

Groundwater in Colombia

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ABSTRACT In tropical Colombia, where 75% of groundwater exploitation is concentrated in two limited areas, successful agricultural ventures proved its economic value. It is therefore imperative to assess the development possibilities of this almost untouched resource to complement surface water in irrigation and water supply projects, and in some cases to replace contaminated sources. The present paper introduces the major aquifer units of the country and discusses the state of exploitation and approximate recharge values.

Les eaux souterraines en Colombie

RESUME Dans la Colombie tropicale où 75% de l'exploitation des eaux souterraines est concentrée dans deux zones limitées, le succès des entreprises agricoles a prouvé leur valeur économique. Aussi, l'évaluation des possibilités de développer l'exploitation de ce genre de ressources en eau à peine utilisé est indispensable pour compléter ou remplacer les eaux de surface polluées, dans les projets d'irrigation et d'alimentation en eau. Cet article présente les aquifères principaux du pays et discute du stade de leur exploitation et des valeurs du taux de recharge approximatif.

INTRODUCTION

Colombia, the fourth largest country in South America, covers 1 138 914 km². Due to its position within the tropics and bounded by two oceans, Colombia enjoys precipitation rates above 2000 mm year⁻¹ (Fig.1). Rainfall less than 1000 mm year⁻¹ is limited to the extreme northern lowlands, to the semiarid Guajira Peninsula, and to some highlands on the Andean ridges.

The abundant rainfall, resulting in severe floods on the lower parts of the large unregulated catchment areas (Magdalena, Cauca and many others), combined with the low water demand are the main reasons why groundwater is barely exploited in Colombia. Large centres of water consumption such as big cities are supplied by surface water installations. The only two important centres of groundwater exploitation are encountered in the Cauca Valley and in the Sabana of Bogota.

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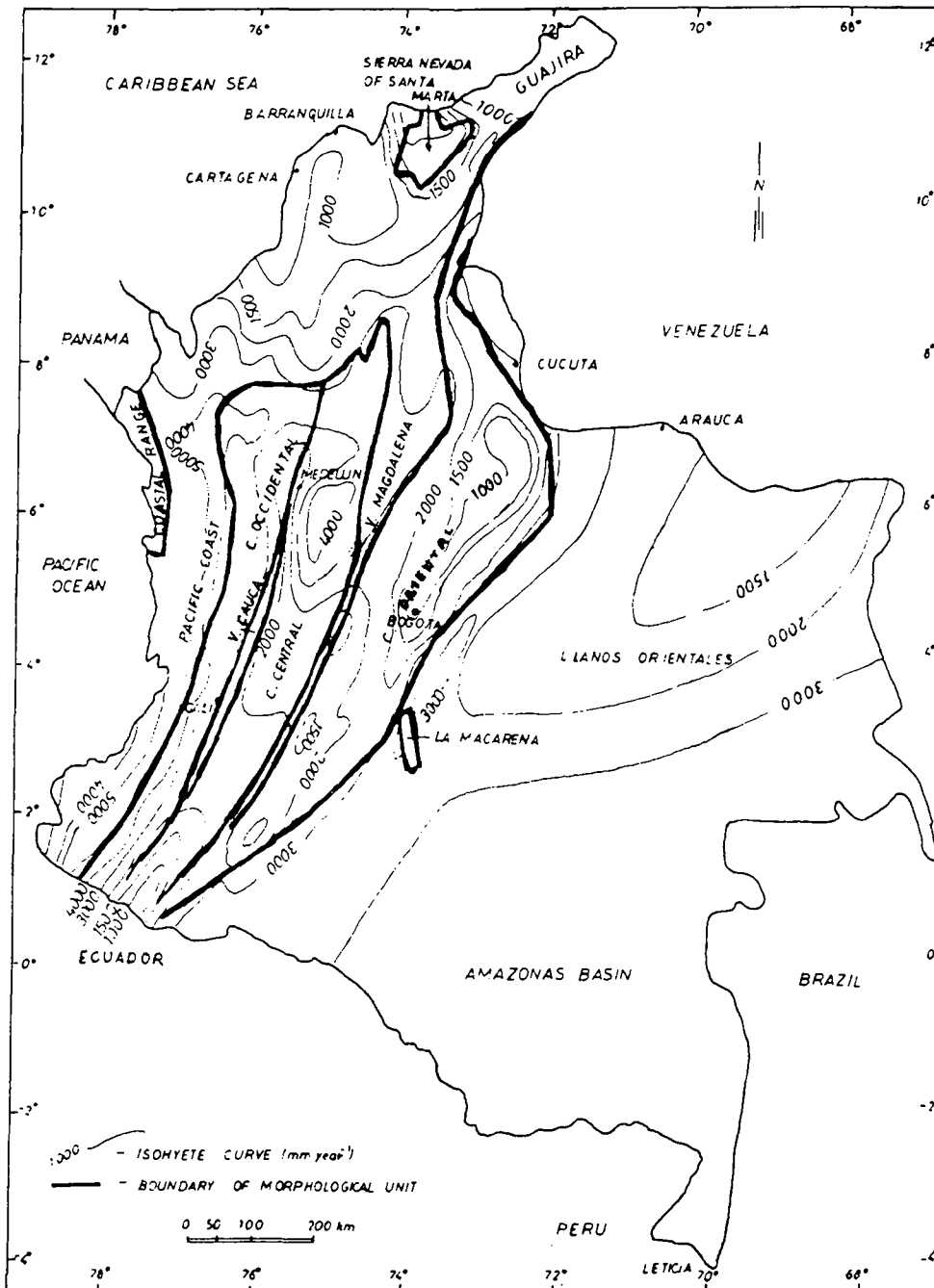


Fig. 1 Isohyetal map of Colombia.

Topographic and economic constraints are reducing the feasibility of further surface water development through expensive regulation projects and the widely occurring groundwater should be used to meet many new water requirements. Leading and flourishing agricultural enterprises, supplied partially by groundwater, like the sugar cane crops in the Cauca Valley, the banana plantations in Uraba and in the delta of the Magdalena River, the flowers in the Sabana of Bogota and the cotton in the Cesar Valley, prove the importance of

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Even though most of the existing water supply systems are based on surface water intakes, a re-evaluation of their soundness is called for. Recent natural calamities like the eruption of the Nevado Ruiz Volcano, which buried the town of Armero, and smaller disasters like the floods in Villavicencio and Cucuta, demonstrate the vulnerability of these systems. Increasing pollution hazards and elevated costs of treatment also make surface water less attractive. Therefore, thousands of villages and small towns are to be considered for installation of an appropriate groundwater supply system.

Most of the numerous existing reports on groundwater in Colombia deal with local aspects of groundwater supply. Only a few regions are covered by extensive studies (Cauca Valley, Sabana of Bogota, La Guajira, parts of the northern Atlantic Coast and the Cesar Valley, Cucuta). Recently, a first attempt was made to elaborate, on a large scale and as part of the National Water Study, the information on groundwater, and the country was divided into 28 hydrogeological zones (Mejia *et al.*, 1983; Lobo Guerrero, 1984). This attention is a logical response to the proven economic advantage of groundwater use in irrigation schemes. The present paper provides a preliminary evaluation of groundwater in Colombia.

GENERAL DESCRIPTION

Colombia is divided into two major and different regions:

(a) The low and flat *eastern region*, 100 to 500 m a.m.s.l., covers 670 000 km² and is crossed by large rivers that drain east and south into the bounding Orinoco and Amazonas Rivers. This vast region is divided into the northern "Llanos Orientales" (plains) and the southern, jungle covered, Amazonas basin. In this eastern region, relatively thin Palaeozoic-Cenozoic sediments lie on top of Precambrian metamorphic and igneous rocks of the Guayana Shield.

(b) The remaining 469 000 km² cover the *central and western regions*. They consist of three, NNE-SSW trending, mountain ranges (the Andean Cordilleras; Oriental, Central and Occidental) and the humid coastal plains. The Cordilleras, with elevations up to 5000 m a.m.s.l., are separated by low, 100 to 500 m intermontane valleys (Magdalena and Cauca). Along the northern Pacific Coast and the Panama border, remnants of a low coastal range separate the plains from the ocean. The highest peak of Colombia, 5800 m a.m.s.l. (Sierra Nevada of Santa Marta), is located in an isolated range on the Atlantic coast (Fig.1).

About 20% of Colombia is formed by igneous and metamorphic rocks, concentrated in the three Cordilleras, the isolated Sierra Nevada of Santa Marta and in the Guayana Shield (INGEOMINAS, 1976). The rest of the Andean mountain ranges are composed of Palaeozoic and thick Mesozoic and Cenozoic sedimentary rocks. The low plains and depressions are filled with thick Tertiary and Quaternary sediments.

The climate is tropical, with an average precipitation above 2000 mm year⁻¹ and average temperature of 28°C at sea level (Fig.1). Temperatures decrease as altitude increases. The pleasant temperatures attracted the major part of the population to the highlands.

For instance, the capital, Bogota, with its 5 million inhabitants, is located in a flat valley as high as 2650 m a.m.s.l., enjoying an average temperature of 14°C.

Except for streams in the Guajira Peninsula and in a few small inland areas like Northern Huila (Neiva), all the rivers are perennial. They are grouped in 12 major hydrographical basins, of which the most important are: the Amazonas, Orinoco, Magdalena and Cauca (Fig.2).

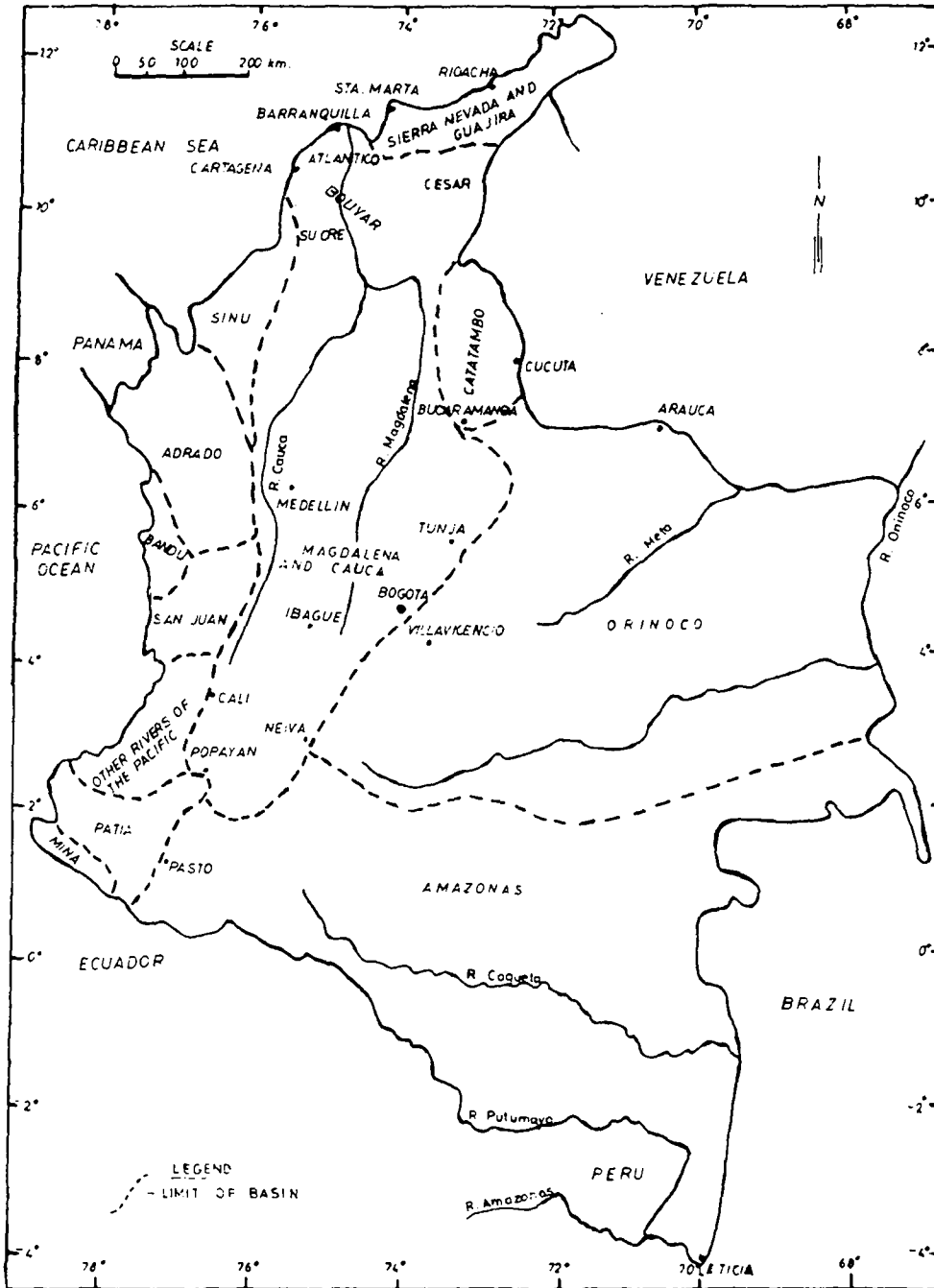


Fig. 2 Major basins of Colombia.

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THE AQUIFERS

Excluding 237 000 km² formed by igneous and metamorphic rocks and 502 000 km² by impervious shales, claystones and turbidites, the remaining 400 000 km² contain aquifers of some importance (INGEO-MINAS, 1976, 1977; Rubio *et al.*, 1978). They are, from east to west (Figs 3 and 4):

- the Quaternary aquifers of the Llanos Orientales, Cucuta and the Amazonas basin;
- the Quaternary fill and the Cretaceous-Tertiary sediments in the synclinal troughs of the Cordillera Oriental;
- alluvial fill and Tertiary beds of the Upper and Middle Magdalena Valley;
- alluvial fill and Tertiary beds of the Cauca Valley;
- alluvium and Quaternary deposits of the Pacific coastal area;
- Quaternary beds and Tertiary sediments of the Lower Magdalena Valley, Cesar Valley and the Atlantic coast; and
- Quaternary-Tertiary aquifers of La Guajira Peninsula.

Details of the different aquifers are summarized in Table 1 and Fig.5.

The volcano-sedimentary beds in the south, between Popayan and Pasto, have unknown potential. The small Caribbean Island of San Andres, of Tertiary and Pleistocene karstic limestones, suffers from serious problems of sea water encroachment. Several of the Tertiary and Quaternary aquifers of the Pacific coast, Lower Magdalena, Atlantic coast and La Guajira are brackish.

While in the igneous-metamorphic domain, water circulation is limited mainly to fault zones, the occurrence of detritic and calcareous horizons and lenses within the otherwise impervious Cretaceous-Tertiary shales and clays enables local groundwater extraction.

The Quaternary aquifers of the Llanos Orientales, Cucuta and the Amazonas basin

The recent unconsolidated alluvium that covers the flat drainage areas of the rivers that end in the Orinoco and the underlying Quaternary beds form the large aquifers of the Llanos Orientales. Their granulometry changes from very coarse and poorly sorted in the piedemont alluvial cones in the west to fine grained loose sand intercalated with clay in fluvial braided deposits eastwards. Near the Andean Cordillera, boulders and coarse gravels present drilling difficulties as do artesian pressures in low-lying zones.

This vast humid region, covered by grass and by marshes formed by frequent floods and with a sparse population, has a very small water demand. The actual groundwater consumption, mainly for domestic use, is less than 15 million cubic metres (MCM) per year, extracted by a few boreholes, with depths around 100 m. With modification of the water supply schemes in the largest and rapidly growing towns in the region (such as Villavicencio, Yopal and Arauca), and plans for secondary recovery by water injection wells in the recently discovered oil fields near Arauca and Villavicencio, future consumption will increase and wells are expected to be deeper and of larger capacities.

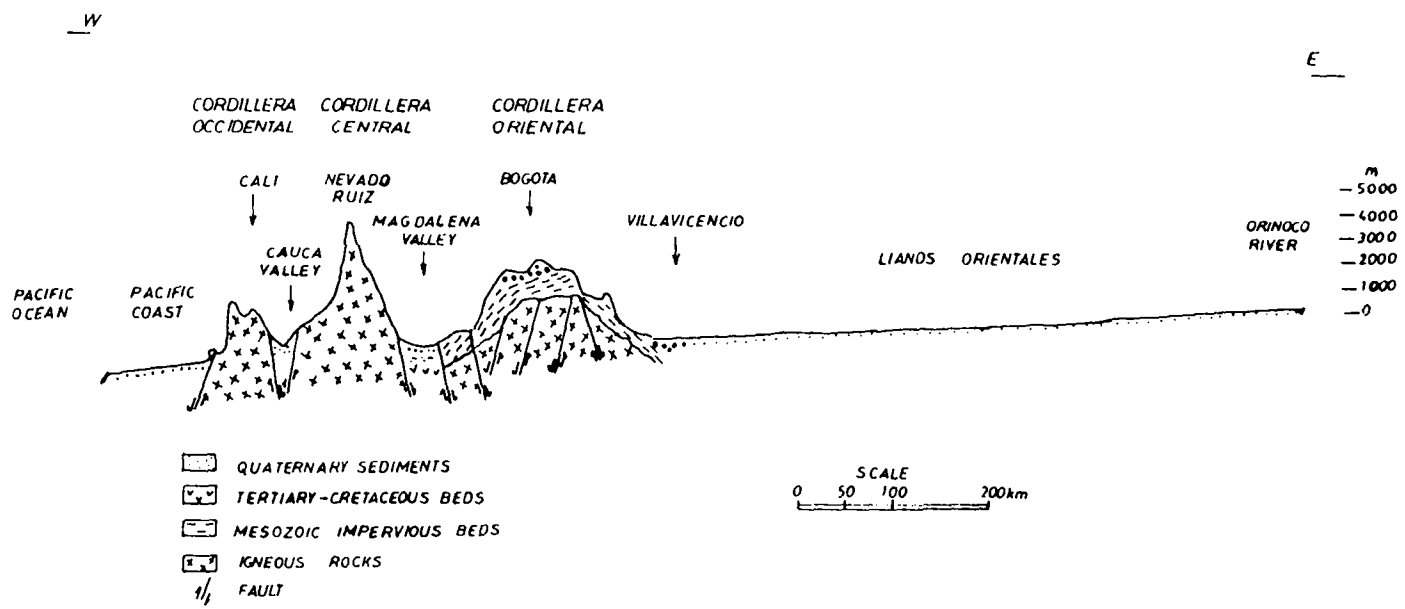
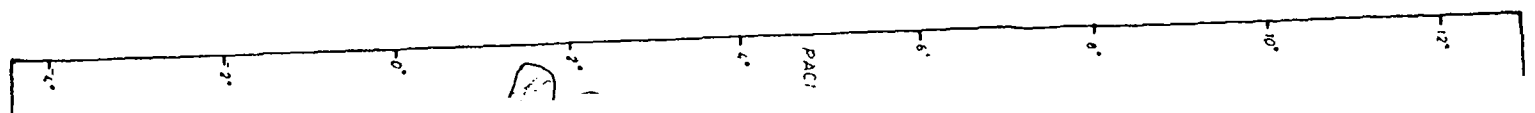


Fig. 3 Schematic geological cross section between the Pacific Ocean and the Orinoco River.



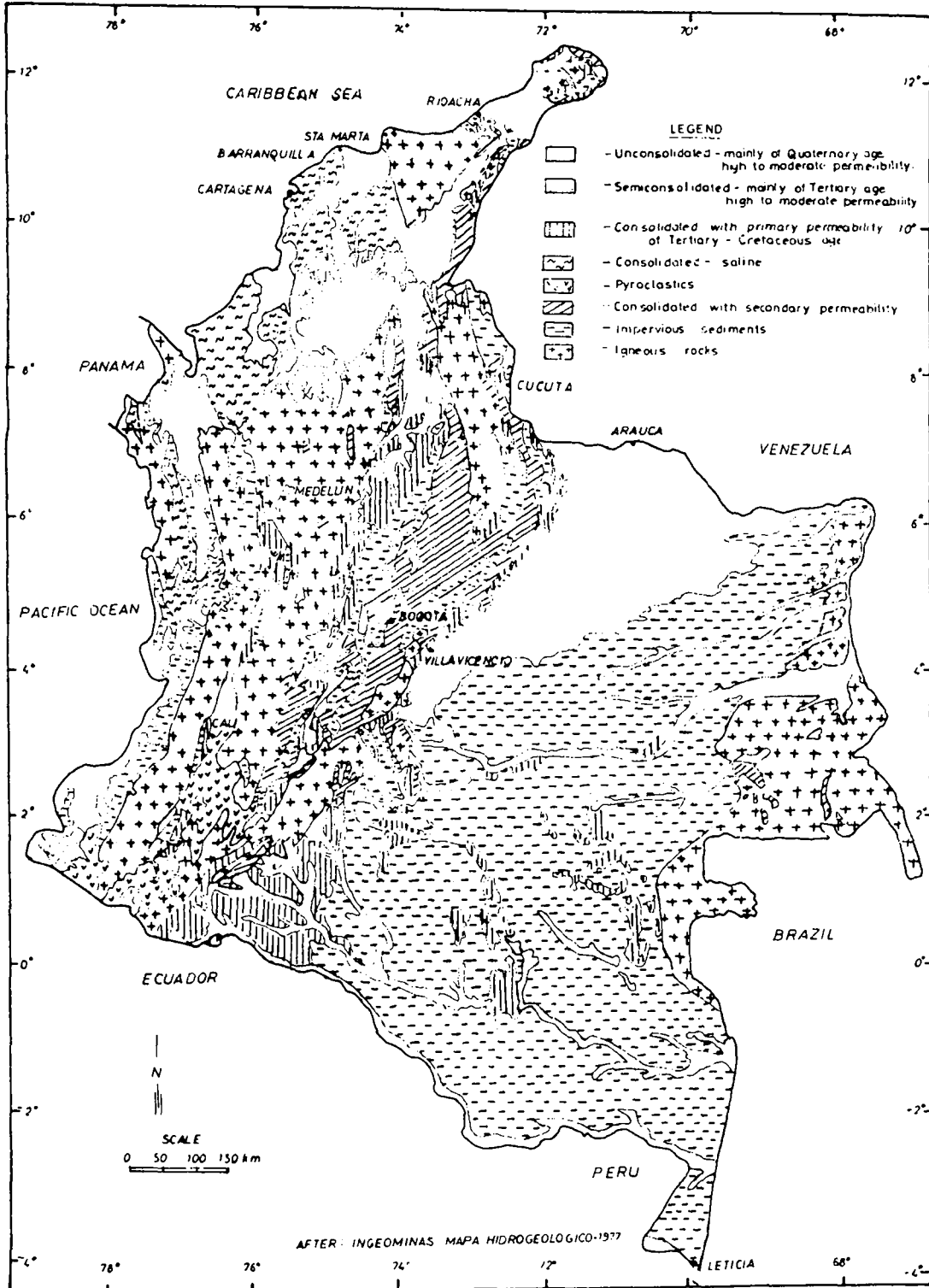


Fig. 4 The aquifers of Colombia.

The vast region to the south, covered by dense tropical forests, belongs to the Amazonas basin. The igneous-metamorphic basement, exposed in a few marginal areas, is covered by Tertiary, slightly compacted, clays and silts. The alluvial fill of recent river

Table 1 The aquifers of Colombia

Location	Aquifer	Area (km ²)	Lithology	Thickness (m)	Source of recharge	Total recharge (MCM year ⁻¹)	Number of wells	Depth of wells (m)	Yield of wells (m ³ h ⁻¹)	Quality of water	Estimated production (MCM year ⁻¹)
LLANOS ORIENTALES	Alluvium	107 000	Boulders, gravels, sand, clay	100	Rainfall and infiltration from rivers	2500-7500	50	50-150	115-300	Good	15
Amazonas basin	Alluvium	50 000	Gravels, sand, clay	30	Infiltration from rivers	850-4300	10?				<10
CORDILLERA ORIENTAL											
Sabana of Bogota	Sabana Fm	1 250	Clay, gravel, sand	300	Rainfall	35-60	1500	50-300	3-50	Good, slightly ferruginous	80
	Tilata Fm	1 500	Gravel, sand, clay	200	Rainfall, infiltration from rivers	30-60		50-500	3-125	Good	
	Guadalupe Fm	4 000	Sandstone, chert, shales	700	Rainfall	80-120	50	100-700	3-350	Good, slightly ferruginous	20
Other valleys: Ubate-Chiquinquirá, Tunja, Paipa-Duitama, Sogamoso, Bucaramanga, Cucuta, etc.	Alluvium and Tilata Fm	2 000	Sand, clays, gravel	400	Rainfall, infiltration from rivers	60-100	200	10-300	3-35	Good, slight ferruginous	20
	Guadalupe Fm	34 000	Sst., chert, shale	250-600	Rainfall	300-1000	10	100-400	3-70	Good	5
	Fractured Tertiary-Cretaceous Formations		Sst., conglomerate, limestone		Rainfall		20	100-375	2-40	Good to poor	<5
UPPER AND MIDDLE MAGDALENA	Alluvium	15 000	Sand, silt, clay, gravel, boulders	80	Rainfall, infiltration from rivers	600-1200	100	50-80	5-65	Good	20
	Gigante and Mesa Fms, Honda Group	21 000	Sst., claystones, conglomerates	4000	Rainfall, infiltration from rivers	300-600	100	50-200	5-170	Good to calcareous	<20
	Pyroclastic sediments	20 000	Tuff, aglomerate, claystone, boulders	25-350	Infiltration from rivers	200-800	50	25-140	3-30	Hard, slightly ferruginous, manganese	5
CAUCA VALLEY	Valle Fm	3 160	Sand, gravels, clay, boulders	150-450	Rainfall, infiltration from rivers	400-600	1500	100-200	250-400	Good, in northern part regular	800

Rainfall

900-1000

20?

Brackish, some

<5

PACIFIC COAST	Alluvium	22 000	Sand, gravel, clay		Rainfall	900-1800	20?			Brackish, some good	<5
ATLANTIC COAST											
Cesar	Alluvium	12 000	Sand, gravel, clay	25-150	Rainfall	400-700	750	50-100	10-300	Good	30
Lower Magdalena	Alluvium	4 000	Sand, gravel, clay	50-150	Rainfall, infiltration from rivers	140-240	750	50-150	10-100	Good, locally to the north — brackish	20
Bolívar	Alluvium	23 000	Sand, silt, gravel, clay	50	Rainfall	1400-2300	7100	15-120	5-50	Brackish; some good	20
Atlántico	Tertiary Fms	15 000	Sandstones, conglomerates, claystones	1000	Rainfall	150-600	7100	12-260	5-150	Hard	20
Sucre	Brackish water aquifers	38 000	Sst., conglomerates, limestones, claystones			75-750	—			Brackish to saline connate water	—
Uraba	Alluvium	8 000	Gravel, sand, clay	200	Rainfall, infiltration from rivers	300-900	60	100-200	150-250	Good, some sites brackish	30
LA GUAJIRA	Alluvium	9 000	Sand, silt	50-100	Rainfall, infiltration from rivers	30-120		50-100	3-10	Brackish	15
	Mongui Fm	10 000	Calcareous sst., limestones, conglomerates	200	Inflow through major fault zone	10-30	500	180-300	20-130	Good to brackish	<5
OTHER AQUIFERS											
Popayan-Pasto	Pyroclastics	25 000				400-1200	750				<5
Cordillera Central	Pyroclastics-sedimentary rocks										
Cesar-Guajira	Fractured Consolidated Palaeozoic-Mesozoic Fms										
TOTAL		400 000					4970				1150

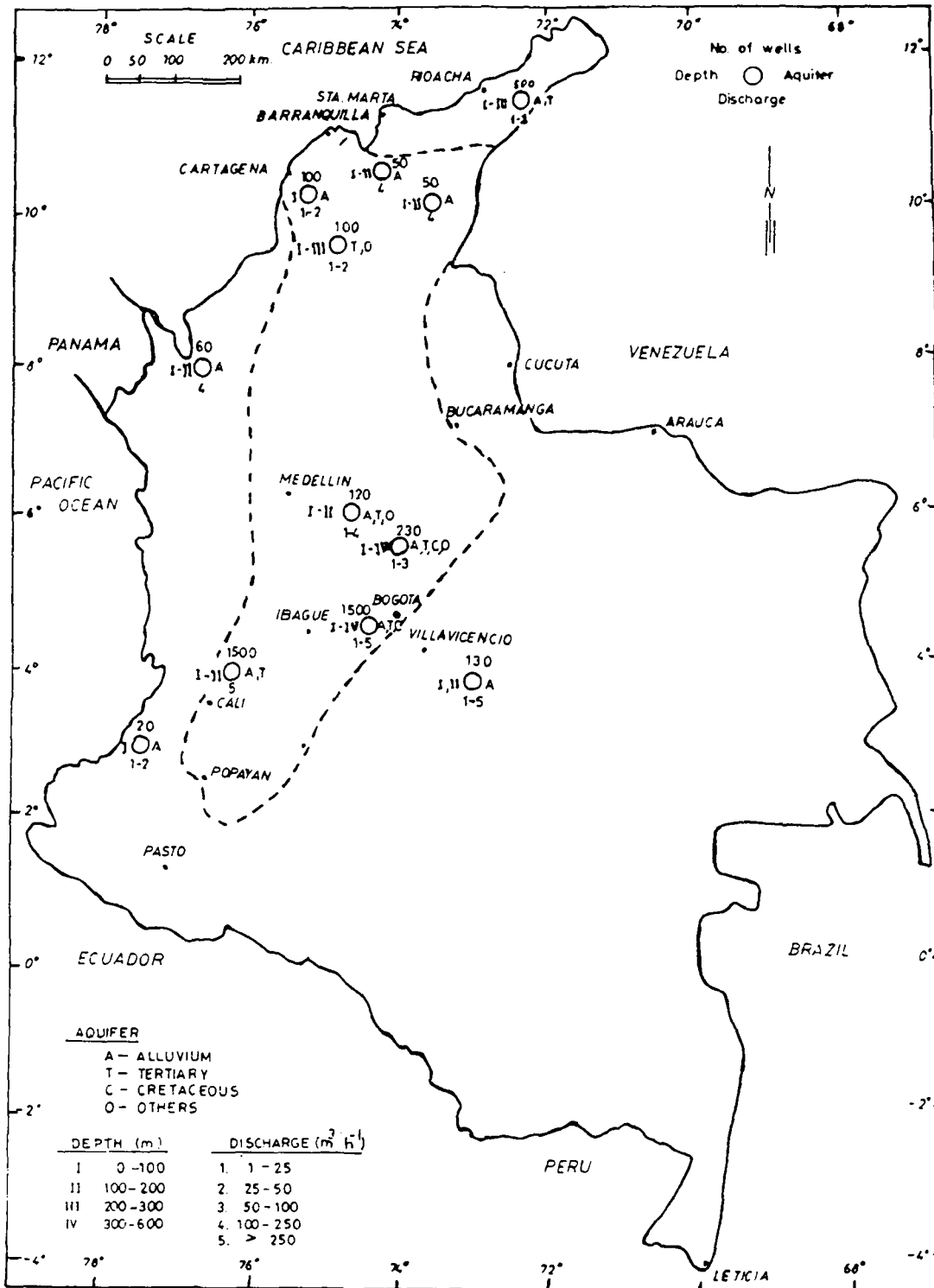


Fig. 5 Water wells distribution in Colombia.

courses and outcrops of fractured Tertiary consolidated sediments form separate aquifers, bounded by impervious layers. In this large jungle area, with abundant rainfall, very little groundwater is pumped.

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The Quaternary fill and the Cretaceous-Tertiary sediments in the Cordillera Oriental

Aquifers are encountered within the sedimentary strata of the Cordillera Oriental in the Cretaceous to Quaternary formations that compose the sub-surface of the elevated plateaus and depressions. Examples are the 1250 km² Sabana of Bogota, the Valleys of Ubaté-Chiquinquirá, Tunja, Paipa-Duitama-Sogamoso, the low plateau of Bucaramanga and the Cucuta Valley (Figs 3 and 4). Due to the high population density and the intensive economical activities of this region, these superimposed aquifers play an important role in water supply schemes and in industrial and agricultural ventures.

The aquifers vary from highly permeable unconsolidated recent alluvial deposits through Cretaceous-Tertiary consolidated rocks with primary permeability (Cacho Sandstone) or with secondary permeability due to fracturing (like the Guadalupe Sandstones) or solution (limestones), to the semiconsolidated beds with high permeability such as the Tilata formation or with moderate permeability like the fluvio-lacustrine sediments of the Sabana formation, the Chicamocha formation in Paipa-Duitama-Sogamoso and the Tilata formation of Boyaca.

The most important centre of groundwater extraction in the region is the Sabana of Bogota, where the aquifer overlies the impervious shaley Villeta Group. Due to faulting and erosion, the stratigraphic sequence above the Villeta Group is not complete. Along the centre of the Cordillera the lowermost aquifers are composed of the 700 m thick fractured sandstones of the Guadalupe formation. Where not exposed, the Guadalupe Formation is covered by the impervious Guaduas formation and younger sediments, and is considered to be a confined aquifer. It yields important amounts of somewhat ferruginous groundwater. Where the Cacho sandstones are conserved above the Guaduas formation, boreholes achieve moderate yields. The depression of the Sabana of Bogota is filled with the fluvio-lacustrine semiconsolidated sandy, argillaceous and locally gravelly Sabana and Tilata Formations. More than 1500 shallow boreholes, less than 100 m deep, and a few deep wells extract water from the gravel and sand beds encountered within these formations.

All the aquifers in the Sabana of Bogota are recharged directly by precipitation, some also by infiltration from river courses. As shown by the schematic cross section, some of the aquifers may be interconnected (Fig.6). The high rates of exploitation from the Sabana and Tilata Formations are reaching the estimated safe yield values and question future large-scale development of this resource. Even though extraction from the Guadalupe aquifer is relatively small, concentrated pumping seriously affects certain zones of the Sabana of Bogota. In spite of recent efforts by the responsible local authority to control drilling activities, no accurate information regarding the actual state of exploitation is available.

Alluvial fill and Tertiary beds of the Upper and Middle Magdalena Valley

The Upper and Middle narrow reaches of the Magdalena Valley separate the Cordillera Oriental from the Cordillera Central. Within the

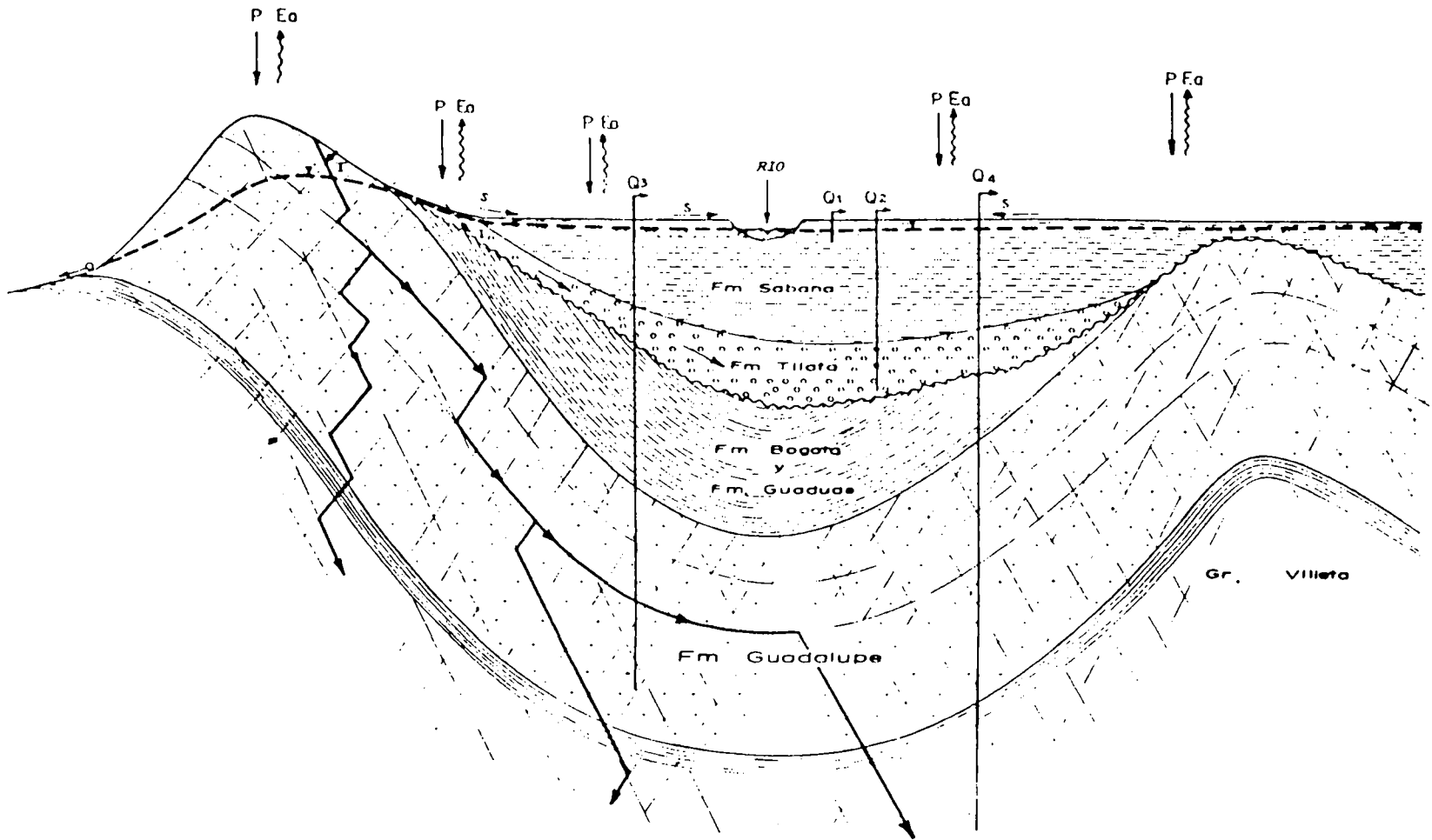


Fig. 6 Hydrogeological model of the Bogota River basin.

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topographic low valley, Quaternary alluvial deposits near rivers and streams form highly permeable aquifers. The Quaternary-Tertiary Gigante, Mesa and Honda Formations, that consist of poorly-cemented sands and gravels, sandstones and conglomerates with some claystones, form phreatic and confined aquifers. Pyroclastic beds and mudflows that form large fans, mesetas and high terraces, like the Ibague Fan, present possibilities as aquifers, but are exploited by only a few wells, due to difficult drilling conditions. The aquifers are recharged by precipitation, water courses and from bounding Cordillera formations. Salinization from deeper horizons is a permanent danger for certain aquifers.

Alluvial fill and Tertiary beds of the Cauca Valley

The Cauca Valley, drained by the river with the same name, separates the Cordillera Central from the Cordillera Occidental. In this section, the 3160 km² of the low lying valley consist mainly of Recent-Quaternary coarse alluvial fill, 50 m to a maximum of 450 m thick. These beds contain the most exploited, and also best studied and controlled, aquifers in Colombia. About 1500 wells, 100-200 m deep, with yields of 250-400 m³h⁻¹ and total installed pumping capacity of 400 000 m³h⁻¹ are extracting 800-1000 MCM year⁻¹ from these phreatic and semiconfined aquifers.

Locally, beneath the Valle formation and in the foothills of the Cordilleras, are other aquifers of Tertiary age: the Zarzal Formation (Pliocene) with semiconsolidated and semiconfined aquifers; La Paila Formation (Miocene), with consolidated, primary permeability and good confined-to-semiconfined aquifers; and the Cauca group (Palaeocene-Miocene) with consolidated sandstones and conglomerates, with secondary permeability.

The groundwater extracted is used mainly for the irrigation of large sugar cane plantations.

The aquifers are recharged by precipitation, rivers and inflow from the bounding Cordilleras.

Alluvium and Quaternary deposits of the Pacific coastal area

Located in the wettest region of Colombia, along the Pacific coast, the aquifers are covered by dense tropical forests or inundated by marshes. The scarce population, concentrated mainly in a few small towns along the coast, is supplied by surface water installations. Sporadic shallow wells represent the minimal groundwater exploitation. In spite of their potential, it seems that the aquifers in this region will remain practically untapped.

Quaternary beds and Tertiary sediments of the Lower Magdalena Valley, Cesar Valley and the Atlantic coast

The Recent-Quaternary alluvium and coarse fluvio-lacustrine Holocene deposits are by far the most important aquifers in this region viz. Cesar, Delta of the Magdalena River, Mompos and Uraba. Reaching a thickness of 150 m in certain areas, these aquifers give rise to borehole yields above 250 m³h⁻¹.

The Tertiary sequence, thousands of metres thick, contains

moderate to poor aquifers. These are composed mainly of detritic formations, of continental or marine origin, with primary or secondary permeability.

Over large areas between the Sierra Nevada of Santa Marta and the Gulf of Uraba, these aquifers contain brackish to saline water and are not considered as exploitable aquifers. Where they contain fresh water, the aquifers supply, with moderate-to-high borehole yields, various small towns in the northern Departments of Atlantico, Bolivar and Sucre.

Other aquifers, like the Popa coralline limestone along the coast (Bolivar-Atlantico) and the fractured consolidated clastic or calcareous formations that bound or are confined below the Quaternary fill of the Cesar Valley (La Luna Formation), complement the aquifer potential of this region.

Quaternary-Tertiary aquifers of La Guajira Peninsula

The northernmost peninsula of La Guajira, with a rainfall of 300-1000 mm year⁻¹, is the most arid region of Colombia (Hoffman, 1975). The search for water there started several decades ago, and a few poor to moderate aquifers that yield fresh to highly brackish water were discovered.

The alluvial fill and semiconsolidated Quaternary terraces in the middle and lower zones of the peninsula have watertable aquifers that yield small amounts of water to hundreds of boreholes and dug wells, with the quality deteriorating from south to north. Underlying the recent fill of the plains are fractured limestones in the Upper Guajira, the semiconsolidated Mongui Formation in the Middle Guajira and other rocks in the Lower Guajira. These aquifers are also saline toward the coast. A centre of fresh groundwater pumping from the Mongui Formation is located near the capital of the Department, Rioacha, on the Atlantic Coast.

Recharge is attributed to rainfall and to inflow through major fault lines from the Sierra Nevada of Santa Marta.

REPLENISHMENT POSSIBILITIES

Direct rainfall is the main source of groundwater replenishment, and infiltration rates depend on the amount and frequency of precipitation, the evapotranspiration, the type of soil, the vegetation and the depth to the water table. Many untapped aquifers in Colombia are saturated up to ground level and thus infiltration is rejected.

Absence of pertinent data impedes the establishment of the relationship between the aquifers and the baseflow of rivers. However, it can be observed that the outflow from the shallow aquifers forms the baseflow of streams. Aquifers with deep or depleted water tables are recharged from the river courses. It is assumed that a high percentage of the total runoff serves as transitory recharge, appearing later as baseflow in the rivers.

Rapid evaluations, based on baseflow separation of the river flow data, were undertaken recently in one or two small areas, in order to obtain some idea of the order of magnitude of groundwater recharge. The computational method introduced in Sao Paulo, Brasil,

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was modified for Colombian conditions (Gilboa et al., 1976). Deep infiltration rates, varying between 0.1 and 5% of total precipitation, were used in accordance with the topographic, morphological, lithostratigraphic and aquifer saturation conditions.

The total runoff of Colombia is estimated to be about $1500 \times 10^9 \text{ m}^3 \text{ year}^{-1}$, part of it as torrential surface runoff and most of it as transitory flow. Transitory recharge taking place in the crystalline rocks through faults and fractures feeds the baseflow of the rivers or recharges connected aquifers.

Deep recharge, attributed only to direct precipitation, is estimated to be $9\text{-}25 \times 10^9 \text{ m}^3 \text{ year}^{-1}$, and is less than 2% of total runoff (Table 1). In the Magdalena basin, deep groundwater recharge is about 3-7% of total runoff. The recharge estimates do not include additional amounts infiltrating from river courses and canals, return flow from irrigation and inflow from adjacent aquifers, since there is no way yet to evaluate these. Recharge values are considered conservative, as demonstrated by the following example.

The Cauca Valley is an elongated and narrow valley, extending near Cali over 3160 km^2 , and with limited outlets between two bounding Cordilleras, the Central and Occidental. Consequently, in its lower reaches, the main aquifer drains into the river course. By using high rainfall infiltration rates, the recharge of the aquifer is estimated to be 400-600 MCM year^{-1} . These values are below the discharge rates through pumping from wells (800 MCM year^{-1}), but except for small areas where pumping is heavily concentrated and leading to local water table depletion, no serious overpumping has been detected. The lack of negative effects is attributed to entrances from other sources: infiltration from streamflow, inflow through Cordillera faults, and return flow from irrigation of the sugar cane plantations. This supplementary recharge may even be enhanced in the vicinity of pumping centres. In the areas where the water table has been depleted, the rate of recharge enhancement is probably too small to balance the amounts of groundwater extracted. In spite of the fact that only 6% of total runoff recharges the aquifer, a flow of $13 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ is gauged at the lower end of the Cauca Valley (HIMAT, 1983). The aquifer is thus the largest regulating reservoir in the whole Cauca basin.

In the Sabana of Bogota, the sand lenses of the Sabana and Tilata Formations are recharged by rainfall and infiltration from streamflow. Intensive pumping led to water table depletion and some isolated lenses even dried up. However, to compensate for the amounts extracted, additional sources such as inflow from the Guadalupe Formation are assumed to recharge both aquifers (Fig.6). The Guadalupe Formation itself has limited natural drainage outlets. Overlying the impervious Villeta Shales, the Guadalupe aquifer remains saturated even at low rates of recharge, as is demonstrated by a series of springs. By increasing the extraction of groundwater, this spring discharge may be reduced and result in an increase of replenishment rates. Nevertheless, intensive faulting dissects the aquifer into deep buried and sometimes isolated blocks, and calls for special attention. Wherever pumping is concentrated in such a block (e.g. Madrid-Bojaca) considerable water depletion occurs. The increasing demand for groundwater has led in recent

years to drilling deeper than the Guadalupe Formation and it has been found that the Villeta Shales are also fractured and yield some water from jointed zones.

Large areas in the lower reaches of the Magdalena basin, as well as in the Orinoco-Amazonas and the Pacific basins, are frequently flooded and remain under water. Due to high rates of evaporation, inundated aquifers are salinized and have to be discarded as exploitable aquifers.

Deterioration of water quality was observed also in the semiarid La Guajira Peninsula, where salinization is related to mineralized aquifer beds. Sea water encroachment is observed, following high tides, near the Pacific and Atlantic coasts and on San Andres Island, where pumping has depleted the karstic limestone aquifer to dangerous levels.

DISCUSSION

About 5000 wells in Colombia produce annually 1100-1400 MCM of groundwater, 95% of this amount coming from the Magdalena-Cauca basin. The wells in the Cauca Valley alone extract 70% of the total amount pumped in Colombia.

The total extracted amount of groundwater is only a small proportion (6-15%) of conservative recharge estimates, thus leaving room for more development. Drilling costs, including casing, screens, gravel pack and well testing, vary from US\$ 100/m for small diameter and less than 100 m deep boreholes, to US\$ 200-250/m for large diameter deeper boreholes. The actual drilling costs combined with the low costs of energy make the exploitation of groundwater in Colombia economically attractive.

Even within the Magdalena-Cauca basin where groundwater pumping reaches 10-25% of the estimated recharge and where the major economic activity of the country takes place, there are many possibilities for additional quantities of groundwater to supply centres of demand. Only in two areas should measures be introduced to prevent irrevocable damage to these important resources: the Cauca Valley where exploitation is approaching the estimated safe yield, and in the Sabana of Bogota where production reaches 40-60% of total recharge.

In the Cauca Valley, reducing development in the upper aquifer and enhancing exploitation, already initiated, from the deeper aquifer is the correct step to attenuate or reverse negative effects. Another measure, still to be studied, is the augmentation of infiltration rates in the depleted areas by artificial recharge through the construction of spreading basins. The possibility of recharge through existing wells that remain idle more than 6000 h per year should not be discarded, in spite of the problematic clogging hazard.

To contain the alarming depletion in the aquifers of the Sabana of Bogota, controlled exploitation is imperative. This calls for the implementation of a tight programme with stress on effective licensing. A thorough groundwater investigation of the whole basin is needed to identify clearly the problem areas. Recharge of the aquifers could be augmented by spreading basins along various stream

courses like the Lower Tunjuelo, the Subachoque and possibly the Rio Frio.

The regulation capacity of the large aquifers is an asset to surface runoff. The huge aquifers in the Orinoco-Amazonas and in the Pacific basins, located in high rainfall regions with insignificant water demands, will remain practically untapped in the long term future. Therefore, groundwater integration in Colombia will be concentrated in the Magdalena-Cauca basin with the two largest exploitation centres, the Cauca Valley and the Sabana of Bogota, nearing the limits of their capacity.

Moderate demands in smaller or marginal aquifers call for innovative approaches and appropriate solutions, such as:

(a) Dispersal of pumping and sealing of certain sections in fresh water aquifers to reduce the danger of deterioration from nearby saline formations (Uraba, northern coastal area, middle reaches of the Magdalena Valley).

(b) Artificial recharge combined with sewage reclamation to halt sea water encroachment in San Andreas Island.

(c) Increasing the well production capacity in La Guajira Peninsula and development of agricultural ventures based on small-scale brackish water projects.

(d) Conveyance of fresh groundwater to towns located on saline aquifers, alleviating the serious water supply deficiencies. The feasibility of this solution was recently demonstrated by two wells, drilled near the Ariguani River (tributary of the Lower Magdalena River), that with yields of $250 \text{ m}^3 \text{ h}^{-1}$ supply the town of El Difícil, located some 20 km to the west.

The actual drilling capacity for water in Colombia is about 200 boreholes per year. The 50-600 m deep wells are drilled mainly by the direct rotary method and, on a smaller scale, by reverse circulation and percussion methods. There is a need to at least maintain and probably increase this capacity.

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