived from interpretation of the available borehole data. Due to the lack of data on the base of the Colima Inferior aquifer and the fact that it probably comprises several lavas, a fixed depth of 80 m was used in the model. Data values for selected cells were read from the contour plots and input to a program which then extrapolates the data values for other cells.

6.3.2 Hydraulic Properties

(a) The model requires input data on aquifer permeability not transmissivity. Transmissivity values for each cell are computed from the product of permeability (hydraulic conductivity k) and saturated aquifer thickness. The spatial variability of permeability in the Colima aquifers is not known accurately but has been extrapolated approximately from the available field data and the calibration of the previous model.

(b) The vertical hydraulic conductivity of the Puente de Mulas layer is also required. Because field data for this parameter is very limited and the thickness of the layer is a factor controlling the amount of leakage, the permeability is specified such that the vertical conductivity divided by the thickness is a constant value (0.7×10^{-4}).

(c) Storativity may be input for each cell of the model but in this case a single approximate value is employed for each aquifer layer.

6.3.3 Groundwater Levels

(a) For a chosen set of cells, the groundwater level of each aquifer is extracted from contour plots and input to the model which extrapolates the values for remaining cells. A computer contour plot can be generated from the data in the cells and compared against the original.

6.3.4 Aquifer Recharge and Discharge

(a) The model is calibrated on the basis of a minimum annual throughflow of 5500 l/s in the combined Colima aquifer system. The groundwater recharge is input to the uppermost aquifer layer which is the Colima Superior except where it is absent in which case the recharge is input to the Colima Inferior. The total annual recharge is distributed spatially on a relative basis according to a simplification of the recharge model outlined in section 3.6. Where there is thought to be significant inflow of groundwater across the boundary of the modelled area this is simulated by extra recharge to the marginal cells.

(b) Groundwater discharge is computed by the model according to the flow in the aquifer and the relative head difference between the aquifer and the river. It has been calibrated against the approximate discharge distribution shown in Fig 3.1.

6.4 Steady State Calibration.

(a) The steady state version of the model, in which there is no significant abstraction of groundwater from the system, is used to test the hypotheses of recharge and permeability distribution in the aquifer. The pre-1973 situation is assumed to represent approximate steady state conditions in the Valle Central.

(b) The model is run iteratively for a long simulation period using the estimated transmissivity and recharge distributions until a steady state (minimal change) is achieved. The simulated groundwater levels and aquifer discharge distributions are then compared with those observed in the field. Differences between the modelled and observed steady state conditions indicate errors in the assumed permeability and recharge distributions which are then modified and further steady state simulations are carried out. After a series of such adjustments, reasonably close agreement between the model and the observed conditions is achieved and the model is considered to be calibrated in the steady state.

(c) The conductances between the river and the aquifers were adjusted to give reasonable outflows and appropriate proportioning of flows from the Colima Superior and Inferior. These adjustments were carried out in conjunction with changes to the vertical leakage between the aquifers. Increasing the vertical leakage tendedto cause the Colima Superior aquifer to dry out.

(d) The steady state output results are illustrated in the form of contoured plots in Figs 6.2a and 6.2b. It will be seen that over the major central area of both aquifer layers the agreement is good. There are some discrepancies on the fringes of the model but these are in areas where field data is poor or non-existant. The annual throughput of water on the steady state calibration which is equivalent to the recharge input and discharge output was 175 MCM/a (≃ 5550 l/s). This was made up of 95.5 MCM/a (≃ 3025 l/s) from the Colima Superior and 79.6 MCM/a (≃ 2525 l/s) from the Colima Inferior.

6.5 Non-Steady State (Transient) Calibration.

(a) The transient model uses the final water level and transmissivity values from the steady state calibration. All other parameters are the same except that the transient model requires the input of storativity values as a fixed parameter and the historical record of groundwater abstractions for each stress period (equal to 4 months).

(b) From this data the model is able to compute water levels in each aquifer for each stress period. The computed groundwater level drawdowns resulting from the abstraction are then compared against the real data which in this case is almost all for the area of the Valencia wellfield. If there is disagreement then modifications can be made, notably to the storativity values which were not tested by the steady state calibration, and the model is re-run. The transient flow model is calibrated when a

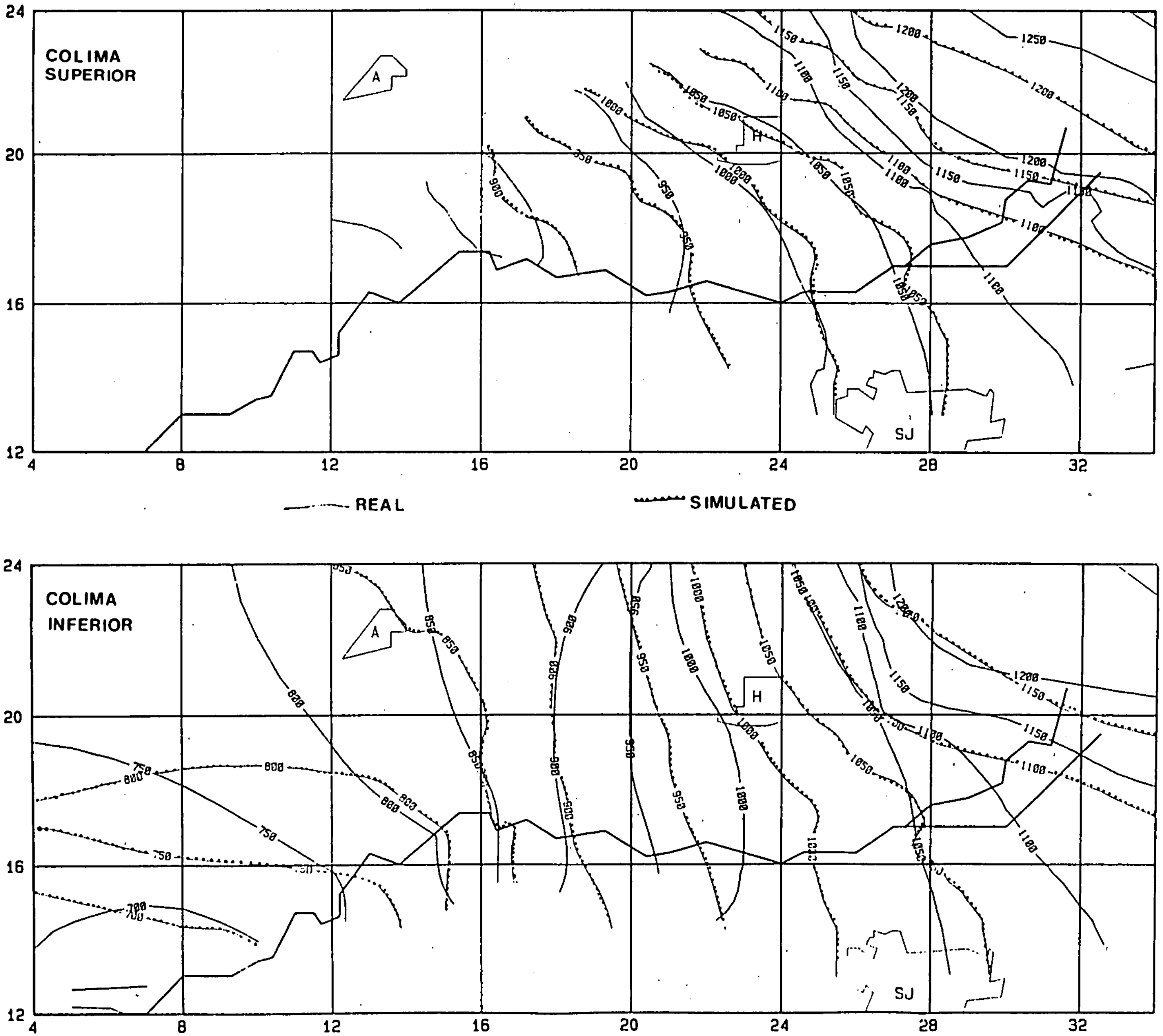


Fig 6.2 Groundwater levels for the steady state model calibration.

reasonable agreement is achieved between the observed and simulated drawdowns in the aquifers. It is not generally possible to separate the observed field drawdowns into components from the Colima Inferior and Superior. The drawdown values for each aquifer layer computed by the model are therefore averaged for comparison with observed data for boreholes which penetrate both aquifers.

(c) The initial non-steady state calibration was undertaken with a confined storage coefficient of 1.4×10^{-4} in the Colima Inferior and specific yield of 1% in both aquifers. This calibration yielded a mean drawdown of 12 m in the wellfield area after 14 years of pumping with a 50%/50% distribution between the Colima Superior and Colima Inferior. This value of drawdown was thought to be too large although good observation borehole data is not available.

(d) Attempts were made to reduce the model drawdown by increasing in turn the storage coefficients of the two aquifers. However it was found that even substantial increases in this parameters only produced marginal reductions in the drawdowns.

(e) Further attempts to improve the non-steady state calibration were made by increasing the permeability of the Colima Superior in the region of the wellfield. A slight improvement was achieved but further increase of the permeability resulted in the drying out of the aquifer where the original saturated thickness is thin. Similar attempts to increase the permeability of the Colima Inferior caused deterioration in the calibration of the steady state configuration. This same effect also occurred when the throughflow on the model was increased to 6000 l/s from 5500 l/s and when the proportion of abstraction in the Colima Superior was increased to 60%.

(f) It was therefore concluded that with the presently available data, and bearing in mind the very large number of unknown parameters, that the calibration was probably the best that could be achieved at this stage and should form the basis for the proposed wellfield simulations.

(g) The non-steady state groundwater levels for the two aquifers are illustrated in Fig. 6.3a and b and Fig. 6.4a and b show the drawdown for each layer. The distributions of hydraulic conductivity are shown in Figures 6.5a and b and the recharge distribution in Figure 6.6.

(h) Table 6.1 summarises the conditions of the final non steady state calibration in relation to the Valencia Wellfield. The total abstraction from the Colima aquifers over the whole model is 1123 l/s. The transmissivity in the area of the wellfield is 7000 m^2/d made up of 1000 m^2/d in the Colima Superior and 6000 m^2/d in the Colima Inferior and the drawdown at the location of several observation boreholes is recorded for each aquifer layer. The Colima Superior is assigned a specific yield of 10% and the Colima Inferior a value of 3%.

(i) It should be noted that in the non steady state calibration, the Colima Superior becomes dry in several cells the most notable of which are the cell containing borehole W7 at the southern end of the Valencia Wellfield and the cell that represents the Puente de Mulas spring. Since the aquifer is not dry at either of these locations in reality there are clearly some inaccuracies in the model configuration. Attempts to modify the model to prevent the aquifer becoming dry at these cells were unsuccessful. In the case of the Puente de Mulas springs the problem

(a) Colima Superior

(b) Colima Inferior

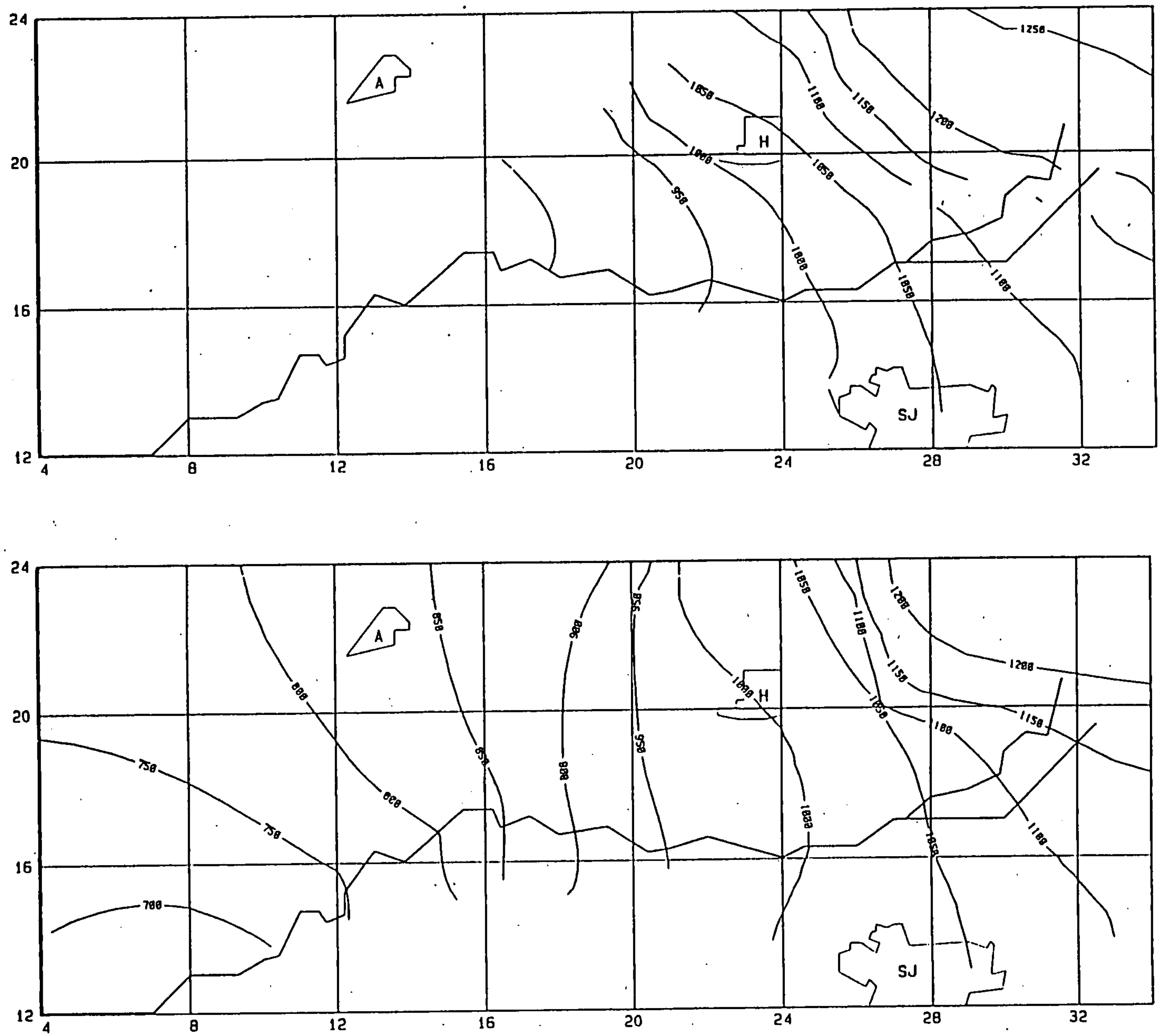
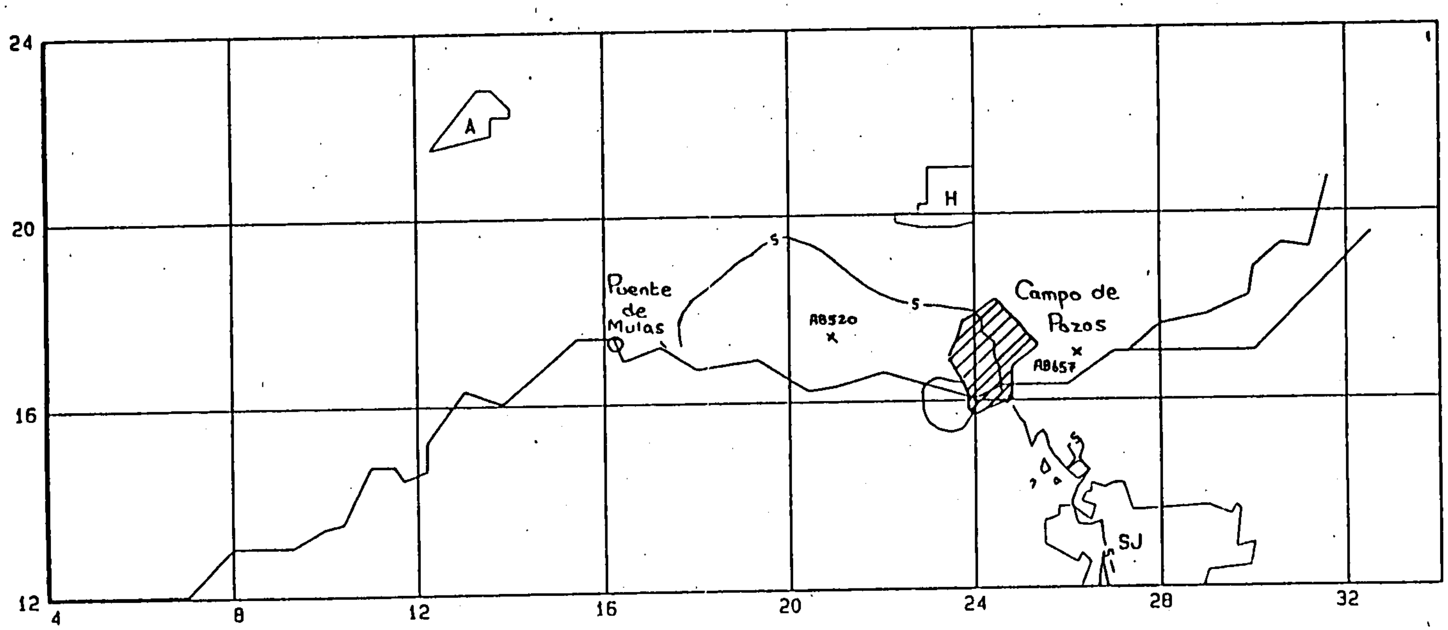


Figure 6.3 Groundwater levels for non steady state model calibration.

(a) Colima Superior



(b) Colima Inferior

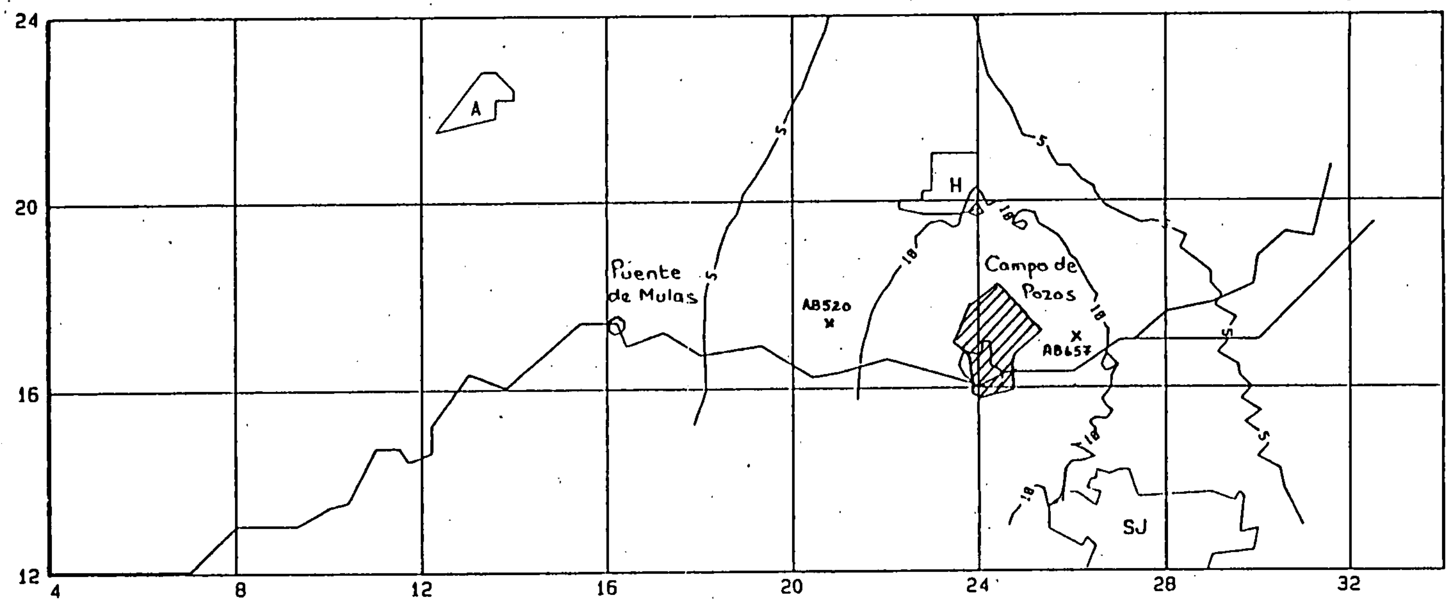


Fig. 6.4 Drawdowns for non steady state model calibration.

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Fig. 6.5(a) Transmissivity of Colima Superior for non steady state model calibration.

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TRANSMISSIVITY          FOR LAYER    2

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X= 10000.0001
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Fig. 6.5(b). Transmissivity of Colima Inferior for non steady state model calibrations.

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Fig. 6.6 Recharge distribution used for non steady state model calibration.

Table 6.1 Summary of Results from Mathematical Model.

	Non Steady State Calibration Final		Simulation 1		Simulation 2		Simulation 3		Simulation 4		Simulation 5		Simulation 6	
	CS	CI	CS	CI	CS	CI	CS	CI	CS	CI	CS	CI	CS	CI
ABSTRACTION l/s	1123		1386		1586		1586		2086		2387		1586	
PROPORTION	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
VALENCIA WELLFIELD														
W3 s(m)	10	18	2	6	2	6	2	4	2	8	4	12	0	2
AB520 s(m)	6	10	4	4	6	10	4	8	10	16	12	18	2	2
AB657 s(m)	4	14	2	4	2	4	2	4	2	6	2	10	0	2
PUENTE MULAS s(m)	4	3	2	2	4	2	4	4	7	5	8	6	2	4
APPROX. CENTRE NEW WELLFIELD s(m)	n/a		6	7	7	13	9	14	10	18	n/a		-	14

arises because the spacing between the cells of the model is too great to allow accurate representation of the very steep hydraulic gradient that occur in the aquifers. The tendency for the Colima Superior in these and adjacent cells to become dry is repeated in all the model simulations. In many of the simulations an area in the extreme north-east of the Colima Superior aquifer is also drained dry in the model. Further refinement of the model may be able to correct these discrepancies in future.

6.6 Application of the Mathematical Model.

(a) The aquifer model has been calibrated using the steady state water levels prior to exploitation of the aquifer and also the transient drawdowns over the 14 year period of development. The combination of the Colima Superior and Colima Inferior forms a very complex aquifer system with a considerable number of unknown parameters. The calibration so far achieved has been undertaken using the best available estimates of the aquifer parameters. Inevitably there is much uncertainty about some of these estimates and for this reason some care must be exercised in use of the model for predictive purposes. The present calibration of the model should be viewed as a first stage which can subsequently be developed and improved as further data on field parameters becomes available.

(b) Nevertheless, bearing in mind these reservations, it is possible to use the groundwater model for sensitivity analysis and to simulate the possible effects of proposed new wellfields. For this project the model has been used to predict the drawdowns likely to occur for a number of proposed configurations of new pumping boreholes. The resulting drawdowns, which are additional to any drawdown due to existing abstractions, are plotted as contours of 5 m interval. Table 6.1 summarises the transient simulations indicating the approximate drawdowns at specific locations.

6.7 Results of Wellfield Simulations.

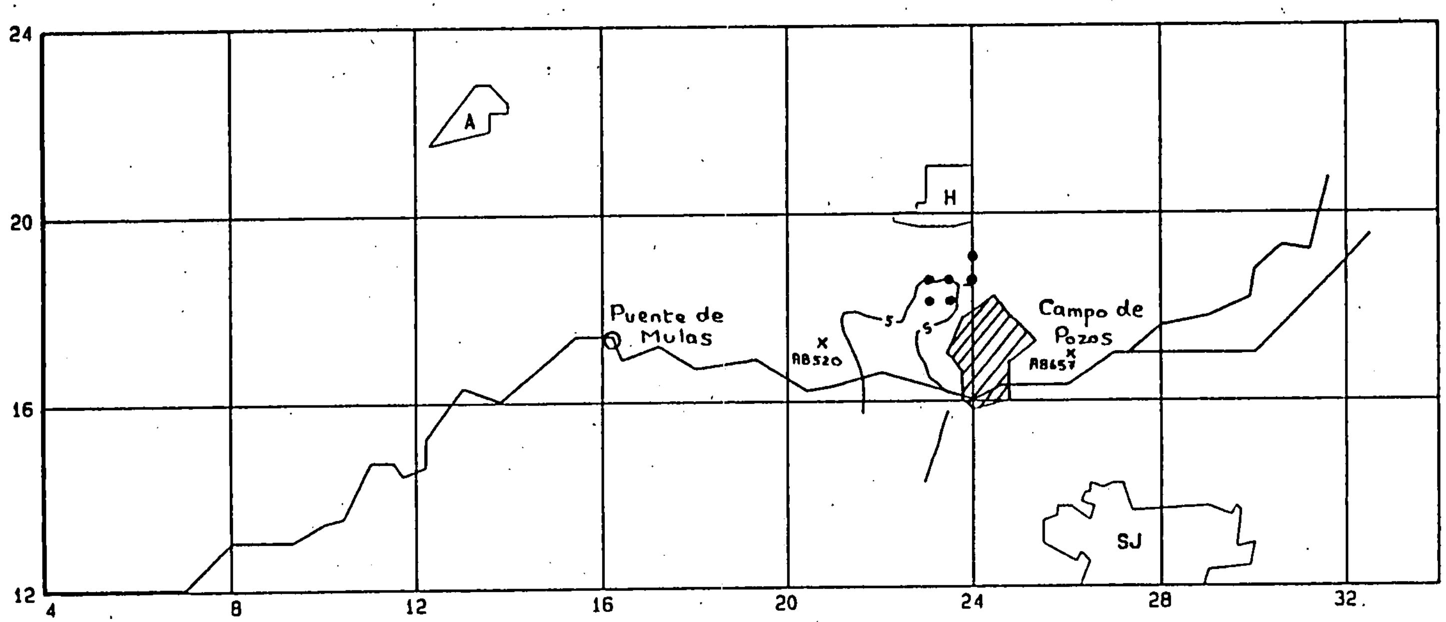
(a) From the appraisal of Colima groundwater resources in the Valle Central, several areas have been identified as potential locations for new wellfields. The mathematical model was used to prove the potential for abstraction in each different area and simulate the effect of the proposed groundwater abstraction on groundwater levels.

6.7.1 Valencia Wellfield Extension

(a) An expansion of the Valencia Wellfield was simulated in the form of six new boreholes each with an assumed yield of approximately 50 l/s, spaced 500 m apart in the area immediately north-east of the existing wellfield (Fig. 6.7). This additional 300 l/s abstraction split equally between the Colima Superior and Inferior, would bring the total yield of the Valencia wellfield to approximately 1300 l/s.

(b) The additional drawdown in each aquifer layer that occurs as a result of this simulated abstraction is illustrated in Figure 6.7a and b. In the centre of the existing wellfield it is calculated there would be an extra 4 m of drawdown (average of 2 m in the Colima Superior and 6 m in the Colima Inferior). Most of the existing boreholes could sustain this additional fall in water levels without problem but it might be necessary to lower the position of the pump in some boreholes. The reduction in the saturated thickness of the Colima Superior might also cause a slight

(a) Colima Superior



(b) Colima Inferior

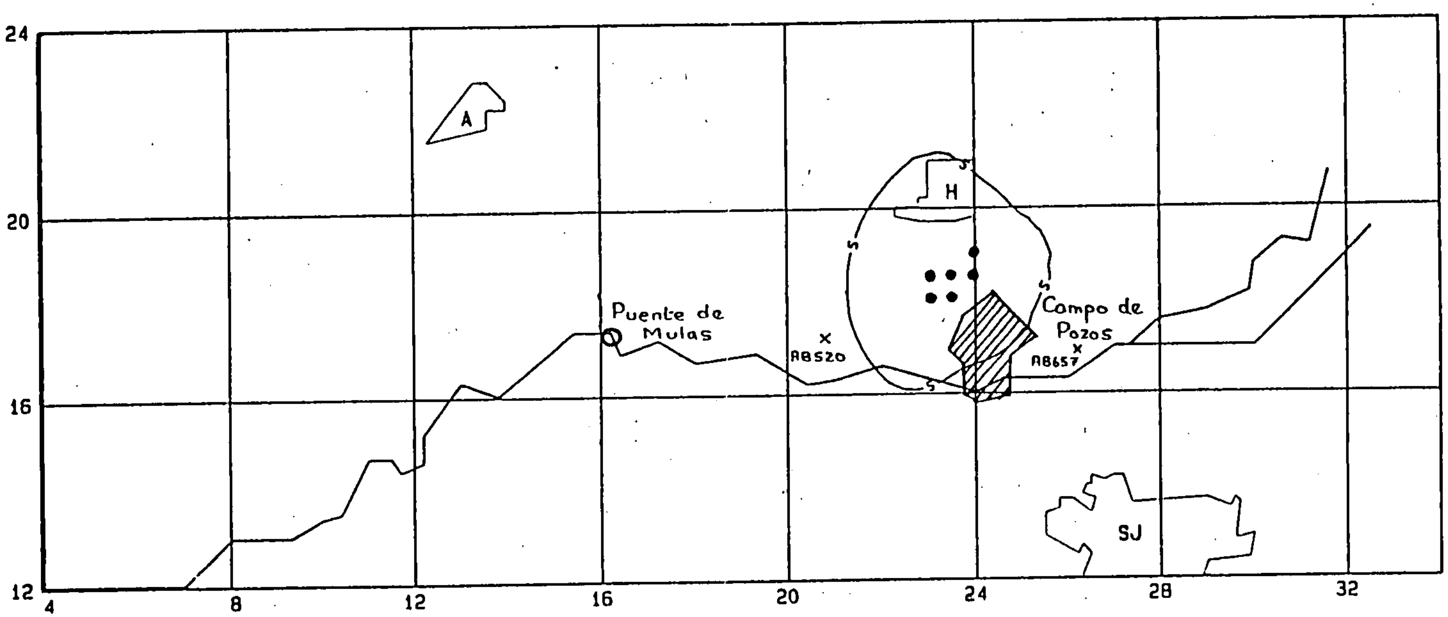


Fig. 6.7 Drawdowns for model simulation 1: Extension of Valencia Wellfield.

reduction in the yield of some boreholes if particularly productive flow horizons in the lava were dewatered. The drawdown on the new pumping boreholes is 6-7 m.

(c) According to the model, the effect of this modest additional abstraction is to increase groundwater level drawdowns over a wide area. A drawdown of 2 m in the Colima Superior would occur 7 km west and 4 km east. The spread of influence is greater in the Colima Inferior with a 2 m drawdown at approximately 6 km west and 9 km east. The net effect could be an extra 2 m of drawdown at the Puente de Mulas springs.

6.7.2 Pitahaya-Barreal Wellfield

(a) Two areas between the Valencia Wellfield and the Puente de Mulas springs have potential for development of perhaps 500 l/s of new groundwater abstraction. They are an area between the Animas spring and Barreal and an area around Pitahaya. The model was used to simulate separately a new wellfield of 500 l/s capacity in each of these two areas. Another simulation was based on a wellfield of about 1000 l/s capacity spread between the two.

(b) Figure 6.8 illustrates the location of a possible wellfield in the Barreal-Animas area consisting of 10 boreholes of 50 l/s yield located 250 m apart. The results of the model simulation are summarised in Table 6.1 and Figures 6.8a and b. The drawdown in the new wellfield is about 10 m and it produces an additional 4 m of drawdown on average in the Valencia Wellfield. The predicted drawdown in the Colima Superior is greater to the west than to the east and it is estimated the additional abstraction could cause an extra 4 m of drawdown in the Colima Superior at the Puente de Mulas springs.

(c) The saturated thickness of the Colima Superior aquifer in the region of the Puente de Mulas springs is not known with precision, but less than 10 m of the aquifer was saturated in the cored investigation borehole PM-2N which is very close to the springs. Given this uncertainty and the difficulty of obtaining accurate drawdown predictions for the Puente de Mulas area (see section 6.5) from the model, it is not possible to deduce whether or not there will be a significant reduction in flow from the Puente de Mulas springs. However, if the model is accurate it implies that a wellfield of this specification is likely to interfere with the spring flow and should consequently be developed in stages in conjunction with careful monitoring of the spring discharge.

(d) A wellfield with similar specification (10 boreholes of 50 l/s spaced 250 m apart) but located in the Pitahaya area has a broadly similar effect on grundwater levels (Table 6.1 Simulation 3, Figs. 6.9a and b). The drawdown in the wellfield itself is around 12 m and the zone of influence spreads to produce a 3 m average drawdown in the Valencia Wellfield and about 4 m drawdown in the Colima Superior at Puente de Mulas.

(e) From the model simulations therefore, both wellfields are theoretically viable and produce a similar overall aquifer response. Neither has an obvious advantage and the choice of one or the other would therefore depend on factors such as site acquistion, proximity to demand and local hydrogeological considerations.

(a) Colima Superior

(b) Colima Inferior

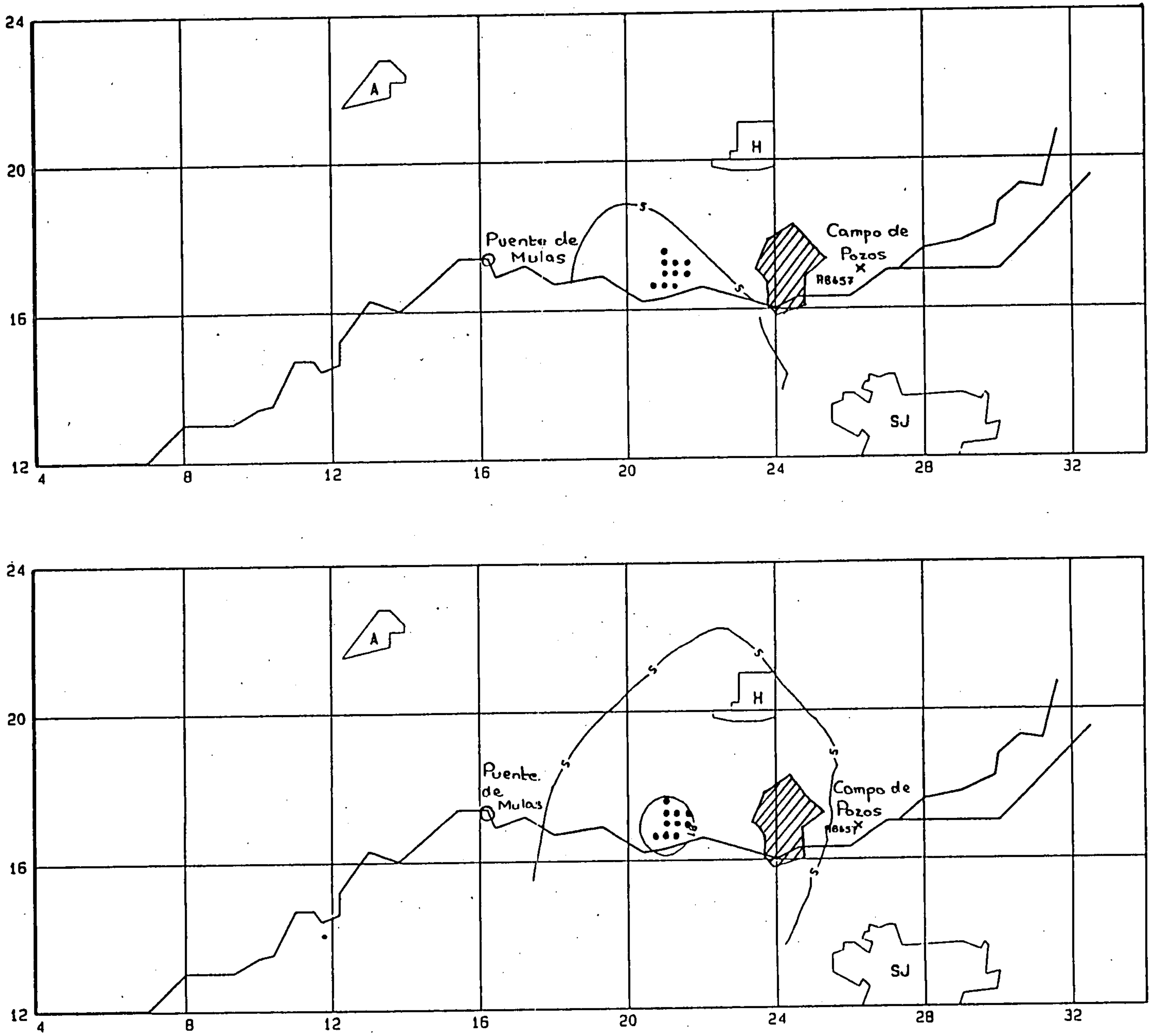
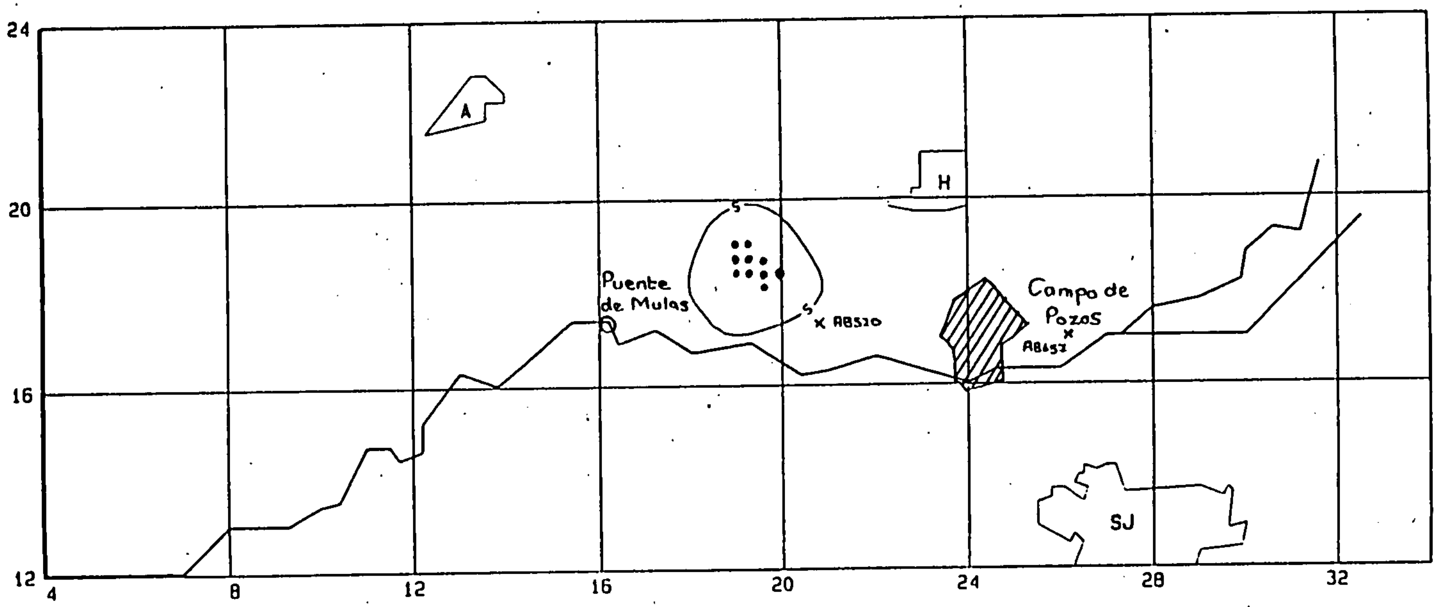


Fig. 6.8 Drawdowns for model simulation 2: Animas-Barreal Wellfield.

(a) Colima Superior



(b) Colima Inferior

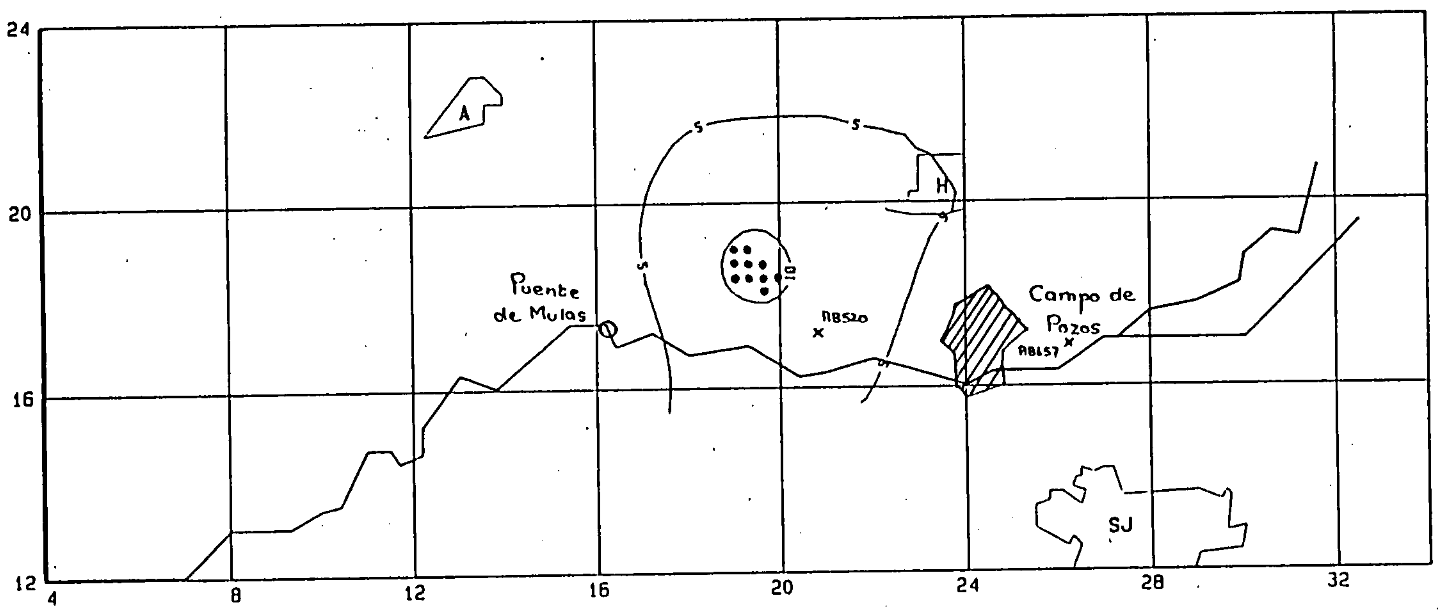


Fig. 6.9 Drawdowns for model simulation 3: Pitahaya Wellfield.

(f) If a greater total abstraction is required, a combination of the two separate wellfields is conceivable. This was simulated in the form of 20 boreholes of 50 l/s spaced at 500 m intervals across the zone between the two proposed wellfields giving a total potential of 1000 l/s. The results of this simulation are given in Table 6.1 (Simulation 4) and Figure 6.10a and b.

(g) The effect of doubling the groundwater abstraction is to increase drawdowns. Across the new wellfield drawdowns are 10 to 15 m which will reduce the saturated thickness of the Colima Superior but not dewater the aquifer. The impact of this major new abstraction on the Valencia Wellfield is a predicted 5 m of extra drawdown. Of much greater concern is the estimated 8 m of additional drawdown in the Colima Superior aquifer at the Puente de Mulas springs. Although this figure is only a fairly rough approximation, it does suggest that the proposed wellfield could cause a reduction in flow or even dry up the Puente de Mulas springs. A carefully monitored phased development of such a wellfield would therefore be absolutely essential.

(h) A final simulation was carried out to assess the likely impact of a major expansion of groundwater abstraction incorporating the proposed 300 l/s extension of the Valencia Wellfield plus the 1000 l/s Pitahaya-Barreal wellfield (Table 6.1 Simulation 5, Figs. 6.11a and b). On the model, this combined abstraction, which effectively doubles the present groundwater abstraction from boreholes in the Colima aquifers, generates about 8 m more drawdown in the Valencia Wellfield. There is also about 8 m of drawdown in the Colima Superior at Puente de Mulas which is the same as for the previous simulation.

(i) The drawdown produced by this scale of new abstraction will almost certainly cause some reduction in the yield of existing groundwater sources. It is unlikely therefore that the increase in total abstraction will be equal to the capacity of the new wells because this must be offset against any reductions in yield that occur elsewhere in the groundwater system.

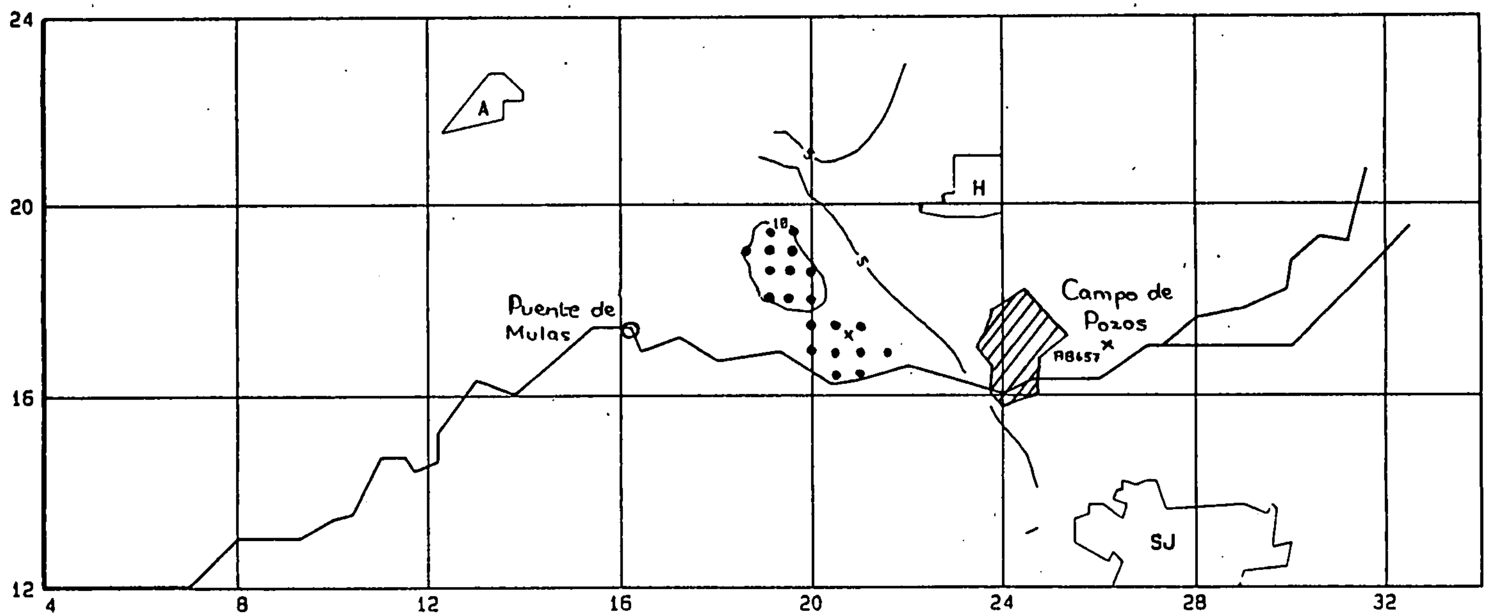
6.7.3 South of Aeropuerto Juan Santamaria

(a) The groundwater resource appraisal concluded that there may be potential for up to 500 l/s of groundwater abstraction from the Colima Inferior aquifer in the area south of the airport. The feasibility of such a wellfield and its impact on groundwater levels was modelled on the basis of 10 boreholes of 50 l/s yield at 500 m spacing (Fig. 6.12).

(b) The present configuration of the model is such that a wellfield of this specification could be operated in the area. The major impact is on the Colima Inferior water levels which show a drawdown of some 14 m in the new wellfield, decreasing to less than 5 m in the area of the Potrerillos springs (Fig. 6.12). This may cause some reduction in flow of springs in the Potrerillos group but it is impossible to predict whether it will affect those springs that have been captured for supply. The effect on the Colima Superior aquifer is limited to the drainage of small amounts of water from the aquifer where it extends to the west of the Puente de Mulas springs and possibly some drawdown further east.

(c) Overall the model simulation of a wellfield located south of the airport is favourable but this result should not be overinterpretted. The field information for the Colima Inferior in this part of the Valle Central is

(a) Colima Superior



(b) Colima Inferior

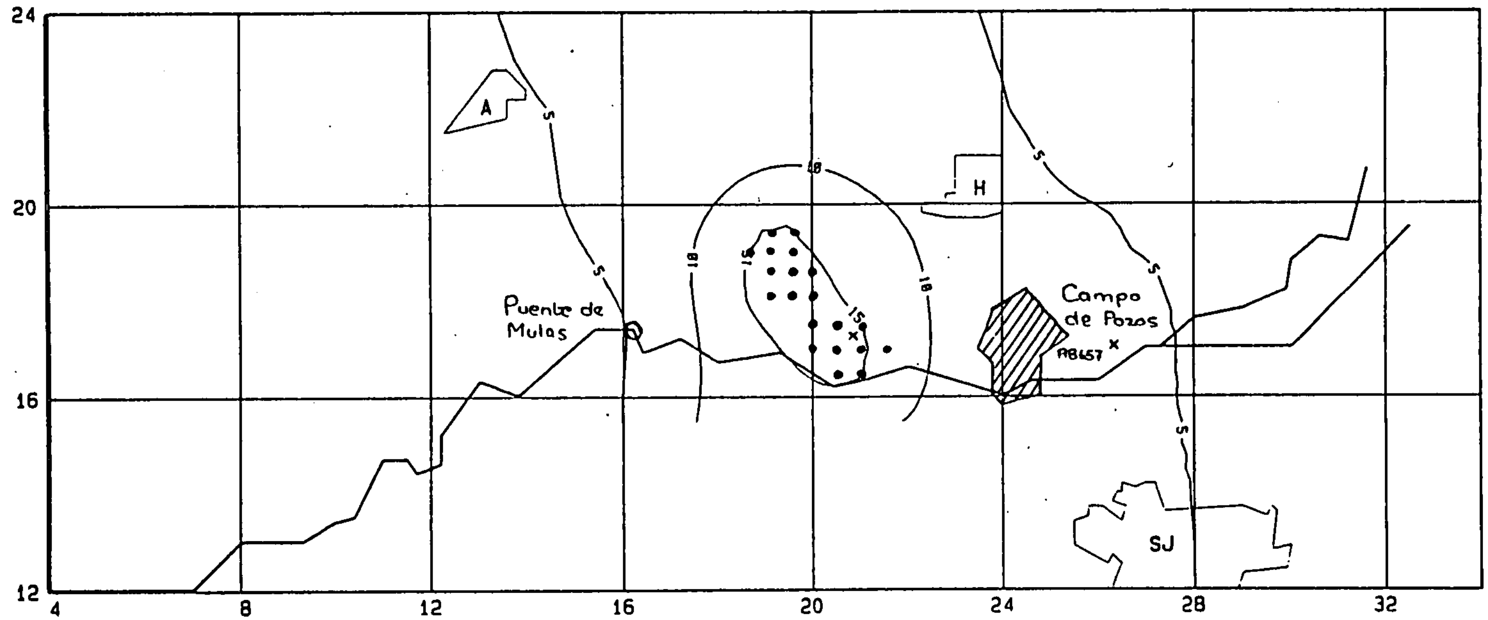
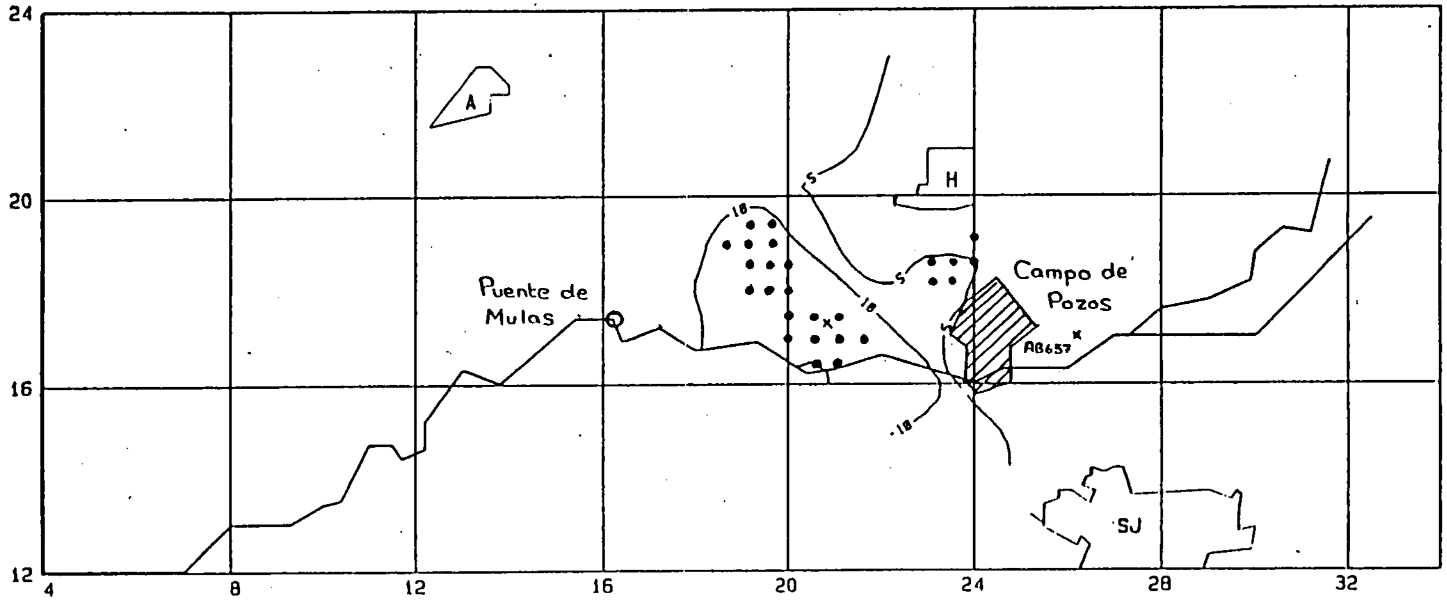


Fig. 6.10 Drawdowns for model simulation 4: Pitahaya-Barreal Wellfield.

(a) Colima Superior



(b) Colima Inferior

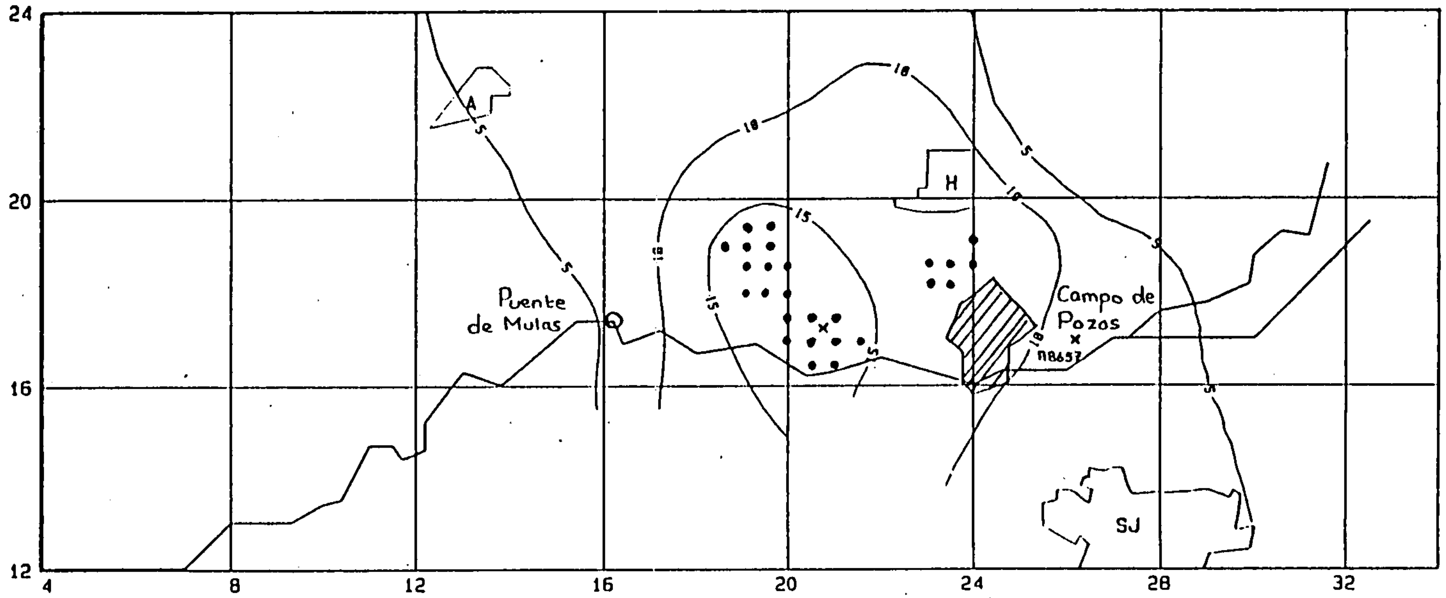


Fig. 6.11 Drawdowns for model simulation 5: Combined Valencia and Pitahaya-Barreal Wellfields.

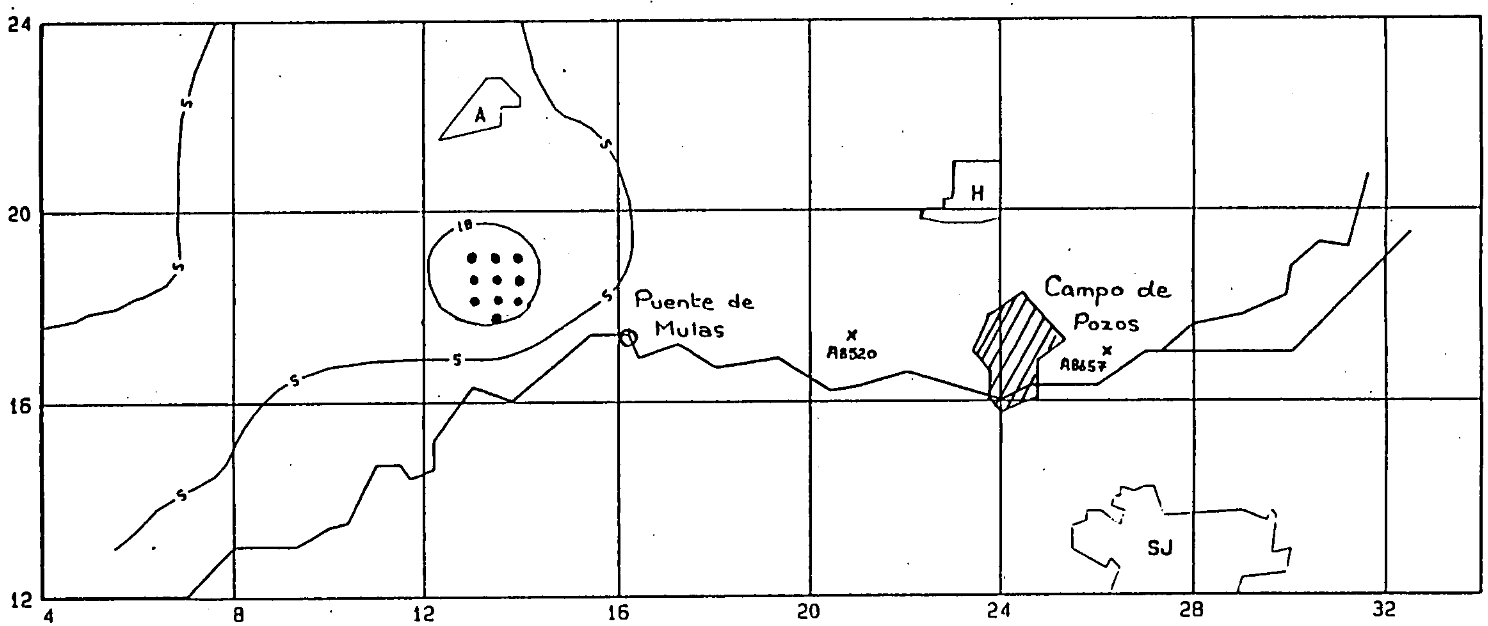


Fig. 6.12 Drawdown for model simulation 6: Wellfield south of airport.

extremely limited and many of the parameters for this part of the model are estimates. Also the Colima Inferior aquifer is modelled as a single aquifer layer whereas there is reason to believe that it comprises several lavas in the area in question. The model predictions for this wellfield should therefore be regarded a first approximation only and further field tests should be carried out before a decision is made to exploit the Colima Inferior in this area.

7. RECOMMENDATIONS

7.1 Groundwater Development North of the Rio Virilla.

(a) The Colima aquifers occur throughout the region north of the Rio Virilla which includes the investigation areas of the Campo de Pozos (CP), Puente de Mulas (PM) and Zona Barba (ZB) (Fig 1.3). Existing abstraction from springs and boreholes amounts to no more than 40% of the estimated minimum resource and the aquifers are capable of significant further development. It is realistic, given the right strategy, to develop an additional 1000-1500 l/s of the Colima groundwater resource. This should be able to be achieved without greatly escalating the unit cost of groundwater supplies, but it requires progressively more careful management because of increasing interference between abstraction sources.

7.1.1 Strategy for Groundwater Development

(a) Potential groundwater supplies of at least 30 l/s per production borehole are widely available throughout the area. A decision needs to be taken about the likely maximum local demand for Colima groundwater within the area. Currently local demand is dispersed and totals about 300 l/s, but if such development is likely to expand considerably due to urban and industrial growth, then obviously this will pose constraints on the availability of further concentrated development of groundwater for export to adjacent areas.

(b) Dispersed local development of supplies up to about 10% of the total Colima resource is unlikely to conflict with new development schemes. Individual users whose borehole supplies suffer interference from new development should be compensated, if necessary being supplied with water from the new wellfield. If, however, local groundwater use exceeds this level then there could be increasing conflict with any new groundwater wellfields.

(c) Closer control on groundwater development should be exerted in the form of licensing for all new abstractions over, say 10 l/s. The licensing procedure should take into account not only the progressive reduction of dry weather riverflows but also potential interference with existing borehole abstractions and captured springheads.

(d) Further development of the downstream springs should be avoided because the location of these springs is such that the water has to be pumped against a large head to demand centres. Furthermore such development places undue constraints of subsequent wellfields closer to the demand centres.

(e) A strategy for further groundwater exploitation should be developed in conjunction with that for surface water use to be incorporated in the new Master Plan for Water Supply. The most effective strategy for the Colima aquifers will probably be one of concentrated development involving the construction of one or more new wellfields.

(f) In view of the heterogeneity and complexity of the Colima aquifer system, resource prediction is subject to uncertainty. It will always be preferable to stage development in new wellfields and monitor initial aquifer response and interference effects. One problem with this type of strategy for groundwater development is that the construction of major pipelines must be delayed until the resource potential of a prospective new wellfield is adequately proven. However, considering the rapid development in this part of the Valle Central, it should be possible to obtain operational experience with several trial production boreholes supplying growing demand locally, before reaching the final decision on the major financial commitment to a long-distance pipeline.

7.1.2 Location of New Wellfields

(a) From consideration of the hydrogeological conditions, the possible interference with existing major abstractions and likely demand areas, three preferred locations for further groundwater development have been identified (Fig 5.1). They are :-

(i) An expansion of the Valencia wellfield to the NW.

(ii) An area running NW-SE between Pitahaya and Barreal.

(iii) The area south of Aeropuerto Juan Santamaria.

(b) The characteristics of these three areas are summarised in Table 7.1 in terms of key hydrogeological criteria and resource potential. It should be emphasised that these data are intended only as a general guide and that actual potential for large scale groundwater development in any one of the locations should be confirmed by a strategy of staged development as outlined above. The average borehole yield has been assumed to be 50 l/s for a drawdown of about 10 m and the average borehole depth 150-200 m. Preliminary cost estimates should be based on the same general criteria.

(c) An extension of the Valencia Wellfield to the north-west is proposed to produce an additional 200-300 l/s from about six new boreholes of depths up to 200 m. Hydrogeological characteristics of this area are thought to be slightly less favourable than those in the main part of the present wellfield and new boreholes may not achieve the excellent yield-drawdown characteristics of some existing boreholes. Yields of 50 l/s are, however, realistic although operational pump water levels could exceed 100 m below surface in boreholes located at the higher elevations.

(d) A large area between Barreal and Pitahaya has potential for major additional development of Colima groundwater. A wellfield with a total output of 600-1000 l/s is recommended, again with phased development, based on boreholes pumping at 50 l/s and spaced at intervals of 250-500 m depending on aquifer behaviour in trial boreholes. Such a wellfield will cause some reduction in flow of the Puente de Mulas springs and may increase drawdowns in the Valencia

Table 7.1 Characteristics of preferred areas for further major groundwater development in the Colima aquifers of the Valle Central.

WELLFIELD AREA	VALENCIA WELLFIELD NW EXTENSION	PITAHAYA-BARREAL	AEROPUERTO JUAN SANTAMARIA (SOUTH)
Extension (km^2)	1-2	4-6	3-4
Aquifer(s)	CS + CI	CS + CI	CI
PB Depth (m)	170-200	170-200	140-160
Average PB Operational Yield (l/s)	50-70	40-80	30-50
Total Scheme Yield (l/s)	200-300	500-1000	300-500
Ground Level (mASL)	1060-1110	980-1020	870-890
Operational PWL (mASL)	970-990	910-930	760-780

PB = Production borehole

Wellfield. These effects are not likely to be critical but the real severity of interference can only be determined by monitoring the impact of new abstractions in the early stages of development.

(e) Less problems of interference are likely to occur if groundwater development takes place in the third location, south of the Aeropuerto Juan Santamaria. This proposal involves abstraction almost exclusively from the Colima Inferior. A maximum wellfield yield of 500 l/s is recommended at this stage because less is known about the resource potential and borehole yields of 50 l/s may be more difficult to achieve. An operational pump water level of less than 100 m is anticipated but it may be necessary to space boreholes at 500 m intervals to reduce interference.

(f) The most logical order of development of further groundwater supplies from the Colima aquifers north of the Rio Virilla would be first to lay a pipeline from the Valencia Wellfield to Heredia to provide drought supply and simultaneously to expand potential in the wellfield by sinking several new production boreholes in the area north-west of the existing wellfield. The next stage should be the development of another major wellfield. The best prospect for a single large wellfield is in the area between Pitahaya and Barreal where it <u>may</u> be possible to develop up to 1000 l/s without significant interference with existing groundwater sources.

7.1.3 Groundwater Resource Management

(a) As an increasing proportion of the available groundwater resources are developed, it becomes more necessary to monitor aquifer response. To improve the precision of resource estimates regionally and locally, it is necessary to monitor groundwater levels not only in the wellfields but throughout the region. This will require more observation boreholes at which water levels are regularly measured. If there is a shortage of manpower or transport to undertake this task, then greater use could be made of automatic water level recorders. The quantities of groundwater abstracted from individual boreholes should also be recorded to improve the accuracy of estimates of resource exploitation.

(b) Similarly it will become increasingly necessary to monitor spring flows so that interference effects can be detected and quantified. This is particularly important in the case of those springs that are already being used for major public water-supply.

(c) Although natural groundwater quality is excellent, there are some indications of deterioration, which are probably related to wastewater disposal. Further investigations of this problem are recommended (see 7.3). Decisions must be made about the sewering of urban and industrial areas and the conservation or improvement of quality of some rivers in relation to groundwater quality protection. This topic should be given consideration in the Master Plan for Sewage.

(d) As a matter of course, ICAyA should continue to monitor nitrate, ammonium and chloride in a network of groundwater sources on a regular basis to provide indication of any changes in groundwater quality. It is important that seasonal variations in these constituents should continue to be monitored in several key sources.

7.2 Groundwater Development in the Zona Este.

(a) Although the groundwater resources of the Valle Central should be viewed as a whole and developed within the same strategy, the aquifers of the Zona Este have characteristics which differ from the main Colima aquifers north of the Rio Virilla and their development merits separate discussion.

(b) In the Zona Este Norte, Colima lavas are present but their groundwater levels are deep and the aquifers do not provide a good economic prospect for large scale development. Shallow aquifers, notably the La Libertad, offer some limited potential but should only be considered for exploitation to meet the local needs of small scale urban and industrial development.

(c) The aquifers of the Zona Este Sur are very different to the Colima aquifers and are generally unfavourable for large-scale development. Modest supplies (up to 25 l/s for large drawdowns) might be obtained from individual boreholes in some areas and it is recommended that development of a groundwater resource should be as an emergency standby or for local demand only.

7.3 Further Investigation Requirements.

(a) There is a clear requirement for further investigations of groundwater quality aimed at confirming the levels, distribution, origin and seasonal fluctuation of the elevated DOC and increasing nitrate concentrations which have been detected. The implications of the results need to be carefully assessed in relation to groundwater pollution vulnerability.

(b) Also for groundwater pollution risk assessment and for assigning priorities in the Master Plan for Sewage, an improved inventory of industrial effluents should be compiled. The volume of effluent and current method of disposal should be recorded and chemical analysis of some effluents should be carried out to determine toxic constituents.

(c) Further inadequately controlled pumping tests are unlikely to improve existing knowledge of the Colima aquifer properties. Instead, emphasis should be placed on completing several carefully controlled pumping tests in which measurements are made in properly constructed observation boreholes at critical locations. Such tests are the only means of obtaining much needed field data on aquifer storativity and transmissivity.

(d) There is still limited information about the origin and location of productive horizons within the Colima aquifers. Such information is very important for the efficient design and operation of production boreholes and it is strongly recommended that, since the appropriate equipment is now available in Costa Rica, flow and formation logging is carried out in new production boreholes.

(e) A two-layer aquifer model of the Colima aquifers has been developed and installed at SENARA. As new data is acquired and understanding of the aquifer system is improved, the model should be updated and refined.

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P = Project management
F = Fieldwork
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M = Mathematical modelling
R = Primarily responsible for report
H = Hydrogeological interpretation

SELECTED BIBLIOGRAPHY

Howard Humphreys & Sons, 1974
Study of water resources and sewage disposal in the Central Valley.
Servicio Nacional de Acueductos y Alcantarillado, Costa Rica

Losilla, M & Rodriguez, H, 1978
Consideraciones sobre recarga y descarga del acuifero de Colima en el area del Campo de Pozos de Santo Domingo.
SENAS, informe tecnico 102

Losilla, M, Foster, S, Rodriguez, H & Kitching, R, 1982
Estudio Hidrogeologico para el desarrollo de los acuiferos Colima. Aplicacion del modelo matematico IGS-SENARA.
SENAS, informe tecnico 153

BGS-SENARA, 1985
Hydrogeological map of the Valle Central of Costa Rica.

Foster, S, Ellis, A, Losilla, M & Rodriguez, H, 1985
Role of volcanic tuffs in ground-water regime of Valle Central, Costa Rica.
Ground Water, 23, No. 6

Darling, G, Parker, J, Rodriguez, H & Lardner, A, 1987
Investigation of a volcanic aquifer system in Costa Rica using environmental isotopes.
International Atomic Energy Agency, in press