Pacific Science (1976), Vol. 30, No. 1, p. 91–100
Printed in Great Britain

The Hydrogeology and Water Supply Problems in North-Central Chile[1]

JOHN W. LLOYD[2]

ABSTRACT: The north-central zone of Chile is described with respect to groundwater supply problems. In this region, groundwater is almost exclusively obtained from the thin alluvium in the main transverse valleys, which descend from the Andes in those sections where the valleys cross the northerly trending "central valley." Because of the steep groundwater gradients prevailing, the groundwater resources are closely related to seasonal recharge. As the area is arid to semiarid and has been showing indications of increasing aridity over the past few years, water supply problems are proving to be a serious development constraint. Throughout the area, many examples of insufficient water supply may be encountered, and the problems of water use management and the utilization for industrial purposes of supplies such as seawater, brines, and sewage are now being considered.

THE NORTH-CENTRAL ZONE of Chile discussed in this paper is located between latitudes 26° and 32° S. It is bounded on the east by the mountain chain of the Andes reaching up to 6900 m above sea level and on the west by the Pacific Ocean. A range of mountains of altitudes up to 1950 m rises from the coastline and is separated from the Andes throughout much of the area by a northerly trending "central valley" system which ranges in altitude from 350 to 1200 m. The width of the area does not exceed 280 km and in places is as little as 90 km. The area location is shown on Figure 1.

The climate is arid in the north and semiarid in the south. From April to September, sporadic precipitation occurs and temperatures vary from about −8° to +20° C. From October to March, the area is usually dry with a temperature range of about 5°–32° C.

Geologically, the area spans the Precambrian to the Cenozoic eras and is a complex history of sedimentation, intrusion, and moderately severe structural movement. With respect to groundwater, the pre-Miocene rocks, which are of widespread occurrence, are of negligible importance, and the only significant resources occur in the younger sediments, particularly the Recent alluvial deposits which are confined to the present-day drainage systems.

The chief population concentrations with the exception of major ports occur in the central valley at its junction with major transverse valleys descending from the Andes to the Pacific.

Two main industries, copper and agriculture, are important. The area produces a large percentage of the copper which forms the basis of the Chilean economy, and the exploration and assessment of unexploited deposits indicate that the reserves are considerable and that the area will continue to have a high priority in the industrial and mining development of the country. In view of the future role of this industry, much attention is now being focused on the availability of long-term water supplies that are essential in the ore-processing stages.

In the central and western parts of the catchments of the ríos Copiapó, Huasco, Elqui, Limarí, and Choapa are large cultivable areas that in times of adequate water supply support a thriving agricultural industry based on grapes, cereals, and vegetable crops. Because of the dry climate, the agriculture is almost exclusively dependent upon irrigation.

---

[1] Manuscript received 3 January 1974.

[2] The University of Birmingham, Department of Geological Sciences, P.O. Box 363, Birmingham B15 2TT, England.

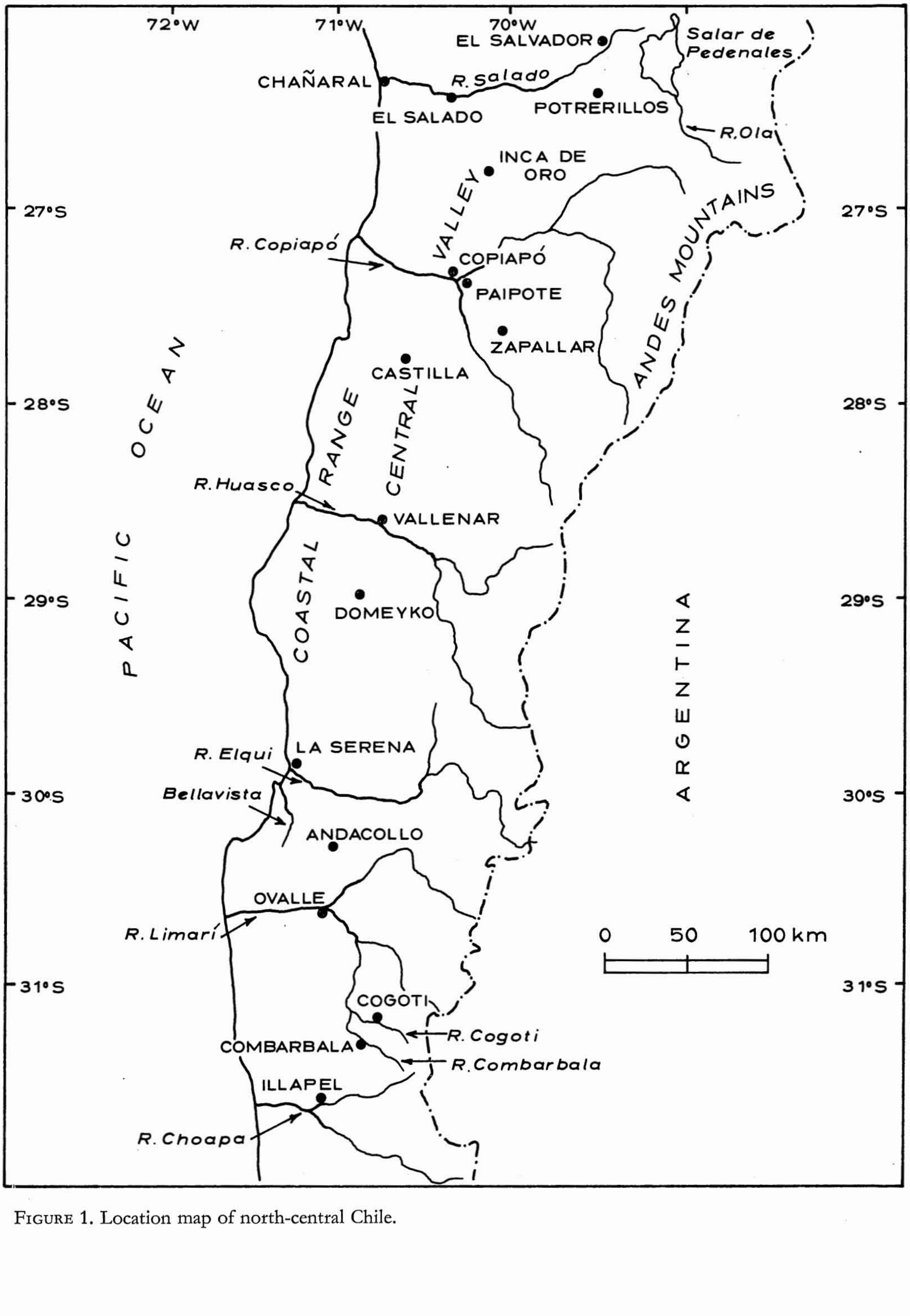

FIGURE 1. Location map of north-central Chile.

CLIMATE AND HYDROLOGY

The climate is closely associated with that of the Atacama Desert, which, as far as is known, has an intensity of aridity unequalled in the world (Trewartha 1961: 22–31). This extreme aridity is the result of a unique combination of several climatic and geomorphic controls. Of primary importance is the fact that the region is under the influence of strong air subsidence associated with the eastern limb of the South Pacific anticyclone. The anticyclone is a strong permanent feature in the region; it fluctuates very slightly and is abruptly terminated by the wall of the Andes. A persistently low temperature inversion therefore occurs in the air mass overlying the narrow strip of land and the adjacent sea west of the Andes. The inversion, which frequently reaches down to sea level, is intensified by the cold Humboldt Current flowing northward from the Antarctic parallel to the Chilean coast. The current reduces air temperatures over the sea and stabilizes the surface air.

The coincidence between the north-south trend of the coast and the eastern margin of the anticyclone is considered to be a supplementary aridifying factor (Lydolph 1967). The circulation along the eastern side of the cell produces southerly winds and a flow of air parallel to the coast. The difference in drag exerted by the land and sea surfaces upon this flow produces a stress differential in the air mass that results in a wind divergence to the east and subsidence in the surface air, particularly along the coast.

Further littoral subsidence of the air mass is associated with the onshore sea breeze that occurs during the day and that produces a strong temperature inversion at the boundary where maritime air is in contact with the warmer land air. As the maritime air spreads farther inland during the day, subsidence occurs.

During the period September to March, the area experiences the arid conditions outlined above. However, during April to August, occasional cold fronts penetrate into the area from the Antarctic and produce precipitation. This northerly movement of frontal passages is considered to reflect a seasonal weakening of the South Pacific anticyclone. The precipitation that occurs decreases in amount from south to north across the area. The orographic effects of the coastal mountains and the Andes produce local increases in precipitation while the coastal mountains give rise to rain shadow effects in the central valley. In Figure 2, the annual precipitation distribution for 1931–1960 and 1968 is shown. Schneider (1969) has analyzed the climatic data to indicate the Thornthwaite aridity features of the area for the period 1931–1960, which are also reproduced in Figure 2. These indices will vary with the period analyzed but give a good general picture of the arid-semiarid environment.

A feature of the climate is the extremely variable precipitation frequency and intensity. The main precipitation falls in the Andes as both snow and rain and forms the chief contribution to the runoff of the transverse rivers which flow to the Pacific. There are two conditions governing runoff: (1) the amount of snow and the period and intensity of melt, and (2) the amount, intensity, and frequency of rain storms.

As the transverse river systems are the chief source of water supply in the area, availability is closely related to runoff conditions. Runoff in turn controls the indirect recharge to the valley alluvium and is the only significant recharge element. Bed gradients are extremely steep, as would be expected from the topography; they range down to about 1 in 110 in the upper sections of the valleys but flatten considerably in the central valley sections. As a result, unless significant snow and slow-melting conditions occur, there is a rapid surface runoff which is also reflected in the alluvial groundwater discharges. The valley alluvium is thin, in consequence of which little groundwater storage is available so that groundwater supplies must depend almost exclusively upon throughput. In essence, therefore, the availability of water depends directly upon the amount of weakening of the South Pacific anticyclone. Because of the semiarid to arid nature of the area, any variation in the degree of weakening of the anticyclone is immediately reflected in water resources.

Since the early 1960s, the South Pacific anticyclone has proved unusually stable during the winter season, resulting in a marked fall in precipitation and, consequently, in water resources in the area. The general climatic

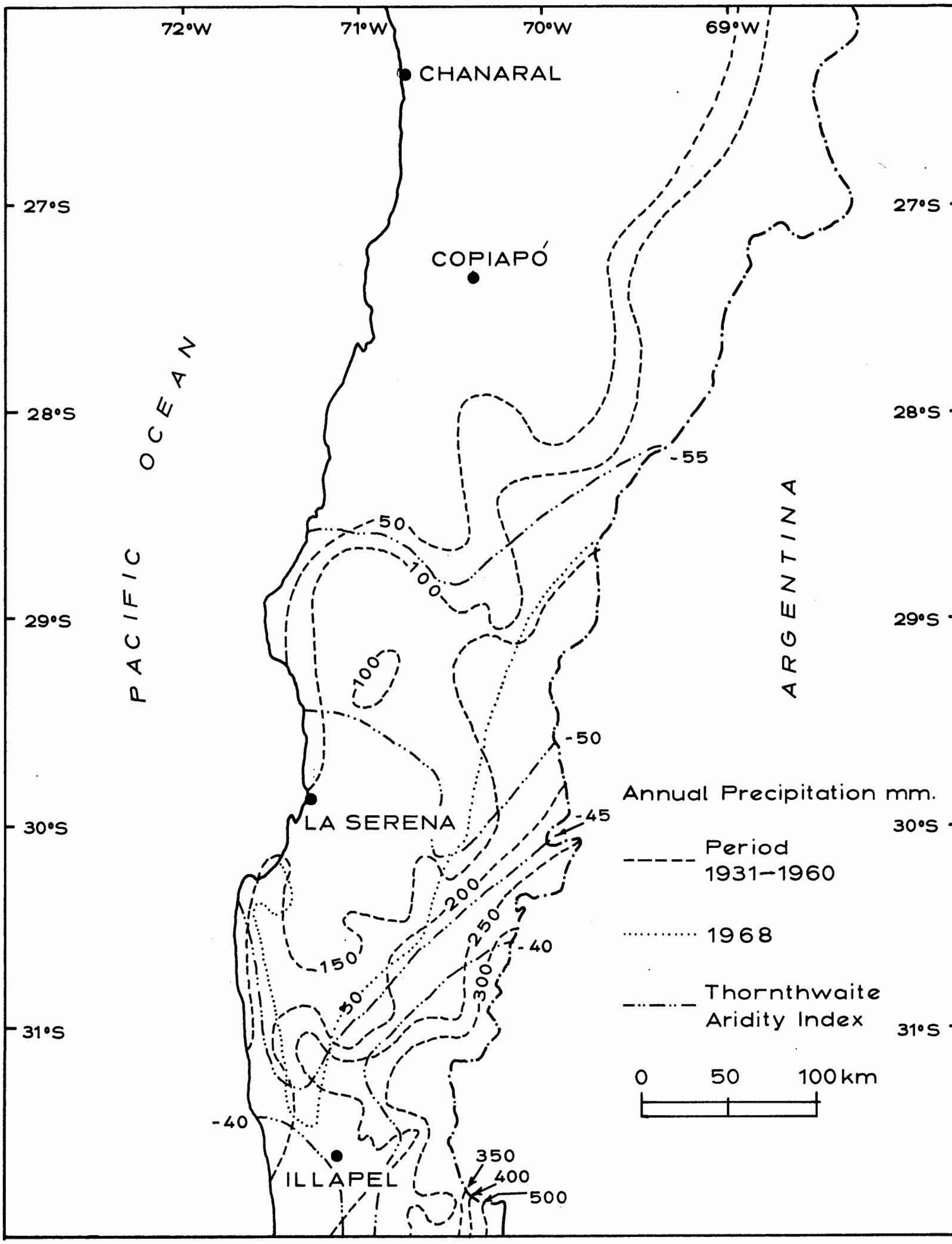

FIGURE 2. Climatic features, north-central Chile.

change is related to worldwide events (Lloyd 1973*a*) as described by Lamb (1966). Conditions in the area have changed from a moderately consistent annual precipitation between 1900 and 1960 to a lower modal annual fall but with more extreme variability, a situation which it is postulated could last until the end of the century. As such, the conditions resemble the pre-1900 type of climate that existed in the area.

This change in climate and water availability has come at a time when industrial expansion is being attempted in north-central Chile and, as a result, when management of the total water resources of the region has become of paramount importance.

HYDROGEOLOGY AND WATER SUPPLY

The area hydrogeology may be divided geographically into three parts. The southern part consists of ríos Choapa, Limarí, and Elqui, the central part of the ríos Huasco and Copiapó and the north of the Río Salado.

There are few Miocene-Pliocene terrace deposits in the southern valleys and the Recent alluvium is very thin, normally less than 25 m. This lack of extensive fluviatile deposits is attributed to the very limited development of the central valley, in which such deposits are well developed farther north.

Surface runoff is the most important water source in this sector supporting agriculture and population. Groundwater resources are poor due to the very thin aquifer thicknesses. In the Río Choapa system, the only groundwater development is in the vicinity of Illapel. Here some 1450 m^3/day are abstracted from the Recent alluvium for town and ore processing requirements. As with the other valleys in the south, the Recent alluvium in the Río Choapa consists of a clay unit overlain by coarser material. At Illapel the clay is up to 6 m thick and is overlain by 5 m of gravels. Seismic profiling at several sites in the southern sector has indicated the presence of material interpreted as gravel below the clay, which has later been revealed to be weathered granitic material that produces ghost seismic reflection surfaces within the basement. From the groundwater-resources point of view, the coarse upper alluvium and the weathered granitic zone produce water.

Because of the limited thickness of gravels at Illapel, the most efficient well design has proved to be one of 2–3 m of screen located at the base of the aquifer with blank casing above. Screen slots are selected to allow the removal of 60 percent of material from around the well to produce minimal well losses. Screen development is carried out by careful surging inside the screen and this process has proved considerably more effective than surging above the screen. Pump settings are also within the screen. Yields have been obtained of up to 27 liters/sec for 0.7 m of drawdown with the water table near the surface during winter and spring; the rapid throughput, however, results in a drastic drop in water level (1.5 m) in the autumn with a corresponding drop in well yields by some 60 percent. Throughputs vary considerably from about 6000 m^3/day in spring to about a minimum recorded 2200 m^3/day in autumn when water supplies are marginally below projected requirements. As all available surface water is used for irrigation in the Andes foothills, there is a marked need for the implementation of careful water management plans.

An interesting feature of the groundwater in the Illapel area is its chemistry. The groundwater in the alluvium is SO_4 in character, with positive tritium values of 16–20 TU. During summer, however, wells that penetrate to the granitic weathered zone beneath the clay and draw from both aquifers produce non tritiated HCO_3 water. This water is believed to originate from the weathered zone but initially must have passed into the zone from the overlying alluvium, presumably at some distance from the wells. As the water throughout the catchment is SO_4 in character, ionic exchange must occur within the weathered granitic zone.

In the catchment of the Río Limarí, the central valley features are poorly developed. A limited but prosperous agriculture based upon surface-water-irrigated terraces does occur at Ovalle and, throughout the broad valleys of the major tributaries, surface water irrigation is quite extensive but heavily dependent upon three major dams which have frequently failed to supply sufficient water over the past decade. Because of the thin alluvium in the valleys and the construction of the dams with cutoff walls to bedrock, groundwater developments in the Limarí catchment have been minimal. The main interest in the vicinity of Combarbala has been to provide water for copper ore processing.

In the Río Combarbala, minimum autumn throughput has been measured at 170 m^3/day on the basis of discharge from a drain constructed to bedrock to abstract the total groundwater flow. The drain, which is situated near the town, commands a catchment of 245 km^2 in a relatively high rainfall zone; the runoff, however, is used largely for irrigation upstream and the thin nature of the alluvium (up to 4 m thick) precludes any significant groundwater resources. In the neighboring major valley, the Río Cogoti flows from the Andes with high winter and spring discharges. Due to a combination of fast runoff and irrigation use, groundwater discharges are also insignificant. Attempts to obtain supplies near to Cogoti have revealed similar stratigraphy to that in the Río Choapa catchment. Clays overlie the bedrock and are overlain by coarser material—in this case, fine to coarse sands with boulders and up to 6.5 m thick. Both dug wells with slotted pipe and screened percussion wells have been constructed for supply but neither has proved capable of yielding more than 1.5 liter/sec during the dry periods. A minimum throughput of 520 m^3/day, with permeabilities of the order of 370 m^2/day, has been calculated. For supply purposes, the available water is insufficient during drought periods.

The chemistry of the groundwater reflects the geology of the catchment of the Río Cogoti in that it is HCO_3, derived from the predominantly granitic terrain, and differs in this respect from all other major water sources in the area which have sulphate chemistry.

In the Río Elqui, catchment groundwater is abstracted from a few wells near La Serena where the wells induce their discharge effectively through the alluvium from the base flow. In dry seasons, discharges reduce drastically as base flow becomes negligible. Yields range up to 20 liters/sec with alluvial thicknesses of up to 25 m; permeability values are of the order of 700 m^2/day. The water is sulphate in quality and used extensively for irrigation. No surplus water is available in the catchment and a major new ore processing supply required for Andacollo is to be obtained from the sea through a 23-km pipeline (Lloyd 1974*a*).

Close to the sea in the vicinity of La Serena, shallow-dug wells tap thin lenses of freshwater. There is recent evidence of overdevelopment from the increase of chlorides in some of the wells, which is attributed to the poor recharge conditions over the past few years.

To the south of La Serena, groundwater is abstracted from late Tertiary fluviatile gravels in the Bellavista valley. Rainfall to the catchment is low, with annual averages not exceeding 100 mm. The recharge to the valley is limited, as indicated by the absence of significant groundwater gradients and by the low tritium content of the groundwater which is less than 0.5 TU. Although several wells tap the alluvium, they have been brought into commission only recently so that no noticeable water level decline has yet occurred. The valley, however, has been subjected to late-faulting river capture and base level changes that may have resulted in the impounding of a limited volume of groundwater in the Tertiary deposits.

To the north of the Río Elqui catchment the central valley becomes a dominant topographical feature, with its boundaries being defined by a system of faults related to the late movements associated with the creation of the Andes.

Throughout this central valley section, considerable thicknesses of late Tertiary gravels have accumulated. The maximum thickness recorded is 400 m, 8 km to the west of Vallenar (Lloyd 1973*b*). The gravels have been eroded to form an impressive series of terraces in the Huasco and Copiapó valleys. Base level rises since the formation of the terraces have resulted in deposition of Recent alluvium which is most pronounced in the central valley sections of the transverse valleys. Where the valleys emerge from the Andes foothills, a marked reduction in bed gradient occurs and the valleys widen. The widening is attributed to lesser flow velocities that have produced braided channels and to the fact that the late Tertiary gravels are more easily eroded than are the older harder rocks of the hinterland.

In the Huasco valley in the vicinity of Vallenar where main groundwater development is operative, the Recent alluvium comprises the main aquifer, ranging up to 50 m in thickness. Except for periods of extremely high floods, a 6-km section of the valley at Vallenar receives no surface flow, although the water table is only very shallow. The lack of flow is attributed to irrigation offtake upstream. Surface flow reappears downstream of the town.

Numerous wells have been constructed in the valley for potable and industrial uses. Yields range up to 25 liters/sec, with specific capacities of the order of 12 liters/sec/m. The permeability of the gravels is variable, 1100 to 4200 m^2/day, and, as a result, standard well design is difficult to implement. The most effective designs incorporate screens at the well base where coarse material generally is present, with the slotted pipe sections being used against any higher high permeability zones.

Hydrogen sulphide has been recognized at very low levels (up to about 1 ppm) in parts of the valley, and it has resulted in corrosion and incrustation of the slotted pipe that have affected yield-drawdown relationships drastically in a matter of 2 years. Step-drawdown data indicate that the effects are localized at the wells and do not penetrate the formation; in consequence, in these areas, slotted pipe is being avoided to reduce active cathodic surfaces, and stainless steel screens alone are being recommended for the production zones.

Immediately downstream of Vallenar, total flow in the Huasco valley was measured during the 1972 drought period and calculated to be 5.4 10^4 m^3/day of which 3.4 10^4 m^3/day comprised irrigation and surface flow. The 2.0 10^4 m^3/day of groundwater flow in the vicinity of the town is adequate for the present water supply demands of about 1.24 10^4 m^3/day, although future development needs have not been established. Downstream of the town, the Huasco valley water is of limited value because of a rapid increase in water salinity from 680 to 3450 ppm. This increase is a function of summer evaporation of the shallow groundwater depositing salts in the gravels, which are redissolved by spring flows with the consequent rise in dissolved salts content in the water. With a view to groundwater management, wells for copper ore processing have been constructed to tap the saline water in places contaminated with sewage, as quality is not a severe constraint.

Seasonal recharge to the Recent alluvium aquifer in the Río Huasco is through surface runoff into the gravels in the Andes. The water is $CaSO_4$ in character with high tritium values, but, in the vicinity of Vallenar, Ca-$NaSO_4$ water is present in a zone along the northern side of the valley; this indicates a limited lateral nontritiated recharge to the main aquifer from the adjacent late-Tertiary gravels.

During studies in the ríos Huasco and Copiapó, specific yield values were established for a number of areas, with traditional pumping test analysis techniques being used, particularly that of Boulton (1963). In general, even with delayed yield effects accounted for, the values (0.9–3.7 percent) have appeared to be low for the lithologies present. A possible explanation for this may be postulated from water level data obtained in July 1971. A continuous water level recorder that was in operation during a grade 6 (Richter scale) earthquake at Vallenar recorded a water level rise of 0.07 m at the time of the quake with no return to the prequake level. Similar changes have since been noted in minor quakes. It is considered, therefore, that the loose valley alluvium is being compacted by earthquake shaking and, as a result, porosity and specific yield are being reduced, causing a further constraint on groundwater availability.

To the west of Vallenar, the central valley is controlled by northerly trending faults. Some of the faulting is late-Tertiary in age and has affected the Tertiary gravels of the central valley. In some of the lesser transverse valleys, which rise in the foothills of the Andes, an easterly downthrow of the western central valley boundary faults has not been countered by subsequent effective downcutting, as has been the case in the main transverse valleys such as the Huasco; therefore, groundwater flowing from the Andes in the Tertiary and younger gravels in such valleys has been impounded at the faulted margins and has not been released westward by subsequent erosion (with the exception of minor overspill).

In the vicinity of Domeyko and Castilla, such resources have provided limited groundwater supplies but water level declines and salinity increases are now occurring as the effect of groundwater mining becomes apparent. Tritium evidence indicates that the waters are dead and, unfortunately, radiocarbon dating has proved valueless because of the very low bicarbonate content of the waters. The situation is particularly serious in Domeyko where the supply of one of the main wells had dropped from 1400 to 170 m^3/day since 1942.

In the Río Copiapó, groundwater abstraction occurs at a varying amount from a point some 42 km upstream of Copiapó to the river mouth. Requirements are for irrigation, population (1.6 10^4 m^3/day), and copper processing (1590 m^3/day). Italconsult (1963) calculated the total groundwater throughput for the valley to be 7.8 10^4 m^3/day. This value is certainly lower in drought periods and in 1972 it was estimated to be about 4.0 10^4 m^3/day.

Tertiary gravels are not so well developed in the Río Copiapó valley as in the Río Huasco and are of negligible groundwater importance. The Recent alluvium is much thicker here than it is to the south, however, with thicknesses of up to 120 m recorded in wells near Paipote. Chemical characteristics of the groundwater do not appear to be detrimental to well construction, so that slotted pipes can be used. Highly efficient wells can be constructed up to 70 m deep in which naturally developed slotted pipe sections are distributed against selected coarse alluvial zones. Specific capacities of the order of 30 liters/sec/m can be obtained. Throughout the valley, individual well yields have decreased over the past few years, particularly in shallow wells where water level decline has been most significant. As water requirements have risen in the valley, overall availability has declined and, although the situation is not critical, the main problem revolves around the management of water resources and the balance between a socially important agricultural industry, a highly profitable copper industry, and potable requirements.

The changing climate of the region is causing more emphasis to be placed on the water resources of the main transverse valleys than before. Whereas previously tributary and minor transverse valleys were able to support minor agriculture and small copper ore processing plants, today in many such valleys only abandoned farms and dying stands of trees are present. An example of the reliance of the copper industry on the main transverse valley system can be seen at Zapallar, 30 km to the east of the Río Copiapó. The ore deposit is significant, consisting of 15 million tons of 0.5–1.5 percent copper. The processing plant requires a supply of 4150 m^3/day, but, under the present climatic regime, only 160–250 m^3/day can be obtained at sites near the deposit; as a result the ore will have to be trucked to a plant located in the main Copiapó valley. In such areas, any copper deposit must be of sufficient grade to counter the additional cost of long haulage to main water sources. In many instances, the economics prove impossible; for example, in the vicinity of Inca da Oro on the watershed between the ríos Copiapó and Salado, a supply of only 2000 m^3/day cannot be obtained for a plant, even if a 42-km pipeline is taken into consideration. In another example, to the northeast of Vallenar, the mining of a porphyry copper deposit of 60 million tons of 1 percent copper ore with 0.04–0.05 percent molybdenum has proved to be totally unfeasible due to the lack of a local water supply and of its uneconomic distance from the Río Huasco.

In the region to the north of the Copiapó valley, freshwater resources are virtually nonexistent except in the high Andean streams. In the Río Salado valley, the most northerly of the major transverse valleys, the potable water supply for the port of Chañaral is obtained by pipeline from the Copiapó valley. The most important water requirements, however, are industrial. The area is a major world copper-producing area with the two large porphyry deposits of Potrerillos and El Salvador located in the upper Río Salado catchment. Apart from these developments, there is a large investment in small- and medium-scale mining that supports 60 percent of the employment in the area and this activity in such a climatic zone poses significant water supply problems (5000 m^3/day requirement).

The area is mountainous and highly dissected. The watershed between the Río Salado and the Salar de Pedernales rises to between 3500 and 5280 m elevation above sea level. The latter catchment extends nearly to the Argentinian border and rises to just below 6000 m in the main Andes range. As with the other major transverse valley, during the uplift of the Andes the proto-Río Salado originated in the Andes and cut across the central valley and the Coastal Range to the sea. Sometime during the later history of the uplift, the upper catchment of the system was tilted to the northwest (Mortimer 1969), thus separating the system into the high level Salar de Pedernales internal drainage catchment in the east and the present Río Salado catchment drains to the Pacific in the west.

The hydrogeology of the two present-day catchments is unusual. Base flow from the Andes occurs mainly in the Río Ola and flows into the Salar de Pedernales salt flats. The important water supply for Potrerillos and El Salvador, which amounts to 5.1310^4 m^3/day, is obtained from a small impounded reservoir on the Río Ola. Some 110 liters/sec, however, pass to the salt flats (Constantini 1960). The inflow water (2500 ppm total dissolved solids) is enriched in salts in the basin and overspills as groundwater flow through volcanic ejecta of the watershed into the upper Río Salado catchment where the head springs contain 70,760 ppm total dissolved solids. The Río Salado is perennial for several kilometers before it infiltrates into the Recent alluvium of the valley floor and reappears as springs (73,040 ppm total dissolved solids) at El Salado.

Because of the absence of other water resources and because copper ore processing is not seriously constrained by water quality, the El Salado springs are being exploited for processing purposes (Lloyd 1974*b*). To obtain both surface and groundwater flow to dewater the seepage area where evaporation occurs and to limit the effects of flash floods on surface structures, a subsurface abstruction system using drains has been designed. The drains are backfilled with filtered materials and have perforated wooden-cased wells for pump installation.

CONCLUSIONS

The hydrogeological environment of the area described is very distinct, consisting almost exclusively of groundwater resources in thin valley alluvium. The nature of the terrain, with the towering Andes range close to the Pacific Ocean, results in very steep bed gradients in the major transverse valleys that flow from the Andes to the sea. These gradients are mirrored by the groundwater gradients in the alluvium, so that groundwater availability is closely related to the seasonal recharge, which is a feature of the climate, and little storage water is available.

The area under discussion borders the Atacama Desert and is semiarid to arid. Because of the climate and hydrogeological environment, groundwater resources have historically proved to be a problem; over the past decade, unfortunately, there are indications of a lower modal annual rainfall with droughts possibly related to climatic change effects in the region. This factor has worsened an already difficult water supply situation.

Surface water supplies are largely canalized in the Andes foothills and are used for irrigation purposes. As a result, in the central valley area where the main population occurs and where industry is most prevalent, water supply is largely dependent upon groundwater. In addition, the decrease of bed gradient in the transverse valleys within the central valley allows surface water to infiltrate, thus accentuating the predominance of groundwater.

It is within the central valley area that the main groundwater management problems are now being posed. Because of the decrease in rainfall, the minor tributary valleys no longer provide dependable groundwater supplies, so that water requirements for any developments in these valleys are consequently being transferred to the main transverse valleys. The population is increasing in the main transverse valleys and, as that population becomes more sophisticated, it requires more domestic water; this factor, together with the emphasis on industrial development largely centered on the copper industry with its significant water needs, means that the overall water requirement is multiplying at an alarming rate.

Government agencies are looking at the need to ensure reliable potable supplies, but the main problem is the need to balance water use between agriculture and industry so that water resource use is optimized to the greatest advantage. Agriculture already has been hit severely by recent droughts and will probably suffer far more. Increased efficiency in water use is being effectively promoted by the increase in production of higher value cash crops and by the renovation of irrigation distribution systems. It would appear, however, that agriculture will more and more suffer from a lack of sufficient water as farming uses considerably more water than do industry and population.

The copper industry is the major industrial user of water (Lloyd 1974*c*). Its requirement as compared to agriculture is small, but the cash value of copper far exceeds that of agricultural products so that the reliability of the long-term supplies for copper processing is an important economic factor and must be assured. It is important that the industry should use its water efficiently. Closer attention to the recirculation of processing water where recovery efficiencies are often low would be advantageous. More consideration should be given to the utilization of seawater and water such as brines or sewage that are not generally suitable for other uses. Costs may prove to be higher than those incurred by use of freshwater but, in the long term, more use of seawater, particularly, may prove unavoidable because of its reliability.

Eventually, if conditions continue to deteriorate, it will be necessary to determine water-use priorities, a socioeconomic problem outside of the scope of this paper. In any case, with the implementation of comprehensive groundwater investigations and coordinated water management policies, a sound basis can be constructed on which to found development decisions. Sufficient work has already been carried out to indicate the critical nature of the water supply situation, but, because of the unusually difficult hydrogeological environment, much more study is required.

ACKNOWLEDGMENTS

The writer would like to thank the staff of the Water Resources Office of the Chilean Empresa Nacional de Minería for their assistance in data collections and analyses. This paper has been published with the permission of the Director, Institute of Geological Sciences, London.

LITERATURE CITED

BOULTON, N. S. 1963. Analysis of data from nonequilibrium pumping tests for delayed yield from storage. Proc. Inst. Civ. Eng. (London) 26 (6693).

CONSTANTINI, R. 1960. Process water and hydroelectric plant, El Salvador. Min. Eng. (N.Y.). April: 375–378A.

ITALCONSULT. 1963. Aprovechamiento de recursos hidráulicos en el valle de Copiapó. Consultants Rep., Dep. Recursos Hidráulicos, Corp. de Formento de la Producción, Chile. 253 pp.

LAMB, H. H. 1966. Climate in the 1960s. Geogr. J. 132(2): 183–212.

LLOYD, J. W. 1973*a*. Climatic variations in north-central Chile from 1866 to 1971. J. Hydrol. 19: 53–70.

———. 1973*b*. Hydrogeology of Quaternary sediments in the vicinity of Vallenar, Atacama Province, Chile. Paper presented at Second Latin American Geological Congress, Caracas.

———. 1974*a*. Water supply for the Andacollo copper ore processing plant, Chile. Trans. Inst. Min. Metall., London 83: 1–6A.

———. 1974*b*. The hydrogeology and utilization of brines in El Salado, Chile. Groundwater 12(2): 72–77.

———. 1974*c*. Importance of water resources in the development of the Chilean copper industry. Trans. Inst. Min. Metall., London 83: 63–66A.

LYDOLPH, P. 1967. On causes of aridity along a selected group of coasts. UNESCO Conferencia Regional de Zonas Aridas, Lima. 6 pp.

MORTIMER, C. A. 1969. The geomorphological evolution of the southern Atacama Desert, Chile. Ph.D. Thesis. University of London.

SCHNEIDER, H. 1969. El clima del Norte Chico. Pages 43–125 *in* Publ. Departamento de Geografía, Universidad de Chile, Santiago.

TREWARTHA, G. T. 1961. The earth's problem climates. University of Wisconsin Press, Madison.