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EFFECT OF OUTFLOW DIVERSION ON CIRCULATION AND WATER QUALITY OF LAKE CHAPALA

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Executive Summary

Lake Chapala is the largest lake in Mexico and accounts for 85% of the water supply to Guadalajara, a city with a population of 3.3 million. The current water intake is located in the Santiago River which is the only outlet of lake Chapala. In order to meet the growing demand and improve the quality of the water supply, it is planned to build an aqueduct with a flow capacity of 12 m^2/s to pump the water directly from the lake. The purpose of the present study is to evaluate effects of this diversion on the patterns of water movement and water quality in the lake.

The study employs a hydrodynamical model which computes vertically-averaged current patterns induced by inflows, outflows and winds blowing over the lake. Since the lake is relatively shallow, the circulation patterns adjust themselves rapidly to changing winds and, hence, the model is based on quasi-steady dynamics. The computations are carried out by electronic computer and results are obtained with and without the planned aqueduct.

The model results show that wind-driven circulations are much stronger than those associated with inflows and outflows for typical wind conditions. Since the proposed diversion of part of the outflow does not cause significant modifications of the pattern of these circulations, it is concluded that it will not lead to significant changes in water quality of Lake Chapala.

Sommaire

Le lac Chapala est le plus grand lac du Mexique et assure 85 % de l'alimentation en eau de Guadalajara, une ville de 3.3 millions d'habitants. L'eau est actuellement prise dans la rivière Santiago, l'unique émissaire du lac Chapala. Afin de combler les besoins grandissants de la population et d'améliorer la qualité de l'eau, les autorités envisagent de construire un aqueduc d'une capacité de 12 m^2/s pour pomper l'eau directement dans le lac. Le but de la présente étude est d'évaluer les effets de ce prélèvement sur les configurations du mouvement des eaux et sur la qualité des eaux du lac.

L'étude est fondée sur un modèle hydrodynamique qui calcule les configurations moyenne verticales des courants engendrés par les tributaires, les émissaires et les vents qui soufflent sur le lac. Comme le lac est relativement peu profond, la circulation des eaux s'ajuste rapidement à celle du vent et le modèle est donc basé sur une dynamique quasi-constante. Les calculs sont faits par des calculatrices électroniques et les résultats obtenus suivant deux hypothèses: avec et sans construction d'aqueduc.

Les résultats du modèle indiquent que les circulations d'eau engendrées par le vent sont bien plus fortes que celles qui sont dues

1. INTRODUCTION

Lake Chapala is the largest natural body of water in Mexico (Table 1). It accounts for 85% of the water supply to Guadalajara, a city of 3.3 million people. In addition it is used extensively for irrigation, commercial fishing and recreation.

The current water intake for the city of Guadalajara amounts to 8 m^3/s and is located at the Corona Dam in the Santiago River (Fig.1). In order to meet the growing demand and improve the quality of the water supply, it is proposed to pump the water directly from the lake at the location of Santa Cruz de la Soledad (Fig.1). The new aqueduct is designed to carry a flow of 12 m^3/s which is expected to lead to a corresponding reduction of the outflow through the Santiago River.

Limnological studies of the past decade have shown that the area near the mouth of the Lerma River has a much lower water quality than the rest of the lake. For example, the average concentration of nitrogen nitrate during 1980 decreased from 1.3 mg/l at the Lerma River to 0.4 mg/l near the Santiago River while a concentration of 0.2 mg/l prevailed over most of the lake.

The purpose of the present study is to evaluate effects of the new water intake at Santa Cruz on the patterns of water movement and distribution of water quality in Lake Chapala. The problem is addressed by recourse to a hydrodynamic model.

2. WATER BALANCE

According to the water balance for 1935-1970 (bottom of Table 1), the average amount of water lost through evaporation (45 m^3/s) is approximately balanced by the gain of water from precipitation (26 m^3/s) and direct runoff (22 m^3/s). Assuming that the latter is distributed rather uniformly around the perimeter of the basin, it may be neglected for the purpose of computing lake circulations. The loss of water other than that due to evaporation and Santiago outflow may be largely accounted for by irrigation at the east end of the lake. Since this leads to local re-circulation of the Lerma River inflow, the details of this flow will not be considered. Hence, before diversion, the outflow through the Santiago River (40 m^3/s) may be taken to be balanced by an equal inflow from the Lerma River. After diversion, the outflow will consist of a flow of 12 m^3/s through the aqueduct at Sta Cruz and a reduced outflow of 28 m^3/s through the Santiago River.

As shown in Table 2, the water balance varies greatly between the rainy season (June-September) and the dry season (October-May). In addition, as shown at the bottom of Table 2, the recent water balance has been quite different from the long-term average. Therefore, computations will be made for the recent water balance as well as for the earlier balance. Also, seasonal effects will be estimated.

In recent years, the loss of water through evaporation has not been balanced by the gain of water from precipitation and runoff. This has resulted in significant reductions of total volume and surface area of the lake (Fig.2). These changes in depth and shoreline must be taken into account when computing currents due to river flows and winds. However, precipitation and evaporation have no direct effect on water motions.

If, as before, the water used for irrigation at the east end of the lake is subtracted from the Lerma River inflow, the water balance for 1978-1983 may be approximated as follows (in m^3/s).

	Jan.-Dec.	June-Sept.	Oct.-May
Lerma River inflow-irrigation	17	51	0
Santiago River outflow	-17	-17	-17
Change of volume due to rivers	0	34	-17
Precipitation-evaporation & runoff	-17	30	-40
Total change of volume	-17	64	-57

Averaged over the whole year, the river flows are in balance. The same will be true after diversion but then the outflow will consist of 12 m^3/s through the aqueduct and 5 m^3/s through the Santiago River. During the rainy season, the inflow is three times as large as the outflow while during the dry season the inflow is essentially zero.

3. METHOD OF STUDY

A hydrodynamic model suitable for simulating water movements in Lake Chapala is presented in the Appendix. The model computes vertically-averaged current patterns induced by the Lerma River inflow, the Santiago River outflow, and effects of winds blowing over the lake. Since the lake is relatively shallow (Fig.1), the circulation patterns adjust themselves rapidly to changes in wind forces and, hence, the model is based on quasi-steady dynamics. The computations are carried out by electronic computer.

The nearest meteorological station is at Guadalajara International Airport, 30 km north of the lake, but the wind information at the airport is not applicable to Lake Chapala due to topographic effects. Limnological surveys including wind measurements indicate that the prevailing wind direction is from the east while winds from the west occur about half as frequently. A typical wind speed is 9 km/h. Assuming the conventional relationship for the wind stress as a function of the square of the wind speed, the corresponding stress at the water surface is about 0.1 $dyne/cm^2$.

The model results are presented in the form of transport streamlines as illustrated in Figure 3. The difference of the values of two adjacent streamlines represents the total mass of water (m^3/s) flowing between these streamlines. The direction of the flow is such that the streamline with the highest value lies to the right of the current. Since only the difference of the values of the streamlines is of interest, the reference value is arbitrary. For all computations presented in this report, the reference value is prescribed on the east bank of the Santiago River and is taken to be equal to the total outflow. Before diversion, the west bank of the Santiago River has a streamline value of zero. After diversion, the west bank of the

Santiago River will have a value of 12 m^3/s. In that case, the same streamline value applies to the whole shoreline east of Sta Cruz, while the shore to the west of Sta Cruz has a value of zero thus giving a transport of 12 m^3/s across the shoreline near Sta Cruz.

According to Figure 3, the mean current may be estimated by dividing the transport by the distance between two streamlines and the depth. In the present study, the streamlines will be presented at intervals of 10 m^3/s. Thus, if the distance between two adjacent streamlines is 2 km and the local depth is 5 m, the mean current is 0.1 cm/s or about 0.1 km/day.

4. MODEL RESULTS FOR 1935-1970 WATER BALANCE

Results will be presented for the case of no wind and for winds of 9 km/h from the east and west, respectively. In each case the outflow before diversion will be compared with the outflow after diversion.

No wind, outflow before diversion (top of figure 4)

The water moves directly from the Lerma River to the Santiago River without affecting the rest of the lake. Away from the rivers a typical distance between streamlines is 3 km. For a depth of 3-5 m the corresponding current speed is 0.1 km/day and, hence, it takes more than 100 days for the Lerma River water to reach the Santiago River.

No wind, outflow after diversion (bottom of Figure 4)

The portion of the outflow which is diverted to the Sta Cruz aqueduct is distributed rather uniformly over the width of the lake. The distance between streamlines is about 10 km which, for a mean depth of 8 m, is equivalent to a water velocity of 10 m/day. The corresponding travel time from the Lerma River to the Sta Cruz aqueduct is 10-15 years.

Eastwind of 9 km/h, outflow before diversion (Top of Figure 5)

It is known from hydrodynamic studies of lake currents that the general effect of wind is to move coastal currents in the same direction as the wind while a compensating return flow occurs in deeper parts of the lake. This is clearly visible in the present case. Nearly all the water from the Lerma River joins the wind driven westward flow along the southshore and flows all the way to the west end of the lake. It then returns through the middle of the lake towards the Santiago River. The northern half of the lake is not affected by the inflow but displays a closed circulation. The zero streamline has been accentuated to make this more evident.

The wind-driven currents are much faster than the currents induced by the rivers. They vary from 0.5 km/day in the coastal zones to 0.1 km/day in deep water. However, the distance travelled by the river water in the presence of wind is so large that it would require many years for this water to traverse the lake.

Eastwind of 9 km/h, outflow after diversion (bottom of Figure 5)

The diversion of one-third of the Santiago outflow does not change the overall circulation pattern. As before, the Lerma River water flows along the southshore to the west end of the lake and then returns in deep water. Just before reaching the Santiago River, part of this water joins the westward coastal flow along the northshore to end up at the Sta Cruz aqueduct.

Westwind of 9 km/h, outflow before diversion (top of Figure 6)

The wind-driven part of the circulation is the exact opposite of that induced by an eastwind. In this case, part of the Lerma River inflow moves directly to the Santiago River but most of the inflow joins the westward return flow of the wind-driven circulation and then flows back along the northshore towards the Santiago River. The southern half of the lake is not affected by the inflow but displays a closed circulation.

Westwind of 9 km/h, outflow after diversion (bottom of Figure 6)

The water intake at Sta Cruz simply removes part of the eastward flowing coastal current along the northshore. This results in a corresponding reduction of the Santiago outflow. The overall lake circulation is not affected.

5. MODEL RESULTS FOR 1978-1983 WATER BALANCE

For these calculations the lake depths are reduced by 3 m in accordance with Fig.2 and the shoreline corresponds with the 3 m depth contour of Fig.1.

Annual Mean Currents

Averaged over the year, the Lerma River inflow balances the outflow and is equal to 17 m^3/s. Results of calculations for the case of no wind are presented in Fig.7 and results for east and west winds are shown in Fig.8 and Fig.9.

In the absence of wind (Fig.7) the effect of diversion is more pronounced than previously (Fig.4) because the diverted water constitutes a much larger portion of the total inflow and outflow. In the presence of wind (Figs.8 and 9) the lake circulations are again dominated by the wind. However, the transports are only half as large as previously (Figs.5 and 6) because the water depths are much smaller than before while the currents remain more or less the same. Thus for the recent water balance, the river transports and the wind-driven transports are both reduced by approximately one-half as compared to the earler water balance. Since the diversion through the aqueduct is the same in each case, its effect is twice as important for the present water balance. While in Figs.5 and 6 the diversion at Sta Cruz removed only part of the coastal flows along the north shore, in Figs.8 and 9 it diverts almost the total coastal transports.

Seasonal Currents

The computations for the wet and dry seasons are complicated by the change of surface level resulting from the difference between inflow and outflow. The stream function model presented in the Appendix does not permit such changes of water levels and should be replaced by a time-dependent model with a free surface. However, the stream function model can be used to give an approximate solution as follows.

When the inflow is greater or smaller than the outflow, the difference will be distributed rapidly over the whole lake to raise or lower the surface uniformly. Thus, the transport across any north-south cross-section of the lake must be proportional to the surface area to the west of that section. For instance, with an inflow of 50 m^3/s and an outflow of 17 m^3/s, an amount of 33 m^3/s is available to raise the surface of the whole lake. Thus, if the surface area to the west of a given cross-section is one-third of the total surface, then the transport across this section must be 11 m^3/s. In this manner values of the stream function can be prescribed along the whole shoreline, starting from the reference values at the Santiago River. It may be noted that this procedure is equivalent to assuming that the excess inflow runs out equally across the whole shoreline instead of changing the surface level. For a long, narrow lake such as Lake Chapala, this should be a good approximation for computing currents. Another advantage is that the results can be prescribed by stream lines as done for the earlier computations.

Results of computations for the case of no wind are shown in Fig.10 for the rainy season and in Fig.11 for the dry season. In the first case, the diversion affects primarily the north-east corner of the lake. In the second case, the diversion separates the lake into two parts as shown by the dashed line. The water to the east of this lake flows out through the Santiago River, the water to the west is removed through the aqueduct. Effects of wind are similar as before and therefore are not shown.

6. CONCLUSIONS

Hydrodynamic model calculations show that for typical wind conditions on Lake Chapala, the inflow from the Lerma River does not move directly to the Santiago River but tends to flow towards the west end of the lake. For winds blowing from the east, the Lerma River water joins the relatively fast westward flow along the southshore, while for winds from westerly directions the river water becomes imbedded in the slower westward transport through the centre of the lake.

It is unlikely that a particular wind direction will persist long enough for the Lerma River water to cross the whole lake. The average water movement over a long period of time may be estimated from observations indicating that the relative frequency of eastwinds on Lake Chapala is about twice as high as that of westwinds. Since currents induced by a westwind are exactly opposite to those caused by an eastwind, the long-term pattern of water movement should be similar to that for an eastwind (Figs.5 and 8).

It follows that even before diversion, the Lerma River water will to some extent affect the whole lake rather than being confined to the north-east corner as it would be in the absence of wind. Therefore, any gradients of water quality in the east end of the lake such as the rapid decrease of nitrogen nitrate from the Lerma River towards the west, cannot be a result of the fact that the present outflow is confined to the Santiago River but must be due to biochemical processes such as denitrification.

Since the proposed diversion of part of the outflow through the Sta Cruz aqueduct does not cause significant modifications of the pattern of wind-driven circulations, the conclusion is that it cannot lead to significant changes of the water quality of Lake Chapala.

Acknowledgments

The author wants to thank Dr. Gualberto Limon for providing the data for this study and for his advice. The support received from the Pan American Health Organization is also gratefully acknowledged.

Table 1

Principal morphological and hydrologic characteristics of Lake Chapala

A) Location

Latitude 20° 15" lat N

Longitude 103° long W

Elevation 1,524 m above sea level

B) Morphology

Volume 7,862 10^6 m^3

Area 1,112 square kilometers

Maximum length 76.6 kilometers

Maximum width 22.5 kilometers

Average depth 7.2 meters

Maximum depth 17.6 meters

C) Climatology

Average annual precipitation * 770 mm

Annual evaporation (average) 2,000 mm

Annual temperature (average) 20° C

D) Hydrology

Area of total drainage 52,500 square kilometers

Area of drainage of lake 8,660 square kilometers

Contributions *:	Lerma 49.11 m3/s
	rain 25.81 m3/s
	other 21.98 m3/s
Extractions *:	Santiago 39.78 m3/s
	evaporation 45.03 m3/s
	other 10.85 m3/s

*promedio 1935-1970.

Table 2: Water balance of Lake Chapala (m^3/s)

1934/1983		inflow-outflow		precip -evap	volume change	water level changes (m)
	Lerma	Santiago	other			
Jan.	17.1	-33.4	-7.7	-28.3	-52.3	-.13
Feb.	13.0	-30.2	-3.4	-38.9	-59.5	-.14
Mar.	11.6	-33.3	-6.3	-56.9	-84.9	-.20
Apr.	11.2	-31.6	-9.5	-62.2	-92.1	-.22
May	15.3	-32.4	-1.8	-58.4	-77.3	-.19
June	33.5	-30.0	5.2	6.1	14.8	.03
July	106.6	-37.6	34.5	33.5	137.0	.33
Aug.	130.1	-43.6	24.7	22.0	133.2	.32
Sept.	147.6	-56.8	30.7	12.9	134.4	.32
Oct.	120.9	-64.7	-2.1	-21.8	32.3	.08
Nov.	42.5	-52.5	-14.6	-29.9	-54.5	-.13
Dec.	20.6	-40.3	-14.6	-25.0	-59.3	-.14
June/Sept	104.5	-42.0	23.8	18.6	104.9	1.00
Oct./May	31.5	-39.8	-7.5	-40.2	-56.0	-1.07
Year	55.8	-40.5	7.9-5.0	-20.6	-2.4	-.07

1978/1983

June/Sept	51.0	-17.0	10.5	19.5	64.0	.60
Oct./May	4.0	-17.0	-4.0	-40.0	-57.0	-1.08
Year	19.7	-17.0	3.5-2.7	-20.2	-16.7	-.48

APPENDIX: Hydrodynamic Model of Lake Chapala

The hydrodynamic model equations and methods of solution have been presented in detail by T. J. Simons: "Circulation models of lakes and inland seas", Can. Bull. Fish. Aquat. Sci. 203 (1980). Under homogeneous conditions and assuming quasi-linear accelerations, the equations of motion and the continuity equation may be integrated over the depth of the lake to yield

$$\frac{\partial U}{\partial t} = -gH\frac{\partial h}{\partial x} + fV - \frac{\tau_{bx}}{\rho} + \frac{\tau_{sx}}{\rho}$$

$$\frac{\partial V}{\partial t} = -gH\frac{\partial h}{\partial y} - fU - \frac{\tau_{by}}{\rho} + \frac{\tau_{sy}}{\rho}$$

$$\frac{\partial h}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}$$

where t is time, x and y are the horizontal coordinates, U and V are the corresponding components of the vertically-integrated current, h is the free surface perturbation, H is the water depth, g is gravity, f is the coriolis parameter, ρ is water density, τ_b is bottom stress and τ_s is wind stress.

For a shallow lake the bottom friction has a large damping effect on water movements. Thus, when a wind starts blowing over the lake, the currents will rapidly reach a state of equilibrium. Therefore, the time-dependent part of the water circulation may be ignored. This means that the left-hand-sides of the equations may be set to zero and the bottom friction may be approximated by the quasi-steady Ekman formulation for shallow water. The equations of motion become

$$gH\frac{\partial h}{\partial x} - fV + \frac{b}{H^2}U = \frac{\tau_{sx}}{\rho}$$

$$gH\frac{\partial h}{\partial y} + fU + \frac{b}{H^2}V = \frac{\tau_{sy}}{\rho}$$

where b is a constant bottom friction coefficient equal to 75 cm^2/s.

The quasi-steady continuity equation is satisfied if the vertically integrated currents are expressed in a stream function as follows

$$U = -\frac{\partial S}{\partial y} \qquad V = \frac{\partial S}{\partial x}$$

The equations of motion are now divided by the depth and the first one is differentiated with respect to y and the second with respect to x. The equations are then subtracted and the stream function is substituted to yield

$$\frac{\partial}{\partial y}\left(\frac{f}{H}\frac{\partial S}{\partial x} + \frac{b}{H^3}\frac{\partial S}{\partial y}\right) - \frac{\partial}{\partial x}\left(\frac{f}{H}\frac{\partial S}{\partial y} - \frac{b}{H^3}\frac{\partial S}{\partial x}\right) = \frac{\partial}{\partial x}\left(\frac{\tau_{sy}}{\rho H}\right) - \frac{\partial}{\partial y}\left(\frac{\tau_{sx}}{\rho H}\right)$$

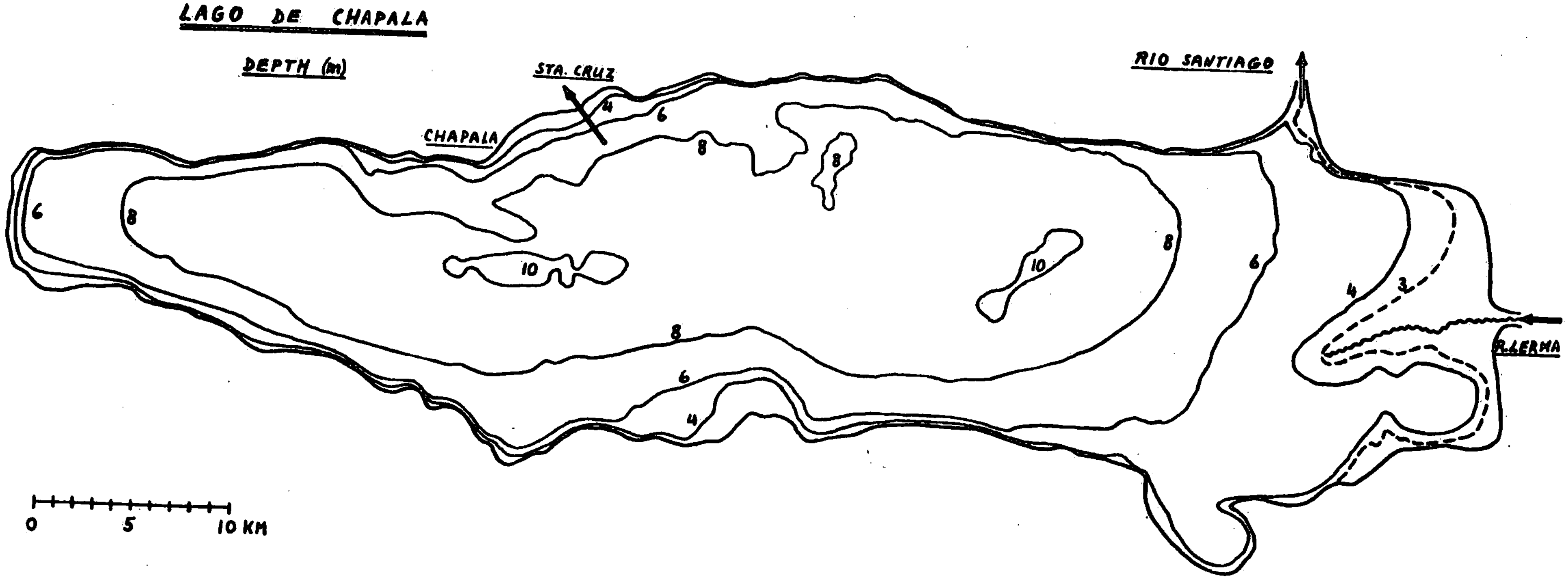
Since f is approximately constant and the wind stress may be assumed to be uniform over a lake, the equation may be written as follows

$$\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} - A(x,y)\frac{\partial S}{\partial x} - B(x,y)\frac{\partial S}{\partial y} = \frac{H}{b}\left(\frac{\partial H}{\partial y}\frac{\tau_{sx}}{\rho} - \frac{\partial H}{\partial x}\frac{\tau_{sy}}{\rho}\right)$$

$$A(x,y) = \frac{3}{H}\frac{\partial H}{\partial x} + \frac{fH}{b}\frac{\partial H}{\partial y} \qquad B(x,y) = \frac{3}{H}\frac{\partial H}{\partial y} - \frac{fH}{b}\frac{\partial H}{\partial x}$$

This equation can be solved for the stream function if the wind stress and the inflow and outflow of river water are known. The solution is obtained by replacing the derivatives by finite differences on a rectangular mesh of gridpoints. For the present calculations a grid spacing of 2 km was used.

Fig 1



LAGO DE CHAPALA

DEPTH (m)

Fig 2

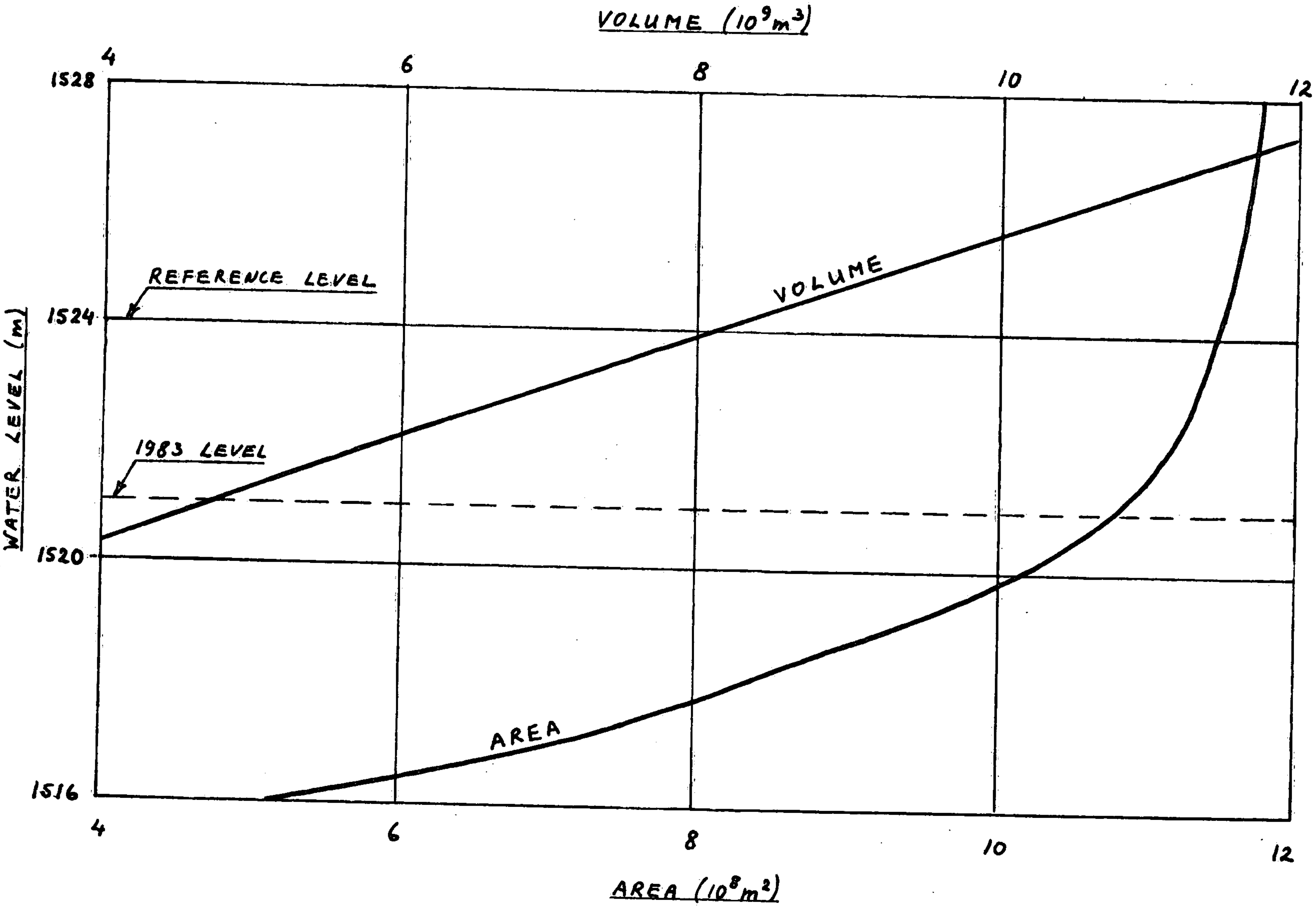
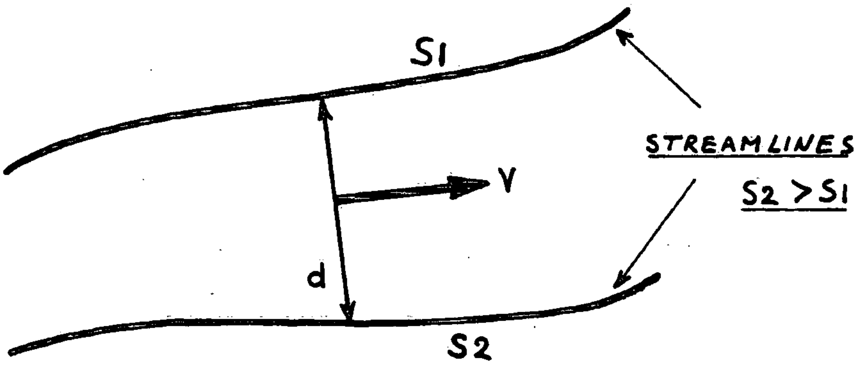

VOLUME ($10^9 m^3$)
4
6
8
10
12
1528
1524
1520
1516
WATER LEVEL (m)
REFERENCE LEVEL
1983 LEVEL
VOLUME
AREA
4
6
8
10
12
AREA ($10^8 m^2$)

Fig. 3



$$V = \underline{\text{CURRENT}} = \frac{S_2 - S_1}{d \cdot H} \qquad (H = \underline{\text{DEPTH}})$$

LAGO DE CHAPALA

TRANSPORT (m³/s)

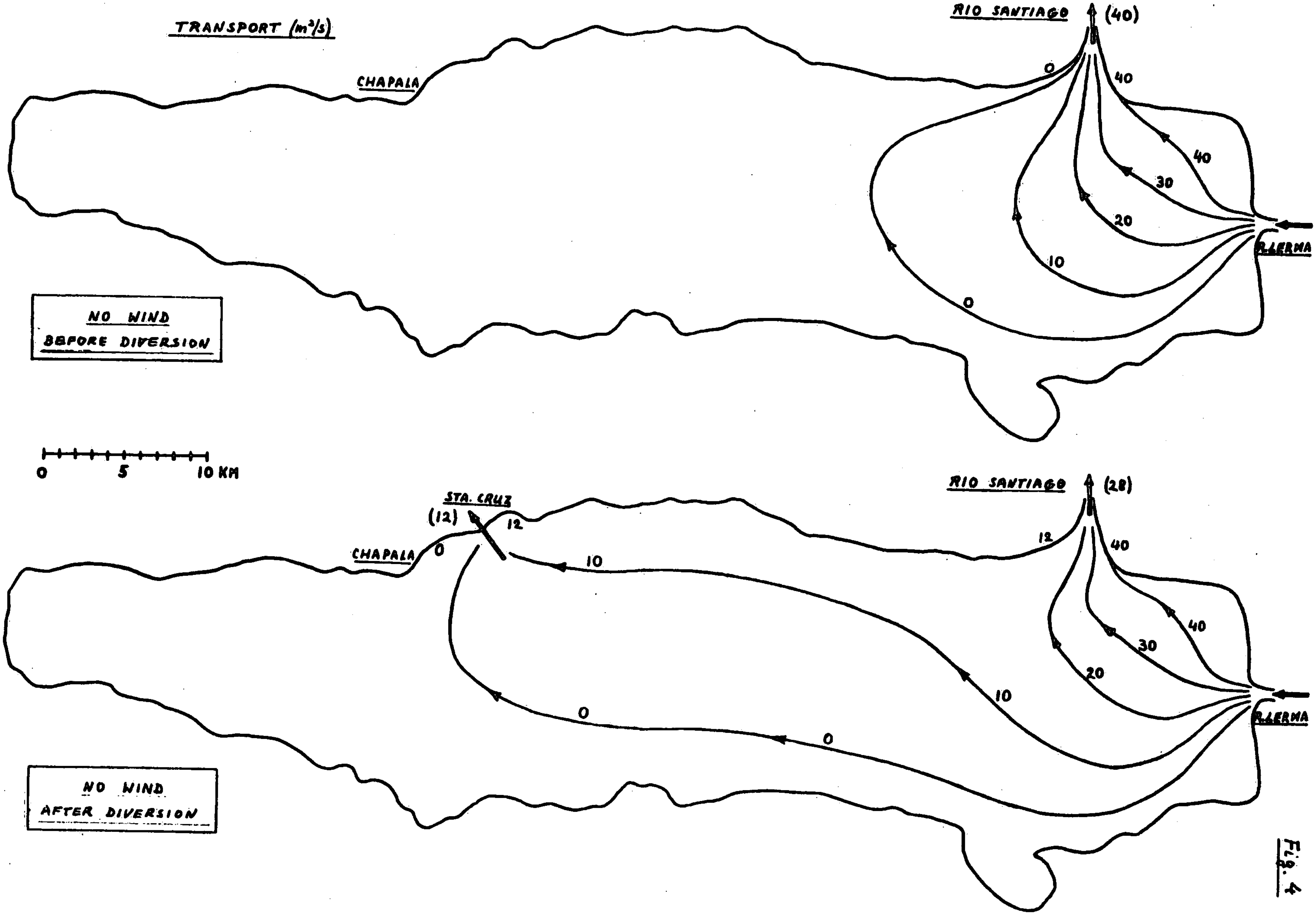


Fig. 4

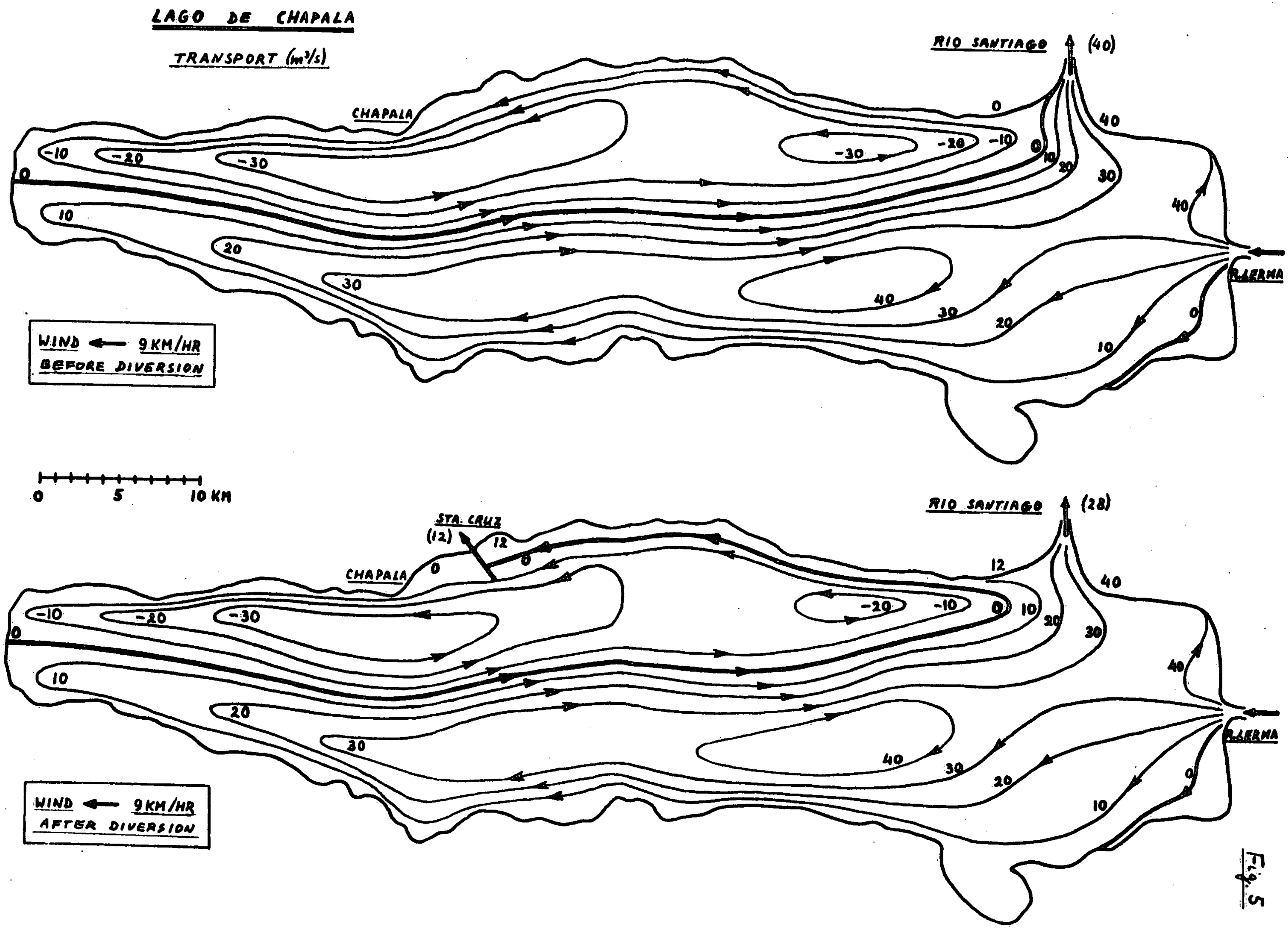

LAGO DE CHAPALA
TRANSPORT (m³/s)
RIO SANTIAGO
(40)
CHAPALA
R. LERMA
WIND ← 9 KM/HR
BEFORE DIVERSION
0
-10
-20
-30
10
20
30
40
0 5 10 KM
RIO SANTIAGO
(28)
STA. CRUZ
(12)
12
CHAPALA
R. LERMA
WIND ← 9 KM/HR
AFTER DIVERSION

Fig. 5

LAGO DE CHAPALA

TRANSPORT (m³/s)

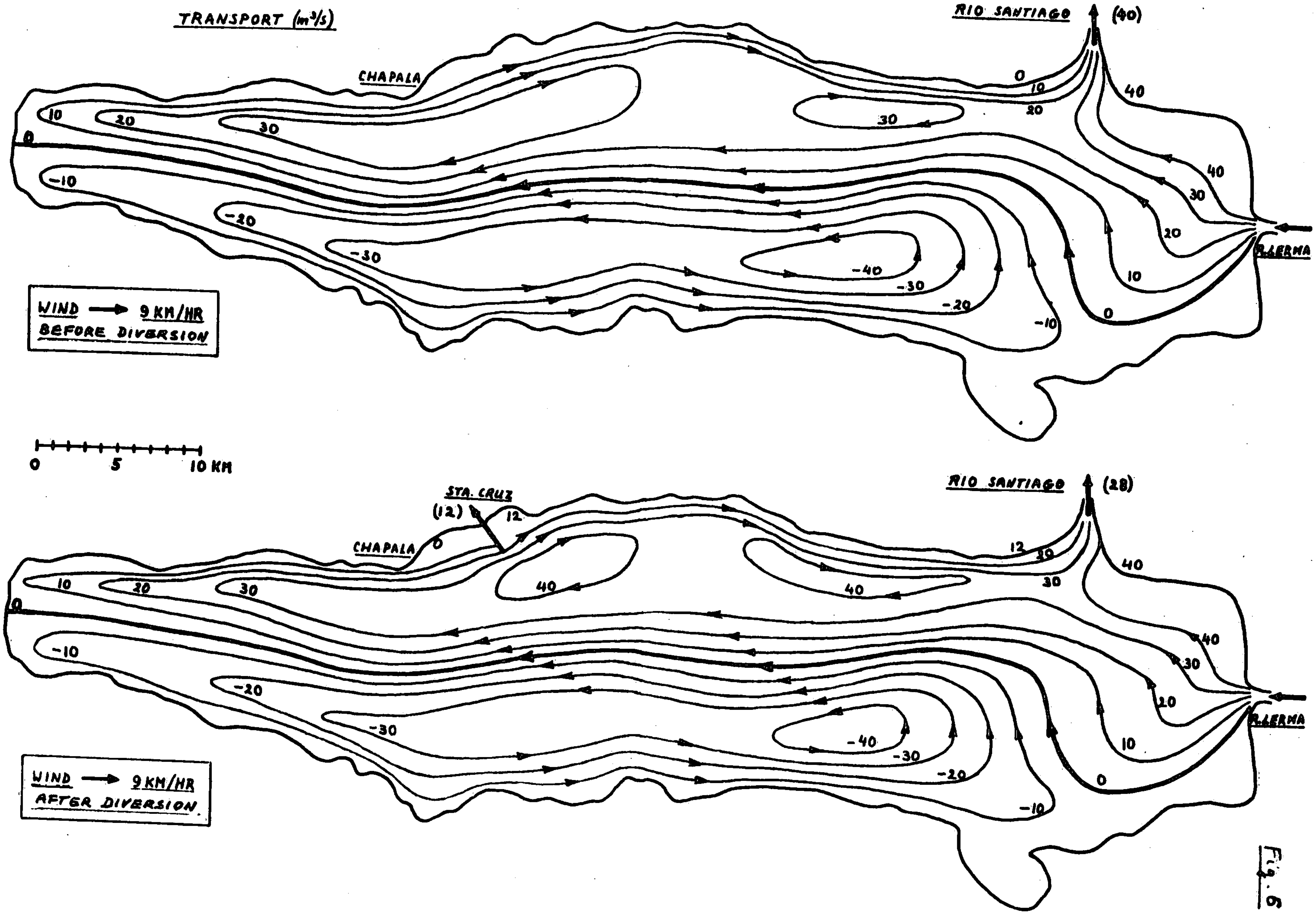


Fig. 6

LAGO DE CHAPALA

TRANSPORT (m³/s)

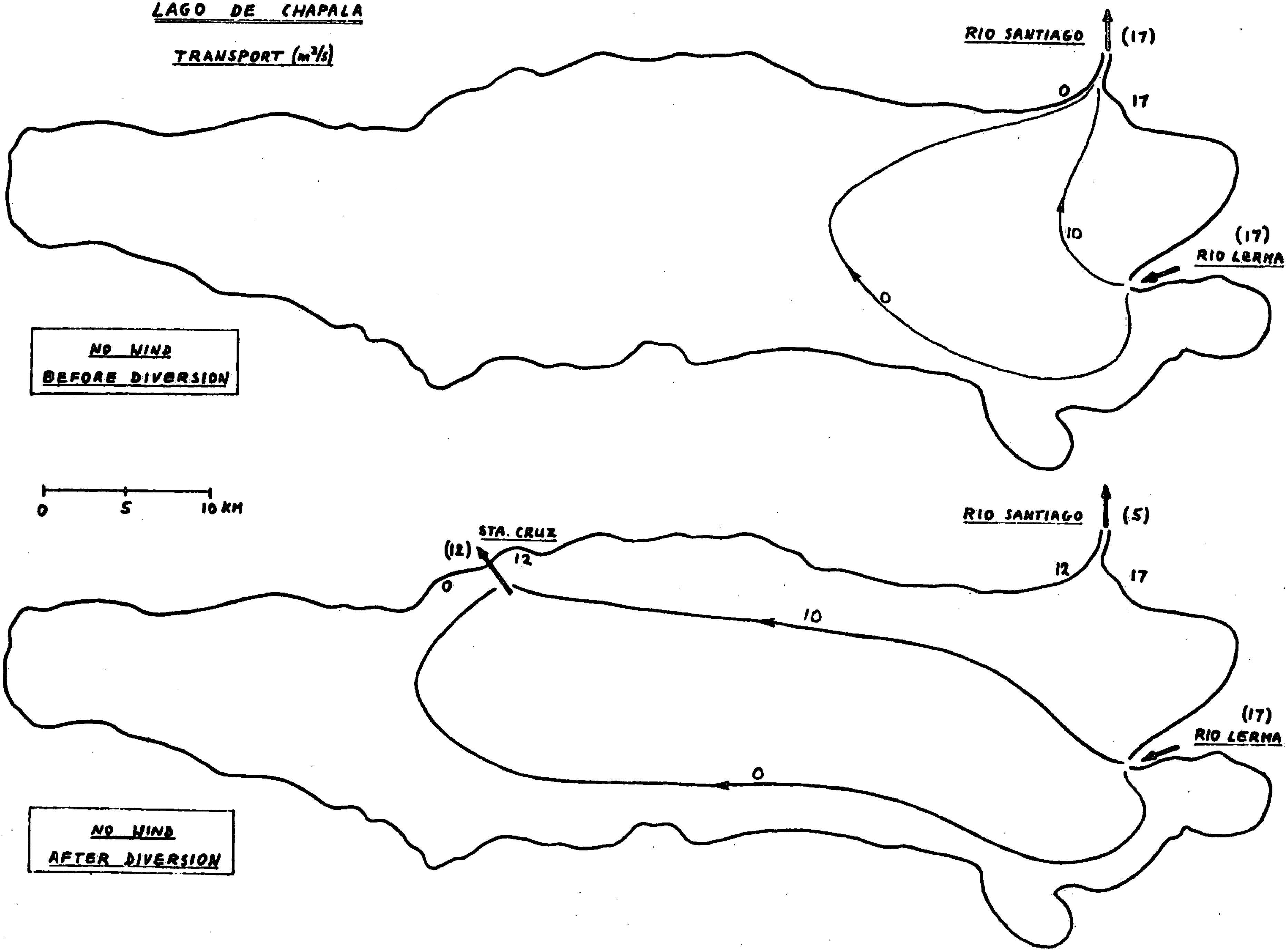
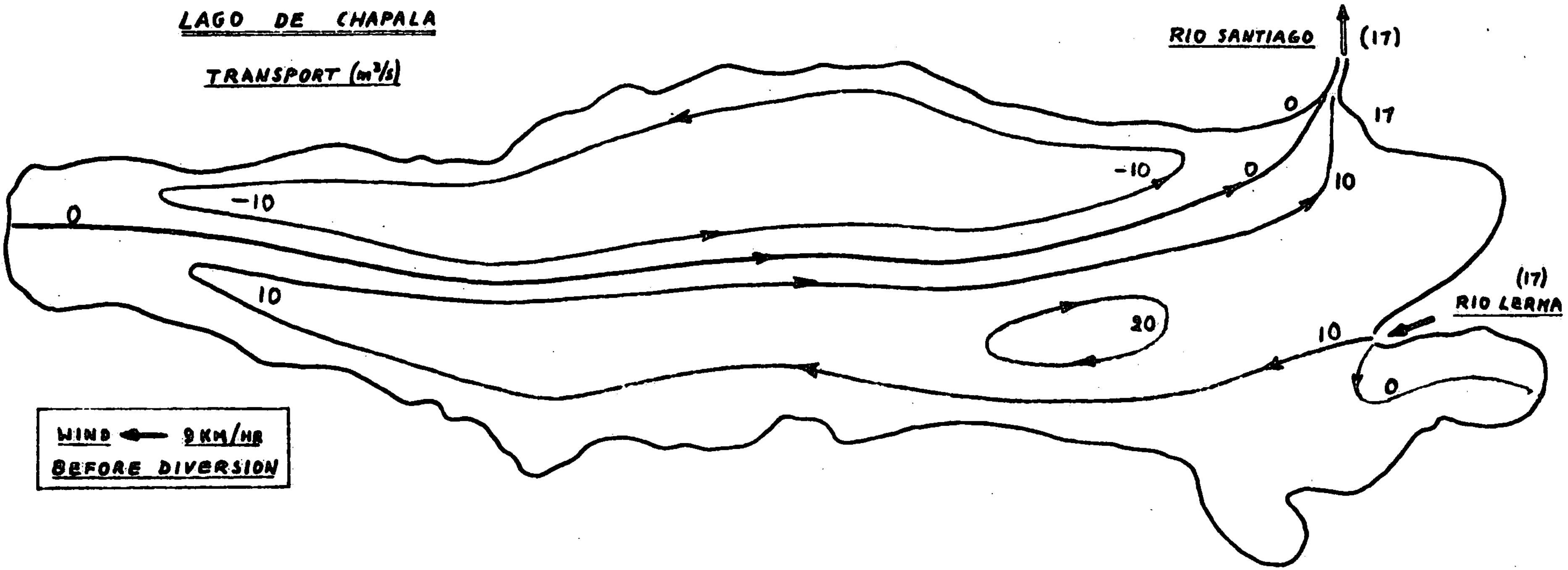


Fig. 7

LAGO DE CHAPALA

TRANSPORT (m³/s)



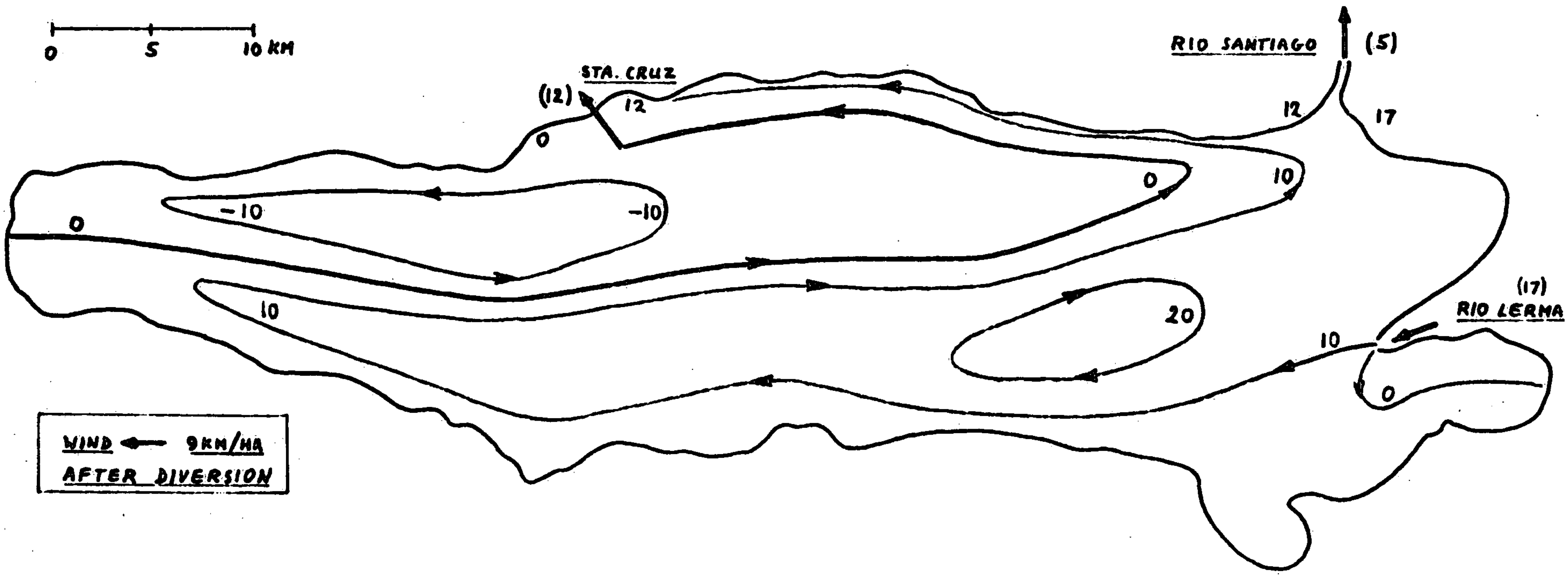


Fig. 8

LAGO DE CHAPALA

TRANSPORT (m³/s)

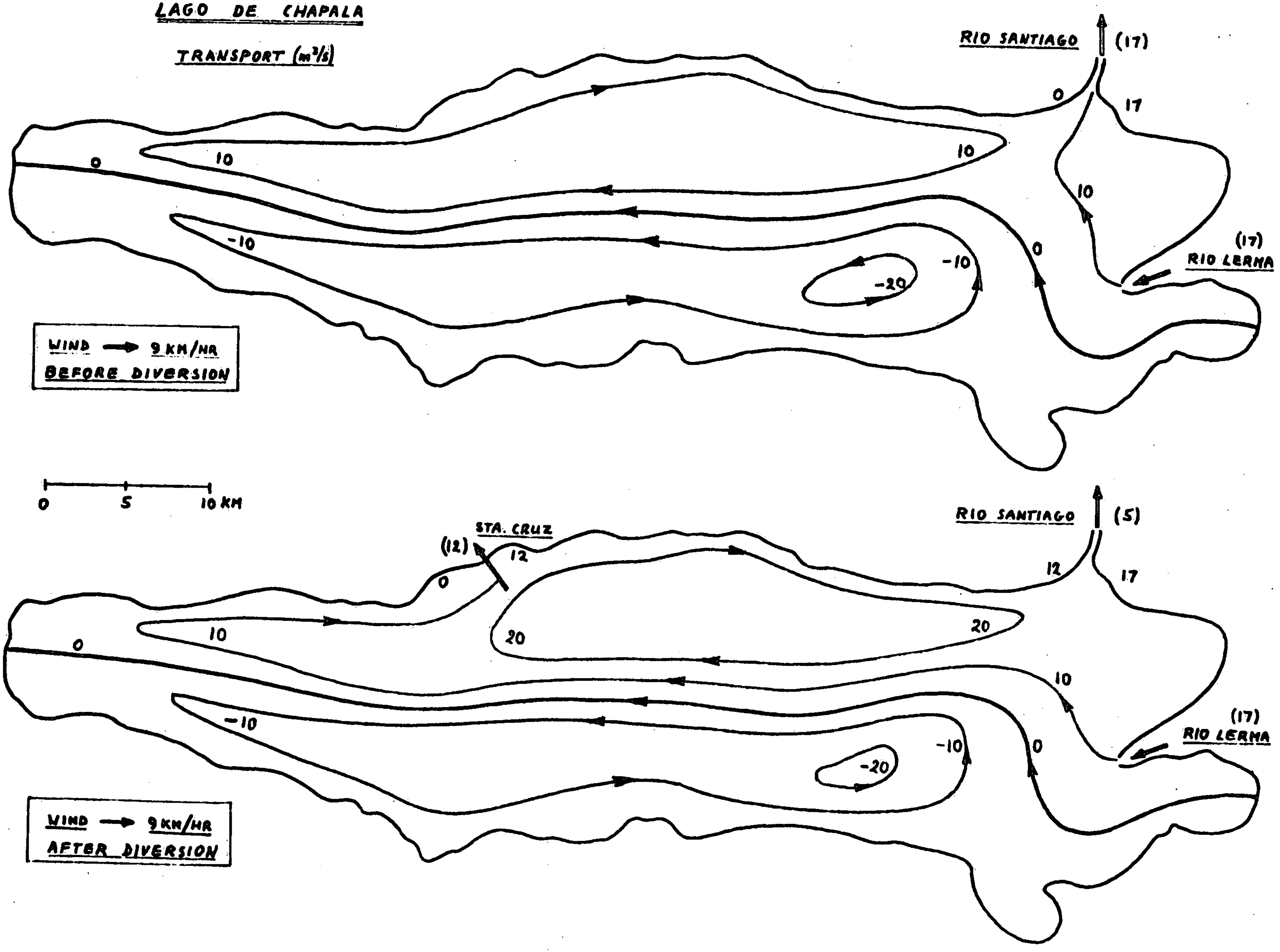


Fig. 9

LAGO DE CHAPALA

TRANSPORT (m^3/s)

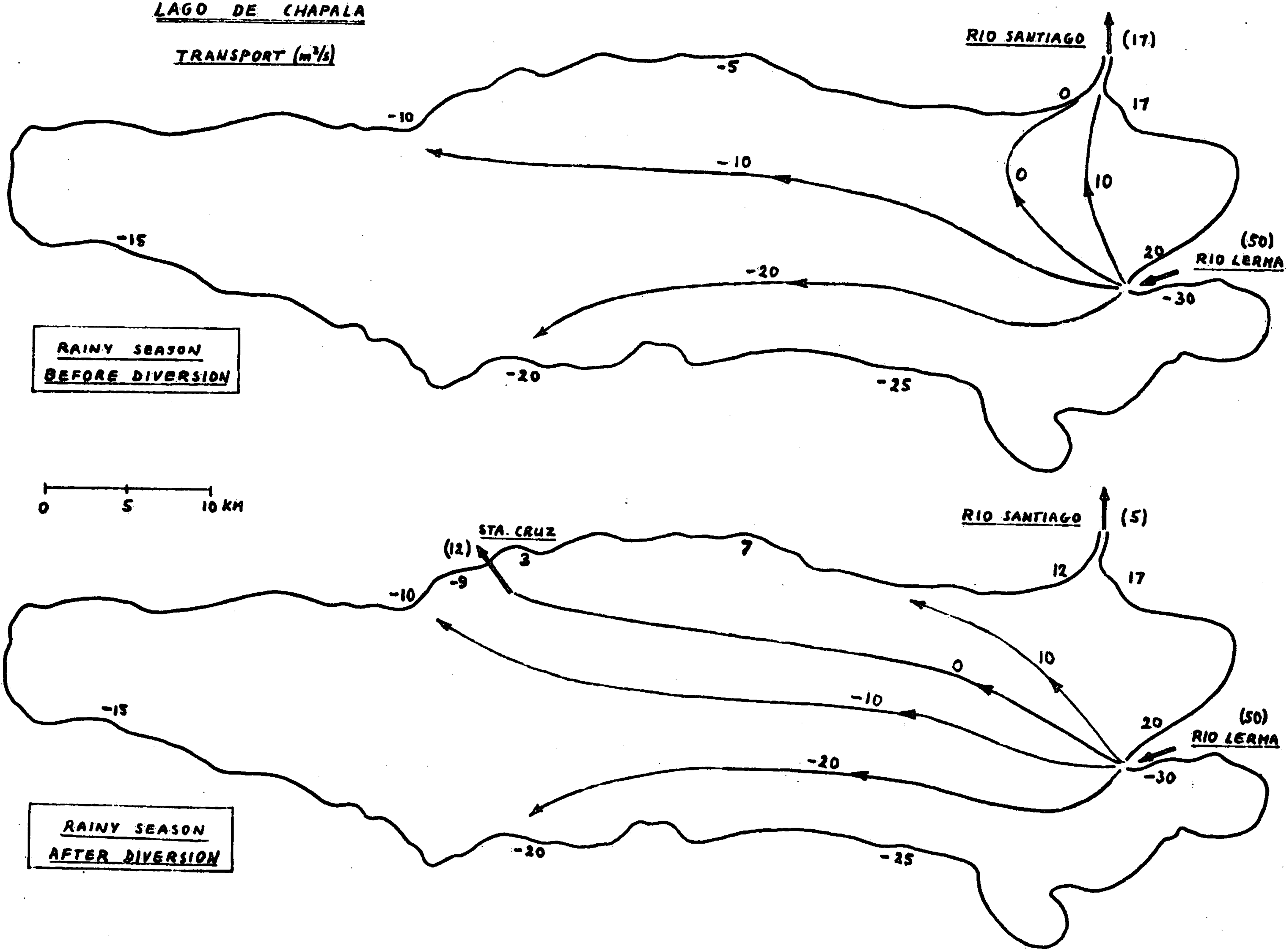
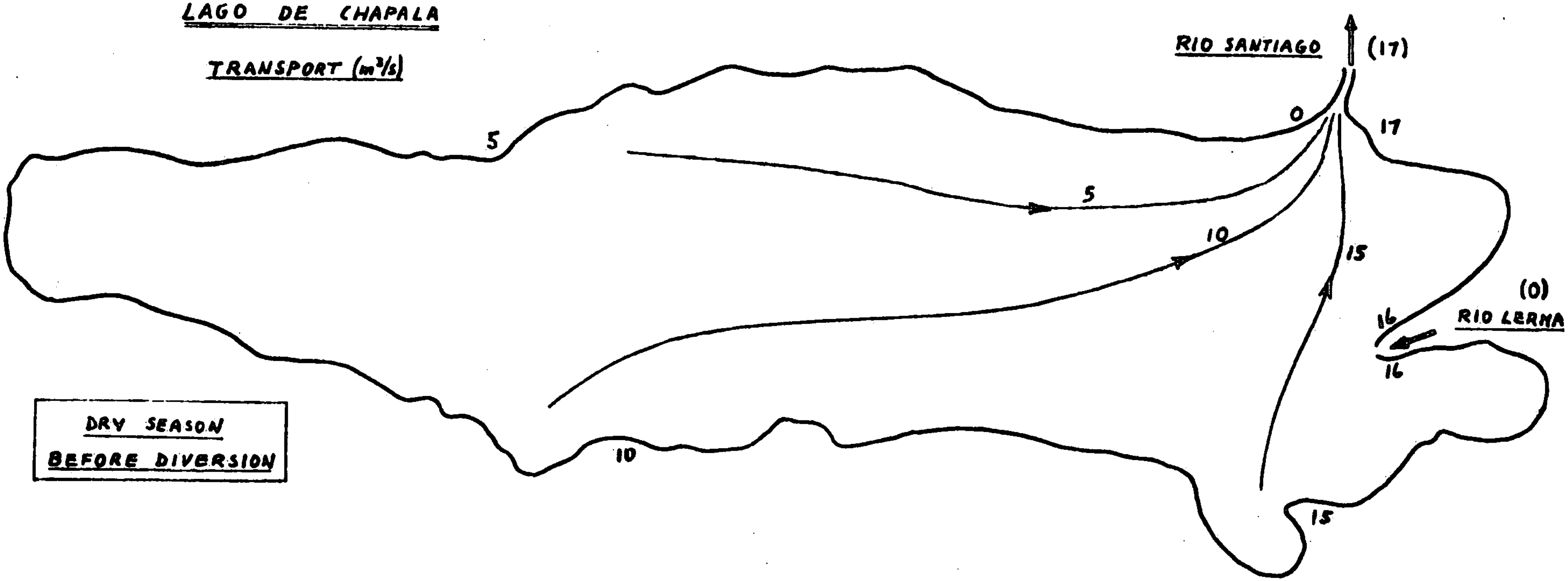


Fig. 10

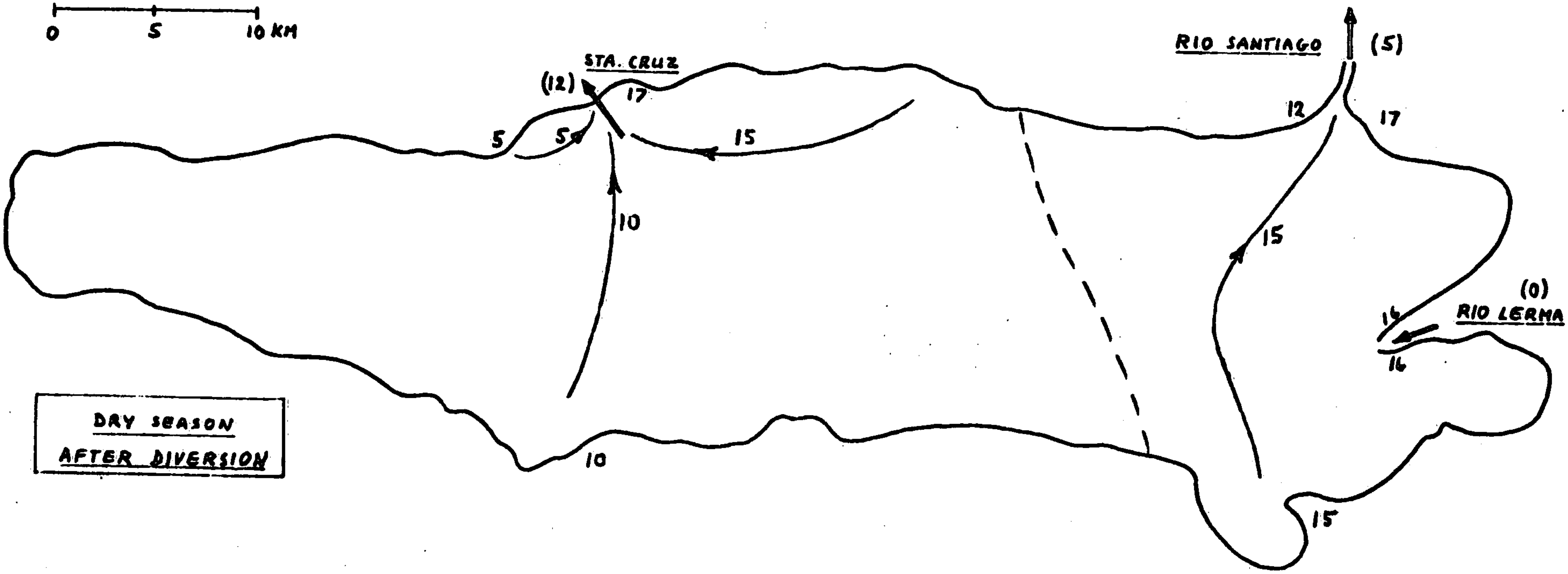
Fig. 11

LAGO DE CHAPALA

TRANSPORT (m^3/s)



DRY SEASON
BEFORE DIVERSION



DRY SEASON
AFTER DIVERSION