Provincia de Atacama

GROUND WATER

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The Hydrogeology and Utilization of Brines in El Salado, Chile

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ABSTRACT

The Rio Salado catchment is located in the southern Atacama Desert. The area is distinctly arid and no ground-water reserves originating from local recharge exist. To obtain water for a new copper ore processing plant, brines are being utilized. The complex hydrogeology of the brines from their origin in the Andes to their emergence as springs in the vicinity of El Salado is described.

The surface and ground-water discharges indicate that the long-term supply of brine will be adequate for the processing plant. A design for abstraction incorporating three filter drains with wooden pump-housings has been adopted to combat corrosion, incrustation and flood damage.

INTRODUCTION

The valley of the Rio Salado is located approximately along latitude 25°21'S in the southern Atacama Desert of Chile (Figure 1). It extends from Chanaral on the Pacific Ocean some 140 km. inland to the watershed with the Salar de Pedernales internal drainage catchment. A map of the two catchments is shown on Figure 2.

The area is mountainous and highly dissected. The watershed between the Rio Salado and the Salar de Pedernales rises to between 3,500 and 5,280 m. elevation above sea level. The latter catchment extends nearly to the Argentinian border and rises to just below 6,000 m. in the main Andes range.

The area is a major world copper-producing area with the two large copper porphyry deposits of Potrerillos and El Salvador located in the upper Rio Salado catchment. Apart from these developments there is a large investment in small and medium scale mining. The output from this sector is in no way comparable with the major industry, but is of considerable importance with respect to employment in that some 60% of the total labour force in the area is involved.

Ore processing facilities for the small and medium scale mines are limited. At present a small capacity flotation and lixiviation plant exists at El

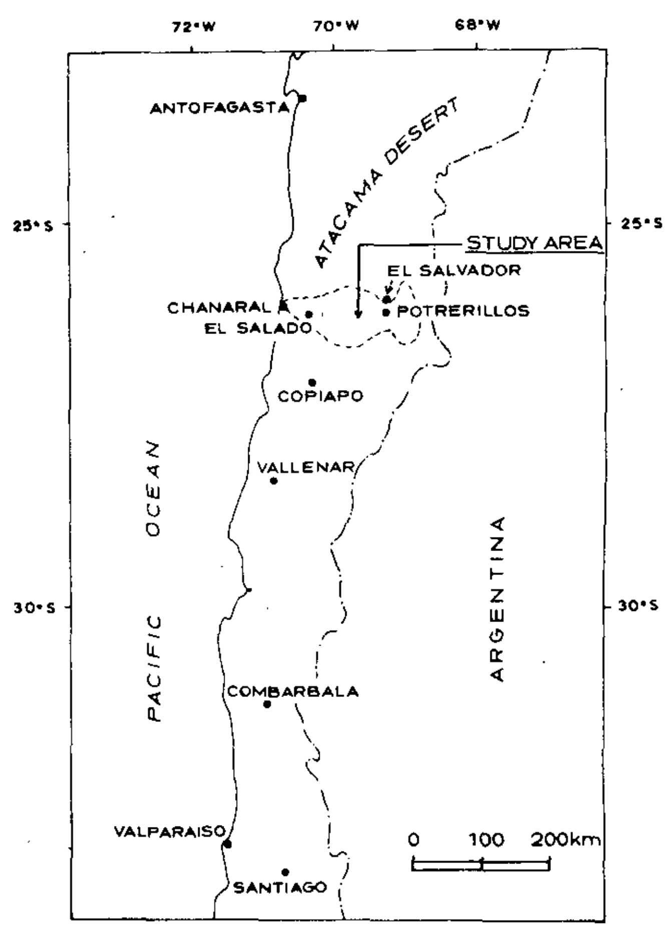

Fig. 1. Location map.

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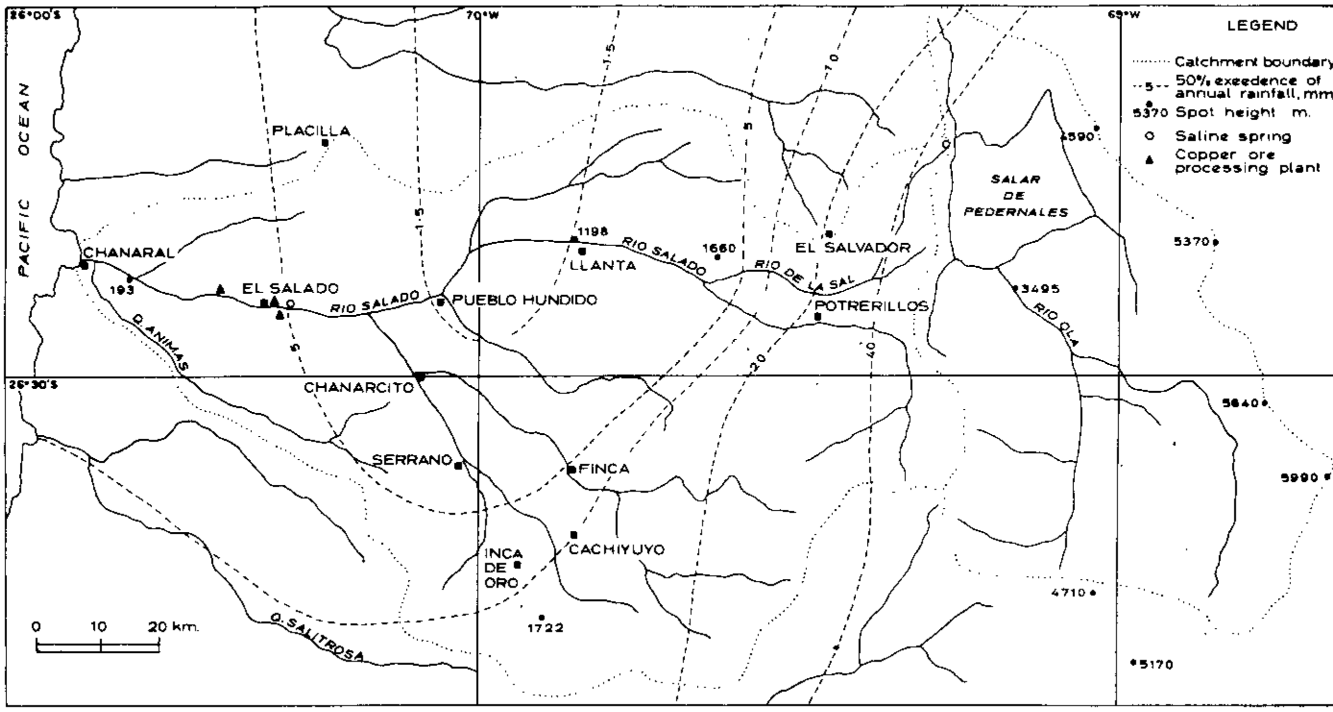

Fig. 2. Surface catchment areas of the Rio Salado and Salar de Pedernales.

Salado and, nearby, a small flotation plant reprocesses the tailings stream which flows from El Salvador to the sea.

To expand production, the construction of a new lixiviation plant under the auspices of the Empresa Nacional de Mineria (E.N.A.M.I.) has been planned 7 km. downstream of El Salado. The plant location has been selected on the basis of its proximity to the main producing mines and adequate space for tailings disposal. The feasibility of the project, however, has been heavily dependent upon the availability of an adequate long-term water supply which is essential for the processing involved.

It has been calculated that the new plant will require a supply of 50 lit./sec. which will be coupled with the supplies of the existing plants for a total requirement of just below 60 lit./sec.

HYDROLOGY

The Atacama Desert has an intensity of aridity unequalled in the world (Trewartha, 1961) so it is not surprising that water availability in the Rio Salado catchment is limited.

The northeastward passage of depressions across the area in winter results in a marked decrease in precipitation northwards. The pattern is influenced strongly by topography, and orographic rainfall increases eastwards into the Andes as shown on Figure 2 with a slight increase also in the coastal mountains.

The precipitation which falls chiefly between June and August is variable in intensity and amount. Data are sparse, but, on the basis of the annual precipitation statistics shown in Table 1, the unfavourable inference for any water resources dependent upon local recharge in the Rio Salado catchment is clearly demonstrated.

The catchment of the Salar de Pedernales cannot be considered as part of the Atacama Desert. No data are available for precipitation in the catchment, but it is believed to be substantially higher than in the Rio Salado from the observed runoff. Precipitation occurs in winter, and some-

Table 1. Annual Precipitation Statistics (mm.)

Station	*Mean*	*Max.*	*Min.*	*S.D.*	*Coef. of Var.%*	*Years*
Chanaral	12.3	81.0	0.0	15.7	128.1	47
Potrerillos	40.9	232.4	0.0	52.5	128.3	45
Pueblo Hundido	7.3	30.0	0.0	10.1	138.4	10
Llanta	9.2	21.0	0.0	8.3	89.6	9
Inca de Oro	14.3	52.8	0.0	16.1	112.8	11

times also in the summer when the area falls sporadically under climatic influences extending from northern Argentina.

The major river in the catchment is the perennial Rio Ola which flows into the "Salar" (salt flats) from the south. Peak flows occur in July and August but there is little fluctuation as much of the flow originates as spring flow. In addition runoff is modified and controlled by the rate of snow-melt as most of the precipitation in the area occurs as snowfall. Under natural conditions the Rio Ola flow passes into the "salar" where it evaporates or infiltrates.

GEOLOGY

Over the years considerable attention has been paid to the problems of water supply in the Rio Salado catchment chiefly with a view to obtaining potable supplies for the local settlements. Due to the nature of the climate all studies have been restricted to ground-water assessments.

Rocks ranging from the Paleozoic to the Lower Tertiary predominate in the area but the geology is complex and no significant aquifers are present in rocks of pre-Miocene age.

Faulting occurred in the area throughout the Tertiary and into the Quaternary and culminated in the formation of the Andes (Clark *et al.,* 1967; and Mortimer, 1969). In the Lower Tertiary block, faulting gave rise to the initial delineation of the three dominant topographic features present in the area today—a Coastal Range extending inland to El Salado, the Andean Cordillera rising to the Argentina border from the vicinity of Llanta, and an intervening northerly trending "longitudinal valley".

During the various phases of the Andean uplift, valleys such as the Rio Salado were initiated. These valleys originated in the Andes and cut transversely across the "longitudinal valley" and the Coastal Range to the Pacific. Following canyon development which was associated with uplift in the Miocene, marine transgressions caused widespread deposition throughout the "longitudinal valley". These deposits are predominantly coarse to medium-grained, partially cemented, fluviatile sediments which form a very low-yielding aquifer in the triangle between El Salado, Inca de Oro and Llanta.

Sometime during the late history of the Andean uplift, the upper catchment of the proto-Rio Salado was tilted to the northwest (Mortimer, 1969). This movement separated the Andean drainage from the western drainage and created the two catchments existing today. The separation resulted in the formation of the Salar de Pedernales as an internal drainage basin and thus excluded the present Rio Salado drainage from the direct hydrological influence of the high cordillera. The "salar" has since accumulated a sequence of evaporites of unknown thickness and composition. At the surface, gypsum and rock-salt are developed and saline standing water occurs in the north.

Following the separation of the catchments, renewed uplift produced headward erosion in the Rio Salado catchment, which in the Rio de la Sal has cut almost into the "salar" area. At present, aggradation is occurring in the valleys on a very minor scale and headward erosion is minimal.

Due to the arid climate, the present alluvium being deposited is not very extensive; it forms the existing river courses and is composed mainly of sands and gravels with a silt matrix. It is, however, more permeable than the Miocene fluviatile sediments and forms the most important, though very limited, aquifer in the area.

WATER SUPPLY

In the Salar de Pedernales catchment, water supply has to date proved satisfactory. The important water supply for Potrerillos and El Salvador, which amounts to 620 lit./sec., is obtained by the means of a small dam on the Rio Ola. The scheme has been in operation since 1927 and uses the bulk of the river's flow. Constantini, however, estimated that in 1960 approximately 110 lit./sec. still flowed on an average into the "salar".

In the Rio Salado catchment the water-supply situation has proved far from encouraging. Studies of the ground water in the Miocene and Recent sediments in the catchment have been carried out by Barraza (1969) and Monti (1973). The results have been largely negative and the potable water solution has been solved by piping water into the catchment from the Copiapo area. Similarly no local fresh water is available for copper processing but due to the general scarcity of water in north-central Chile it is not possible to import water for processing purposes. Fortunately an alternative solution has been provided by the use of brine. This has been made possible by the fact that water quality does not pose a significant problem in copper ore flotation and lixiviation.

The small plants at El Salado have for many years obtained their supplies totalling 6.9 lit./sec. from a zone of saline seepages which rise from the Recent alluvium in the river bed upstream of the plants (Karzulovic, 1970). In the absence of any other supplies it was decided to study these seepages with a view to fully exploiting them for the new expansion. They have accordingly been investigated with respect to their origin and discharge in order to assess their use as a long-term supply.

The hydrogeology of the seepages was found to be unusual. Saline water which flows perennially in the Rio de la Sal rises from head springs along the watershed with the Salar de Pedernales, and flows to just upstream of Llanta where it infiltrates into the Recent alluvium to reappear in the El Salado seepages. The seepage line in the Rio de la Sal occurs in permeable volcanic ejecta overlying impermeable Jurassic rocks and the flow in fact represents ground-water overspill from the internal drainage basin of the Salar de Pedernales.

To assess flow variation in the system, measurements were taken at the El Salado seepage zone. Canals were excavated approximately 0.5 m. deep across the zone to determine the discharge potential and to drain the area. Weekly measurements of surface flow were made between January 1972 and May 1973. The total flow obtained ranged randomly between 67.3 and 71.8 lit./sec. which was a considerable increase over the previous uncanalised flow. As spring flow would normally portray any seasonal variation in the system, it was concluded that such variation does not exist.

The lack of seasonal variation is seen as being due to the following sequence of events--the initial steady flow of the Rio Ola from springs, the smoothing influence of the large Salar de Pedernales ground-water basin, and finally, a similar smoothing influence of the long ground-water flow section in the Rio Salado valley between Llanta and El Salado.

Due to the problems of inaccessibility, only two surface flow measurements were made in the Rio de la Sal, both of which gave a discharge of 65 lit./sec. The figures tend to indicate that the discharge from the Salar de Pedernales is essentially constant. Further, as the Potrerillos-El Salvador water-supply scheme has been in operation since 1927, it is fairly certain that the artificial influences are well established in the system.

A further interesting factor is that there is little change in the chemistry between the Rio de la Sal surface water and the El Salado seepages. As can be seen in Table 2 the total dissolved solids increase from 70,758 ppm to 73,040 ppm. This indicates that there is no significant ground-water contribution from the tributaries of the Rio Salado where much fresher water is encountered (i.e. see Table 2) and is some indication of the poor potential of the ground water originating within the catchment. It also indicates that the additional ground-water flow of 28 lit./sec. at El Salado discussed below must originate as subsurface overspill from the Salar de Pedernales.

In view of the flow data and the assessment of the hydrogeological system, it was concluded that the saline springs at El Salado could support the long-term plant requirement.

With respect to abstraction it was decided on the basis of the following factors to adopt a subsurface method in preference to a simple surface off-take system.

1. Additional discharge could be obtained for ground-water flow allowing a larger safety margin.

2. The seepage area would be dewatered with time, reducing evaporation and increasing water availability.

3. Subsurface structures would not be readily subject to flash flood damage.

Initially the possibility of using wells or a well-point system incorporating screens was studied. The presence of extensive salt deposits in the seepage area, however, is obvious evidence of incrustation where the water comes into contact with the atmosphere and is subject to evaporation. It was concluded that similar incrustation could occur in a well system within the cone of depres-

Table 2. Hydrochemical Analyses from the Rio Salado Catchment, Sample Date January 21, 1971 (ppm)

Water point	*Total dissolved solids*	*Ca*	*Na*	*SO_4*	*Cl*
Rio de la Sal	70,758	1,100	26,100	2,200	41,900
El Salado Spring	73,040	1,048	26,100	2,200	41,900
Cachiyuyo	1,253	200	190	630	193
Seranno	738	118	120	350	84

sion and cause closure of the screen slots. For continual operation therefore a standby system would be necessary to facilitate cleaning. In addition, the chemistry of the water shows that it has a pH of the order of 7.2 with a dissolved CO_2 content of 31 ppm and an alkalinity of 90 ppm $CaCO_2$ indicating a strongly corrosive water which would necessitate expensive noncorroding steel for screening purposes.

From the above observations it was decided that filter drains would prove cheaper, and simpler to maintain and operate than screens. Properly designed filter drains were chosen to avoid turbulent flow conditions which might cause incrustation and reduce permeability in the aquifer at the drain face. A site for the construction of the drains was selected downstream of the main seepage area to allow easy operation of earth-moving equipment and five test-pits were excavated to approximately 4 m. It was intended that the pits should reach 8 m. but this was not possible due to continual collapse below the water table between 1-2 m. below ground surface. A depth of 8 m. was chosen from "bedrock" indications of seismic soundings. The lithology proved consistent throughout being composed of fine-grained sands and silty sands with gravel lenses and cobbles.

Pumping tests were carried out on the pits and an average permeability of 32 m./day was determined. No diminution in surface flow was observed. With a drain design depth of 7.5 m. the value of throughput amounts to 28 lit./sec. over the valley width under the existing ground-water gradient. With the surface flow, the total flow within the influence of the drains therefore amounts to approximately 98 lit./sec., well in excess of the processing plant requirement of 60 lit./sec. It will be noted that the total figure is close to the flow entering the Salar de Pedernales from the Rio Ola.

The drains were designed in a V-shape as shown on Figure 3 to provide a large open aquifer section area. To combat corrosion the pump-housings were designed as wooden tubes perforated with 3/8" holes from 3.5-7.5 m. below the surface. The main filter (F1) was chosen on the basis of the grading analyses from the aquifer material and the upper 3/8" entry holes in the wooden tubes (Figure 4). A second filter (F2) was incorporated to avoid the movement of fine material into the main filter from the overlying spoil back-fill.

To provide a single abstraction a wooden T-pipe has been incorporated in the largest drain to

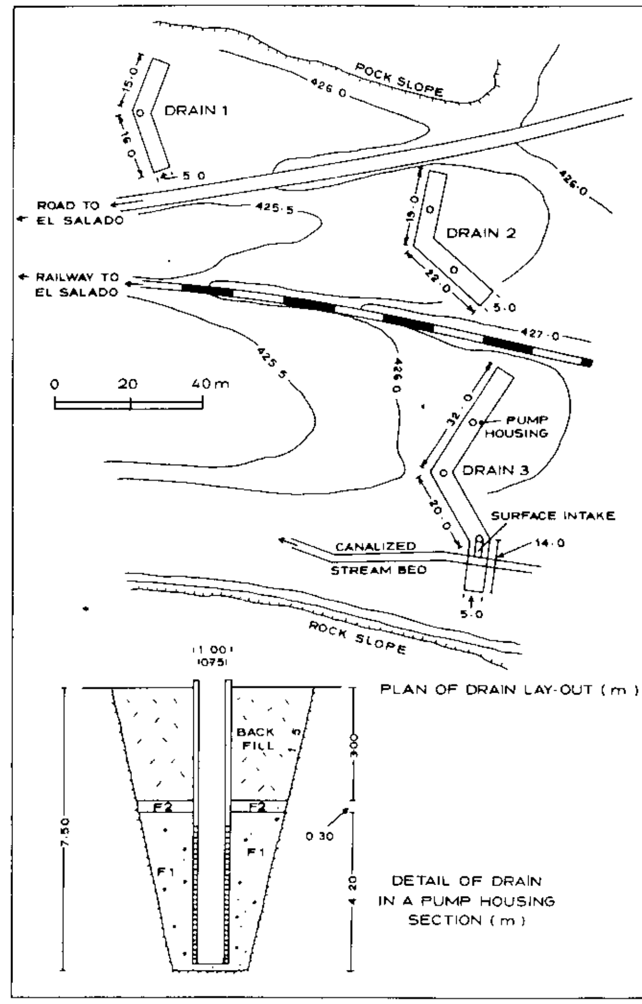

Fig. 3. Design of abstraction drains.

convey the surface water into the drain. The tube is inclined to avoid excessive aeration and incrustation and feeds directly into a pump-housing. The tube can also function as a surface-water bypass if necessary.

It is thought that under continual drawdown conditions, salt deposition will occur below the static water level in the spoil section. It is possible

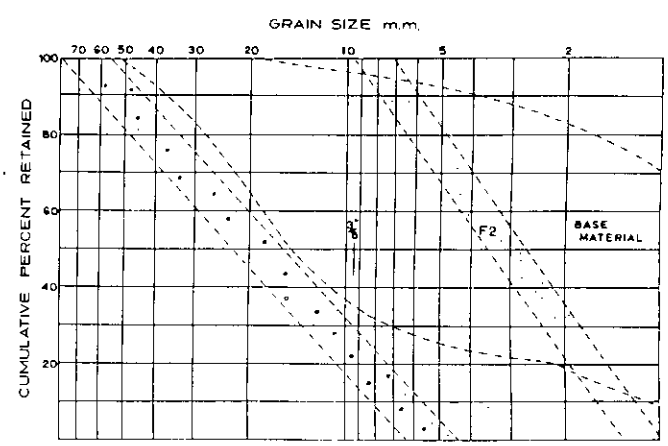

Fig. 4. Grain size analysis and filter selection.

also that the filter (F2) and the upper part of the main filter (F1) may eventually incrust. It is imperative therefore that stable drawdown is maintained at a reasonable level within 1 m. of the base of filter (F2).

CONCLUSIONS

To obtain a water supply for the planned expansion in copper ore processing at El Salado, it has been necessary to study saline waters in the absence of any alternative sources. The origin of the brines has been traced to ground-water overspill from the Salar de Pedernales which receives a relatively constant recharge from its main tributary, the Rio Olá.

From measurements in the El Salado area it was found that no significant changes in discharge occur. This is attributed to the modifying hydrological and artificial flow controls acting in both the Salar de Pedernales internal basin and in the Rio Salado catchment. It was found that the discharge of the brines was adequate for the required long-term supply. To obtain the supply a subsurface abstraction system was chosen in preference to a surface system in order to increase water availability and minimize flash flood damage. To avoid problems of incrustation and corrosion a filter drain abstraction system has been constructed that has been designed with a safety margin of approximately 60% in excess of the requirement.

It is unlikely that any use will be made of the brines within the Rio Salado catchment upstream of El Salado and thus affect the processing supply. However, due to the hydrogeological peculiarities of the system the flow data shows that the use of the brines at El Salado also precludes any further significant development of the water resources in the Rio Ola-Salar de Pedernales system.

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