A LIMNOLOGICAL STUDY OF LAKE PATZCUARO, MEXICO, WITH A CONSIDERATION OF THE APPLICABILITY OF REMOTE SENSING TECHNIQUES.

by

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THIS THESIS IS DEDICATED TO

THE P'URHEPECHA PEOPLE

Stirling, Scotland, 15 May 1989.

The work presented in this thesis is the result of my own investigations. It has not been, nor will be, submitted for any other degree.

ARTURO CHACON TORRES

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ABSTRACT

This thesis presents the results of a hydrobiological study with implications for lake management obtained during six months of field work in Lake Patzcuaro, Michoacan, Mexico. The conventional data are coupled with surveys made with multispectral satellite imagery.

Lake Patzcuaro, Michoacan, Mexico is a tropical high altitude freshwater lake located in the southern edge of the Mexican plateau. The lake originated from tecto-volcanic processes associated with the Eje Neovolcanico Transversal during the late Tertiary and Quaternary periods.

Data for 25 morphometrical parameters describing the geomorphology of Lake Patzcuaro were derived from an up-to-date bathymetric survey with contour lines at 1.0 m intervals: Maximum depths were observed in the northern part of the lake whereas considerable shallow areas are developing in the south: insulosity is continuously modified due to certain areas becoming part of the mainland and the appearance of new islands with increasing shallowness and man-made channels.

The lake is an endorheic basin and the annual water balance is primarily controlled by differences between rainfall and evaporation. Since annual evaporation is higher than rainfall, it is considered that net water inputs to the lake come as seepage from the drainage area. However, by using a simple mass balance simulation model it is illustrated that the contribution of seepage is being reduced due to the continuous deterioration of the catchment area.

The lake is well mixed and high oxygen levels are always present from surface to bottom. The lake is alkaline-carbonate with moderate levels of hardness and high concentrations of total phosphorus, chlorophyll-a and suspended solids. By comparing three conventional trophic state indices and input-output phosphorus models, Lake Patzcuaro is considered to be mostly eutrophic with some isolated mesotrophic and oligo-mesotrophic areas. High turbidities are observed possibly due to volcanic silt, raw sewage and increasing erosion loads. It is considered that Lake Patzcuaro is principally light-limited due to scattering and attenuation effects from inorganic materials.

A predictive model of water quality variables has been developed for SPOT-1 multispectral imagery, and applied to Lake Patzcuaro. By using canonical and principal component analysis it is shown that, at most, two water quality variables, chlorophyll-a and suspended solids concentration, can be derived from the SPOT data. Having established the independent predictiviness of a set of empirical relations between the SPOT data and the water quality parameters, the whole lake was analysed to reveal the spatial distribution of chlorophyll-a and suspended solids. It is revealed that a very dense algal bloom had occured during the period of study. No bloom of such intensity has ever been observed before in Lake Patzcuaro. The applicability of SPOT imagery to water quality monitoring is clearly demonstrated. The cost-effectiveness of remote sensing techniques for water quality mapping and lake management is discussed using the Lake Patzcuaro as an example.

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Colour code

Dark blue	Submerged macrophytes	
Blue green	< 50	ug/l
Dark green	50 - 100	ug/l
Yellow	100 - 250	ug/l
Orange	> 250	ug/l

Colour code

Blue	Submerged macrophytes	
Green	5.0 - 10.0	mg/l
Yellow	10.0 - 30.0	mg/l
Orange	30.0 - 45.0	mg/l
Purple	> 45.0	mg/l

Chapter 1

Introduction

Current knowledge of high altitude lakes situated in tropical latitudes is fragmentary. The effects of elevation ecologically differentiate such lakes from those tropical lakes located near sea level, particularily in terms of thermal regime (Loffler, 1972). According to Kaul (1987), the highest and greatest number of montane lakes is located in the Andes. Similarly high altitude lakes are also situated in Central America and Mexico within an altitudinal range from 1000 to 6000 metres above sea level. The number of lakes throughout Latin America is estimated at several thousand, most of which are sources for drinking water, irrigation, hydroelectrical power and fish production (Kaul, 1987).

Many of these Latin American freshwater lakes and reservoirs are under severe anthropogenic pressure. The disturbance and degradation of their catchment areas and overexploitation of natural resources have a negative socio-economic impact on rural economy and food production. The processes responsible for environmental and resource deterioration in inland waters are poorly understood, and little information is available to provide the basis for a strategic management plan for these threatened environments, some of which contain unique indigenous fauna of ecological and commercial importance.

Lake Patzcuaro, located in the State of Michoacan at 2035 metres above sea level, represents one of the most important water bodies in Mexico. Its geographical location, native fish fauna and the settlements of P'urhepecha Indian villages around its shores, identify Lake Patzcuaro as a national inheritance with historical, ecological, social and cultural value.

For centuries, the local fisheries have been based upon captures of the "Pescado blanco" (Chirostoma estor Jordan: Atherinidae) which has a high market value nationally, the "Charales" (species of the same genus but smaller in size), and the "Acumara" (Algansea lacustris Steindachner: Cyprinidae), all of which are considered as unique and endemic fish fauna. Traditionally, fishing activity has represented the basis of the subsistance economy of the P'urhepecha people in Patzcuaro. However, the lake has been subjected to irrational exploitation, and at present is in an accelerated process of ecological degradation.

Some of the reasons which have been identified as responsible for the deterioration of Lake Patzcuaro are indiscriminate deforestation within the catchment area, organic pollution, overfishing, introduction of exotic fish species, lake management programmes incompatible with the social and cultural reality, lack of coordination between different institutions which are involved with the administration of the lake, and fractionary and frequently incomplete ecological assessment. Such circumstances are increasingly apparent not only in Mexico but throughout Latin American rural communities.

The region of Lake Patzcuaro has been the center of numerous studies, particularly in the fields of socio-economics, history, anthropology and biology. A bibliographic review (Argueta, 1979) reported a total of 548 titles distributed among 20 different topics, some of them from the past century. However, most of the past research has been focused only on particular points and isolated aspects. Consequently, a complete ecological assessment of the physical, chemical, biological and socio-economic factors affecting the lake and its productivity is required.

Satellite remote sensing of freshwaters is a very new field which has been shown to have great potential for providing an alternative cost-effective technique in the assessment of water resources. Satellite imagery can have certain advantages over conventional ground surveys. It can provide a synoptic view which is unobtainable by conventional methods, repetitive coverage of a given area, almost instantaneous spatial data over the area of interest, and a significant reduction in the requirements for time and personnel. Although the suitability of this technology for continuous freshwater monitoring depends greatly upon the final objectives of a particular project, the availability of satellite data, the development of accurate predictive models for water quality mapping and the cost-effectiveness of these techniques in relation to conventional surveys play an important role in the successful application of remote sensing to aquatic sciences.

Despite the fact that satellite digital imagery for water quality mapping started as early as 1972 (Brooks, 1975; Egan, 1972; Lillesand and Kiefer, 1979; Lindell, et al, 1985) and has been applied in many developing countries (Cheney and Rabanal, 1984; Howard, 1985; Lemoalle, 1979), the use of satellite imagery in Mexico has been limited and isolated, in as much as only cartography, forest classification, geothermal research and marine observations have been reported (Soto et al, 1977; Graham, 1981; Ruiz-Azuara, 1985).

In order to improve the understanding of Latin American high altitude freshwater lakes, and to provide information on which to base strategies for lake restoration and fisheries management, this thesis presents the results of analyses on the physical and chemical factors affecting the basin and the productivity of Lake Patzcuaro, Michoacan, Mexico using both conventional hydrobiological techniques and satellite digital multispectral imagery. Thus, the aims of the present research were:

a) To produce an accurate bathymetric chart with associated morphometric parameters describing the geomorphology of Lake Patzcuaro, Michoacan, Mexico.

b) To describe the climate of the lake and its possible short term trends during the past sixty-six years, to identify the main climatic components which affect the water level and hence the water budget of the basin and to describe the general water motions which affect the hydrodynamics of the lake.

c) To describe the physical and chemical properties of the water over a 6 month sampling period, to estimate the primary production from both phytoplankton populations and macrophyte communities and to examine the environmental parameters affecting the primary productivity.

d) To evaluate the applicability of remote sensing techniques for water quality assessment using multispectral digital imagery generated from the earth resources satellite SPOT-1.

Based on these data trophic classification, primary productivity and fish yields for the lake are discussed.

Chapter 2

The study area.

Geographic location.

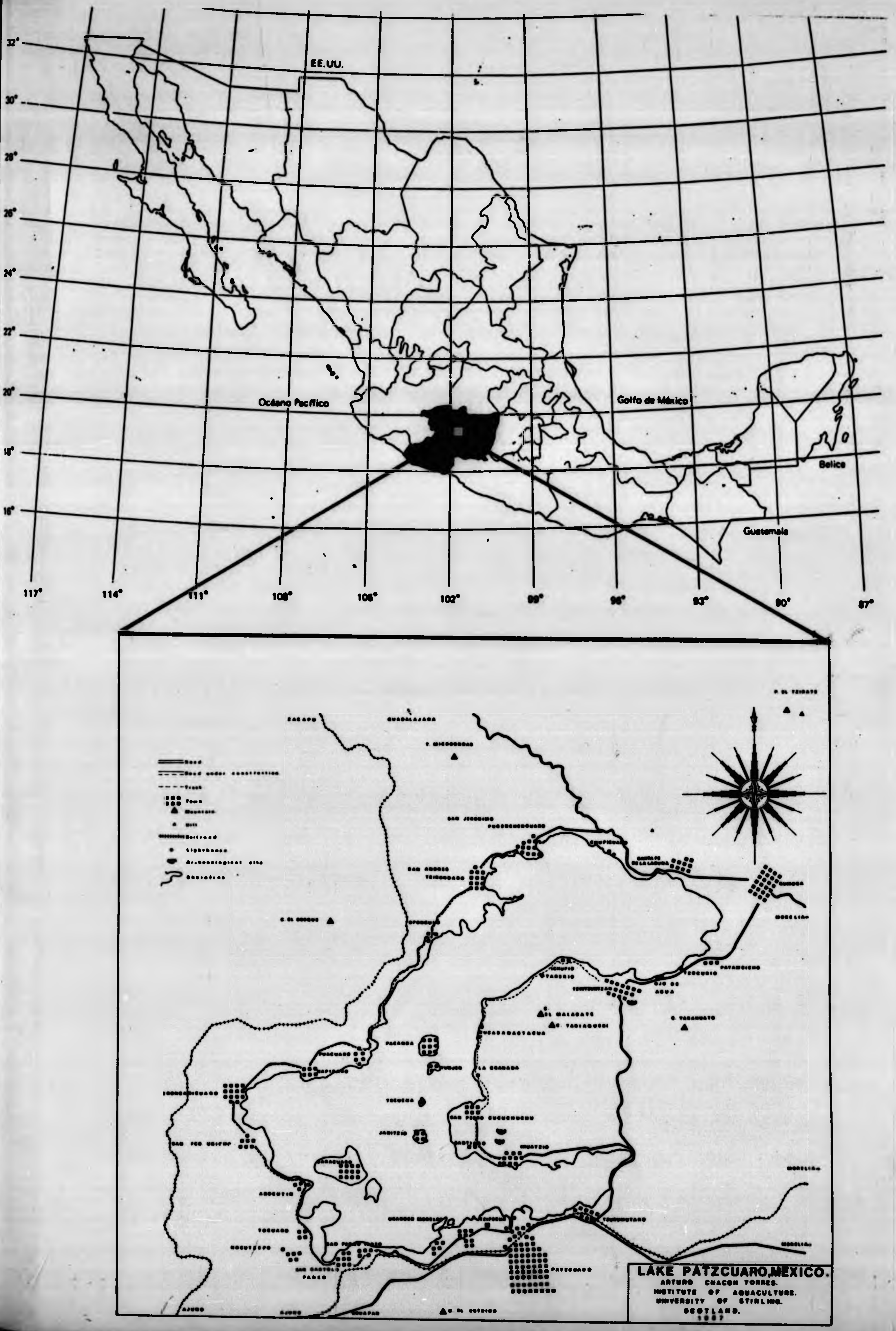
Lake Patzcuaro situated in the Mexican altiplano 360 km north-west of Mexico City, lies between 19° 32' and 19° 42' N, and 101° 32' and 101° 43' W (Figure 2.1). The lake is C-shaped and has eight islands, the largest being connected to the mainland by an earthen road, whilst two others are separated only by marsh and narrow man-made channels. The lake has no outlet and no important inlets, being fed by surface temporary streams during the rainy season. The water inputs to the lake are derived solely from seasonal rainfall and seepage, and so variations in lake level are continuous. However, an average water height of about 2035 m above sea level has been recorded (De Buen, 1944c; Gorenstein and Pollard, 1983 and Secretaria de Agricultura y Recursos Hidraulicos, SARH, Mexico, personal communication).

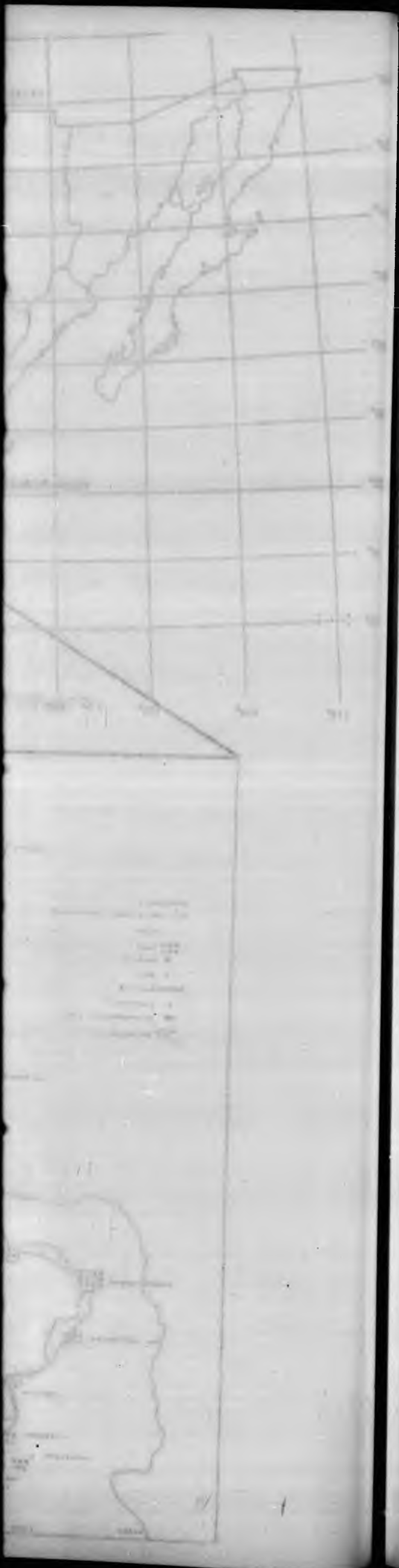
General geomorphology and soils.

Lake Patzcuaro is situated in the southern part of the Mexican Plateau. The margins of the plateau are the Sierra Madre Oriental in the east and the Sierra Madre Occidental in the west. The southern limit of the Plateau is the Eje Neovolcanico Transversal which extends across Mexico from east to west between the 19th and 20th latitudinal

Figure 2.1

Geographical location of Lake Patzcuaro, Michoacan, Mexico.





parallels. Within the Eje Neovolcanico Transversal is a large concentration of cinder cones, lava cones and central volcanoes (Demant, 1978; Robin and Demant, 1975). The youngest of these, Volcan El Paricutin, erupted in 1943-1952, 60 km from Lake Patzcuaro. Hasenka and Carmichael (1985) estimated that about 1000 volcanoes of the Eje Neovolcanico Transversal are found in the State of Michoacan with the highest density of 11 volcanoes/100 km2 located in El Paricutin region. The intensive mid-Tertiary to late Quarternary volcanic activity, frequency of seismicity and the high instability of the Eje Neovolcanico Transversal which continues to the present has been related to the subduction process of the Cocos plate into the North American plate. These tectonic movements take place at the Middle America Trench which is located along the continental margin in the Pacific Ocean (Nixon, 1982; Canul and Rocha, 1985; Canul, 1985).

Although the Mexican Plateau has a long history of instability, the origin of Lake Patzcuaro is considered geologically recent. During the Tertiary and early Pleistocene, an ancestral Rio Lerma probably flowed westward from Central Mexico to the Pacific Ocean (De Buen, 1943a; Alvarez, 1972). Subsequent uplift and vulcanism during the late Pleistocene resulted in a series of large lakes occupying the drainage system of the Rio Lerma (Maldonado-Koerdell, 1964; Barbour, 1973b). Most of these lakes were eventually drained by the present Rio Lerma but some small basins remained closed. Lake Cuitzeo, Lake Patzcuaro and

Lake Zirahuen were thus formed as a result of successive compartmentalizations by lava flows of a tributary to the Rio Lerma (De Buen, 1943a; Alvarez, 1972). De Buen (1943a) suggested that an ancestral connection existed north from Lake Zirahuen to Lake Patzcuaro and then from the southern basin of Patzcuaro northeast to the valley of the city of Morelia following the Rio Grande de Morelia drainage and finally into the south side of Lake Cuitzeo, the latter connected in the past with the Rio Lerma.

The three lakes, Cuitzeo, Patzcuaro and Zirahuen, are each quite different in morphometry and habitat diversity. Lake Cuitzeo is very shallow and occupies a relatively large basin with two major tributaries, Rio Grande de Morelia and Rio Querendaro. The building of the modern dam of Cointzio now retains most of the water of the Rio Grande, and most of the Rio Querendaro is diverted for irrigation. Lake Cuitzeo now receives only a third of the former discharge from its tributaries (Maldonado-Koerdell, 1964). Over two thirds of the lake's surface area dries up frequently and according to De Buen (1943a), the lake is geologically decadent or near to extinction. Lake Zirahuen, with a small stream tributary and only 12 km south of Lake Patzcuaro, is considered to be the youngest and deepest of the three lakes (De Buen, 1943a). Lake Patzcuaro with frequent variations in water levels, no major tributaries and continuous loss of depth was considered geologically mature by De Buen (1943a).

Lake Patzcuaro is surrounded by volcanic mountains which determine a topography with a high degree of slope for the drainage area such that, in a relatively short horizontal distance (1.5 km), the altitude increases from 2040 m to 2600 m (Gomez-Tagle, in preparation). Gorenstein and Pollard (1983) recognized six topographic environments, a) open water, as represented by the lake basin, b) Tule-reed marshes, which are large littoral areas associated with marginal aquatic vegetation, c) lakeshore, located at 2034-2035 m including lake islands, flat plains and alluvial deposits affected by the seasonal oscillations of lake level, d) lower slopes of the Sierra, with an altitude range of 2100-2300 m, represented by the lower slopes of volcanic hills and mountains, and some lava flows, e) upper slopes of the Sierra, with an altitude range of 2300-2800 m, and f) Alpine, at 2800-3200 m represented by the upper peaks of volcanic mountains. The maximum altitude in the drainage area is the peak of El Zirate at 3300 m.

The bedrock of Lake Patzcuaro as in most of its drainage basin, consists of Cenozoic volcanic rocks and fluvial lacustrine sediments. The recent volcanic rocks are mostly basalts. The Tertiary rocks are mainly andesites containing olivine, albite, biotite, augite and hypersthene (Villarello, 1909; Saporito, 1975; INEGI, 1985). Soil types also are associated with the volcanic origins of the region and these are mostly represented by Andosols and Luvisols. Andosols are soils originated from volcanic ash, dark in colour with high phosphorus content, and susceptible to erosion (Toledo and Barrera-Bassols, 1984). Luvisols are also soils located in volcanic regions, red in colour, rich in clay, acidic, and very susceptible to erosion. Other types of soils are located in isolated areas of the drainage area particularly on the eastern side of the lake. These are mainly Acrisols, Vertisols and Gleysols, the latter a primary component of the shoreline of the lake (Toledo and Barrera-Bassols, 1984).

Vegetation.

At present the prevailing vegetation is a direct or indirect result of centuries of anthropogenic influence. However, there is much evidence indicating that the exploitation of the natural resources during the fifteenth century P'urhepecha civilization was based on diversified and multiple resource utilization in which the magnitude of ecological disturbance was negligible. Although anthropogenic activities have been present for centuries, the most drastic environmental change has been observed during the last century with the introduction of modern but inappropiate production systems (Argueta and Cuello, 1985; Caballero et al, 1981; Gorenstein and Pollard, 1983; Toledo et al, 1980; Toledo and Barrera-Bassols, 1984).

In most of the lakeshore areas, the original vegetation has been removed and the area used for agriculture or grazing. The vegetation of the lower and upper slopes of the Sierra does not follow a particular pattern but a complex mosaic of plant associations is present which is determined by a combination of edaphic, topographic, mesoclimatic and land use factors (Caballero et al, 1981).

The following description is only a selection of the most abundant vegetation of the basin, more detailed botanic information being provided by Caballero *et al* (1981), Leavenworth (1946), Rzedowski (1978) and Toledo *et al* (1980). Maximum elevations or alpine environments (2800-3200 m) are represented by fir forest (*Abies religiosa*) with some associations of pine (*Pinus pseudostrobus*) and alder (*Alnus arguta*). Ecological disturbance in these areas has stimulated the growth of alpine grass (*Festuca* sp and *Muhlenbergia* sp). Upper slopes of the Sierra (2300-2800 m) are represented by pine forest (*Pinus leyophylla*, *P. michoacana*, *P. pseudostrobus* and *P. montezumae*), oak forest (*Quercus rugosa*, *Q. castanea*, *Q. laurina*) and pine-oak forests (*P. leiophylla* and *Q. castanea*; *P. montezumae* and *Q. rugosa*). Other commercially valuable trees (*Tillian mexicana*, *Clethra mexicana* and *Terstroemia pringlei*) are near to erradication. Deforested and eroding areas at this altitude support less robust vegetation (*Bursera cunnueata*, *Agave* sp., *Senecio preacox*, *Clusia salvinii*). Lower slopes of the Sierra (2100-2300 m) are mainly associated with grass and secondary herbaceous vegetation (*Acacia pennatula*, *Yucca filifera*, *Opuntia* spp, *Agave* spp, *Mimosa buncifera*, *Croton calvenscens*) and agriculture (maize, bean, wheat, lentil, squash). The lakeshore (2035-2100 m) is mostly under agricultural production (alfalfa, peas, lentil, and others).

Aquatic vegetation is represented by 49 species included in 23 families (Lot and Novelo, in press). The emergent macrophyte communities are represented by tules (*Scirpus americanus*, *Typha latifolia*, *Sagittaria graminea*, *Cyperus* niger), which, given favourable light conditions, can be found up to 4 m deep. Submerged macrophytes with floating leaves are represented by only two communities dominated by Nymphaea mexicana and Potamogeton illinoensis, these are frequently associated with submerged macrophytes (Potamogetum latifolius, Najas guadalupensis, Ceratophyllum demersum, Utricularia gibba and U. vulgaris) and they have been found up to 7 m depth in clear water (Caballero et al, 1981).

Fish fauna.

The fish fauna of Lake Patzcuaro is represented by 10 indigenous and 4 introduced species (Table 2.1). The amphibian "achoque" (Bathyserodon dumerilii), also represents an important resource in the fishery.

The average total annual fish catch between 1980 and 1987 was 1,029 tonnes. The composition of the fishery is represented by carps (21.7%), charales (21.3%), lobina negra (21.3%), acumara (19.9%), pescado blanco (8.9%), mojarra (5.1%) and chehuas (2.2%) (Lizarraga and Tamayo MS). Pescado blanco (Chirostoma estor) is one of the highest market value species in the country (US $10.0/kg).

Fishing methods include the seine known as "chinchorro" which average from 100 to 200 m in length, 5 m in width and 1 or 2 cm mesh size. The middle section of "chinchorros" is made of finer mesh and in the form of a pocket or "bolsa" whose position in the water is marked by a float. The gill net or "cheremekua" is made in two mesh sizes, a fine mesh

Table 2.1. Fish fauna of Lake Patzcuaro, Michoacan, Mexico.

* Indigenous species; + Introduced species.

Family and species	common name	P'urhepecha name	Food habits
ATHERINIDAE		khuruchecha	
Chirostoma estor Jordan	* "Pescado blanco"	khurucha-urapiti	Carnivorous (fish)
Chirostoma grandocule (Steindachner)	* "Charal blanco"	chakuami	Carnivorous (zooplankton)
Chirostoma bartoni Jordan and Evermann	* "Charal prieto"	khuerepo-turipiti	Carnivorous (zooplankton)
Chirostoma patzcuaro Meek	* "Charal pinto"	khuerepo	Carnivorous (zooplankton)
GOODEIDAE		Tirhuecha	
Alloophorus robustus (Bean)	* "Chehua"	Chehua	Carnivorous (fish & insects)
Neoophorus diazi Meek	* "Tiro"	Choromu	Carnivorous (zooplankton)
Allotoca vivipara De Buen	* "Tiro"	Tirhu-sapichu	Carnivorous (zooplankton)
Skiffia lermae Meek	* "Tiro"	Tirhu	Omnivorous (plankton)
Goodea atripinnis R. Von Bayner and Steindachner	* "Tiro"	Tirhu-pitsupiti	Herbivorous (phytoplankton)
CYPRINIDAE			
Algansea lacustris Steindachner	* "Acumara" * "Sardina"	Akumara	Omnivorous (plankton)
Cyprinus carpio Linne	+ "Carpa"	-	Omnivorous (benthos)
Ctenopharyngodon idella (Cuvier and Valenciennes)	+ "Carpa"	-	Herbivorous (Macrophytes)
CENTRARCHIDAE			
Micropterus salmoides (Lacepede)	+"Trucha" +"Lobina negra"	-	Carnivorous (fish)
CICHLIDAE			
Tilapia sp	+ "Mojarra"	-	Omnivorous

(0.5-0.8 cm) for the "charales" and a larger mesh of up to 8 cm for "pescado blanco" and "trucha". Gill nets are measured as the number of meshes contained in a section of about one metre in width. These can be joined together to form long nets sometimes the size of seines. A third type of fish net used in Lake Patzcuaro was the butterfly-shape dip net known as "cuchara", "mariposa" or "uiripu". Although fishing with the "uiripu" was probably a common practice in the past, today this net has been abandoned for more efficient fishing gear. Other fishing methods in the lake include rod-and-line and spearing with the "atlatl" or "fisga".

Numerous studies have been orientated towards the systematics, diversity, reproduction, feeding habits and aquaculture of the indigenous fish species of Lake Patzcuaro (Barbour and Brown, 1974; Barbour and Miller, 1978; De Buen, 1940a; 1940b; 1940c; 1940d; 1941d; 1941f; 1941g; 1941h; 1941i; 1942a; 1942b; 1942c; 1944a; Espinosa, 1941; Gonzalez, 1985; Lara, 1974; Martin del Campo, 1940 and Solorzano, 1961; 1963).

From a biogeographic point of view the genus <u>Chirostoma</u> and the family Goodeidae have been considered unique endemic components of the Mexican fish fauna (Barbour 1973a; De Buen, 1945a; 1946). Hypotheses about the possible origin and distribution of the these groups in the basin of the Rio Lerma system suggest that these fish species are biological evidence of an ancestral connection between the Valley of Mexico and lakes Cuitzeo, Patzcuaro and Zirahuen through the

Rio Lerma (Barbour 1969; De Buen 1943b). The family Atherinidae is represented mostly by marine fish, however small individuals can penetrate estuaries and colonize freshwater streams. This is common in the coast of Michoacan where the genus Melaniris (Atherinidae) is found in freshwater bodies far from brackish waters. The familiy Goodeidae is considered to be descended from the family Cyprinodontidae which is common in marine, brackish and freshwater environments. Species of Goodeidae and the genus Chirostoma are found only in basins related to the Eje Neovolcanico Transversal. The indigenous cyprinid Algansea is considered a component of the Neartic fish fauna colonization (Alvarez 1972; Barbour and Miller, 1978; Jensen and Barbour, 1981).

According to Alvarez (1972), the Valley of Mexico at the end of the Cretaceous period was probably covered by the Atlantic Ocean. Subsequent continental uplift resulted in the formation of various brackish lagoons in the plateau inhabited by fish of the families Atherinidae and Cyprinodontidae. As a result of the progressive loss of salinity by continuous rainfall, and isolation processes by volcanic activity, only Chirostoma and Goodeidae survived the ecological transformation and generated the diverse genera of Goodeidae and the diverse species of Chirostoma. The systematics of this group is very complex and it has been the focus of numerous studies (Barbour, 1973a; 1973b; Barbour and Chernoff, 1984; De Buen, 1940c; 1945a, 1946; Echelle and Echelle, 1984). The current taxonomic uncertainty is considered to be due to relatively recent evolution of the *Chirostoma* species of the Mexican Altiplano.

During the 1930s Mexican authorities introduced *Micropterus salmoides* into Lake Patzcuaro with the purpose of increasing fish production. This action however, generated a long and indeed strong controversy regarding the ecological impact of this species on the populations of *Chirostoma estor* (Berriozabal, 1936; De Buen 1941c; Lara, 1980; Quevedo, 1936a). Shortly after the introduction, the Mexican Government issued a decree declaring illegal any introduction of exotic species without previous ecological studies (Quevedo, 1936b).

De Buen (1941c) found no strong evidence of the predation of *M. salmoides* on the populations of *C. estor*, nor was any significant scientific evidence provided in this respect for the following 43 years. However, Garcia (1985) demonstrated not only that the feeding habits of these two species overlap during their adult life, but also the clear predation of *M. salmoides* on *C. estor*. The increase in distribution of *M. salmoides* was favoured by the ecological disturbance and the extensive macrophyte distribution in the lake. Further evidence on predation over *Chirostoma* was also provided by Toledo (1986).

Given the high commercial value and the progressive decline of captures of *Chirostoma estor*, attempts to reproduce and culture this species have been made, but only on an experimental scale (Armijo and Sasso, 1979; Rosas, 1970;

Lara, 1974). The slow growth rate, nutritional problems, high mortality during larval stages and pelagic behaviour of the species have been attributed as the major reasons for failure. At present, P'urhepecha communities and Mexican research authorities (CRIP) are carrying out an experimental cage incubation in natural conditions of fertilised eggs of C. estor for immediate release and restocking of the lake. Recent preliminary trials on egg incubation of Algansea lacustris under laboratory conditions have been successful (Rivera and Orbe, 1988). The ecological effect of the introduction of exotic cyprinids and tilapias into Lake Patzcuaro during the 1970s has not yet been evaluated.

The P'urhepecha settlements.

During the fifteenth century the southern Mexican plateau was the center of two cultures. The P'urhepechas were settled in the basin of Lake Patzcuaro and the Aztecs in the Valley of Mexico. As the P'urhepechas extended their territory to the east and the Aztecs to the west, their armies eventually met in battle. Victory alternated constantly between the two forces, and in the sixteenth century the Aztec Emperor Moctezuma accepted the P'urhepechas as the only other existing empire in the world legitimatized by the gods and recognized by himself (Relacion de Michoacan 1541, 1956.).

The history and development of the P'urhepecha civilization before the Spanish contact is poorly known. The P'urhepechas never recovered from the massacre and destruction caused during the military campaign of Nuno de Guzman in 1530. Most of the cultural and historical evidence of the P'urhepechas was destroyed by the Spanish army and the Church. Ecclesiastic chronicles and pictographic representations made during the 17th and 18th century by Hispanic missionaries have revealed many features of the colonial times in Lake Patzcuaro including some descriptions of the pre-conquest civilization derived from P'urhepecha sources (Basalenque, 1673; Beaumont, 1932; De la Rea, 1882; Relacion de Michoacan, 1956).

Although specific age could not be established, pollen investigations of sediments of Lake Patzcuaro by Deevey (1944) and Hutchinson et al, (1956) suggested that the occurrence of small portions of Zea pollen grains confirmed that agriculture has been practiced in the basin for a long time. However, new paleolimnological evidence from Watts and Bradbury, (1982) indicated that the beginning of agriculture in the basin of Lake Patzcuaro was about 3500 years ago.

From the Relacion de Michoacan, historians agreed that a group of nomads known as Chichimecas and agricultural inhabitants of the basin of Patzcuaro made contact probably 1000-1200 years ago. Vapeami, leader of the nomads met a fisherman on the lake and exchanged for fish, which he had never seen, some rabbits, which the fisherman had never seen (Argueta and Cuello, 1986). The fusion of these two cultures and their military expansion to control the basin probably represented the beginning of the P'urhepecha civilization (Ramirez, 1986).

The ancient capital of the P'urhepecha civilization was based in the town of Tzintzuntzan on the shore of Lake Patzcuaro which controlled approximately 92 settlements around the shores of the lake (Gorenstein and Pollard, 1983; Stanislawsky, 1947). Estimates based on potential maize consumption patterns of the 15th-century P'urhepecha population living in the basin of Lake Patzcuaro indicated that this population was well over the carrying capacity of the basin (Pollard and Gorenstein, 1980). It was through an efficient multiple use of the ecosystem and an exchange system of lake products for basic resources such as maize from outside the basin that the P'urhepechas achieved maximum development (Pollard and Goresntein, 1980).

Recent ethnobiological studies have demonstrated the P'urhepecha knowledge of soils, metereology, botany and zoology (Toledo *et al*, 1980). The ecologically balanced management of hunting, fishing, collecting, extracting, agriculture, horticulture, animal farming and handicraft production continues to be an important factor in the P'urhepecha people's strategy to resist the damaging effects of the modern economy (Toledo *et al*, 1980).

At present the P'urhepecha population represents 25% (21,000) of the total population in the basin of Lake Patzcuaro, distributed in 24 communities of which two are in the mountains, five are on the islands and 17 are on the shores of the lake (Toledo *et al*, 1980).

Chapter 3

Lake morphometry.

Introduction.

Morphometric data for both marine and freshwater basins are a basic tool for the interpretation and understanding of hydrological and ecological processes. Moreover, with the expansion of modelling and simulation techniques to predict the direction and in some cases possible changes in ecological systems, detailed information on the physical characteristics of the environment is required and the usefulness of such predictions can be greatly improved for scientific and management purposes when accurate morphometric data are available.

Despite the large number of contributions from national and international scientists in relation to Lake Patzcuaro and its resources, the morphometry of the lake is poorly understood. During the latter half of this century the Mexican Government, through numerous institutions, has introduced a range of different programmes on erosion control, dredging, introduction of exotic species to increase fish production, chinampa agriculture, and *Chirostoma* sp. cage aquaculture. The establishment of a Centre for Nuclear Reactors has even been considered (SUTIN, 1981). However, much of the basic data emerging from the different publications on Lake Patzcuaro is highly contradictory. As an example, De Buen (1944c) reported a lake surface area of 111 km2 whereas Ziesler and Ardizzone (1979) assigned the lake a surface area of 77 km2. Some of these data have been used for proccess-orientated research (Munoz, 1981; Barbour and Brown, 1974) and fisheries assessment (Henderson, 1974; Rosas, 1981) and this can obviously lead to confusion and misinterpretation of data. Moreover, the use of such data by decision makers who take actions for environmental control and resource exploitation can result in mismanagement and waste of both human effort and economic resources.

The earliest cartographic representations of the basin of Lake Patzcuaro were produced during the first Spanish settlements. The existance of two maps (Figure 3.1, a and b) probably drawn in the decade after 1540, suggest that Lake Patzcuaro was one of the first lakes to be mapped in the New World (Foster, 1948; Deevey, 1957). Of these maps, one was reproduced in the chronicle of Beaumont (1932) (Figure 3.1 a), and the other was reproduced in Seler (1908) (Figure 3.1 b). These maps were produced during a historical dispute in 1538-1540, when Vasco de Quiroga, the Bishop of Michoacan decided to move the cathedral from Tzintzuntzan to Patzcuaro against the wishes of both P'urhephecha and Spanish settlers. The maps provided only a pictorical view of the basin during the early Hispanic settlement. However, these documents have been used in anthropological studies by Gorenstein and Pollard (1983), for the interpretation and reconstruction of what could be the sixteenth-century's lake basin (Figure 3.1 c).

Figue 3.1

Existent cartographic representations of the basin of Lake Patzcuaro, Michoacan, Mexico.

a) Beaumont (1932). Map of Lake Patzcuaro basin (1520-1550).

b) Seler (1908). Map of Lake Patzcuaro basin (1520-1550).

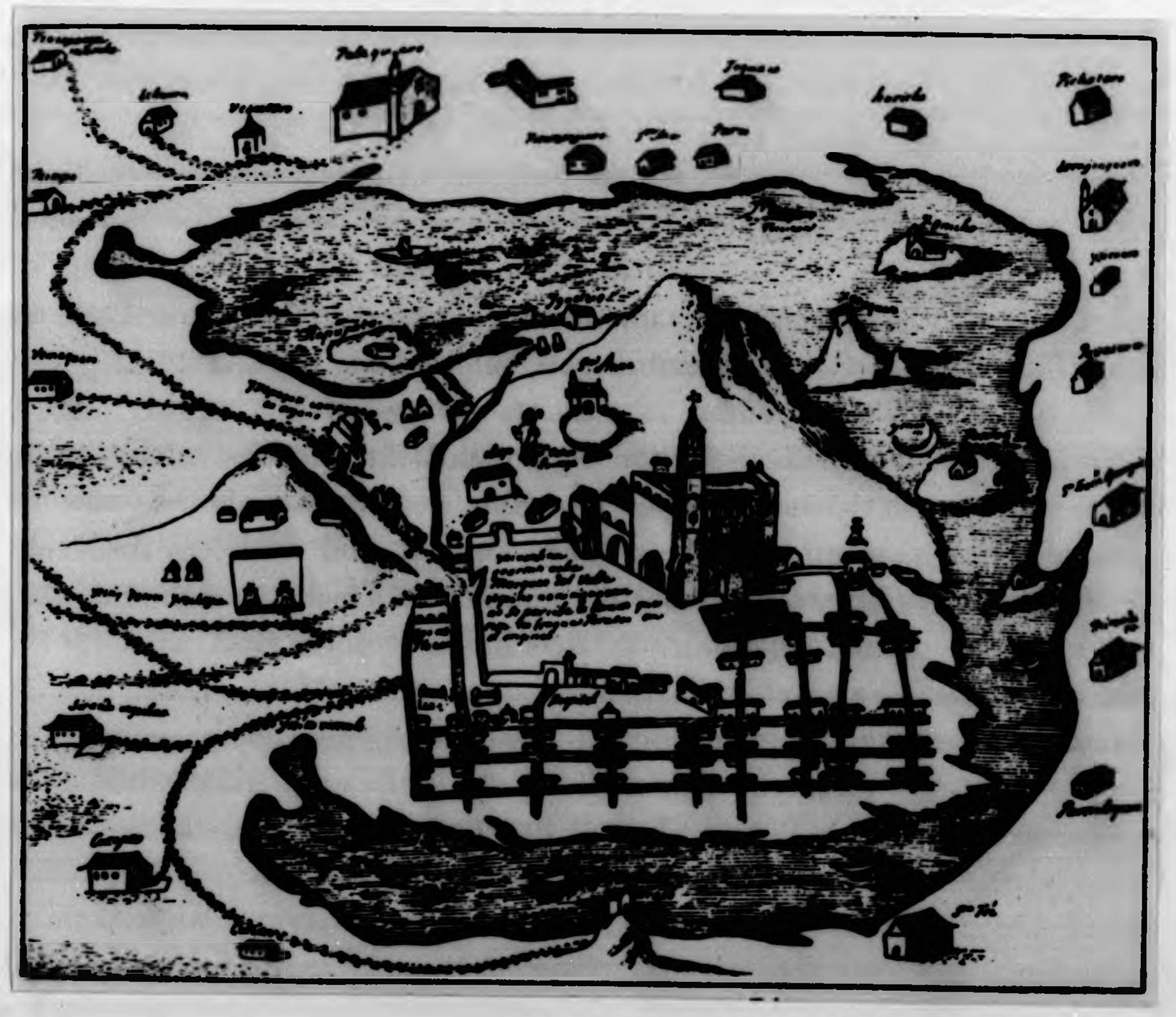
c) Gorenstein and Perlstein (1983). Early Hispanic and Protohistoric lake extent (1520-1550).

d) Yamashita (1939). Map of Lake Patzcuaro (1938).

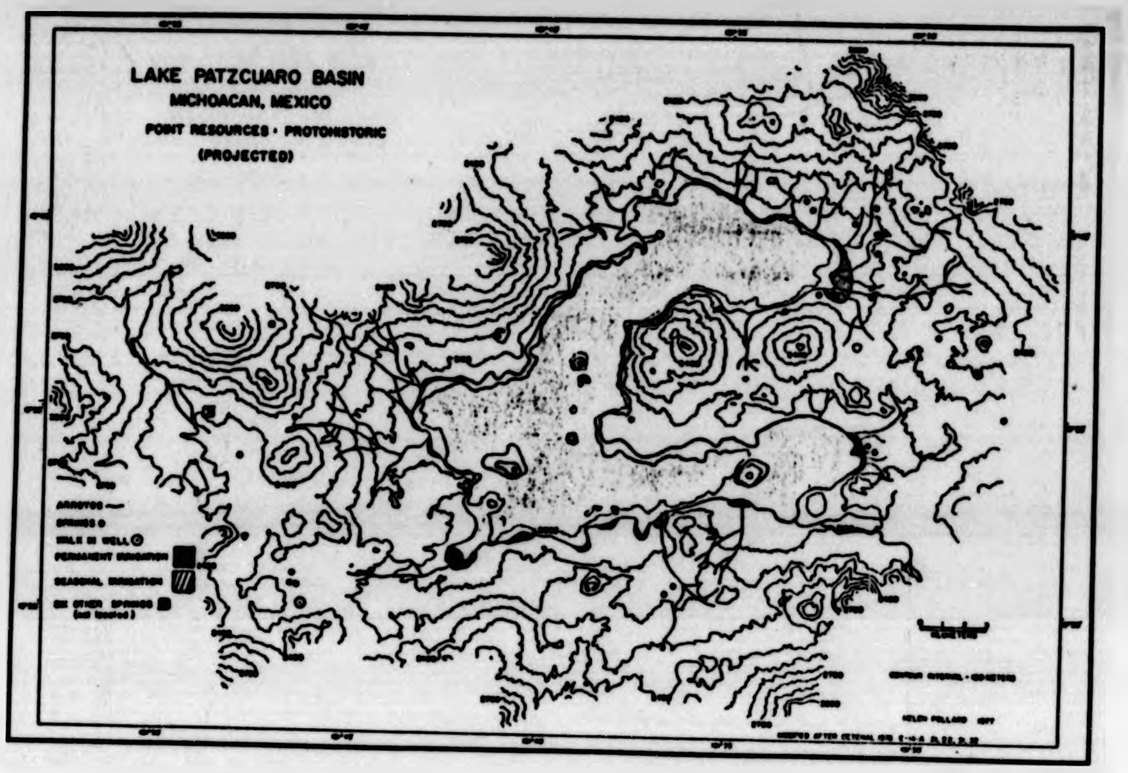
e) De Buen (1941a). Map of Lake Patzcuaro (1940).

f) Tellez and Motte (1980). Bathymetric map of Lake Patzcuaro (1976).

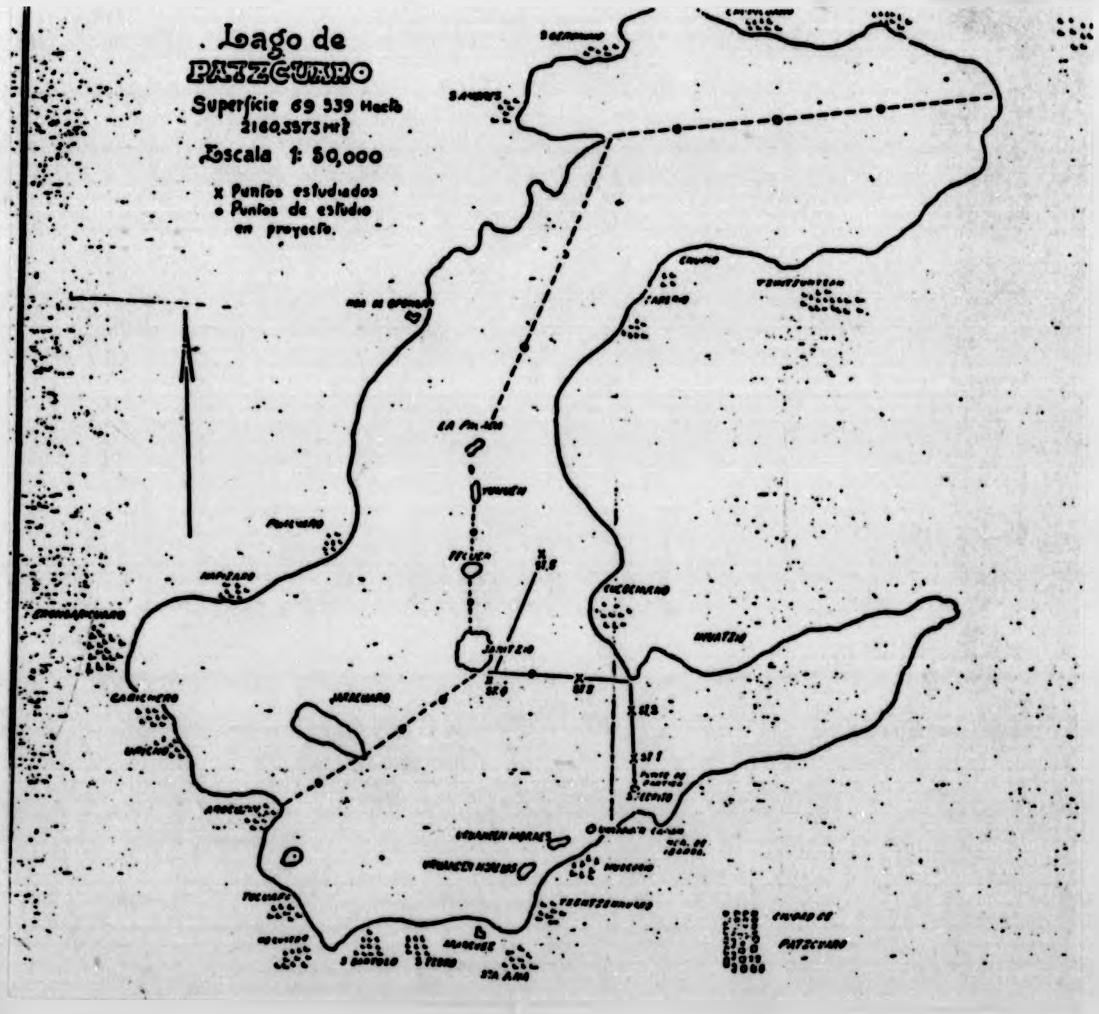
a



b


LAKE PATZCUARO BASIN
MICHOACAN, MEXICO
POINT RESOURCES · PROTOHISTORIC
(PROJECTED)
ARROYOS
SPRINGS
WALK IN WELL
PERMANENT IRRIGATION
SEASONAL IRRIGATION
SIX OTHER SPRINGS (not located)
HELEN POLLARD 1977

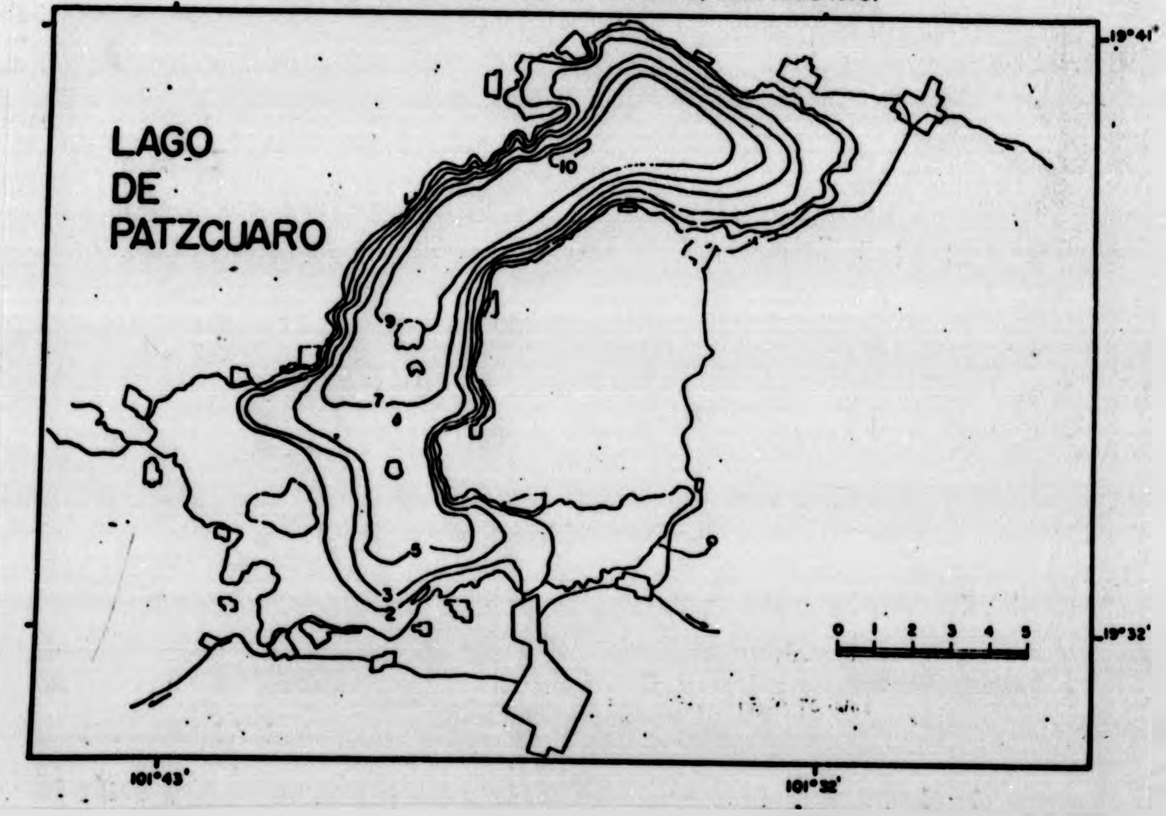
c


Lago de
PATZCUARO
Superficie 69 339 Hect
2160,3373 m³
Escala 1: 50,000
x Puntos estudiados
o Puntos de estudio en proyecto.
JANITZIO
JARACUARO
TZINTZUNTZAN
CIUDAD DE PATZCUARO

d

e

FIG.2 BATIMETRIA DEL LAGO DE PATZCUARO, MICH. MAYO 1976.



f

Other historical references regarding the morphometry of Lake Patzcuaro during the early Hispanic period are the chronicles written by the friars Alonso De la Rea (1882) and Diego Basalenque (1886). De la Rea estimated in 1639 the shoreline of the lake to be approximately fifteen "leguas", from Espasa-Calpe (1916) the "legua" commonly used in the sixteenth century was approximately the equivalent of 5,556 meters.

Yamashita (1939) and De Buen (1941a) outlined the lake and included estimates of the lake area (Figure 3.1, d and e). Although De Buen (1943a; 1944c) was perhaps the first to provide primary bathymetric profiles of both Lake Patzcuaro and Lake Zirahuen, a bathymetric sketch was only produced for the southeast basin of Lake Patzcuaro (De Buen, 1944c).

In the past 45 years only one general bathymetric chart has been completed (Tellez and Motte, 1980), (Figure 3.1 f) but this does not give a description of any basic morphometrical parameters. It is known that a team of Governmental institutions (Delegacion Federal de Pesca and Secretaria de Fomento Rural del Estado de Michoacan) made a hydrographic survey in 1982 but unfortunately no data have yet been published or made available. With the increasing human activity on Lake Patzcuaro and exploitation of its resources it is essential that data describing the morphometry of the basin and its catchment area are collected and disseminated to engineers, limnologists and decision makers.

This chapter describes work designed to produce an accurate bathymetric chart with associated morphometrical parameters describing the relevant physical and geomorphological features of the basin of Lake Patzcuaro.

Material and methods.

Working map.

An up-to-date working outline of the lake, with a scale of 1:25,000 was produced from a range of cartographic sources. The general lake outline was traced from maps published by CETENAL (Nos. E14A21 and E14A22, 1:50,000, 1976.) and corrected using aerial photographs (CETENAL, 1974, 1:50,000; 1978, 1:35,000; Sist. Inf. Geo. S.A., 1982, 1:35,000). The aerial photographs were carefully rescaled from terrestrial baselines established in the field 1986-1987 and the lake margins were further adjusted, where neccesary, from concurrent field observations of macrophyte development.

Field work

A reconnaissance survey was conducted in September 1986 in order to identify reference points and possible navigation obstacles. From this survey the main echo-sounding programme was designed and this consisted of twenty-nine sounding transects, some parallel to the maximum length, and others intersecting at right angles whenever possible. The echosounder used was a 'SEAFARER 700' operating at 150 kHz and this was calibrated against a lead-line during the survey. The transects were traced onto field maps and were located using 'SILVA' survey compasses which were also used for navigation. Starting and finishing points along transects were located by bearing triangulation.

The south-east zone of the lake is less than one metre deep with considerable areas of submerged macrophytes and abandoned fishing nets. Hence navigation and echosounding is risky and difficult, and the above transect method proved impossible. Instead, thirty triangulated "spot" depths were measured in this area using a lead line. In addition, the slope and the distance to the first contour line (i.e. 1.0 m) was determined at forty two locations around the lake and their depth values were incorporated with those from the echosounding transects.

Data processing.

Bathymetric map construction, morphometric parameters and the accuracy of the hydrographic survey were determined following the criteria proposed by Hakanson (1981).

Since aerial photographs give only an approximate scale derived from the altimeter of the aircraft, a series of straight baselines was established in the field near the lake shoreline in order to improve the accuracy of the scale.

Both the working map and aerial photographs were divided into nine sections. Each section was digitised using a Graphpad2 digital pad with a BBC microcomputer running the DIGIT image analysis software (Hayes and Fitzke, 1987). A minimum of five replicates was used and the mean of these measurements was taken for absolute calculations. The accuracy of the digital pad was checked using a polar planimeter and a map measurer.

Results

Bathymetry.

Figure 3.2 is a scaled reproduction of the resulting bathymetric map for Lake Patzcuaro with contour-lines at 1.0 m intervals, derived from the original 1:25,000 drawing. Maximum depths are in the northern part of the basin whereas considerable shallow areas are present in the south. Hydrological boundaries are less defined in the south due to the increase of macrophyte settlement, marsh environment and very low slope between contour lines. With time some islands have become part of the mainland and new islands have appeared as the lake becomes shallower. This is clearly the case of Jaracuaro island which is the biggest island in the lake and at present is connected to the mainland by an earthen road. Close to this is the new island of Pastora.

Figure 3.2

Scaled bathymetric map of Lake Patzcuaro, Michoacan, Mexico, with contour lines at 1.0 m intervals.

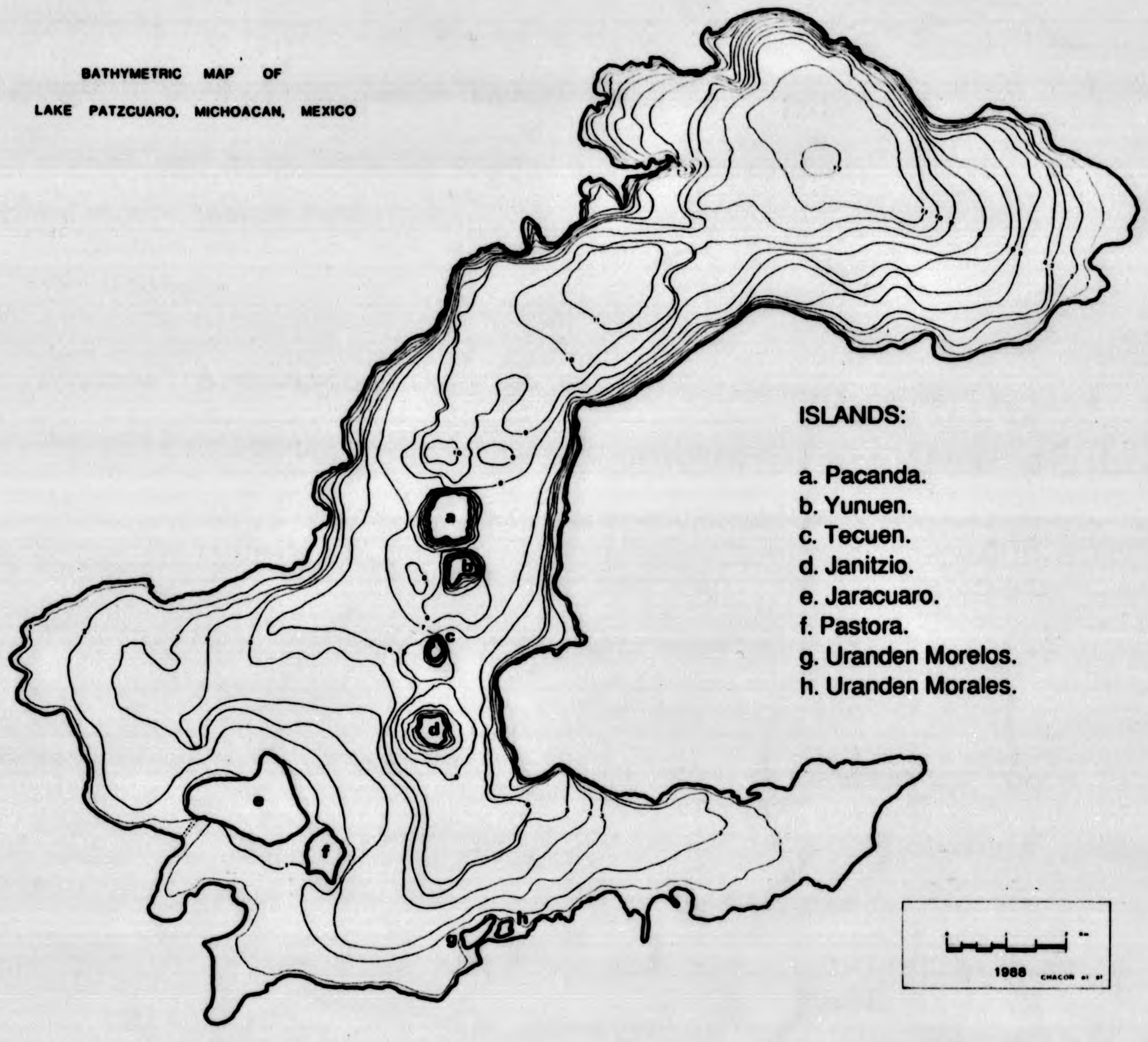


Figure 3.2

Scaled bathymetric map of Lake Patzcuaro, Michoacan, Mexico, with contour lines at 1.0 m intervals.

Figure 3.3 illustrates the distribution of the shoreline mean gradient (slope) for the first metre of depth. As can be observed the profile of the basin is represented by gradients greater than 5% slope with a frequency of about 52.4%. Smooth profiles (< 5% slope) are mostly in the southern basin particularly in areas near the island of Pastora. Steep profiles (up to 33%) are found particularly in the northern and eastern side the of the lake. However, the shoreline near the town of Quiroga presents an exceptionally smooth profile (0.97% slope).

Morphometry

Figure 3.4 a, b and c show the direct, percentage and relative hypsographic curves obtained using the digitised data from Figure 3.2. According to Hakanson (1977) the definition of lake form has an important role when statistical work and morphometrical calculations are to be made on a particular lake. The calculation of lake volume, for example, can be made in two ways depending on lake form. The relative hypsographic curve of Lake Patzcuaro (Figure 3.4 c) shows that the lake is slightly convex in form, and since the curve does not have any point of inflection (i.e. is parabolic), it is considered as the "macro" type (Hakanson, 1977).

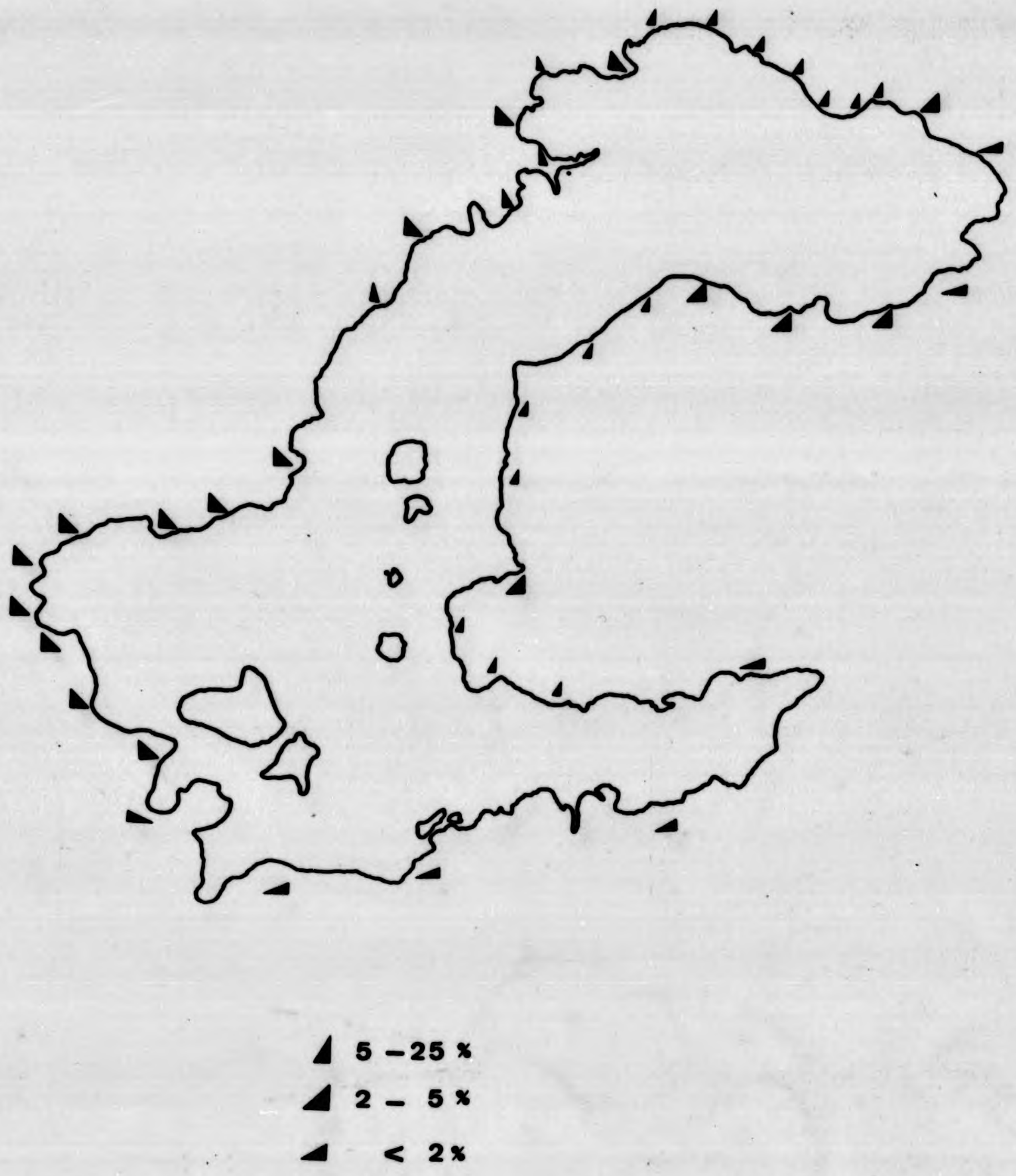


Figure 3.3
The distribution of the shoreline slope in Lake Patzcuaro, Michoacan, Mexico. Slope is given as a percentage of the height versus the length.

Figure 3.4
Hypsographic curves for Lake Patzcuaro, Michoacan, Mexico, derived from the bathymetric map. a) Direct b) Percentage c) Relative.

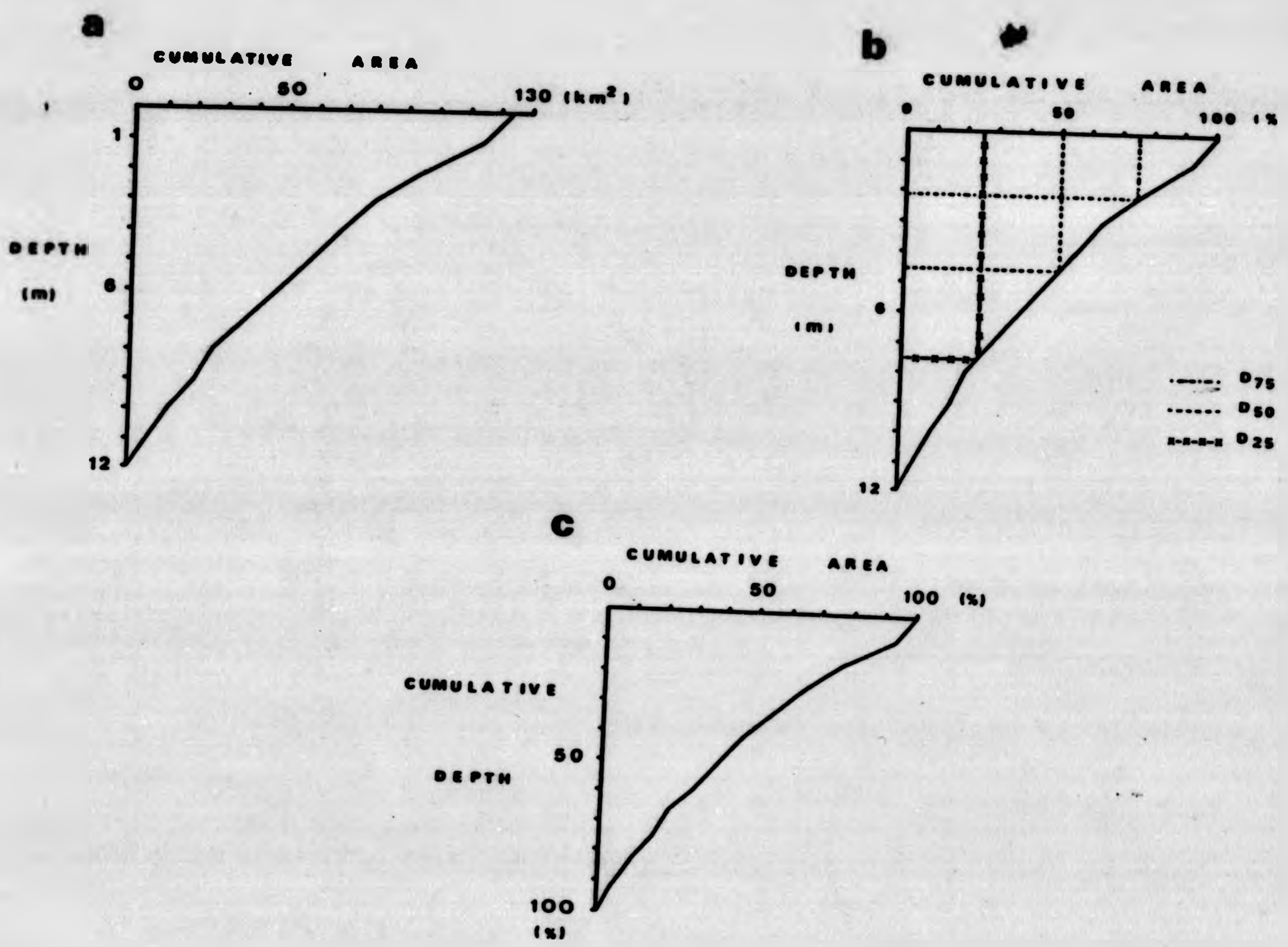


Table 3.1 presents the results of morphometrical data for Lake Patzcuaro following the criteria suggested by Hakanson (1981). Most calculations are based on the map at a scale of 1:25,000 but for lake area and shoreline length the most recent aerial photographs and field baselines were used.

Discussion.

Despite the intensive research activity on Lake Patzcuaro and its resources, a complete and dynamic picture of the chemical and biological components is not yet available. Processes such as eutrophication, fisheries yield, and environmental impact can not be accurately evaluated, in part because of the lack of basic data on the lake and its catchment area. The first useful, up-to-date data about the cathment area were provided by Gorenstein and Pollard (1983) and Gomez-Tagle (in preparation). However morphometric data and a bathymetric map are needed in order to complete the link between the terrestrial dynamic processes and their affects on the lacustrine environment. Although the present bathymetric map does not disagree markedly with the previous map generated by Tellez and Motte (1980), it does provide much more detail and a complete set of morphometric data in order to support modelling and process orientated studies useful for the design of environmental programmes.

Table 3.1. Morphometrical data for Lake Patzcuaro, Michoacan, Mexico.

Total lake area (A) including islands, km2	130
Lake area (a) excluding islands, km2	126.4
Area of islands, islets and rocks, km2	3.6
Volume, (V) x 10^6 m3	628
Maximum depth (Dmax), m	12.2
Mean depth (D), m	4.9
Median depth (D50), m	4.5
1:st Quartile depth (D25), m	7.5
3:rd Quartile depth (D75), m	2.2
Relative depth (Dr), %	0.09
Maximum length (Lmax), km	19.8
Maximum effective length (Le), km	18.2
Maximum width (Bmax), km	10.9
Maximum effective width (Be), km	8.3
Mean width (B), km	6.4
Maximum effective fetch (Lf), km	1.8
Shoreline length (lo), km	114
Mean slope (α), %	0.50
Median slope (α 50), %	0.47
Shore development (F), dimensionless	2.82
Lake bottom roughness (R), dimensionless	6.03
Volume development (Vd), dimensionless	1.22
Insulosity (In), %	2.42
Direction of major axis	SSW - NNE
Lake form	SCxma

Using the optimization model suggested by Hakanson (1978; 1981) the following relationship gives the information value of the bathymetric map:

$$I = I' \times I''$$

$$I' = I/a \left[a - 0.14 \times Lr \times F^{2} \times \sqrt{1/n+2} \times \sum_{i=1}^{n} \sqrt{ai} \right]$$

$$I'' = \frac{e^{0.4 \times n} - 1}{e^{0.4 \times n} + 0.02}$$

Where:

I = The information value of the bathymetric map. It is 1 when the information in the map is complete and correct.

I' = Correctly identified area in the bathymetric map. It is 1 when all given contour lines are correctly placed.

I" = Information number which depends on the number of contour lines. It approaches 1 as the number of contour lines increases.

a = The lake area in km2.

Lr = The distance in km between parallel tracks (lake area in km2 divided by the total length of the echosounding transects in km).

F = The normalised shore development, dimensionless.

ai = The total lake area in km2.

n = The number of contour lines.

e = The base for natural logarithms (=2.718)

Table 3.2 shows the results of the determination of the optimal value (I) for a series of optimal numbers of contour lines (n) for Lake Patzcuaro. Note that for a 12 contour-line bathymetric map I' is 0.788, which means that 78.8% of the area is correctly mapped. Therefore the area error (E) will be I' = 1-E; equivalent to 21.2%; approximately 26.80 km2. The total length of the contour lines in the bathymetric map is 616.37 km with Lr = 1.2 km. This implies that the average error, in length units, perpendicular to the contour lines is 0.043 km or 43 metres. If say, a map of 95% correctly identified area is required it would be neccesary to conduct a hydrographic survey with 71 transects spaced 279 metres apart (Lr = 0.279).

Some of the morphometric data presented in this study appear to disagree with data published previously (Table 3.3). However, this is principally due to the lack of standarisation of the criteria used to evaluate the morphometry of lake basins. Hakanson (1978, 1981) gives an account of how the definition of different morphometrical parameters varies between authors. As can be seen from earlier papers, (Table 3.3) some morphometrical parameters were not given, or were simply not measured. Others such as maximum length, show enormous discrepancy, although this is primarily due to a redefinition of how this parameter is measured (see Hakanson, 1981). Mean depth is a useful parameter for fisheries modelling although it may generate

Table 3.2. Determination of information values (I) for different numbers of contour lines (n) in the bathymetric map (1:25,000) for Lake Patzcuaro. Lc = distance between contour lines in m.

Lc	n	I"	√ai	I'	I
6.0	2	0.5458	16.74	0.907	0.4950
4.0	3	0.6946	22.87	0.887	0.6161
3.0	4	0.7949	28.58	0.871	0.6923
2.0	6	0.9076	40.33	0.843	0.7651
1.0	12	0.9916	74.57	0.788	0.7813
0.5	24	0.9999	154.88	0.667	0.6669

Table 3.3. A comparison between different reports on morphometry of Lake Patzcuaro.

	De Buen 1944 a	Herrera 1979	Rosas 1981	Velasco 1982	Present project
Maximum length (km)	20.8	18.6	36.0	17.6	19.8
Maximum width (km)	15.4	13.5	10.0	7.5	10.9
Maximum depth (m)	15.0	10.8	?	12.5	12.2
Mean depth (m)	?	?	7.0	8.0	4.9
Total lake area (km2)	111	104.6	107.37	88.7	130
Volume (x 10^6 m3)	?	?	700.0	700.0	628
Catchment area (km2)	695.4+	?	?	?	929*
Islands	11	5	?	6	8

\+ Figure reported by De Buen in previous publication (1941).

* The same figure has been reported before by Gorenstein and Perlstein (1983), and Gomez-Tagle (in preparation).

poor results if reliable data are not used. For example, The Morphoedaphic Index (MEI) originally developed by Ryder (1965) as an estimator of potential fish yield divides the total dissolved solids concentration (TDS) in the lake by the mean depth. Taking Velasco's figure of 8.0 m for mean depth (Table 3.3) and assuming an average total dissolved solids concentration of 600 mg/l it can be seen that the resulting MEI for Lake Patzcuaro value would greatly underestimate potential fish yield when simple regression models are applied as yield predictors, compared with the data presented here.

The maximum depth contour line is 12 m. De Buen (1944c) reported a maximum depth of 15 m in the same area, and the figures for maximum depth vary among authors. It is clear however, that these values tend to decrease with time, and they probably are due to sedimentation. During the present survey the echosounder registered an isolated maximum depth of 13 m only. It is difficult to compare the present map with the previous charts since all other previous attempts have been substantially incomplete. However, the data generated here form the basis for all measurements and models used in this thesis.

Chapter 4

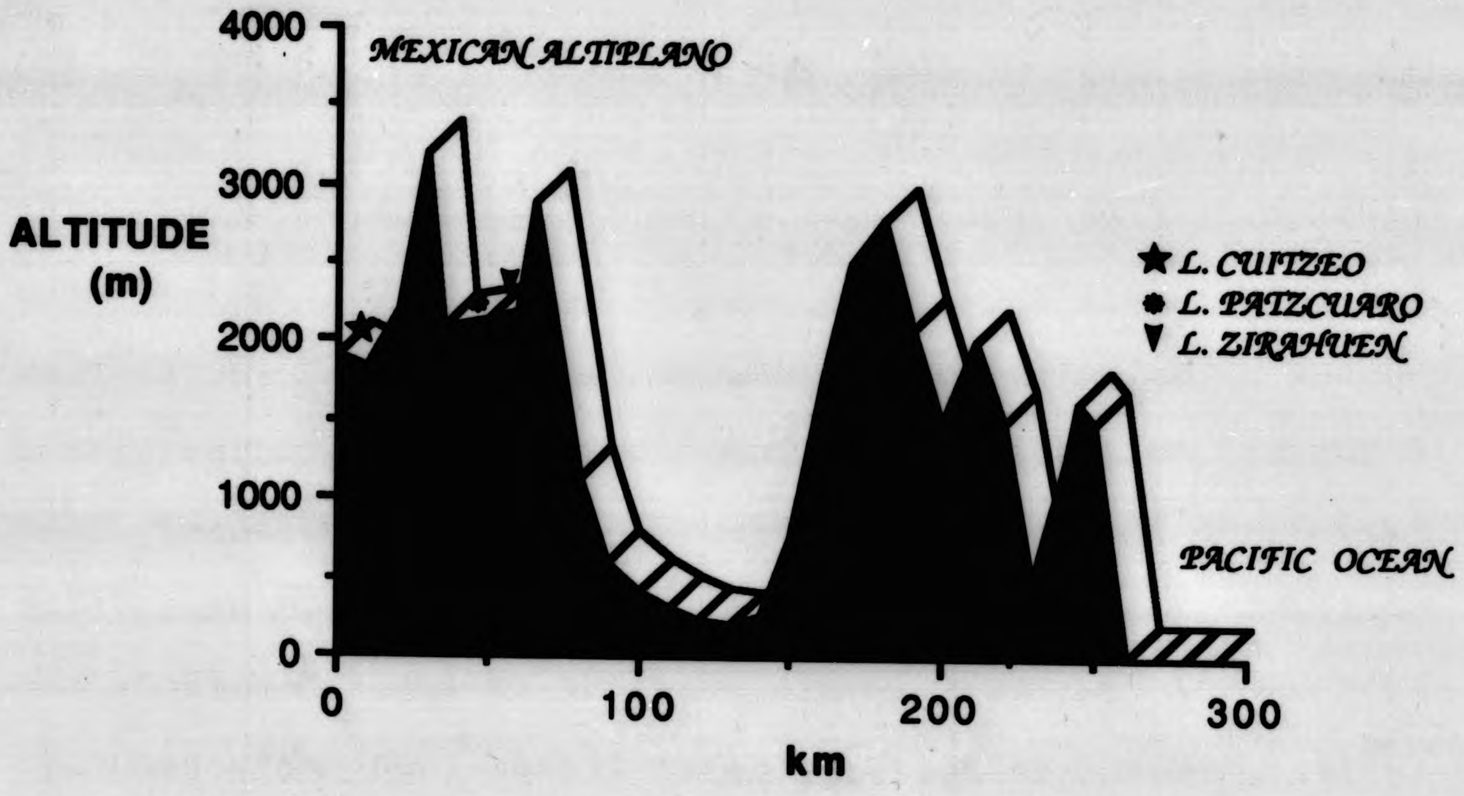
General climatic influences on the Lake.

Introduction.

The climatic distribution in the State of Michoacan, as in most of the country, is determined by the altitude above sea level and the orography of the region. Although latitude determines the inclination of the sun's rays, thus regulating both the intensity and the potential daily duration of sunshine, the effects of latitude on climate in the Central Mexican Plateau are significant only in relation to seasonal atmospheric circulation shifts. As Michoacan is located within the tropics, the sun passes directly overhead twice a year, and never deviates farther than 47 degrees from the vertical at noon. The result is an even distribution of insolation throughout the year. It is however, the interaction of atmospheric circulation features with the abrupt relief of the Plateau which defines temperature and rainfall distribution from sea level to elevations of about 3 200 m (Figure 4.1). Thus, the region shares not only climatic characteristics of low tropical environments but also those from middle latitudes. Seasonal variations are related to annual latitudinal movements of the Intertropical Convergence Zone (ITCZ). Here, humid eastern winds from northern and southern hemispheres meet. Therefore, the geographical location, altitude differences

Figure 4.1

Diagramatic representation of altitudinal distribution in the State of Michoacan, Mexico. Transect from Lake Cuitzeo located in the Mexican Altiplano, to Tizupan located on the Pacific Coast. Total length of the transect is 300 km.



and orographic effects make the Mexican Plateau a climatically sensitive region. This sensitivity has been indicated previously by Mosino and Garcia (1974), Gonzalez Quintero (1980) and Metcalfe (1987).

Although the climate for the area of Lake Patzcuaro has been previously described by Garcia (1981) based on data recorded over 23 years, no attempt has been made to observe possible climatic change. The lake, as a closed basin with no major inlets, can be more sensitive to water input imbalances than open systems. Its annual volume variations are determined mainly by differences between precipitation, evapo-transpiration, surface runoff and water filtration (seepage) from the catchment area. Runoff is that part of the water falling on the soil surface, which does not penetrate into the soil and, due to the land slope, runs off the surface together with soil particles and aggregates (Hudson, 1971; ILRI, 1981).

There are some reports suggesting that the lake is decreasing in volume and that annual rainfall is less each year (Herrera, 1979). Evidence of lake level variations associated with soil deposition from higher locations in the catchment area, is the disappearence of the small group of islets located at the southern end of the lake known as Taza China, San Pedrito, Corian and Cuyameo. These islets, reported by De Buen (1941a; 1944c), are now part of mainland. Similarily, Apupato hill was identified by Brand (1943) and Hutchinson et al (1956) as an island during the sixteenth-century. A photogrametric study complementing the field survey conducted by Gorenstein and Pollard (1983) revealed soil differences along the entire margin of the lake suggesting that in the prehispanic period the lake shoreline was approximately 2050 m altitude. There have been several reports suggesting the possible presence of temporal crevices and groundwater inputs originated by volcano-tectonic activity in the region which may affect the water balance (West, 1948). However, no evidence of such components has yet been produced.

Information regarding the water budget of the lake is non-existent. A complete field survey including the collection of data on soil characteristics, vegetation cover, land use, evapotranspiration, erosion processes, sedimentation, runoff and water seepage rates is required to understand the complex interrelantionships between climate and the catchment area and the latter possible effects on the water budget of Lake Patzcuaro. Studies on erosion dynamics of the catchment area, however, are in progress (Gomez-Tagle, in preparation).

The water balance of a lake is closely related to climatic conditions such as precipitation and evaporation, the catchment area and the outflow from the lake. As Lake Patzcuaro and its watershed are typically an endhoreic system, outflow rates are negigible and water used for irrigation purposes inside the basin either evaporates or eventually reaches the lake via seepage. Therefore, a description of the local hydrological cycle for Lake Patzcuaro would be useful to identify the main components affecting its water budget.

Hydrodynamic processes have significant effects in aquatic environments. Transport and distribution of different forms of energy, dissolved gases, nutrients, sediments and planktonic organisms are determined by different types of water movements (Hutchinson, 1957; Wetzel, 1983). Therefore, the study of water motions in aquatic systems is fundamental to the understanding of more complex processes such as primary productivity, effects of waste water, mixing and sedimentation.

Water movement in lakes and reservoirs is primarily generated by wind shear acting on the water surface. Inflows, outflows, and temperature or density differences produce additional dynamic effects on water movement in the system. Water circulation patterns for a particular aquatic system are a result of the interactions between basin size, wind stress, internal motions and the earth's rotational effects (Mortimer, 1974).

Criteria to classify water motions in lacustrine environments are basically the same among authors. Boyce (1974) summarized water movements according to their associated length and time scales. Other classifications are generally according to the place where the movements occur, i.e. epilimnion or metalimnion (Goldman and Horne, 1983; Wetzel, 1983). More generalized descriptions are summarized by Henderson-Sellers, 1984; Cole, 1983 and Welch, 1980.

The understanding of hydrodynamic processes in limnology requires not only a very complex experimental approach, but also a theoretical and numerical experimental appreciation for mathematical modelling (Mortimer, 1974). The response in time and magnitude of a particular lake to thermo-gravitational forces, wind or combination of both is variable and depends upon the morphometry of the basin, meteorological and local frictional forces such as rivers, runoff and erosion loads. However, approximate mathematical models have been applied with satisfactory results which have suggested practical ideas for lake management. These models when combined with statistical procedures and frequent field verifications can achieve reasonable agreements with the natural fluid dynamics of that particular aquatic system.

No experimental programme to study water movements of Lake Patzcuaro has been undertaken and hence to date, data on its hydrodynamics are not available in the literature. However, taking into account historical records of temperature and oxygen profiles reported by Matsui and Yamashita (1936), Yamashita (1939), De Buen (1941b), and Tellez and Motte (1980), it is evident that Lake Patzcuaro is a well mixed water body, without a thermocline and dissolved oxygen always present near the bottom of the lake. Under these circumstances it is reasonable to assume that most of the water movements take place in a single epilimnetic water column zone, as occurs in any non-stratified shallow lake. In the absence of hydrodynamic field data, seiches and waves can be predicted within a reasonable range of accuracy by using mathemathical models which have been succesfully verified in other water bodies.

The present chapter aims to describe the climate of Lake Patzcuaro and its possible short term trends during the past 66 years, to identify the main climatic components which affect water level and hence the water budget of the basin and to describe the general water motions which affect the hydrodynamics of the lake.

Materials and methods.

Data collection.

In Lake Patzcuaro, two climatological stations administrated by SARH are located at the northern and southern ends of the basin.

1. "Estacion Patzcuaro", now located at 2043 m above sea level in the southern shore and near the city of Patzcuaro, has recorded meteorological data since 1878. However, its archives are incomplete and hence compilation of daily and monthly data is difficult to acquire. Some tabular data for observations made in the past century at this station are summarized by the National Meteorological Observatory

located in Tacubaya, Mexico City. This institution provided a complete data set for rainfall recorded at Patzcuaro corresponding to a period of 66 years (1921-1986). Monthly data for temperature and rainfall were also acquired from SARH for the period 1921-1944, and some observations for evaporation and lake levels initiated by F De Buen and M Zozaya at the limnological station for 1939-1944 are published in the station's investigation reports (1942, 1944). Due to both the possible lack of continuity in weather observations (SARH, personal communication) and the difficulty of finding complete data in archives, monthly meteorological data were not available. However, using tabular data extracted by the National Meteorological Observatory in Tacubaya, it was possible to complete a comparative table for temperature, precipitation and evaporation for two periods of time, 1939-1944 and 1970-1986.

2. "Estacion Santa Fe", located at 2034 m above sea level in the northeastern end of the basin and 5 Km West of the city of Quiroga, was established in 1949 originally as a hydrometric station for lake level measurements. During the 1960s it was equipped for temperature, rainfall and evaporation measurements. Data for lake levels were used for water balance calculations.

Climate description.

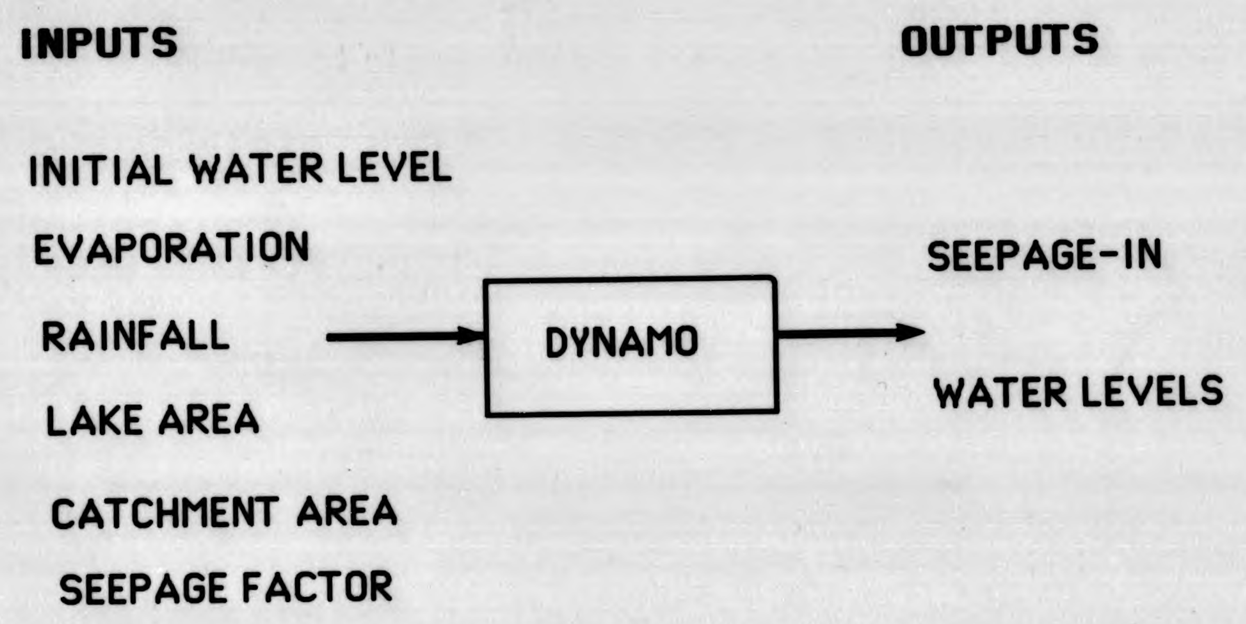
The criterion for climate description in Mexico is essentially the classification system suggested by Koppen (1936). However, this system was designed to classify large climatic areas around the world, distributed at different latitudes. As quoted by Koppen himself, this system did not consider differences which actually exist in plains located in high latitudes nor existing in high mountains located in low latitudes. In Mexico, due to the climatic changes that occur in very short distances caused by the orography and altitude differences of the region, this classification system had to be modified and adapted to the actual conditions of the country by Garcia (1981). Therefore, in the present study the same classification is used to observe any possible climatic change between the periods of 1921-1944 and 1970-1986.

Lake levels.

In order to obtain a general idea about climate phenomena and its possible effects on lake levels a simulation computer model requiring only data on rainfall and evaporation was used. The programme used the DYNAMO simulation package (Gordon, 1969; Pugh, 1973), compiled in FORTRAN language and run on a VAX mainframe system. A schematic representation of the input and output parameters for the simulation programme is presented in Figure 4.2.

Figure 4.2

Schematic representation of the input and output parameters of the DYNAMO simulation programme for water balance in Lake Patzcuaro, Michoacan, Mexico.



The programme is based on a simple mass balance equation commonly used in limnology which assumes that a) seepage out from the lake and temporary stream inputs is negligible, and b) actual lake level values were recorded with reasonable accuracy. The main water inputs and outputs to the lake are rainfall (Rain), evaporation (Evap), seepage (Seep) and runoff. These variables have effects on lake levels by the relationship:

Water level = Initial Water level+ DS * (Rain - Evap + Seep)

Where:

Initial Water = 2036.45 m for 1971-1985 or 2035.4 for 1939-1942

Seep = (Catchment area * SF * Rain)/Lake area (x 10^6 m3)

SF = Seepage factor which is assumed = 1 - runoff factor (dimensionless)

DS = Change in storage (x 10^6 m3)

By specifying among the input parameters a seepage factor equivalent to one minus the runoff coefficient value, it is possible to predict values for water recieved by seepage filtration from the catchment area and the lake level. This seepage coefficient value was assigned in an iterative fashion until the predicted lake levels from the model were similar to the actual lake level values. The model was run for both periods of time and predicted values were plotted against actual values.

Water balance.

Using the results produced by the DYNAMO simulation model, a seepage factor was applied to compute monthly water budgets for the lake. The average of 66 years of rainfall data (1921-1986) and 23 years for evaporation (1939-1944; 1970-1986) were used to estimate the water balance. Calculations for water balance were based on the assumptions that a) given the annual higher evaporation rate over rainfall input and the lack of data to compute watershed evapotranspiration, the latter parameter was considered to be the same as open water evaporation. Hence, water input from runoff and temporary streams is considered to be zero and the only contribution from the catchment area is the rate of seepage in, b) catchment and lake area were assumed to be constant throughout the considered period (803 and 126 km2 respectively) and c) rainfall is equally distributed over the entire basin.

The water balance equation for the lake can be written as follows

$$DS = (Pw + SF) - Ew$$

Where:

DS = Change in water storage ($\times 10^6$ m 3)

Pw = Precipitation falling over the lake ($\times 10^6$ m 3)

SF = Seepage of water into the lake from the catchment area ($\times 10^6$ m 3).

Ew = Evaporation from the lake ($\times 10^6$ m3).

Wind.

In order to identify dominant winds throughout the year which may induce water movements and hence sediment, nutrient and dissolved gases distribution, a review of existing data for both periods of time was made.

Monthly data for wind speed and direction were obtained from the meteorological station "Patzcuaro" for the period 1978-1986. Tabular summaries for mean monthly wind speed and direction were acquired for the period 1942-1944 (Secretaria de la Marina Nacional/Estacion Limnologica de Patzcuaro, Informes No. 2-3, 4, 39, 40, 41, 44, 45, 46, 49; 1940-1946). Historical data collection was completed with some field observations made by De Buen (1941a; 1941b) and Zozaya (1941).

Monthly frequencies for both speed and direction were computed and the pattern of annual wind distribution was determined. Due to the lack of adequate instrumentation in this particular area, wind speed is quoted by SARH as wind strength based on the Beaufort scale. Conversions to metric equivalents were computed by using the relation $V = 0.836 B^{1.5}$ (LMO/HMSO, 1982), where V is the wind speed in m/s and B is the Beaufort value. Wind direction is specified as that direction from which it is blowing and expressed in terms of the points of the compass (WMO, 1971; SARH, pers. comm.)

Measurement of water currents.

The use and accuracy of drogues or drifters for the estimation of water currents and the description of circulation patterns in lentic environments are widely documented (Shulman and Bryson, 1961; Landless and Edwards, 1976; Bhowmick and Stall, 1978; Goldman and Horne, 1983). The results suggest that these devices are cheap, easy to operate and accurate at low current velocities (< 3 cm/s).

The use of drogues was adopted for observations on water currents in Lake Patzcuaro. A set of four drogues was constructed to enable measurements at a depth of approximately 25 cm from lake surface. The vanes were made from 2 mm thick aluminium plates, 0.5 m x 0.5 m, set at 90 degrees to each other and suspended by a nylon cord below a small polystyrene marker buoy. A small plastic flag was attached to the polystyrene by a thin rigid wire, so that movements could be followed without resistance to wind.

Twenty four drogue tracking trials were carried out in Lake Patzcuaro during a three month period, from December 1986 to February 1987. Drogues were released mainly at the southwestern end of the lake. Due to the continuous water disturbance by commercial navigation, dredging and fishing in the south-east end of the lake, no observations were made in this area.

Drogues were followed by boats from approximately 250 m distance to avoid water disturbance in the vicinity and located employing "SILVA" survey compasses by bearing triangulation using previously fixed reference points. Wind speed and direction were recorded using a hand-held "DWYER" anemometer and survey compasses. Starting and finishing time for each trial were recorded using a stopwatch. Drogue tracks were traced onto a map with an approximate scale of 1:25,000. Distances covered by drogues at each selected location were used to compute the velocity and to identify the direction of the current. A general sketch map was made to describe the circulation pattern for Lake Patzcuaro. These wind-driven currents are described as surface drift which can be defined as the movement of the uppermost layer of water as a result of wind shear or blowing wind (Haines and Bryson, 1961; Goldman and Horne, 1983). In the present case the depth of the uppermost layer was considered 50 cm.

Seiches and wave height predictions.

Using basic morphometric data and wind speed records for Lake Patzcuaro, computations were made to estimate theoretical water movements other than unidirectional surface drift. Calculations for wind stress factor, Coriolis effect and surface seicches followed the criteria suggested by Mortimer (1974) and Smith (1975).

Predictions for maximum wave heights were calculated using the Sverdrup-Munk-Bretschneider (SMB) method described by the US Army Corps of Engineers (1962; 1984). This prediction system is a combined empirical-analytical procedure which has been continuously revised and widely used when limited data are available. The maximum wave height depends upon the wind velocity, the time that wind blows over the water surface, and the fetch, defined as the distance of open and unobstructed water across which the wind blows (Bascom, 1964. Cited by Beveridge, 1987). Therefore, given an average wind speed, wave generation may be fetch-limited in a particular aquatic environment.

In order to use the SMB method for wave prediction observed winds over Lake Patzcuaro were corrected for elevation, stability, duration-average windspeed, fetch and coefficient of drag. In Lake Patzcuaro winds are frequently generated in the early afternoon with a range of exposure from 1 to 8 hours. By means of preliminary SMB forecasting curves for shallow waters and accounting for the 12.97 km maximum fetch in Lake Patzcuaro, maximum wave height becomes fetch limited in between one and three hours average wind-duration. Therefore, windspeed duration was adjusted for one-, two- and three-hour periods.

Wave height measurements were made by visual observation against a vertical scale mounted approximately 100 m from the most wind-exposed shore along the maximum fetch. Values for ten wave heights were recorded and averaged for comparison with the predicted values of the SMB method.

Comparisons for wave height predictions were made using effective fetch applicable to inland reservoirs. Calculations were made using the formula suggested by US Beach Erosion Board Corps of Engineers (1962)

Results.

Climate.

Some of the climatic elements for Lake Patzcuaro are listed on a monthly basis in Table 4.1 for the two periods in consideration, 1921-1944 and 1970-1986. The annual mean temperature and precipitation for the period 1970-1986 were 16.3 C and 900.7 mm, respectively. Temperature was approximately equal to the average value for 1921-1944. However, the average value for annual rainfall for 1970-1986 represented a decrease of about 140.1 mm when compared with the value for 1921-1944 (1040.8 mm). The annual rainfall distribution is shown in climograms for each period of time (Figures 4.3 and 4.4). No appreciable difference was found in the cold and dry season (December-February), but less precipitation was observed from the beginning of the warm season with a maximum difference in summer (June-September), when 80% of the annual precipitation fell as heavy showers and thunderstorms.

Following the Koopen's modified system for Mexican orographic effects (Garcia, 1981) and using the climograms of Figures 4.3 and 4.4, formulae for the classification of

Table 4.1 Climatic parameters for Lake Patzcuaro

	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
TEMPERATURE MEAN	1921-1944	12.4	14.1	16.2	18.2	19.9	19.5	17.7	17.3	17.1	16.4	14.5	12.8	16.3
(CELSIUS)	1970-1986	12.8	13.7	15.8	17.7	19.1	18.8	17.6	17.6	17.5	16.6	14.5	13.5	16.3
MEAN MAX	1921-1944	20.2	23.0	24.7	27.0	28.0	25.4	23.6	22.7	22.4	22.7	21.6	20.4	23.5
(CELSIUS)	1970-1986	24.8	25.8	29.1	30.2	31.0	29.2	26.3	25.4	25.4	23.6	24.8	24.4	26.7
MEAN MIN	1921-1944	4.5	5.6	7.7	9.6	12.1	13.6	12.4	12.6	12.1	10.2	7.2	5.5	9.4
(CELSIUS)	1972-1982	4.0	5.0	6.4	8.7	10.7	12.9	12.4	12.2	12.0	10.1	6.3	5.1	8.8
RAINFALL	1921-1944	14.3	12.0	9.6	4.9	35.2	176.0	236.6	236.9	190.1	76.6	29.1	19.8	1040.8
(mm)	1970-1986	13.8	6.7	5.5	9.6	38.9	144.9	224.5	198.5	164.8	63.2	16.0	14.0	900.7
MAX. RAINF.	1921-1944	35.0	27.0	25.0	19.7	33.8	50.0	48.7	75.7	61.5	51.5	44.7	52.5	75.7
IN 24 Hs	1972-1982	52.0	15.7	16.5	57.7	28.0	57.0	62.5	56.0	64.0	60.1	20.3	28.0	64.0
EVAPORATION	1921-1944	100.6	124.4	158.7	203.1	197.9	125.1	112.5	112.6	91.7	101.7	89.5	96.5	1524.5
(mm)	1970-1986	89.8	115.6	168.7	187.3	180.9	134.9	115.5	112.1	99.2	96.3	86.6	77.6	1437.0
WIND SPEED	1939-1944	2.2	3.8	3.8	2.2	2.2	0.8	2.2	2.2	2.2	2.2	2.2	2.2	2.2
(m/s)	1978-1986	4.4	9.4	9.4	4.4	4.4	2.2	2.2	2.2	4.4	4.4	4.4	4.4	4.4
DIRECTION	1939-1944	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0
(DEGREES)	1972-1982	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0
No. OF DAYS CLEAR SKY	1924-1946	18.0	16.0	17.0	20.0	9.0	2.7	4.2	3.5	1.7	8.2	10.5	8.5	119.3
	1972-1982	18.3	18.8	22.9	20.5	13.2	4.2	1.0	3.1	5.7	8.5	17.8	16.7	151.1
THUNDERSTOM	1924-1946	0.5	0.5	0.7	0.8	2.2	3.3	4.9	6.9	3.8	2.1	0.8	0.5	28.0
	1972-1982	0.0	0.0	0.0	0.2	0.2	0.2	1.9	1.9	1.2	1.5	0.0	0.2	7.5
FROST	1924-1946	11.3	6.7	2.0	0.1	0.0	0.0	0.0	0.0	0.1	0.8	5.0	9.8	35.8
	1971-1982	9.9	5.1	1.5	0.2	0.1	0.0	0.0	0.0	0.0	0.1	2.5	6.5	26.0

Figure 4.3

Climogram for Lake Patzcuaro, Michoacan, Mexico, for the period 1921-1944.

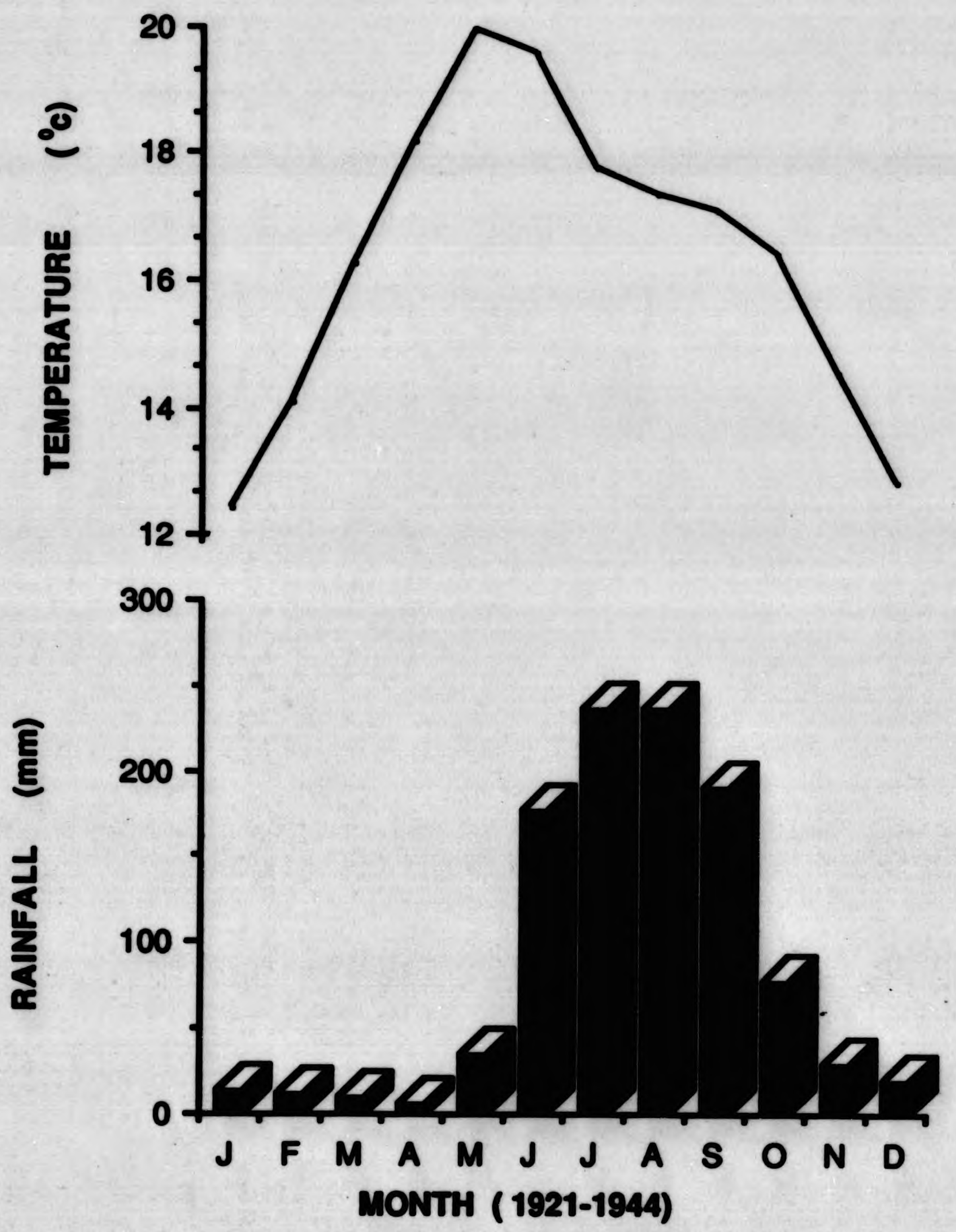
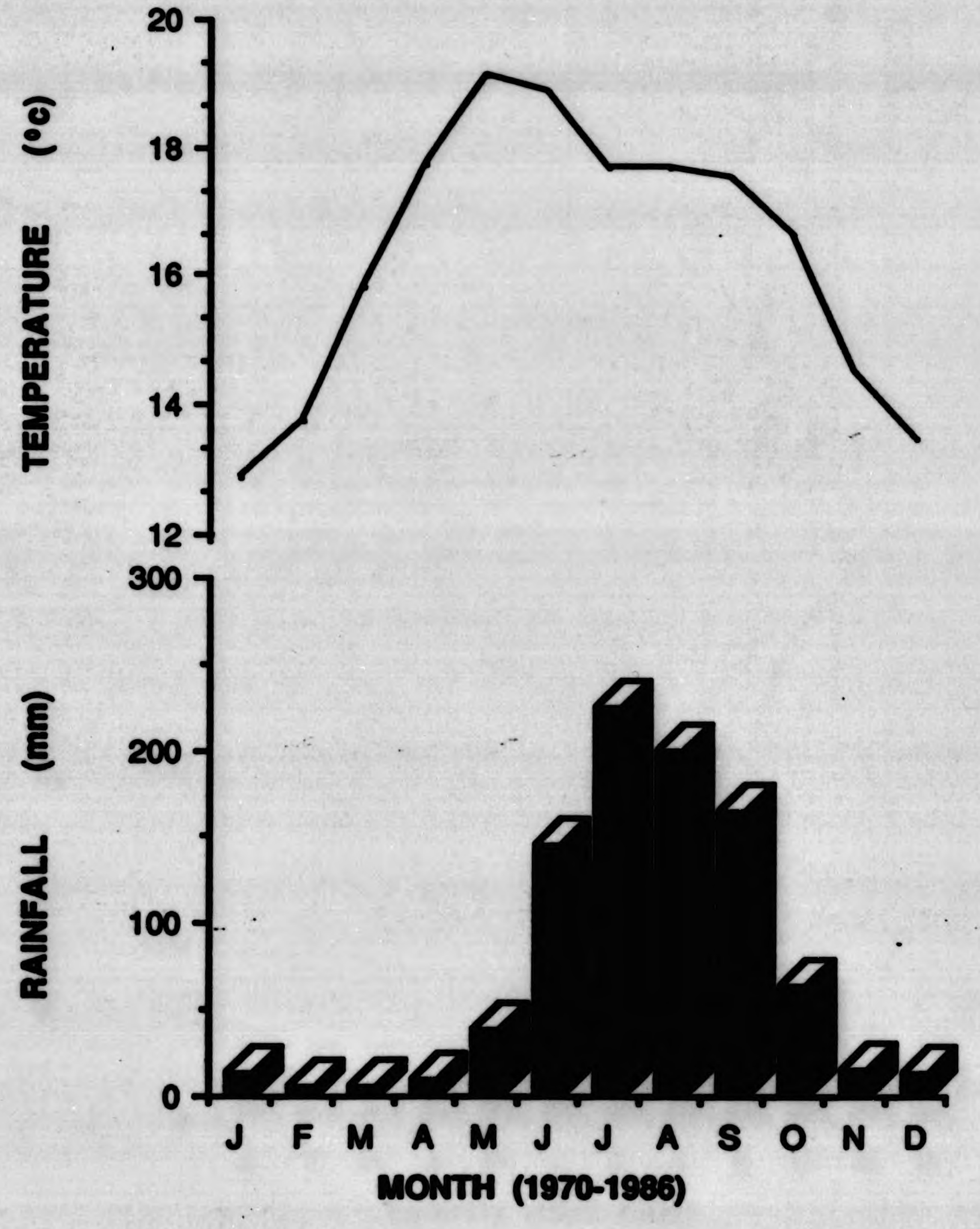


Figure 4.4

Climogram for Lake Patzcuaro, Michoacan, Mexico, for the period 1970-1986.



climate for Lake Patzcuaro, for 1921-1944 and 1970-1986 are as follows:

1944. C (w 2) (w) b (e) g

The above formula describes the wettest sub-humid Mexican highland temperate type, with summer rain and dry winter, P/T (precipitation/temperature) quotient of more than 55.3 (i.e. 63.8), percentage of winter precipitation less than 5% with respect to the total annual precipitation, mean annual temperature between 12 and 18 C, with warm summer, but with an extreme thermal oscillation (7-14 C), and annual temperature described as subtype Ganges with the warmest month before the summer solstice.

1986. C (w 1) (w) b (i') g

The formula for 1986 describes an intermediate sub-humid temperate type, with the same distribution of rainfall and temperature as 1944. However the P/T quotient is just below 55.3 (e.g. 55.2) and the temperature oscillation is low (5 - 7 C). Given the sensitivity of the system a P/T quotient of more than 55.3 can be obtained if a longer period of time is considered. Thus the area would remain within the C (w 2) climatic sub-division, but even so, a significant drop in the P/T quotient is evident.

The variability of the rainfall data over the catchment area for the period of 66 years (1921-1986) is presented in Figure 4.5. Although two significant rainfall peaks and two drought periods are evident in the graph, a trend for rainfall is difficult to discern given the extreme values presented over the period of time. In Figure 4.6, raw precipitation data were smoothed statistically using a

Figure 4.5

The distribution of total annual rainfall for the period 1921-1986 in Lake Patzcuaro, Michoacan, Mexico. n = 66

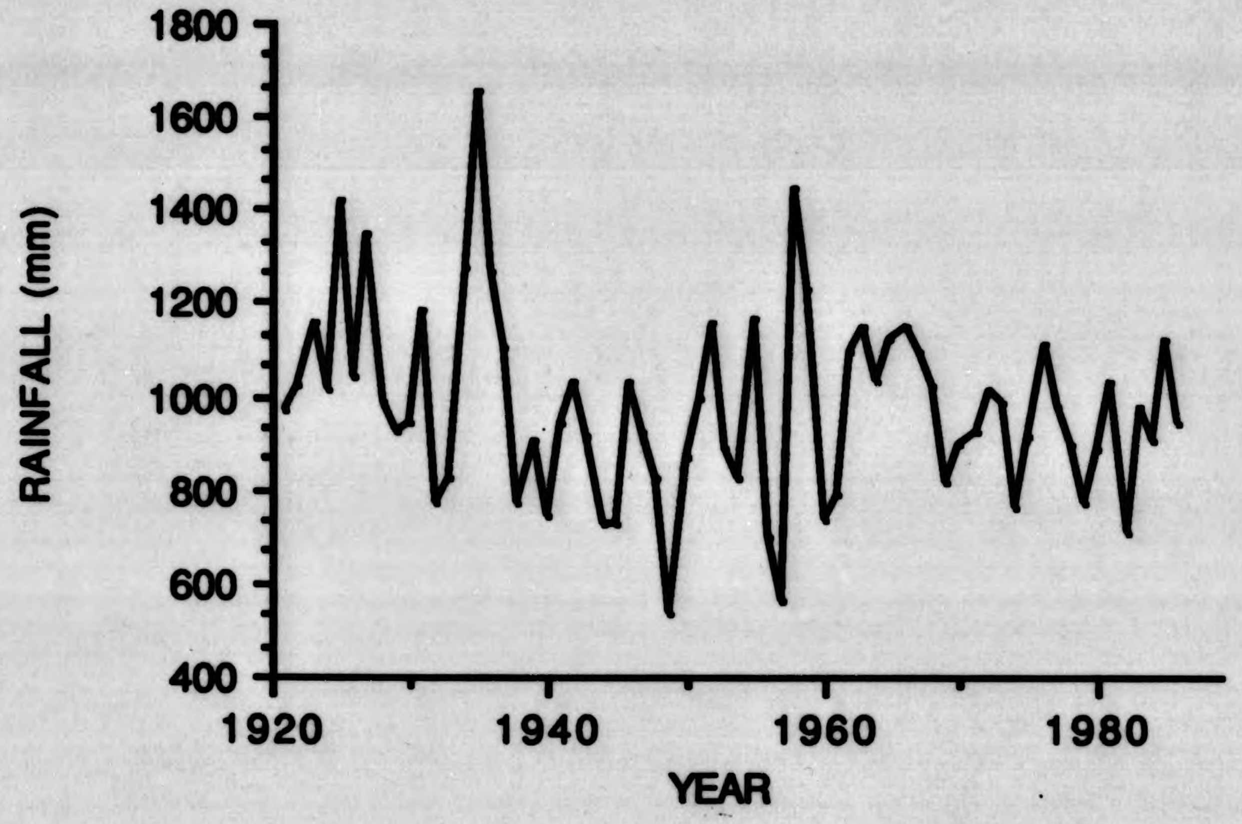
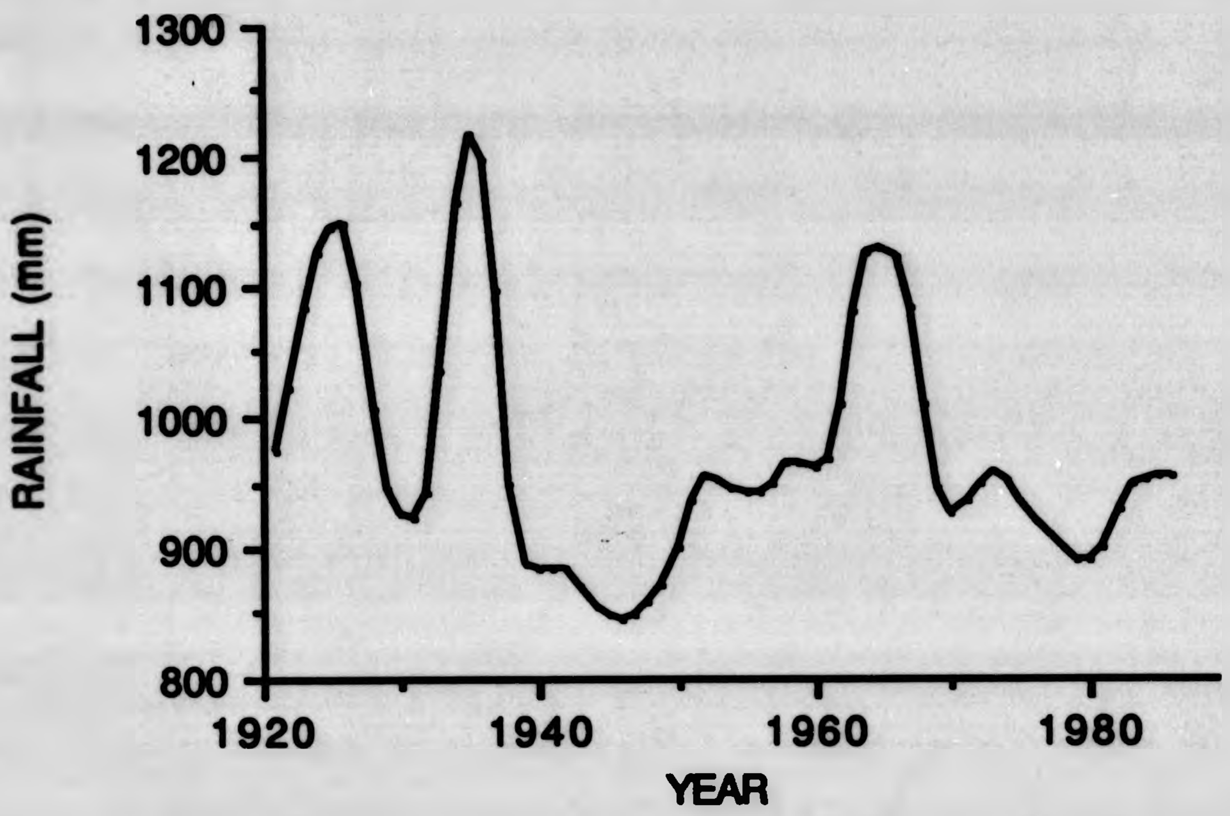


Figure 4.6

The distribution trend in total annual rainfall for Lake Patzcuaro, Michoacan, Mexico. Data is statistically smoothed by a MINITAB technique. n = 66

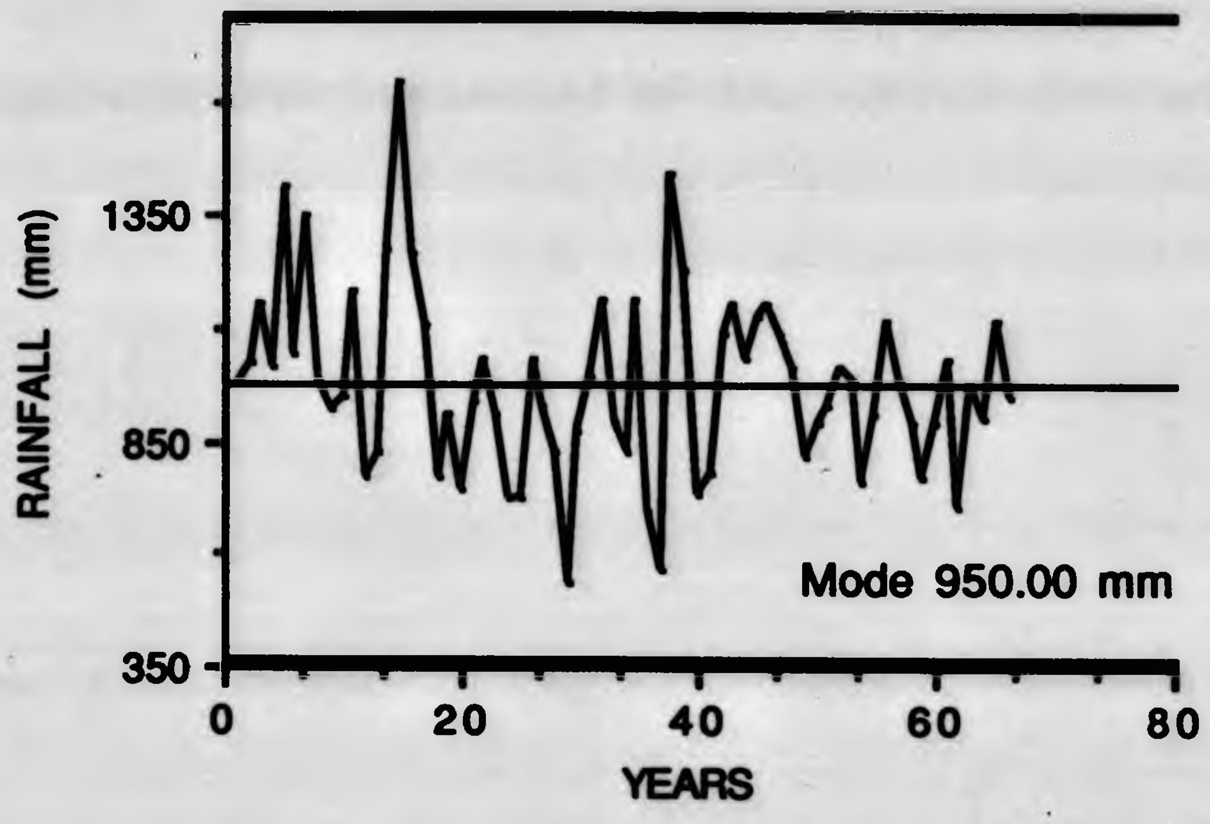


MINITAB technique (Ryan <u>et al</u>, 1985; Velleman, 1980) in an attempt to reveal more general patterns. As is evident, severe periods of drought and high rainfall have occured with a general trend of a decrease in precipitation during the late 1930's to early 1950's, followed by an increase of rainfall towards the 1970's. Although the 1980s tend to be more humid, a decline in rainfall is becoming increasingly apparent. The long period of drought reported during the 1940s to early 1950s has been considered the most serious in Mexico in this century (Metcalfe, 1987). This long drought has been associated with an interruption of the trade winds by a cold western Atlantic front which brought a rain-deficient period.

In Lake Patzcuaro there have been considerable variations in the amount of precipitation from one year to another during the last century. The maximum annual amount of precipitation recorded in 1935 (1653.8 mm), is three times as much as the minimum recorded in 1957 (566.5 mm), a standard deviation of about 204.51 and a coefficient of variation of 20.8% is computed over a period of 66 years. These figures are similar to the computations made by Mosino and Garcia (1981) using the Gamma Distribution to determine the variability of rainfall in Mexico. The same authors (1978) suggested using the statistical modal value for large data sets in order to determine what may be called the "anomaly" of a rainfall recorded in a particular year. Thus, every value of rainfall less than the mode implies an effective water deficit. In Figure 4.7 the annual anomaly in rainfall for Lake Patzcuaro

Figure 4.7

The distribution of total annual rainfall for the period 1921-1986 for Lake Patzcuaro, Michoacan, Mexico, with respect to the statistical mode. The mode was estimated as Mean - [(Standard deviation)^2 / Mean]. (Mosino and Garcia, 1981).



is presented by plotting annual values of rainfall against the rainfall modal value for Lake Patzcuaro (950 mm). Years with effective water deficits account for approximately 54.5%. However, using the smoothed data for annual rainfall plotted against rainfall modal value (Figure 4.8) it is possible to identify short periods of water gains separated by longer periods of water deficit. The contribution of water gains during the last 40-year period does not compensate for the occurrence of long periods of water deficit terms. The occurrence of high precipitation values seems to have a periodicity of 20 years during the period 1921-1986, although the data record is statistically not long enough to test this.

Lake levels.

The variation in the amount of precipitation directly affects changes in the water level of Lake Patzcuaro. In Figure 4.9, the variation of monthly precipitation, evaporation and mean water level of the lake is presented over the period 1971-1986. It is possible to observe the imbalance between precipitation and evaporation rates and its effects on lake level. Although these variations do not show a long-term trend, maximum water levels are observed following the rainy season (October-November), whereas minima are recorded in early summer (June-July). It is evident that year-to-year lake level variations are not exactly in phase with precipitation and evaporation maximum values as a consequence of the velocity of seepage going

Figure 4.8

The distribution trend in total annual rainfall for the period 1921-1986 for Lake Patzcuaro, Michoacan, Mexico, using smoothed data with respect to the statistical mode.

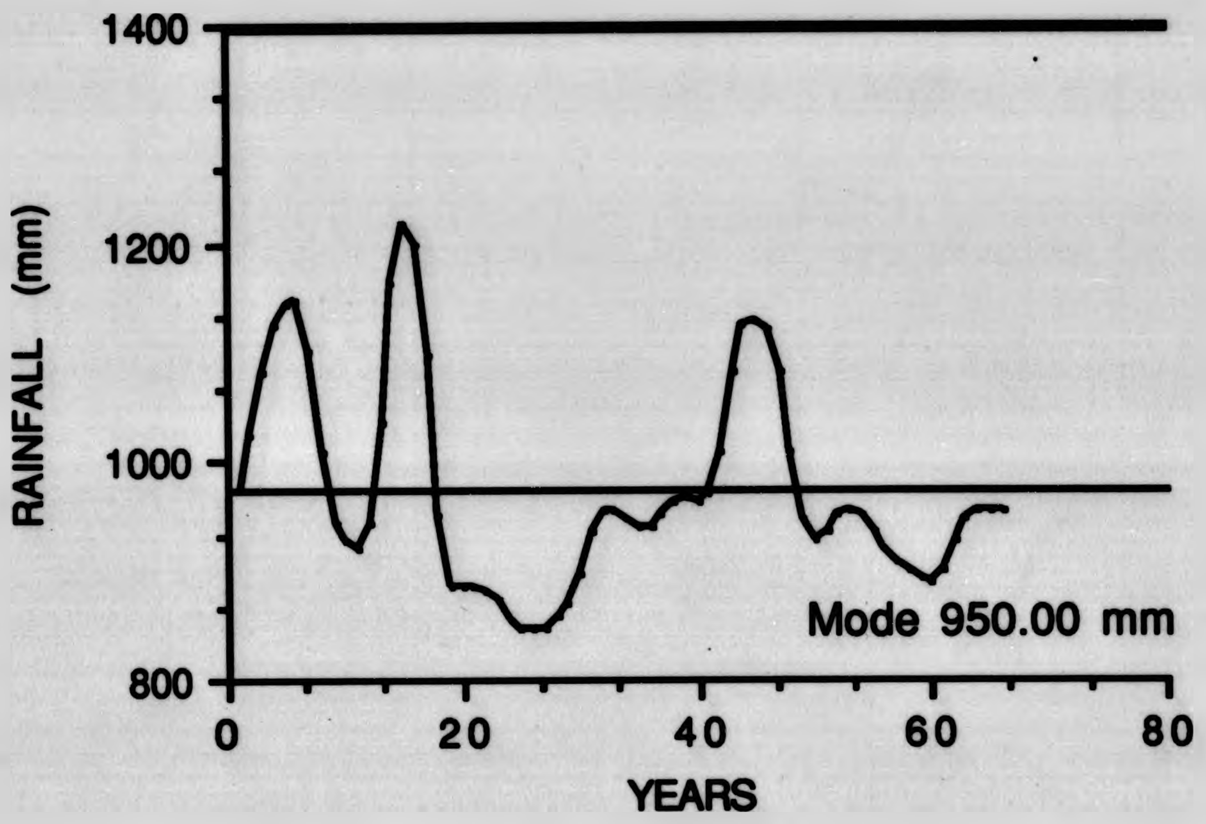
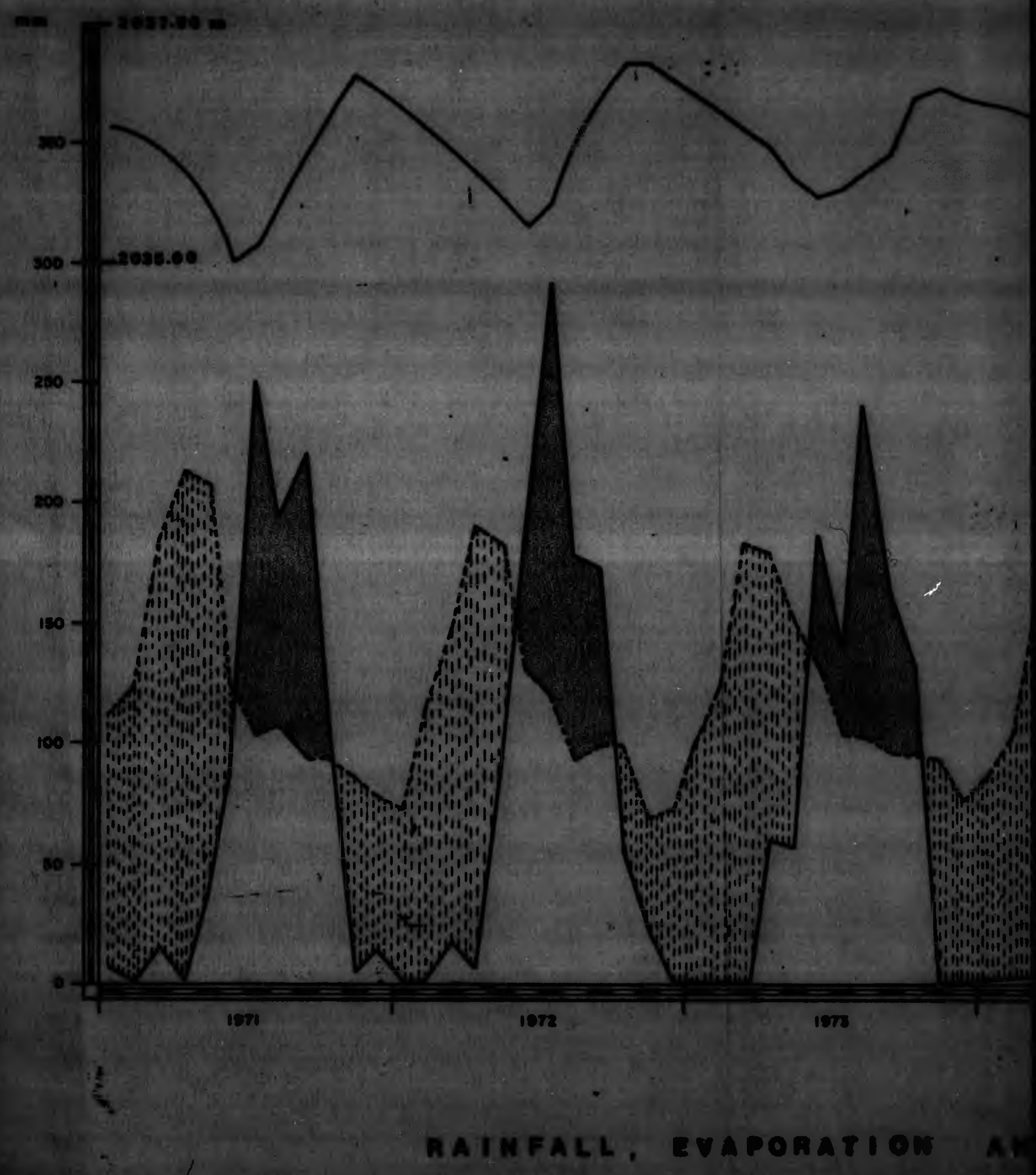
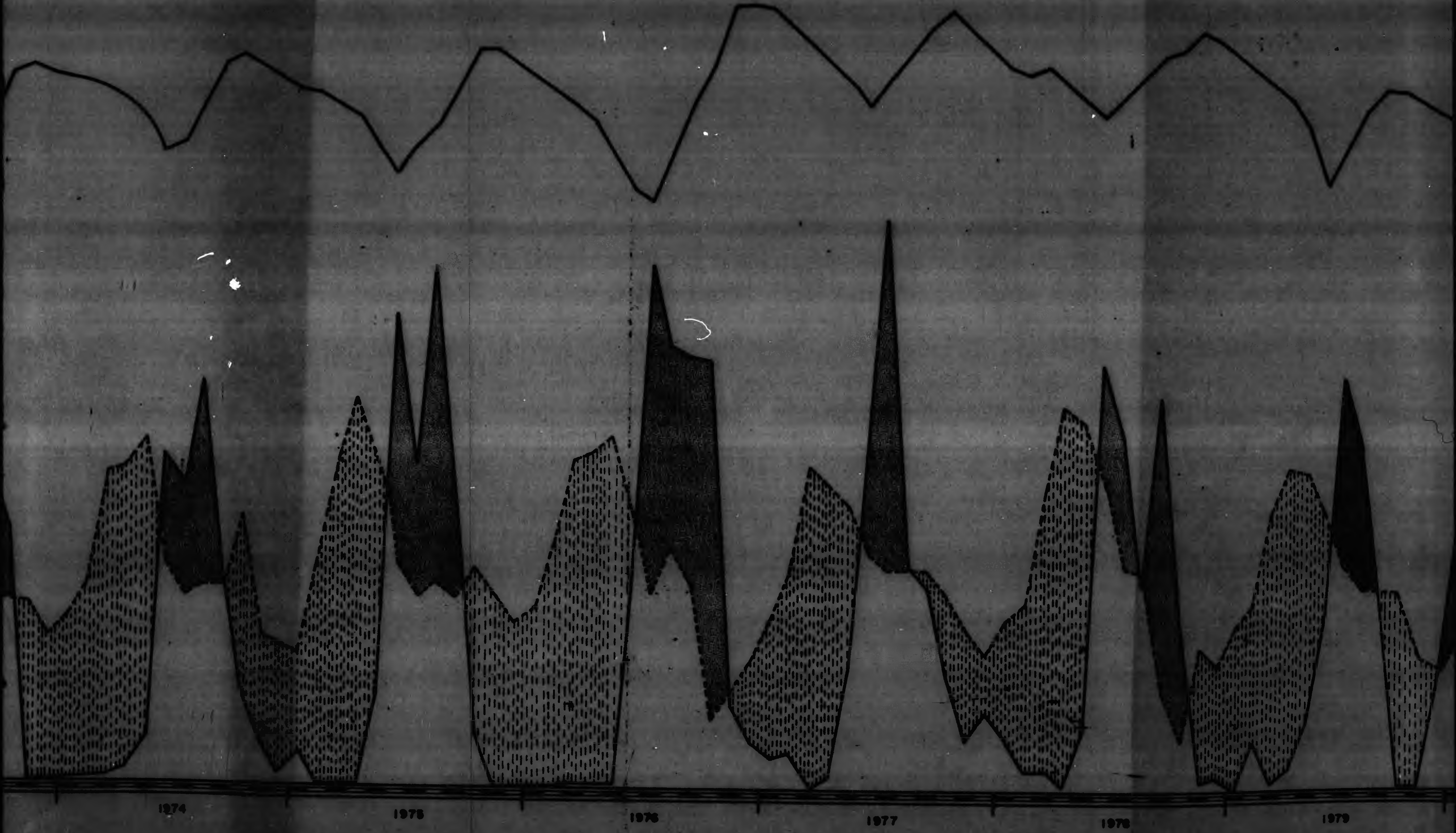
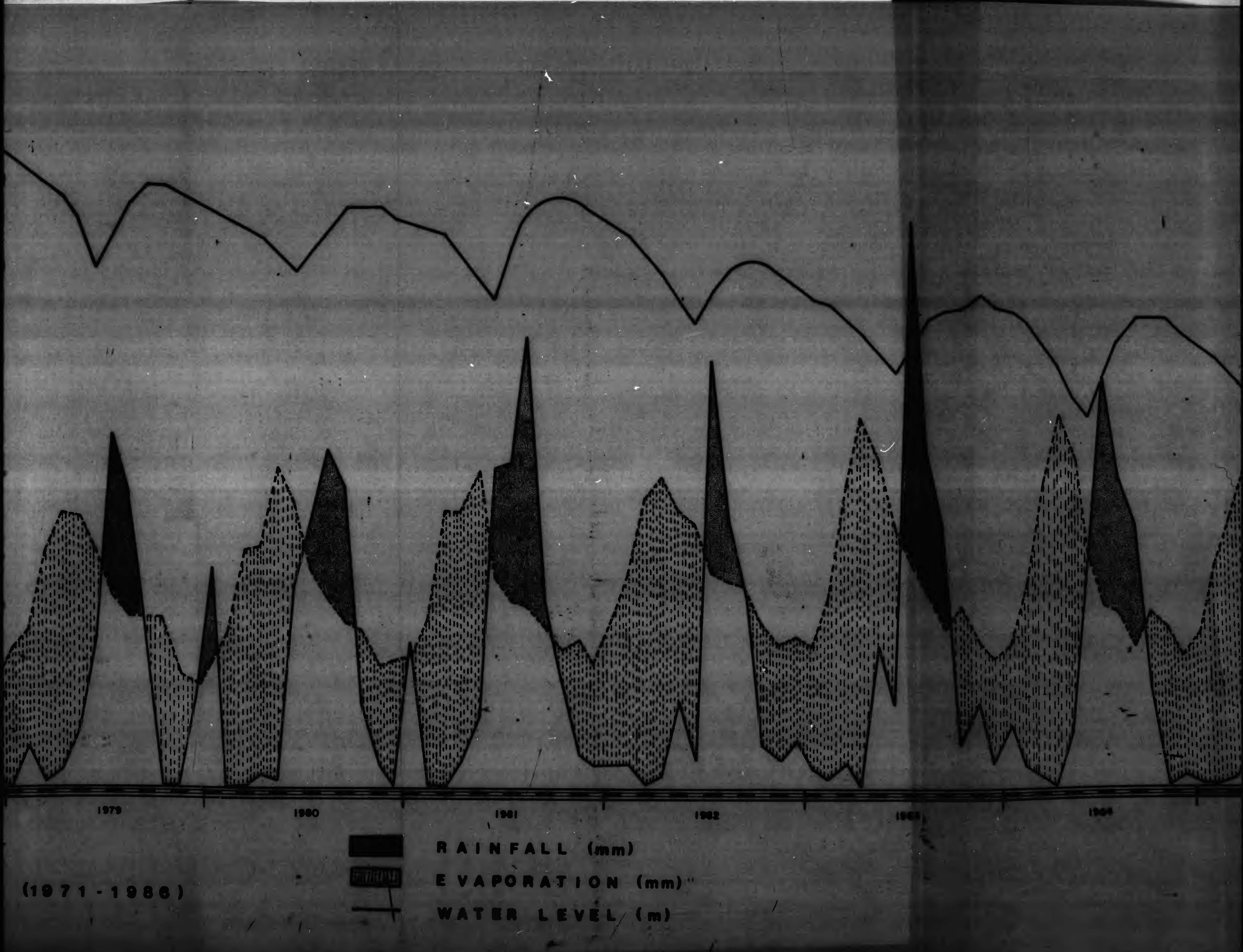


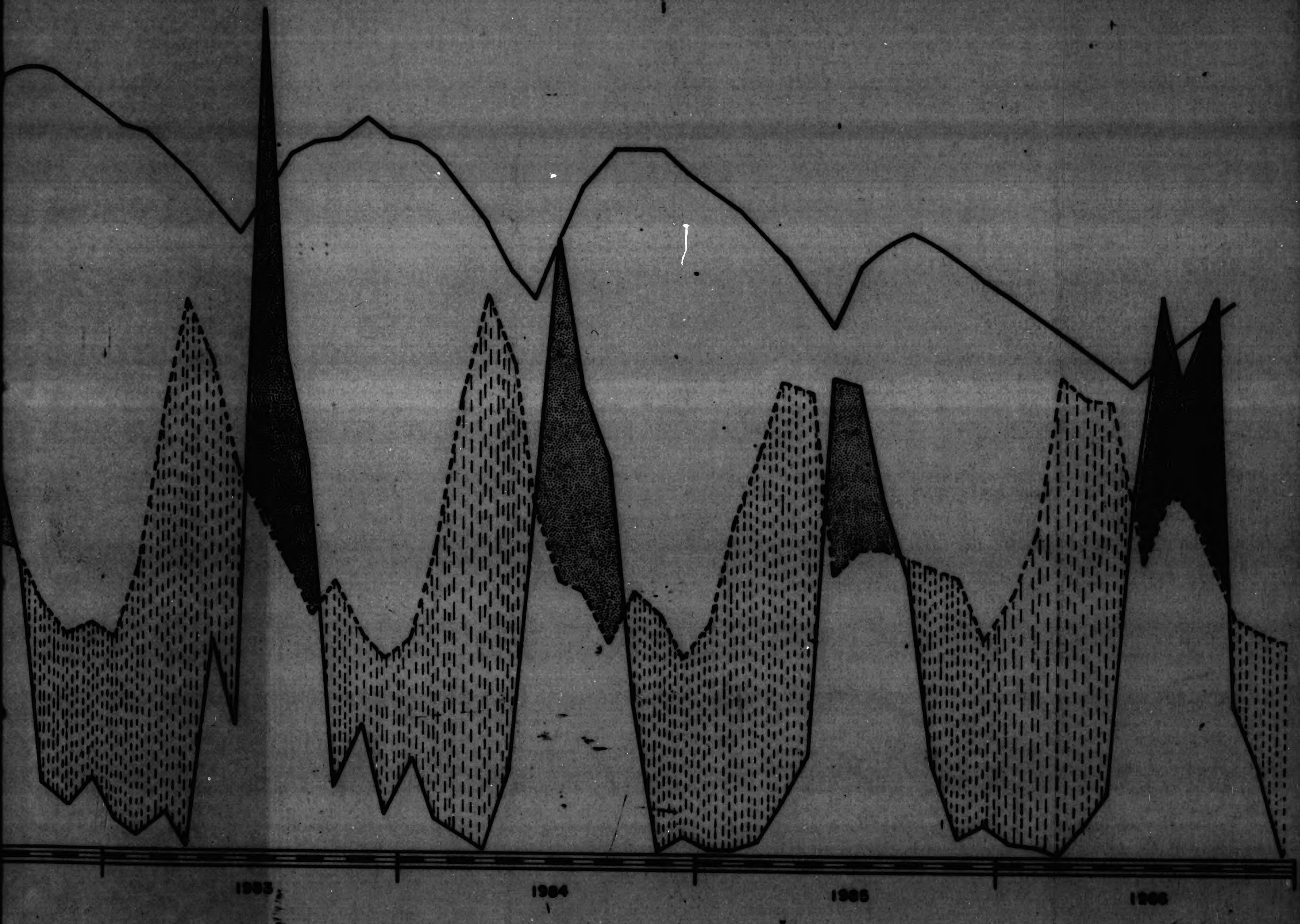
Figure 4.9
The variation in annual rainfall, evaporation and water levels in Lake Patzcuaro, Michoacan, Mexico, for the period 1971-1986.





H AND WATER LEVEL VARIATIONS LAKE PATZCUARO, MEXICO (1971-1986)


1979
1980
1981
1982
1983
1984
RAINFALL (mm)
EVAPORATION (mm)
WATER LEVEL (m)
(1971-1986)


1983
1984
1985
1986

into the lake from the catchment area. These water input variations in combination with the ecological conditions of the catchment area have strong effects on the lake water level. To illustrate these variations, a DYNAMO simulation programme was used to observe the influence of the watershed on lake water levels.

Soil types in the catchment area of Lake Patzcuaro are mostly Andosols, Luvisols, Acrisols, Vertisols and Gleysols (FAO-UNESCO, 1975). These have been identified by Gomez-Tagle (in preparation) as soils originating from volcanic activity and particularly susceptible to erosive factors, such as rainfall and wind. Given the high steepness of the watershed (up to 37% slope) and the intensity of summer rainfall (up to 75 mm/24 hrs), the seepage factor is expected to decrease due to erosion processes as the vegetation cover is removed by inappropriate land-use techniques.

To illustrate the effect of catchment area deterioration on lake level variations, actual and predicted lake levels for two periods (1939-1942 and 1970-1985) are presented in Figures 4.10 and 4.11. The best correlation between predicted and actual lake level values was found with a seepage factor of 12.0% for 1939-1942 and 8.0% for 1970-1985. Other seepage factor values used in the model either over- or under-estimated actual lake levels. The accuracy of the model can be observed in Figure 4.12 a and b where correlation coefficients between observed and predicted values were 0.86 and 0.93 for 1939 and 1970 respectively.

Figure 4.10
The variations in water level for Lake Patzcuaro, Michoacan, Mexico, using observed values and predicted values from DYNAMO for the period 1939-1943. n = 44

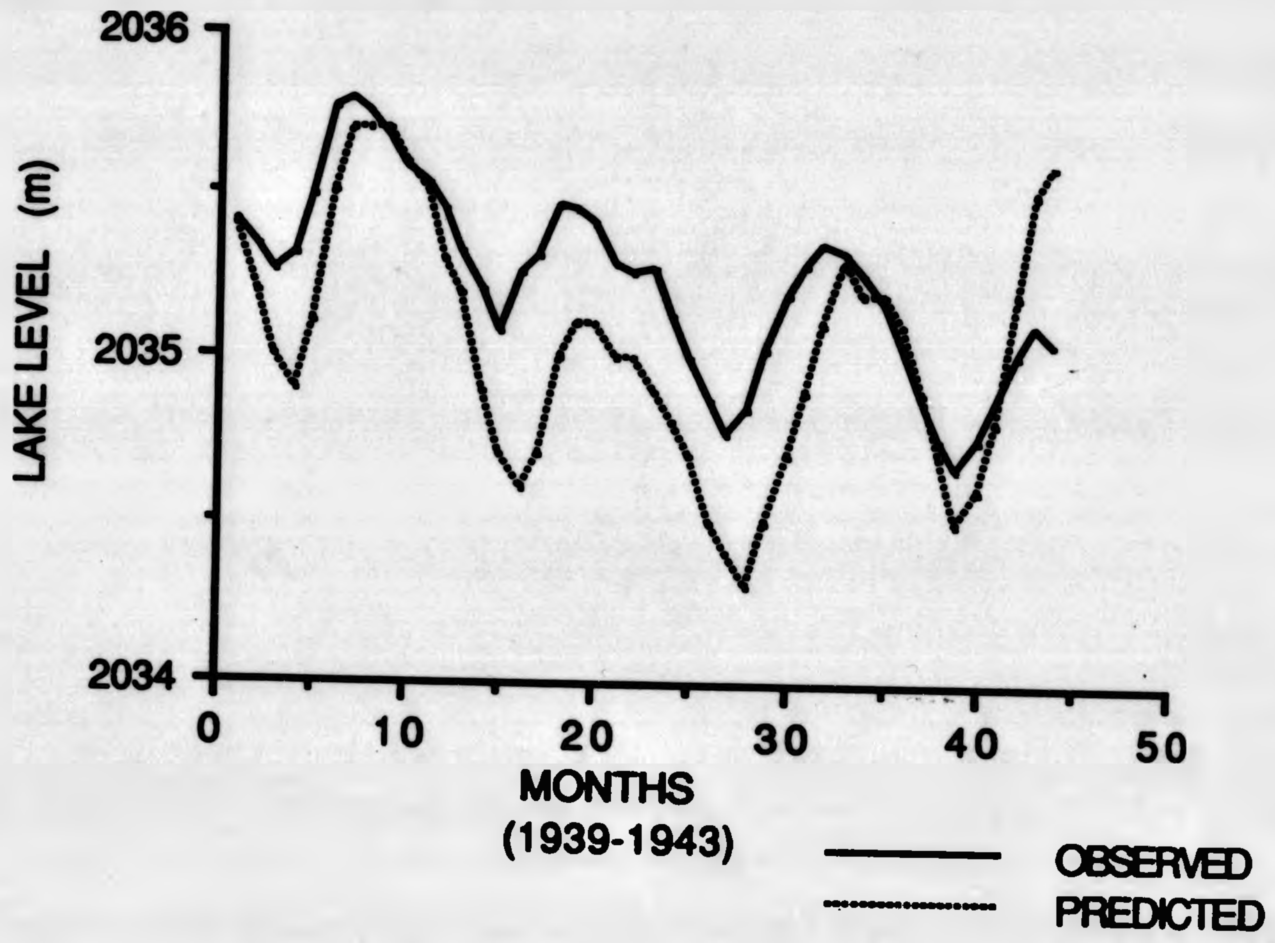


Figure 4.11

The variations in water level for Lake Pátzcuaro, Michoacan, Mexico using observed values and predicted values from Dynamo for the period 1970-1986. n = 204

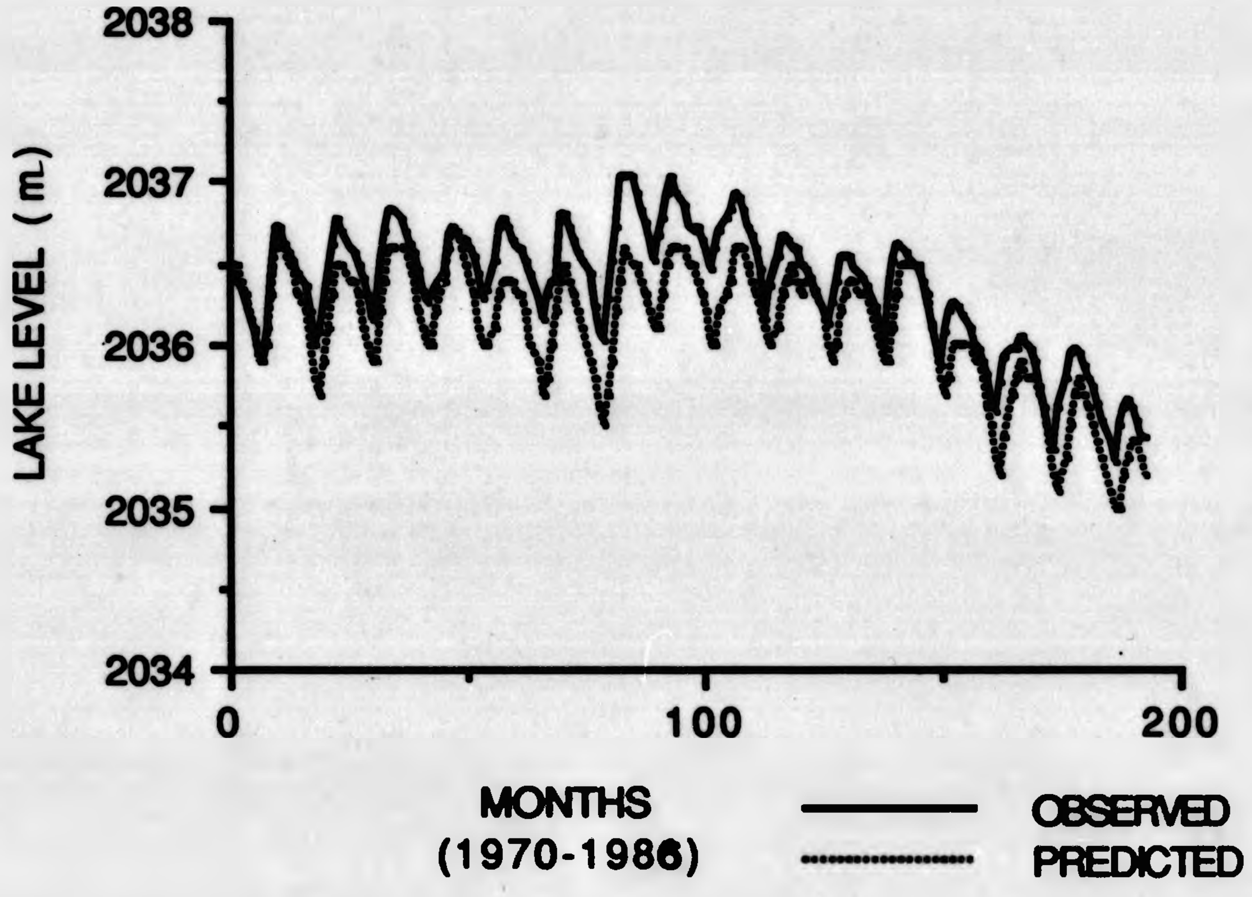
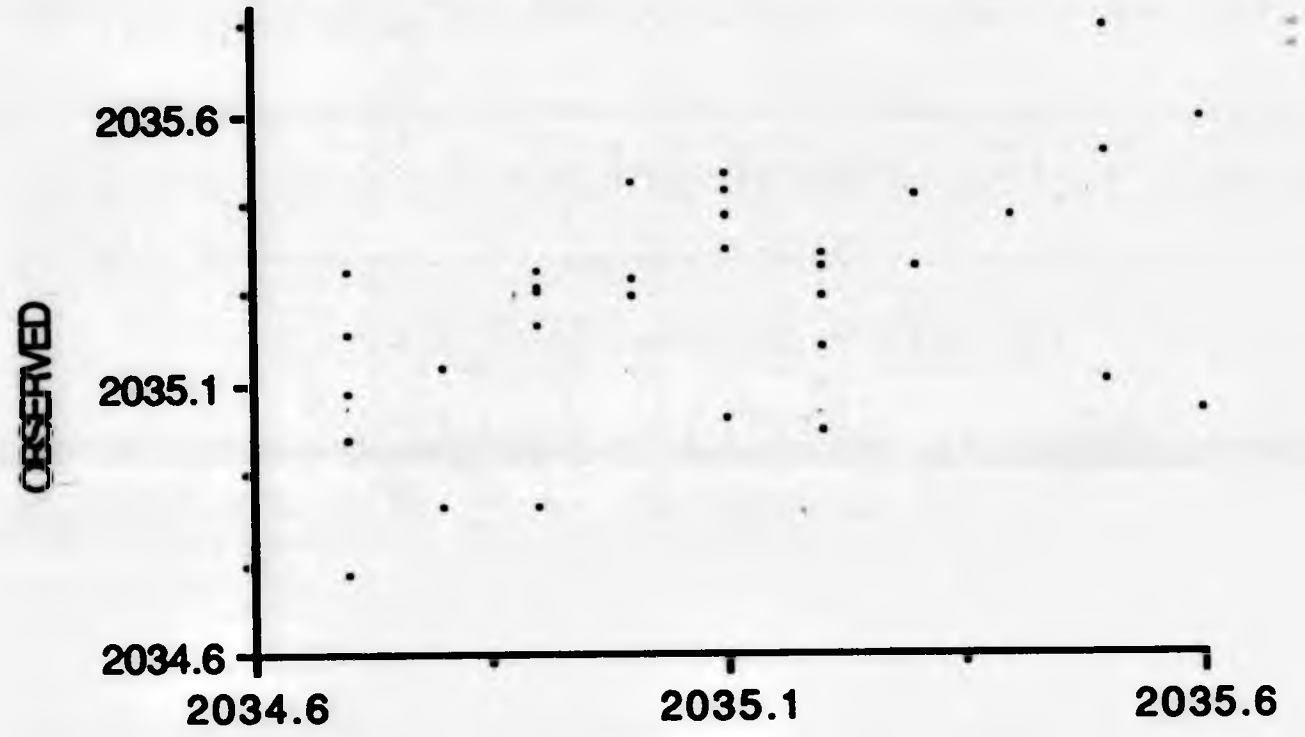


Figure 4.12

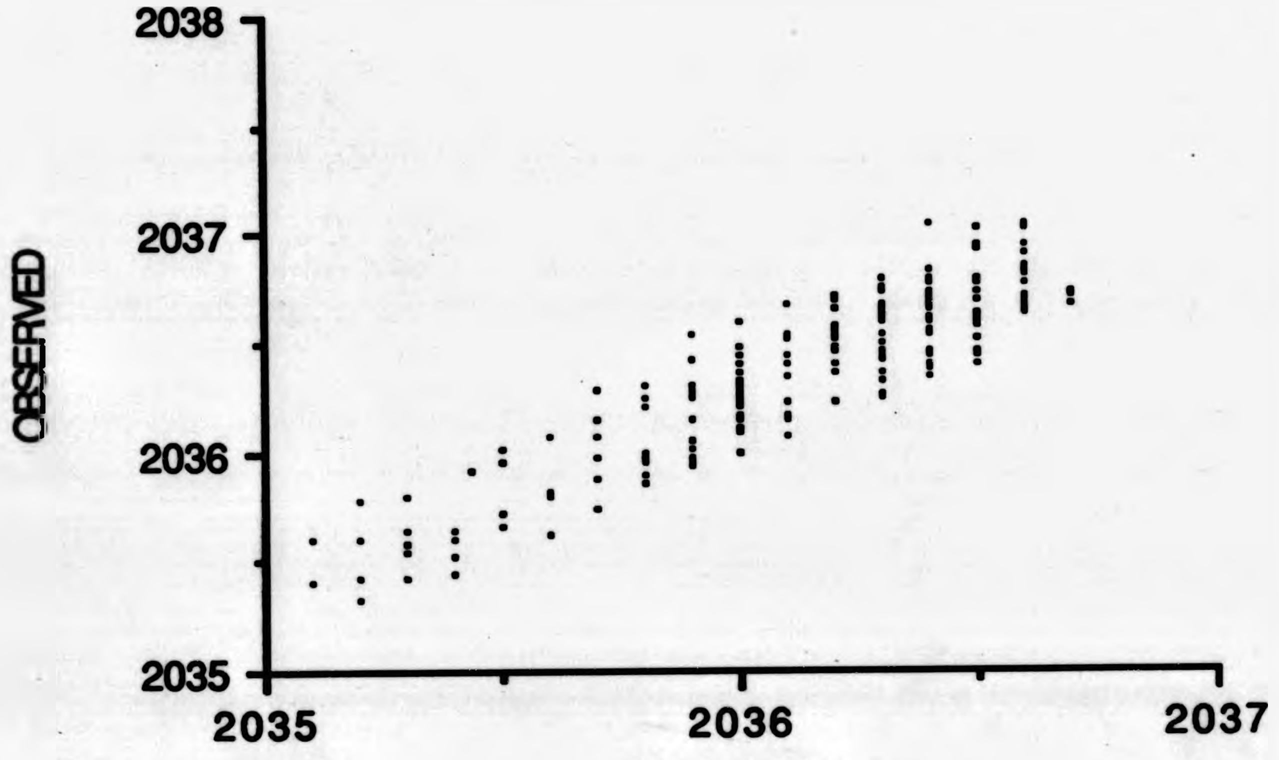
The correlation between predicted values and actual values of water levels for Lake Patzcuaro, Michoacan, Mexico.

a) 1939-1943. $R^2 = 0.860$, $P < 0.001$, $n = 44$.

b) 1970-1986. $R^2 = 0.926$, $P < 0.001$, $n = 204$.



a) (1939-1943)



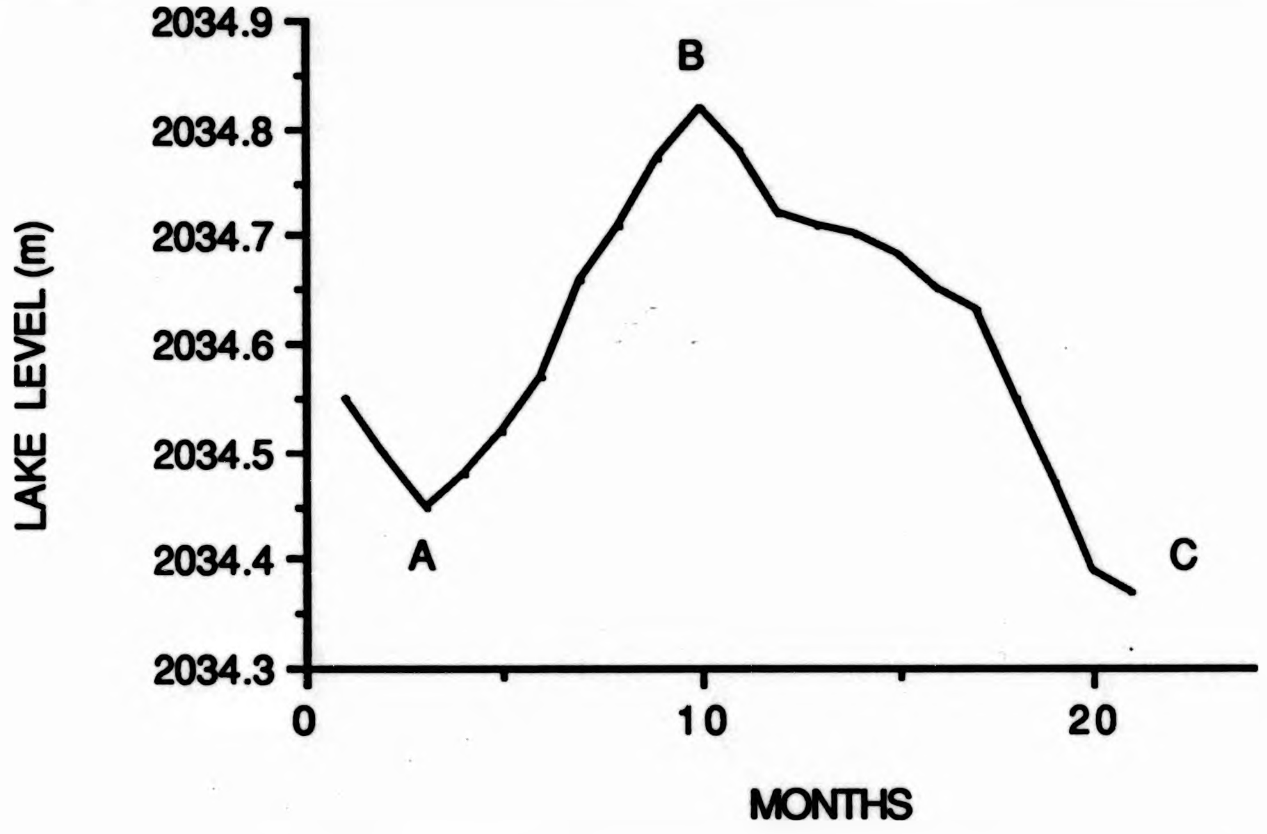
b) (1970-1986)

Low correlation values for 1939 were mainly due to the short period of time considered and because of a great discrepancy between predicted and observed data after October 1942. This disruption in rainfall and lake level oscillations is possibly associated with the volcanic activity of the Paricutin volcano (19° 28' 30" N-102° 15'45" W), which was active for 9 years between February 1943 and February 25 1952. Trask (1943) reported that by February 1943 more than 300 earth movements had been registered in Mexico City and by March and April 1943, Yarza de la Torre (1971) reported that heavy ash rains had fallen up to 400 km away. Lake Patzcuaro, located at only 60 km away from the volcano, could have been influenced by the eruptive activity, which could also have modified the hydrological cycle temporarily. One of the most significant short-term impacts of Paricutin was the heavy volcanic ashfalls (Bullard, 1947a; 1947b). Intensified erosion is a consequence of any ashfall as ground covered by fine deposits is not permeable enough to contain heavy rains which follow most of volvanic events, accelerating runoff and mudflows (Rees, 1979). This is speculative, however, as there have been no reports on the effects of the Paricutin on the lake basin to date.

On an annual basis, if average monthly rainfall values (with the exception of the rainy season) are less than average monthly evaporation, then runoff and rainfall over the lake do not have a significant effect on lake levels. Therefore, an influx of water from seepage is expected to be the net annual major input to the lake. With an increase in human activities in the catchment area leading to massive deforestation of the surrounding woodlands, the erosion process was accelerated and consequently, there was a progressive reduction in seepage, thus affecting the amount of water entering the lake. This catchment area deterioration has been more intensive since the beginning of the twentieth century which, combined with long periods of drought, lowered the lake to its minimum level in 1955. Although the lake level recovered and a higher shoreline was recorded during the 1960s and 1970s (2037.04 m by 1976), the decrease in seepage factor from 12% in 1939 to 8% in 1985, probably reduced the contribution from the catchment area and hence the capacity of the lake to maintain more stable levels. In order to evaluate these level oscillations and to identify its possible trends, De Buen and Zozaya (1942) proposed the use of the Level Oscillation Index (ION) for Mexican lakes. This index was successfully applied by Cortez et al (1980) and Alvarado et al (1985) to describe lake level oscillations in Lake Cuitzeo. Based on annual periods (Figure 4.13) Lake Patzcuaro has an initial minimum level (A), then when the rainfall ends a maximum level is identified (B), and finally the curve declines again to a second minimum level (C). The increase from A to B is called the "curve of flooding" and the decrease from B to C is called the "curve of evaporation". The ION is the quotient of the "curve of flooding" over the "curve of evaporation". If the ION is more than 1.0 it represents net gain in water level, if it is less than 1.0 the loss of water predominates over water gains. Equality represents an equilibrium between losses and gains. Figure 4.14 presents the ION for Lake Patzcuaro for 1939-1944 using data from De Buen and Zozaya

Figure 4.13

Description of the Oscillation Level Index (De Buen and Zozaya, 1942), for Lake Patzcuaro, Michoacan, Mexico.



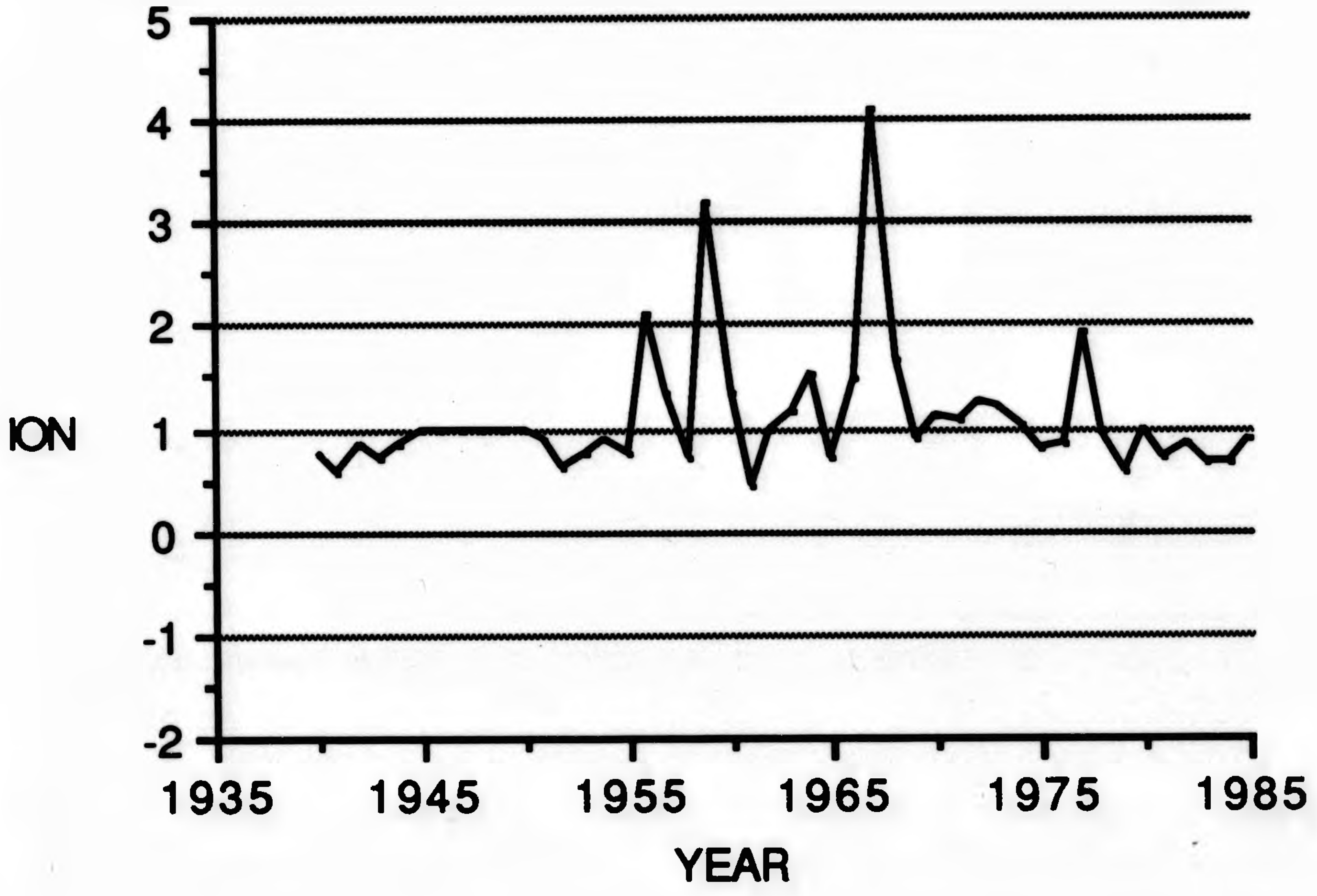
OSCILLATION LEVEL INDEX (ION)

A = FIRST MINIMUM = 2034.45 m
B = MAXIMUM LEVEL = 2034.82 m
C = SECOND MINIMUM = 2034.87 m

CURVE OF FLOODING = B - A = 0.37 m
CURVE OF EVAPORATION = B - C = 0.47 m
ION = 0.37 / 0.47 m = 0.78

Figure 4.14

Oscillation Level Index (ION) for Lake Patzcuaro, Michoacan, Mexico, for the period 1939-1986. Data for 1945-1950 was assumed ION = 1.0. n = 47



(1942) and for 1950-1986 using data recorded at "Santa Fe station". No data are available for the missing 5-year period of 1945-1950. By using the ION it is possible to identify net losses of water during the last 35 years. Although the lake registered its lowest level in June 1955 following the drought of the 1940s and early 1950s, its rapid recovery as a result of the particularly wet summer (four months above 200 mm rainfall) restored the lake level to higher values than those of the previous five years, giving a value of ION of 2.15. By contrast, following dry periods in 1956-1957 and 1960-1961, Lake Patzcuaro lost 1.14 m in height in 18 months (January 1960-June 1961) with a ION value of 0.45. A new sequence of four wet years (1964-1967) restored high lake levels with a maximum level registered in December 1976 (2037.05 m). However, low values of ION since 1968 suggest that losses through evaporation occur more frequently than gains due to flooding in Lake Patzcuaro.

Water balance.

The annual water balance of Lake Patzcuaro is summarised in Figure 4.15. Lake Patzcuaro annually receives 123.3 million m3 (979.2 mm) of precipitation. About 186.2 million m3 (1477.9 mm) of water is lost by evaporation from the lake surface. It is estimated that presently seepage from the catchment area is approximately 8%. Therefore, about 62.9 million m3 (498.6 mm) of water is transfered to the lake from the watershed annually.

Figure 4.15

Annual water balance for Lake Patzcuaro, Michoacan, Mexico. Estimates are given in millions of cubic metres.

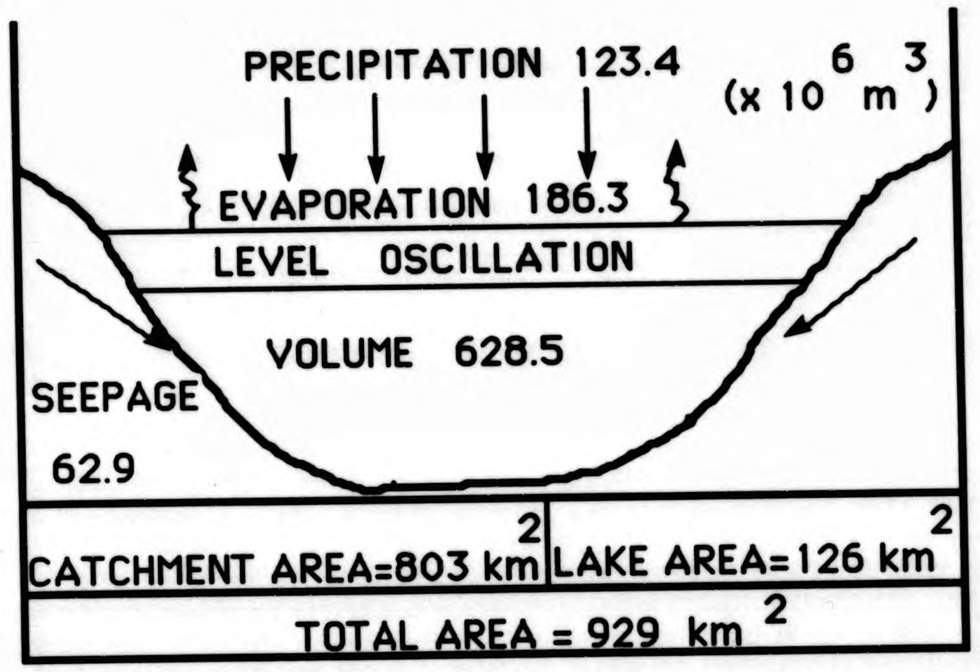


Table 4.2 shows the annual variation of the water balance components for Lake Patzcuaro. Inputs into the lake are at a minimum in March corresponding to the end of the dry season. However, as shown previously, minimum lake levels are recorded in June, probably because evaporation rates remain high in April and May and the contribution from the catchment area is very low during the dry season. The inverse relationship is observed between lake evaporation and water inputs during the summer when lower air temperatures and cloudiness lead to high lake levels by the end of the rainy season.

Wind.

In Lake Patzcuaro, SW and SE winds predominate as illustrated in Figure 4.16. The frequency of the SW wind accounts for 40.20% of the annual average and winds from the SE for 25.20%; the frequency of the wind from these two directions accounts for about 65.40% of the whole. This pattern of wind rose was found to be similar throughout the year with some occurrences of northern winds during the winter when occassional outbreaks of cold polar air bring sharp falls in temperature and increases in wind speed. Figure 4.17 illustrates the wind speed distribution and its annual frequency occurring over the basin. Maximum average wind speeds are 6.7 m/s mostly blowing from SW and SE. No data is available for maximum instantaneous wind speed in Lake Patzcuaro, but high wind speeds are more frequent during the winter and these can reach up to 20 m/s (Observatorio Metereologico de Morelia, personal communication).

Table 4.2 Annual water budget for Lake Patzcuaro (1989)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAINFALL	1.977	1.105	0.929	1.429	4.717	21.347	29.469	27.229	21.556	8.957	2.485	2.186	123.390
SEEPAGE (8%)	1.008	0.563	0.473	0.729	2.405	10.883	15.025	13.882	10.990	4.567	1.267	1.115	62.907
EVAPORATION	11.670	14.859	20.934	24.125	23.354	16.675	14.453	14.148	12.262	12.309	11.015	10.406	186.210
CHANGE IN STORAGE	-8.685	-13.191	-19.533	-21.968	-16.231	15.555	30.040	26.962	20.284	1.215	-7.263	-7.106	0.077

Figure 4.16

Wind distribution for Lake Patzcuaro, Michoacan, Mexico.

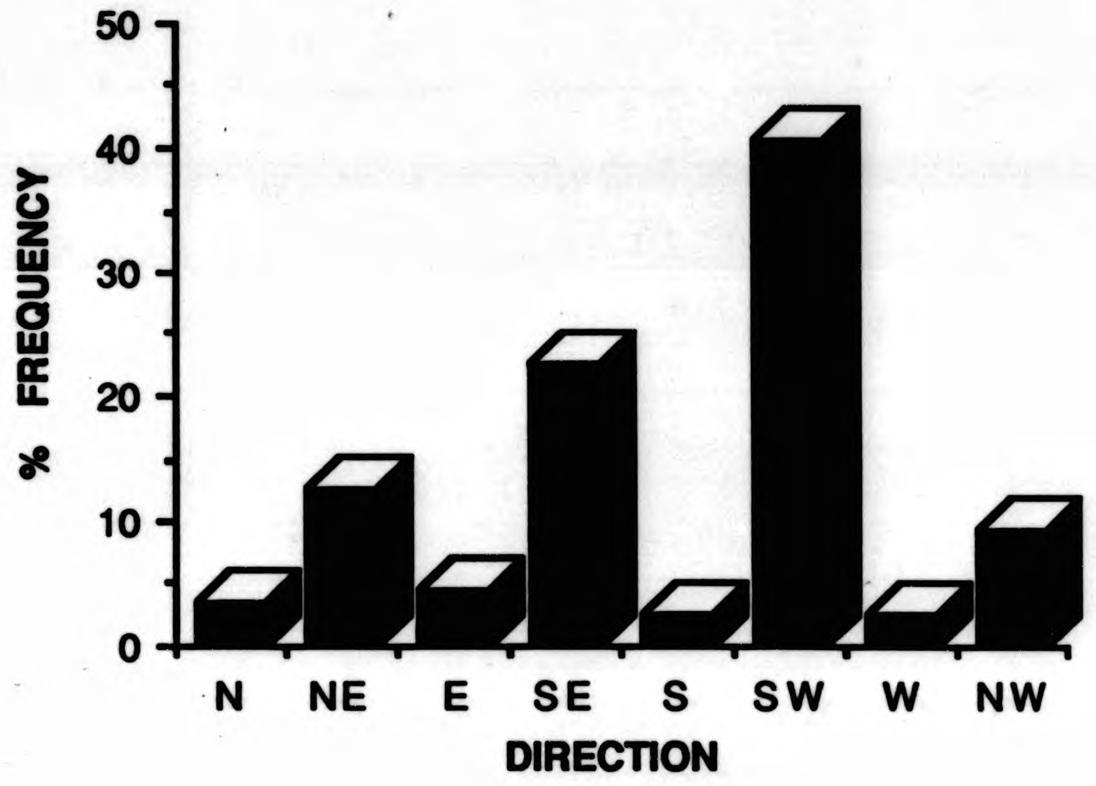
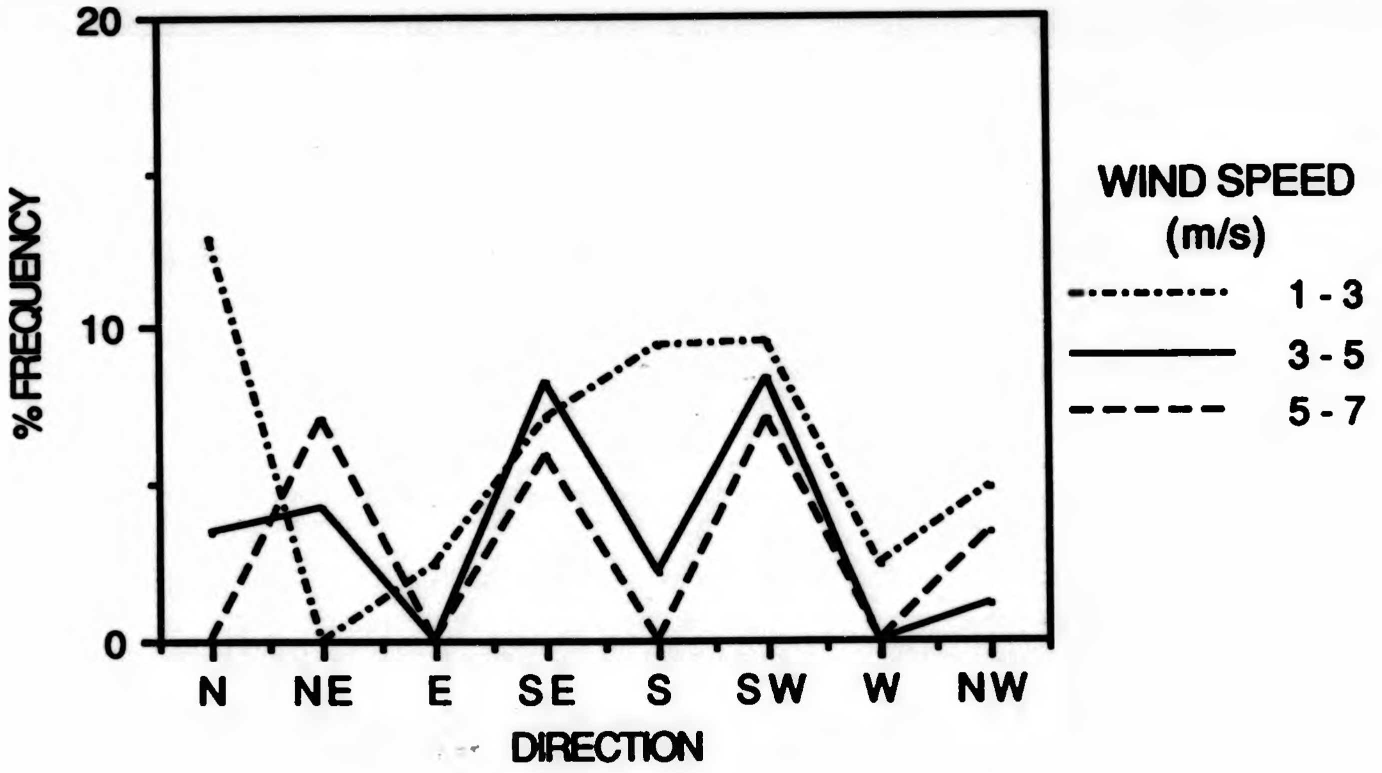


Figure 4.17

Wind speed and wind direction distribution for Lake Patzcuaro, Michoacan, Mexico.



Water currents.

Data collected on surface drift are shown in Table 4.3. The wind factor, defined as the ratio of surface drift to wind speed, varied from 1.89% to 3.88% with an average of 2.73% and a standard deviation of 0.51%. Figure 4.18 shows the drogue paths observed in Lake Patzcuaro during the winter of 1986. Wind directions were consistently from the south and southwest. Figure 4.19 shows the correlation between wind speed and surface drift. The effect of the wind on the generation of surface currents is clearly demostrated. The surface current is predominantly in the direction of the wind and possible deviations may occur in a clockwise drift due to the Coriolis effect. The deflection of the current can be negligible in shallow or small basins but may be as great as 45 degrees east to the direction of the wind in large lakes and oceans (Smith, 1975). According to Mortimer (1974), rotational effects become important in wide basins. Lake Patzcuaro has a mean width of 6.40 km, but its maximum width is 10.95 km. Although the Coriolis effect is not significant at high current velocities in Lake Patzcuaro, it may have some contributions in slow currents and hence in the general circulation pattern, especially in northern areas.

Seiches and wave height predictions.

Surface seiches are oscillating motions commonly generated when the wind blows constantly from one direction. Water masses are driven across the lake and accumulated at the

Table 4.3. Surface drift and wind factor in Lake Patzcuaro, Mexico.

TRACK No.	DATA COLLECTION DATE	SURFACE DRIFT (cm/s)	WIND SPEED (m/s)	WIND FACTOR (%)
1	1-DEC-1986	5.95	2.23	2.66
2	1-DEC-1986	4.95	2.23	2.22
3	1-DEC-1986	7.20	2.68	2.68
4	1-DEC-1986	5.69	2.23	2.55
5	1-DEC-1986	4.22	2.23	1.89
6	1-DEC-1986	7.72	2.68	2.88
7	1-DEC-1986	6.66	2.68	2.48
8	1-DEC-1986	7.18	2.68	2.67
9	1-DEC-1986	9.90	3.13	3.16
10	1-DEC-1986	10.08	3.13	3.22
11	1-DEC-1986	11.45	3.13	3.65
12	1-DEC-1986	11.11	3.13	3.55
13	1-DEC-1986	13.88	3.57	3.88
14	21-DEC-1986	8.33	3.13	2.66
15	21-DEC-1986	6.94	2.68	2.59
16	21-DEC-1986	7.97	2.68	2.97
17	17-JAN-1987	6.25	3.13	1.99
18	17-FEB-1987	12.00	5.81	2.06
19	18-FEB-1987	14.58	4.91	2.97
20	18-FEB-1987	12.44	6.25	1.99
21	18-FEB-1987	16.20	6.70	2.41
22	18-FEB-1987	12.00	4.47	2.68
23	18-FEB-1987	12.35	4.47	2.76
24	18-FEB-1987	9.89	3.13	3.16

Figure 4.18

Surface drogue tracks observed at Lake Patzcuaro, Michoacan, Mexico. n = 24.

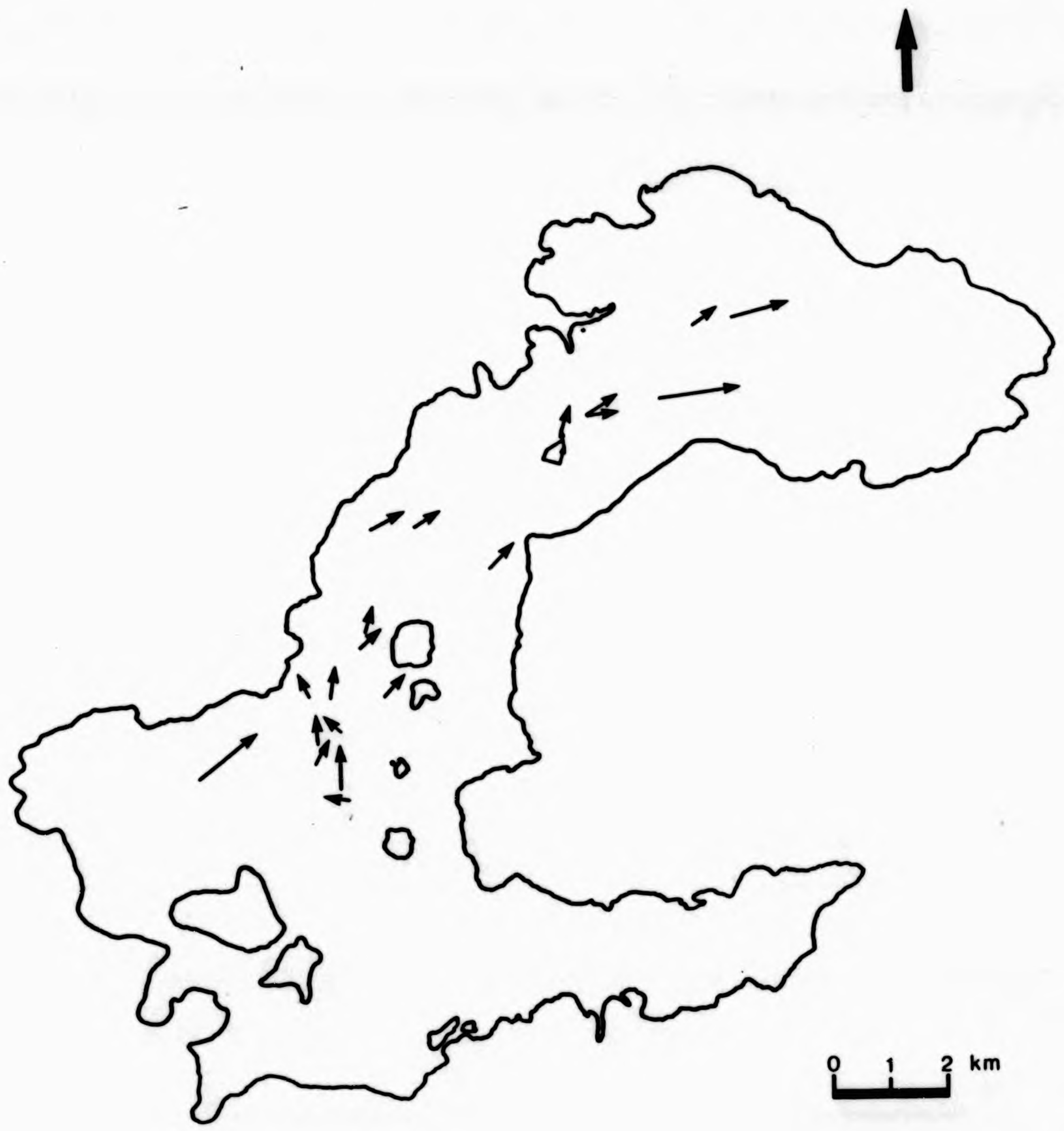
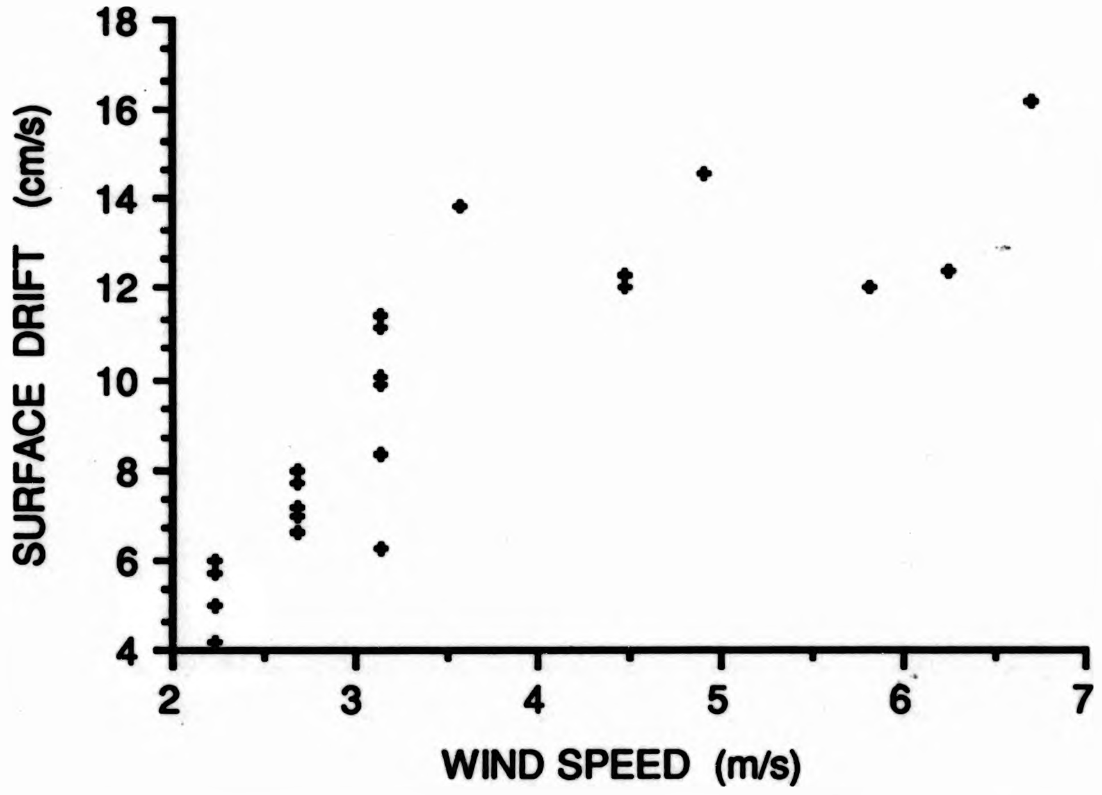


Figure 4.19

Correlation between surface drift and wind speed in Lake Patzcuaro, Michoacan, Mexico.
$R^2 = 0.83$, n = 24, $P < 0.001$



downwind shore of the lake. As the wind diminishes, gravity forces the accumulated water to move back thus causing an oscillation which eventually restores the equilibrium (Figure 4.20). Table (4.4) shows the maximum theoretical amplitude for seiches expected at Lake Patzcuaro at different wind speeds. Although surface seiches may have limited effects in Lake Patzcuaro due to their small amplitude compared to the larger size of wind waves, seiches may have some effect on current velocities and circulation patterns once the wind has ceased.

Given the small effect of the Coriolis force due to the relatively narrow shape of the lake and the absence of thermal stratification throughout the year, it is expected that a deep return current in the opposite direction to the surface drift could occur as a result of the need to retain mass continuity. This pattern of water circulation could explain the homogeneity of temperature and oxygen distribution in Lake Patzcuaro. The flow pattern is typical in closed basins and was originally described by Hellstrom (1941) (cited by Smith, 1975).

Table 4.5 is a summary of wave height estimation for Lake Patzcuaro. During the period of observation wind direction was consistently in the same direction as the maximum fetch length, e.g. from S and SE. In order to compare the approximation of both concepts to field observations at Lake Patzcuaro, maximum fetch and effective fetch lengths were used to compute wave heigths. From Table 4.5 it is clear

Figure 4.20

Description of a uninodal surface seiche.

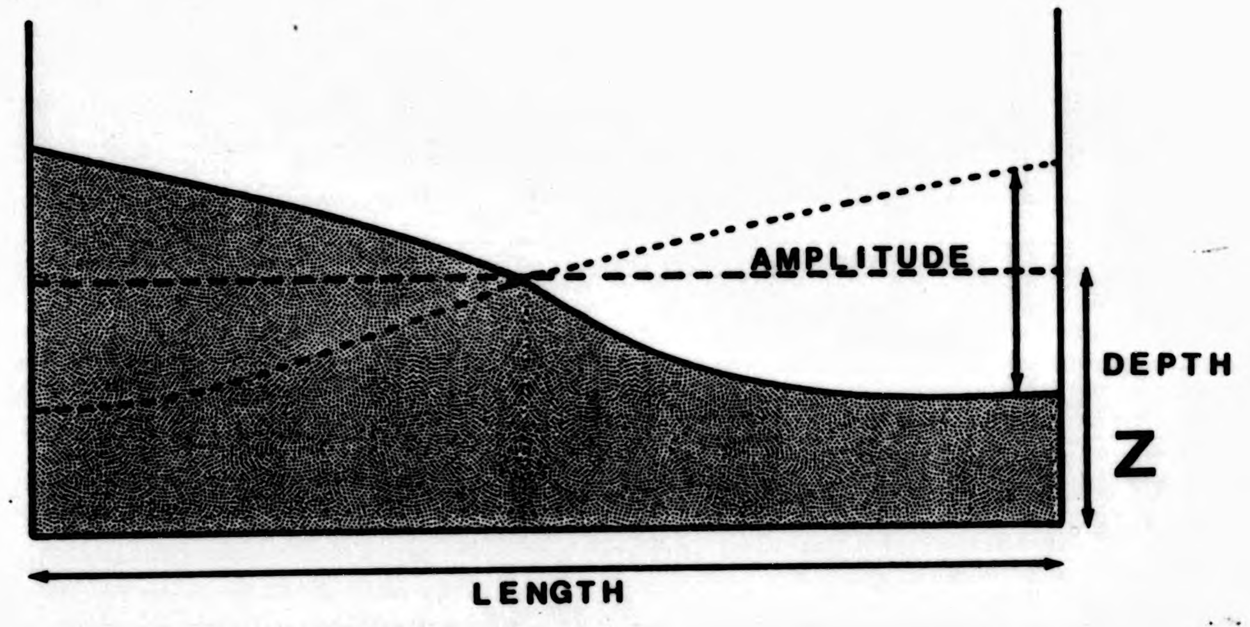


Table 4.4. Maximum theoretical amplitude for uninodal seiches expected for Lake Patzcuaro, at different wind speeds.

WIND SPEED (m/s)	AMPLITUDE (cm)
3.0	1.16
5.0	3.24
7.0	6.35
10.0	12.96
15.0	29.17
20.0	51.86
25.0	81.04

Table 4.5. Observed and predicted wave heights for Lake Patzcuaro, using maximum and effective fetch length, and different wind duration period.

DATE	FETCH LENGTH (Km)	WAVE HEIGTH VALUES (m)					AVERAGE WIND STRESS FACTOR (m/s)		
		OBS	PRED 1 hr	PRED 2 hr	PRED 3 hr	PRED Eff.	1hr	2hr	3hr
01-12-86	18.7	0.12	0.18	0.17	0.16	0.07	2.65	2.50	2.42
01-12-86	18.7	0.15	0.18	0.17	0.16	0.07	2.65	2.50	2.42
01-12-86	18.7	0.17	0.22	0.21	0.20	0.09	3.28	3.10	3.00
01-12-86	18.7	0.19	0.18	0.17	0.16	0.07	2.65	2.50	2.42
01-12-86	18.7	0.21	0.18	0.17	0.16	0.07	2.65	2.50	2.42
01-12-86	18.7	0.22	0.22	0.21	0.20	0.09	3.28	3.10	3.00
01-12-86	18.7	0.24	0.22	0.21	0.20	0.09	3.28	3.10	3.00
01-12-86	18.7	0.25	0.22	0.21	0.20	0.09	3.28	3.10	3.00
01-12-86	18.7	0.30	0.27	0.25	0.24	0.11	3.93	3.71	3.59
01-12-86	18.7	0.32	0.27	0.25	0.24	0.11	3.93	3.71	3.59
01-12-86	12.5	0.16	0.22	0.21	0.20	0.11	3.93	3.71	3.59
01-12-86	12.5	0.19	0.22	0.21	0.20	0.11	3.93	3.71	3.59
21-12-86	12.5	0.22	0.26	0.24	0.24	0.12	4.57	4.32	4.18
21-12-86	8.0	0.14	0.18	0.17	0.16	0.11	3.93	3.71	3.59
21-12-86	8.0	0.10	0.15	0.14	0.13	0.09	3.28	3.10	3.00
17-02-87	8.0	0.15	0.15	0.14	0.13	0.09	3.28	3.10	3.00
17-02-87	10.1	0.16	0.20	0.19	0.18	0.11	3.93	3.71	3.59
18-02-87	10.1	0.30	0.41	0.38	0.37	0.21	7.99	7.55	7.31
18-02-87	12.5	0.30	0.37	0.35	0.34	0.18	6.60	6.23	6.03
18-02-87	12.5	0.40	0.49	0.46	0.45	0.23	8.69	8.21	7.94
18-02-87	12.5	0.43	0.53	0.50	0.49	0.25	9.40	8.88	8.60
18-02-87	12.5	0.37	0.33	0.32	0.31	0.16	5.92	5.60	5.42
18-02-87	12.5	0.30	0.33	0.32	0.31	0.16	5.92	5.60	5.42
18-02-87	12.5	0.26	0.22	0.21	0.20	0.11	3.93	3.71	3.59

that once wind duration reaches one to two hours along the maximum fetch in Lake Patzcuaro, maximum wave heights are generated. As can be seen, at constant wind velocity longer periods of wind would not increase wave height, hence the lake becomes fetch limited.

Figure 4.21 (a, b, c and d) shows the correlation between observed and predicted wave height using wind stress for 1-, 2-, 3-hour period and effective fetch. The best correlation value is found for the 2-hour wind stress period, however, there is no statistical difference for 1- and 3-hour periods. By contrast, predictions for wave generation using effective fetch underestimated wave heights by up to 67%. Moreover, the concept of effective fetch tends to generalize the effect of the wind over the water at different individual lengths, thus predicting similar wave heights for different fetch lengths.

Windspeeds in Lake Patzcuaro are variable throughout the year but commonly reach a maximum of 10 m/s and storms are unusual in the area. However, gales have been recorded with windspeeds of up to 20 m/s (SARH personal communication) and these can occur any time of the year. Assuming a potential wind stress of 20 m/s over the water along the maximum fetch (SW-NE) and with a minimum duration of two hours, the SMB method would account for a wave height of about 1.0 m (Table 4.6).

Figure 4.21
Correlation between observed and predicted wave heights in Lake Patzcuaro, Michoacan, Mexico, using maximum fetch at a) 1-, b) 2-, c) 3-hour wind period and d) effective fetch.
n = 24, P < 0.001

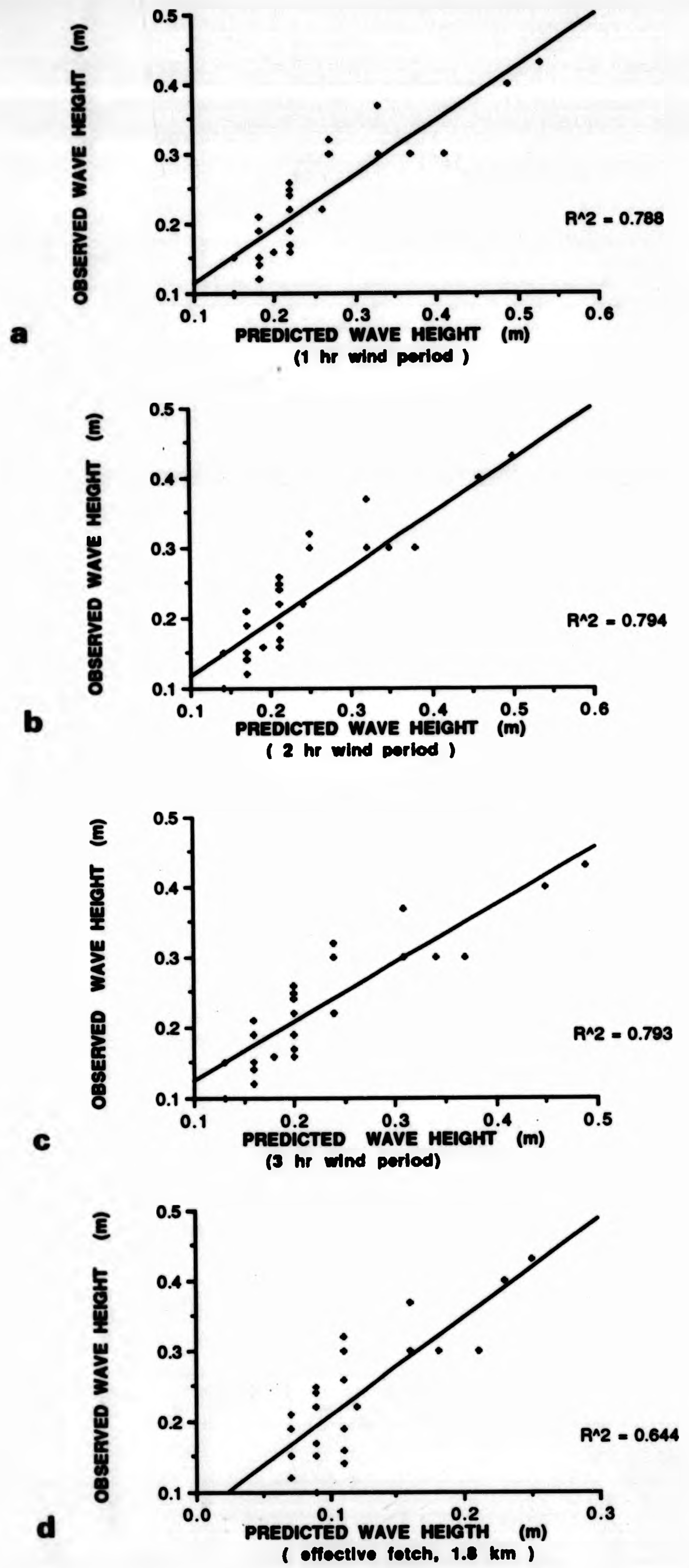


Table 4.6. Summary of calculated water movements for Lake Patzcuaro *

PARAMETER	VALUE
Coriolis parameter	0.0000489
Inertial period (hr)	35.6
Geostrophic drift (cm/s2)	0.000244
Radius of inertial circle (km)	5.11
Amplitude of seiche (cm)	3.24
Mean seiche velocity (m/s)	6.97
Period of seiche (min)	94.29
Maximum wave heigth (m)	0.58

* For illustration purposes a windspeed of 10 m/s and surface drift of 5 cm/s are assumed.

Discussion

Historical data suggest that regional variations of rainfall for Lake Patzcuaro from one year to another are determined basically by shifts in the atmospheric circulation which affect most of the country. Although other climatic parameters such as mean annual temperature and annual evaporation have been relatively constant during the last century, a decrease in the amount of rainfall is observed for the period of 1970-1986. The rain factor (P/T) suggested by Lang (1915), has been adapted by Garcia (1981) to the Koppen's climatic classification in order to more accurately differentiate regional climates in Mexico. This value in climate classification represents to a certain extent a gross estimate of atmospheric humidity which in Lake Patzcuaro has shown a significant reduction. The increasing frequency of long periods of drought in Lake Patzcuaro over periods of heavy rainfall can be responsible for the low values of the rain factor.

As Lake Patzcuaro is an endorheic system the water balance is predominantly controlled by rainfall, evaporation and seepage from the catchment area. Although accurate hydrological data are not available to determine the contribution from the catchment area, changes in the water budget have been illustrated by a simple simulation model. This is clearly demonstrated by year-to-year lake level oscillation changes which correlate with water balance computations. On an annual basis, given the high evaporation rates over the rainfall contributions, a hydrological deficit is estimated in the lake budget which was partially compensated by the seepage from the catchment area. Although there are considerable variations in annual precipitation, the proportion of seepage was observed to decrease with time. The drought during the early 1940s and early 1950s caused the very low level in 1955. However, an approximate seepage of at least 12% represented the hydrological contribution of the watershed to the lake. It is estimated that the present seepage factor has been reduced by the watershed deforestation and erosional processes from 12% to 8%. Assuming the occurence of a new dry period in the basin, the contribution of the catchment area becomes more critical in maintaining water levels in equilibrium. As erosional processes continue, further decrease in water inputs can be expected due to a reduction in the seepage factor.

The wind system in the lake is mainly dominated by southern winds throughout the year which are higher during the winter season. It is very possible that the pattern of wind is affected by the relief of the basin.

Maximum elevations around the catchment area are El Tzirate, El Tariaqueri, Cerro del Frijol, Huacapian and La Virgen located north, northeast, southeast, west and northwest respectively with altitudes ranging from 2500 to 3300 m. These mountains provide shelter to the basin from most air currents originating outside the basin. The general pattern of wind circulation is that following a morning of calm weather, by noon the wind flows into the basin from the exposed southern lowlands (S-SW). The wind then flows across the main axis (SW-NE) where it gathers strength due to the narrow and long lake fetch (18.7 km) and eventually leaves the basin at the northeast end (Quiroga town). This type of wind circulation along the maximum lake length has significant effects on the pattern of water movements in Lake Patzcuaro.

The hydrodynamics of Lake Patzcuaro are mainly represented by wind driven surface drift, Coriolis effects, surface seiches and waves. Surface currents originated in the south are relatively lower than those observed in the central and northern parts of the lake. Although the pattern of surface drift follows the direction of the wind, there is a slight deflection of these currents to the east. This deviation can be originated by two possible motions. One could be a deep-water return current following the morphometry of the eastern edge. Alternatively a small scale Coriolis effect may deflect the surface current to the right. Although the existence of these motions has not been measured in the field, empirical computations using the morphometry of the basin and data for gravitational forces suggest that Coriolis effects may be significant at low current velocities.

Estimation for wave height by the SMB method has been mainly applied in coastal areas where land frictional forces are more limited and wind exposure is wide (US Army Corps of Engineers, 1984). The same method has been adjusted and to inland reservoirs (US Beach Erosion Board Corps of Engineers, 1962). However, the effectivness of wave prediction is critical when fetch distance is used to compute wave heights. Early applications of the SMB model in reservoirs and lakes reported that wave heights were overestimated (Saville, 1955). It was assumed that fetch length was affected by neighbouring land features and that rough slopes along the shoreline increased frictional forces with the result that wave growth was more limited than in open sea conditions. The concept of effective fetch was thus introduced to reduce the fetch length for narrow conditions which are common in inland reservoirs (US Beach Erosion Board Corps of Engineers, 1962). The method was based on the consideration that the width of a fetch in inland reservoirs has a limiting effect on wave generation, in that the less the width-length ratio, the smaller the effective fetch. However, results obtained in Lake Patzcuaro indicated that the criteria for effective fetch greatly underestimated wave height in comparison with the use of individual fetch lengths. It is observed that wave heights in Lake Patzcuaro are fetch limited and only strong winds (>20 m/s) can significantly increase the wave height in the lake.

Experimental trials for fish cage acuaculture have been done in small scale by the Mexican Department of Fisheries with the aim of restocking native fish fauna. If a larger scale culture system is considered then further data on wave height in the lake would be advisable to enable proper structure design and site selection.

Chapter 5

Water Quality

Introduction.

Water provides a medium in which a wide range of substances will dissolve and others will remain in suspension. In this environment chemical reactions will take place due to the polar nature of the water molecule. Natural waters contain a large amount of dissolved and suspended elements from the earth's crust which together with organic compounds provide the chemical constituents upon all the entire aquatic biological processes are based.

The contribution of photosynthesis from phytoplankton and macrophytes is the energetic basis of the aquatic ecosytem. In aquatic ecosystems the availability of underwater light determines the rate of phytoplankton growth and primary productivity. Particularly in turbid ecosystems, light becomes limiting on both the diversity and distribution of phytoplankton.

The penetration and distribution of sunlight with depth in the aquatic medium is determined by a combination of absorption and scattering processes (Jerlov, 1976), which together contribute to what is known as light attenuation. Significant contributions to light absorption and scattering can be made by the water itself, dissolved yellow substances, inorganic particles, detritus and phytoplankton (Kirk, 1981). Thus, the optical properties of the water will depend upon the nature of the catchment area and its effects on water quality. Optical properties most commonly measured in freshwater lakes are secchi transparency, vertical attenuation coefficient, beam attenuation coefficient, scalar irradiance and reflectance.

Theoretically, light is never totally extinguished. However, photosynthetic activities take place efficiently within a limited water depth known as the euphotic zone. A practical limnological approximation of the euphotic zone is that area above the optical depth at which sunlight falls to 1% of that measured just below the surface. At a depth of 1% incident light, the compensation depth, photosynthesis is in equilibrium with respiratory activities. The compensation depth separates the trophogenic zone above from the tropholytic zone or area of dominant respiratory activity below (Talling, 1971; Wetzel, 1983; Kirk, 1983).

Indirect estimates of primary production, predictive models of fish yields and trophic status using these underwater optical properties have been made for both lake and fisheries management (Carlson, 1977; Oglesby, 1977; Lorenzen, 1980; Megard <u>et al</u>, 1980).

Freshwater phytoplankton populations, in combination with macrophytes, are a major biological component in lakes and littoral zones. Their abundance influences the dynamics of the aquatic system because the initial production of organic matter in freshwater systems is achieved by these plants through photosynthesis, the process of transforming, solar energy into chemical energy (Krebs, 1963). The amount of chemical energy (or organic matter) produced by plants in a specific time period is defined as primary production or productivity (Westlake, 1963). Net primary production is considered as the proportion of productivity after respiration losses are substracted. Therefore the amount of net chemical energy produced by primary production which can be transferred to animals and non-photosynthatic organisms determines the capacity of the ecosystem to sustain maximum biomass.

The rate of primary production has been commonly used as an indicator to classify aquatic ecosystems on a scale ranging from unproductive to productive (Beveridge, 1984). This classification has also been used as the basis for water quality modelling and biomass prediction (Shannon and Brezonik, 1972; Lorenzen, 1970; Melack, 1976; Thomann and Mueller, 1987).

Light measurements and assessment of optical properties to date for Lake Patzcuaro have been limited only to secchi disc transparency. In 1982, a hydrobiological survey conducted by Mexican authorities (Delegacion Federal de Pesca and Secretaria de Fomento Rural del Estado de Michoacan) made individual measurements in 5 locations in the lake, using a beam transmissometer and an irradiance meter. However, detailed results from the study were not published and only raw data are available from the survey. Therefore, an enhanced description of the optical properties of Lake Patzcuaro would be useful to understand the procesess which affect the primary productivity.

The water chemistry of the aquatic ecosystem is a balance between the solubility of the rocks and soils of the drainage area, water movements, chemical and biochemical processes within the lake, and the dynamics of the local hydrological cycle. The integration of these processes ultimately determines the ecological state and hence the productivity of the aquatic ecosystem at a given time. Although the ecological processes that occur in freshwater lakes are generally the same, the level of productivity is a response to local environmental conditions for each particular lake. Hence, characterisation of the chemical composition of the water in a particular lake is essential for the understanding of the environmental structure in which biological processes take place.

Water quality studies in Lake Patzcuaro have been numerous during the last fifty years. However, many of them include only a limited number of water quality parameters which makes environmental assessment difficult. First observations on the chemical constituents of Lake Patzcuaro were made by Yamashita (1939) reporting a uniform pH distribution of 8.5, high levels of silicon (12 mg/l) and relatively low concentrations of dissolved phosphorus (10 ug/l). Ancona _et al_ (1940) determined additional chemical parameters including values for nitrates which were reported as relatively "low" values (7.3 mg/l). Similar figures were also reported by De Buen (1941e; 1944c). Hutchinson _et al_ (1956) and Deevey (1957) determined moderate amounts of chloride (21.3 mg/l) and low values of sulphate (0.2 mg/l) with a chemical dominance of bicarbonates. Deevey (1957) also quoted values for chlorophyll for both Lake Chapala and Patzcuaro (12.5 to 15 mg/m3). During the 1960's no significant contributions were made to the understanding of the physical and chemical environment of Lake Patzcuaro. Saporito (1975) during a study on chemistry of sediments of the lake reported high values of phosphorus (93 ug/l), however no information was given about the referred fraction of phosphorus. Rosas (1976) presented a table with similar water quality parameters to previous studies in order to compare changes in the lake. This table included data on total dissolved solids for Lake Patzcuaro (380 mg/l). Tellez and Motte (1980) described the horizontal distribution of several physical and chemical parameters and their implications in phytoplankton diversity, abundance and distribution. They reported diurnal oxygen depletions, high turbidities and other chemical changes at the southeastern lobe of Lake Patzcuaro and thus described this location as the area with most environmental deterioration. This was also confirmed by Velasco (1982) and Rosas et al (1985) where high values of total phosphorus, up to 0.31 mg/l, correlated with biological indicators of polluted waters. As can be seen most studies have been mainly descriptive and incomplete. However, the latter have been the only group of studies orientated towards an environmental assessment of Lake Patzcuaro and evaluation of its trophic status. Since 1984 the Laboratorio de Biologia Acuatica, of the University of Michoacan has continuously monitored water quality parameters for Lake Patzcuaro. Although the results have not yet been published, preliminary descriptive tables have been presented in national meetings, and high values of total solids (650 mg/l) and biochemical oxygen demand (21.9 mg/l) have been reported.

Studies on primary productivity in Lake Patzcuaro are practically non-existent and most contributions have been basically related to the diversity, distribution and succession of aquatic vegetation (Ancona et al, 1940; Osorio-Tafall, 1941a; 1941b; 1944; De Buen, 1944b; Calderon and Angeles, 1971; Tellez and Motte, 1980; Velasco, 1982; Lot and Novelo, in press). However, Velasco (1982) reported

71 species of phytoplankton, of which, 25 had not previously been noted, suggesting the possibility of environmental change. This was supported by a series of correlations between chlorophyll-a content and water quality parameters. By using species of *Ceratium*, *Pediastrum*, *Melosira*, *Anabaena*, *Aphanizomenon* and *Microcystis* as algal indicators, Lake Patzcuaro was described as an ecosystem with ecological conditions ranging from mesotrophic, to meso-eutrophic and eutrophic status (Velasco, 1982).

As described earlier, Lake Patzcuaro is a closed drainage basin and the rough topography of its watershed produces a variety of physical environments. Consequently a combination of wind action and sediment loads can have a major influence on light conditions, nutrient availability and littoral profile which therefore may affect the distribution of both macrophytes and phytoplankton, and hence the rate of primary production in the lake.

The present chapter aims to describe the physical and chemical properties of the water of the lake at 24 locations over a 6 month sampling period, to estimate the primary production from both phytoplankton populations and macrophyte communities and to examine the possible environmental parameters affecting its primary productivity.

Materials and methods.

Sampling stations.

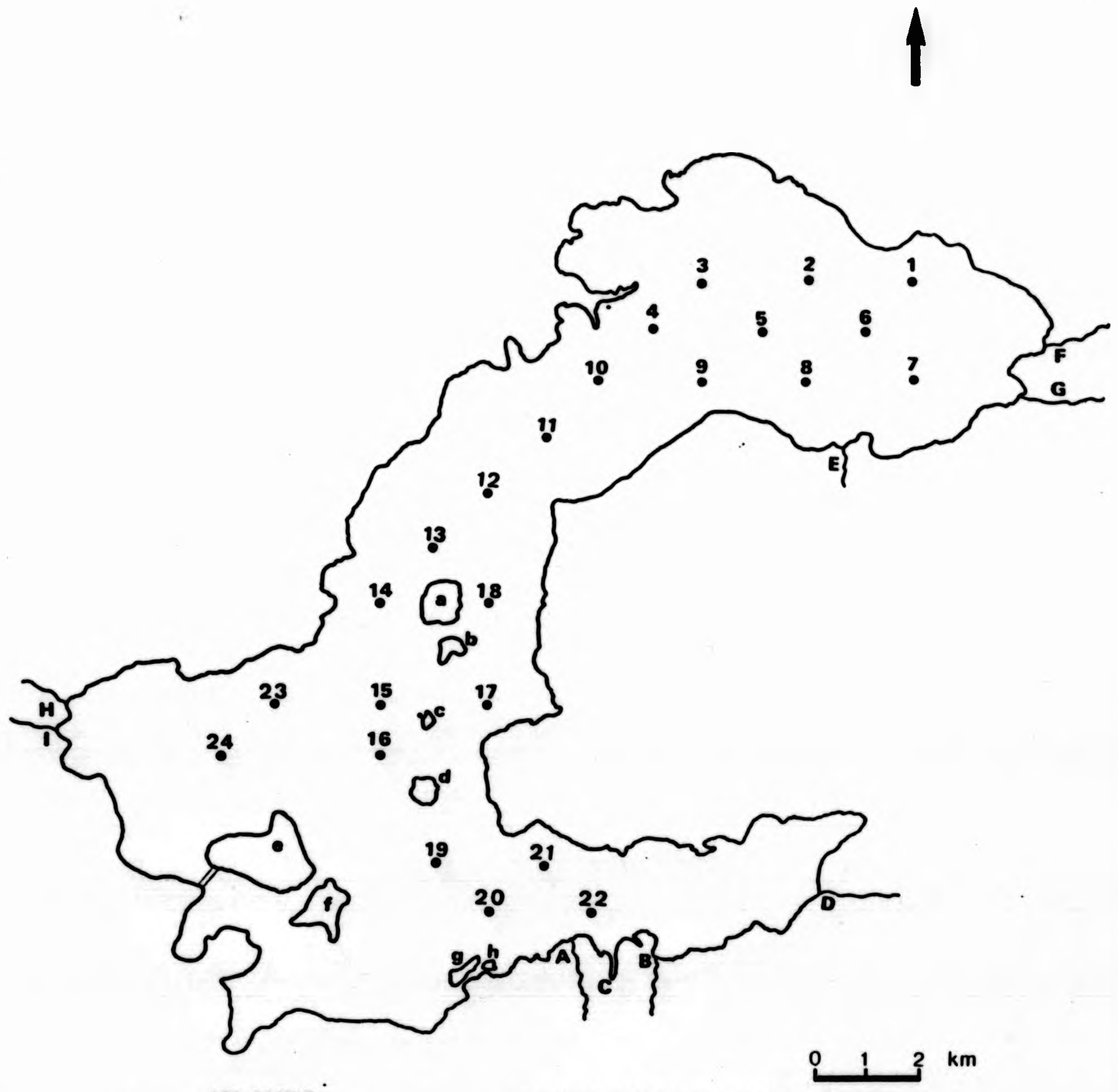
Twenty four sampling stations were established from topographic maps (CETENAL, 1976) and these were selected to ensure representative sampling of the entire lake. The selected set of 24 sampling stations covered most of the lake area, assuming that each sampling station covered an approximate radius of 5.5 km2 (Figure 5.1). Sampling sites were located in the field using professional "SILVA" and "SUNTU" survey compasses by bearing triangulation using predetermined reference points.

Temperature.

Given the overall objectives and the single sampling season for the present project, only surface temperature was routinely recorded in the field. However, during the sampling period several stations located along the main axis of the lake were included for winter temperature profile examination, between October 1986-February 1987. Temperature was measured immediately with a mercury thermometer from samples taken in a 2-l Van Dorn Bottle at surface, 3.0, 5.0, 7.0 m and bottom depths. Sampling time was in most cases between 9:00 a.m. and 11:00 a.m. combined with occasional measurements in the afternoon and at midnight. The area near

Figure 5.1

Location of the sampling stations in Lake Patzcuaro, Michoacan, Mexico.



ISLANDS:

a. Pacanda.
b. Yunuen.
c. Tecuen.
d. Janitzio.
e. Jaracuaro.
f. Pastora.
g. Uranden Morelos.
h. Uranden Morales.

SEWAGE DISCHARGES:

A. Patzcuaro (a).
B. Patzcuaro (b).
C. Propemex.
D. Chapultepec.
E. Tzintzuntzan.
F. Quiroga (a).
G. Quiroga (b).
H. Erongaricuaro (a).
I. Erongaricuaro (b).

Erongaricuaro reported by De Buen (1941b) was also visited for temperature measurements. A thermometer was fitted inside the Van Dorn bottle and lowered to a series of depths, the bottle was kept at the required depth for a about three minutes before closing the system by the messenger.

Light measurements.

A total of 53 light observations were obtained with readings at different depths from the predetermined 24 sampling stations. Given the normal dry season in winter, sky conditions were always nearly or totally clear and water surface was typically calm. No measurements were made under rough conditions.

Transmittance readings were taken at just below the surface, 0.2, 0.5, 1.0, 1.5 and 2.0 m depth until the transmittance percentage was typically less than 1%. Beam transmittance was measured using a 1-m path length transmissometer (Kahlsico Digital in-situ transmittance meter No. 269WA170) the probe of which was suspended in clear water prior to lowering in Lake Patzcuaro and the controls adjusted until the transmittance reading was 100% (Plate 5.1 a). The length of the water path chosen was 0.40 m.

Plate 5.1

Instrumentation used for the assessment of the optical properties of the water in Lake Patzcuaro, Michoacan, Mexico.

a) beam transmissometer,

b) irradiance meter.

The beam attenuation coefficient (c) was calculated according to Jerlov (1976) as

$$c = -[\ln(1 - C)]/r$$

Where
c = Beam attenuation coefficient (m)
C = Attenuance, $1 - C = T$ (beam transmittance which is given by the transmissometer).
r = The water path length (m), 0.40.

An irradiance meter (Kahlsico Underwater Irradiameter No. 268WA310) was used for measuring ambient and water-attenuated solar irradiance. The irradiameter consisted of a conventional Lambert-type, opal, cosine corrector plate to measure irradiance as incident upon a flat surface. The deck control module has two indicating meters which provide simultaneous measurements of total energy values (microwatt per square centimetre) from both surface and underwater cells (Plate 5.1 b). Irradiance measurements were made at just below the surface, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 m depth.

Vertical attenuation coefficient (Kd) was calculated by using the relation derived from Beer-Lambert's Law suggested by Kirk (1983).

$$\ln Ed(z) = -Kd\ z + \ln Ed(0)$$

Where

Ed(z), Ed (0) = Values of downward irradiance at depth (z), m, and just below the surface, respectively (mW/cm 2).

Kd = Vertical attenuation coefficient calculated by linear regression of ln Ed(z) with respect to depth (m).

The depth of the euphotic zone was calculated by linear regression of depth and the natural of logarithm light at different depths by means of the equation

$$Ed(z) = Ed\ (0)^{(-Kd\ z)}$$

For comparative purposes and in order to check the performance of the instrumentation under very clear water conditions a series of visits were made to Lake Zirahuen, located 12 km from Lake Patzcuaro. Lake Zirahuen is a deep (approximate maximum depth 38 m) clear water lake which represents one of the clearest water bodies in the region due to its high secchi disc transparency (7.00 m) and low total suspended solids concentration (<2.0 mg/l).

Simultaneous with the above instrument observations secchi disc transparency (Zsd) was recorded by means of a standard disc (0.20 m in diameter), painted in black and white quadrants. Readings were taken at an average dissappearance depth where the disc was lowered and raised again and when the line supporting the disc was vertical.

In order to minimise sampling errors, all light observations were made on the sunny side of the boat and readings were performed within two hours around solar noon (10:00 - 14:00 h).

Water sampling and field measurements.

Integrated water quality samples (3.5 1) were collected from the first meter of the water column at each of 24 sampling sites by using a weighted hose. Sampling was carried out from three speed boats between 9:00 a.m. and 11:45 a.m. local time. The sampling procedure, was practiced in the field by all crews to obtain maximum uniformity. Water samples were kept in cool plastic boxes out of direct sunlight and taken to the laboratory for immediate analysis.

Water samples and flow measurements were taken from nine main sewage discharge sites located along the shoreline (A to I, Figure 5.1). Flow estimations were made where possible in existant V-notch weirs by using the equation described by Ven te Chow (1964)

$$Q = 1.4 \tan \theta H^{5/2}$$

Where:

Q = Water flow in m3/s
θ = Angle of the V-weir.
H = Height of the water level.

Where weirs were non-existant then both the float technique and Manning's equation were used (ILRI, 1981)

$$V = 1/n \; R^{2/3} \; S^{1/2} \quad \text{and} \quad Q = V \times A$$

Where:

V = Average velocity in m/s

n = Roughness coefficient

R = Hydraulic radius of flow cross-section in m.

R = cross sectional area / wetted perimeter.

A = Cross sectional area in m2

S = Energy loss of hydraulic gradient (slope).

Lake water sampling was conducted on five occasions on the following dates; 2nd December 1986, 18th December 1986, 3rd January 1987, 19th January 1987, 4th February 1987.

Laboratory analysis.

Determinations of electrolyte conductivity, pH, alkalinity, dissolved oxygen, chlorophyll-a, suspended solids, ammonia, nitrate, nitrite, dissolved reactive and total phosphorus were made for all twenty four sampling stations. However, at twelve sampling stations additional analysis were made for total solids, dissolved and particulate matter, water hardness and cationic microelements (Na, K, Ca, Mg and Fe).

Electrolyte conductivity (COND) and pH were measured by using a "Jenway" portable conductivity meter and a "Corning Delta" ph meter respectively.

Alkalinity (ALK) was determined by the titrimetric method using sulphuric acid 0.1 N and phenolphthalein as indicator (APHA, 1985).

Dissolved oxygen content (DO) was determined by the Winkler iodometric method using starch as indicator and modified with sodium azide to correct for nitrite interferences. In order to complete empirical data for oxygen saturation calculations (% DO) occasional measurements of barometric pressure (P) were made during sampling times using a field altimeter "TOMHEMN" Mod. 2000. The instrument was calibrated in the climatological observatory of Morelia city and when possible measurements were made at 12:00 h with dry and sunny atmosphere.

Dissolved and particulate organic matter were determined by biochemical oxygen demand (BOD) and chemical oxygen demand (COD). For BOD analysis samples were diluted 25%-50% with distilled, air-saturated water and incubated at a constant temperature for a 5-day period (APHA, 1985). Initial and final oxygen concentrations were calculated by the Winkler technique. COD was analysed by the open dichromate reflux method. Water samples were refluxed in strong acid solution with a known excess of potassium dichromate for a period of two hours. After digestion, the remaining unreduced dichromate was titrated with ferrous ammonium sulfate (APHA, 1985).

Total solids (TS) and suspended solids (SS) were determined by the gravimetric method. Total solids were determined by evaporating a known volume of sample to dryness in a preweighed dish at 105 C until constant weight was achieved (APHA, 1985). For suspended solids, samples were collected by vacuum filtration on preweighed 0.45 um glass fibre filters, dried at 105 C, and reweighed on an analytical balance to a 0.01 mg precision (Strickland and Parsons 1972). Total dissolved solids (TDS) were estimated by substracting SS from TS.

The concentration of photosynthetic pigments (CHL) was determined by filtering a known volume of water sample (0.25 to 1.0 l) through a 0.45 um glass fibre filter, extracting the pigments in 90% methanol buffered with magnesium carbonate (Holm-Hansen and Riemann, 1978) and measuring their absorbance in a double cuvette spectrophotometer. The absorbance at 750 nm was subtracted from that measured at 665 nm for inorganic turbidity correction. Concentrations of chlorophyll-a were calculated using the equation suggested by Jones (1979),

$$\mathrm{Chl}\ a = Ve/Vs \times f/e \times A$$

Where:

Chl a = Concentration of chlorophyll-a in ug/l

Ve = Volume of the extract in ml.

Vs = Volume of the filtered sample in l.

f = Factor equivalent to the reciprocal of the specific absorption coefficient of chlorophyll-a multiplied by 1000. For chlorophyll-a in absolute methanol Holm-Hansen and Riemman (1978) gave a value of specific absorption coefficient of 77.9 l/g cm. Therefore, 1/77.9 x 1000 = 12.84. Factor (f) = 12.84.

e = Path length (1.0 cm).

A = Corrected absorbance at 665 nm (i.e. absorbance at 665 nm - absorbance at 750 nm).

Dissolved reactive phosporus (DRP) and total phosphorus (TP) were determined spectrophotometrically at 882 nm by the molybdate reaction technique suggested by Eisenrich et al (1975).

Nitrate (NO3) quantification was made by cadmium-copper reduction to nitrite. Nitrite (NO2) was then determined spectrophotometrically using the sulphanilamide/N-(1-naphthyl)-ethylenediamine dihydrochloride (NED) colorimetric reaction (Golterman et al, 1978; APHA, 1985).

Ammonia (NH4) determination was made spectrophotometrically by the indophenol blue reaction using the phenol-hypochlorite method described by Solorzano (1969).

Calcium (Ca++), magnesium (Mg++), sodium (Na+) potassium (K+) and iron (Fe+++) concentrations were determined by flame atomic absorption spectrophotometry. Total water hardness was determined by calculation from the values for calcium and magnesium (APHA, 1985; Stirling, 1985).

The average value of a total of 120 water samples were used to describe the chemical environment of Lake Patzcuaro during the winter season.

For comparitive purposes, occasional hydrobological surveys were made to Cuitzeo and Zirahuen lakes, located 39 km north of Morelia city and 12 km southwest of Lake Patzcuaro, respectively.

Primary Production.

Phytoplankton

Primary production was estimated by measuring the variation in dissolved oxygen concentrations per unit volume using the dark and light bottle technique (Vollenweider, 1969). Incubations were made at two sites; station 2, located in the north and station 21, located in the south. Two replicates per location were incubated at surface and at 2.0 m depth for a eight-hour period, from 9:00 a.m. to 5:00 p.m.

Oxygen determinations were made in situ by the Winkler method. In order to achieve maximum precision, oxygen determinations were made in triplicate. These determinations were carried out on five occasions, each one being made on the day after general water quality sampling was completed in the field.

Calculations of primary production in g of Carbon / m2 day were made as suggested by Vollenweider (1969) and Cole (1983). A photosynthetic quotient of 1.2 was used in all computations. Thus, g of Carbon fixed / m2 day = mg of Oxygen released per litre divided by the incubated period in hours x (12/32 x 1.2) x 12. Primary productivity rates for the Central part of the lake were assumed to be similar to those in the northern section.

Macrophytes

Forty-two littoral sampling sites were established covering most of the lake shoreline. Locations which had been disturbed by dredging or macrophyte harvesting were avoided. Submerged and emergent macrophytes were sampled along transects running perpendicular from shore to the first meter isopleth. Littoral slope was estimated according to Hakanson (1981). All plants within a quadrat of 0.5 m2 were manually harvested at ground level and transported immediately for gravimetric analysis. In the laboratory the plants were rinsed to remove animals and sediments and dried at 70 C to a constant weight.

Using the criteria suggested by Duarte and Kalff (1986) power transformations were used to model the relationships between littoral slope and macrophyte productivity. Once the best exponent was found, the slope was transformed using the exponent to linearize the relationship between slope and macrophyte biomass (MB).

Macrophyte coverage was further estimated using the 1:25,000 bathymetric map presented in Figure 3.2 and completed with field observations using conventional photography.

Data for primary productivity were transformed from macrophyte (MB) in grams of dry weight / m2 into grams of Carbon fixed / m2 assuming an organic carbon content of 37% (Westlake, 1963). Given the season of the sampling it was assumed that macrophyte productivity would correspond to the minimum yield in a year period.

Diel cycles.

In order to observe the possible pattern of photosynthesis during daylight, diurnal oxygen changes were measured on four occasions at the same two locations established for primary production. Surface and bottom temperature and oxygen concentrations were determined at 6:00, 12:00, 24:00 and 6:00 h.

Results.

Temperature.

During the winter season of 1986-1987 (November-February) Lake Patzcuaro had a mean water temperature of 16.3 C. The lake reached a maximum temperature of 20.0 C and a minimum of 12.7 C. No thermal stratification was observed through the water column. Results are very similar to those from previous studies suggesting that the lake is well mixed throughout the year (De Buen, 1941b; Tellez y Motte, 1980). Although two spots were detected with a sharp decrease in temperature (1.9 C over 4.0 m), oxygen concentrations were uniform from surface to bottom (Table 5.1). Therefore, the small amount of field data collected in this study do not suggest groundwater currents in the lake. A more adequate survey with sensitive instrumentation would be required in order to detect thermal conditions in the Erongaricuaro region.

Light.

The data on the optical properties of both Lake Patzcuaro and Lake Zirahuen are presented in Table 5.2 and Appendix 1. The contrast in water clarity between the two water bodies is obvious given vertical attenuation coefficients for Lake Patzcuaro of between 3.97 and 2.22 m with a mean value of 3.10 m, whereas the mean value in Lake Zirahuen was 0.3 m. A similar trend was found in beam attenuation coefficients where a range between 11.99 and 8.54 m with a mean value of 10.26 m was recorded for Lake Patzcuaro, and a mean value of

Table 5.1. Temperature and dissolved oxygen profile obtained from Erongaricuaro area in Lake Patzcuaro. Mean values of three visits.

Depth (m)	Temperature (C)	Oxygen (mg/l)
Surface	19.0	9.74
0.25	19.0	9.74
0.50	19.0	9.74
0.75	19.0	9.73
1.00	19.0	9.73
1.25	19.0	9.73
1.50	19.0	9.73
1.75	19.0	9.73
2.00	18.5	9.73
2.25	18.0	9.72
2.50	17.7	9.72
2.75	17.5	9.72
3.00	17.5	9.72
3.25	17.3	9.70
3.50	17.3	9.70
4.00	17.1	9.69

Table 5.2. Optical parameters for Lakes Patzcuaro and Zirahuen, measured in the winter of 1986-1987.

Station	Zsd (m)	Kd (m)	Eu (m)	c (m)	Kd + c (m)	Ratio Eu/Zsd
1	0.34	3.85	1.34	10.98	14.83	3.94
2	0.36	3.30	1.55	11.09	14.39	4.30
3	0.39	3.28	1.53	10.56	13,84	3.92
4	0.39	3.30	1.47	10.60	13.90	3.77
5	0.33	3.91	1.37	11.52	15.43	4.15
6	0.33	3.80	1.36	11.45	15.25	4.12
7	0.33	3.97	1.35	11.99	15.96	4.09
8	0.35	3.62	1.35	11.19	14.81	3.86
9	0.43	3.30	1.47	8.60	11.90	3.42
10	0.37	3.19	1.55	10.33	13.52	4.19
11	0.38	3.08	1.55	10.86	13.94	4.08
12	0.39	3.23	1.58	10.55	13.78	4.05
13	0.40	3.15	1.59	9.88	13.03	3.98
14	0.40	3.23	1.55	9.79	13.02	3.88
15	0.48	2.69	1.72	8.54	11.23	3.58
16	0.44	2.83	1.70	9.49	12.32	3.86
17	0.44	2.85	1.69	9.33	12.18	3.84
18	0.42	3.06	1.59	9.78	13.77	3.78
19	0.43	2.87	1.64	9.32	12.19	3.81
20	0.42	2.78	1.71	10.45	13.23	4.07
21	0.43	2.97	1.66	9.74	12.71	3.86
22	0.44	2.22	2.10	10.04	12.26	4.77
23	0.44	2.76	1.68	9.71	12.47	3.81
24	0.45	2.81	1.71	8.67	11.48	3.80
Zirahuen	5.75	0.30	15.10	1.20	1.50	2.62

1.20 m for Lake Zirahuen. For Lake Patzcuaro, secchi disc readings ranged between 0.33 and 0.48 m with a mean value of 0.40 m, whereas a mean secchi disc value of 5.75 m was obtained for Lake Zirahuen.

Generally in Lake Patzcuaro, maximum turbidities were observed at the northern end of the lake whereas maximum values of light penetration were recorded in the central and southern end.

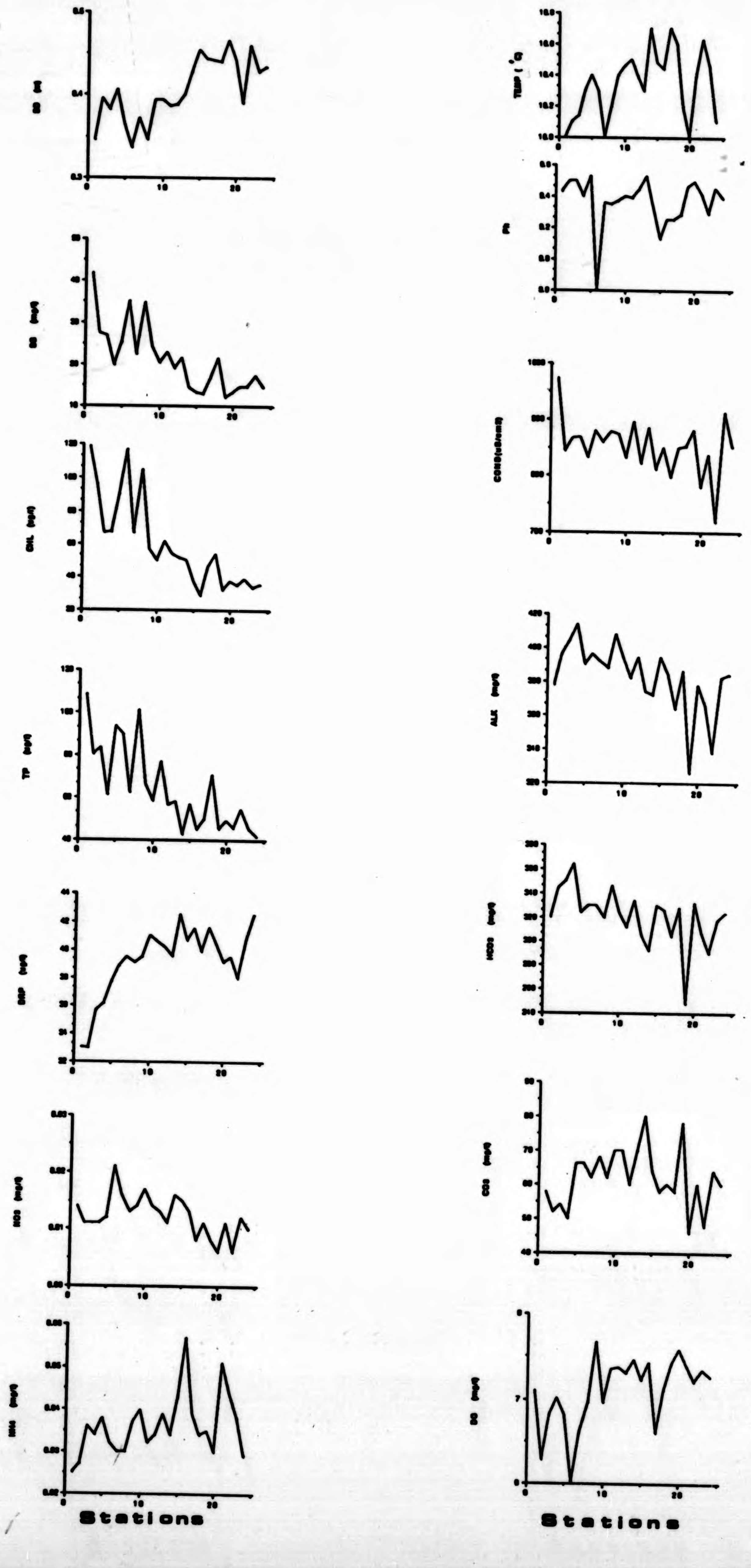
Lake water quality.

Water quality data for Lake Patzcuaro are illustrated in Figure 5.2 and Appendix 2.

An average value of electrolyte conductivity of 820 uS/cm was observed in the Lake Patzcuaro with no significant variations in most of the water body. This value indicates moderate water mineralisation. However, higher values up to 2500 uS/cm have been previously recorded in areas of high disturbance including dredging, sewage inflows and navigation channels (Tellez and Motte, 1980; Laboratorio Biologia Acuatica UMSNH, unpublished data). Values of pH were always in the alkaline range with an average value of 9.3. However, lower values down to 7.8 were recorded near sewage inlets. Values of pH of 8.34 are accepted as the pH above which carbon dioxide is absent and below which no carbonate occurs. As can be seen total alkalinity is primarily the result of bicarbonate and carbonate ions. However, the present mean total alkalinity, 400 mg/1, is not

Figure 5.2

Average spatial variation of water quality parameters in Lake Patzcuaro, Michoacan, Mexico, during October 1986 - February 1987.



markedly different from that reported by Deevey (1957), 450 mg/l, but is significantly higher than values reported by Tellez and Motte (1980), 100.3 mg/l. These differences may be explained due to a higher concentration of ions with excessive evaporation rates which coincide with Deevey's survey. Given the relatively low values of calcium and magnesium it is likely that bicarbonates and carbonates may be associated with sodium and potassium. This is further supported given that total alkalinity was greater than total hardness. Using the categorization described by Sawyer and MacCarty (1967) concentrations of total hardness are moderate (125.26 mg/l). Comparisons of individual cation concentrations demonstrated that sodium was the dominant cation ranking the series of analysed cations as follows: Na > Mg > K > Ca > Fe. Therefore, most of the moderate hardness of the lake is likely to be attributed to magnesium rather than calcium.

Values for dissolved oxygen are near saturation (7.10 mg/l = 92.0%). However, lower concentrations (6.0 mg/l) were detected mostly at station 6 located in the north basin and station 17 in the central basin.

Concentrations of ammonia and nitrites were within a low range (0.022 and 0.018 mg/l respectively) indicating that the processes of nitrification are efficient at the lake surface. From Trussell's tables (1972) it is estimated that for a pH of 9.4 and a mean temperature of 16 C, about 42.67% of the ammonia is in un-ionized state. This percentage is mainly determined by the high pH of the lake and could increase with the higher temperatures of May and June.

Nitrate concentrations were very low with a mean value of 0.012 mg/l. The horizontal distribution of nitrates did not indicate a defined pattern of distribution. Maximum and minimum values (0.061 mg/l and 0.002 mg/l) were at station 12 and 17 respectively, both located in the central basin whereas intermediate concentrations were detected in both north and south. In general, the low concentrations of nitrates in the lake indicated that there is a continuous utilization of inorganic nitrogen by algae.

Phosphorus, chlorophyll-a and suspended solids clearly showed horizontal variation in the lake. This variation was manifested as a decline from maximum values in the north basin to minimum levels in the south basin. Average dissolved reactive phosphorus concentrations were relatively high (39.2 ug/l) suggesting a constant availability of orthophosphate for phytoplankton growth during the winter season. Maximum concentrations of orthophosphate (48.8 ug/l) were detected in stations 11, 16 and 24 located in the central and south basins respectively, and minimum values (26.2 ug/l) were found in the north. Mean total phosphorus concentrations for the lake were also high (64.4 ug/l) and according to Goldman and Horne (1983) high levels of TP are a clear manifestation of high inflows from erosion and municipal sewage. Maximum levels of total phosphorus were measured in station 8 (204.2 ug/l) in the north basin and minimum values (30.9 ug/l) were detected in stations 16 and 21 both located in the south.

Although fractions for iron compounds were not measured mean concentrations of total iron were relatively high (0.60 mg/l). Given the geological genesis of the region, most of the soils are rich in ferrous compounds which are easily identifiable by their deep red colour (Toledo and Barrera-Bassols, 1984). Therefore, the existence of high amounts of iron in the water is due to the nature of the lake sediments and the continous loading of allocthonous materials.

Sewage water quality.

Point sources of discharge into Lake Patzcuaro are indicated alphabetically in Figure 5.1. There is no previous waste treatment for any of the raw sewage before it is discharged into the lake. Although some of these sewage streams are used for agriculture in the plains located near the lake during the dry season, in most circumstances the inputs to the lake are continuous. The nature of the sewage is mainly associated with municipal wastewater (Table 5.3) and the flow rate is variable throughout the year with a maximum peak during the rainy season when urban run-off is added to the disposal systems. Two exceptions are the Productos Pesqueros Mexicanos (Propemex) fish processing plant (C) and the Chapultepec channel (D).

The Propemex fish plant is located at the western side of the jetty of the town of Patzcuaro. The industry is Government owned and its products are basically fish meal

Table 5.3. Location, nature and flow rates of the main sewage discharges in Lake Patzcuaro. Flow rates are estimated for the dry season when volume of disposal are minimum.

Location	Sewage nature	Flow rate	
		1/s	m3/day
A. Patzcuaro (a)	Urban, Artisanal	20	1728
B. Patzcuaro (b)	Urban, Artisanal	15	1296
C. Propemex Fish Plant	Food Industrial	<1	3
D. Chapultepec channel	Agricultural	247	21340
E. Tzinztuntzan	Domestic	3	260
F. Quiroga (a)	Urban, Artisanal	25	2160
G. Quiroga (b)	Domestic, Farming	12	1037
H. Erongaricuaro (a)	Domestic	4	345
I. Erongaricuaro (b)	Domestic	3	260
	Total	329	28429

pre-products and fillets. Detailed information of production activities is not available to the public or academic institutions and hence an accurate assessment of the environmental impact of Propemex was not possible in this project. However, it was observed that approximately 20 tonnes of fish per week are processed, mostly as tilapia (Oreochromis niloticus) (90%) and carp (various species) (5%) from the "Infiernillo" dam (located 100 km south), and occasionally channel catfish (Ictalurus punctatus) and others fish species (5%). An estimated 40% of production is fillets and 60% is pre-fish meal products. The fish processing plant uses ground water for fish cleaning, gutting and instrumentation washing. A hopper with a water capacity of 1.5 m3 is used for the first steps of the processing. There is a quality control laboratory for routine chemical and bacteriological analysis. Water consumption and disposal is estimated at a minimum of 3 m3/day containing mostly organic wastes and some laboratory chemicals.

Chapultepec channel (D) is mainly an irrigation system which delivers water to an approximate area of 2000 ha. Several animal farms (poultry and cattle) receive water from the Chapultepec channel. The water is returned to the mainstream with a subsequent increase of organic matter, total solids, fertilizers and pesticides. The channel is administered by the local water authority (S.A.R.H.) and the stream is permanent throughout the year.

The components of the sewage streams from the town of Quiroga (F, G), like those from the town of Patzcuaro, are a combination of a) the domestic sewage, b) the sewage from cattle farming in the southern end of the town and c) the artisanal wastes which in this case are principally pottery, leather and skin crafts.

Physico-chemical characteristics of the raw sewage discharges located around the lake are presented in Table 5.4. Maximum values for most parameters were found in samples taken from industrial and agricultural discharges of the Propemex fish processing plant and in those from the Chapultepec channel. The major contribution of sediments and nutrients is from the agricultural source whereas the major concentration of organic matter is from the fish processing plant.

Principal sources of domestic sewage are those located in the towns of Patzcuaro (A) (B) and Quiroga (F) (G). These cities are the main tourist centres in the area and a large number of visitors is always present in both locations using hotel and catering services. Hence tourist activities necessarily involve significant contribution to the volume of waste water. Artisanal activity and trade represent a major income in the region and given the proximity of Patzcuaro and Quiroga to major highways connecting Morelia, Uruapan and Guadalajara an increase of artesanal production has been observed. This development involves the use of artificial paints, solvents, resins and different hydrocarbon products. Although results from only

Table 5.4. Water quality characteristics for the main sewage discharges in Lake Patzcuaro. Figures represent mean values of five sampling dates.

Sewage location point.	COND uS/cm2	pH	DRP ug/l	TP ug/l	TS mg/l	SS mg/l	BOD mg/l	COD mg/l
A.Patzcuaro (a)	2960	7.6	2621	4500	1982	192	243	633
B.Patzcuaro (b)	2850	7.4	2926	4337	2105	184	265	576
C.Propemex	3700	6.8	3560	5325	2372	298	452	720
D.Chapultepec	3280	7.2	3120	5874	2230	270	225	475
E.Tzintzuntzan	1850	7.8	2120	4120	1866	170	198	580
F.Quiroga (a)	2540	6.2	2730	4217	1652	182	261	601
G.Quiroga (b)	2720	6.7	2821	4325	1740	196	274	597
H.Erongaricuaro(a)	1870	7.3	1470	3524	1238	150	161	440
I.Erongaricuaro(b)	1990	7.5	1640	3780	1250	182	174	468

conventional water analysis are available, the relatively low pH detected in one of the streams (F) (Quiroga (a)) may indicate the occurrence of strong acids from local artisanal tanneries.

The sewage systems in Tzintzuntzan (E) and Erongaricuaro (H) and (I) are relatively new and the population of these towns is smaller than those in Patzcuaro and Quiroga.

Primary Production.

Table 5.5 shows the results for gross and net primary productivity for the phytoplankton in Lake Patzcuaro based on the dark and light bottle technique. It can be seen that the northern part of the lake has considerably higher rates of primary production than the southern part. Surface values were generally higher than values recorded at 2.0 m depth. The average net primary productivity for surface waters was 492.4 mg C/m2/day in the north, and 255.4 mg C/m2/day in the south. Maximum values of net primary productivity (890.0 mg/C/m2/day) were recorded in the north.

The area occupied by open water is estimated to be 82.9 km2, 30.3 km2 in the north basin, 24.4 km2 in the central section and 28.2 km2 in the south. By using the average values of phytoplankton productivity for each section of the lake, annual primary productivity can be calculated as approximately 5,442 tonnes in the north, 4,381 tonnes in the central section and 2,626 tonnes in the south representing a

Table 5.5. Primary production rates for Lake Patzcuaro during the winter of 1986-1987. GP= Gross primary production; NP= Net primary production. S= Surface; B= Bottom (2.0 m depth).

		NORTH		SOUTH	
TRIAL No.		GP (mg C/m2/day)	NP	GP (mg C/m2/day)	NP
1	S	997.0	856.0	281.0	281.0
	B	93.6	-	515.0	-
2	S	477.0	93.6	608.0	379.0
	B	379.0	192.0	238.0	145.0
3	S	1422.0	192.0	571.0	285.0
	B	1263.0	-	472.0	93.0
4	S	655.0	430.0	515.0	234.0
	B	51.5	-	566.0	285.0
5	S	1872.0	890.0	192.0	98.0
	B	1310.0	-	140.0	-
$\bar{x}$	S	1084.6	492.4	433.5	255.4
	B	619.5	192.0	386.2	174.3

total phytoplankton primary production of 12,450 tonnes of carbon in the open water area of the lake per year (Table 5.6)

Figure 5.3 illustrates the distribution of emergent and submerged macrophytes in Lake Patzcuaro. For computations of areal coverage the lake was considered to be in four sections, north, central, south and islands. Data from Table 5.7 suggest that the northern part of the lake has an approximate area of 10.2 km2 covered by macrophytes, the central part 38.3 km2 and the contribution of the shoreline from islands about 1.1 km2.

The mean slope for the forty-two sampling points and the average macrophyte biomass (MB) as g dry weight/m2 are indicated in Appendix 3. The relationship between slope of the littoral zone and MB is illustrated in Figure 5.4. A power transfromation with an exponent of -0.68 was found to give the best transformation to linearize the relationship. The equation predicting MB from the slope in Lake Patzcuaro was,

$$MB = - 2.0 + 504 \text{ slope}^{-0.68} \qquad (4a)$$

$$R^2 = 0.88, \quad n = 42, \quad F = 311.58, \quad p < 0.0001$$

Tables 5.8 and 5.9 present the results of macrophyte biomass estimates using equation (4a). In contrast to the trends in phytoplankton production, the productivity of macrophytes is mostly located in the south of the lake. The maximum estimated value of primary production was 3,480 tonnes of

Table 5.6. Total net phytoplankton productivity (PP) for Lake Patzcuaro (1986-1987). PP = Primary production; Sect = Section of Lake (North, Central and South).

	MEAN NET PP (mg/m2/day)	AREA (Ha)	TOTAL PP (Tons/Sect/year)
NORTH	492.32	3028.6	5442.30
CENTRAL	492.32	2438.3	4381.38
SOUTH	255.40	2817.2	2626.81
TOTAL		8284.1	12450.49

Table 5.7. Macrophyte coverage for Lake Patzcuaro

	NORTH	CENTRAL (Areas in km2)	SOUTH	ISLANDS	TOTAL
EMERGENT	4.85	2.77	20.61	1.10	28.23
SUBMERGED	5.31	1.85	17.71	-	25.97
TOTAL	10.16	4.62	38.32	1.10	54.20

Figure 5.3

Emergent and submerged macrophyte coverage for Lake Patzcuaro, Michoacan, Mexico, during October 1986 - February 1987.

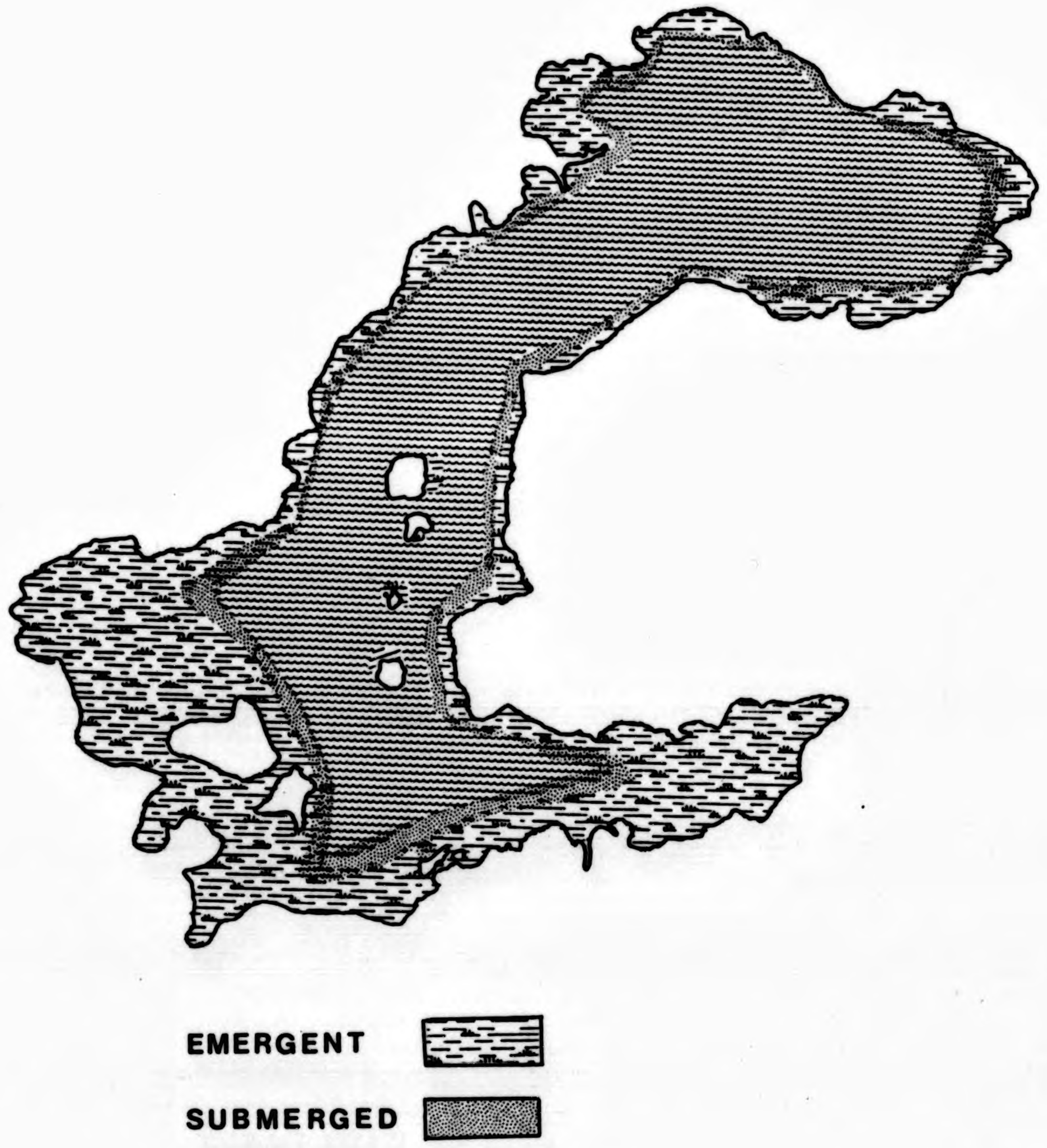


Figure 5.4

The relationship between macrophyte biomass and the slope of the littoral zone for Lake Patzcuaro, Michoacan, Mexico.

$\text{Biomass} = -2.0 + 504\ \text{slope}^{-0.68}$

$R^2 = 0.88,\ P < 0.001,\ n = 42.$

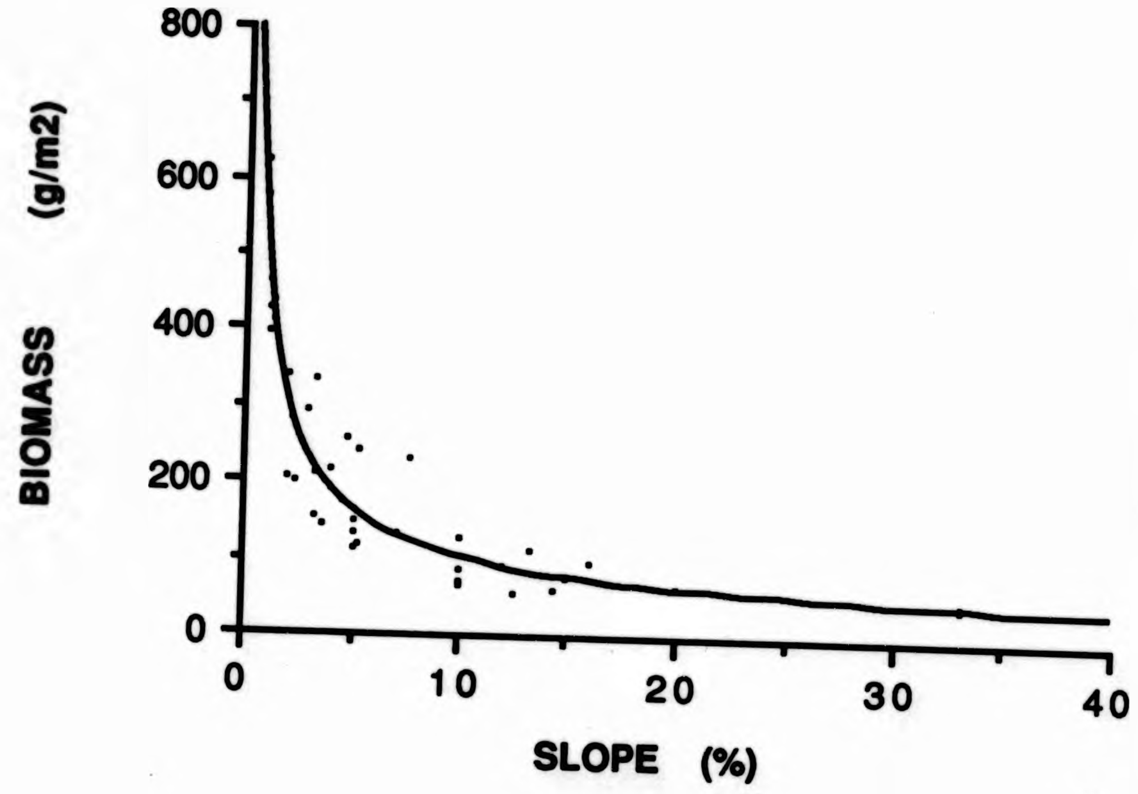


Table 5.8. Slope, area and estimated dry weight of emergent and submerged macrophyte biomass for different locations in Lake Patzcuaro (1986-1987). (N)=North, (C)=Central, and (S)=South.

LOCATION	SLOPE (%)	AREA (km2)	BIOMASS (Tonnes)
EMERGENT MACROPHYTES			
Santa Fe-Ichupio (N)	2.08	2.76	840.4
Ichupio-Ihuatzio (C)	13.60	1.22	102.1
Ihuatzio-Napizaro (S)	2.85	20.61	5059.8
Napizaro-San Andres (C)	6.46	1.55	217.0
San Andres-Santa Fe (N)	3.00	2.09	495.3
Islands	10.00	1.10	113.8
SUBMERGED MACROPHYTES			
North	3.00	5.31	1 258.9
South	2.85	17.71	4 347.3
Central	10.00	1.85	191.5

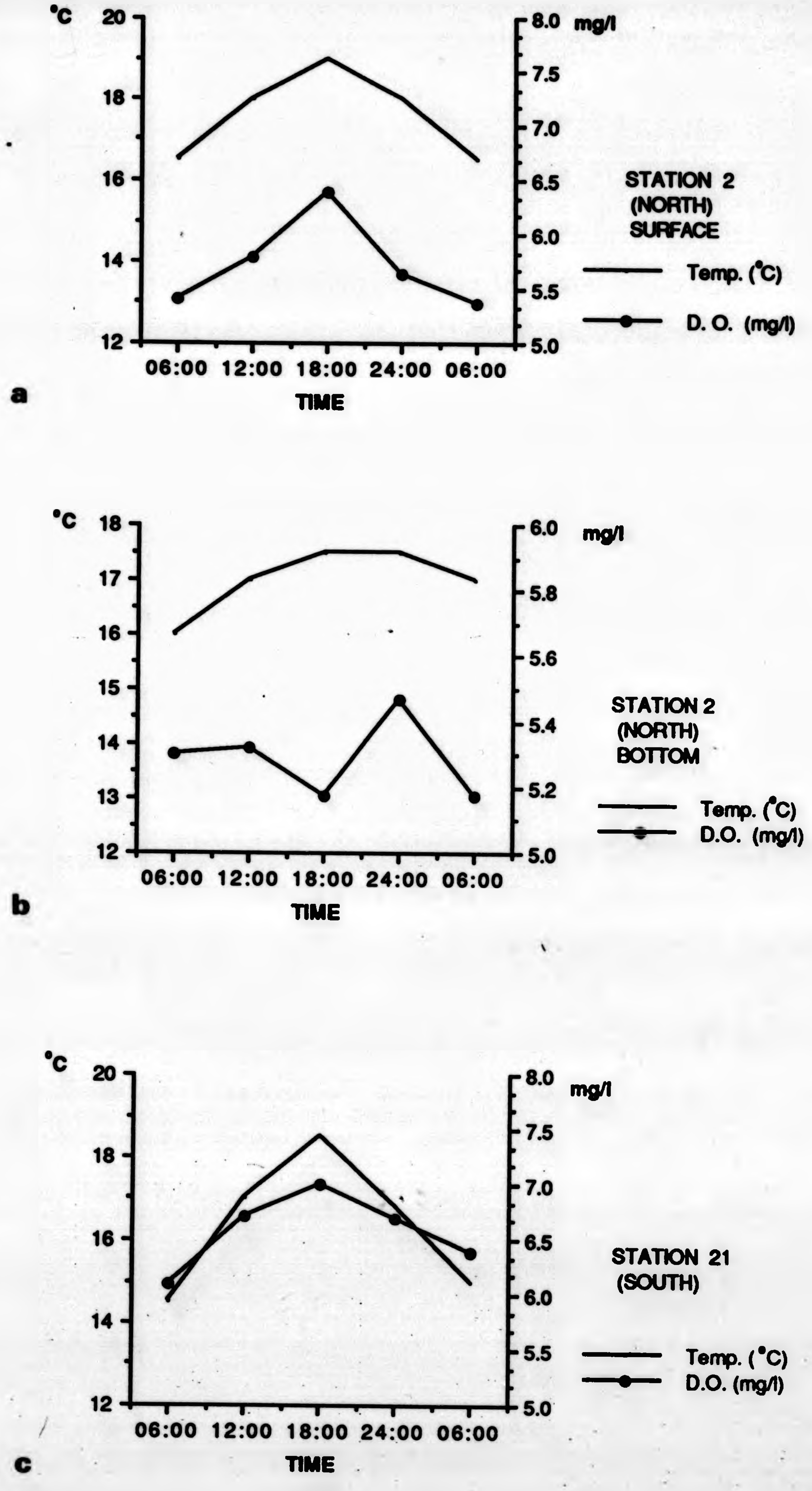
Table 5.9. Estimated dry biomass and primary production as carbon fixed for the main four sections of Lake Patzcuaro PP = Primary Production

	EMERGENT (Tonnes of dry weight)	SUBMERGED (Tonnes of dry weight)	TOTAL	PP (Tonnes of C)
North	1 335.7	1 258.9	2 594.6	960.0
Central	319.1	191.5	510.6	188.9
South	5 059.8	4 347.3	9 407.1	3 480.6
Islands	113.8	-	113.8	42.1
TOTAL	6 828.4	5 797.7	12 626.1	4 671.6

carbon fixed for the southern part of the lake whereas minimum values were estimated for the central section of the lake and the islands (188.9 and 42.1 tonnes respectively). The north was estimated to have a standing crop of about 960 tonnes of carbon fixed. Considering that the lake had a low standing crop because of the winter season the figures are assumed to be the minimum productivity that the lake would attain in one year. Thus, overall, a conservative estimate of total macrophyte productivity of 4,671 tonnes of carbon fixed per year can be made.

In order to illustrate the diel distribution of oxygen concentrations in the lake, data for the 17th January 1987 are represented in Figure 5.5 (a, b and c). As can be observed surface concentrations in both locations followed an increase in dissolved oxygen from dawn to sunset, and a decrease at night. No significant differences were observed between the two locations. However, slightly lower concentrations occured in the north basin (5.3-6.4 mg/l), whereas the south showed higher oxygen levels (6.1-7.0 mg/l). Given the homogeneity of the concentrations in the water column in station 21 (south) data from bottom are not included in Figure 5.5. Bottom concentrations of dissolved oxygen in station 2 (north) followed a different pattern than the surface. Low concentrations (5.17 mg/l) were detected in daytime whereas maximum concentrations were measured at midnight (5.47 mg/l) with further decrease at dawn.

Figure 5.5
Diel cycle for dissolved oxygen and temperature in Lake Patzcuaro, Michoacan, Mexico. a) Station 2 at the surface b) Station 2 at the bottom c) Station 21 at the surface. Date: 17th January 1987.



Discussion.

Using data from De Buen (1941b; 1941e), Herrera (1979) and Laboratorio de Biologia Acuatica of the University of Michoacan (unpublished), it is possible to identify the annual thermal variations in Lake Patzcuaro. In January the temperature at the surface is about 14.5 C with a maximum difference of 2.0 C at the bottom (i.e. 12.5 C). In February the surface temperature starts to rise (17.0 C) and there is less difference with the bottom water temperature (15.8 C) which also is rising. As the warm season continues from March to June maximum water temperatures are registered, 22 C at surface and 20 C at the bottom. This range of temperature remains constant during the rainy season (July, August and September). Temperature falls slowly from October to January with the coldest temperature occuring in the latter month.

A common system to classify freshwater lakes according to temperature is that proposed by Forel (1895) and modified by Whipple (1898). The system divides lakes into three types, according to their surface temperatures, and into three orders according to their bottom temperatures resulting in nine classes of freshwater types; polar, temperate and tropical designated with first, second and third order. Lake Patzcuaro was classified by De Buen (1941b) as a tropical lake of third order because its surface temperature is never below the maximum water density point (i.e. 4 C) and its bottom temperature is very close to that at the surface, resulting in complete water mixing from surface to bottom throughout the year. Using the revised classification of lakes based on mixing proposed by Lewis (1983) Lake Patzcuaro is considered a continuous warm polymictic type.

In order to compare possible changes from previous years, optical parameters for Lake Patzcuaro were calculated from raw data taken by Mexican authorities in May 1982 (Table 5.10). Although these values of optical properties suggest that the lake was less turbid in 1982, this higher transparency can be attributed to the season. May is the end of the dry season and the effects from the catchment area (runoff, sewage, wind and dust clouds) are more limited. In 1987, maximum values of vertical attenuation coefficient (Kd) increased by 67% over those reported for 1982, whereas maximum values of beam attenuation coefficient (c) in 1987 were 34% higher than in 1982. Previous reports on secchi disc measurements (Table 5.11), show generally higher transparencies in Lake Patzcuaro apparently decreasing with time (Figure 5.6). It is evident that today Lake Patzcuaro has very high turbidities in most parts of the water body, which cannot be attributed to a seasonal process. De Buen (1943a) reported transparencies for Lake Zirahuen of about 7.0 m which do not differ greatly with those reported in the present study (6.5 m).

Secchi disc transparency has been frequently interpreted as a direct measure of water transparency assuming that a constant relationship exists between secchi depth (Zd) and vertical attenuation coefficient (Kd) based on Lambert-Beer's Law (Poole and Atkins, 1929; Carlson, 1977; Lorenzen,

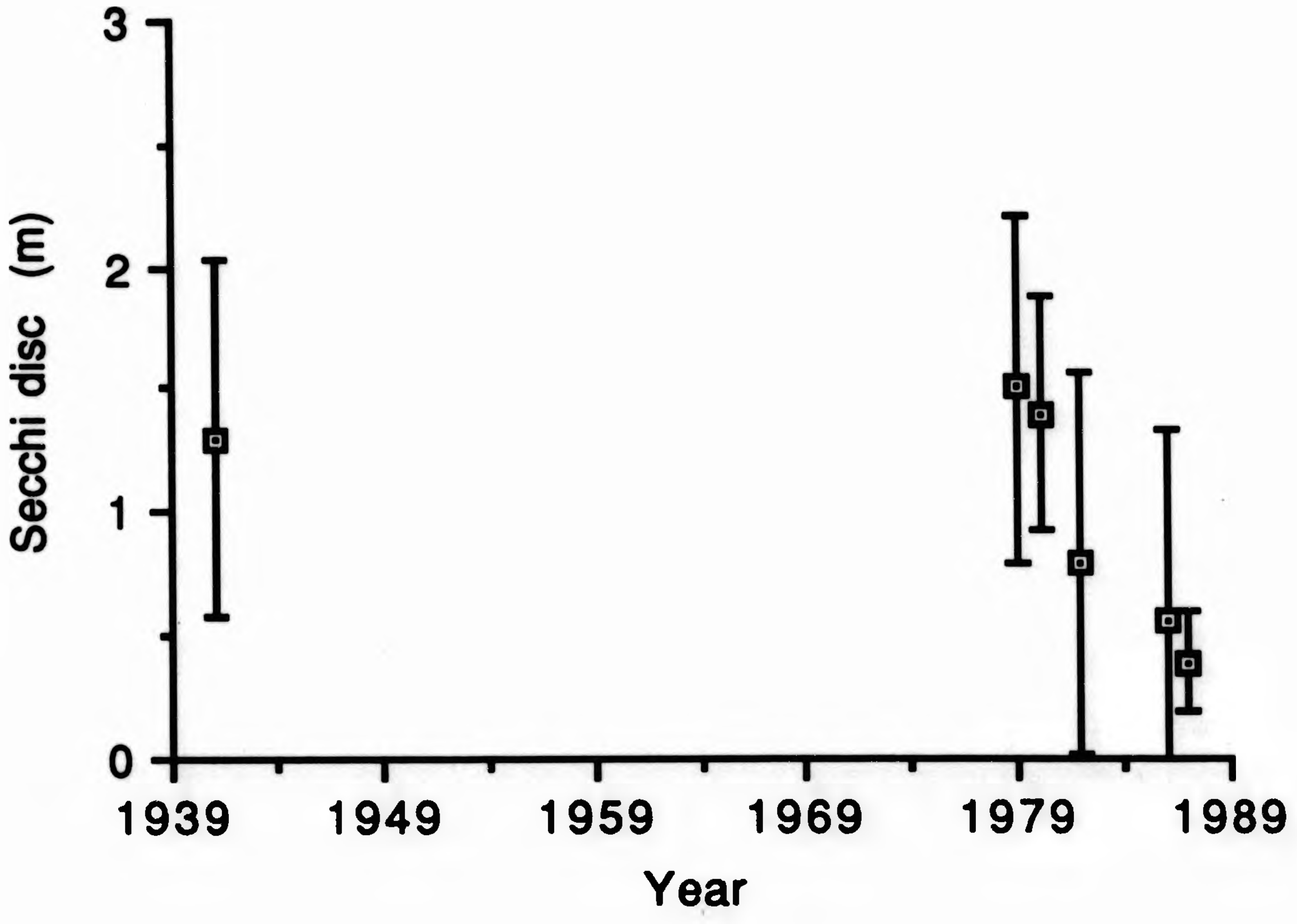
Table 5.10. Calculated optical parameters for Lake Patzcuaro for May 1982. (Raw data on light taken from Delegacion Federal de Pesca-Secretaria de Fomento Rural del Estado de Michoacan, 1982, internal report).

Location No.	Zsd (m)	Kd (m)	Eu (m)	c (m)	Kd + c (m)	Ratio Eu/Zd
1	0.90	1.23	2.85	7.45	8.68	3.1
2	1.00	1.20	2.92	6.38	7.58	2.9
3	0.98	1.22	2.81	6.43	7.65	2.8
4	0.94	1.30	2.67	7.01	8.31	2.9
5	0.92	1.20	3.11	6.20	7.40	3.4

Table 5.11. Secchi disc readings reported from previous limnological surveys in Lake Patzcuaro.

Reference	Secchi disc range (m)
Yamashita (1939)	2.40 - 2.20
De Buen (1941b)	1.67 - 0.94
Herrera (1979)	1.85 - 1.15
Tellez y Motte (1980)	1.64 - 1.16
Velasco (1982)	1.18 - 0.41
Perez (1986)	0.95 - 0.19
Present project (1987)	0.50 - 0.29

Figure 5.6
Variations of secchi disk transparency in Lake Patzcuaro, Michoacan, Mexico. Data from previous studies. Squares indicate the mean value of data reported. Lines represent the range values.

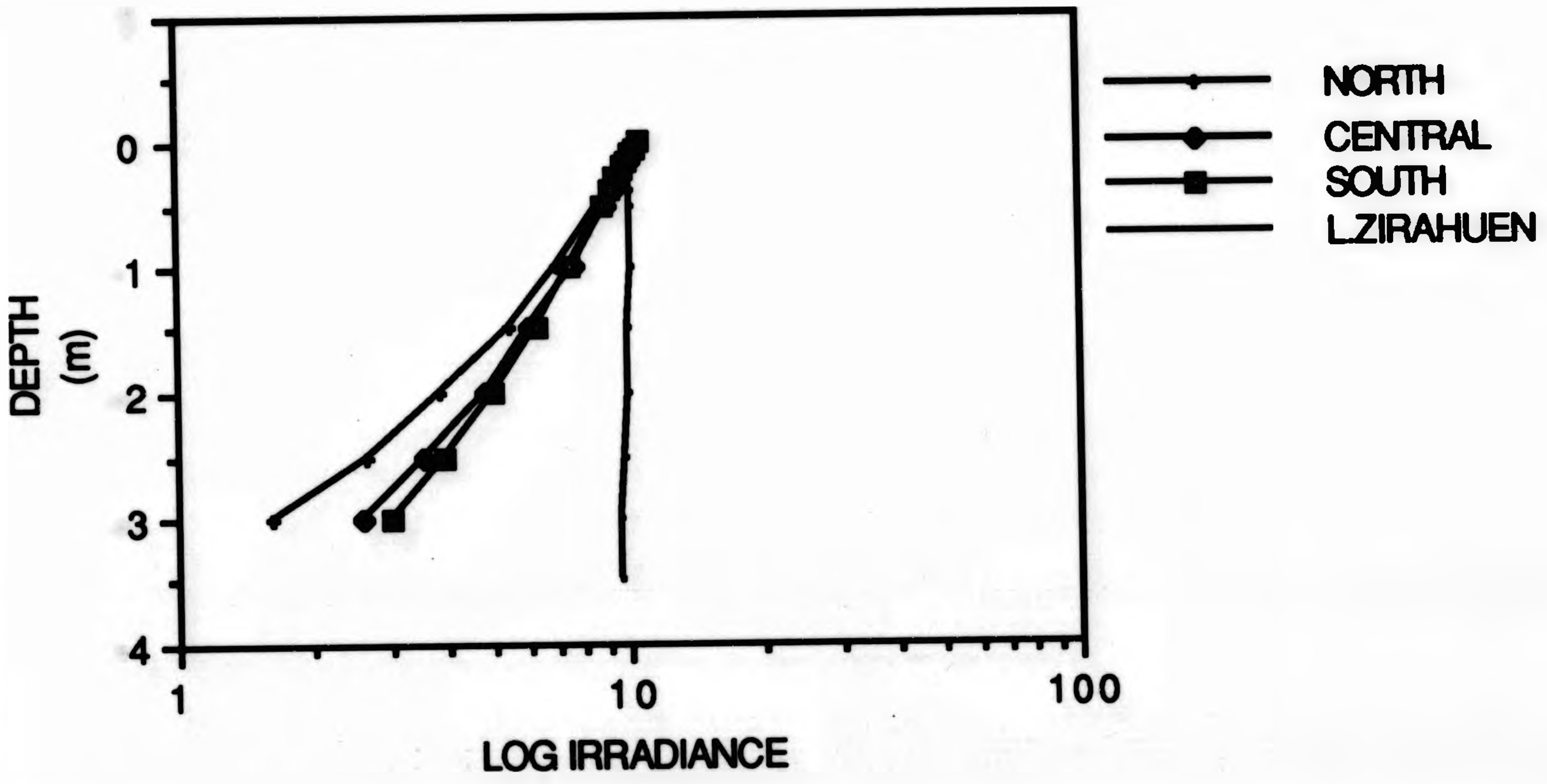


1980; Megard <u>et al</u> 1980). This relationship has been expressed as Zd=R/Kd, where R is a .pa constant in a narrow range between 1.44 and 1.70 (Poole and Atkins, 1929; Holmes, 1970; Walker, 1982). From this relationship the depth of the euphotic zone can be derived by Eu=ln(100)/Kd. Ratios of Eu/Zd have been suggested for use in primary production modelling, which range between 2.7 and 3.2 (Tilzer, 1988) for most temperate lakes. Similar values were obtained for Lake Zirahuen (2.62) showing a reasonable agreement with this assumption. This criterion has been successfully applied in clear lakes where light attentuation is mainly associated with seasonal fluctuations of phytoplankton concentrations. However, in Lake Patzcuaro higher values of Kd and c differ significantly from those of Lake Zirahuen and hence ratios between Eu and Ezd do not agree with those for clear lakes. Figure 5.7 illustrates the profile of light attenuation for the three main sections of Lake Patzcuaro and Lake Zirahuen. As can be observed the line representing Lake Zirahuen indicates low values of light attenuation for a large water column whereas the lines for Lake Patzcuaro indicate that very high sunlight attenuation occurs in a small water column. The distribution of light attenuation in Lake Patzcuaro can also be observed in Figure 5.7. A profile from high light attenuation values was found in the north basin decreasing towards the south basin with intermediate values in the central section of the lake.

According to Jerlov (1976) and Kirk (1983), scattering under clear water conditions is minimal and beam attenuation only exceeds vertical light attenuation by a relatively small

Figure 5.7

Depth profiles for downward irradiance in Lakes Patzcuaro (North, Central and South) and Zirahuen, Michoacan, Mexico. Log irradiance is the natural logarithm of light intensity at different depths.



amount. However, particles which occur in natural waters will determine the magnitude of the scattering effect. Scattering does not remove light by itself but interferes with the vertical penetration of light. This increases the pathlength which the photons have to cross in a certain depth. Thus the effect of scattering is to intensify the vertical attenuation of light. This effect is dominated by particle size and it increases with the concentration of particulate matter.

Given the present condition of the catchment area of Lake Patzcuaro (Gomez-Tagle, in preparation), it is clear that heavy allocthonous sediment loads from the continuous erosion process in the region (Plate 5.2 a and b), contribute significant amounts of silt and inorganic particulate matter thus increasing the vertical attenuation of light in the lake. This reduction of light in the water column will directly decrease the diversity and distribution of phytoplankton in the water column and thus optical estimations of the euphotic zone and predictions of primary productivity using the secchi disc can be misleading.

The relatively lower Kd values (mean 1.23 m) obtained in 1982, suggest low vertical light attenuation by phytoplankton, but high beam attenuation coefficients (mean 6.69) indicate scattering effects by inorganic materials.

Low photosynthetic activity can be explained on the assumption that May is not a month with particularily high phytoplankton growth in Lake Patzcuaro. But, in the case of

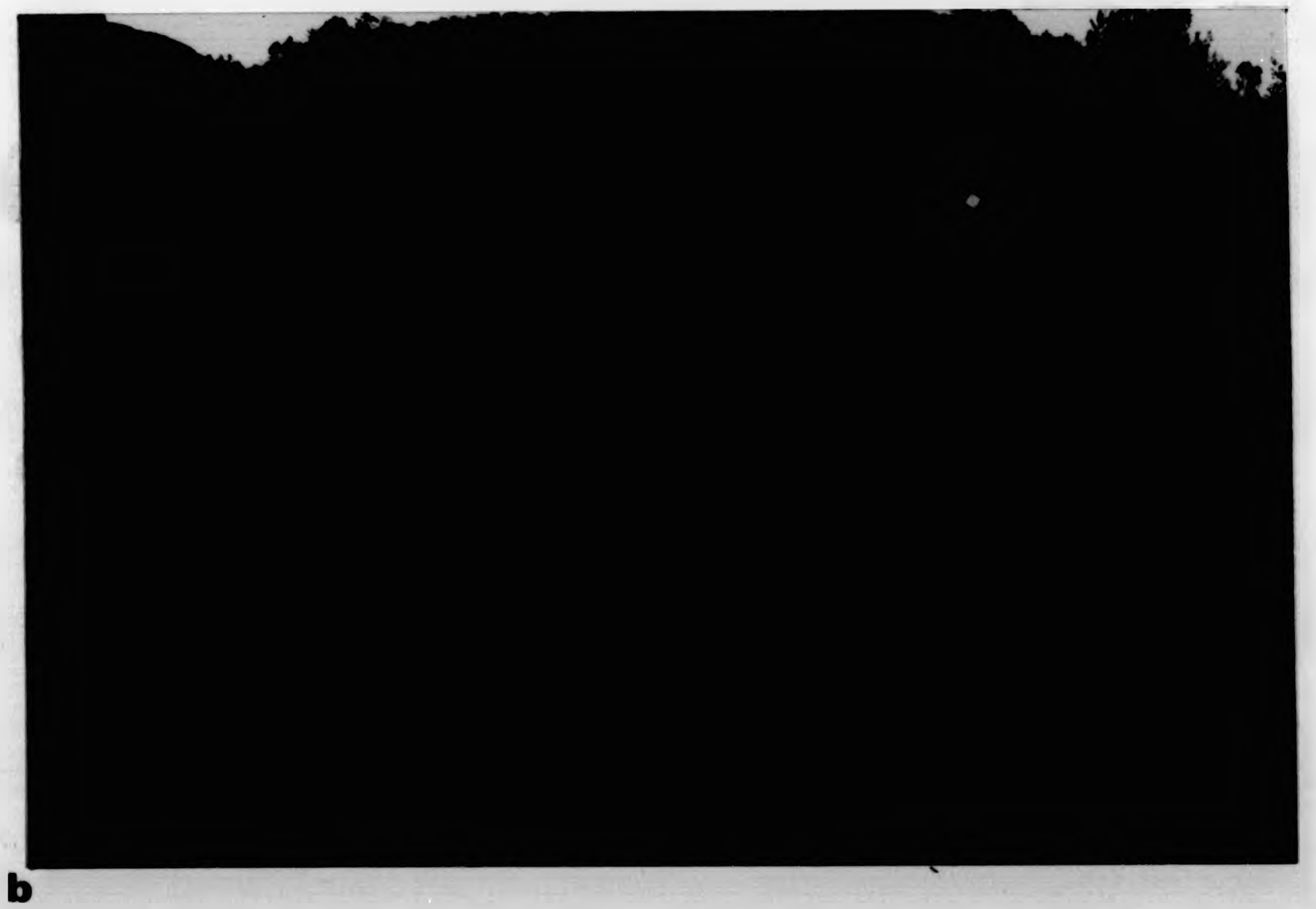
Plate 5.2

The erosion process of the drainage area in Lake Patzcuaro, Michoacan, Mexico (1986-1987).

a) Tzurumutaro - Patzcuaro transect,

b) Sanabria - Tzintzuntzan transect.

a



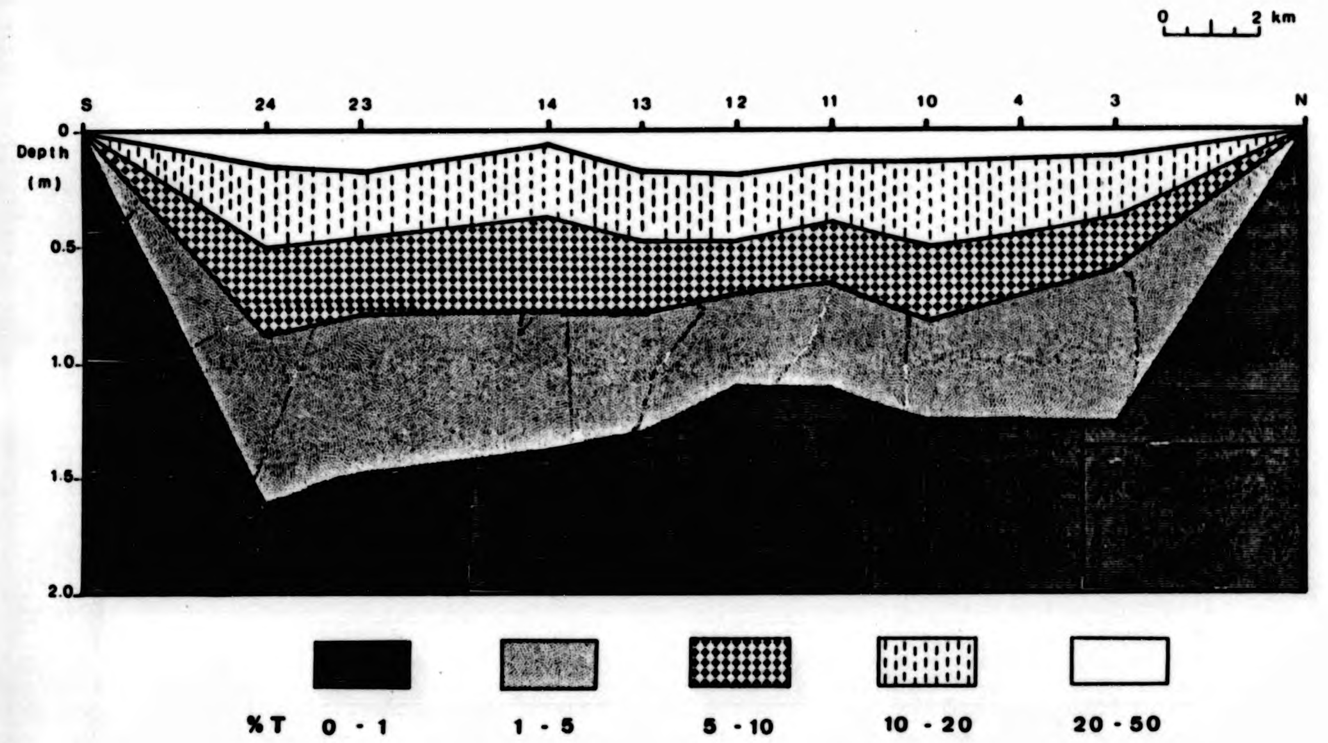
b

high beam attenuation coefficients, it is possible that fine clay particles can remain for long periods in suspension (Kirk, 1983). Furthermore, the profile of decreasing beam transmission illustrated in Figure 5.8, clearly shows a gradient of sedimentation levels which could depend on particle size and hence be responsible for lower light transmission in relation to depth. The higher values of Kd in winter 1986 suggest high concentrations of both algae and inorganic suspended material. Although light measurements were made in middle winter when runoff and sediment transport from the catchment area are very low, observed values of beam attenuation coefficient suggest the influence of the continuous high sediment loads. This effect can be explained by possible long residence times for small suspended particles and the establishment of a sedimentation profile through the water column. This can be observed by the decreasing light transmission with depth in most of the lake.

The occurrence of high concentrations of inorganic materials in the water affects the phytoplankton diversity due to light limitation (Kirk, 1985). This reduction of light in combination with other ecological parameters such as nutrients and temperature can give competitive advantages to single-species of phytoplankton populations. Values for ratios Eu/Zsd ranged from 4.77 to 3.42 which do not agree with those quoted by Tilzer (1988). Vollenweider (1969), placed a limit of visibility of secchi disc at about 15% of the surface intensity with possible variations due to local conditions and observer deviations.

Figure 5.8

Horizontal and vertical distribution of beam transmission light in Lake Patzcuaro, Michoacan, Mexico. Light transmission is given as the percentage of light transmitted at a standard pathlength of 0.40 m.



Lake Zirahuen and Lake Cuitzeo.

Water quality data for Lake Zirahuen and Lake Cuitzeo are presented in Table 5.12. As can be observed physical and chemical characteristics are very different from each other.

Lake Zirahuen with an estimated area of 7 km2 is a deep (mean depth 18.0 m) clear lake with low concentrations of dissolved nutrients and suspended matter. Its lower pH (8.10) and alkalinity (70.0 mg/l) indicates that inorganic carbon compounds are different from those of Lakes Patzcuaro and Cuitzeo. This is also shown by the lack of carbonates and the existance of dissolved carbon dioxide (6.16 mg/l). Total hardness was very low (24.18 mg/l), and as at Patzcuaro and Cuitzeo most of the water hardness apparently is due to magnesium rather than calcium. However, magnesium concentrations were the highest within the ion distribution. Thus ranking of microelements observed were Mg > Na > K > Ca > Fe.

Dissolved oxygen levels in Lake Zirahuen were always near saturation (93.0%) and given the low values of chlorophyll-a (3.77 ug/l) and the small size of macrophyte communities in the littoral zone, it is expected that the major contribution of dissolved oxygen originates from wind and wave action rather than photosynthetic activity.

Table 5.12. Physical and chemical characteristics of Lake Zirahuen, Lake Patzcuaro and Lake Cuitzeo.

		Lake Zirahuen	Lake Patzcuaro	Lake Cuitzeo
P	(mm Hg)	580.0	605.0	620.0
Z	(m)	18.0	4.9	0.26 +
T	(C)	15.0	16.3	18.0
Zd	(m)	6.50	0.40	0.03
COND	(uS/cm)	75.0	820.0	6595.0
pH		8.1	9.3	10.4
CO2	(mg/l)	6.1	0.0	0.0
ALK	(mg/l)	70.0	390.7	750.0
CO3	(mg/l)	0.0	118.6	240.0
HCO3	(mg/l)	63.8	272.1	510.0
HARD	(mg/l)	24.18	125.26	202.12
DO	(mg/l)	7.30	7.10	1.82
%SAT		93.0	92.0	23.7
DRP	(ug/l)	5.39	39.17	867.60
TP	(ug/l)	8.69	64.36	938.10
CHL	(ug/l)	3.77	59.75	T. I.*
TS	(mg/l)	14.0	593.6	4216.0
SS	(mg/l)	0.8	21.1	624.0
TDS	(mg/l)	13.2	572.4	3592.0
BOD	(mg/l)	1.55	10.77	230.0
COD	(mg/l)	2.3	42.5	782.0
NO3	(mg/l)	0.015	0.012	0.26
NO2	(mg/l)	0.006	0.018	0.29
AMM	(mg/l)	0.028	0.022	0.38
Na	(mg/l)	2.38	63.65	165.5
K	(mg/l)	1.84	17.60	45.8

Fe	(mg/l)	0.74	0.78	-
Ca	(mg/l)	1.77	13.77	22.2
Mg	(mg/l)	4.80	22.07	35.5

\+ Cortez _et_ _al_ (1980)

T.I * Interferences caused by high turbidity.

The major tributary into the lake is the small stream La Palma which consists mainly of water from the regional runoff. Deforestation of the watershed is increasing and some effects of the erosion processes on the water transparency during the rainy season have been reported (Laboratorio de Biologia Acuatica, UMSNH, personal comunication).

Lake Cuitzeo is a relatively large (420 km2) and very shallow lake (mean depth 0.26 m). The lake is very turbid with a progressive loss of depth. This is mainly due to the high siltation rates and the permanent imbalance between rainfall and evaporation (Alvarado <u>et al</u>, 1985). The lake recieves raw sewage from 3,675 km2 of agricultural watershed and from the city of Morelia with an estimated half a million population.

Given the accelerated processes of deterioration of Lake Cuitzeo, values for most of its physical and chemical characteristics are very extreme. This is reflected by very high conductivity, alkalinity, pH, solids, organic matter and nutrients. Similarly, extremely low values for dissolved oxygen, transparency and chlorophyll-a were observed during the period of study. The distribution of microelement concentration is mainly dominated by sodium, giving a rank order of Na > K > Mg > Ca.

Continuous mixing processes take place in the lake and most of the inorganic chemical components of the water in Lake Patzcuaro exhibit an even horizontal distribution. This is demonstrated by homogeneous values of pH, conductivity, alkalinity and total dissolved solids.

Chemical characteristics of the water also reflect the geological and edaphic nature of the basin. Soils located around the catchment area are basically derived from volcanic ash, magma and basic lavas rich in olivine $[(Mg, Fe)_2 SiO_4]$, andesite $[(Na Al Si_3 O_8) + (CaAl_2 Si_2 O_8)]$ and pyroxene. These materials are mostly alkaline-ferromagensian minerals and susceptible to weathering (Mohr <u>et al</u>, 1972). Relatively young soils originating from volcanic products are characterised by high humus accumulation, high suceptibility to erosion processes and partial leaching of bases. Thus, dissolution of these solid materials from the drainage area appears to have an important effect on ion concentrations in the water.

Given the relatively high pH and alkalinity of the lake, it can be considered mainly as alkaline type with its inorganic carbon components dominated by bicarbonates and carbonates. In general, pH values were found to be similar in most locations, however the lowest value (pH=8.8) was observed in the north basin (Figure 5.2). Although this value does not differ greatly from the estimated mean value, it may be the result of night time respiratory processess and the possible influence of acid pollution recieved from the nearby sewage discharges from Quiroga town.

Higher concentrations of Na and Mg over K and Ca can be attributed to the olivine basalts in the basin which act as a probable source of these two cations. However, the amounts of dissolved solutes carried into the basin by the Chapultepec channel could also represent a great contribution to ion concentration.

Although conductivity values showed no significant differences in the lake, the relatively high values of both conductivity and total dissolved solids suggest that general runoff from the drainage area in combination with evaporative processes could be responsible for the high ion concentrations in the water.

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The horizontal distribution of chlorophyll-a and suspended solids is perhaps most evident in Lake Patzcuaro. Figure 5.2 clearly indicates that maximum concentrations were located in the north basin whereas the lower concentrations were common in the south. Although chlorophyll-a and suspended solids have been rarely mapped in Lake Patzcuaro this pattern of horizontal distribution does not agree with previous results (Velasco, 1982). Figures 5.9 and 5.10 illustrate the horizontal distribution of chlorophyll-a and suspended solids during the winter of 1986-1987. By mapping the values for the twenty four sampling stations it is possible to identify the general pattern of distribution for these two water quality parameters. Although the maps do not provide high levels of accuracy it is possible to visualise the areas with maximum and minimum concentrations. If more detailed mapping is required then the number of sampling stations would need to be increased or the use of different detection techniques considered. Figures 5.9 and 5.10 show the existence of gradients of minimum concentrations in the south increasing towards the north basin. Mean values of chlorophyll-a for Lake Patzcuaro are particularly high given that the lake was sampled during the winter season when lower values of chlorophyll-a are expected.

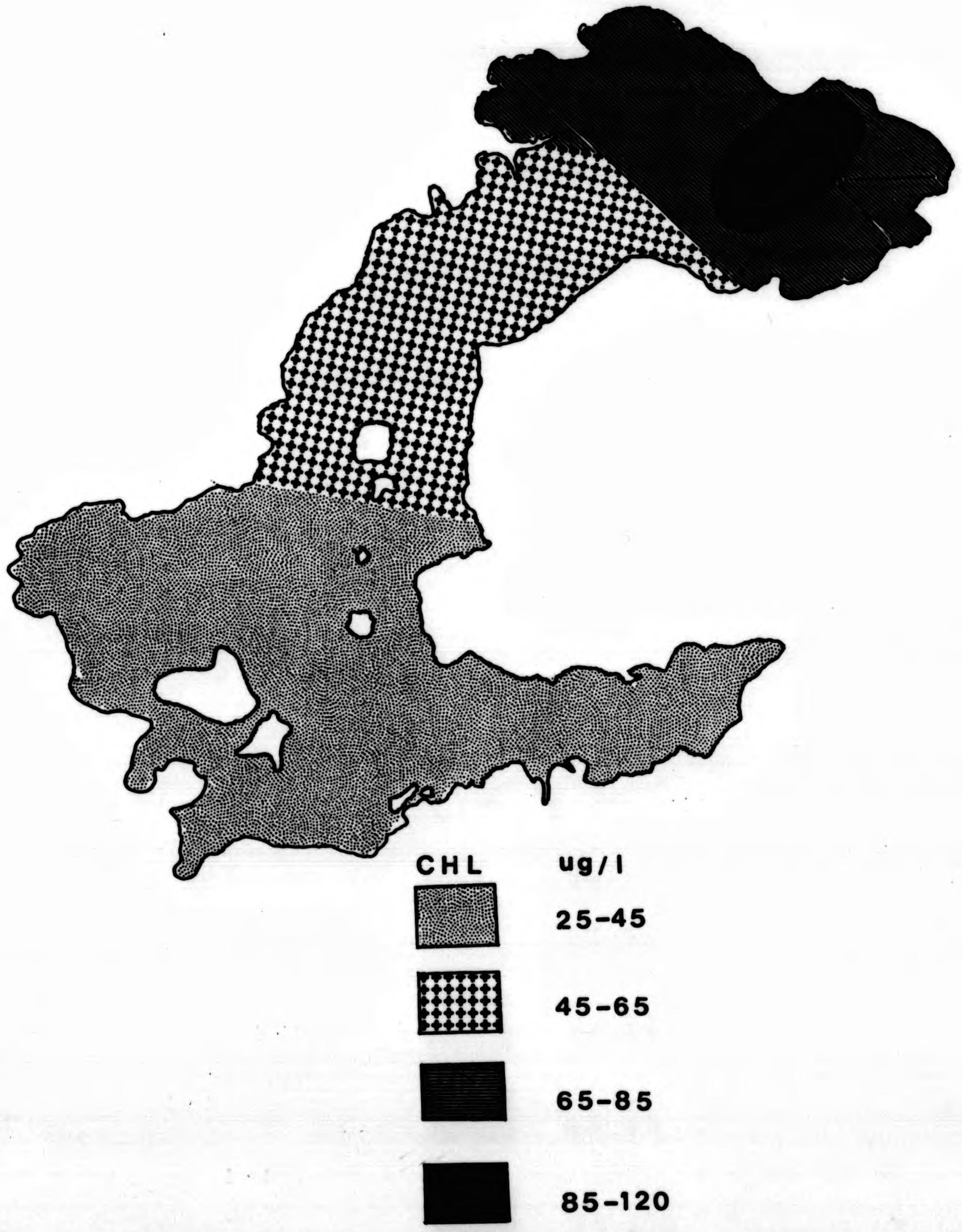
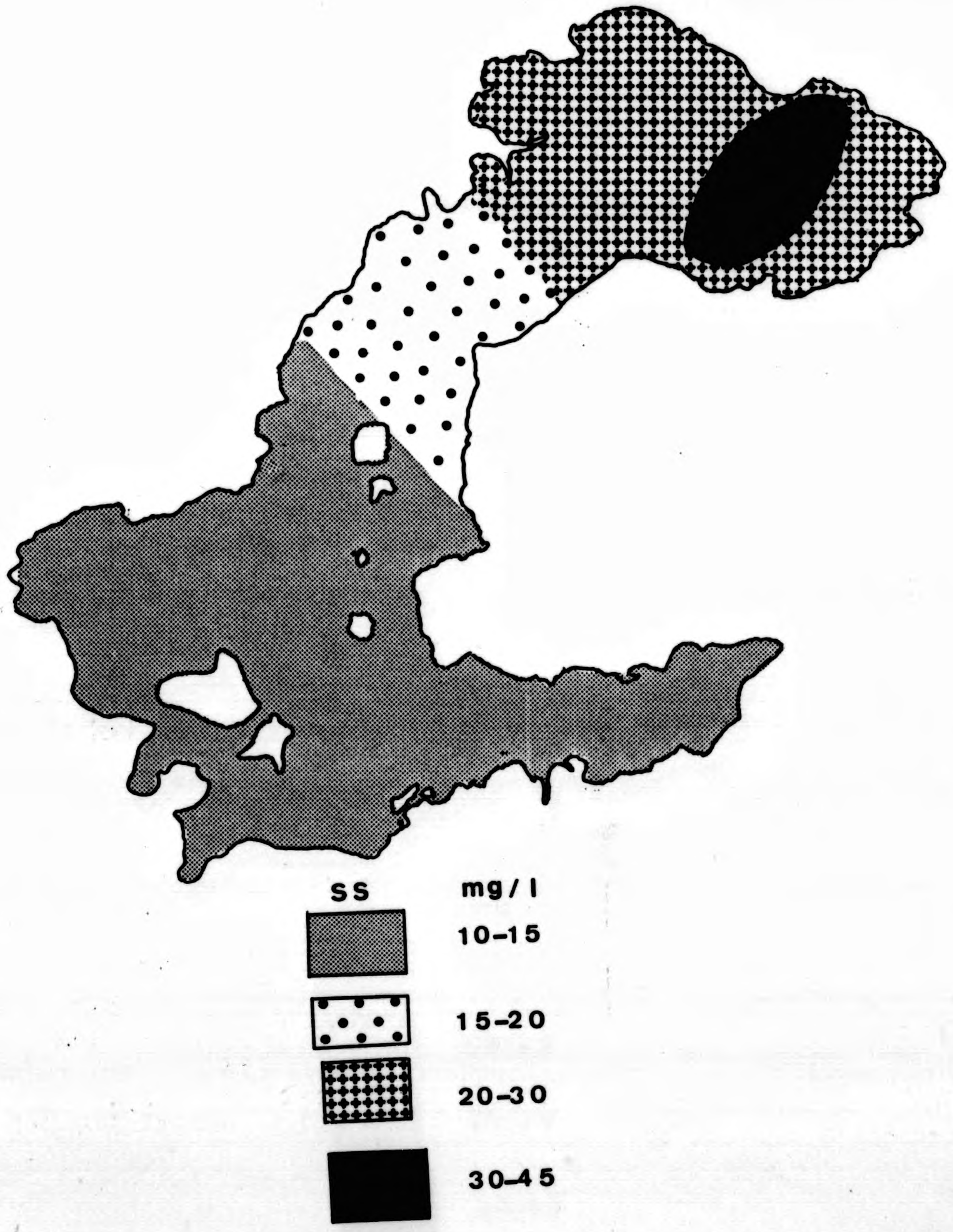


Figure 5.9

Horizontal distribution of chlorophyll-a in Lake Patzcuaro, Michoacan, Mexico. The map is derived from the mean value of 120 samples per station.

Figure 5.10

Horizontal distribution of suspended solids in Lake Patzcuaro, Michoacan, Mexico. The map is derived from the mean value of 120 samples per station.



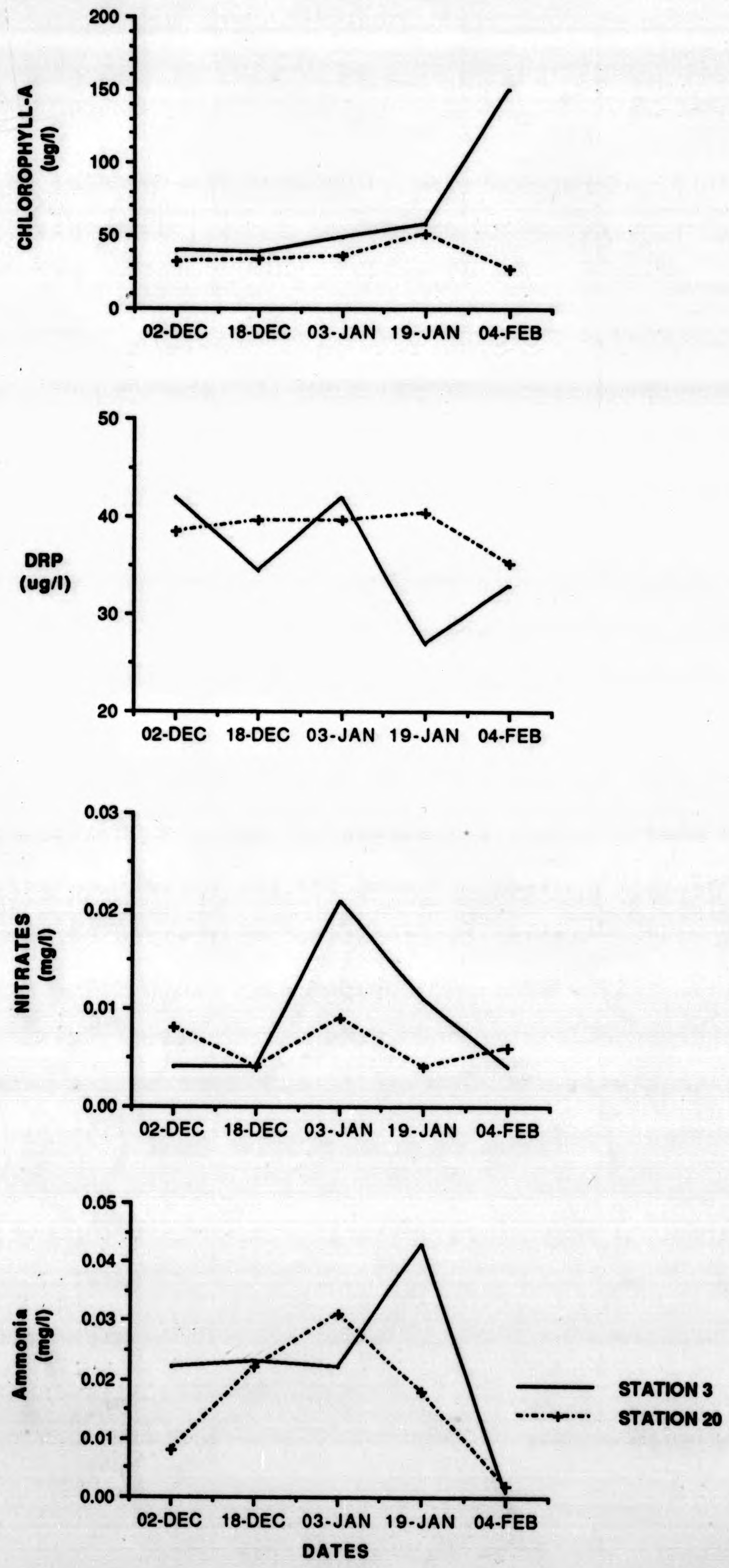
A similar pattern was observed with total phosphorus. Maximum concentrations were always associated with high values of chlorophyll-a and suspended solids. However, values of dissolved reactive phosphorus did not follow the above distribution. Although the range of concentrations was very small, higher values were represented in the south. The large macrophyte communities of the south basin should represent an efficient nutrient filtration unit in the system, but given that some sewage discharges are directly loaded into the lake in areas with low macrophyte density (Propemex and Patzcuaro town), higher values of dissolved reactive phosphorus can be expected. The low values detected in the north may be the result of continuous nutrient utilization by phytoplankton. Given the relatively high values of phosphorus in the lake as compared with other reports (OECD, 1982; Henderson-Sellers and Markland, 1987) it is likely that phosphorus in Lake Patzcuaro is not the limiting factor for phytoplankton growth. However, the role of phosphorus in the lake cannot be defined without longer periods of sampling over at least an entire year.

By contrast, most of inorganic nitrogen compounds (NH4, NO2 and NO3), were particulary low for most locations in the lake. These low levels of dissolved inorganic nitrogen suggest that both nitrates and ammonia are efficiently utilized by algae. Hence, it is possible that nitrogen represents a limiting nutrient in Lake Patzcuaro for phytoplankton growth.

High levels of chlorophyll-a detected in late winter could be explained by assuming that early phytoplankton populations can be stimulated just before the spring when solar irradiance, nutrients and temperature are not limiting. Moreover, February is the month with strongest winds which could increase water mixing and resuspension giving environmental advantages to phytoplankters. In order to visualise possible changes of water quality during the winter in Lake Patzcuaro time series plots are presented (Figure 5.11 a, b, c and d) for stations 3 and 20 located in the north and south respectively using CHL, DRP, NO3 and NH4 as indicators. As can be observed the availability of phosphorus in the north basin was relatively high by the end of autumn, increased further by early winter whilst relatively low values of chlorophyll-a remained, and then decreased by late winter corresponding to maximum levels of chlorophyll-a. Nitrogen concentrations were very low throughout the season particularly in the case of nitrates. However, it can be observed that low levels of nitrates correspond to higher levels of ammonium and viceversa. This may be interpreted as an indication of the continuous nitrification process in the lake. By contrast, the south basin did not show significant variations of nutrient concentration with time and lower levels of chlorophyll-a were observed associated with low levels of nitrates.

Although, volumes of sewage discharges in the south are higher than those located in the north the effects of wastewater in the lake were more evident in the north basin.

Figure 5.11
Temporal variations of chlorophyll-a, dissolved reactive phosphorus, nitrates and ammonia in two locations of Lake Patzcuaro, Michoacan, Mexico. Station 3 is located in the northern basin, whereas Station 20 is located in the southern basin.



Values of dissolved organic matter in the north were frequently higher than those recorded in the south. This horizontal distribution may be the result of organic matter accumulation in the north induced by water movements in the lake. An estimated volume of 28,429 m3 per day of raw wastewater is discharged into the lake from nine sewage outfalls. However the total volume of organic matter is likely to be higher if non-point sources are considered, particularly in the case of agricultural and suburban runoff.

Other lakes in the region contrast sharply when compared with Lake Patzcuaro. Lake Zirahuen represents an exceptional example of clear and deep water for the region. The lake is the deepest (maximum depth 38 m) water body of the central plateau. Although thermal stratification was not detected during the period of study it is possible that the lake may develop a thermocline during the summer. Water transparency was very high. Deforestation however, is increasing and siltation is becoming more evident in progressive rainy seasons. Oxygen levels were always near saturation both at the surface and bottom. Due to the low concentrations of dissolved organic matter, phosphorus and nitrogen compounds in the water, the effects of the catchment area deterioration on Lake Zirahuen are not clear yet. However, given the depth of the lake, it is likely that the system has a considerable storage capacity for nutrients. The occurrence of iron in the form of Fe III hydroxides and oxides under oxygenated conditions adsorb and precipitate phosphate in the sediments layer (Moss, 1980). This oxidized state prevents the dissolution of phosphates into the water column. However, if anaerobic conditions are present near the bottom of the lake then by redox potential change Fe III is transformed into Fe II and phosphates are integrated into the water. In Lake Zirahuen, high levels of dissolved oxygen were always detected near the bottom, thus the sediments remain as efficient traps for phosphate. However, given the endorheic conditions of the basin, increasing phosphorus accumulations may develop as the watershed deteriorates. Should anaerobic conditions arise in the hypolimnion of Lake Zirahuen, then large quantities of phosphates may be released into the water with consequent changes in phytoplankton and water quality.

Lake Cuitzeo by contrast, is an obvious example of rapid lake degeneration caused by anthropogenic activities. The lake is very shallow due to the permanent imbalance between rainfall and evaporation and watershed deforestation. Water circulation is minimal and sediments are periodically resuspended by wind action. External nutrient loading is extreme and enters the lake from both municipal and agricultural sources. Water quality deterioration is evident by observing the extreme values of total dissolved solids, pH, alkalinity and conductivity indicating the increasing salination of the lake. High values of phosphorus and dissolved organic matter are constantly integrated into the water column by high pH values, wind action and sediment resuspension.

Dissolved oxygen levels are very low and anoxic periods have been reported to be frequent throughout the year (Alvarado et al, 1985) indicating the dominance of polysaprobic conditions, where processes of respiration are higher than processes of productivity (Sladecek, 1979). This ecological instability in Lake Cuitzeo has resulted in dense phytoplankton blooms and massive fish mortalities during the present decade (Alvarado et al, 1985).

Water quality characteristics in Lake Patzcuaro suggest that the lake shows more physico-chemical similaraties with Lake Cuitzeo rather than Lake Zirahuen. Although, dramatic lake deterioration is not the case in Lake Patzcuaro, the increase of turbidity, nutrient levels and chlorophyll-a as compared to previous studies (De Buen, 1944c; Tellez and Motte, 1980; Velasco, 1982) clearly demonstrates a progressive water quality enrichment caused by anthropogenic activities.

From this limited assessment of primary productivity in Lake Patzcuaro it is difficult to compare the results obtained with data from previous studies in order to observe possible temporal changes. Although observations were made during the winter of 1986-1987 only at two locations at opposite ends of the lake, the results suggest that primary production was highest in the northern basin lower in the southern basin. This profile is clearly associated with the chlorophyll-a distribution. This pattern of distribution is probably the result of continuous phytoplankton accumulation in the northern end of the lake by wind and surface currents. The vertical distribution of photosynthesis clearly showed the effect of the euphotic zone and light limitations. Although gross production was present at 2.0 m of depth, net production was negligible. From underwater light measurements (Table 5.2 and Appendix 1), the theoretical depth of the euphotic zone at station 2 was approximately 1.55 m. This suggests that an effective compensation point was established between 1.55-2.0 m depth. Results from the south basin (station 21) showed slightly higher rates of photosynthesis at 2.0 m depth corroborating the deeper 1.66 estimate of the euphotic zone (Table 5.2).

By contrast, macrophyte productivity in Lake Patzcuaro is mostly concentrated in the southern part of the lake. It was estimated that about 64.53% of the southern basin is covered by emergent and sumerged macrophytes. The distribution and density of macrophytes is strongly correlated with the slope of the littoral zone. This relationship was initially suggested by Margalef (1984) and subsequently quantified by Duarte and Kalff (1986) for other geographical locations. The results suggested that variations in slope could be a useful predictor for macrophyte modelling. In Lake Patzcuaro high densities of macrophytes were observed in areas with very gentle slopes such as marginal areas of the southern basin. By contrast, macrophyte biomass decreased in the central section of the lake where nearshore slope was steep.

Although the slope of the littoral zone was a good predictor to explain the distribution of macrophytes, there may be other ecological factors which were not considered in the analysis. For example, it was observed that gentle slopes were also associated with areas well-protected from winds and waves, better underwater light conditions and steady sediment deposition.

Results from diel oxygen measurements showed significant fluctuations in the level of dissolved oxygen although the minimum was not extreme. This is probably because of the equal horizontal distribution of photosynthetic organisms and the continuous vertical mixing processes. The deep waters of the northern basin are primarily represented by phytoplankton communities which are the major contribution to the primary productivity, whereas macrophyte communities have more predominance in the shallow waters of the southern basin. The fluctuations of oxygen levels in the bottom of northern basin can be explained by the location of the euphotic zone. In station 2 (north) the water column is approximately 12.0 m in depth with maximum euphotic depth of 2.0 m. This indicates that approximately 83% of the water column is light limited. However, as wind action generates water mixing by middle afternoon, this would result in higher oxygen levels in deeper parts later at night. Although this pattern of vertical oxygenation was distinctive during the period of study seasonal changes could establish a different bottom oxygen profile.

Given that the sampling period was restricted to a period of six months, levels of primary productivity observed almost certainly do not represent the annual productivity of Lake Patzcuaro. Nutrient levels are likely to be increased by rainfall and erosion loads and by concentration during the dry season. Temperature does follow a seasonal pattern which may affect species composition and biomass and in the case of Lake Patzcuaro would increase the biomass during the spring and summer rather than decrease it. From the above, it is probably reasonable to assume that data obtained during the winter of 1986-1987 represent the minimum productivity of the lake in one year. Therefore, the phytoplankton productivity in the lake is estimated to be an average of 179.6 g C/m2 per year in the northern basin and 93.2 g C/m2 per year in the south, with a mean lake value of 136.4 g C/m2 per year. Although, this figure seems conservative for Lake Patzcuaro it could be reduced even more if underwater light conditions change due to further siltation processes and the increase in allochthonous inorganic materials.

In summary, Lake Patzcuaro is a tropical high altitude lake with continuous water mixing processes throughout the year. The lake is highly turbid due to the suspended volcanic silt, high and increasing erosion loads, and untreated sewage inputs. The lake is moderate in hardness and is a carbonate-alkaline water body with a predominance of sodium and potassium cations. Oxygen levels are frequently near saturation due to wind action and photosynthetic activities.

The lake is receiving untreated wastewater from nine municipal and agricultural sources. Thus, the water has high levels of suspended matter and phosphorus compounds. However, concentrations of inorganic nitrogen are very low, suggesting that Lake Patzcuaro may be a nitrogen limited system.

Productivity data from a range of deep and shallow aquatic systems have been compared by several investigators (Likens, 1975; Westlake et al, 1980; Hill and Rai, 1982; Marten and Polivina, 1982; Beveridge, 1984). Data included results from temperate and tropical ecosystems throughout the world. The values for Lake Patzcuaro indicate that the lake is a productive system, when compared with levels found within the range of both temperate and tropical ecosystems.

These values are related to the primary production of phytoplankton. Although various aquatic ecosystems depend mostly upon phytoplankton productivity, others recieve considerable contribution from macrophytes, periphyton and microphytobenthos (Winberg, 1980). In the case of Patzcuaro approximately 37.5% of the annual productivity of the lake is provided by macrophytes which indicates that phytoplankton is not the only important source of organic carbon.

Chapter 6

Remote sensing

Introduction.

Multispectral satellite imagery is a relatively new tool in aquatic sciences which, when combined with other conventional hydrobiological techniques, can provide synoptic data on environmental parameters that may affect aquatic systems and fish production. Experiences using the Multispectral Scanner (MSS) and Thematic Mapper (TM) from the Landsat series of satellites have shown great potential in water resources assessment (Khorram, 1981; Witzig and Whitehurst, 1981; Carpenter and Carpenter, 1983; Verdin, 1985; Kapetsky _et_ _al_, 1987). With the advent of SPOT-1, it would seem that this satellite also, may provide a means of assessing water quality parameters. The use of remote sensing in water quality investigations for aquaculture and fisheries has been recently reviewed by Chacon-Torres _et_ _al_ (1988).

Most remote sensing water quality studies make use of digital imagery and concurrently acquired surface sampling measurements, known as "ground truth" data. Correlations between measurements at sample sites and multispectral scanner data at these same points are exploited to develop predictive equations for a set of water quality parameters (suspended solids, secchi disc transparency, chlorophyll-a) or trophic state indexes (Butter and Voros, 1981; Lillesand et al, 1983; Sugihara et al, 1985). Several studies have attempted to correlate multispectral scanner data with multiple water quality parameters (Rogers et al, 1978; Khorram, 1985; Khorram and Cheshire, 1985; Ruiz-Azuara, 1985). Although the results were reported as significant, the independence of each water quality parameter was not considered. Criteria for water quality modelling, using remote sensing techniques, must include not only high correlation coefficients, but also statistical independence of the modelled variables. Such an approach ensures that the information extracted from the imagery is not repetitively applied in the predictive models.

The use of a secchi disc has been a practical and useful way to measure the clarity of natural waters. However, this visual approximation cannot define the actual inherent optical properties of the water body without considerable deviations (Preisendorfer, 1986). Therefore, remotely sensed multispectral data and secchi disk data would not be expected to correlate well. In the case of Lake Patzcuaro, high turbidities are within a range in which a secchi disc data are of limited use to differentiate spatial variations. Furthermore, the secchi disc provides very little information when chlorophyll concentrations are large (Megard et al, 1980). Data obtained from optical .pn 168 instrumentation such as the irradiance meter and the beam transmissometer can provide more accurate information about the turbidity of the lake which may be highly correlated with multispectral data. However, these instruments cannot separate the physical or biological components which affect the optical properties of the water and hence only determinations of suspended sediments can be made. Total phosphorus, which is the result of its dissolved and suspended portions, has been estimated using multispectral data but, given the strong relationship with phytoplankton growth (OECD, 1982), these measurements cannot be entirely independent from particulate material.

Most natural waters contain a variety of organic and inorganic materials that influence the optical properties of the water, and which can be expected to correlate with multispectral imagery. Suspended solids and chlorophyll-a are probably the most important of these components, and both are closely related to other ecological components, such as primary production, water clarity and phytoplankton abundance, the latter having been used in trophic state assessements (Megard _et al_, 1972; Carlson, 1977). Chlorophyll-a and suspended solids can be estimated separately in the laboratory, and therefore provide convenient "ground truth" data.

Multivariate regression analysis has been used frequently to establish the relationship between these two water quality parameters and multispectral imagery. However, given that chlorophyll-a and suspended solids have similar spectral characteristics, development of individual predictive models from multispectral imagery is difficult, especially when both materials are spatially associated (Alfoldi, 1982).

Hence, the development of independent statistical models for the continuous monitoring of chlorophyll-a and suspended solids separately in highly turbid aquatic environments is essential for quantitative mapping with concurrent satellite imagery.

Given the high turbidity of Lake Patzcuaro due to both erosion loads and high phytoplankton growth, the development of an appropiate methodology for monitoring the eutrophication processes affecting environmental quality in this and other similar water bodies, clearly, would aid the continuous monitoring of water resources.

The aim of the present chapter is to evaluate the applicability of remote sensing techniques for water quality assessment , in Lake Patzcuaro using XS multispectral digital imagery generated from SPOT-1.

Materials and methods.

Sampling sites.

In order to increase the efficiency of remote sensing mapping, criteria for the selection of sampling sites were based on previous experiences and recomendations from previous authors. The twenty-four sampling stations described in Figure 5.1 were used to verify remote sensing at Lake Patzcuaro, and these were selected to ensure representative sampling of the entire lake and statistical validity.

Sampling stations were located in deep waters and avoided shorelines and submerged macrophytes as these can present bottom reflectance effects which strongly influence the relationship between optical water quality parameters and satellite digital data (Carpenter and Carpenter, 1983; Lillesand *et al*, 1983).

Water sampling.

Sampling surveys were carried out twice a month from December 1986 to February 1987, and were conducted simultaneously with approximate dates of SPOT-1 flyovers. Water sampling was carried out as described in Chapter 5. Water samples were taken to the laboratory for immediate analysis of chlorophyll-a and suspended solids.

Image analysis.

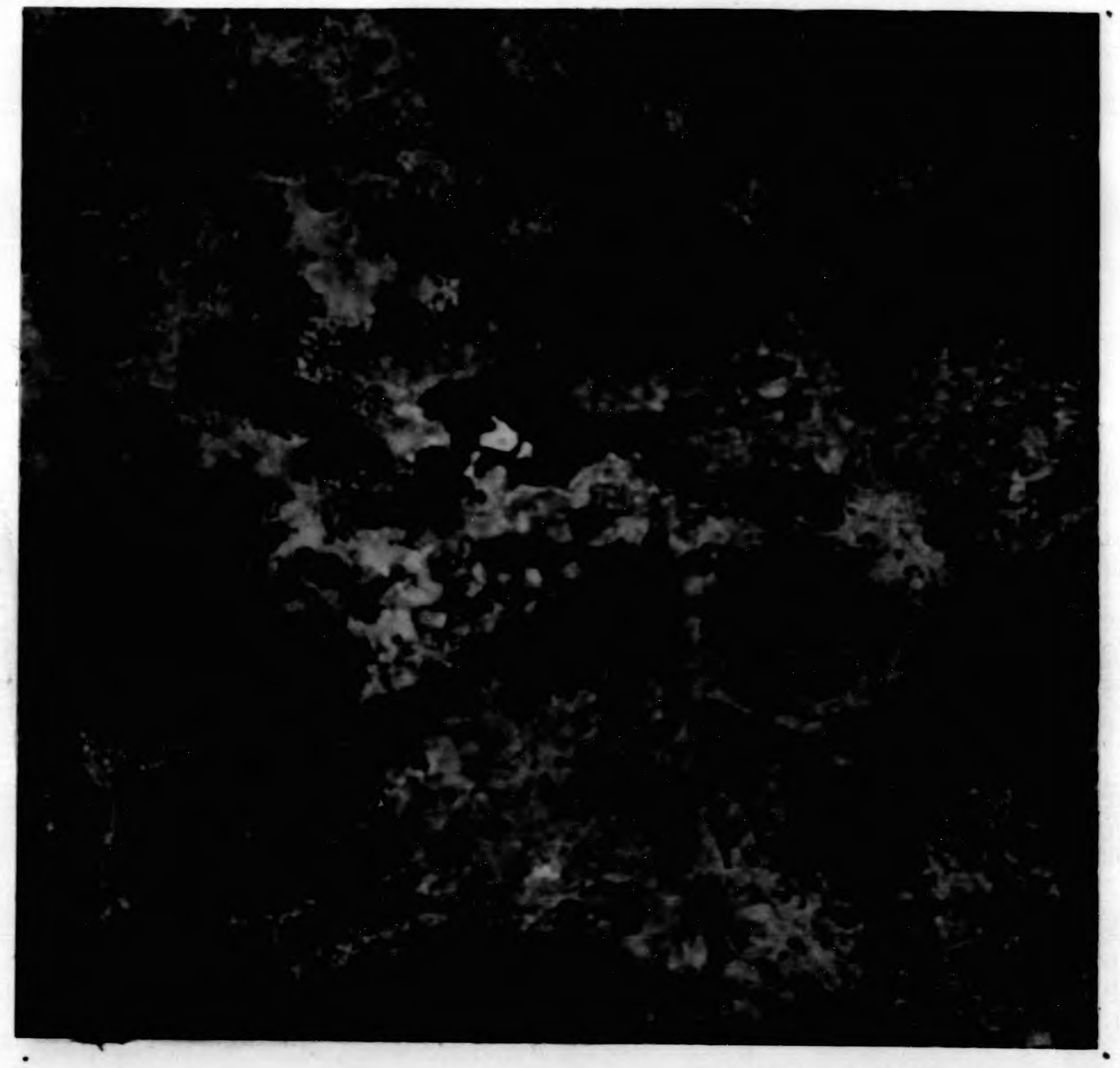
A multispectral XS, HRV-1 computer compatible tape (CCT) for 17th February 1987 was obtained from SPOT IMAGE, Toulouse, France. The tape was acquired at 1A processing level, where most of the radiometric data remain in the original state and no geometric modifications are made on the product. The importance of acquiring radiometric "raw" data for remote sensing of water quality parameters has been previously discussed by Verdin (1983). Digital data were loaded onto a MicroVax system and displayed on a DIAD and ERDAS PC-AT systems (Plate 6.1). The characteristics of the acquired SPOT-1 XS image are described in Appendix 4.A.

Geographic locations.

A set of sixteen ground control points was located from topographic maps (CETENAL,1976; Nos. E14A21 and E14A22, scale 1:50,000), and were fully identified in the SPOT coordinate system. The Universal Transverse Mercator (UTM) coordinates and SPOT coordinates (L and C) for these control points were determined from the CETENAL maps and SPOT tape data respectively. From these control points a second order polynomial regression equation (Moik, 1980) was developed and then applied to the 24 sampling stations to determine their SPOT coordinates. The minimum correlation coefficient achieved in this transformation was r2 = 0.999, with a level of significance of $p < 0.0001$.

Plate 6.1

Colour composite SPOT XS image of Lake Patzcuaro, Michoacan, Mexico. Date : 17th February 1987. Digital data is at 1A processing level.



Data extraction.

Given the uncertainty of the position of the sampling site, and to ensure a correspondence between site data and radiometric values, the mean count values on all three XS bands were extracted from 3 x 3 pixel squares surrounding each estimated sampling site. An exception was made with Lake Zirahuen, located near Lake Patzcuaro, where the mean value of a block of 5 x 5 pixels was found from the central part of the lake. These mean values were used as an estimate of the digital values for clear water. Light extinction depth (Kd) in Lake Zirahuen was 0.25 and light beam transmission (c) was about 65% indicating exceptionally clear water.

Atmospheric correction.

As with Landsat and other multispectral images, Spot digital images on CCT are represented by dimensionless digital numbers, ranging from 0 to 255, in all three XS bands. These digital numbers have been used widely to classify different terrain features (Robinove, 1982), and have proved satisfactory when only a single image was analysed, and no accurate comparisons were required. However, digital numbers do not quantitatively represent physical values (i.e. radiation values emitted or reflected by the earth's surface), and hence, comparative studies between images or spectral bands are impossible. Moreover, the presence of the Earth's atmosphere, continuously affects data recorded by the satellite, owing to attenuation and scattering processes. If changes in optical properties of aquatic systems are under study, and comparisons of these changes on different dates are to be considered, then the original digital values recorded in magnetic tapes are inadequate. The digital value must be transformed to radiation values, and also corrected for atmospheric interferences. The effect of the atmosphere on remote sensors has been previously described by Turner et al (1971), Rogers and Peacock (1973) and Potter and Shelton (1974).

Commonly, two methods have been used for the removal of atmospheric effects in satellite multispectral imagery. The first method involves the use of irradiometers in the field at the time of image acquisition. These instruments, when used at the same wavelength as the satellite's sensor, measure the irradiance at the surface, whereas the remote sensor measures the irradiance at the top of the atmosphere. Simple substractions between extra-atmospheric and surface irradiances should remove the effects of the atmosphere with a high degree of accuracy. This method has been successfully applied by Smith and Baker (1982) and Gordon et al (1983) for the Coastal Zone Colour Scanner (CZCS) on Nimbus-7, and Sugihara et al (1985) for Landsat. The second method consists of the application of empirical radiative transfer models, involving atmospheric and geometric calcualtions for the specific location, and date of image acquisition. These models assume a clear sky and homogeneus atmosphere. They also use ground standard reflectors, such as large concrete buildings, airstrips or very clear water lakes, which either reflect or absorb almost 100% of solar irradiance. Although the method is not as accurate as the use of irradiometers, it has the advantage that it does not involve ground-based instrumentation, and provides reasonable accuracy, when effective standard reflectors, pollutant-free atmospheres and good quality imagery are available. Numerous remote sensing studies have effectively included radiative transfer models, and related techniques for Landsat MSS and TM (Ahern et al, 1977; Scarpace et al, 1979; Richarson et al, 1980; Lopez-Casillas and Caselles, 1987). The results suggest that these models can also be applied to XS multispectral imagery generated from Spot.

Based on local meterological records and field observations in the area, a clear atmosphere was assumed in the present study. In order to remove the effects of the atmosphere without ground measurements, Turner et al (1971) and Turner and Spencer (1972) described a deterministic model for atmospheric radiative transfer assuming a plane-parallel, homogeneous, aerosol-filled atmosphere, whose haze content is defined by the horizontal visual range at the surface.

This model has been successfully applied by Verdin (1985), in multitemporal lake assessments using Landsat MSS. Therefore, the Turner-Spencer model (Turner and Spencer, 1972) was considered suitable for atmospheric corrections in Lake Patzcuaro. Lake Zirahuen located 12 km south from the center point of the image was selected as a standard oligotrophic reflector for the calculations. A FORTRAN version of the Turner-Spencer model (Kortesoja, unpublished) was used in a VAX system following the criteria suggested by Verdin (1985) for inland waters.

Water quality models.

Generally, a stepwise regression is used to determine the optimum set of independent variables for statistical water quality models. Computed reflectances for each spectral band, after atmospheric corrections, are transformed into ratios and these are regressed against the actual values of chlorophyll-a and suspended solids. The criteria for selecting the optimum model from stepwise regression are based on the fewest possible variables, and the correlation coefficient closest to the value of 1.0 (Shu and Chen, 1988), no consideration is given to the possible correlation between estimations. This approach has been widely used for CZCS and Landsat.

The reflectances of suspended solids and chlorophyll-a are not very different for the spectral bands recorded by Spot-1 and other satellites. If the spatial distribution of these two water quality parameters is similar, then stepwise regression becomes of very little use. Any regression fit would be very likely to be biased by information for both chlorophyll-a and suspended solids, and consequently mapping each independently becomes difficult. This does not necessarily mean that natural waters would present similar distributions and concentrations but differences between chlorophyll-a and inorganic-suspended sediments (such as erosion loads) would be difficult to discriminate in the imagery. The water quality results for Lake Patzcuaro showed a high correlation between chorophyll-a and suspended solids, although the distribution of suspended solids is homogeneous whereas the chlorophyll-a distribution is more heterogeneous.

In order to formulate a valid statistical model, several conditions must be observed. First, the inherent dimensionality, N, of the radiance data must be established. This limits the number of independent water quality parameters that can be derived from the radiance data to, at most, N. Principle components if used on the radiance data (in this case 33 combinations were chosen, see Appendix 4.K) can reveal the inherent dimensionality (in this case N = 2).

The second condition to be met is that the water quality parameters should be statistically independent of one another. Simple regression of each water quality parameter against radiance will produce a model in which the estimates of each water quality parameter are influenced by the value of the other parameters. The degree of "influence" is determined by the correlation between the parameters; the larger the correlation, the greater the "influence".

By first carrying out linear transformations of the actual water parameters, using canonical methods, into independent intermediate variates, these latter variables can then be linked by canonical regression to the principal component of the radiance data. Hence, for each pixel, the value of the principal components is found from the reflectances for that pixel, and then the intermediate independent variates can be estimated. These estimates give a set of N independent linear equations, which can then be solved for the N water quality parameters. Thus, the procedure ensures the independent estimations of the water quality parameters from the radiance values.

It was found for the sampling sites that the reflectances were essentially two dimensional, where the linear combination of variables can be written as follows:

$$Zi = a_{i,j} X_j + a_{i,j} X_j + \ldots\ldots\ldots + a_{i,p} X_p \quad (6.1)$$

Where

Z_i = The largest PCA, i=1,2.

$a_{i,j}$ = Principal component coefficients. i= 1,2. j = 1,2..p

X_j = SPOT ratio combinations (the variables). j = 1,2..p

The pairs of values, for chlorophyll-a and suspended solids, for the sampling sites, were subjected to canonical correlation analysis to yield two linearly independent variables Y1 and Y2 (Equation (6.2)). The values of Y1 and Y2 were regressed, canonically, against the principal component scores, PCA1 and PCA2, for the known sampling points (Equation (6.3)).

$$\begin{aligned} Y1 &= a_{1,1}\,\mathrm{CHL} + a_{1,2}\,\mathrm{SS} \\ Y2 &= a_{2,1}\,\mathrm{CHL} + a_{2,2}\,\mathrm{SS} \end{aligned} \qquad (6.2)$$

$$\begin{aligned} Y1 &= c_{1,1}\,\mathrm{PCA1} + c_{1,2}\,\mathrm{PCA2} \\ Y2 &= c_{2,1}\,\mathrm{PCA1} + c_{2,2}\,\mathrm{PCA2} \end{aligned} \qquad (6.3)$$

Where

Y1, Y2 = The canonical variates.

a,c (i,j) = Canonical coefficients.

CHL = Chlorophyll-a concentration.

SS = Suspended solids concentration.

PCA1 = Principal component 1.

PCA2 = Principal component 2.

Hence all the parameters were found for the model. The values were incorporated into a programme. Thus, starting from the raw digital values the following transformations were performed to give independent estimates of chorophyll-a and suspended solids:

DIGITAL VALUES-----> REFLECTANCES-----> PCA1,PCA2----->Y1,Y2

Then by solving the simultaneous equations (6.2) CHL and SS can be predicted.

All statistical treatments were made using SPSS-X V3.01 (SPSS Inc., 1986) and MINITAB V6.1.1 (Ryan et al, 1985) statistical packages.

Results.

A detailed summary of the computations made for geometric location, atmospheric correction and statistical predictive models is presented in Appendix 4.

Geographic locations.

Equations (a) and (b) from Table 6.1 were obtained using the selected set of sixteen ground control points. These equations were used to locate the 24 sampling stations in the lake, with the UTM coordinates extracted from topographic maps. Despite the high statistical significance obtained by the polynomial equations, the standard deviation

Table 6.1. Polynomial regresion for sampling site location in Lake Patzcuaro, Mexico using SPOT coordinate system. r2 = correlation coefficient; p = significance level; SD = mean standard deviation

	Polynomial regression	r2	p	SD
a)	SPOT-L = 108302 - 8.64 UTM-X - 48.8 UTM-Y	1.00	0.0001	+2
b)	SPOT-C = 16359 + 49.00 UTM-X - 12.4 UTM-Y	0.99	0.0001	+3

Table 6.2. Mean digital counts for the selected targets.

	Mean water values	Land locations				Mean land values
Band	Lake Zirahuen	Jaracuaro Island	Janitzio Island	Propemex Plant	Patzcuaro School	$\bar{X}$
XS1	23.0	61.5	53.4	113.5	52.9	70.32
XS2	10.1	56.6	49.0	90.1	51.8	62.02
XS3	8.0	52.0	52.0	82.2	72.4	70.02

remained relatively high, and implies a degree of uncertainty in the location of sampling sites. However, given that all locations were in deep and open water, no serious errors are likely to have arisen from misalignment of imagery and sampling points.

Atmospheric correction.

According to Verdin (1985), the apparent Lambertian reflectance of a surface target, can be computed as follows:

$$R = \frac{Pi\ (Lsat-Lp)}{Htot^{(-t\ \sec\ \theta n)}} \qquad (6.4)$$

Where:

R = Lambertian reflectance (dimensionless).

Lsat = Radiance sensed by the satellite in a given spectral band (mW cm -2 sr).

Lp = Atmospheric path radiance (mW cm -2).

Htot = Total irradiance incident on a horizontal surface at the bottom of the atmosphere (mW cm-2).

t = Total optical depth of the atmosphere (dimensionless).

θn = Satellite nadir view (degrees).

Ahern <u>et al</u> (1977) proposed the use of oligotrophic lakes as standard reflectors, which could be used to evaluate Lp, by means of the expression

$$Lsat = (Lv + Ls + Lg)^{(-t \sec \theta n)} + Lp \qquad (6.5)$$

Where

Lv = Water volume radiance.

Ls = Water surface radiance.

Lg = Sun glint radiance produced by solar zenith angles less than 30 degrees or wave action due to strong winds.

Where, $Lv = rv\ Htot$ (6.6)

and rv = water reflectance.

From Richardson <u>et al</u> (1980) rv was found to be equal to 0.0035-0.0036 x wavelength (um). Also they defined Ls = 0.006 x Hsky. Hsky, the diffuse sky irradiance cannot be directly measured. Given the solar position in Mexico and the evidence in the field of no wave action in either Lake Zirahuen or Lake Patzcuaro at the time of the acquisition, Lg was assumed to be equal to zero.

Total optical depth (t), path radiance (Lp), direct solar irradiance (Htot), and diffuse sky irradiance (Hsky) can be calculated from an appropiate atmospheric radiative transfer model.

For the application of the Turner-Spencer model the required input parameters are:

1. Satellite altitude (km)
2. Ground visibility (km)
3. Wavelengths for each band (um)
4. Nominal background reflectance (decimal)
5. Nominal oligotrophic target reflectance (decimal)
6. Solar zenith angle (degrees)
7. Relative azimuth angle (degrees)
8. View nadir angle (degrees)

The geometry of the remotely sensed imagery is illustrated in Figure 6.1.

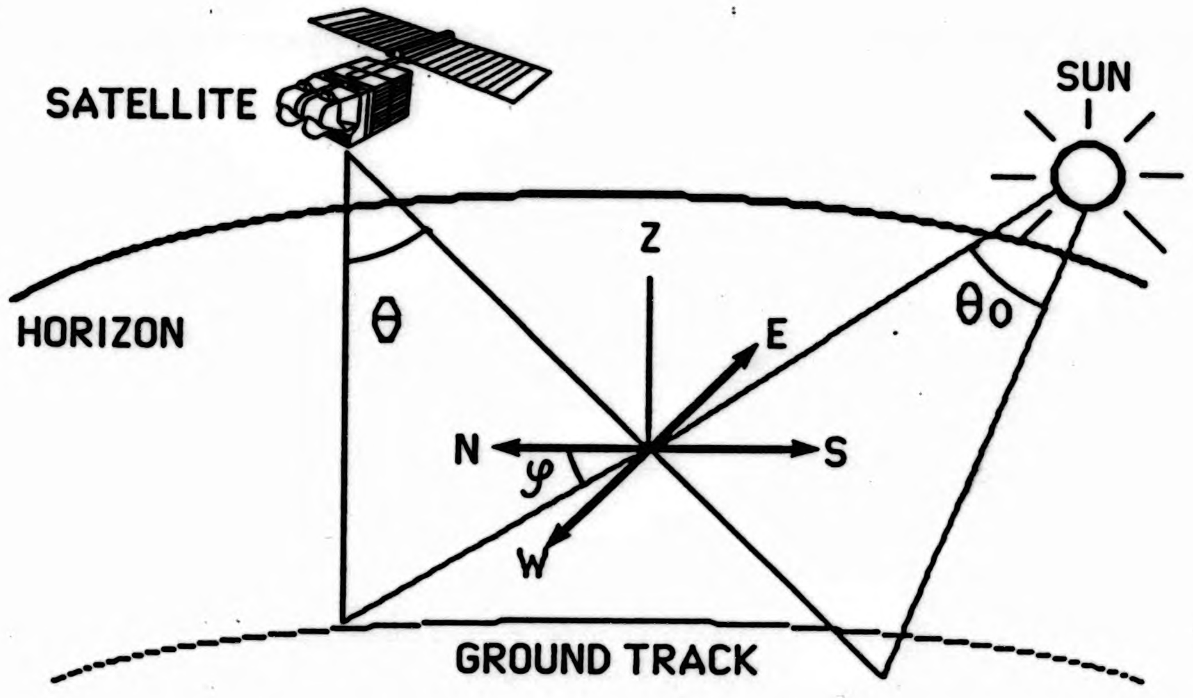
An area (5 x 5 pixels) at the centre of Lake Zirahuen was selected as a nominal oligotrophic target due to its low turbidity, deep waters, freedom from bottom and edge effects, and close proximity to Lake Patzcuaro. The average values of four highly reflective land locations in the vicinity of Lake Patzcuaro, were used, to compute the nominal land background reflectance (Table 6.2).

Since visual range values are only roughly estimated at the local meteorological station, the value of visual range for each spectral band was found, by running the Turner-Spencer model iteratively with visual range values in one-kilometre steps until the relation $Lsat-(Lv + Ls + Lg) \exp(-t \sec \theta n) - Lp = 0$ gave residual values less than 0.001 mW cm^{-2} sr.

Figure 6.1

Schematic illustration of the geometry of the remotely sensed imagery via satellite. θ_o = Solar zenith angle; θ_n = Nadir view angle; = Azimuth view angle; Z = Zenith; N, E, S, W = Wind rose bearings.

Date: 17th February 1987.



This method was applied on the assumption that uniform atmospheric conditions prevailed in the basin at the time of the image acqusition. Given the rough topography of the region, and the season selected for the survey, air masses are characteristically clear and dry. Adjacent human settlements are typically villages, and no industrial activity is located in the neighbourhood. A possible source of anomalous atmospheric influence could be the capital of the State, Morelia (located 57 km northeast of Lake Patzcuaro), with a population of approximately half a million and moderate industrial activity. However, prevailing winds in the region are typically from the southeast and southwest of Lake Patzcuaro throughout the year, and, hence non-homogeneous aerosols are unlikely over the lake.

The day, month, year, and local time of the satellite flight and the latitute and longitude of Lake Zirahuen, were used in separate calculations to solve the geometry of the imagery. A solar ephemeris was used to compute solar zenith and azimuth angles for Lake Zirahuen at the time of the acquisition (Appendix 4.F).

The average digital values for the water and land targets, were converted to the equivalent nominal radiances for each XS band by using the calibration values for the HRV-1 sensor given by Begni (Personal communication) as follows,

$$\overline{Lsat} = \frac{X}{A\ (Gm)} \qquad (7)$$

Where

$\overline{Lsat}$ = Nominal radiance for the target (mW cm-2 sr).

X = Average digital value for the target.

A = Absolute calibration coefficient.

XS1:0.8619; XS2:0.7986; XS3:0.9515

Gm = Amplification (gain sensor) coefficient.

XS1:1.69; XS2:2.20; XS3:1.69

Nominal apparent Lambertian reflectances required by the Turner-Spencer model were computed from nominal radiances values by using Equation 6.4. Scene geometry and nominal radiometric data to run the Turner-Spencer model are presented in Table 6.3.

The results of the radiometric correction procedure for Lake Zirahuen, using the Turner-Spencer model, are presented in Table 6.4. Equation 6.4 was used to compute Lambertian reflectance values for all surface sampling locations in Lake Patzcuaro. Corrected radiometric data and concentrations of chlorophyll-a and suspended solids are presented in Table 6.5.

Table 6.3. Scene geometry and nominal radiometric data to run the Turner-Spencer model for atmospheric correction in Lakes Zirahuen and Patzcuaro, Mexico.

1. Altitude (km)	832.0
2. Visibilities (km)	iterative (10-90)
3. Wavelengths (um)	0.540; 0.640; 0.840
4. Background albedo for each XS band	0.22015; 0.24079; 0.33702
5. Target albedo for each XS band	0.07200; 0.03921; 0.03850
6. Solar zenith angle (degrees)	51.0
7. Relative azimuth angle (degrees)	97.75
8. View nadir angle (degrees)	0.826

Table 6.4. Radiometric data obtained from the Turner-Spencer model.

	XS1	XS2	XS3
Visual range (km)	42.000	89.000	36.000
Total optical depth	0.272	0.121	0.147
Path radiance (mW/cm2 sr)	0.227	0.080	0.075
Diffuse sky irradiance (mW/cm2)	0.773	0.750	0.888
Total irradiance (mW/cm2)	7.560	6.590	6.310

Table 6.5. Computed reflectances and water quality concentrations for sampling stations in Lake Patzcuaro, Mexico, from Spot-1, HRV-1 multispectral data. (CHL = chlorophyll a, ug/l; SS = suspended solids, mg/l).

Station	XS1	XS2	XS3	CHL	SS
1	0.12700	0.10040	0.07764	298.97	81.0
2	0.13009	0.10228	0.06599	248.16	72.4
3	0.13498	0.11266	0.04109	150.43	69.5
4	0.13384	0.11454	0.03421	138.20	23.2
5	0.13498	0.11077	0.03421	122.43	32.2
6	0.12985	0.09945	0.06705	255.92	78.2
7	0.12871	0.11171	0.03633	140.77	26.2
8	0.13100	0.11030	0.03421	157.92	34.2
9	0.13498	0.11455	0.03315	94.47	23.4
10	0.13491	0.11171	0.03485	97.50	23.8
11	0.13498	0.11501	0.04004	146.16	53.6
12	0.13612	0.11973	0.03739	94.91	25.6
13	0.13669	0.11879	0.03951	113.33	44.7
14	0.13840	0.11784	0.03739	109.40	17.8
15	0.13840	0.11226	0.03210	36.18	13.8
16	0.13726	0.10700	0.02945	24.87	12.6
17	0.13726	0.11124	0.03315	28.12	15.0
18	0.13498	0.11832	0.03951	30.53	46.8
19	0.14067	0.11171	0.03263	23.03	11.2
20	0.13555	0.10935	0.03421	27.39	14.4
21	0.13726	0.10887	0.03315	30.19	14.8
22	0.12130	0.09285	0.02945	37.60	18.4
23	0.14068	0.11596	0.03792	29.05	15.0
24	0.13042	0.10464	0.03263	41.36	16.8

Water quality models.

Appendix 4.K contains the reflectance ratios used in the Principal Component Analysis. The first principal component (PCA1) had a variance (i.e. eigenvalue) of 23.597. The second principal component (PCA2) had a variance of only 7.981. These two PCAs represent 97% of the data and suggest that the radiance bands are basically two dimensional. Using equation 6.1, the two PCA values for each of the sample sites were found, and then the canonical analysis was completed and the constants for equation 6.2 and 6.3 were obtained. These are listed in Appendix 4.K. The correlation between observed and radiance-predicted chlorophyll-a concentration was 0.73 and is significant at $p < 0.001$ level (Figure 6.2 a). The correlation between the observed and radiance-predicted suspended solids was 0.47 and, as chlorophyll-a it was significant at $p < 0.001$ (Figure 6.2 b).

Image classification.

The distribution of chlorophyll-a and suspended solids for Lake Patzcuaro using XS Spot imagery, is illustrated in Plates 6.2 and 6.3. In Plate 6.2, an unusually dense phytoplankton bloom can be seen in the northern end of the lake. The bloom is dominated mainly by algal populations of Microcystis spp and Aphanizomenon spp. Although high summer phytoplankton growth is common in this high altitude lake, no algal blooms have been reported previously. The image

Figure 6.2

Predicted values and observed values of a) chlorophyll-a and b) suspended solids.

a) R^2 = 0.73, n = 24.

b) R^2 = 0.47, n = 24.

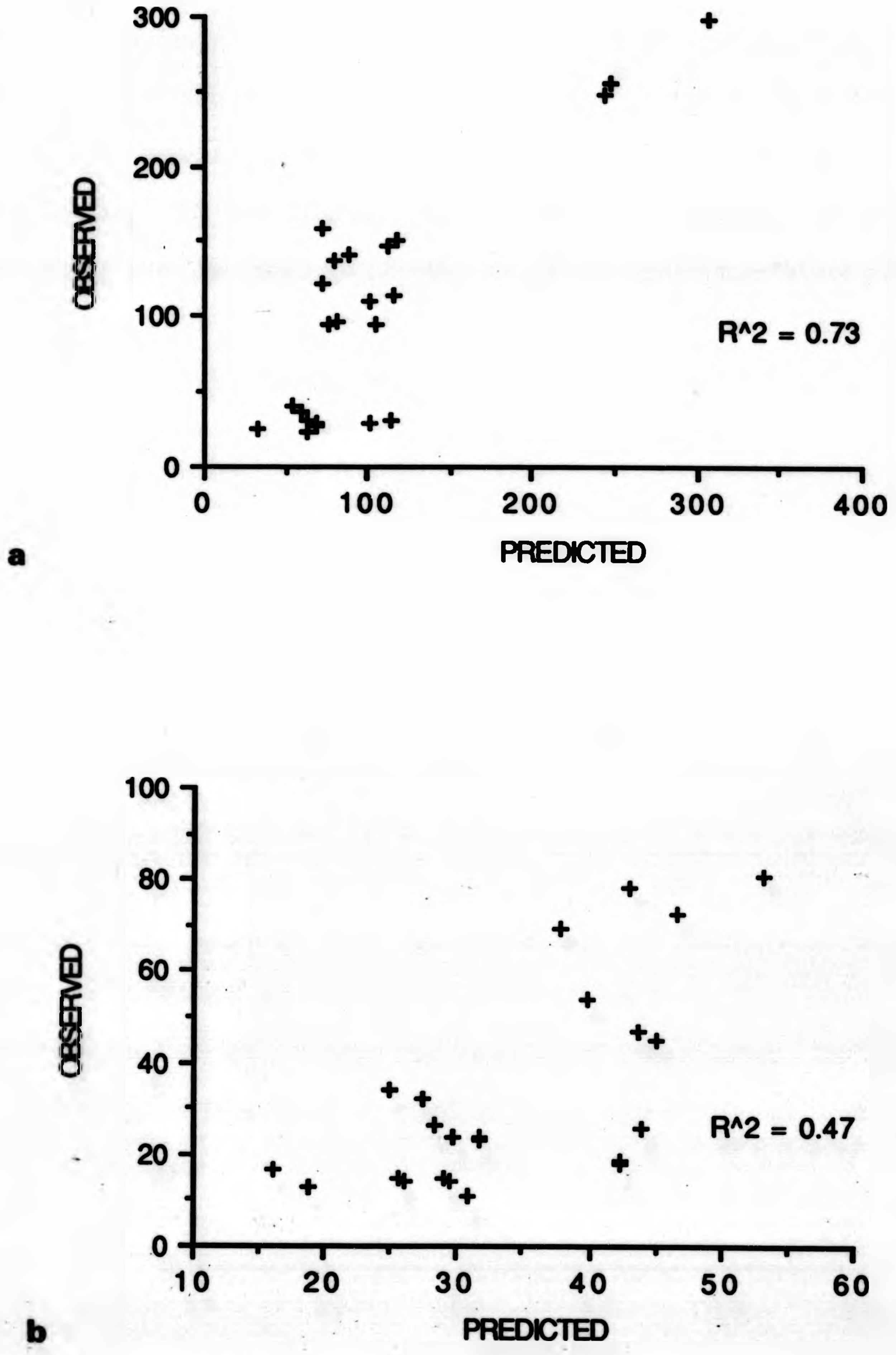


Image classification.

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Plate 6.2

Chlorophyll-a (CHL) distribution over Lake Patzcuaro, Michoacan, Mexico, as derived from SPOT XS digital data. Date: 17th February 1987.

Colour code

Dark blue	Submerged macrophytes	
Blue green	< 50	ug/l
Dark green	50 - 100	ug/l
Yellow	100 - 250	ug/l
Orange	> 250	ug/l

Plate 6.3

Suspended solids (SS) distribution over Lake Patzcuaro, Michoacan, Mexico, as derived from SPOT XS digital data. Date: 17th February 1987.

Colour code

Blue	Submerged macrophytes
Green	5.0 - 10.0 mg/l
Yellow	10.0 - 30.0 mg/l
Orange	30.0 - 45.0 mg/l
Purple	> 45.0 mg/l

also clearly illustrates the general variation in the distribution of chlorophyll-a from maximum concentrations in the north to minimum values in the south. The highest water reflectances were detected in a strip 2 to 3 pixels in width indicating very narrow dense belt of phytoplankton. Values of up to 2,200 ug/l of chlorophyll-a were estimated in an approximated area of 20 x 20 m. However, given the extreme concentration of chlorophyll-a, maximum values should be interpreted with caution. Clear water areas were also apparent in the northern end of the lake, and increase in ocurrence towards the southern end. Although untreated sewage discharges are located at both ends of the lake, the distribution of chlorophyll-a suggests that water currents, originating in the south, accumulate nutrients at the north end of the lake.

The distribution of suspended solids, as represented in Plate 6.3, indicates a more homogeneous pattern in the lake. The maximum concentrations of suspended solids, up to 423 mg/l, were mainly associated with the bloom distribution and sewage discharges, although high concentrations (80 mg/l) were also detected in the southern shallow waters. Gomez-Tagle (in preparation) has described this particular area as having the highest soil erosion loads in the entire catchment area. The effects of land deterioration on water quality are demonstrated by the low values of chlorophyll-a and the high values of suspended solids detected in the south. Similar values of chlorophyll-a and suspended solids, were detected also at the northeastern edge of the lake, in areas of deep water (6 - 8 m). This distribution is possibly due to the effect of inorganic pollution, which is also identifiable in the XS imagery. However, given that the pollutant has a different reflectance than the normal sediment, the concentration estimates are likely to be innaccurate, and only give a qualitative impression of the pollutant.

Large submerged macrophyte communities affected water quality mapping (coloured blue) in the area of Jaracuaro Island located at the southwestern corner of the lake. This area had very low values of reflectance indicating high levels of absorption and scattering.

Finally it should be noted that there appears to be a slight variation in sensitivity in the CCD arrays. This is revealed by the vertical colour striping of both images.

Discussion.

The analysis of the image from XS multispectral Spot data indicates that during the winter of 1986-1987 a dense algal bloom took place in Lake Patzcuaro. The image also revealed a well defined gradient in the distribution of chorophyll-a with minimum values in the south with an average of about 70.03 ug/l, a central region with intermediate values of about 103.20 ug/l and maximum mean values in the north of approximately 149.57 ug/l. This pattern of phytoplankton concentration can be attributed to the effects of the southern winds which accumulate nutrients and phytoplankton populations at the north end of the lake. Algal blooms in Lake Patzcuaro have not been reported before and most previous authors had referred to the north of the lake as the least polluted area (De Buen, 1941a; Tellez y Motte 1980; Rosas et al 1985). Although the present study involved a very intensive field survey at the same time as the satellite overpass, professional ground crews did not identify the occurrence of the algal bloom. The usefulness of synoptic satellite imagery for water resources assessment is clearly demonstrated in this case.

The distribution of suspended solids in the lake was shown to be more homogeneous but high concentrations were detected in association with a dense phytoplankton bloom in the north, and also in areas where high degrees of erosion are known to accur in the south.

From this study it can be concluded that despite the limited spectral resolution of XS Spot imagery for water quality monitoring, and especially for independent mapping of chlorophyll-a and suspended solids, satisfactory results can nonetheless be obtained through an appropiate statistical approach.

Finally, the mismatch in the sensitivty of the CCD arrays which produced a vertical striping effect, may prove to be a limiting factor in the application of SPOT imagery to water quality assessment.

Chapter 7

Discussion

Lake Patzcuaro is a high altitude lake located within the tropical belt. Similar to many of the freshwater lakes in the Mexican Plateau, it is considered that the lake was formed by partition of the Lerma-Santiago system, a large, ancient drainage basin, during late Tertiary and early Quaternary tecto-volcanic activity. The basin of the existing lake belongs to the Eje Volcanico Transversal which extends from the Pacific coast to the margins of the Sierra Madre Oriental. The continuing vulcanism of the system manifests the process of tectonic subduction of the Cocos Plate under the American Plate.

The natural evolution of most lakes, from origin to extinction, follows a succession of productivity states which are the result of a series of associated physical, chemical and biological changes which take place in the system (Goldman and Horne, 1983). The word "trophy" was initially introduced by Weber in 1907 to describe qualitatively the level of nutrients and productivity in German peat bogs (Waite, 1984). It is now widely applied in limnology to classify freshwater ecosystems according to their natural production, ranging from low biological activity and low fertility oligotrophic sytems, through intermediate mesotrophic to eutrophic lakes with high levels of fertilization and biological activity (Waite, 1984).

Hypertrophic systems have been described as the ultimate stage of eutrophy, characterised by a high degree of ecological disturbance and instability (Barica, 1980). Additional descriptors have been included to identify the trophic level of lakes, although a degree of uncertainty is introduced when this classification is used in quantitative studies (Goldman and Horne, 1983; Henderson-Sellers and Markland, 1987).

With the increase in anthropogenic activity and the intensification of use of water resources as a means of food production, power generation, irrigation, recreation and sewage disposal, the natural ageing process of many freshwater systems has been accelerated. This process of cultural eutrophication results in nutrient enrichment, increase of productivity, decrease of biotic components and ecological instability of freshwater systems as a result of human pressure (Hasler, 1947; Hutchinson, 1973). National and international programmes for lake restoration and control of excessive eutrophication (USEPA, 1974; OECD, 1982) have suggested the need to classify aquatic systems according to their productive condition or trophic status before any resource exploitation project is proposed.

A number of attempts have been made to establish a trophic index as a function of commonly measured water quality variables (i.e. secchi disc, chlorophyll-a, total phosphorus, primary production, macrophyte coverage) which could represent the basic concept of eutrophication and hence trophic status with predictive capability (Carlson, 1977; Porcella et al 1980; Sakamoto, 1966; Shannon and Brezonik, 1972; Walker, 1979). These indices have been developed either using a single variable or using multivariate analysis to combine several environmental variables in a one-dimensional index.

Empirical models based on lake morphometry and water quality variables have also been used to predict fish yields. Rawson (1952) estimated fish yields for a particular set of lakes using mean depth as a predictor. Ryder (1965) developed this approach by introducing the potential lake fertility expressed as total dissolved solids. This empirical model is known as the Morphoedaphic Index (MEI). The MEI has been reviewed and applied in both temperate and tropical locations (Henderson and Welcomme, 1974; Schlesinger and Rieger, 1982).

Other contributors have shown that alternative lake quality descriptors can also be applied to predict fish production. For example, Oglesby (1977) used gross primary production as a predictor of fish yields, whereas Hanson and Legget (1982) and Jones and Lee (1986) used total phosphorus concentrations and annual phosphorus loading to estimate fish yields.

Lake restoration and management strategies have been developed and used for the most part in Europe, Japan and North America. The criteria for these strategies are supported by long periods of monitoring physical, chemical and biological processes in temperate lakes. However, given the ecological differences with tropical environments, these models cannot be considered universal and they must be examined and verified at different locations, most particularilly at lower latitudes.

Although eutrophication and environmental deterioration in Lake Patzcuaro have been mentioned in numerous reports, only a few studies have been orientated towards an environmental assessment of the lake and an evaluation of its trophic status (Tellez and Motte, 1980; Velasco, 1982; Rosas et al, 1985). As anthropogenic activity in Lake Patzcuaro has increased, the environmental impact on the lake has also increased. However, neither the potential impact of these activities nor the development of restoration programmes have been considered. In order to provide the basis for lake management strategies and fish resource assessment it is necessary to identify the environmental factors which affect the productivity of the lake and the applicability of trophic state indices for regional water resources assessment.

Morphometry of the lake.

Results of the bathymetric survey carried out during the winter of 1986-1987 indicated that Lake Patzcuaro is a shallow water body with deeper waters located in the north and continuous modification of the shallow southern areas due to formation of new islands and macrophyte communities. The morphometry of the basin as derived by the relative hypsographic curve is considered as the slightly convex form of the macro type. This corresponds to a lake with a principally even profile, and with a parabolic shape involving a gentle relief in littoral zones and a relatively steep relief in limnetic areas. The lake presents a medium bottom roughness which is typical of a volcanic region. However, slopes less than 5% are observed in most littoral zones which according to Hakanson (1981) are highly sensitive to sediment deposition.

Climate.

The climate of the Mexican Plateau is mainly determined by the interaction of the general atmospheric circulation with the abrupt relief of the volcanic region of Mexico. Thus, significant variations in rainfall are frequent in the basin of Lake Patzcuaro. Garcia (1981) described the climate of Patzcuaro based on data over a 23-year period using temperature and rainfall as climatic variables. The results of the climatic classification in the present study using the same criteria, indicated that the rainfall in the region has been comparatively less during the last sixteen years in relation to the previous classification. This reduction in precipitation has had substantial effects on lake levels.

Water budget and erosion.

The annual water budget of Lake Patzcuaro is mainly determined by differences in total precipitation and evaporation. It is apparent that lake evaporation rates are usually higher than direct precipitation inputs. Therefore the only net hydrological contribution is that derived from the catchment area via seepage. It is assumed that much of the superficial runoff is lost by high evaporation rates. The possible effect of seepage from the catchment area on the lake volume is observed in the annual lake level fluctuations which are identical to but are out of phase with the sinusoidal curve of precipitation. The hydrological contribution from the catchment area has decreased over the last thirty years as a consequence of the increasing erosion process. The deterioration of the drainage area is illustrated in Figures 7.1 and 7.2 based on data from Gomez-Tagle (in preparation). The drainage area was subdivided by Gomez-Tagle into eight sub-catchment areas which were assessed for intensity of soil losses. As can be observed, 75% of the erosion loads originate in the southern basin. It is estimated that 140 million cubic metres of sediments are transported from the catchment area annually by erosion, although it is clear that not all of this is deposited around the shoreline of Lake Patzcuaro. The effects of these sediment loads are not only evident in the decrease in water inputs from the catchment area but also in the increased turbidity, nutrient concentration and productivity of the lake.

Light.

For most freshwater lakes, the availability of sunlight, the depth of the lake basin, and the rate of supply of nutrients particularly phosphorus and nitrogen, seem to explain much of the variation in primary productivity and hence in secondary production and fish production (Brylinsky and Mann, 1973; Schindler, 1978; Moss, 1980; Vollenweider, 1975;

Figure 7.1
Sub-catchment areas of Lake Patzcuaro, Michoacan, Mexico, according to Gomez-Tagle. (Redrawn from Gomez-Tagle, in preparation). Star points indicate soil sampling stations.

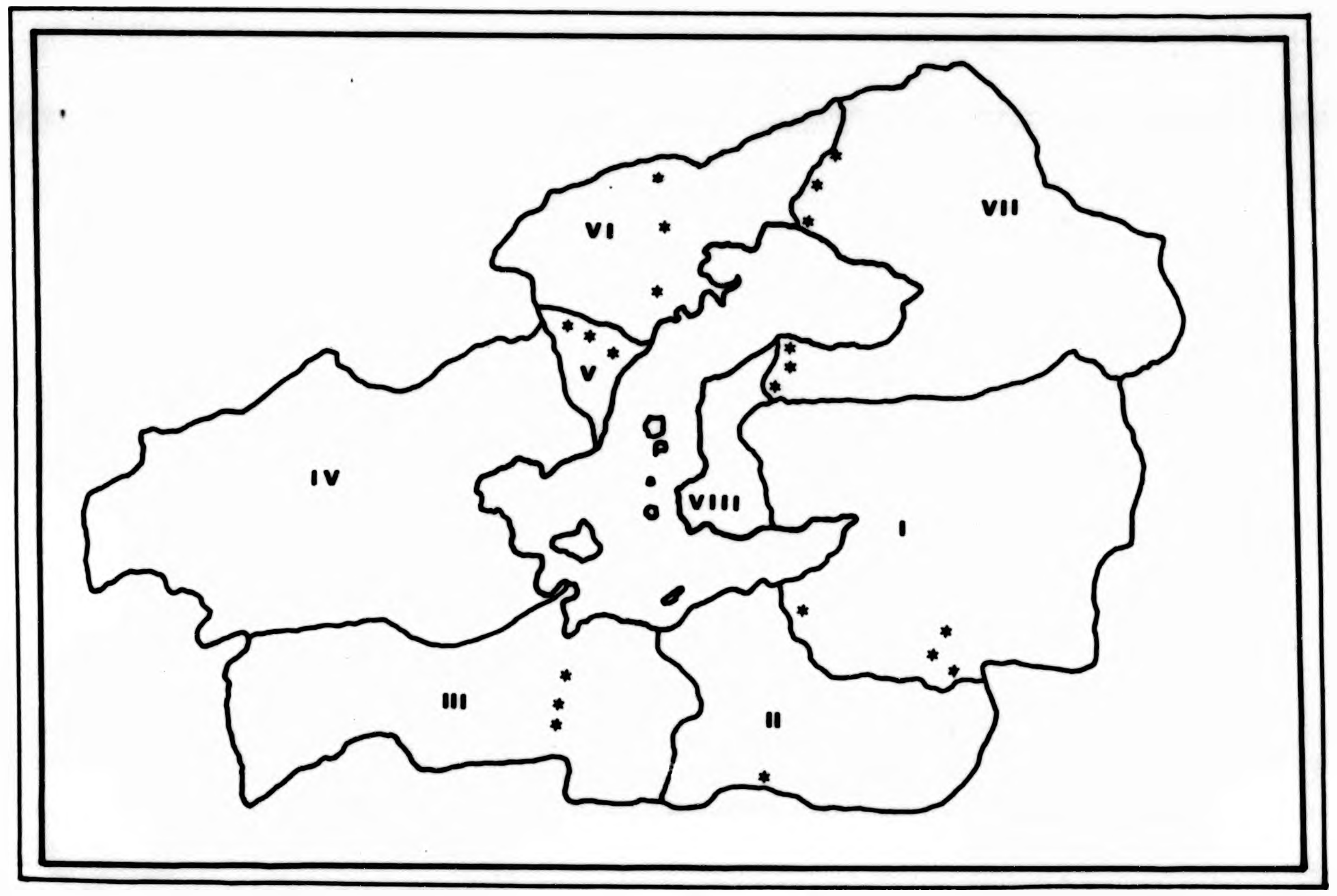
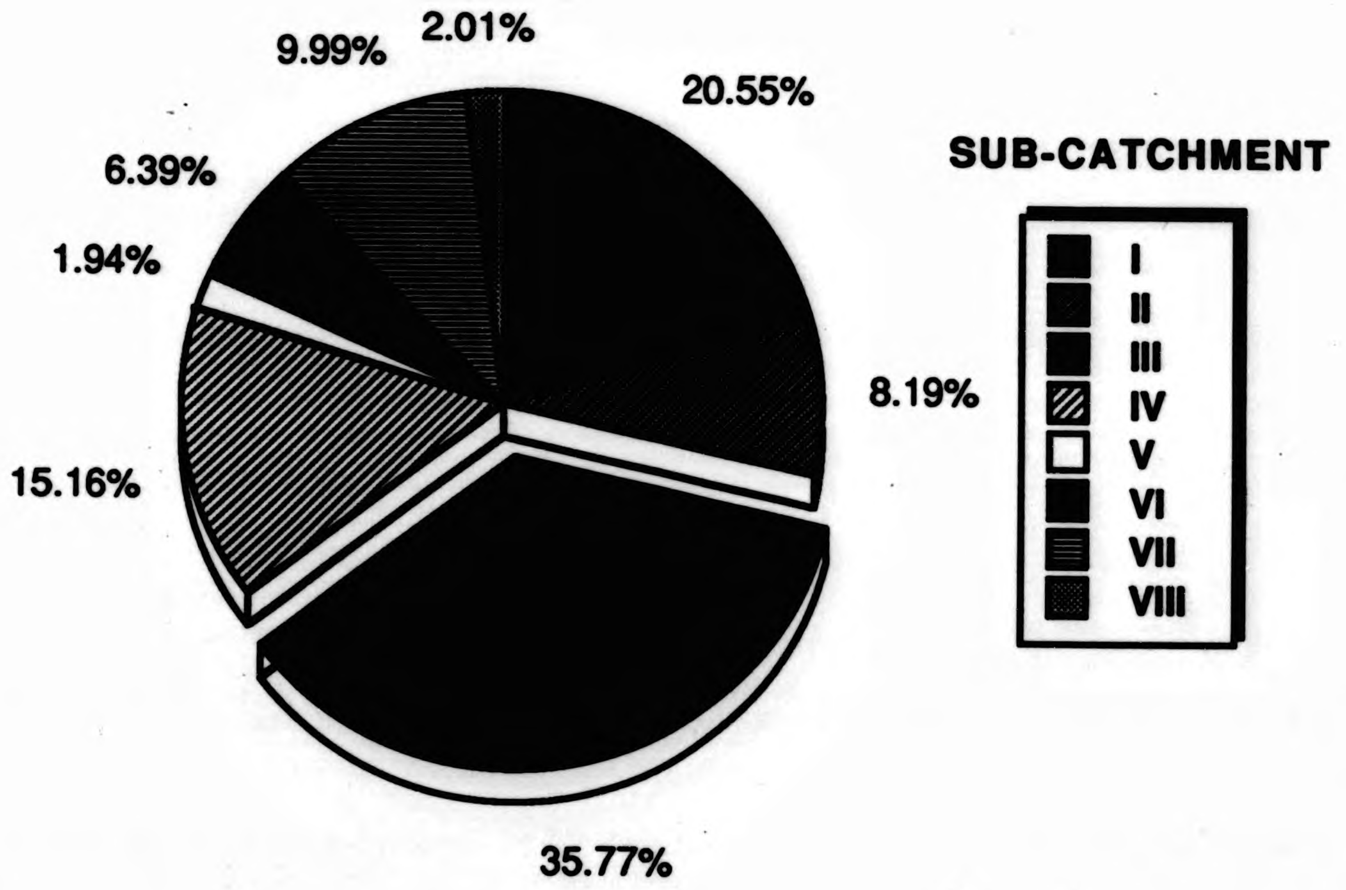


Figure 7.2

Erosion load estimates per catchment area of Lake Patzcuaro, Michoacan, Mexico. (Redrawn from Gomez-Tagle, in preparation). Total annual sediment loading to the lake is estimated at approximately 140,000,000 m^3.



Ryder *et al*, 1974; Oglesby, 1977). Aquatic plant productivity can be limited if one nutrient is not sufficiently available in the system or alternatively, by light.

Chlorophyll-a has been used as an indicator of trophic state because it is the principal photosynthetic pigment in most phytoplankton. Solar irradiance in the region of Lake Patzcuaro is not limiting at any time during the year although the optical properties of the water are such that the efficient use of sunlight by phytoplankton is diminished. The underwater light conditions in the lake can be assessed by examining the relationships between optical parameters, chlorophyll-a and suspended solids.

According to Tyler (1968) and Preisendorfer (1986) the relationship between secchi disc depth and the apparent optical parameters of water is given by

$$SD = \frac{A}{(c + Kd)} \qquad (7.1)$$

Where

SD = is the depth of the secchi disc (m).

A = the coupling constant; representing the natural logarithm of the ratio (Co/Cr) of the inherent contrast of the secchi disc (Co) and its apparent contrast (Cr), as seen by the observer.

c = is the beam attenuation coefficient (m).

Kd = is the vertical attenuation coefficient (m).

The sum of the two attenuation coefficients (Kd + c) has been used frequently as an optical value for water clarity, and it is this sum which is most readily related to secchi disc depth. Reasonable estimates for A have been suggested in the range of 8 and 9 (Preisendorfer, 1986). Tyler (1968) assigned a value of 8.69 which has been used widely in oceans and clear freshwaters. The value for A found in Lake Zirahuen was very similar to that reported by Tyler (1968). Thus following Equation 7.1 for Lake Zirahuen;

$$A = SD \times (c + Kd) = 5.75 \times (0.3 + 1.2) = 8.65$$

However, values of A were significantly different in Lake Patzcuaro (Appendix 1), ranging from 4.52 to 5.94 and with a mean value of 5.25. Preisendorfer (1986) defined "ten laws" describing the factors which cause variations in the secchi depth and thus in the coupling constant. Of these "laws", nine involve the observer's procedural variability. However, weather conditions in lakes Patzcuaro and Zirahuen were always calm and sunny during light measurements and hence the variations in the coupling constant in Lake Patzcuaro are unlikely to be attributed to variability of measuring procedure. Moreover, Gordon and Wouters (1978) and Tilzer (1988) have found that a very narrow subjective error is observed between different secchi disc viewers when the secchi disc procedure is standardised. Therefore, the differences in the coupling constant between Zirahuen and Patzcuaro are more likely to be related to underwater optical factors than variation associated with the viewers.

Given the narrow range of secchi disc measurements in Lake Patzcuaro and the high values of attenuation, it is difficult to determine accurately the component which contributes most to the variations in secchi disc transparency. However, an examination of the relationship between optical parameters of the water and water quality parameters can be useful in helping to identify qualitatively the effect of these water quality paameters on water transparency. Table 7.1 summarizes the correlation matrix relating secchi disc transparency to the major optical parameters of Lake Patzcuaro. To assess the contribution of water quality parameters such as (CHL) and (SS) to light attenuation, it is necessary to identify the maximum variation between the two optical parameters affecting the coupling constant. A relatively low but significant correlation was found between (Kd) and (c) as illustrated in Figure 7.3. The greater scatter of (c) against the narrow range of measurements of (Kd) suggest that the high variability in the coupling constant could be greatly influenced by (c). This is further supported by the correlation of the coupling constant with (c) and (Kd) separately. The higher correlation of (c) with (Kd+c) demonstrates the large influence of beam attenuation rather than vertical attenuation (Kd) on the total light attenuation (Kd+c). Variations in beam attenuation can be explained by the differences in proportions of phytoplankton and inorganic particles in the water with subsequent variations in both absorption and scattering.

The variability of (c) seems to have more effect on water transparency than the variability of (Kd). Figure 7.4 a and b illustrate these differences of secchi disc versus beam and vertical attenuation coefficients.

Table 7.1. Correlation matrix relating Secchi disc transparency (SD), vertical attenuation coefficient (Kd), beam attenuation coefficient (c), the coupling constant (Kd+c), chlorophyll-a (CHL) and suspended solids (SS) for Lake Patzcuaro. n = 53

	SD	Kd	c	Kd + c	CHL	SS
SD	1					
Kd	-0.726	1				
c	-0.825	0.560	1			
Kd + c	-0.882	0.759	0.963	1		
CHL	-0.596	0.711	0.575	0.673	1	
SS	-0.669	0.679	0.526	0.631	0.628	1

Figure 7.3

The relationship between vertical attenuation coefficient (Kd) and beam attenuation coefficient (c) in Lake Patzcuaro, Michoacan, Mexico.

$R^2 = 0.560$, n = 53, P < 0.001

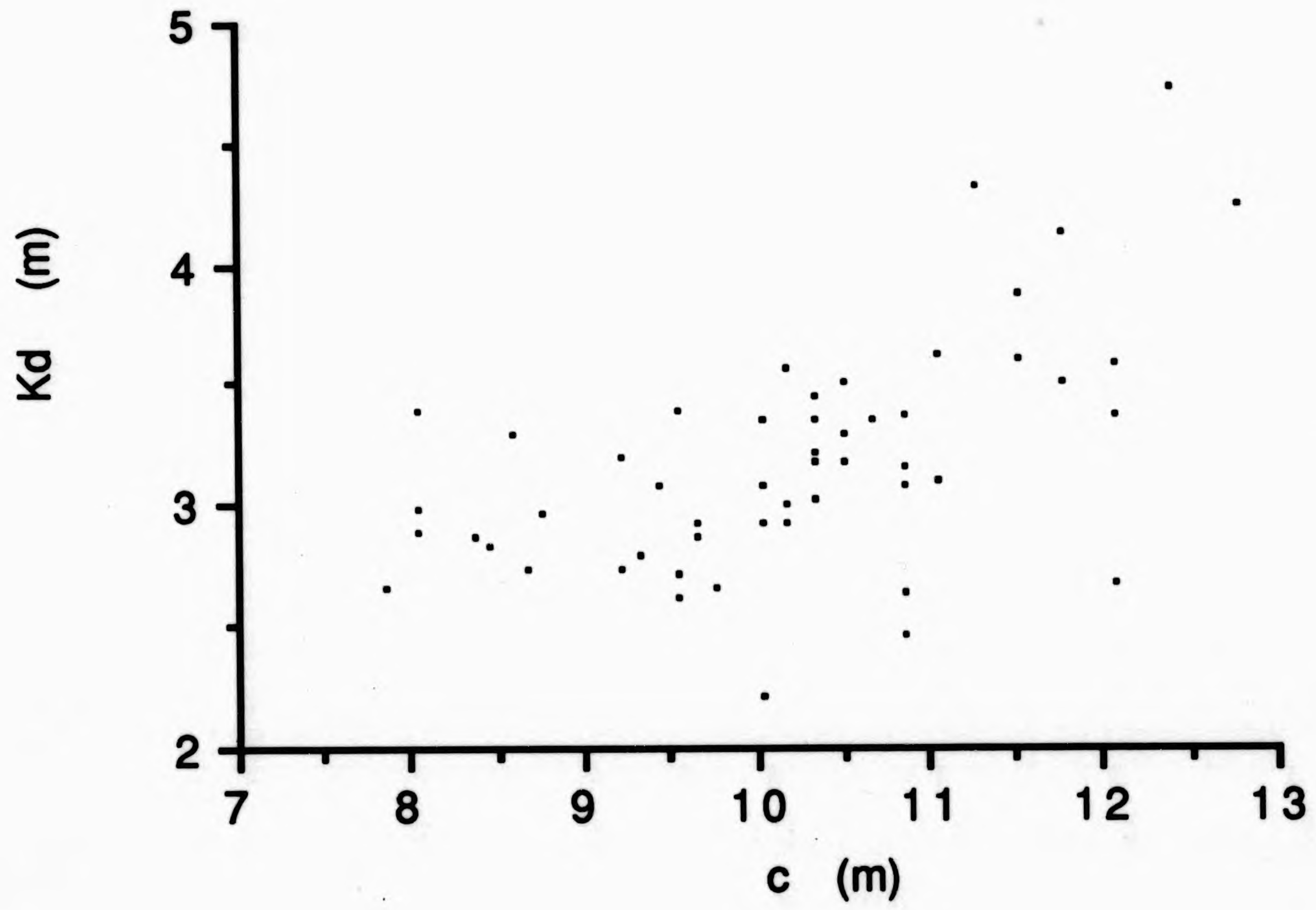
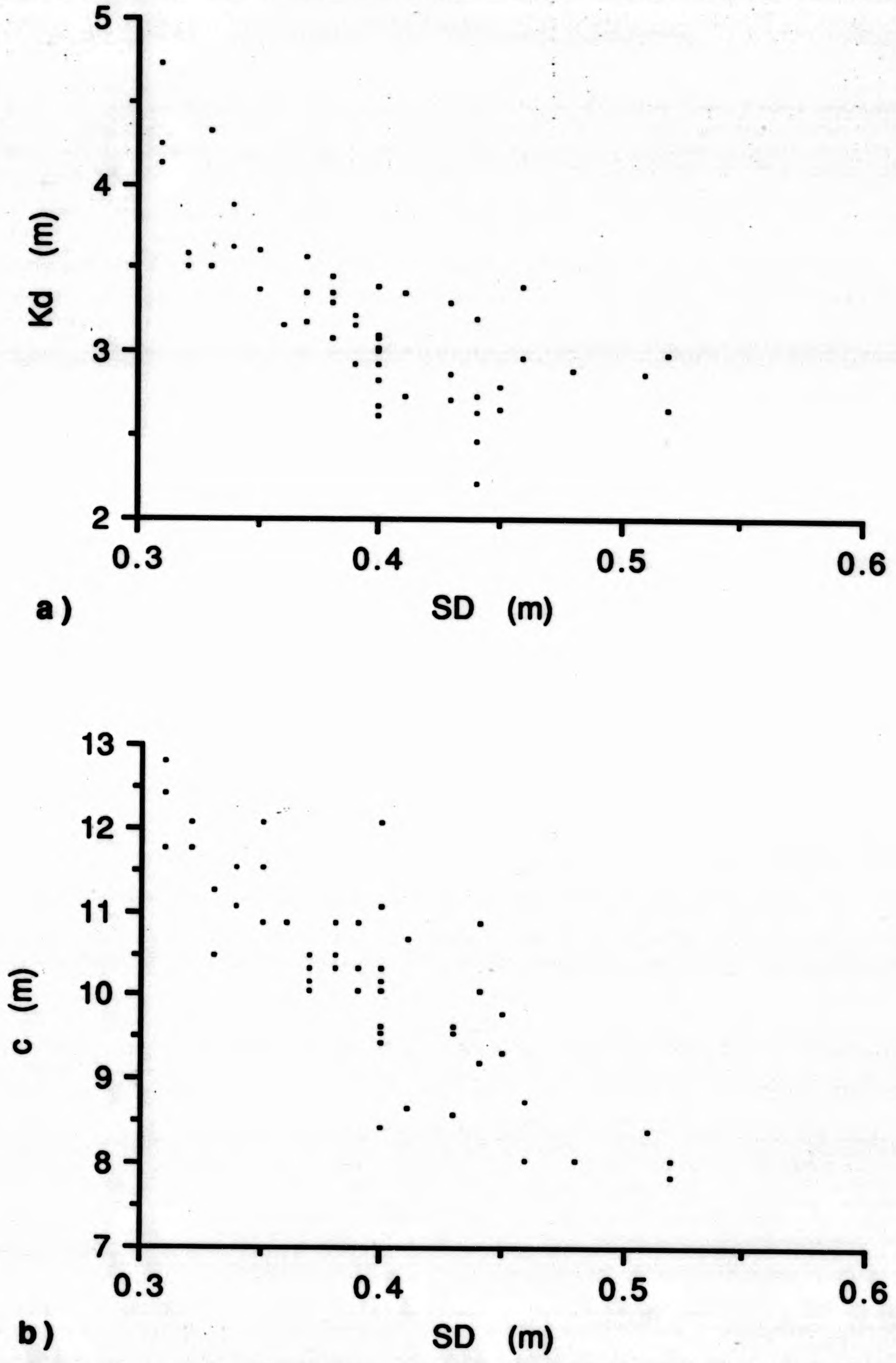


Figure 7.4

The relationship of a) vertical attenuation coefficient (Kd) and b) beam attenuation coefficient (c) versus secchi disc depth (SD) in Lake Patzcuaro, Michoacan, Mexico.

a) $R^2 = -0.726$, n = 53, $P < 0.001$

b) $R^2 = -0.825$, n = 53, $P < 0.001$



Secchi disc depth, as demonstrated by Preisendorfer (1986), is to a great extent a function of beam attenuation of light which is highly sensitive to light scattering from particles. Euphotic depth, by contrast, has been considered a function of vertical light attenuation which also depends on absorption and scattering, although scattering has less effect on vertical attenuation than it does on beam attenuation (Tilzer, 1988). This concept has been used in conjunction with the Lambert-Bouger Law to relate chlorophyll-a, secchi disc depth and vertical attenuation coefficient to chlorophyll-a and secchi disc predictions (Lorenzen, 1980; Megard et al, 1980). Although the high turbidity in Lake Patzcuaro represents a strong limitation for secchi disc predictions, the secchi disc chlorophyll-a relationship can be used to determine the effect of the vertical attenuation coefficient on the secchi disc depth for the lake. According to Lorenzen (1980) the secchi disc depth follows the relationship SD = (-ln Zsd)/(Kd+ b CHL), where Zsd is the percentage of surface light at secchi disc depth in decimals and b is the constant for the incremental extinction coefficient from algae. When chlorophyll-a concentrations are high, the vertical attenuation coefficient is controlled by chlorophyll-a. From Lorenzen (1980), a constant of 0.02 was assumed for b. In order to complete the equation the percentage of surface light at secchi disc depth must be found. Using Equation 65 from Preisendorfer (1986) and the value for the coupling constant for Lake Patzcuaro, the depth of the secchi disc in Lake Patzcuaro gives a range of 21% to 37% surface light with a mean value of 28%. By applying Lorenzen's equation it is possible to predict secchi disc depths for Patzcuaro using the coefficient of light attenuation and chlorophyll-a. Figure 7.5 shows the correlation between observed and predicted values of secchi disc using Lorenzen's equation. As can be observed, despite the interference due to high turbidity, the relationship between the vertical attenuation coefficient and chlorophyll-a and its effects on secchi disc depth is evident. Therefore, the amount of chlorophyll-a in the lake has an influence on vertical attenuation and secchi disc values.

In order to differentiate the fraction of vertical attenuation coefficient which corresponds to chlorophyll-a, Megard <u>et</u> <u>al</u>, (1980) propose that the total attenuation coefficient depends linearly upon concentrations of chlorophyll-a according to the expression $Kd = Kw + Kc\ CHL$, where Kw is the specific attenuation due to substances other than algae and Kc is the specific attenuation due to chlorophyll-a. These partial coefficients were calculated from the intercept (Kw) and the slope (Kc) of the linear regression of Kd versus chlorophyll-a. This relationship has been applied in different locations with reasonable predictions (Schanz, 1985; Weidemann and Bannister, 1986; Tilzer, 1988). Figure 7.6 illustrates the relationship between diffuse attenuation and chlorophyll-a for Lake Patzcuaro. The linear relation is expressed as

$$Kd = 2.14 + 0.0249\ CHL$$

Figure 7.5

The correlation between predicted and observed values of secchi disk (SD) for Lake Patzcuaro, Michoacan, Mexico. Predicted values estimated from Lorenzen (1980). $R^2 = 0.910$, n = 53, $P < 0.001$

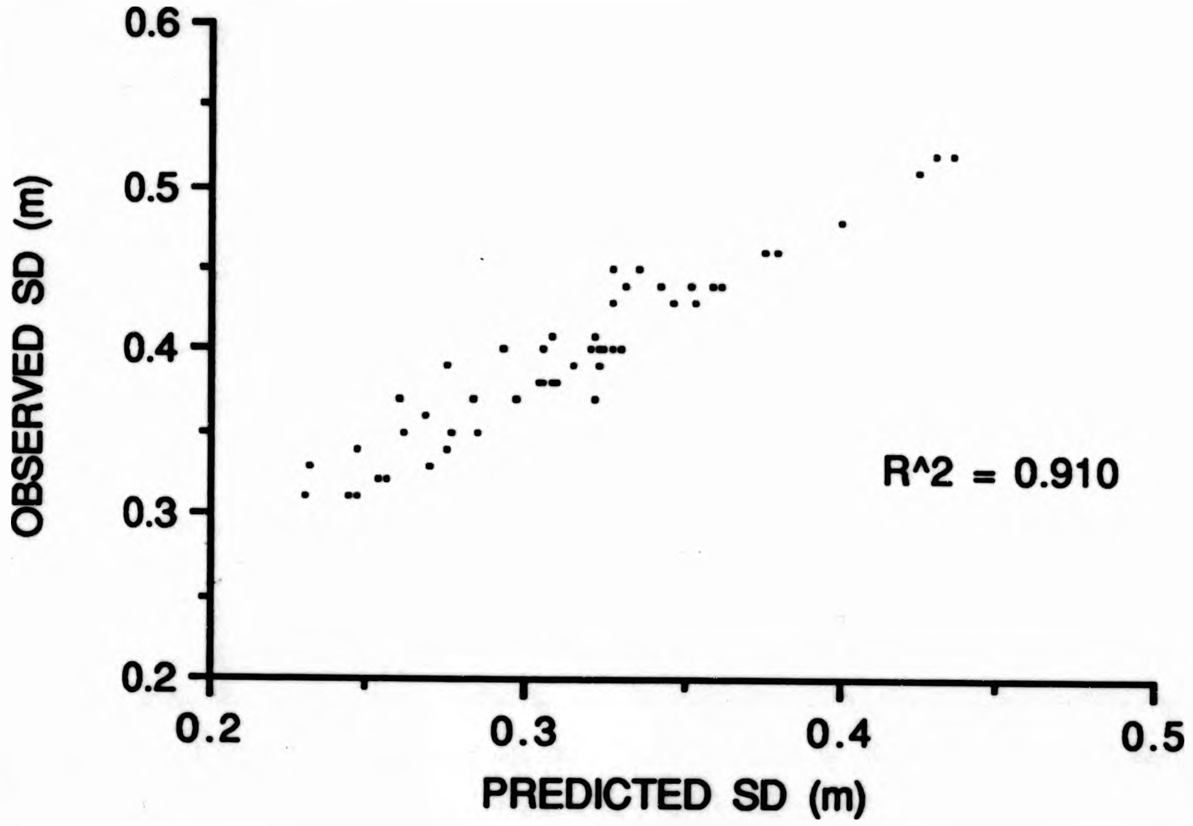
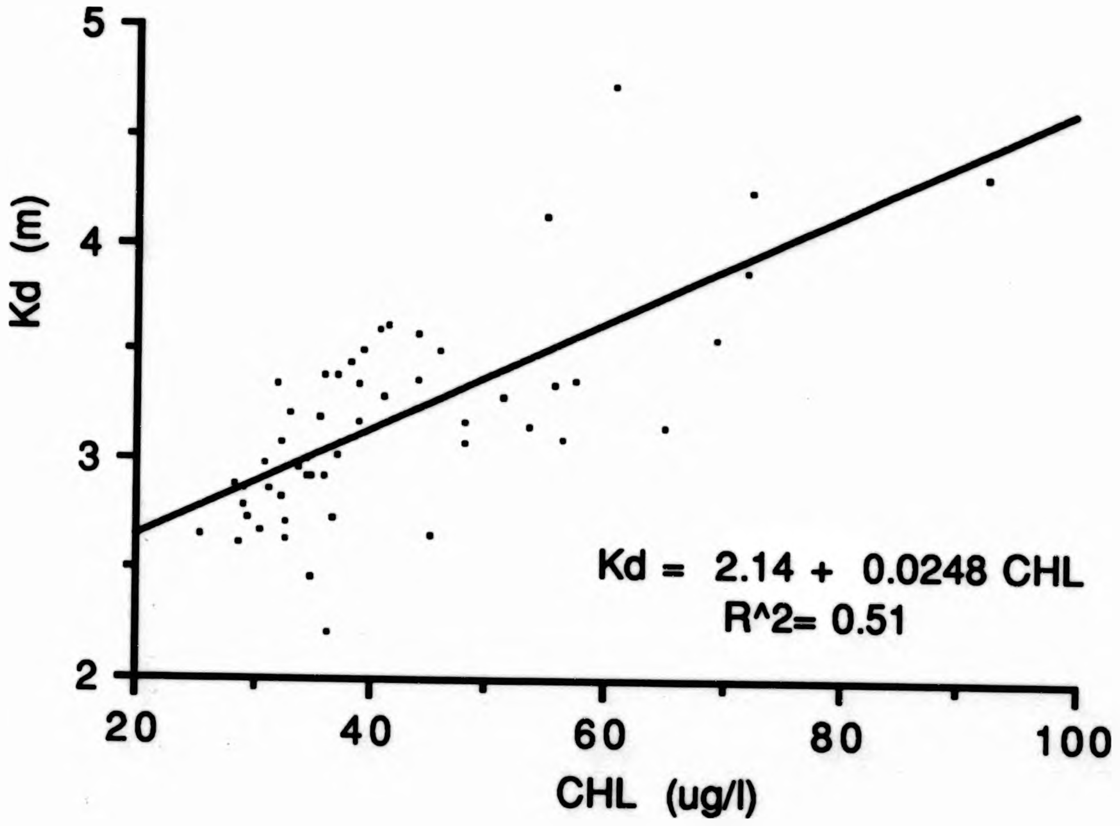


Figure 7.6

Linear regression of vertical attenuation coefficient (Kd) and chlorophyll-a (CHL) for Lake Patzcuaro, Michoacan, Mexico.

Kd = 2.14 + 0.0248 CHL.

$R^2 = 0.51$, n = 53, P < 0.001



This relationship can be compared with previous reports in other locations (Table 7.2). The high value of Kw for Lake Patzcuaro as in Lake George, Uganda, indicates that non-chlorophyll particles have a considerable influence on vertical light attenuation. This is also supported by the relatively high correlation of suspended solids with chlorophyll-a (Table 7.1 and Figure 7.7). The average ratio for CHL/SS is approximately 0.003 by weight. If chlorophyll-a is assumed to be 1.0% of the ash-free dry weight of algae (Lorenzen, 1980) then algal biomass represents 30% of the total suspended solids in Lake Patzcuaro. Therefore, the remaining 70% of total suspended solids is likely to be inorganic particles and decomposing organic matter. The relatively lower but significant correlation of beam attenuation coefficient with suspended solids (Table 7.1 and Figure 7.8) suggests that beam attenuation is not only affected by suspended solids but also dissolved inorganic materials which account for a large proportion of scattering.

These results from Lake Patzcuaro in relation to the underwater light environment suggest that high levels of turbidity, probably induced by silt and other inorganic minerals from erosion processes and water mixing, intensify light scattering. Consequently, high coefficients of light attenuation and a shallow euphotic depth (1.5 m) are observed. These conditions necessarily limit primary productivity by reducing the volume of water in which phytoplankton communities are photosynthetically efficient.

Table 7.2. A comparison of specific attenuation coefficients for chlorophyll-a (Kc) and inorganic particles (Kw) for Lake Patzcuaro (Mexico), Lake Zirahuen (Mexico), Loch Leven (Scotland), Lake Windermere (England), Lake Zurich (Switzerland), Lake Constance (West Germany), Lake Minnentonka (USA) and Lake George (Uganda).

	Kw (m2/mg)	Kc (m2/mg)	Reference
Lake Patzcuaro	2.14	0.025	Present thesis.
Lake Zirahuen	0.22	0.018	Present thesis.
Loch Leven	0.70	0.009	Bindloss, (1974)
Lake Windermere	0.32	0.020	Talling, (1960)
Lake Zurich	0.30	0.020	Schanz, (1986)
Lake Constance	0.27	0.015	Tilzer, (1988)
Lake Minnentonka	0.68	0.022	Megard _et al_, (1979)
Lake George	2.50	0.021	Ganf, (1974)

Figure 7.7

The relatioship between chlorophyll-a (CHL) and suspended solids (SS) in Lake Patzcuaro, Michoacan, Mexico.

$R^2 = 0.628$, $n = 53$, $P < 0.001$

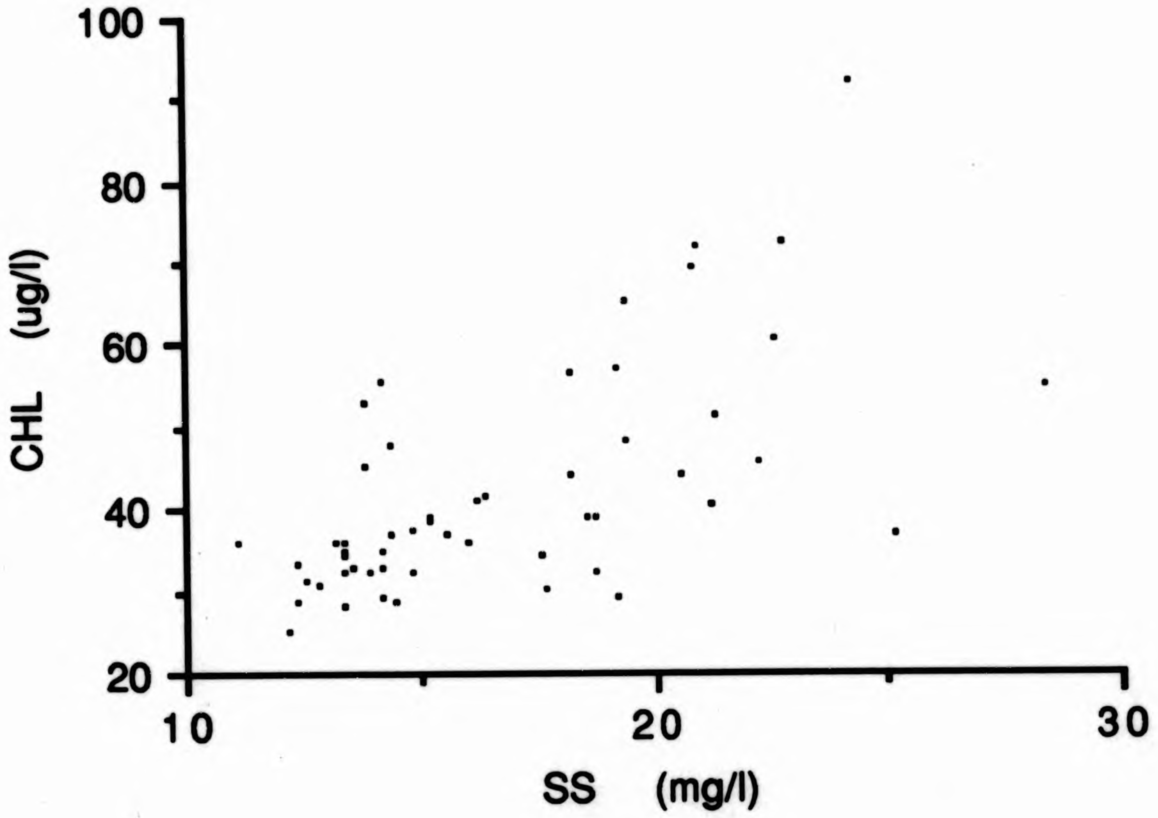
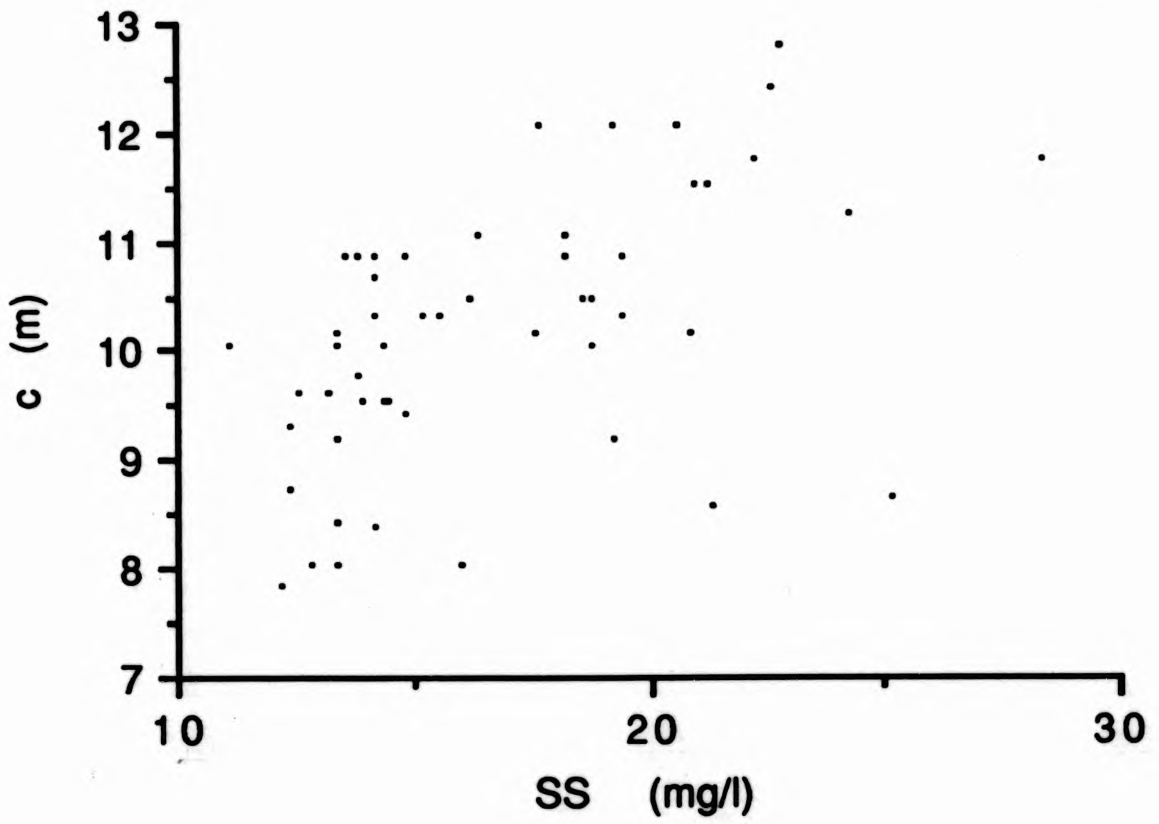


Figure 7.8

The relationship between beam attenuation coefficient (c) and suspended solids (SS) in Lake Patzcuaro, Michoacan, Mexico.

$R^2 = 0.526$, n= 53, $P < 0.001$



Cost-effectiveness of using remote sensing.
Chlorophyll-a is considered one of the most important ecological indicators in marine and freshwater ecosystems, and its monitoring and mapping is essential to evaluate aquatic productivity and environmental impact. Mapping chlorophyll-a distributions to provide detailed synoptic information on the productivity of extensive areas of aquatic environments has recently been the focus of numerous studies.

Substantial progress has been made in the last two decades in applying remote sensing observations from aircraft and spacecraft in aquatic sciences. Particular emphasis has been placed on measurements of water quality, pollution problems, coastal processes and water body inventory and classification. The final objective of this approach is usually the design of mathematical models which are applied for monitoring and prediction of environmental processes. The information value from remote sensors depends primarily upon three factors; spatial resolution (the minimum area detectable by the sensor); spectral resolution (a function of the range of wavelengths in which an object on the ground emits or reflects the radiant energy); and temporal resolution (the ability to obtain data at regular intervals). Spatial and spectral resolution are strongly interdependent. The finer the spatial and spectral resolution, the better the information content for water resources assessments. Better temporal resolution increases the possibility to detect changes. The benefits of such models depend however, on further verification procedures.

To date, high spatial resolution in multispectral digital imagery has been achieved by SPOT-1 to a reasonable resolution (20 m x 20 m) in which relatively small aquatic systems (up to 1.0 ha) can be evaluated. However, the low spectral resolution given by the limited number of spectral bands is a potential disadvantage for aquatic investigations.

Chlorophyll-a has a specific and distinctive spectral response in the electromagnetic spectrum. Maximum irradiance absorption of chlorophyll-a occurs in the range of 0.40-0.51 um, with a maximum absorbance at 0.44 um. Beyond this range chlorophyll-a has a strong reflectance similar to suspended sediments thus making differentiation difficult in aquatic systems. The spectral range of maximum absorbance for chlorophyll-a cannot be obtained by SPOT-1 XS imagery. Better spectral resolution using multispectral digital imagery has been achieved by the LANDSAT series of satellites using the Thematic Mapper system, which provides digital data in seven bands, including that for chlorophyll-a (0.45-0.52 um). However, less spatial resolution is provided (30 m x 30 m) by this system.

Although recent experiences reported from different latitudes suggest that remote sensing can make a major contribution to the assessment of water resources, a better spectral resolution would be beneficial in lake management, fisheries and aquaculture projects in order to determine independently the concentration and distribution of more water quality indicators such as salinity, suspended solids, transparency, nutrients, and phytoplankton and macrophyte group associations.

In Lake Patzcuaro the reflectances of chlorophyll-a and suspended solids were not different for the spectral bands recorded by SPOT-1. The water quality results indicated a strong correlation between these two parameters and hence a similar distribution in the lake was expected. The number of independent components within the reflectance values in the image limit the number of independent water quality parameters that can be determined. Despite these limitations, it was possible in this study to identify two components in the digital data using an appropriate statistical approach, thus enabling advantage to be taken of the excellent spatial resolution provided by SPOT-XS imagery.

Significant improvements in both spatial and spectral resolution are expected in the next generation of the LANDSAT series of satellites. The new Advanced Landsat Sensor (ALS) Spectrometer is designed to operate in contiguous spectral bands of 20 nm width with improved spatial resolution to 7 m x 7 m. This will dramatically enhance spectral sensitivity compared with the 100 nm of the MSS, 70 nm of the TM and 80 nm of the XS.

The benefits of remote sensing techniques are not only derived from the accuracy and amount of information acquired for water resource assessment but also from providing an alternative, cost-effective procedure over conventional surveillance methods. The costs of using remote sensing techniques vary greatly according to the equipment and processing facilities which may be available for the project. In the case of Lake Patzcuaro, for example, occasional hydrobiological surveys (e.g. once a year) in order to detect changes in water transparency would not be sufficient to justify the use of digital satellite data. This is because the lake can be easily surveyed by boat, light aircraft or motor vehicle along the shore which would provide useful information at low cost when only occasional surveillance is required.

If a longer term lake management programme is envisaged, however, then baseline data on catchment area, soil classification, erosion loads, land use classification, water quality monitoring, primary productivity rates and macrophyte mapping are all required for the design of appropiate ecological recovery strategies, fisheries assessment and aquaculture appraisal. The estimated cost per year of using conventional surveys for such a study would be approximately US $112 per km2 of catchment area (Chacon-Torres <u>et</u> <u>al</u>, 1988) (Table 7.3). This figure would increase by around 15% if aerial photography were used since more professional services would be needed. Aerial photography

Table 7.3. Cost estimation of three alternative methods for lake assessment, using Lake Patzcuaro Basin, Mexico, as a model. (930.00 km2) * +

Description	Ground-based conventional survey	Ground-based and aerial photography	Ground-truth and digital MSS imagery
Personnel[a]	50,000	50,000	8,500
Terrestrial[b] and aquatic transportation	15,000	15,000	3,000
Fuel	2,000	2,000	400
Equipment[c]	10,000	10,000	10,000
Laboratory[d] analysis	18,000	18,000	3,000
Aerial survey[e]	-	6,000	-
Digital imagery[f]	-	-	14,000
Computing:			
-Hardware[g]	7,000	12,000	24,500
-Software	2,000	3,000	7,000
TOTAL	104,000	116,000	70,400

* Costs are based on actual survey carried out in Lake Patzcuaro, Mexico, 1986-1987.

+ Costs expressed as US $ dollars.

[a] Assuming 5 personnel (US $ 850.00 per person per month).

[b] Includes lorry and two boats to achieve 100 km2 lake sampling in 45 minutes.

[c] Includes field equipment for water sampling and <u>in-situ</u> water analysis.

[d] Includes reagents, general glassware, spectrophotometer and Millipore filtration unit.

[e] Two aerial surveys would be required ; one in the rainy season and one in the dry season.

[f] Four full scene TM computer compatible tapes would be required to cover seasonal changes. (US $ 3500 each including shipping costs). For conventional survey, image processing is not required.

[g] Minimum hardware components include an IBM PC-AT computer (or compatible), 640 Kb RAM, hard disk with 30-70 Mb storage, graphics processor, mouse, high resolution graphics printer, image display (512 x 512 bits) and CCT tape drive. A more powerful alternative processing system could replace the PC by a MicroVax computer.

Aerial photography would require a digitising video camera with frame store for accurate mapping.

would increase the spatial resolution but would not improve the cost-effectiveness. If multispectral imagery were employed, ground/water sampling crews would be necessary only for the first date of satellite flyover, although a second simultaneous sampling is recommended for possible corrections in ground truth data or model verification. Seasonal changes could then be observed by selecting the best sets of digital data available from the satellite through the year.

Since digital imagery data are provided on computer compatible tapes (CCT), a mainframe computer has usually been used for digital image processing, because the volume of one image is approximately 100 Mb in size. Subscenes of digital imagery are now available on 5.25" floppy discs from both LANDSAT and SPOT satellites. The data are provided in MS/PC-DOS format to be used in IBM PC-AT and compatible systems. Minimum hardware components include an IBM PC-AT computer (or compatible), 640 Kb RAM, hard disk with 30-70 Mb storage, graphics processor, mouse, high resolution graphics printer or plotter, image display (512 x 512 bits) and a CCT tape drive. A more powerful alternative processing system would replace the PC unit by a MicroVax, or similar, computer. The software required depends on the quality of the image which may, for example, need corrections for cloud removal, enhancement and image restoration techniques; the software is widely available commercially and is routinely used (DIAD, ERDAS, and others).

Thus, estimated costs, for Lake Patzcuaro, using multispectral imagery would be approximately US $76 per km2 if the purchase of complete image processing instrumentation and personnel were included in the budget. A decrease of about 33% from a conventional annual survey could thus be achieved (Chacon-Torres et al, 1988). If computing and image processing were not available and it was necessary to hire professional services, then estimated costs per km2 of catchment area would be about US $46. Thus, it appears at first sight as if remote sensing processing using professional companies is the cheapest option. However, cost-effectiveness in remote sensing will be further improved when personnel, hardware, and basic software are available and many governmental and educational institutions do have these facilities. Therefore, once the capital equipment has been purchased, then annual in-house costs estimates of US $76 per km2 will be drastically reduced. With advances in computer technology, new opportunities have been created to edit and display large volumes of geographical data. Different thematic maps of a particular area may be in different scales and in different formats (maps, aerial photography, satellite imagery, statistical data, diagrams and drawings). Data on water quality, land use, fisheries, social and economic statistics can be integrated into a database by using a combination of programmes to store, process and display the information for further classification and assessment. Recently these techniques have been developed into Geographical Information Systems (GIS). The combination of remote sensing technologies with data models generated by Geographical Information Systems can provide an up-to-date environmental integrated baseline on water and land resources of a particular region.

Kapetsky et al, (1987) provided an example of the potential benefit of using the GIS for natural resources assessment as a tool to plan aquaculture expansion in developing countries. The results give an excellent illustration of the application of these technologies in providing a variety of environmental information useful to aquaculture.

The results from the hydrobiological survey of Lake Patzcuaro indicate that remote sensing costs for preliminary surveillance in aquatic sciences remain high. However, the advantages of satellite data over conventional sampling procedures include repetitive coverage of a given area, a synoptic view which is not possible to obtain by conventional methods, and almost instantaneous spatial data over the area of interest. Once it is possible to combine the data collected on the ground with satellite data, detailed mapping and monitoring of water resources becomes a more feasible task in terms of time and spatial coverage.

Trophic state of Lake Patzcuaro.

Nutrients.

Numerous studies have shown either nitrogen, or phosphorus, or both to be limiting nutrients in the productivity of lakes (Sakamoto, 1966; Vollenweider, 1968; Dillon and Rigler 1974; Schlinder, 1975). Temperate zone studies have shown that the concentration of total phosphorus can be used as a predictor of chlorophyll-a or algal biomass (Jones and Bachmann, 1976; Jones and Lee, 1986). Nitrogen rather than phosphorus is believed to be the limiting nutrient in tropical freshwater (Talling, 1966; Lewis, 1974; Henry et al, 1984), although a number of recent studies of African lakes have indicated that phosphorus limits algal growth in some tropical lakes (Melack et al, 1982; Kalff, 1983; Thorton and Walmsley, 1982).

Water quality data for Lake Patzcuaro collected during the winter of 1986-1987 indicated a significant correlation between chlorophyll-a and total phosphorus concentrations (Figure 7.9). Although it was not possible to obtain total organic nitrogen values during the field work, the relationship between orthophospate and mineral nitrogen concentrations (the sum of ammonia, nitrite and nitrate) (Figure 7.10) indicated a very low N:P ratio (1.5:1), suggesting N limitation. On the other hand, low values of mineral nitrogen can also represent a residue from algal growth since most of the nitrogen may be bound in phytoplankton biomass. Assuming an average conversion

Figure 7.9

The relationship between chlorophyll-a (CHL) and total phosphorus (TP) in Lake Patzcuaro, Michoacan, Mexico.

$R^2 = 0.780$, $n = 120$, $P < 0.001$

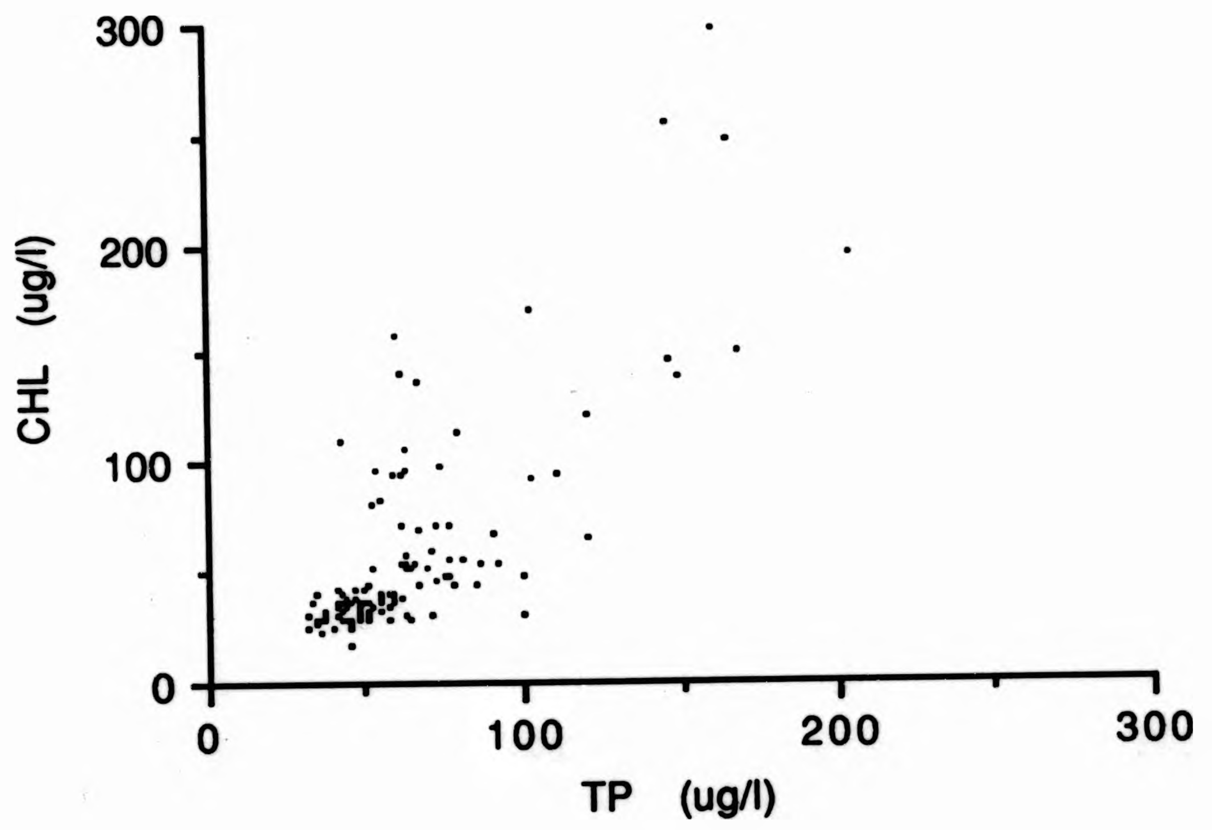
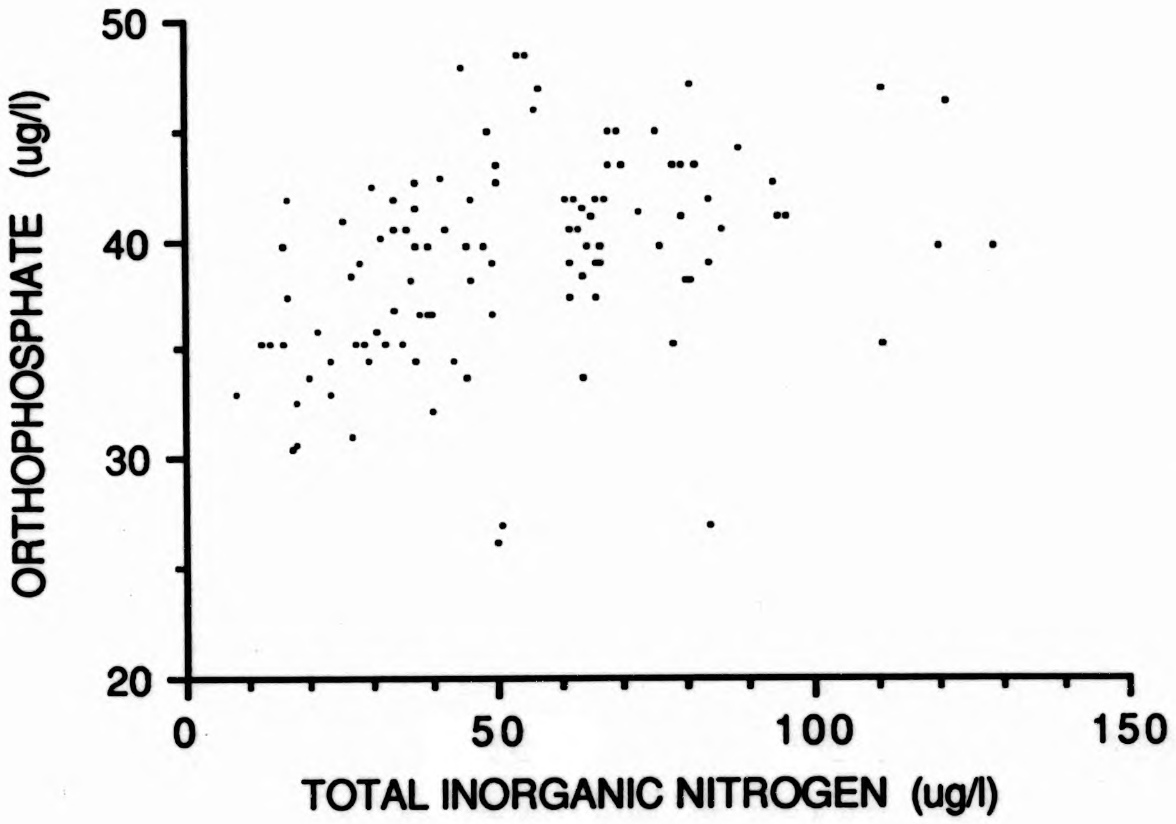


Figure 7.10

The relationship between dissolved reactive phosphorus (DRP), measured as orthophosphate, and total organic nitrogen, measured as the sum of ammonia (NH_4), nitrite (NO_2), and nitrate (NO_3), in Lake Patzcuaro, Michoacan, Mexico. $R^2 = 0.158$, $n = 120$, $P < 0.1$



factor of 16 (and a range between 10-25), theoretical total nitrogen concentrations can be estimated from chlorophyll-a determinations (Vollenweider, personal communication). The difference between total phosphorus and dissolved orthophosphate is roughly the value bound in biomass. Thus the chlorophyll-a/phosphorus ratio contained in biomass would be at least 2. Consequently, the nitrogen/phosphorus in biomass would represent a value of 36, which is characteristic of phosphorus-limited phytoplankton growth (Vollenweider, personal comunication).

Trophic state indices.

Trophic state indices (TSI) are essentially single dimension values associated with lake trophic state. Within this single dimension the index can summarize various water quality variables representing the same basic concept of eutrophication (Reckhow and Chapra, 1983). Trophic state indices are frequently used in lake management because of the advantage of summarizing water quality information in a numerical mode ranging from oligotrophy to eutrophy. However, trophic state indices should be interpreted as indicators of trophic state and they should not be used to define the trophic state of a particular lake which is a more complex concept. Moreover, conventional trophic state indices have been developed and applied mostly in temperate zones using local water quality data and their use in low latitudes where sunlight exposure, temperature and lake productivity are generally higher may result in an overestimate.

In order to examine the applicability of trophic state indices in Lake Patzcuaro, three multivariate TSI indices were selected and compared in this study; those of Shannon and Brezonik (1972), Carlson (1977), and Walker (1979) (Appendix 5). Criteria for TSI selection were that multivariate indices which include two or more water quality variables provide a more "robust" TSI value as an indicator of trophic state than a single water quality variable. Figure 7.11 illustrates the distribution of trophic state indicators in Lake Ptazcuaro using the TSI index proposed by Shannon and Brezonik (1972). As can be seen, the TSI was sensitive enough to classify water quality indicators ranging from hypereutrophic conditions, such as those areas related to the algal bloom in the northern basin, to oligo-mesotrophic conditions in an area located west of Janitzio and Yunuen Islands (Station 16). Although the distribution of the TSI is somewhat crude, areas of clear and turbid water were similar to those detected by SPOT-1 satellite imagery (Plate 6.2).

Another site of acceptable resolution was that located in the Central basin (Station 11) where the TSI indicated a boundary of meso-eutrophic conditions. This area was also detected by satellite as one with high concentrations of chlorophyll-a (Plate 6.2). By contrast, TSI indices proposed by Carlson (1977) and Walker (1979) (Figures 7.12 and 7.13) both greatly overestimated trophic state indicators in Lake Patzcuaro and their resolution compared with the TSI of

Figure 7.11

Trophic state index (TSI) for Lake Patzcuaro, Michoacan, Mexico, using the TSI proposed by Shannon and Brezonik (1972).

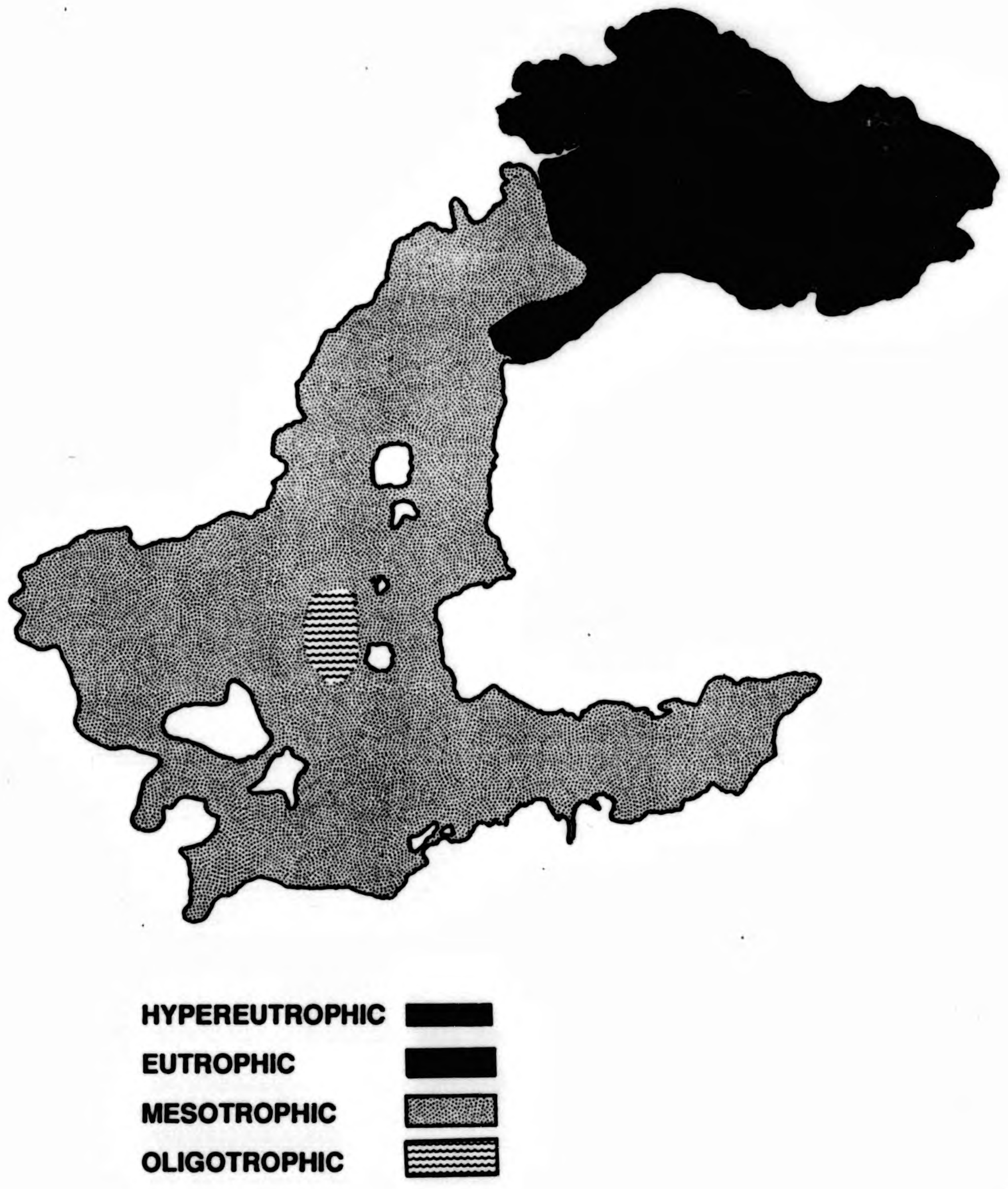


Figure 7.12

Trophic state index (TSI) for secchi disk (XSD), chlorophyll-a (XCHL) and total phosphorus (XTP), for Lake Patzcuaro, Michoacan, Mexico, using the TSI proposed by Carlson (1977).

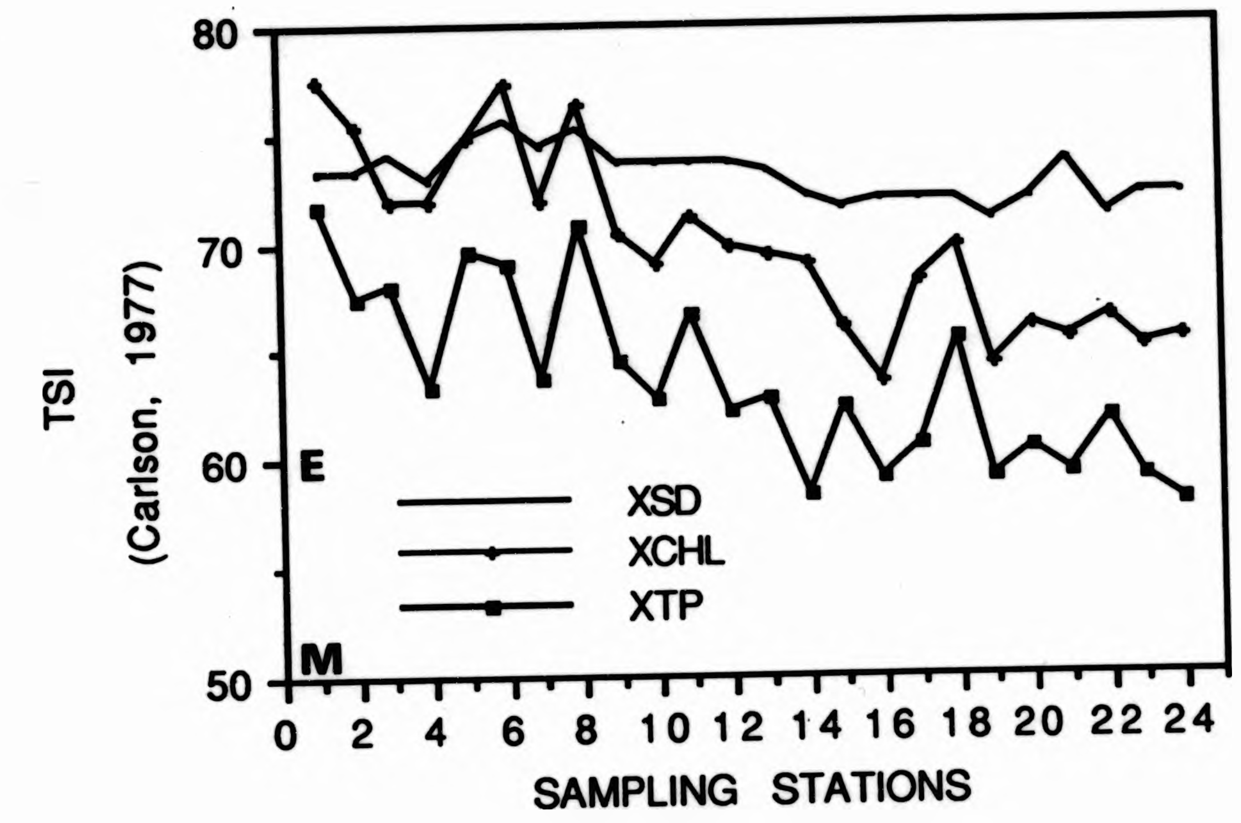
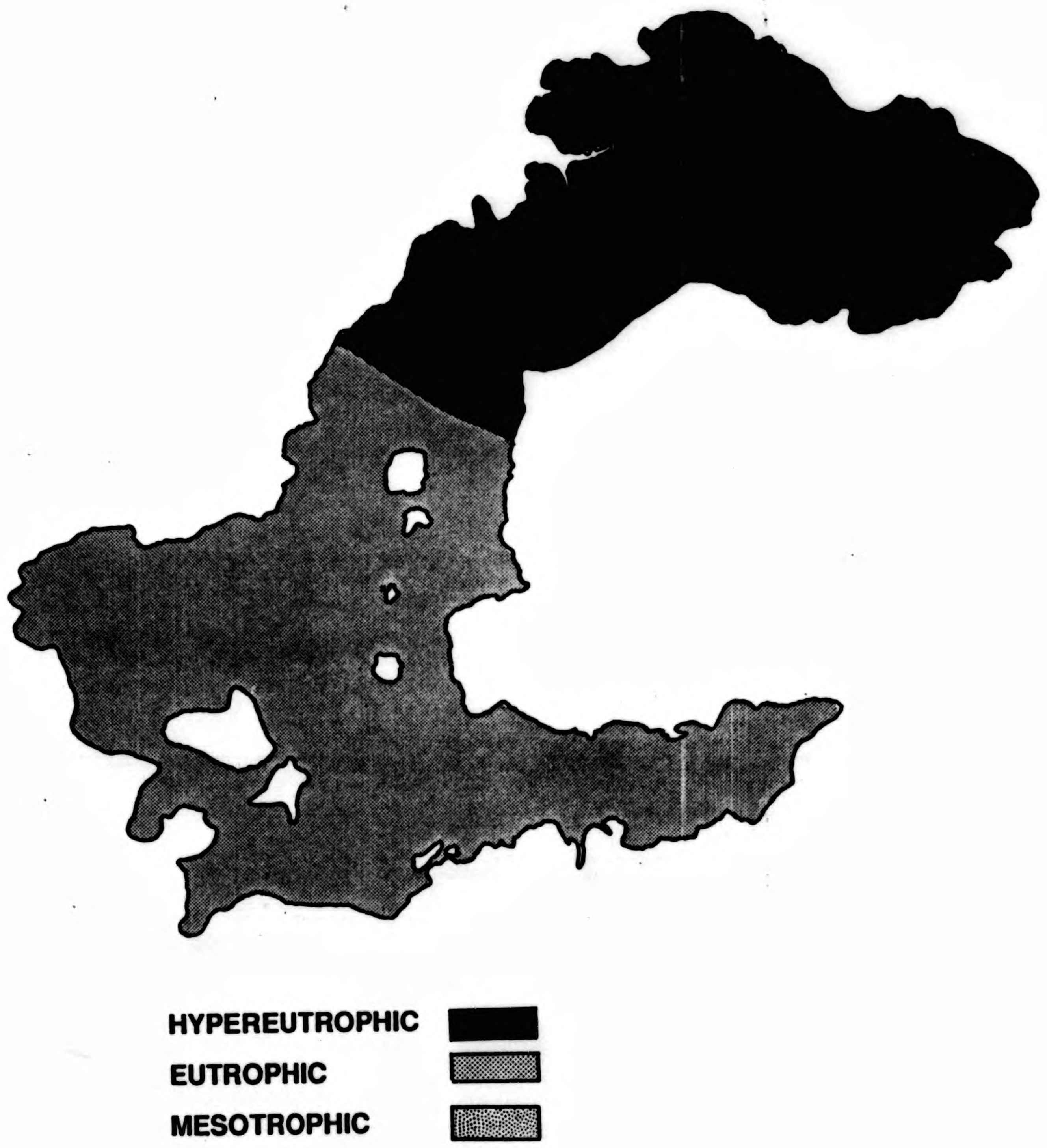


Figure 7.13

Trophic state index (TSI) for Lake Patzcuaro, Michoacan, Mexico, using the TSI proposed by Walker (1979).



Shannon and Brezonik was very poor. This overestimation is explained firstly because of the apparent bias that secchi disc transparency imposes on both Carlson's and Walker's indices, and secondly because these indices were developed in clear, thermally-stratified lakes located in temperate zones where allochthonous materials were not significant.

In the case of Shannon and Brezonik, the index was formulated using principal component analysis incorporating seven physical, chemical and biological trophic state indicators. In this index, the influence of secchi disc transparency due to inorganic materials is offset by the inclusion of primary production data. Their TSI quantified 55 Florida lakes with a wide range of environmental conditions in which anthropogenic activities were the major factor influencing the trophic state classification. Although the TSI formulated by Shannon and Brezonik was formulated for lakes in higher latitudes, its sensitivity was acceptable for Lake Patzcuaro. However, the index should not be considered definitive and verification studies would need to be carried out on different water bodies located in the Mexican Plateau. It also would be appropiate to apply the same statistical technique of principal component analysis for regional classification, incorporating additional environmental factors which seem to have significant effects on primary productivity and the general trophic state. In the case of Lake Patzcuaro, the role of suspended solids, total solids and light attenuation instead of secchi disc values should be considered before applying trophic indices for lake management.

From the present study, and by using the Shannon and Brezonik TSI index, it is considered that meso-eutrophic conditions predominate in Lake Patzcuaro with some northern areas susceptible to temporary hypereutrophication mainly associated with dense algae blooms and municipal sewage. Comparatively small areas appear to indicate oligo-mesotrophy in the western region of Janitzio Island. This areal distribution is supported by concurrent analysis and modelling of chlorophyll-a and suspended solids derived from SPOT-1 digital multispectral imagery.

Phosphorus models.

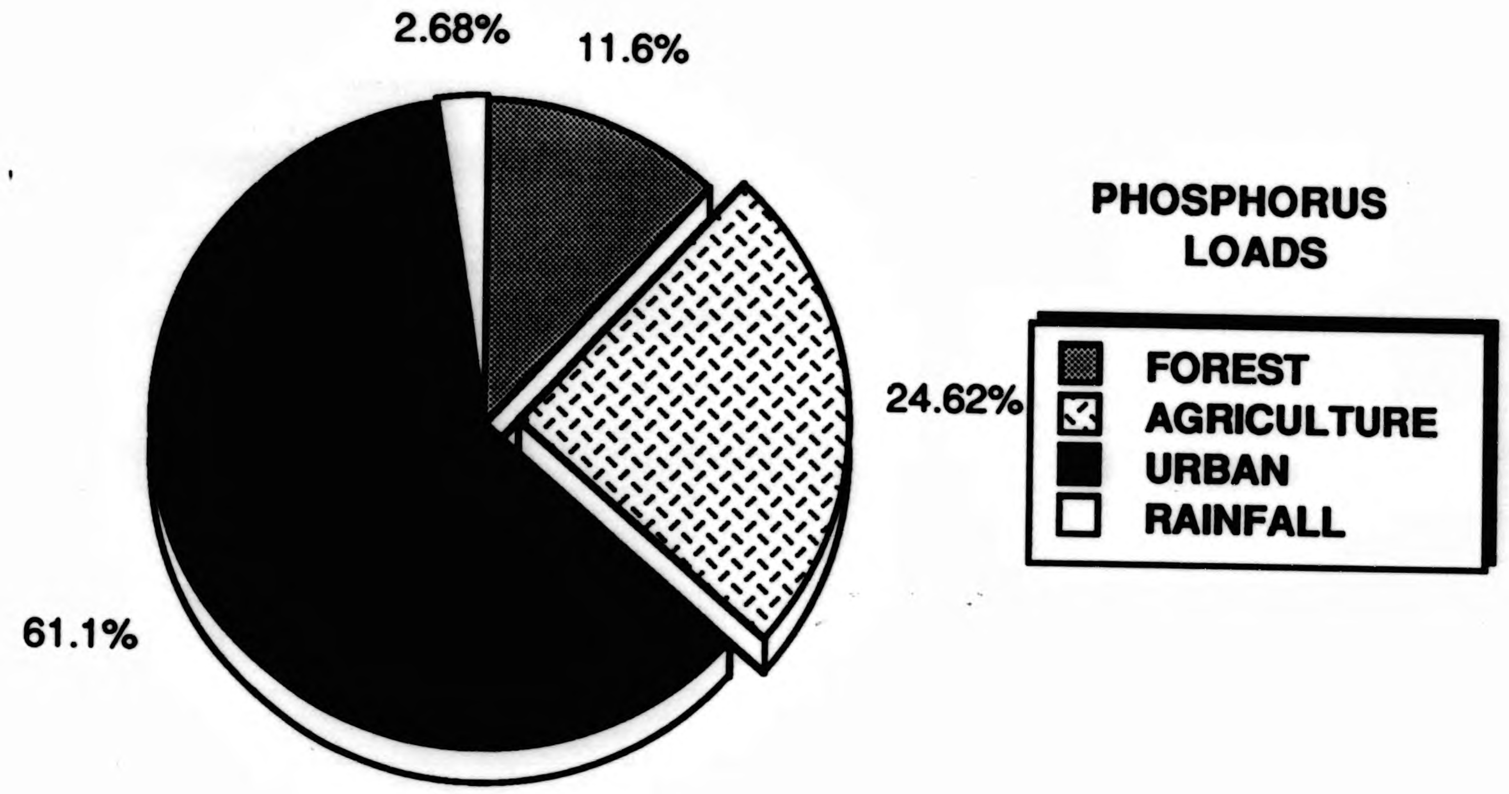
An alternative approach to evaluation of lake trophic state is the use of the input-output limiting nutrient models, which relate the response of trophic status to allochthonous loadings such as natural and agricultural runoff and municipal and industrial contributions (Stumm and Baccini, 1978; Reckhow and Chapra, 1983; Henderson-Sellers and Markland, 1988). The first statistical models using phosphorus as a limiting nutrient based on empirical data were described by Vollenweider (1968, 1975, 1976), and later developed by Dillon and Rigler (1974), Kirchner and Dillon (1975), Jones and Bachmann (1976) and Reckchow (1979, 1988). By using mass balance equations these models are formulated to predict lake phosphorus concentrations which can then be correlated to different lake trophic states (Beveridge, 1984). In general, the input-output models are expressed so that a lake is assumed to behave as a static (steady-state) system and is thus time-independent, and to be completely mixed with instantaneous reactions and uniform concentrations throughout. These models have been widely applied in both temperate and tropical latitudes using shallow and deep lakes (OECD, 1982; Thornton and Walmsley, 1982; Beveridge, 1984) and have shown a considerable variety of correlations, standard errors and uncertainties. However, mass balance models have been considered a valuable approach for lake management when accurate regional data are incorporated and verified within a statistical uncertainty context (Mueller, 1982). In the case of Lake Patzcuaro, the application of mass balance models for lake trophic assessment has not been considered previously. Although the effectiveness of these models has not been examined on a regional basis, this approach could be useful in the evaluation of the effects of anthropogenic activities on the productivity of the lake.

In order to evaluate the applicability of mass balance models in Lake Patzcuaro, two phosphorus loading models were applied to predict lake total phosphorus concentration as a response to external phosphorus sources. Calculations for phosphorus loadings were made using the criteria suggested by Dillon and Rigler (1975) and Reckhow and Chapra (1983) (Appendix 6). Given the difficulties associated with the calculation of the phosphorus sedimentation rate coefficient, the models were applied using the equation proposed by Dillon and Rigler (1975) incorporating the retention coefficient in the first model, and the equation proposed by Reckhow (1979) incorporating the settling velocity in the second model. The latter included the uncertainty analysis procedure (Reckhow and Chapra, 1983).

Phosphorus export loadings from the catchment area in Lake Patzcuaro (Figure 7.14) suggested that the major contribution to total phosphorus loads (61.1%) is from point sources represented by domestic, agricultural and industrial sewage and urban runoff. This was followed by the estimated rural non-point sources (24.6%) from an approximate 43,553 population distributed in 30 towns and villages without sewer systems. By using the model suggested by Dillon and Rigler (1975) lake phosphorus concentrations were overestimated by 30% (85 ug/l) of the average observed value (65 ug/l). The calculation of the apparent sediment retention coefficient (0.943) used the approximation of Dillon and Rigler (1975). Given that oxygen depletion was not observed near the bottom of the lake it is possible that the actual sediment retention coefficient was slightly higher than that computed by the Dillon and Rigler method (e.g. 0.953). A higher value of sediment retention coefficient was achieved by using the relationship formulated by Reckhow and Chapra (1983; Equation 8.23), which yields a value for lake total phosphorus concentration

Figure 7.14

Estimated phosphorus loads from the catchment area of Lake Patzcuaro, Michoacan, Mexico. Phosphorus export loads are based on Reckhow (1979).



of 71 ug/l. In the case of the equation suggested by Reckhow (1979) lake phosphorus concentrations were overestimated by only 8% (71 ug/l) using the average settling velocity coefficient suggested by Reckhow and Chapra (1983). The results of the uncertainty analysis indicated that Lake Patzcuaro has a predicted value of lake phosphorus concentration of 71 ug/l with 55% confidence limits bounding the true phosphorus concentration between 42 ug/l and 129 ug/l.

By using the minimum values predicted by the model and the probability distribution categories presented by OECD (1982), Lake Patzcuaro can be classified as a meso-eutrophic lake with a 55% probability of being mesotrophic and 40% eutrophic (TP=42 ug/l). If the maximum value is considered (TP=129 ug/l) then the lake would be considered as 90% hypereutrophic and 10% eutrophic. An average value (71 ug/l) assigns Lake Patzcuaro as 65% eutrophic and 35% mesotrophic.

From the analysis of phosphorus loading models it can be seen that Lake Patzcuaro is predominantly eutrophic with major contributions from anthropogenic activities. The sensitivity of trophic state assessment can be greatly improved by incorporating field data on phosphorus export coefficients from the watershed and on settling velocity in the lake.

Fish yields.

The potential of using biotic and abiotic variables as predictors of fish yields in freshwater ecosystems has been evaluated intensively. Recent reviews have been presented by Henderson et al (1973), Ryder et al (1974), Marten and Polovina (1982), Oglesby (1982), Ryder (1982), Beveridge (1984) and Kerr and Ryder (1988). Some of the variables include mean depth (Rawson, 1952), total dissolved solids (Ryder, 1965), total phosphorus (Hanson and Legget, 1982), phosphorus loading (Jones and Lee, 1986), and primary productivity (Melack, 1976; McConnell et al, 1977). Useful applications in different latitudes and environmental conditions have been achieved by using the Morphoedaphic Index (MEI) (Henderson et al, 1973) and primary productivity (Liang et al, 1981; Schlesinger and Rieger, 1982; Beveridge, 1984).

The Morphoedaphic Index (total dissolved solids divided by the mean depth), applied originally to estimate sport fish yields in northern temperate latitudes, has been applied extensively to predict fishery potential in tropical latitudes, particularly in African lakes (Henderson and Welcomme, 1974). Statistical regressions between MEI and annual fish yields are used to predict potential fish yields. The index represents the effects of two components, lake morphometry and basin geology, on fish production. However, common causes of failure of the model as a fish yield predictor have been attributed to the inclusion of lakes with limnological anomalies in essentially homogeneous data sets and the use of inaccurate field data (Ryder, 1982). Although the high turbidity of Lake Patzcuaro and the intensity of fishing may adversely affect the estimation of potential fish yields when using existing worldwide MEI data sets, rough approximations can be made which support the usefulness of the index in Mexican lakes. Given the lack of field data during a field survey of Mexican lakes, Henderson (1974) suggested the use of the equation derived from African lakes to approximate fish yields.

Using chemical and morphometric data reported for 1974 (Rosas, 1981) and data from the present study during the winter of 1986-1987 (Tables 3.1 and 5.12), the MEI for Lake Patzcuaro was estimated to be 57.1 for 1974 and 115.2 for 1986-1987, corresponding to fish yields of 67.9 kg/ha/year for 1974 and 89.0 kg/ha/year for 1986-1987. Based upon the catch records from Rosas (1981) and the Fisheries Department in the city of Patzcuaro (Lizarraga and Tamayo, CRIP-PESCA, manuscript, 1987), the total fish landings from the lake for 1974 were 305 tonnes (23 kg/ha/year) and 1,350 tonnes for 1986 (103.8 kg/ha/year). As can be observed, the MEI-fish yield relationship for African lakes overestimated fish yields in Lake Patzcuaro for 1974 by 60%, whereas the prediction for 1986-1987 was a slight understimate (14%). However, as indicated by Henderson _et al_ (1973), differences in prediction can be greatly influenced by changes in fishing effort. Moreover, Schlesinger and Regier (1982) concluded that a decrease of temperature due to altitude can have a major effect on fish yield predictions. There should thus be a temperature input into the MEI if the model is to be applied beyond regional climatic boundaries. In the case of Lake Patzcuaro mean annual temperature is significantly less than that recorded for the African lakes data set. If the equation suggested by Schlesinger and Regier is applied for Lake Patzcuaro, then the predicted fish yields would account for 35.4 kg/ha/year for 1974 and 41.0 kg/ha/year for 1986-1987.

Since fishing is not a full-time activity in some villages around the shores of Lake Patzcuaro there are uncertainties about the total number of fisherman in the lake which makes fishing effort difficult to evaluate. Henderson (1974) estimated a total number of 5,000 fisherman, Toledo _et al_ (1980) estimated a total of 1,500 and Lizarraga and Tamayo (manuscript) reported a total of 1,120 fishermen for 1987. Figure 7.15 (a, b) illustrates the catch estimates during the 1950s (Solorzano, 1955) compared with the 1980s. The large increase in fish yields during the present decade may be the result of a) the complete adaptation to the lake of _Micropterus salmoides_ (introduced during the 1930s), _Ctenopharyngodon idellus_, _Cyprinus carpio_ (introduced in 1972) and _Tilapia melanopleura_ (introduced in 1974) (Rosas, 1981), b) the increase in fishing efficiency with the use of new nylon nets with small mesh size (0.5 cm to 13 cm), and c) the improvement in the fish catch monitoring programme by governmental institutions. The decline in fish size and the

Figure 7.15

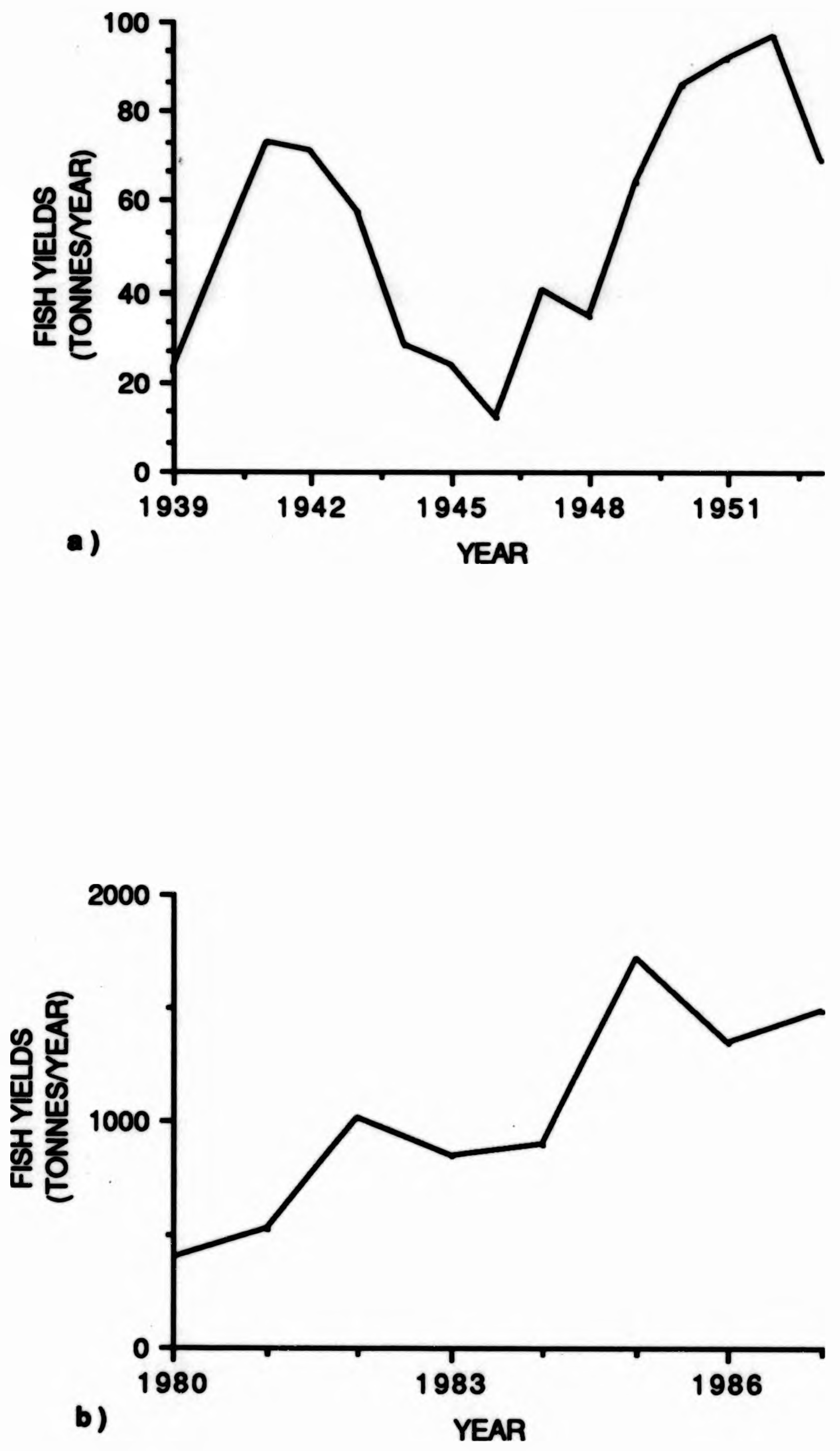
Fish yields recorded for Lake Patzcuaro, Michoacan, Mexico;

a) 1939-1953*, (Solorzano, 1955),

b) 1980-1987+, (Lizarraga and Tamayo, MS).

* Data from market survey (see text).

\+ Data from fish landings.



lower frequency of major commercial fish species in the catch during the last decade (Laboratorio de Biologia Acuatica, UMNSH, personal communication) suggest that fish populations are currently overexploited and that fishing effort (8.6 fishermen/km2) could be well beyond the optimum maximum sustainable yield. Hence, the more conservative MEI model suggested by Schlensinger and Regier (1982) seems more appropiate for Lake Patzcuaro.

Estimates of fish yields using the Morphoedaphic Index in Lake Patzcuaro do not provide high level accuracy with the existing data. However, the sensitivity of MEI models in Lake Patzcuaro for fish yield predictions could be greatly improved if limnological data were collected from similar lakes in the region and assessed in conjunction with accurate data on annual fish landings and fishing effort for each particular lake.

Although the use of a single fish yield model can be a useful estimator for fish production potential, there are possible risks of miscalculations if predictions rely on a single empirical correlation. A second approach is to estimate fish yields based on annual primary productivity.

Since photosynthetic organisms represent the primary source of energy in aquatic ecosystems, significant correlations have been reported between primary productivity and fish yields (Melack, 1976; Marten and Polovina, 1982; Oglesby, 1977). A major limitation of this approach is that energy transfer efficiencies vary with the position of fish species in the production chain. Even a single species requires a certain diversity of food items. Fish larvae start feeding by consuming small items and the proportion of larger particles grazed usually increases with age and size. The composition of the diet can shift either to plant material or benthic fauna and larger animals (Blazka *et al*, 1980). A second limitation (as in MEI models) is the accuracy of data for fish catches and the intensity of fishing. This is further complicated by differences in criteria about whether to use macrophyte productivity inputs and whether to use gross or net primary production values for fish yield predictions.

Apart from latitude effects, lakes at high altitudes tend to have lower annual productivities as a consequence of lower temperatures. Hence, Lake Patzcuaro is expected to have a lower productivity compared with an African lake located approximately at the same latitude but at lower altitude. Beveridge (1984), using the extensive data set from Marten and Polovina (1982), determined the relationship between primary productivity and fish yield for tropical lakes. The line which best fit the data was curvilinear, of the form of an exponential regression. Although the general shape of the curve follows an exponential line, Liang et al (1982) suggested that the curve may actually be sigmoidal if it is extended to incorporate very high primary productivity levels (> 2500 g C/m2/year).

In the present study it was considered that primary productivity in Lake Patzcuaro depends upon the contribution of both phytoplankton and macrophytes (60% and 40% respectively). An average of 334.0 g of C/m2/year is estimated to be the minimum that the lake will produce, given that measurements were made during the winter. Using the equation given by Beveridge (1984), theoretical fish yields for Lake Patzcuaro for 1986-1987 were estimated to be 23.20 kg/ha/year. This represents only 22% of the actual fish landings in Lake Patzcuaro for the same year. Apparently the discrepancy is due to the trophic efficiency transfer. Based on a 10% carbon content per gram of wet fish weight (Gulland, 1970), the present annual fish yield of Lake Patzcuaro is approximately 1.038 g of C/m2/year while the mean annual primary production is about 334.0 g of C/m2/year. The computed carbon transfer efficiency is 0.31%. Comparison of this value with values reported by Oglesby (1977) for temperate lakes and Melack (1976) for African lakes suggest that Lake Patzcuaro may have a relatively high transfer efficiency at low levels of primary production.

However, the results of the worldwide IBP programme indicated that fish production was in a range 0.1% to 1.6% of the gross primary production in lakes and reservoirs (Morgan <u>et al</u>, 1980). Although the present environmental conditions suggest that low levels of primary production predominate in Lake Patzcuaro, more data on annual primary productivity is required before trophic efficiency transfer can be determined accurately. The increase in suspended clay and silt particles in the water, in combination with seasonal fluctuations due to summer rainfall, may be important factors in limiting primary production in the lake.

Final considerations.

In summary, Lake Patzcuaro, situated in the southwestern edge of the Mexican Plateau, is a tropical high altitude lake. Like the rest of the southern plateau the origin of the lake is primarily associated with late Tertiary and Quaternary tecto-volcanic activity, which continues to the present (De Buen, 1943a; Barbour, 1973b; Demant, 1978; Nixon, 1982). The lake is surrounded by volcanic mountains in an endorheic drainage basin.

The lake is becoming shallower due to continuous sediment depositions mainly associated with erosion processes. The annual water balance is primarily controlled by differences between rainfall and evaporation. Since annual evaporation is higher than rainfall, it is considered that net water inputs to the lake come as seepage from the catchment area. It is believed that erosion processes in the drainage area have reduced the contribution of seepage to the lake. This is indicated by the decrease in annual lake levels, the increase in insularity and extensive macrophyte coverage. Water movements in the lake are determined mostly by wind surface drift with possible coriolis effects and deep mixing currents.

The lake is well mixed and high oxygen levels are always present from surface to bottom. However, high turbidities are observed possibly due to volcanic silt, raw sewage and increasing erosion loads. Consequently, Lake Patzcuaro is light-limited due to scattering and attenuation effects from inorganic allochtonous materials. The euphotic zone is located in a shallow depth in comparison with the mixing depth. The lake is alkaline-carbonate with moderate levels of hardness and high levels of total phosphorus, chlorophyll-a and suspended solids.

It is considered that Lake Patzcuaro is mostly an eutrophic lake with some isolated oligo-mesotrophic areas located in the southern basin. However, occasional dense blue-green algal blooms typical of hypereutrophic condition and similar to that detected during the winter of 1986-1987, can develop, particularly in shallow and well sheltered areas located in the northern basin. Most of the total phosphorus loadings entering the lake from the drainage area seem to accumulate in the sediments in combination with iron compounds. However, the stability of these associations depends primarily upon the constant oxygenation of deep waters. If temporal oxygen depletions occur near the bottom, then considerable amounts of orthophosphate may be released into the water with subsequent phytoplankton blooms. Anoxic conditions have been reported previously in Lake Patzcuaro (Tellez and Motte, 1980) mainly associated with municipal sewage.

Lake Patzcuaro, as is the case of many Latin American freshwater lakes and reservoirs, is under severe anthropogenic pressure. As previously discussed, this results in a degradation of both the terrestrial and aquatic environments and in a reduction of the rural economy and food production. During the sixteenth century the P'urhepecha state was known as the most efficient and powerful entity in Mexico and was confirmed as such by the first Europeans who arrived in these central highlands. With a high population density (103/km2), the long-standing success of the P'urhepecha economy was based on optimal human-environment relations, an efficient use of local resources and an extensive trade system to satisfy the local population (Gorenstein and Pollard, 1983). At present, with a population density of 95/km2, indiscriminate deforestation around the catchment area, the increasing use of inorganic fertilizers in modern agriculture technologies, untreated municipal and agricultural sewage discharges, and over-fishing of indigenous species, there is clear deterioration of the economy of the P'urhepecha villages. The socio-economic impact has been manifested not only in the increasing loss of land and fishery resources but also in a gradual emigration of P'urhepecha people, under-employment and nutritional deficiency in rural communities due to the lack of buying power.

A rational procedure for selecting an efficient lake restoration and food production programme compatible with the regional ecology of Lake Patzcuaro, requires consideration of the environmental factors mentioned above. Although the development of possible lake management strategies is beyond the objectives of the present thesis, it is possible to define four main priorities in Lake Patzcuaro:

1. Major problems are the continous loss of depth and the increasing turbidity due to the erosion processes of the catchment area. The steep and high relief of hillslopes accelerate the rate of soil losses from the drainage area with subsequent increments in lake siltation. Although dredging has been carried out along the southeastern shore of the lake, the magnitude of annual erosion loads exceeds the scale and cost-effectiveness of dredging activities.

Furthermore, dredging activities increase turbidity and solids resuspension causing oxygen depletions. Reforestation programmes have been implemented during the last fifteen years by governmental institutions, but no results have been published or made available.

Although reforestation programmes represent an effective measure to reduce erosion loads, the success of this strategy depends upon a) the appropriate selection of indigeneous vegetation species to ensure growth and green coverage with minimum maintenance costs and ecological cometition, b) the simultaneous reduction of downhill sediment transport by the construction of stone and/or wooden walls for soil trapping in highly erosive areas and green terraces in smooth slopes, c) the continuity of such programs, and d) the effective monitoring and control of indiscrimate deforestation activities.

2. A second priority is the design of an appropriate and cost-effective wastewater treatment plant, particularly to treat output from the fish processing plant PROPEMEX, the agricultural channel of Chapultepec and the towns of Patzcuaro and Quiroga. The potential impact of tanneries in the northern basin has been pointed out by satellite imagery. Lake Patzcuaro has a low flushing rate which implies nutrient and pollutant accumulations in the system. This is a potential point of conflict for multipurpose water resource exploitation in the region.

3. A third priority is the development of an integrated regional programme for food production. Traditionally, the productivity of Lake Patzcuaro has been based upon the capture of three endemic fish, one of which commands the highest price in the country. However, the yields of these native species have greatly decreased in comparison with the capture of introduced exotic species. Thus, indigenous fish species which are most favoured by local consumers are endangered. Mexican aquaculture, which remains a small scale enterprise, has been orientated to the culture of exotic species such as rainbow trout, channel catfish, carps and tilapia. However, the culture of these species does not satisfy the demand of the majority of Mexicans for fish protein. Rainbow trout and channel catfish are cash-crop species which are either consumed by a minority of upper social classes or exported to North American markets, whereas carps and tilapias are rarely included in the diet of the Mexican people because of a lack of tradition.

Since the regional economy depends greatly upon the fish productivity of the lake, it is considered of great importance to develop reliable sources of fry of the indigenous fish species. This would be of value not only for the restoration of an endangered natural resource, but also for the introduction of these valuable native fish species into a regional aquaculture programme. Similar attempts at culture of the native Mexican cichlids have been successful in recent years (Ross, 1988). At present, given the increasing cultural eutrophication of the lake and introduced species effects, aquaculture programmes for restocking purposes only would be recommended under an appropriate fishery management strategy.

4. Remote sensing in Mexico is already accepted as a useful tool in geology, agriculture and regional mapping. In many developing countries it has been adopted as a relatively low cost approach for crop monitoring, soil mapping and damage assessment. Given the wide range of applications the use of remote sensing for water quality and environmental monitoring in the basin of Lake Patzcuaro is recommended. Some of the cost-effective benefits of this approach would be the detection of spatial and temporal changes in water quality, the monitoring of erosion processes and the verification of hydrological models. This approach can be significantly enhanced by integrating remote sensing into geographical information systems.

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Appendix 1. Data on optical parameters

	SD	c	Kd	CHL	SS	Kd+c	A
1	0.37	10.19	3.57	69.62	20.83	13.76	5.09
2	0.36	10.86	3.17	53.29	13.80	14.03	5.05
3	0.37	10.50	3.19	38.94	18.76	13.69	5.07
4	0.33	11.27	4.32	92.49	24.27	15.59	5.14
5	0.31	12.79	4.25	72.53	22.77	17.04	5.28
6	0.31	12.40	4.73	60.73	22.60	17.13	5.31
7	0.34	11.51	3.88	72.03	20.93	15.39	5.23
8	0.43	8.60	3.30	51.41	21.33	11.90	5.12
9	0.45	9.78	2.66	45.04	13.83	12.44	5.60
10	0.43	9.54	2.72	32.59	13.93	12.26	5.27
11	0.44	10.86	2.64	32.74	13.60	13.50	5.94
12	0.44	10.86	2.46	34.79	14.23	13.32	5.86
13	0.44	10.04	2.22	36.19	11.13	12.26	5.39
14	0.40	12.07	2.67	30.43	17.63	14.74	5.90
15	0.40	9.54	2.62	28.86	14.43	12.16	4.86
16	0.31	11.77	4.13	54.91	28.40	15.90	4.93
17	0.38	10.33	3.35	39.00	15.20	13.68	5.20
18	0.41	10.67	3.36	55.65	14.20	14.03	5.75
19	0.39	10.86	3.16	65.25	19.40	14.02	5.47
20	0.32	11.77	3.50	45.76	22.20	15.27	4.89
21	0.34	11.05	3.63	41.42	16.40	14.68	4.99
22	0.32	12.07	3.59	44.17	20.60	15.66	5.01
23	0.35	10.86	3.37	44.17	18.20	14.23	4.98
24	0.37	10.33	3.19	48.15	19.40	13.52	5.00
25	0.38	10.86	3.08	37.42	14.80	13.94	5.30
26	0.40	11.05	3.10	56.40	18.20	14.15	5.66
27	0.40	9.43	3.09	32.30	14.80	12.52	5.01
28	0.40	10.04	3.08	47.92	14.40	13.12	5.25
29	0.44	9.22	2.74	29.34	19.20	11.96	5.26
30	0.43	9.65	2.87	31.10	12.60	12.52	5.38
31	0.40	10.19	3.00	34.68	13.40	13.19	5.28
32	0.40	10.19	2.93	34.47	17.60	13.12	5.25
33	0.40	9.65	2.93	36.16	13.20	12.58	5.03
34	0.39	10.04	2.93	34.86	13.40	12.97	5.06
35	0.40	10.33	3.02	37.04	15.60	13.35	5.34
36	0.41	8.68	2.73	36.82	25.20	11.41	4.68
37	0.40	8.45	2.84	32.31	13.40	11.29	4.52
38	0.35	12.07	3.37	57.40	19.20	15.44	5.40
39	0.38	10.50	3.30	40.91	16.20	13.80	5.24
40	0.38	10.33	3.45	38.33	15.20	13.78	5.24
41	0.33	10.50	3.50	39.21	18.60	14.00	4.62
42	0.35	11.51	3.61	40.78	21.20	15.12	5.29
43	0.37	10.04	3.36	32.17	18.80	13.40	4.96
44	0.39	10.33	3.22	33.03	14.20	13.55	5.28
45	0.40	9.54	3.39	36.91	14.40	12.93	5.17
46	0.52	7.86	2.65	25.40	12.20	10.51	5.47
47	0.45	9.32	2.79	29.02	12.40	12.11	5.45
48	0.48	8.04	2.89	28.51	13.40	10.93	5.25
49	0.44	9.22	3.20	35.75	13.40	12.42	5.46
50	0.46	8.76	2.97	33.64	12.40	11.73	5.40
51	0.46	8.04	3.39	35.95	16.00	11.43	5.26
52	0.51	8.38	2.88	29.17	14.20	11.26	5.74
53	0.52	8.04	2.99	30.88	12.80	11.03	5.74

Appendix 2. Water quality data (mean values)

	TEMP (C)	CHL (ug/l)	SS (mg/l)	SD (m)	TP (ug/l)	DRP (ug/l)	DO (mg/l)	Kd (m)	c (m)	% T	Eu z (m)	NO3 (mg/l)	NH4 (mg/l)	Ph	ALK (mg/l)	CO3 (mg/l)	HCO3 (mg/l)	COND(uS/cm2)	Kd•c
1	16.0	118.50	41.80	0.35	108.40	33.06	7.10	3.85	10.98	1.30	1.34	0.014	0.025	9.43	378.0	58.0	320.0	972.4	14.83
2	16.1	96.00	27.40	0.40	80.30	32.99	6.28	3.30	11.08	1.23	1.55	0.011	0.027	9.50	396.0	52.0	344.0	843.7	14.38
3	16.1	67.10	26.90	0.38	83.30	35.65	6.82	3.28	10.55	1.46	1.53	0.011	0.036	9.50	404.0	54.0	350.0	867.1	13.83
4	16.3	67.20	19.70	0.41	60.97	36.15	7.02	3.30	10.59	1.45	1.47	0.011	0.034	9.40	414.0	50.0	364.0	868.4	13.89
5	16.4	89.80	25.37	0.36	93.70	37.67	6.82	3.91	11.52	1.00	1.37	0.012	0.038	9.53	390.0	66.0	324.0	832.0	15.43
6	16.3	116.80	35.00	0.34	89.80	38.84	6.01	3.80	11.44	1.65	1.36	0.021	0.032	8.80	396.0	66.0	330.0	878.8	15.24
7	16.0	67.00	22.52	0.37	62.13	39.44	6.61	3.97	12.00	0.83	1.35	0.016	0.030	9.36	392.0	62.0	330.0	859.3	15.97
8	16.2	104.90	34.60	0.35	101.10	39.04	6.96	3.62	11.18	1.03	1.35	0.013	0.030	9.35	388.0	68.0	320.0	877.5	14.80
9	16.4	56.80	24.13	0.39	66.07	39.44	7.66	3.30	8.60	1.79	1.47	0.014	0.037	9.37	408.0	62.0	346.0	873.6	11.90
10	16.5	50.20	20.40	0.39	58.30	41.03	6.96	3.19	10.33	1.60	1.55	0.017	0.040	9.40	394.0	70.0	324.0	832.0	13.52
11	16.5	61.70	22.74	0.39	76.60	40.53	7.35	3.08	10.86	1.30	1.55	0.014	0.032	9.39	382.0	70.0	312.0	895.7	13.94
12	16.4	53.80	19.07	0.39	56.30	40.13	7.37	3.23	10.54	1.50	1.58	0.013	0.034	9.44	394.0	60.0	334.0	821.6	13.77
13	16.3	51.60	21.53	0.40	58.18	39.55	7.30	3.15	9.88	1.95	1.59	0.011	0.039	9.53	374.0	70.0	304.0	885.3	13.03
14	16.7	50.20	14.42	0.43	42.65	42.53	7.45	3.23	9.79	2.00	1.55	0.016	0.034	9.34	372.0	80.0	292.0	812.5	13.02
15	16.5	37.34	13.29	0.45	56.80	40.68	7.22	2.69	8.54	3.40	1.72	0.015	0.043	9.13	394.0	64.0	330.0	848.9	11.23
16	16.4	28.84	12.96	0.44	45.15	41.53	7.42	2.83	9.48	2.25	1.70	0.013	0.057	9.25	384.0	58.0	326.0	796.9	12.31
17	16.7	46.50	16.85	0.44	50.12	39.84	6.60	2.85	9.33	2.56	1.69	0.008	0.039	9.25	364.0	60.0	304.0	848.9	12.18
18	16.6	54.20	21.45	0.44	70.60	41.58	7.10	3.06	9.70	2.10	1.59	0.011	0.034	9.28	386.0	58.0	328.0	852.8	12.76
19	16.2	32.15	12.02	0.47	45.26	40.38	7.40	2.87	9.31	2.43	1.64	0.008	0.035	9.46	326.0	78.0	248.0	861.4	12.18
20	16.0	37.13	13.16	0.44	49.30	39.14	7.58	2.78	10.45	1.55	1.71	0.006	0.030	9.49	378.0	46.0	332.0	780.0	13.23
21	16.4	34.98	14.52	0.39	45.87	39.44	7.39	2.95	9.74	2.30	1.66	0.011	0.051	9.41	366.0	60.0	306.0	837.2	12.69
22	16.6	38.57	14.68	0.46	54.60	38.00	7.20	2.22	10.04	2.80	2.10	0.006	0.044	9.29	338.0	48.0	290.0	818.9	12.26
23	16.5	33.51	17.33	0.43	45.25	40.78	7.34	2.76	9.71	2.46	1.68	0.012	0.038	9.45	382.0	64.0	318.0	912.6	12.47
24	16.1	35.15	14.56	0.43	41.93	42.48	7.26	2.81	8.67	3.20	1.71	0.010	0.029	9.39	384.0	60.0	324.0	851.5	11.48

Appendix 3. Slope and estimated macrophyte biomass for different transects located in the shoreline of Lake Patzcuaro. MB = Macrophyte biomass.

Location name	Slope (%)	MB (gr/m2)
1. Santa Fe	1.10	395.84
2. 2.5 km East Chupicuaro	15.00	79.80
3. 2.0 km East Chupicuaro	33.00	49.62
4. 1.5 km East Chupicuaro	16.00	99.64
5. Chupicuaro.	10.00	64.90
6. 1.5 km West Chupicuaro	14.30	61.86
7. 2.0 km West Chupicuaro	10.00	88.60
8. 2.5 km West Chupicuaro	12.00	91.90
9. San Jeronimo	3.00	294.00
10. 1.0 km South San Jeronimo	5.20	243.00
11. San Andres Tzirondaro	3.60	143.36
12. 1.0 km Southeast Santa Fe	1.25	424.52
13. 2.5 km Southeast Santa Fe	0.97	580.26
14. Tzocurio	2.00	206.20
15. Tzinztzuntzan	2.20	286.34
16. Ichupio	5.00	135.80
17. Tarerio	13.30	114.00
18. Espiritu	33.00	44.04
19. Ucasanastacua	10.00	129.12
20. La Granada	7.15	135.00
21. Cucuchuchu	4.00	190.02
22. Punta Santiago	20.00	66.78
23. Santiago	7.70	232.88
24. Ihuatzio	5.00	111.72

25. 2.5 km East Ihuatzio	1.10	464.34
26. La Playa	1.30	413.02
27. Tzentzenguaro	1.10	428.26
28. San Pedro Pareo	0.96	627.04
29. Tocuaro	1.20	436.84
30. Arocutin	3.30	213.3
31. 1.0 km North Arocutin	5.00	149.60
32. San Francisco Uricho	3.20	334.18
33. 0.75 km South Erongaricuaro	4.50	175.44
34. Erongaricuaro	2.00	341.48
35. 1.0 km North Erongaricuaro	5.00	166.54
36. Napizaro	3.20	154.60
37. Napizaro-Pacuaro	2.40	203.40
38. Pacuaro-Oponguio	4.70	259.70
39. 1.5 km South Oponguio	5.20	120.40
40. Oponguio	4.00	216.92
41. 0.5 km South Italia Peak	10.00	74.60
42. North face Italia Peak	12.50	55.84

Appendix 4.

A. Imaging characteristics of the acquired SPOT image.

A computer compatible tape was obtained from Diffusion des Images Des Satellites Spot (SPOT IMAGE), Toulouse, France. The tapes was reformed from 6250 bpi to 1600 bpi format compatible with the Remote Sensing Data Processing System, University of Stirling Scotland. The tape was acquired with the following imaging parameters:

satellite name :	SPOT-1	
WRS reference :	583 - 311	
Scene identification :	S1H1870217172717	
Mode :	XS (multispectral mode)	
Number of spectral bands :	3	
Spectral band indicators :	XS1, XS2, XS3.	
Instrument :	HRV1	
Processing level :	1A	
Adquisition time :	1987/02/17 17 h 27 mn 17 s	
Scene center coordenates :	N 019° 30' 59"	Latitude
	W 101° 39' 54"	Longitude
Corner coordinates :	Latitude	Longitude
	N 019° 50' 00"	W 101° 53' 29"
	N 019° 43' 48"	W 101° 19' 50"
	N 019° 18' 08"	W 101° 59' 58"
	N 019° 11' 57"	W 101° 26' 25"
Azimuth :	+ 142.20	
Elevation :	050.70	

Appendix 4.

B. Lake Patzcuaro control points.

UTM and SPOT Coordinates

Control Point	Easting UTM	Northing UTM	SPOT Line	SPOT Column
1. Chupicuaro lighthouse	229375	2177575	123	690
2. Patambicho church	233475	2173350	292	944
3. Ojo de Agua pier	230925	2172600	354	833
4. Tzintzuntzan school	229900	2172600	360	783
5. Tzocurio restaurant	231950	2173000	339	851
6. Tzintzuntzan yacatas	230200	2171850	398	802
7. Sanabria cross road	230075	2165925	690	869
8. Chapultepec bridge	229375	2164175	782	856
9. Propemex fish factory	225325	2162700	887	675
10. Patzcuaro pier	225425	2162870	875	676
11. San Pedrito pier	224840	2163110	869	643
12. Tzipecua manor house	224265	2162710	893	619
13. Janitzio island	221750	2166300	743	457
14. Tecuena rockery	221675	2167850	668	432
15. Yunuen island	222350	2169225	594	449
16. Pacanda island	222250	2170175	552	426

Regressions for sampling site location in the SPOT image.

a) $\text{SPOT-L} = 108302 - 8.64\ \text{UTM-X} - 48.8\ \text{UTM-Y}$

$r2 = 1.000 \quad p = 0.0001$

b) $\text{SPOT-C} = 16359 + 49.00\ \text{UTM-X} - 12.4\ \text{UTM-Y}$

$r2 = 0.999 \quad p = 0.0001$

Where:

SPOT-L = SPOT line coordinate.

SPOT-C = SPOT column coordinate.

UTM-X = Easting UTM coordinate.

UTM-Y = Northing UTM coordinate.

Appendix 4.

C. Universal Transverse Mercator coordenates for sampling sites.

Station	Easting	Northing
1.	231000	2176000
2.	229000	2176000
3.	227000	2176000
4.	226000	2175000
5.	228000	2175000
6.	230000	2175000
7.	231000	2174000
8.	229000	2174000
9.	227000	2174000
10.	225000	2174000
11.	224000	2173000
12.	223000	2172000
13.	222000	2171000
14.	221000	2170000
15.	221000	2168000
16.	221000	2167000
17.	223000	2168000
18.	223000	2170000
19.	222000	2165000
20.	223000	2164000
21.	224000	2165000
22.	225000	2164000
23.	219000	2168000
24.	218000	2167000

Appendix 4.

D. Sampling sites coordenates in the SPOT image using equations a) and b). SD = Standard deviation.

Station	SPOT-L	SD	SPOT-C	SD
1.	189	+2	788	+3
2.	206	+2	690	+3
3.	224	+2	592	+4
4.	281	+2	555	+4
5.	264	+2	653	+3
6.	246	+2	751	+3
7.	287	+2	812	+3
8.	304	+2	714	+3
9.	321	+2	616	+3
10.	338	+2	518	+3
11.	396	+2	482	+3
12.	453	+2	445	+3
13.	511	+2	408	+4
14.	568	+2	372	+4
15.	666	+2	397	+3
16.	714	+2	409	+3
17.	648	+2	495	+2
18.	551	+2	470	+3
19.	803	+2	483	+3
20.	843	+2	544	+3
21.	786	+1	581	+2
22.	826	+1	642	+2
23.	683	+3	299	+4
24.	740	+3	262	+5

Appendix 4.

E. Mean digital count values for each sampling site in all three spectral Spot XS bands.

Station	Band 1	Band 2	Band 3
1.	44.0	30.4	19.2
2.	44.7	30.8	17.0
3.	45.4	33.0	12.3
4.	45.2	33.4	11.0
5.	45.4	32.6	11.0
6.	44.5	30.2	17.2
7.	44.3	32.8	11.4
8.	44.7	32.5	11.0
9.	45.4	33.4	10.8
10.	45.3	32.8	11.1
11.	45.4	33.5	12.1
12.	45.6	34.5	11.6
13.	45.7	34.3	12.0
14.	46.0	34.1	11.6
15.	46.0	33.0	10.6
16.	45.8	31.8	10.1
17.	45.8	32.7	10.8
18.	45.4	34.2	12.0
19.	46.4	32.8	10.7
20.	45.5	32.3	11.0
21.	45.8	32.2	10.8
22.	43.0	28.8	10.1
23.	46.4	33.7	11.7
24.	44.6	31.3	10.7
Zirahuen.	23.0	10.1	08.0

Appendix 4.

F. Summary of solar ephemeris for Lake Patzcuaro.

DATE:	FEB-17-1987
TIME:	17 h 27 m 17 s GMT
COORDENATES:	N 19° 30' 58" LATITUDE
	W 101° 39' 54" LONGITUDE
JULIAN DATE:	$JD = 2446843.455$
	$D = -4700.8178$
	$t = -0.12870137$
TIME INTERVAL (DYNAMIC TIME)	$T = -0.12869996$
GEOMETRIC MEAN ECLIPTIC	
LONGITUDE OF DATE:	$m = 327.168075$
MEAN ANOMALY:	$G = 44.4509$
MEAN OBLIQUITY OF THE ECLIPTIC:	$\epsilon o = 23.43884135$
EQUATION OF THE CENTRE:	$C = 1.36120$
	$\Omega = 13.970$
TRUE OBLIQUITY	
OF THE ECLIPTIC:	$\epsilon = 23.44136$
APPARENT ECLIPTIC LONGITUDE:	$= 328.5224$
APPARENT ECLIPTIC LATITUDE:	$\beta = + 0.00$
	$x = 0.8528$
	$y = -0.4790$
	$z = -0.20772$
RIGTH ASCENSION:	$\alpha = 330.676$ (330° 40' 33.60")
	$\alpha = 022.04506$ (022° 02' 42.24")

DECLINATION OF DATE: δ = -11.98877 (11°59'19.5")

AZIMUTH: A = 141.953389

141° 57' 12.20"

SOLAR ELEVATION ANGLE (ALTITUDE): AL = 50.9859

50° 59' 09.24"

SEMI-DIAMETER: SD = 0.27027

GHA = 78.2185

EQUATION OF TIME: E = -3.36120

HOUR-ANGLE: H = 22.44241

22° 26' 32.68"

GREENWICH SIDERAL TIME: GST = 03.265130

03° 15' 54.47"

LOCAL SIDERAL TIME: LST = 20.48747

20° 29' 14.89"

ZENITH DISTANCE: (90° - ALTITUDE) ZD = 39.0141
39° 00' 50.76"

Appendix 4.

G. Atmospheric correction of SPOT-1 data.

Proper use of multispectral digital data for water quality assessment requires that the digital numbers recorded in the computer-compatible tapes be converted to an equivalent form of physical radiometric values such as radiance (as measured by the satellite in milliwatts per square centimetre per steradian) or reflectance (the ratio of upwelling to downwelling irradiance). These values vary depending on the calibration of the sensor in each satellite at a given time. Atmospheric corrections are also required if multitemporal remote sensing monitoring is undertaken.

The HRV multispectral sensors of Spot-1 measure radiation reflected from the Earth in three bands:

Band	Wavelength (Micrometres)	Band Width (Micrometres)
XS1	0.50 - 0.59	0.09
XS2	0.61 - 0.68	0.07
XS3	0.79 - 0.89	0.10

According to Begni (personal comunication), the physical values of Spot-1 can be derived from the digital numbers for each band by means of

$$Xk = Ak \cdot Gm,k \cdot Lk \qquad (1)$$

where

Xk = Digital value.

Ak = Absolute calibration coefficient.

Lk = Radiance ($W\ m^{-2}$ micrometer $^{-1}$).

Gm,k = Amplification coefficient.

Considering a given spectral band k, Spot-1 absolute calibration coefficient is defined as the ratio between the instrument output Xk and the equivalent radiance Lk,

$$Ak = \frac{Xk}{Lk} \tag{2}$$

Spot-1 is equipped with amplifiers which allow the change of output signal dynamics, by a ratio of 1.3.

$$Gm,k = (1.3)^{(m-3)} \tag{3}$$

Band XS1 gain is 5, then $Gm,k = (1.3)^{(5-3)} = 1.69$

Band XS2 gain is 6, then $Gm,k = (1.3)^{(6-3)} = 2.20$

Band XS3 gain is 5, then $Gm,k = (1.3)^{(5-3)} = 1.69$

Absolute calibration coefficients for 17-Feb-1987 (image acquisition) are assumed to be the same as for 20-Mar-1987 (last calibration date). For HRV 1, the following values are given:

	Begni (1988)	CCT Header
XS1	0.510 x 1.69 = 0.8619	0.86262
XS2	0.363 x 2.20 = 0.7986	0.79872
XS3	0.563 x 1.69 = 0.9515	0.89310

Mean digital counts in bands XS1, XS2 and XS3 for the target site were extracted from a five-by-five pixel block used for atmospheric corrections. A central area of Lake Zirahuen was selected as a nominal oligotrophic target due to its low turbidity, deep waters, freedom from bottom and edge effects, and close proximity to Lake Patzcuaro (12.0 km). The average of three land locations in the image was used for land background reflectance required for atmospheric corrections.

Lake Zirahuen (clear water) location

Latitude and Longitude	UTM
19 26.3' N - 101 44.4' W	212.3 X - 2151.5 Y

5 x 5 pixel block location in the Spot-1 CCT image. Coordinates are given by line and column.

```
150-210 ------- 150-214
   |               |
   |               |
154-210 ------- 154-214
```

Mean digital counts for the selected locations.

	Water	Land			
Band	Lake Zirahuen	Jaracuaro Island	Janitzio Island	Propemex Plant	Patzcuaro School
XS1	23.0	61.5	53.4	113.5	52.9
XS2	10.1	56.6	49.0	90.1	51.8
XS3	8.0	52.0	52.0	82.2	72.4

Target and background mean digital count for conversion to nominal radiances and reflectances

Band	Water	Land
XS1	23.0	70.32
XS2	10.1	62.02
XS3	8.0	70.02

Average digital values were converted into nominal radiances by

$$Lk = \frac{Xk}{Ak \;.\; Gm,k} \quad (\mathrm{W\ m^{-2}\ micrometre^{-1}}) \qquad (4)$$

Where

$Lk = 23.0/0.8619 = 26.6850$

$Lk = 10.1/0.7986 = 12.6470$ ($W\ m^{-2}$ micrometre $^{-1}$)

$Lk = 8.0/0.9515 = 8.4077$

Reflectance values were calculated by using the following expression,

$$Rk = \frac{Pi.\ Lk}{Ek\ .\ Cos\ Z} \qquad (5)$$

Where

Rk = Reflectance value (dimensionless)

Ek = Irradiance at the top of the atmosphere ($W\ m^{-2}$ micrometre $^{-1}$)

Z = Solar zenith angle, (angle between the local vertical nadir and the direct solar beam at the time of the time of the image acquisition (51.0 degrees).

Begni (personal comunication), suggests the following values for irradiance at the top of the atmosphere, Ek, for HRV 1

XS1 : 1850

XS2 : 1610 ($W\ m^{-2}$ micrometre $^{-1}$)

XS3 : 1090

No wavelength centres were given for the above values, but using Thekaekara's tables (1974), corresponding wavelength in micrometres are approximately

XS1 : 0.530

XS2 : 0.625

XS3 : 0.810

Centre wavelengths at the HRV sensor are

XS1 = 0.545

XS2 = 0.645

XS3 = 0.840

The sensitivity of the HRV 1 at different wavelengths is

XS1	XS2	XS3
0.530 = 0.971	0.620 = 0.705	0.810 = 1.000
0.540 = 1.000	0.630 = 0.950	0.820 = 0.966
0.550 = 0.950	0.640 = 0.973	0.830 = 0.925
0.560 = 0.852	0.650 = 1.000	0.840 = 0.870

For the present project wavelengths were centered at

XS1 = 0.540

XS2 = 0.640

XS3 = 0.840

Reflectance values for nominal target (water) and background (land) locations.

Band	Water	Land
XS1	0.0720	0.220
XS2	0.0392	0.240
XS3	0.0385	0.337

In order to remove the effects of the atmosphere without ground measurements Turner <u>et al</u> (1971) and Turner and Spencer (1972) described a deterministic model for atmospheric radiative transfer which assumes a plane-parallel, homogeneus, aerosol-filled atmosphere whose haze content is defined by the horizontal visual range at the surface. Similar techniques have been successfully applied by Ahern <u>et al</u> (1977), Richardson <u>et al</u> (1980) and Verdin

(1985). A FORTRAN version of the Turner- Spencer model was prepared by Kortesoja (unpublished).

The interaction of solar radiation with the atmosphere is stated as

$$Lsat = r\ T\ Htot + Lp \qquad (6)$$

where

Lsat = the radiance sensed by the sensor in a given spectral band (mW cm $^{-2}$ sr).

r = the target reflectance, defined as the ratio of upwelling radiance to downwelling irradiance (sr -1).

T = atmospheric transmittance from surface to satellite (dimensionless).

Htot = total irradiance incident on a horizontal surface at the bottom of the atmosphere (mW cm $^{-2}$).

Lp = atmospheric path radiance (mW cm $^{-2}$).

Target reflectance, r, is an observational quantitiy and differs from R, the reflectance of a Lambertian surface, according to the relation:

$$R = Pi\ r \qquad (7)$$

where R is a dimensionless quantity representing the ratio of upwelling to downwelling irradiance.

Atmospheric transmittance, T, from surface to satellite is defined as

$$T = \exp.\ (-t \sec \theta n) \qquad (8)$$

where t is the total optical depth of the atmosphere, On is the satellite nadir view angle.

Total irradiance, Htot, is made up of direct and diffuse insolation: i.e.,

$$Htot = Ho \cos Z \exp.\ (-t \sec Z) + Hsky \qquad (9)$$

where

Ho = the solar irradiance at the top of the Earth's atmosphere (mW cm $^{-2}$).

Z = the solar zenith angle.

Hsky = the irradiance on a horizontal surface due to diffuse skylight.

Values of Ho are as stated above in digital transformation to physical values. Diffuse sky irradiance, Hsky, cannot be directly measured.

By manipulating the foregoing relationships, the following expression for the apparent Lambertian reflectance of a surface target is generated:

$$R = \frac{Pi\ (Lsat - Lp)}{Htot\ \exp(-t\ \sec\theta n)} \qquad (10)$$

Solution of the above equation for a point of interest requires values of t and Lp which are defined by conditions prevailing at the time of image acquisition. Ahern et al (1977) proposed the use of oligotrophic lakes as standard reflectors which could be used to evaluate Lp by means of the expression

$$Lsat = (Lv + Ls + Lg) + Lp \qquad (11)$$

where

Lv = water volume radiance.

Ls = water surface radiance.

Lg = sun glint radiance produced by solar zenith angles less than 30 degrees or wave action due to strong winds.

$$Lv = rv\ Htot \qquad (12)$$

where

rv = water reflectance (sr^{-1}).

Richarson et al (1980) fitted equations to the field observations of Ahern et al (1977) to obtain the equation

$$rv = 0.0035 - 0.0036\ k \qquad (13)$$

where

k = the wavelegth of interest in the 0.4 - to 3.0 micrometres range.

They also used these observations to define Ls = 0.006 Hsky. For the Canadian lake where Ahern et al carried out their work, Lg was equal to zero. Given the solar position in Mexico and the evidence in the field of no wave action in neither Lake Zirahuen or Lake Patzcuaro, Lg was also assumed to be equal to zero. Solving Equation 11 for Lp requires the use of the radiance over a clear lake appearing in the scene of interest and the appropiate atmospheric radiative transfer model.

A visual range value giving a path radiance value satisfying Equation 11 [i.e. Lsat - (Lv + Ls + Lg)T - Lp = 0] yields results allowing the solution of Equation 10 for other scene targets in the vicinity. Since visual range values in the local meteorological station are roughly estimated the value of visual range in this model can be found in an iterative fashion. For each band, the Turner-Spencer model was run iteratively with a visual range values in one-kilometre steps until Equation 11 gave residual less than 0.001 mW cm^{-2} sr.

This method was applied in Lake Patzcuaro on the assumption that uniform atmospheric conditions prevailed in the basin at the time of the image acquisition. Given the rough topography of the region and the season selected for the survey air masses are characteristically clear and dry. Adjacent human settlements are typically villages and no industrial activity is located in the neighbourhoods. A possible source of anomalous atmospheric influence could be the capital of the of the State, Morelia (located 57 Km northeast of Lake Patzcuaro), with a population of approximately half a million and moderate industrial activity. However, prevailing winds in the region are typically from the southeast and southwest of Patzcuaro throughout the year, hence nonhomogeneous aerosols are non-existant in the area.

For the application of the Turner-Spencer model the required input parameters are in the following order,

1. Altitude (km)
2. Visibilities (km)
3. Wavelengths (micrometres)
4. Background albedo values (decimal)
5. Target albedo values (decimal)
6. Solar zenith angle (degrees)
7. Relative azimuth angle (degrees)
8. View nadir angle (degrees)

The day, month, year, and local time of the satellite flight along with the latitude and longitude of Lake Zirahuen were used in separate calculations to obtain astronomical parameters. A solar ephemeris was used to compute solar zenith and azimuth angles for Lake Zirahuen at the time of image acquistion. Appendix 4.F is a summary of the astronomical data used to complete solar ephemeris. Computations were made following the criteria suggested by Yallop (1988). Solar zenith angle was estimated as follows,

$$\sin a = \sin X \sin Y + \cos X \cos Y \cos H$$

where

a = Solar zenith angle (degrees)

X = Solar declination (degrees)

Y = Geographical latitude (degrees)

H = Hour angle, difference between the local sideral time and the right ascension, alpha (degrees)

For Lake Zirahuen solar zenith was calculated as,

$$a = \text{arc sin} [\ \sin(-11.988)(\sin 19.438) + \cos(-11.988)(\cos 19.438)(\cos 336.56)\ ]$$

$$a = 51.00$$

To compute the relative azimuth required by the model, the calculations for the scan azimuth angle and the solar azimuth angle are needed. Solar azimuth angle, A', is defined as that angle measured clockwise from true north to the solar plane in the tangent plane (Duffett-Smith, 1981) and calculated by

$$A' = \text{arc cos} \ . \ \frac{(\sin X) - (\sin Y)(\sin a)}{(\cos Y)\ (\cos a)}$$

$$A' = 141.80$$

Scan azimuth angle is defined as that angle measured clockwise from true north to the view plane. The target at the central area of Lake Zirahuen is 8.625 Km north and 8.347 Km west away from the Spot-1 nadir view point. By trigonometric functions the straight line distance, the angle from true north and the nadir view angle were calculated using the above distances and the altitude of Spot-1. Scan azimuth angle was found approximately 44.06 degrees and nadir view angle 0.826 degrees.

Relative azimuth angle was then calculated by subtracting the scan azimuth angle from the solar azimuth angle with an approximated value of 97.74 degrees.

Scene geometry and nominal radiometric data to run the Turner-Spencer model are presented as follows

1. Altitude (km)	832.0
2. Visibilities (km)	Iterative from 10-90
3. Wavelengths (micrometres)	0.540; 0.640; 0.840
4. Background albedo for each band	0.22015;0.24079;0.33702
5. Target albedo for each band	0.07200;0.03921;0.03850
6. Solar zenith angle (degrees)	51.0
7. Relative azimuth angle (degrees)	97.74
8. View nadir angle (degrees)	0.826

Since the Turner-Spencer model employs spectral radiances which have units:

$$\frac{\text{milliwatts}}{\text{cm}^2 \;.\; \text{steradian} \;.\; \text{micrometre}}$$

In-band radiances have units:

$$\frac{\text{milliwatts}}{\text{cm}^2 \,.\, \text{steradian}}$$

Multispectral bands in Spot-1 have different width and are less than one micrometre:

$$XS1 = 0.09 \; ; \; XS2 = 0.07 \; ; \; XS3 = 0.10$$

Therefore, outputs from the Turner-Spencer model have to be adjusted for each XS band width. The model does not compute total irradiance. It does, however, provide values that can be used to solve equation 10:

$$Htot = \frac{Pi\ (Lsat - Lp)}{p \exp(-t \sec \theta n)}$$

Results obtained using the Turner-Spencer model for the Spot-1 scene.

	XS1	XS2	XS3
Visual range (km)	42.000	89.000	36.000
Total optical depth	0.272	0.121	0.147
Path radiance (mW/cm2 sr)	0.227	0.080	0.075
Diffuse sky irradiance (mW/cm2)	20.773	0.750	0.888
Total irradiance	7.560	6.590	6.310

Equation 10 was used to compute Lambertian reflectance values for all surface sampling locations in Lake Patzcuaro. Digital values for these sampling locations were previously converted into radiances by Equation 4.

Appendix 4.

H. Scene geometry and nominal radiometric data to run the Turner-Spencer model are presented as follows

1. Altitude (km)	832.0
2. Visibilities (km)	Iterative from 10-90
3. Wavelengths (micrometres)	0.540 ; 0.640 ; 0.840
4. Background albedo for each band	0.22015;0.24079;0.33702
5. Target albedo for each band	0.07200;0.03921;0.03850
6. Solar zenith angle (degrees)	51.0
7. Relative azimuth angle (degrees)	97.74
8. View nadir angle (degrees)	0.826

Appendix 4.

I. Computed radiances for sampling stations in Lake Patzcuaro from Spot-1, HRV 1 digital data. Values are given in mW cm $^{-2}$ micrometre $^{-1}$.

Station	XS1	XS2	XS3
1	0.45945	0.26646	0.20178
2	0.46676	0.26996	0.17866
3	0.47406	0.28925	0.12926
4	0.47197	0.29276	0.11560
5	0.47406	0.28574	0.11560
6	0.46467	0.26471	0.18076
7	0.46258	0.29187	0.11981
8	0.46676	0.28487	0.11560
9	0.47406	0.29276	0.11350
10	0.47302	0.28749	0.11686
11	0.47406	0.29363	0.12716
12	0.47615	0.30240	0.12191
13	0.47719	0.30065	0.12611
14	0.48033	0.29889	0.12191
15	0.48033	0.28925	0.11140
16	0.47824	0.27873	0.10614
17	0.47824	0.28662	0.11350
18	0.47406	0.29977	0.12611
19	0.48450	0.28749	0.11245
20	0.47511	0.28311	0.11560
21	0.47824	0.28224	0.11350
22	0.44900	0.25244	0.10614
23	0.48450	0.29538	0.12296
24	0.46571	0.27435	0.11245

Appendix 4.

J. Computed reflectances for sampling stations in Lake Patzcuaro from Spot-1, HRV 1, digital data.

Station	XS1	XS2	XS3
1	0.12700	0.10040	0.07764
2	0.13099	0.10228	0.06599
3	0.13498	0.11266	0.04109
4	0.13384	0.11454	0.03421
5	0.13498	0.11077	0.03421
6	0.12985	0.09945	0.06705
7	0.12871	0.11171	0.03633
8	0.13100	0.11030	0.03421
9	0.13498	0.11455	0.03315
10	0.13491	0.11171	0.03485
11	0.13498	0.11501	0.04004
12	0.13612	0.11973	0.03739
13	0.13669	0.11879	0.03951
14	0.13840	0.11784	0.03739
15	0.13840	0.11226	0.03210
16	0.13726	0.10700	0.02945
17	0.13726	0.11124	0.03315
18	0.13498	0.11832	0.03951
19	0.14067	0.11171	0.03263
20	0.13555	0.10935	0.03421
21	0.13726	0.10887	0.03315
22	0.12130	0.09285	0.02945
23	0.14068	0.11596	0.03792
24	0.13042	0.10464	0.03263

Appendix 4.

K. Reflectance ratios and combinations computed from SPOT bands XS1, XS2 and XS3, for the development of statistical models. R1 = XS1; R2 = XS2 and R3 = XS3.

Variable X	Band combination
X1.	R1
X2.	R2
X3.	R3
X4.	R1 / R2
X5.	R1 / R3
X6.	R1 / (R1 + R2)
X7.	R1 / (R1 + R3)
X8.	R1 / (R1 + R2 + R3)
X9.	R2 / R1
X10.	R2 / R3
X11.	R2 / (R1 + R2)
X12.	R2 / (R1 + R3)
X13.	R2 / (R1 + R2 + R3)
X14.	R3 / R1
X15.	R3 / (R1 + R2)
X16.	R3 / (R1 + R3)
X17.	R3 / (R1 + R2 + R3)
X18.	(R1 + R2) / R1
X19.	(R1 + R2) / R2
X20.	(R1 + R2) / R3
X21.	(R1 + R3) / R1
X22.	(R2 + R3) / (R1 + R2)
X23.	(R2 + R3) / (R1 + R3)
X24.	(R1 + R2) / (R1 + R3)
X25.	(R1 + R3) / (R1 + R2)
X26.	(R1 + R2 + R3) / R1
X27.	(R1 + R2 + R3) / R2
X28.	(R1 + R2 + R3) / R3
X29.	(R2 + R2 + R3) / (R1 + R2)
X30.	(R1 + R2 + R3) / (R1 + R3)
X31.	R1 + R2 + R3
X32.	(R1 + R2) / (R1 + R2 + R3)
X33.	(R1 + R3) / (R1 + R2 + R3)

Appendix 4. (K continuation)

Variances of the principal components (eigenvalues analysis) of the variables X given in reflectance band rationing.

	Eigenvalue	Proportion	Cumulative
PCA1	23.597	0.715	0.715
PCA2	7.981	0.242	0.957
PCA3	1.334	0.040	0.997
PCA4	0.084	0.003	1.000
PCA5	0.002	0.000	1.000
PCA6	0.001	0.000	1.000
PCA7	0.000	0.000	1.000
PCA8	0.000	0.000	1.000
PCA9	0.000	0.000	1.000
PCA10	0.000	0.000	1.000
PCA11	0.000	0.000	1.000
PCA12	0.000	0.000	1.000
PCA13	0.000	0.000	1.000
PCA14	0.000	0.000	1.000
PCA15	0.000	0.000	1.000
PCA16	0.000	0.000	1.000
PCA17	0.000	0.000	1.000
PCA18	0.000	0.000	1.000
PCA19	0.000	0.000	1.000
PCA20	0.000	0.000	1.000
PCA21	0.000	0.000	1.000
PCA22	0.000	0.000	1.000
PCA23	0.000	0.000	1.000
PCA24	0.000	0.000	1.000
PCA25	0.000	0.000	1.000
PCA26	0.000	0.000	1.000
PCA27	0.000	0.000	1.000
PCA28	0.000	0.000	1.000
PCA29	0.000	0.000	1.000
PCA30	0.000	0.000	1.000
PCA31	0.000	0.000	1.000
PCA32	0.000	0.000	1.000
PCA33	0.000	0.000	1.000

Appendix 4. (K continuation)

Coefficients for the two principal components (PCA1, PCA2) with the maximum variation.

Variable X	PCA1	PCA2
X1	- 0.100	- 0.060
X2	- 0.126	- 0.245
X3	0.199	- 0.084
X4	0.105	0.302
X5	- 0.190	0.128
X6	0.104	0.303
X7	- 0.200	0.085
X8	- 0.168	0.203
X9	- 0.103	- 0.303
X10	- 0.201	0.062
X11	- 0.104	- 0.303
X12	- 0.199	- 0.088
X13	- 0.200	- 0.080
X14	0.201	- 0.073
X15	0.203	- 0.056
X16	0.200	- 0.085
X17	0.203	- 0.061
X18	- 0.103	- 0.303
X19	0.105	0.302
X20	- 0.196	0.099
X21	0.201	- 0.073
X22	0.194	- 0.118
X23	- 0.023	- 0.349
X24	- 0.206	- 0.004
X25	0.206	- 0.000
X26	0.173	- 0.189
X27	0.202	0.067
X28	- 0.196	0.099
X29	0.203	- 0.056
X30	- 0.199	- 0.088
X31	0.095	- 0.236
X32	- 0.203	0.061
X33	0.200	0.080

Appendix 4. (K continuation)

Computed principal component scores for PCA1 and PC2 for the 24 sampling sites.

Sampling station	PCA1	PCA2
1	14.3602	- 1.69165
2	10.7762	0.15629
3	0.3646	- 1.29431
4	- 2.8787	- 1.90415
5	- 1.7898	0.78495
6	11.8094	1.26855
7	- 1.7811	- 2.89453
8	- 2.0477	- 0.70818
9	- 3.2084	- 1.23846
10	- 1.8320	- 0.11168
11	- 0.6257	- 2.50034
12	- 2.7012	- 4.28406
13	- 1.6142	- 3.80362
14	- 2.0243	- 2.25322
15	- 2.8428	1.49364
16	- 2.6142	4.80092
17	- 2.1356	1.65960
18	- 1.6522	- 4.28718
19	- 2.1628	2.91243
20	- 1.3627	1.86586
21	- 1.5137	3.04563
22	- 0.1385	6.59984
23	- 1.1482	- 0.31194
24	- 1.2366	2.69561

Results of the canonical correlation analysis

Data from variables are divided naturally into two groups: CHL and SS, and PCA1 and PCA2

$$Y1 = 0.00620\ (\mathrm{CHL}) + 0.02418\ (\mathrm{SS})$$

$$Y2 = -0.02357\ (\mathrm{CHL}) + 0.08275\ (\mathrm{SS})$$

$$Y1 = 0.18648\ (\mathrm{PCA1}) + (-0.14992)\ (\mathrm{PCA2})$$

$$Y2 = 0.08719\ (\mathrm{PCA2}) + 0.32066\ (\mathrm{PCA2})$$

Appendix 5. A comparison of trophic state indices applied in Lake Patzcuaro.

	Trophic State Index (TSI)				
Sampling	Carlson			Shannon and Brezonik	Walker
Station	XSD	XCHL	XTP	TSI	Iw
1	75.13	77.44	71.72	17.14	78.98
2	73.20	75.38	67.39	10.84	71.11
3	73.94	71.86	67.92	9.86	71.53
4	72.84	71.88	63.42	8.25	66.64
5	74.72	74.72	69.62	11.84	75.88
6	75.54	77.30	69.00	15.05	79.41
7	74.32	71.84	63.69	9.20	72.01
8	75.13	76.25	70.71	14.28	78.04
9	73.57	70.23	64.58	8.31	68.69
10	73.57	69.01	62.77	6.84	67.62
11	73.57	71.04	66.71	9.44	69.56
12	73.57	69.70	62.27	6.84	67.99
13	73.20	69.29	62.75	7.59	66.41
14	72.16	69.02	58.27	4.94	60.00
15	71.50	66.13	62.40	4.76	52.14
16	71.83	63.58	59.09	3.06	53.82
17	71.83	68.26	60.59	5.37	57.12
18	71.83	69.77	65.53	6.77	58.87
19	70.87	64.64	59.12	4.15	41.71
20	71.83	66.06	60.36	3.51	55.64
21	73.57	65.47	59.32	5.39	64.77
22	71.19	66.43	61.83	2.37	45.43
23	72.16	65.05	59.12	5.58	57.54
24	72.16	65.52	58.02	4.53	57.68

Carlson (1977)

$$XSD = 60 - 14.41 \ln SD$$

$$XCHL = 9.81 \ln CHL + 30.6$$

$$XTP = 14.42 \ln TP + 4.15$$

Shannon and Brezonik (1972)

$$TSI = 0.936\ (1/SD) + 0.827\ (COND) + 0.907\ (TON) + 0.748\ (TP) + 0.938\ (PP) + 0.892\ (CA) + 0.579\ (1/CR) + 4.76$$

Walker (1979)

$$Ichl = 20.0 + 14.42 \ln CHL$$

$$Itp = -15.6 + 20.02 \ln TP$$

$$Isd = 75.3 + 19.46 \ln (1/SD)$$

$$Iw = (Ichl + Itp + Isd) / 3$$

Appendix 6. Lake phosphorus concentration predictions.

The model proposed by Dillon and Rigler (1975) states that the lake total phosphorus concentration is given by

$$P = \frac{L(1 - R)}{\bar{z}\,(rw)}$$

Where

L = Annual areal phosphorus loading (mg/m2-year)

R =Sediment phosphorus retention coefficient (dimensionless)

$\bar{z}$ = Mean depth (m).

rw = Flushing rate = 1/Hydraulic retention time (years)

The phosphorus lake model suggested by Reckhow and Chapra (1983) has two major improvements over that of Dillon and Rigler (1975). First is the addition of an error estimation procedure to determine the information value and second the data set for the model includes a wide range of lake types so that the model has a wider range of applicability.

$$P = \frac{L}{Vs + qs}$$

Where :

P = Phosphorus concentration (mg/l)

L = Annual areal phosphorus loading (mg/m2-year)

Vs = Apparent settling velocity (m/year)

qs = Areal water loading (m/year)

1. Estimation of areal loading (qs).

Q = (Ad x r) + (As x Pr)

qs = Q / As   or   qs = $\bar{z}$ / Tw

Where

qs = Areal water loading (m/year)

Q = Inflow water volume to lake (m3/year)

Ad = Watershed area (excluding lake) = 803,000 000 m2

As = Lake surface area = 126,000 000 m2

Pr = Mean annual net precipitation = 0.980 m/year

r = Total annual water seepage into the lake=0.0783 m/year
from Figure 3.15, 0.980 m x 0.08 = 0.0783

$\bar{z}$ = Mean depth = 4.97 m

Tw = Hydraulic retention time (years) = Lake volume (V) / Q

Q = (803,000 000 x 0.0783) + (126,000 000 x 0.980)
= (62,900 000) + (123,480 000)

Since lake precipitation equals lake evaporation, then, total annual inflow volume of water to Lake Patzcuaro: Q = 62,900 000 m3

the areal water loading:

$$qs = \frac{62{,}900\ 000\ m3}{126{,}000\ 000\ m2} = 0.5\ m/year$$

the hydraulic retention time:

$$Tw = \frac{628{,}500\ 000\ m3}{62{,}900\ 000\ m3} = 10.0\ years$$

qs = 5/10 = 0.5 m/year

2. Estimation of areal phosphorus loading (L)

A compiled survey of phosphorus export coefficients screened from different catchment areas was presented by Reckhow *et al* (1980). These data were used to calculate high, most likely, and low total loading estimates for Lake Patzcuaro (Tables I and II).

Table I. Phosphorus export coefficients from catchment area.

Source	Units	High	Mid	Low
Agriculture (Eg)	kg/(ha-year)	3.00	0.40	0.10
Forest (Ef)	kg/(ha-year)	0.45	0.15	0.02
Precipitation (Eat)	kg/(ha-year)	0.60	0.20	0.15
Urban areas (Eu)	kg/(ha-year)	5.00	0.80	0.50
Rural areas (Er)	kg/(capita-yar)	1.80	0.51	0.30

Table II. Estimated areas for phosphorus export in Lake Patzcuaro.

Source	Units	
Agriculture (Ag)	2,450	ha
Forest and grassland (Af)	73,000	ha
Urban (Au)	1,063	ha
Atmospheric rainfall (As)	12,600	ha
Rural (Ar)	43,553	capita
Point sources inputs (PSI)	56,804	m3

Total mass phosphorus loading (W) (kg):

W = (Eag x Ag) + (Ef x Af) + (Eu x Au) + (Eat x As) + (Er x No. of capita) + PSI

High: W = 188,300 kg

Mid: W = 94,368 kg

Low: W = 74,003 kg

Annual areal loading (L) (g/m2/year): L = W/As

High: L = 1.489 g/m2/year

Mid: L = 0.746 g/m2/year

Low: L = 0.585 g/m2/year

Lake phosphorus concentration ([P])

$$P = \frac{L}{Vs + qs}$$

High: Ph = 0.1420 mg/l

Mid: Pm = 0.0710 mg/l

Low: Pl = 0.0557 mg/l

3. Estimation of prediction uncertainty (St)

Following the criteria suggested by Reckhow and Chapra (1983) the quantification of prediction uncertainty could indicate the value of the information provided by the model. The procedure is based on first-order error analysis.

Reckhow (1979) using data from 47 lakes observed and predicted phosphorus concentrations estimated the model standard error (Sm) as

$$Sm = [\ (\log Pobs - \log Ppred)^2 / (n - 2)]^{1/2}$$

Where

Pobs = Observed phosphorus concentration (mg/l)

Ppred = Predicted phosphorus concentration (mg/l)

n = 47 lakes.

For the log-transformed model, Sm equals 0.128. This value is later used to calculate the differences known as positive and negative model error for each particular lake as follows

$$Sm^{+} = \text{antilog } [\log_{10} Pm + Sm] - Pm$$

$$Sm^{-} = \text{antilog } [\log_{10} Pm - Sm] - Pm$$

For Lake Patzcuaro: $Sm^{+} = 0.0464$ mg/l and $Sm^{-} = 0.0279$ mg/l

The positive and negative loading error contributions (Sl) are calculated as

$$Sl^{+} = (Ph - Pm) / 2 \quad \text{and} \quad Sl^{-} = (Pm - Pl) / 2$$

For Lake Patzcuaro: $Sl^{+} = 0.0355$ mg/l and $Sl^{-} = 0.00765$ mg/l

The total positive and negative prediction uncertainties (St) are calculated using the equation:

$$St = [(Sm)^2 + (Sl)^2]^{1/2}$$

For Lake Patzcuaro: $St^+ = 0.0584$ mg/l and $St^- = 0.0289$ mg/l. Finally the prediction uncertainty may be expresed in terms of confidence limits. From Reckhow and Chapra (1983) the confidence limits can be written as:

$$\text{Prob}[(Pm - hSt^-) < P < (Pm + hSt^+)) > 1 - 1 / (2.25 h^2)$$

The equation states that the probability that the true phosphorus concentration lies within certain bounds, defined by a multiple (h), of the prediction error, is greater or equal to $1 / (2.25 h^2)$. A value of 1.0 for h corresponds to a probability of 55% and a value of 2.0 for h corresponds to a probability of 90%. Thus the confidence limits at 55% for Lake Patzcuaro are:

$$\text{Prob}[(0.0421) < P < (0.129)] > 0.55\%$$

$$\text{Prob}[(0.0132) < P < (0.188)] > 0.90\%$$

The results of the phosphorus concentration predictive model using the equation suggested by Reckhow (1979) and for the conditions of Lake Patzcuaro suggest a mean value phosphorus concentration of 0.071 mg/l with 55% confidence limits bounding the true phosphorus concentration between 0.042 mg/l and 0.129. A mean phosphorus concentration of 0.065 mg/l was found in Lake Patzcuaro during the present study.

d

Using the equation of Dillon and Rigler (1975):

$$P = \frac{L\,(1 - R)}{z\,(rw)} = \frac{0.746\,(1 - R)}{5 \times (1/10)}$$

If R is calculated using the relationship presented by Dillon and Rigler (1975):

$$R = 0.426\,e^{(-0.271\,qs)} + 0.574\,e^{(-0.00949\,qs)}$$

For Lake Patzcuaro R = 0.943

Then

$$P = \frac{0.746\,(1 - 0.943)}{5 \times 0.1} = 0.085 \text{ mg/l}$$

If R is calculated using the relationship presented by Rechow and Chapra (1983):

$$R = \frac{Vs}{Vs + (z/Tw)} = \frac{Vs}{Vs + qs} = \frac{10}{10 + 0.5} = 0.952$$

Then

$$P = \frac{0.746\,(1 - 0.952)}{5 \times 0.1} = \frac{0.0355}{0.5} = 0.0710 \text{ mg/l}$$

The same value calculated by the equation suggested by Reckhow (1979).